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A multi-hazard approach for resilient and sustainable disaster-related infrastructure development

Clairine Octha Fedhora[1,*], Oktaviani Novitasari[1], Visky Alfani[1], Eka Fauzia Ramadhani[1], Alidyatul Masruroh[1]
[1] *Environmental Engineering, Faculty of Civil Engineering and Planning, Institut Teknologi Adhi Tama Surabaya, Surabaya, East Java 60117, Indonesia.*
*Correspondence:clairineoctha06@gmail.com

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ABSTRACT
Background: Indonesia is highly vulnerable to natural disasters, making the development of disaster-resilient and sustainable infrastructure a strategic necessity for disaster risk reduction and long-term development. This study aims to examine the concepts, principles, and challenges of developing resilient and sustainable disaster infrastructure based on recent literature. **Methods:** The research employs a qualitative descriptive approach through a literature review of scientific journal articles, policy reports, and publications from national and international institutions. **Finding:** The findings indicate that infrastructure resilience is not solely determined by physical strength but also by the integration of disaster risk analysis, sustainability-oriented planning, and adaptive governance and innovation. Multi-hazard risk-based approaches and the use of digital technologies play a significant role in enhancing the effectiveness of disaster infrastructure development. However, major challenges remain in terms of institutional capacity and coordination among stakeholders. **Conclusion:** This study concludes that the development of resilient and sustainable disaster infrastructure requires an integrated approach that combines technical, policy, social, and environmental aspects to support inclusive and sustainable development. **Novelty/Originality of this article:** This article contributes originality by synthesizing recent literature to frame disaster-resilient and sustainable infrastructure as an integrated multi-hazard system that combines engineering resilience, digital technologies, and adaptive governance, offering a comprehensive perspective aligned with contemporary disaster technology and engineering challenges.

KEYWORDS: disaster infrastructure; disaster risk reduction; resilience; sustainable development.

1. Introduction

Indonesia has been identified by researchers as one of the nations with high levels of vulnerability to disasters because of its geographical location in the Pacific Ring of Fire and the effects of climate change globally. Disasters, including earthquakes, floods, landslides, and tsunamis, pose a substantial risk to critical infrastructure and can cause serious damage to public services as well as threaten social stability and inhibit economic growth. Therefore, developing infrastructure that is structurally resilient as well as adaptive and recoverable from disaster-related disruptions is essential due to this vulnerability. The resilience of infrastructure development has become an internationally accepted framework for disaster risk reduction and sustainable development strategies. The United

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Nations Office for Disaster Risk Reduction (UNDRR) defines resilient infrastructure as being able to perform its core functions when exposed to hazards of all kinds while adapting to the effects of climate change and extreme disasters, and providing essential services (e.g., water supply, transportation, energy delivery) in a sustainable manner (UNDRR, 2017). As part of advancing national resilience to disasters through improved infrastructure, the government of Indonesia has made the development of strong, sustainable infrastructure a top priority. The emphasis placed by the nation's leaders in various strategic forums on the need for a more holistic approach to infrastructure design and construction to reduce the effects of disasters, guarantees that infrastructure will be built with consideration for potential disaster risks with the goal of reducing both property loss as well as ensuring that communities are able to continue economically and socially through any period of disruption caused by the effects of a natural disaster. In addition, building disaster-resilient infrastructure is consistent with sustainable development as it integrates economic, social and environmental factors in a manner that supports long-term community well-being. Infrastructure investments that improve capacity and service delivery include consideration for environmental impact and community preparedness in the event and recovery from a disaster.

Numerous studies about the development and construction of infrastructure support the existence of potential positive outcomes associated with infrastructure projects, however there have also been studies that have documented challenges related to uneven levels of development among regions, environmental impact and successful implementation of infrastructure policies. Some management studies have reported on the successful implementation of infrastructure projects resulting in increased levels of economic development while other studies have reported on difficulties related to community and environment. Differences in research results show that there isn't enough research done about infrastructure improvement and how it affects people. As cities grow and climate change causes extremes to increase, many developing countries, including Indonesia, are experiencing increasing risks from disasters.

The expanding urban areas often have no or very little spatial planning and environmental regulations, which leads to people living in high risk areas of flooding, landslides, and coastal disasters. Per UN-Habitat, resilient urban infrastructure will be important to support the development of sustainable cities and to reduce the social/economic impacts of disasters (UN-Habitat, 2022). Infrastructure resilience is defined not only in terms of strength through structures but also on adaptive governance and environmental stewardship. In addition, providing sustainable benefits through infrastructure investment aligns closely with SDG 9 (Resilient Infrastructure) and SDG 11 (Sustainable Cities and Communities) (UNSD, 2023). By integrating disaster risk reduction with infrastructure planning, a country can increase long-term economic productivity while reducing environmental degradation and the vulnerability of social groups. For this reason, building resilient infrastructure is now a strategic priority for countries confronted with growing climate and disaster risk.

In addition, a multi-hazard approach is necessary for the future of infrastructure development through the application of a sustainable development approach. In Indonesia, the various threats to infrastructure throughout the country can occur either simultaneously or interdependently. Therefore, an integrated analysis of the risks associated with infrastructure is essential. The relationships among different types of infrastructure can contribute to the cascading impact of disasters upon each other (Mühlhofer et al., 2023). This reason, an analysis of multi-hazard risks supporting infrastructure development must lead to infrastructure that is more effective, adaptive, and sustainable

The opportunities provided by ever-increasing advances in digital technologies can provide significant potential to enhance the resilience of infrastructure in relation to the impacts of disasters. Applying these technologies such as Geographic Information System (GIS), Internet of Things (IoT), big data and artificial intelligence (AI) will enable governments to improve their capacity for real-time risk monitoring as well as the optimization of early warning systems. The integration of digital technologies with smart urban systems, as illustrated in Sharifi (2020) and Sharifi & Yamagata (2022) will provide cities with enhanced capacity to manage disaster risks through rapid and accurate information management. Moreover, Pescaroli & Alexander (2019) state that the interconnected nature of disaster risk will necessitate adaptive, data-driven infrastructure systems to mitigate against cascading systemic effects of disaster incidents. This study will systematically analyse the role of the multi-hazard approach, principles of sustainable development, and digital innovation to support the development of disaster resilient infrastructure in Indonesia. This study will identify gaps in literature to establish a basis for future literature development and infrastructure planning (Azmiyati & Poernomo, 2019).

2. Method

2.1 Research stages

This is a descriptive literature review aimed as part of a comprehensive literature review exploring prior research findings and the relationship between existing and new research to the development of infrastructure. Literature reviews are designed to find and evaluate all existing literature about a topic from previous studies that are applicable to this study. There were systemically structured phases followed during the study in relation to the evaluative effectiveness of disaster-related built infrastructure in terms of both resilient and sustainable disaster-related built infrastructure. The first phase identified specific issues with regard to the built infrastructure; specifically, the high levels of vulnerability of infrastructure to natural disasters and the lack of incorporation of resilient disaster-related infrastructure principles and sustainability principles in disaster-prone areas of the built environment. The next phase involved the collection of data through a descriptive literature review of relevant reviewed paper articles published in peer-reviewed journals within the past five years. The literature selection was based on peer-reviewed journals from both national and international sources with articles that were relevant to built–in infrastructure, included a discussion of resilience in the context of disaster-related built–in infrastructure, and included the integration of sustainable development and disaster-related built–in infrastructure. The third phase involved analysing and synthesising the data collected in the previous phases using content analysis methods. In this phase, the literature collected from relevant literature was reviewed in detail for the purpose of identifying key themes, methods used, and the major findings related to the development of disaster-related built–in infrastructure.

An inventory of the information extracted was then categorized into various themes: infrastructure planning methods; ways of analyzing disaster risk; and applying the notion of sustainability to all projects. The next phase consisted of synthesis and conclusion development, where analytical results from each of the studies were compared, and integrated to create a breadth of understanding regarding resilient and sustainable infrastructure development practices related to disaster situations. This phase also contained the intent to identify voids in research and create concepts for future policy-making and infrastructure planning efforts. The literature review process was performed using multiple sources of scientific literature such as Scopus, ScienceDirect, Google Scholar, and SpringerLink. The following terms were searched using keywords including disaster-resilient infrastructure, multi-hazard risk, sustainable infrastructure, climate change adaptation, and infrastructure resilience. The articles included a primary focus on disaster risk reduction, resilient infrastructure, integrating sustainability, and governance in relation to infrastructure development. Articles not focusing on disaster mitigation and/or sustainable infrastructure planning were excluded from the analysis; thus, the articles selected provided a holistic view of current challenges and strategies for resilient infrastructure.

Next, the accumulated literature went through a selection and screening process, which included an assessment of the relevance and recency of their content and how they matched the overall objectives of the research focus. The literature that passed the previous stage was then analyzed to identify common themes, methodologies, and results of the literature reviewed. The results of this analysis were then integrated to create a complete description of the development of robust and sustainable infrastructure. The last step of the project involved drawing conclusions to determine overall trends, implementation issues, and areas for further research.

2.2 Content analysis

In this investigation, content analysis is utilized as a technique for providing a systematic process of interpreting and evaluating existing literature. Utilizing an objective and organized structure, the content analysis enables researchers to identify meanings, patterns, and trends within the available scientific literature. In addition to enabling researchers to summarize literature, content analysis also permits researchers to conduct a detailed examination of literature regarding the methodology and findings presented. The analytical process will involve data coding, which includes identifying keywords, core concepts and key statements related to infrastructure resilience and sustainable development. After the data has been coded, it will then be categorized into thematic areas of analysis (e.g., technical aspects of infrastructure, governance and policy, disaster risk analysis, environmental and social sustainability). Each thematic area will then be assessed for similarities and differences in approaches from the different studies in the literature, as well as to determine the degree of rehabilitation and sustainability principles that have been implemented through studies focused upon the development of disaster-related infrastructure. The findings from this comparative analysis will subsequently be used to generate a conceptual synthesis and identify research gaps specific to disaster-related infrastructure development.

The literature utilized as a source for all three different journals reviewed, demonstrating that while each study presented distinctly different areas of research relating to infrastructure development and resilience, there exists significant inter-relatedness between studies. Gazali provides evidence of the relationship of infrastructure to regional development and resilience to disaster events (Rachman et al., 2025). Harahap has developed a new and comprehensive multi-hazard profile for Indonesia's outermost small islands that addresses both coastal and geophysical hazards and also looks at key variables such as exposure and vulnerability. This is still primarily about risk assessment, and does not yet address how best to use the analytical output for strategies to enhance infrastructure resilience, new policy innovations, or development governance (Harahap et al., 2025). At the same time, Tasya emphasizes how much more resilient we will be to disasters when we connect digital changes in innovative ways with good governance practices by improving our overall infrastructure. This research provides the basis for a comprehensive theoretical model, but it does not provide the necessary evidence to support that model through the examination of risk and damage using specific geographical locations and hazard quantifications. Thus, even though it can be used to develop general policies, the implementation of these policies requires specific consideration of what will work best in specific geographic areas with unique vulnerabilities such as coastal communities or small islands (Tasya, 2025). The findings of the analysis are that the two primary research methodologies, the literature narrative review and the content analysis, can be effectively used to more thoroughly explore the relationship between the risks of disasters, sustainable development, and the governance of infrastructure, as well as to identify existing research voids that can be leveraged into establishing future studies and/or informing public policy.

3. Result and Discussion

3.1 Discussion

This stusy found through this evaluation that in order to create and develop resilient and sustainable disaster-related infrastructure, an integrated approach will be required with respect to the technical, policy, and institutional aspects. Infrastructure resilience cannot be achieved optimally if its development has only been based upon meeting immediate physical needs (e.g. "short-term") without considering the potential risks from disasters, and the associated longer-term sustainability of infrastructures More precisely, by involving disaster risk analysis into infrastructure development policy as noted by Rachman (2025), it will assist with targeted planning for infrastructure development, and result in more efficient and sustainable resource use (Tasya, 2025). Involving an analysis of disaster risk within the infrastructure development policy (as discussed by Rachman (2025), is just one example of how strategic planning can help with reducing the potential losses experienced as a result of disasters (Rachman et al., 2025). Thus, infrastructures function as not only a means of facilitating economic activities, but also as an instrument for disaster risk mitigation

Using a multi-hazard approach to developing infrastructure helps to increase the resilience of infrastructure systems in areas that are highly vulnerable. As pointed out by Harahap, infrastructure development that does not consider the multiple and complex disaster risks can create new vulnerabilities in the long run (Harahap et al., 2025). So, the use of a location-based risk approach is a key component of accomplishing sustainable infrastructure development. Additionally, it is widely accepted by authors that the success of disaster-related infrastructure development is affected by the level of institutional capability and good governance processes. The impact of digital innovations and data-based decision support systems can potentially improve infrastructure planning and evaluation practices. Nevertheless, these innovations will be able to function more effectively if institutions improve their cooperation and work together to support the capacity of human resources to operate at their full potential (Tasya, 2025).

In countries vulnerable to disasters, climate change has raised the vulnerability of their infrastructure, especially in coastal and urban locations. Infrastructure systems are damaged from sea-level rise, extreme rainfall intensity, prolonged droughts, and increased temperatures; thus, disaster relief efforts will be affected. To create resilient infrastructure, the infrastructure development process needs to include climate adaptation strategies, environmental sustainability, and long-term disaster risk reduction in the planning of infrastructure projects. The IPCC has predicted that the frequency and severity of climate-related hazards will continue to increase, thus requiring adaptive, risk-based infrastructure policies from governments (IPCC, 2022). Moreover, applying a multi-hazard approach to increase infrastructure resilience is an accepted method for creating this framework.

There are numerous ways that infrastructure can be affected by different hazards that are connected or occurring at the same time (for example, earthquakes, floods, landslides and tsunamis). Failure to conduct multi-hazard assessments increases the vulnerability of infrastructure to systemic failures, which may result in cascading disaster impacts affecting transportation, energy, and water supply networks (Mühlhofer et al., 2023). Therefore, a comprehensive risk assessment model will support sustainable infrastructure investment and minimize long-term economic losses. Furthermore, digital innovations are a vital element to successfully prepare for disasters and manage our infrastructure. Utilizing digital technologies (such as GIS, remote sensing, AI and early warning systems) allows for increased hazard monitoring by government and stakeholder agencies while enhancing coordination of emergency response (Damaševičius et al., 2023). However, implementing a digital resilience strategy will depend heavily on an organisation's institutional capacity, inter-agency collaboration and suitable financing structures. As such, when building resilient infrastructure, the entire process should include considerations for engineering solutions, governance quality, social inclusion, and community involvement to ensure long-term sustainability.

In the case of the Indonesian infrastructure systems, Table 1 indicates that the weight of the impact from each of the hazard types (flood and earthquake) is highest from both a structural and an environmental standpoint. This means that when developing strategies to improve the resilience of an infrastructure system, there must be consideration for improving both structural and environmental aspects of an infrastructure system in order to minimize the impact of disasters and promote long-term sustainability. As such, there is a need for planning for infrastructure to not just protect the physical assets within an infrastructure system, but also to provide a means of ensuring that the public has access to the services from those assets regardless of the severity of a disaster event.

Table 1. Multi-hazard infrastructure risk analysis

Hazard Type	Infrastructure Impact	Resilience Strategy
Flood	Drainage failure and road inundation	Green infrastructure and retention ponds
Earthquake	Structural collapse	Seismic-resistant design
Landslide	Transportation disruption	Slope stabilization
Tsunami	Damage to coastal infrastructure	

Research conducted by Verschuur et al. (2023) demonstrates that port infrastructure worldwide faces significant risks due to various natural hazards, including tropical cyclones, earthquakes, river flooding, inundation, and coastal flooding. Through a multi-hazard risk analysis of 1,340 ports globally, the study found that more than 86% of ports are exposed to three or more types of hazards, with total estimated losses reaching 7.6 billion USD per year, predominantly attributable to the impacts of tropical cyclones. Beyond physical damage, operational disruptions caused by extreme weather conditions also result in logistical losses and a potential reduction in global trade of up to 66.9 billion USD per year, with small island developing states (SIDS) identified as the most vulnerable. This study underscores the importance of a multi-sector and multi-hazard approach in port resilience planning, encompassing the enhancement of engineering standards, the improvement of supporting infrastructure such as road networks and power supply, and the development of operational and post-disaster recovery capabilities to minimize disruptions to global trade flows and supply chains.

A study by Joshi et al. (2024) highlights the critical importance of integrating local vulnerability factors into multi-hazard risk assessments for rail infrastructure, as exposure to hazards alone does not determine risk levels. The Northern Railway (NR) and Northeast Frontier Railway (NFR), followed by Central Railway (CR), consistently emerged as the highest-risk zones across physical and social vulnerability scenarios, while the North Western Railway (NWR) recorded the lowest risk — a pattern corroborated by historical emergency case data spanning 2005 to 2020, which yielded a moderate but statistically significant correlation of $r(17) = 0.4758$ with the combined mean risk ranks. Notably, physical vulnerability indicators such as bridge health (ORN ratings) demonstrated a stronger correlation with emergency cases ($r = 0.4605$) compared to social and economic vulnerability indicators ($r = 0.2946$ and $r = 0.0512$, respectively), affirming that physical factors contribute more directly to safety losses than socioeconomic ones. The seasonal distribution of accidents — with approximately 50% occurring during the monsoon season due to track washouts, poor visibility at level crossings, landslides, and debris flows — further underscores the disproportionate influence of hydrometeorological hazards on railway operations. An interesting anomaly was observed in Kerala, which despite its relatively strong economic standing, exhibited high risk due to the dense concentration of visibility-impaired level crossings exposed to intense rainfall, illustrating that economic strength alone does not mitigate localized physical hazard exposure. These results collectively suggest that a disentangled, vulnerability-specific approach to risk assessment — one that separates physical, social, and economic dimensions — is more effective for prioritizing infrastructure interventions and allocating limited resources than conventional aggregate assessments, and that future research should incorporate additional vulnerability dimensions such as maintenance staff vacancies, embankment and tunnel health, and cyclone or subsidence hazards to achieve a more comprehensive risk profile for Indian Railways.

Azzahra et al. (2025) demonstrate that the coastal area of Cidaun, Cianjur, exhibits a diverse range of geomorphological and physical characteristics that collectively contribute to its high multi-hazard vulnerability, as evidenced by the identification of eight CHW classification codes across 82 transects along its 26.42 km coastline. The dominance of sloping soft rock coast (39.24%) and sedimentary plain (29.44%) geological layouts reflects the dual nature of Cidaun's coastal topography, where low-lying areas — particularly in Desa Sukapura, Cisalak, and Jayapura — are significantly more susceptible to gradual inundation, saltwater intrusion, and flooding compared to the elevated rocky stretches found in Desa Cidamar and Karangwangi.

The TSR and PL-5 classifications, which together account for nearly 45% of the total coastline, represent the most hazard-prone segments, with both categories recording very high risk levels for erosion and flooding, a finding consistent with the DSAS analysis showing that 59.38% of the shoreline is in a deficit or erosional state. The near-absence of protective coastal vegetation — with 77.30% of the coast classified as not vegetated — further amplifies erosion risk across soft rock and sedimentary plain segments, as natural bioshields such as mangroves are unable to establish themselves given the predominantly highland terrain and microtidal conditions (average tidal range of 1.76 m). In contrast, the R-1 and SR-15 classifications, characterized by elevated rocky terrain with adequate vegetation cover, consistently recorded low risk across all five hazard categories, underscoring the protective role of topographic elevation and vegetative cover in reducing coastal vulnerability. The proposed management options — including Coastal Zoning, Tsunami Warning System, Beach Nourishment, Groundwater Management, Flood Warning System, and Ecosystem-Based Management — are appropriately tailored to address the site-specific risk profiles identified through the CHW framework, and their combined implementation represents a spatially differentiated, integrated approach to disaster risk reduction that can serve as a replicable model for other similarly exposed coastal districts along the southern coast of Java.

3.2 Digital technology and smart infrastructure

The ability to strengthen disaster resilient infrastructures via digital transformation has become more prominent in the mainstream (Damaševičius et al., 2023). The use of Geographic Information Systems (GIS), remote sensing, big data analysis, and artificial intelligence allows government agencies to perform more advanced disaster risk assessments and maintain continuous oversight of critical infrastructure assets (Damaševičius et al., 2023). Digital technologies play a significant role in supporting early warning systems, hazard mapping, infrastructure assessment, and emergency response coordination (Ogie et al., 2018).

Technology can be established as part of an effective early warning system, the creation of hazard maps, the completion of infrastructure evaluations, and work toward building a strong emergency response coordination system among all first responders. In particular, satellite based measurements can reveal flooding-related hazards, subside areas and evaluate environmental degradation in real time (Linkov, 2013). Further, the capabilities of AI will support policymakers as they evaluate and forecast disasters and make informed decisions on the optimal investment in infrastructure (Sharifi, 2020) Smart technologies have brought improvements in both reliability and efficiency of public services and, through intelligent transportation systems, digital water management systems, and smart energy grids, have helped to provide more resilient infrastructure for disaster recovery. Data-driven decision-making improves inter-agency coordination and supports the development of evidence-based policies (Pescaroli, 2021). However, digital transformation presents challenges such as limited technical capacity, high investment costs, cybersecurity risks, and unequal access to digital infrastructure (Argyroudis & Mitoulis, 2019). As such, governments need to develop stronger digital governance frameworks and invest in capacity building programs to help ensure the successful utilisation of smart infrastructure technologies (Tierney, 2012).

With smarter infrastructure comes the implementation of predictive maintenance, which can reduce operational costs and avoid catastrophic failure of major infrastructures as a result of emergencies (Bruneau et al., 2003). Digital twins and simulation technologies allow engineers and policymakers to assess the performance levels of their infrastructures under multiple disaster scenarios (Cimellaro et al., 2010). innovations support proactive planning and increase the effectiveness of disaster mitigation strategies; however, for successful implementation, there needs to be strong institutional coordination, effective data management systems, and public trust in digital governance. In addition, investments in technical education and training for human resources are required to increase overall human capacity for sustainability of digital resilience programs (Damaševičius et al., 2023).

A concrete example of how these principles are being translated into practice can be seen in the work of Ugliotti et al. (2025), who adopts the TERIMAAS framework. The TERIMAAS framework represents a significant methodological advancement in multi-hazard risk assessment by successfully bridging the long-standing divide between territorial-scale GIS analysis and building-scale BIM data through a centralised PostgreSQL/PostGIS database that dynamically incorporates real-time IoT-derived information, thereby overcoming the critical limitation of static, post-event data collection that has historically constrained traditional risk assessment systems.

The flood risk case study applied to the Primary School of Crodo in Val d'Ossola, northwest Italy — a location characterised by both moderate-to-high seismic activity and elevated flood probability — effectively demonstrates how the integration of heterogeneous data streams, including high-resolution DEMs, SCS Curve Number rasters, historical flood footprints, and real-time meteorological inputs retrieved at 15-minute intervals via OpenMeteo APIs, can be operationalised into actionable, element-level risk assessments within a BIM environment. The Dynamo-based bidirectional data exchange mechanism proved particularly valuable in enabling the dynamic recalculation of hazard, vulnerability, and exposure scores at the level of individual building components — including walls, windows, doors, and functional spaces — with the temporal exposure factor accounting for occupancy patterns that significantly elevate overall risk during school hours, a nuance that purely spatial or static assessments would fail to capture.

The colour-coded risk thematisation visualised within the 3D BIM model demonstrated that the framework not only identifies flood-susceptible structural elements and sensitive functional spaces such as basement archives and server rooms, but also supports proactive resource allocation decisions by enabling facility managers and policymakers to anticipate potential damage scenarios before an event occurs. Nonetheless, several limitations temper the framework's current applicability, particularly the substantial resource requirements in terms of technical expertise, data infrastructure quality, and proprietary software dependency, as well as unresolved challenges in BIM-GIS geometric data interoperability during format conversion from IFC to spatial databases — issues that future work integrating open-source BIM tools, AI-assisted predictive analytics, and decentralised data architectures such as blockchain would need to systematically address to enhance the framework's scalability, security, and broader adoption across diverse geographic and socioeconomic contexts. Building upon this building-scale perspective, a complementary yet broader methodological lens is offered by studies that extend multi-hazard risk assessment to the urban infrastructure network level, where the interdependencies between roads, buildings, and lifeline systems become the central analytical focus.

The innovative methodological perspective proposed in this study addresses a critical and long-standing gap in critical infrastructure (CI) assessment by recognising that conventional single-hazard, single-application approaches are fundamentally inadequate for capturing the complex interdependencies and cascading failure dynamics that characterise real-world multi-hazard scenarios, particularly in densely populated urban environments such as Penang, Malaysia. The distinction drawn between intrinsic seismic vulnerability index (ISVI) and eccentric seismic vulnerability index (ESVI) is especially instructive, as the integrated application of both indices was demonstrated to elevate the overall vulnerability rating by approximately 50% compared to assessments relying on either index in isolation — a finding that powerfully underscores the danger of fragmented, siloed assessment models that evaluate roads, buildings, and lifeline systems as disconnected entities rather than as an interdependent networked system where the collapse of one element, such as building debris blocking adjacent road networks, can precipitate cascading disruptions across hospitals, fire stations, and governmental facilities.

The three-step methodological framework — progressing from the construction of integrated vulnerability maps and progressive multi-hazard risk models, through the development of Unreal Engine-based holistic gaming scenarios that visually simulate infrastructure damage states, to the implementation of a Virtual Reality application that renders a real-time, spatially accurate depiction of the disaster-affected urban environment — represents a meaningful departure from the rudimentary, manually compiled functional curves and static GIS outputs that have historically constrained both analytical precision and stakeholder communication. By embedding gaming platforms and VR visualisation tools into the disaster management workflow, the framework not only improves the sequential and realistic representation of multi-hazard consequences but also creates an accessible interface for emergency planners, first responders, and governmental agencies to rehearse evacuation procedures and resource allocation decisions within immersive, high-fidelity simulated environments — a capability that static vulnerability indices and two-dimensional GIS maps are structurally incapable of delivering (El-Maissi et al., 2024).

3.3 Governance and institutional challenges

The way institutions govern themselves plays a vital role in the ability of built environments to provide resiliency to society. Institutional governance that promotes effective disaster risk reduction requires working collaboratively and coordinating with various stakeholders, which include central government, local authorities, the private sector, and the community (UNDRR, 2023). To achieve this goal, policies regarding disaster risk reduction must be integrated with those of infrastructure planning to enable the consistent application of principles of resilience across all sectors (UNDRR, 2015). Unfortunately, many developing nations currently suffer from the problems of fragmentation among their institutions, excessive regulation (or bureaucratic red tape), and the inability to financially support resiliency measures for their infrastructures (Tierney, 2012).

As a result of these weak institutions and governance systems, the potential for inefficient investment in infrastructure and poor preparedness to respond to disasters is highly likely (Rachman et al., 2025). Selain Additionally, resiliency in infrastructure requires prolonged policy commitments from the institution as well as the adaptive capacity to respond to unforeseen events through planning (Vale, 2014). There must also be an effort from governmental entities to foster transparency and accountability through stakeholder participation in order to improve the effectiveness of policy implementation (Adger, 2000). The participation of the community in planning for the resiliency of their local infrastructures is especially significant because of their intimate and knowledgeable understanding of their community's vulnerabilities, which will enable them to develop local resilience strategies specific to their context (UN-Habitat, 2022). Selain are also opportunities for public-private partnerships to expand the financing of infrastructure projects and foster technological advancement (Hallegatte, 2021). International collaboration plays a key role in providing future strength by utilizing knowledge-sharing opportunities, providing technical assistance, and leveraging mechanisms to obtain financing for climate mitigation (Bank, 2020).

Therefore, the two key components that contribute to building a resilient infrastructure are collaborative governance and institutional reform. Governance structures should prioritize policies that ensure the inclusion of disadvantaged groups in disaster planning and post-disaster recovery processes. Furthermore, decentralized governance systems may foster innovation and strengthen community responsiveness to infrastructure-related needs (Francis & Bekera, 2014). However, decentralization will also require sufficient financing and technical skill sets at the community level. As a result, the success of governance relies on the ability to create a balance between national coordination and local flexibility (Birkmann et al., 2013). Robust monitoring and evaluation systems will provide some level of assurance that the policies that have been developed are effective and will help to identify any deficiencies in the way infrastructure resilience is implemented (Cutter, 2020). Ultimately, institutional capacity will remain one of the most important constraints to successful disaster resilient infrastructure development (Francis & Bekera, 2014).

Based on the synthesis of the discussion, this study identifies three main pillars that form an integrated framework for sustainable disaster infrastructure resilience, as illustrated in Figure 1. The first pillar, the multi-hazard approach, emphasizes that infrastructure planning should not focus solely on a single type of hazard, particularly in vulnerable regions such as Indonesia, which simultaneously face risks from floods, earthquakes, landslides, and tsunamis. The second pillar, digital innovation and smart technology, serves as an enabling factor in improving the accuracy of risk assessments, real-time infrastructure monitoring, and emergency response coordination through the utilization of Geographic Information Systems (GIS), artificial intelligence, digital twins, and early warning systems. The third pillar, governance and institutional capacity, forms the foundation for the successful implementation of the previous two pillars, as technical and digital approaches cannot function optimally without cross-sector collaboration, adequate decentralization, and sustainable financing. This framework also demonstrates that climate adaptation and social inclusion act as supporting components that strengthen the three main pillars. As a result, the infrastructure resilience developed is not only technical in nature but also responsive to environmental dynamics and the needs of vulnerable groups within society.

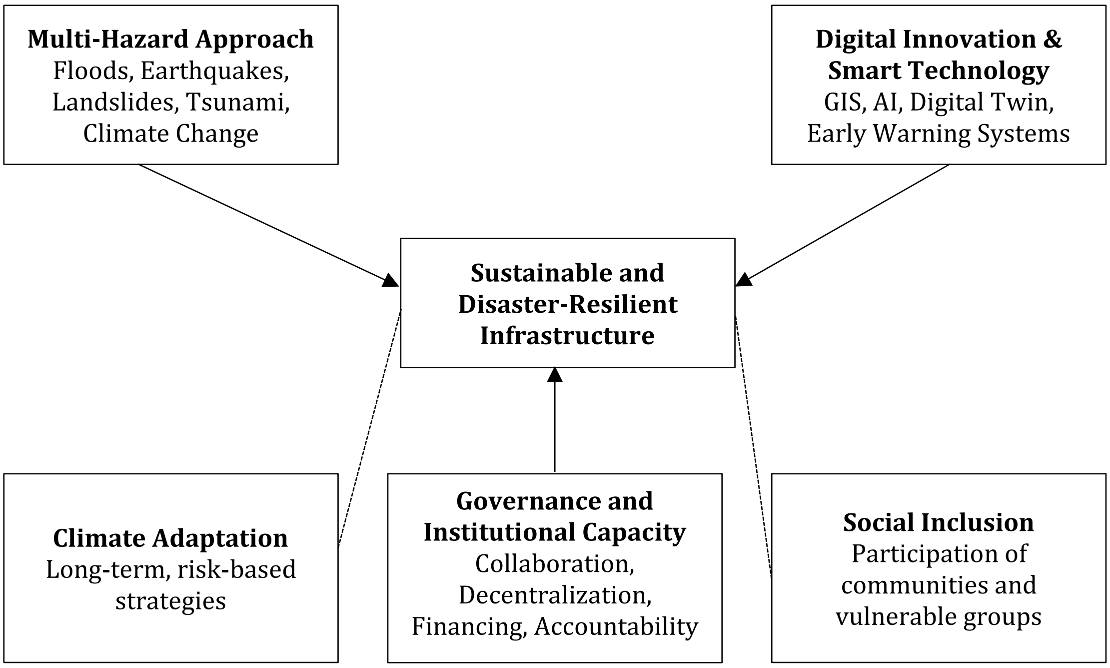

Fig. 1. Integrated framework for disaster infrastructure resilience

4. Conclusion

According to findings from a literature review, developing resilient and sustainable disaster-related infrastructure is intended to provide a strategic framework for building strong, durable, and resilient infrastructure and similarly prepare for and address impacts associated with disasters in a way that is also sustainable over time. Resilience in infrastructure should be viewed as a multidimensional concept that incorporates all facets of technology, policies, and institutions; as well as social considerations. A comprehensive review of the literature demonstrates that the integration of disaster risk in planning and developing infrastructure requires an analytical process that utilizes a number of different types or families of hazards (e.g., floods, hurricanes, etc.) in order to develop and deliver the necessary infrastructure to support sustainable public service operations. These approaches promote decision-making for infrastructure that is adaptable and targeted to disaster-related loss minimization while maintaining the long-term viability of public service operations.

In addition, digital innovations or improvements in governance (or better governance) have been shown to have a substantial impact on the efficiency of developing disaster infrastructure. However, the effectiveness of such methods will heavily rely upon institutions' capacity, stakeholders' coordination, and long-term commitment to policy. Accordingly, creating a resilient and sustainable disaster infrastructure system will require an integrated approach that utilises risk assessment models coupled with sustainability principles, as well as adaptive governance. The expected result is to improve disaster infrastructure resilience and promote inclusive and sustainable development at the national level. Future policy and planning for infrastructure should be directed at three areas: improving adaptive planning processes; creating resilient infrastructure to weather climate change; and creating an inclusive governance process within community-based organisations in order to alleviate disaster risk in vulnerable populations. Collaborations among the public sector, educational institutions, the business community, and local communities are essential for the development of resilient infrastructure. Additionally, ongoing research should include the development of quantitative assessment models for measuring resilience and implementing disaster mitigation plans for specific regions; this will allow for the adoption of evidence-based decision-making within the policy process.

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Biographies of Authors

Clairine Octha Fedhora, Environmental Engineering, Faculty of Civil Engineering and Planning, Institut Teknologi Adhi Tama Surabaya, Surabaya, East Java 60117, Indonesia.

- Surel: clairineoctha06@gmail.com
- ORCID: N / A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Visky Alfani, Environmental Engineering, Faculty of Civil Engineering and Planning, Institut Teknologi Adhi Tama Surabaya, Surabaya, East Java 60117, Indonesia.

- Surel: viskyalfani@gmail.com
- ORCID: N / A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Eka Fauzia Ramadhani, Environmental Engineering, Faculty of Civil Engineering and Planning, Institut Teknologi Adhi Tama Surabaya, Surabaya, East Java 60117, Indonesia.

- Email: ekafauziara@gmail.com
- ORCID: N / A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Alidyatul Masruroh, Environmental Engineering, Faculty of Civil Engineering and Planning, Institut Teknologi Adhi Tama Surabaya, Surabaya, East Java 60117, Indonesia.

- Email: alidyatulmasruroh@gmail.com
- ORCID: N / A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Oktaviani Novitasari, Environmental Engineering, Faculty of Civil Engineering and Planning, Institut Teknologi Adhi Tama Surabaya, Surabaya, East Java 60117, Indonesia.

- Email: oktanovitasari32@gmail.com
- ORCID: N / A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A