https://doi.org/10.1051/e3sconf/202447402013

An integrated review and analysis of urban building seismic disaster management based on BIM-GIS

Irina Maltseva [1,*], *Tianxin* Meng [1], *Shuoting* Xiao[1], *Yizhi* Cao[2], and *Lingjian* Zeng[1,2]

[1]Ural Ural Federal University named after the First President of Russia B. N. Yeltsin, Yekaterinburg, Russia
[2]North China University of Water Resources and Electric Power, Ural Institute, Zhengzhou, China

Abstract. Given the increased frequency and destructive nature of seismic events, the exigencies for enhanced management protocols for urban edifices in the milieu of seismic disaster scenarios have intensified. The role of Building Information Modeling (BIM) and Geographic Information Systems (GIS) in the governance of seismic-induced disasters is integral and merits recognition. The synergistic application of BIM and GIS technologies empowers the strategic articulation of measures that substantially abate the potential hazards associated with seismic events. The present manuscript conducts a comprehensive review of the applications of BIM-GIS synergy in the domains of seismic disaster prevention, emergency response, and in the evaluative and recovery phases following such calamities. It also examines the associated data paradigms and advancements in data interoperability techniques while addressing the prevailing limitations within the scope of contemporary research. This study endeavors to enhance the acumen of urban disaster management operatives in discerning and capitalizing on the collective strengths of BIM and GIS, with the aim of optimizing urban strategies for managing seismic disasters and diminishing the resultant losses sustained by the populace.

1 Introduction

Seismics are recognized as one of the most potentially destructive natural phenomena, posing significant challenges to human habitats and structural safety due to their unpredictable nature. Globally, millions of seismic events are recorded annually [1], highlighting the relentless threat they pose. The accelerated pace of urbanization brings the management of urban seismic hazards into sharp focus. Conventional seismic-resistant practices are increasingly insufficient in addressing the complex dynamics of urban ecologies, necessitating the support of modern technologies to enhance resilience.

Recent interdisciplinary advancements have propelled Building Information Modeling (BIM) and Geographic Information Systems (GIS) to the forefront in the realm of urban seismic hazard management. BIM technology not only provides comprehensive three-

* Corresponding author: i.n.maltceva@urfu.ru

dimensional building models but also extracts essential data regarding the structural and non-structural attributes of buildings, thus ensuring robust seismic risk forecasting and structural health monitoring [2]. The strength of GIS lies in its capacity to assimilate geospatial data, enabling in-depth analysis that incorporates topographic, geological, and geophysical information from multiple disciplines [3]. The integration of BIM and GIS has emerged as a potent approach, making a significant contribution to seismic disaster management [4].

While BIM focuses on the micro-characterization of the buildings themselves, GIS offers a macro-representation of their external environment [5]. The fusion of BIM and GIS not only allows for precise modeling of urban buildings and their surroundings but also enables the anticipation and evaluation of potential seismic threats, thus providing decision-makers with robust data support. Moreover, this technological synergy can deliver smarter and more efficient seismic disaster management strategies for urban structures, significantly enhancing disaster preparedness.

Despite the vast potential of integrating BIM and GIS in seismic hazard management, the challenge of effectively combining these technologies to maximize their benefits remains a pressing research question. This paper provides a comprehensive review and analysis of urban building seismic hazard management based on BIM and GIS, discussing its evolution, current state, and future directions, with the intention of offering insights and guidance for researchers and practitioners in the field.

2 Literature data source and analysis

The literary data for this article were principally retrieved from multiple databases, including Web of Science, Scopus, and Google Scholar. The publication information from the search results was downloaded and filtered, and the records were subsequently imported as text files into VOSviewer for further analysis [6].

Quantitative analysis of the publications, as depicted in Figure 1, reveals the distribution and growth trends of the top nine sources by publication count within the search results. Notably, 'NATURAL HAZARDS' and 'INTERNATIONAL JOURNAL OF DISASTER RISK REDUCTION' have made substantial contributions to this field, underscoring their leading position. Figure 2 illustrates the network of keyword associations among publications. It can be observed that research on BIM's application in earthquake-resistant building practices seldom includes keywords related to GIS. Moreover, the scope of research incorporating GIS applications in building earthquake resistance is relatively more extensive than that of BIM in earthquake hazard mitigation. Furthermore, the clusters marked in red are loosely connected and are distanced from other clusters, whereas the other clusters are more proximate, with the keyword GIS positioned centrally among them. This indicates a common research nexus between GIS, BIM, urban planning, structural earthquake resilience, and architectural damage analysis.

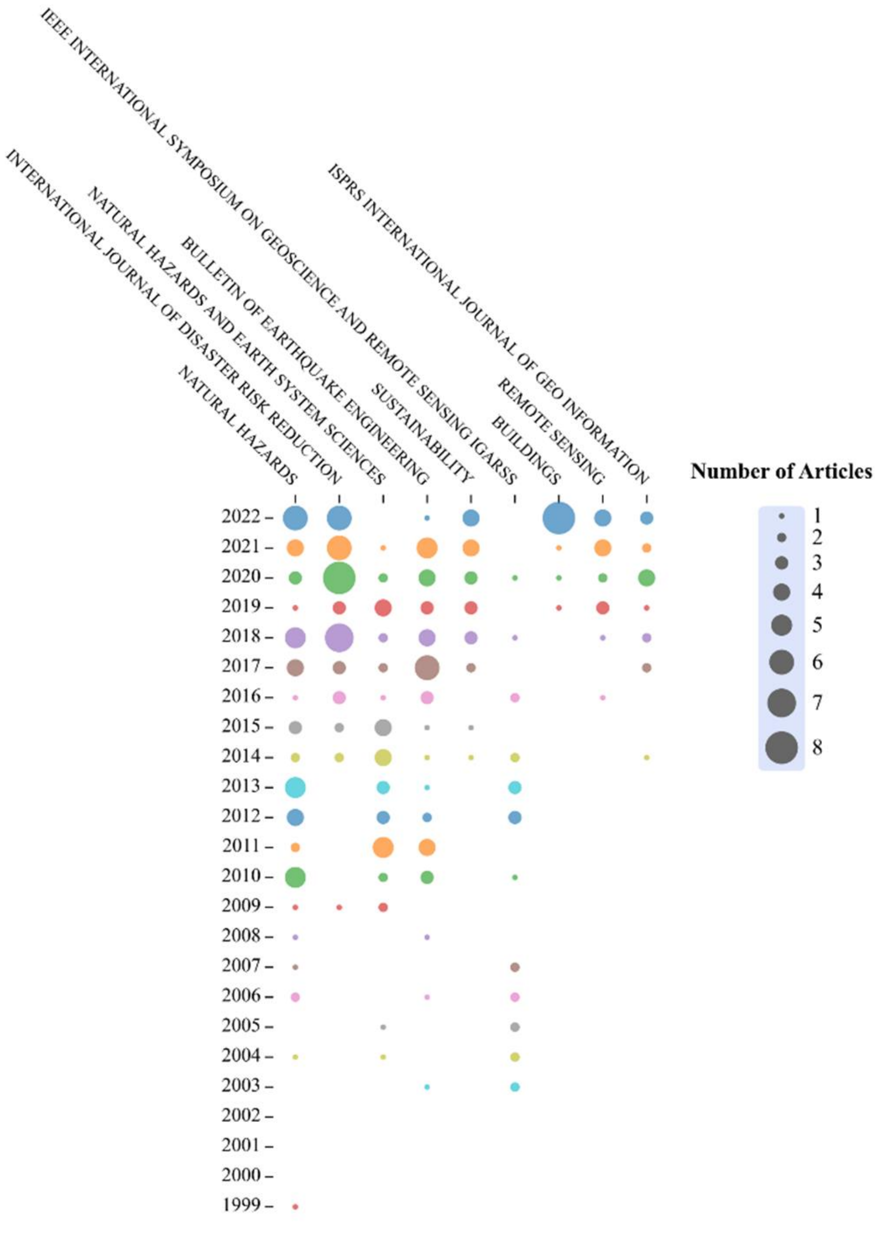

Fig. 1. Map of the Distribution of Publication Sources and Trends of Their Growth.

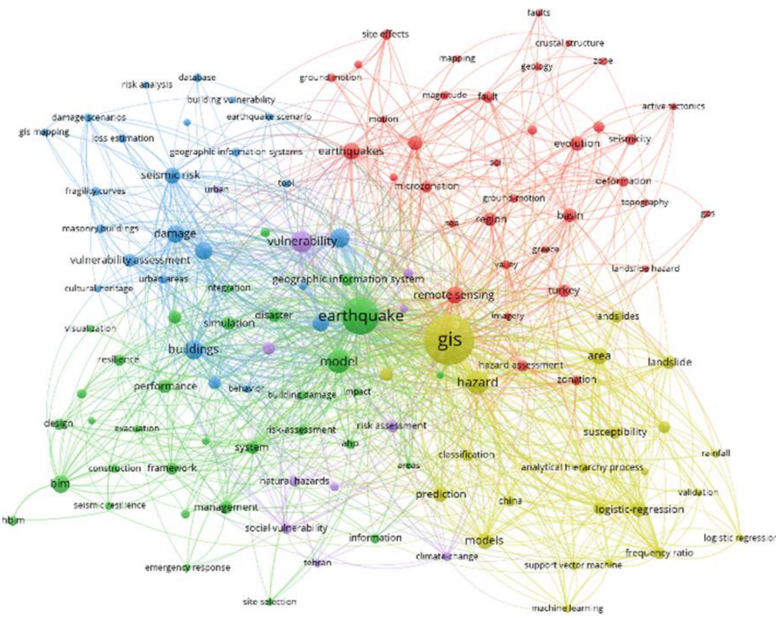

Fig. 2. Map of Keyword Connections.

3 Application of BIM-GIS in Seismic Disaster Management

3.1 Disaster Prevention and Mitigation

The application of GIS is imperative in the assessment of seismic risk, enabling the integration and analysis of seismic activity, geological structure, soil classification, and population distribution data to identify high-risk areas. Sauti N. et al. [7] utilized GIS technology to precisely evaluate the seismic vulnerability of Pahang state, Malaysia, by employing a framework centered around core indicators of exposure, resilience, and capacity, resulting in detailed risk mapping. Hansapinyo C. et al. [8] developed an advanced artificial intelligence model based on GIS architectural data, incorporating Adaptive Neuro-Fuzzy Inference System (ANFIS). This model demonstrated high accuracy in predicting urban building damage, even in the absence of critical dynamic characteristics and seismic effect data. Giovinazzi S. et al. [9] proposed a comprehensive framework to quantify the impact of seismic events on the functionality and structure of historic regions. A case study was conducted in the Camerino-San Severino area in Italy, where the evaluation was implemented within a specially developed WebGIS Decision Support System (ARCH DSS). This system meticulously classified exposed elements within the architectural environment and applied an index-based method to assess the seismic vulnerability of cultural heritage buildings.

The application of GIS in urban and regional planning provides decision-makers with a comprehensive view of the geographic, societal, and infrastructural distribution of a city or region. This aids in the planning of safer communities and the identification of critical areas for seismic-resistant infrastructure protection. Yavuz Kumlu, K. B. et al. [10] identified seismic hazard zones in the city center of Yalova using Multi-Criteria Decision Making

(MCDM) analysis based on GIS, employing the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

In order to enhance public awareness of disaster preparedness and improve crisis and disaster response capabilities, the team led by Alper Kanak [11] has introduced an interactive gaming environment that amalgamates Virtual Reality (VR) with Internet of Things (IoT) technologies. Within this VR setting, they have meticulously simulated scenarios of fire and seismics. Furthermore, they executed a granular subdivision of architectural models within these simulations, delineating danger zones, safety areas, auxiliary objects, and evacuation routes to achieve precise visualization in the VR environment.

Combining BIM with seismic data can effectively simulate the performance of buildings under specific seismic scenarios. Alirezaei M. et al. [12] initially developed architectural models within BIM and imported their properties into the structural analysis software OpenSees, assessing the structural response under certain load conditions. The analysis results from OpenSees were then used to ascertain the potential damage states of the buildings.

3.2 Emergency Response

BIM and GIS technologies demonstrate extensive potential in the response to seismic disasters, facilitating more efficient management and coordination during emergencies.

GIS is instrumental in real-time damage assessment, offering emergency response teams dynamic maps that incorporate data from an array of sensors and sources. These maps provide critical information regarding the affected areas, epicenters, and compromised infrastructures. The research conducted by Mavroulis S. et al. [13] integrated GIS software, online platforms, and drone technology to conduct detailed post-seismic building damage surveys. Utilizing images captured by drones, they constructed 3D models of settlement, generating spatial data sets comprising orthoimagery, digital surface and terrain models. These data sets were vectorized and inputted into GIS for the further development of web maps and applications to facilitate information sharing and decision-making support. Anand M. P. et al. [14] established a GIS-based system underpinned by Building Damage-Estimation Modelling (BDEM) and web technologies, leveraging Spatial Data Infrastructure (SDI) to produce, update, and maintain essential spatial datasets for seismic response, thereby significantly enhancing the speed and efficacy of disaster response. BIM serves as a tool for assessing the extent of damage to specific buildings or structures during seismic events, guiding emergency response, rescue, and subsequent recovery efforts. Quinay P. E. B. et al. [15] employed GIS and BIM data to analyze urban seismic responses for mid-to-low rise reinforced concrete structures, corroborating the accuracy of their models through comparison with empirical data. Their findings underscore the importance of seismic performance evaluations of buildings, alongside analyses of the correlations between structural height and area, in formulating seismic risk reduction and disaster mitigation strategies.

In the domain of navigation and rescue route planning, maps of affected regions provided by these systems enable rescue teams to chart the quickest and safest courses of action. Deng H. et al. [16] advanced this approach by employing a Geometric Network Model (GNM) constructed from BIM information, supplemented by computer vision technology, to optimize indoor positioning and evacuation route planning, ultimately improving rescue efficiency and safety.

3.3 Post-Disaster Assessment and Reconstruction

The integration of BIM and GIS offers novel opportunities for the evaluation and rehabilitation processes following seismic events. This synthesis not only streamlines the amalgamation of spatial and architectural data but also elevates the depth and precision of data available for strategic decision-making.

Regarding damage assessment, the confluence of GIS's spatial analytic capabilities with BIM's detailed structural data enables more accurate appraisals of compromised buildings. Mavroulis S. et al. **Ошибка! Источник ссылки не найден.** have proposed a novel cartographic method for the comprehensive depiction of seismic impacts on the built environment. This technique employs multisource data for the construction of three-dimensional models, from which building polygons are extracted. These polygons are then assessed using the EMS-98 criteria, assigning vulnerability and damage ratings in accordance with the material and structural features of each building unit. The generated maps of vulnerability and damage levels provide clear visualizations of areas most acutely affected by seismic disturbances. Xu Z. et al. **Ошибка! Источник ссылки не найден.** have validated a predictive model for estimating the seismic loss to buildings, based on BIM and FEMA P-58 standards, using a case study of a six-story office building in Beijing.

The formulation of post-disaster reconstruction plans is equally critical. Messaoudi, M. et al. **Ошибка! Источник ссылки не найден.** have introduced a BIM-based Virtual Permitting Framework (VPF) to facilitate the recovery planning in Florida post-disaster. In addition, Zhou Y. et al. **Ошибка! Источник ссылки не найден.** have conceptualized a system that integrates Unmanned Aerial Vehicles (UAVs) with three-dimensional BIM for the post-seismic assessment of bridges, thereby enabling expedited evaluations and remediation of damaged infrastructures.

4 The Application of BIM-GIS Data in Seismic Disaster Management

4.1 Data Types

In the context of seismic disaster management, a variety of related data play an indispensable role. When assessing seismic risk, there is an engagement with diverse data types pertinent to GIS. We primarily focus on the following aspects: a) Seismic source factors, where Mavroulis S. et al. [13] analyzed historical and recent seismic activity, major seismics, and intensity distribution in the region of Lesbos Island in the North Aegean Sea. b) Topographic factors, Liu B. et al. [20] employed GIS technology and the topographic complexity index described by the Terrain Information Entropy Method to analyze the spatiotemporal variations in disaster resilience in hard-hit areas. c) Anthropogenic factors, which Sauti N. et al. [7] considered in their assessment of seismic vulnerability, including elements such as buildings, population, and administrative boundaries. Quinay P. E. B. et al. [15] utilized surface elements to represent the external contours of buildings on the ground, generating 3D models based on polygonal and elevation data. A. Kanak et al. [11] extracted the location of buildings and their upper and lower corner positions from CityGML to verify their precise placement in urban layouts.

Unmanned aerial vehicle (UAV) data are also extensively utilized due to their high-resolution and detailed spatial data capturing capabilities, playing an irreplaceable role especially in rapid post-disaster assessments. Mavroulis S. et al. [13] used UAVs in the initial hours of the disaster response phase to conduct per-building inspections and generated detailed 3D models and imagery, providing invaluable information for disaster response. Park, E. S. et al. [21] combined point cloud data acquired from 3D scanning with spatial information to analyze the exterior smoothness and slope of damaged buildings.

In seismic disaster management, the factors related to BIM can be summarized as follows: a) Architectural Structural Factors, where Quinay P. E. B. et al. [15] utilized information such as the geometry and material properties of beams, columns, nodes, and components obtained from developers to generate detailed structural models. b) Building Performance and Response, A. Kanak et al. [11] focused on key elements such as rooms, doors, windows, columns, beams, fire extinguishers, and nearest gathering points in seismic and fire disasters, with data derived from Industry Foundation Classes (IFC). Furthermore, Kanak A. et al. [11] noted that BIM data provides a wealth of architectural information related to the intricacies of residential life, even enabling the extraction of details such as bedroom locations, bathroom usage times, and water consumption. All this information may reveal numerous clues about individual lifestyles, thereby raising concerns about privacy breaches.

The Internet of Things (IoT) offers many new possibilities for prediction, detection, response, and recovery. Kanak A. et al. [11] employed IoT technology integrating sensors for humidity, temperature, and vibration. Anand M. P. et al. [14] installed seismic active control device systems on buildings, with sensors transmitting information to computers. The system provides intelligence-based decision-making, thus periodically adjusting its own architectural attributes.

4.2 Data Interoperability

H. Wang et al. [22] classified three typical modes of BIM-GIS integration, namely “BIM-led, GIS-supported”, “GIS-led, BIM-supported”, and “Equal emphasis on BIM and GIS”. Similarly, A. Kanak et al. [11] dissected data interoperability across three dimensions: a) Operations within a GIS environment, which involves transforming BIM models into a format usable by GIS; b) Operations within a BIM environment, which involves converting GIS data into BIM models; c) Integration of GIS and BIM at the shell ontology level of basic objects while preserving the original data of each model.

Data interoperability between BIM and GIS is an evolving field. Numerous software developers have begun to directly integrate BIM and GIS functionalities within their products. For instance, Autodesk’s InfraWorks facilitates the integration of Civil 3D, Revit, and GIS data on a single platform. Developers can also create customized integration solutions via Application Programming Interfaces (APIs) or Software Development Kits (SDKs). Shekargoftar, A. et al. [23] proposed a Pipeline Operations and Maintenance Management System (POMMS) that employs Building Information Modeling (BIM), Geographic Information Systems (GIS), and Augmented Reality (AR), integrating various project information source databases through APIs and cloud integration. More complex solutions include database integration of BIM and GIS data, such as storing both in PostgreSQL/PostGIS. Web services are also widely used for the interoperability of BIM and GIS data, facilitating online interoperability. Zhao, L. et al. [24] developed an integrated web platform based on BIM+GIS, demonstrating that the platform could assist in the proper management of large projects by providing necessary information and functionality. New approaches and tools are aimed at creating a shared data model in which BIM and GIS data can coexist and be interoperable within the same model. Such methods are still in the nascent stages but promise to provide more convenient solutions for future interoperability. Semantic interoperability involves more advanced data exchanges, which typically require more complex data mapping and transformation tools. A. Kanak et al. [14] achieved the unification of different data models into a Unified Building Model (UBM). The proposed semantic framework developed a shell ontology according to the integration methods of BIM and GIS, graphically presenting the architectural CityGML and IFC models and enabling quick and simple data queries based on the shell ontology to better manage information about buildings and their surrounding environments. They also utilized the Unity gaming engine to develop a sample of a VR disaster simulator, which was visually demonstrated through Oculus Rift VR glasses connected to a gaming computer equipped with the corresponding software and hardware.

5 Conclusion

The resilience and impact of urban infrastructure during seismic events are increasingly becoming focal points of interest within academic research and engineering practice. The integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) offers a potent suite of tools and methodologies that enhance the efficacy of urban construction within the management of seismic disasters. The synergistic application of BIM and GIS enables more precise and comprehensive simulation and analysis of buildings and their environmental responses to seismic activity.

The deployment of this technology is crucial at every stage of the disaster management lifecycle, yielding significant benefits. Prior to an seismic, it facilitates the planning of effective mitigation actions to diminish potential future impacts; during an event, it provides emergency personnel with estimates of damage extent and impact area, thereby enabling the timely, effective, and efficient allocation of resources and supporting information management for emergency response; following the event, it assists in building resilience, as well as in formulating and implementing improved policies and strategies. This integrated application ensures the continuity and systematization of disaster management measures and further optimizes strategies for disaster risk control and mitigation.

Data resources utilized for seismic disaster management are diversifying, with a rich array of sources encompassing natural and human geography information, architectural structures, and sensor networks; the forms of data are equally varied, ranging from traditional tabular formats to high-dimensional imagery and time-series data. Concurrently, significant technological advancements have been made in data interoperability techniques, with current research trends emphasizing the automated identification, matching, and integration of multi-source, heterogeneous datasets, thereby enhancing the level of automation in data interoperability.

In the sphere of seismic disaster management research, while BIM and GIS technologies have been extensively employed, there are existing limitations that necessitate overcoming through further investigation:

- A deficiency in the study of aged infrastructures: Numerous studies are oriented towards contemporary constructions; however, aged edifices, due to their intrinsic vulnerability, are more prone to damage. These structures are often situated in central areas with cultural significance and hence demand additional scrutiny.
- Concerns regarding informational privacy: The voluminous collection of construction data, especially that of residential dwellings, may encroach upon individual privacy. The governance and safeguarding of such data have yet to be accorded adequate emphasis.
- The absence of universal standards: The data interoperability between BIM and GIS is hampered by the lack of universally embraced open standards, which impairs the efficacy of data exchange.
- A shortfall in studies on response and resilience capabilities: Predominantly, research is preoccupied with preventative measures and emergency responses, with the intrinsic value of the post-seismic recovery and reconstruction phase still ripe for further exploration.

Considering these shortcomings, forthcoming research should engage more profoundly with these matters to enhance and optimize the integrated strategies of seismic disaster management.

References

1. J. O. Oluwafemi et al., Int. J. Civ. Eng. Technol. **9**, 440-464 (2018)
2. D. P. Welch, T. J. Sullivan, A. Filiatrault, Bull. N. Z. Soc. Earthq. Eng. **47(4)**, 253-263 (2014)
3. R. Jena, B. Pradhan, G. Beydoun, A. Al-Amri, H. Sofyan, Arab. J. Geosci. **13**, 1-21 (2020)
4. Y. Cao, C. Xu, N. M. Aziz, S. N. Kamaruzzaman, Remote Sens. **15(5)**, 1331 (2023)
5. H. Wang, Y. Pan, X. Luo, Autom. Constr. **103**, 41-52 (2019)
6. N. J. van Eck, L. Waltman, VOSviewer manual, Leiden: Univeristeit Leiden (2019)
7. N. S. Sauti, M. E. Daud, M. Kaamin, S. Sahat, Geomat., Nat. Hazards Risk **12**, 1948-1972 (2021)
8. C. Hansapinyo, P. Latcharote, S. Limkatanyu, Front. Built Environ. **6**, 576919 (2020)
9. S. Giovinazzi, C. Marchili, A. Di Pietro, L. Giordano, A. Costanzo, L. La Porta, O. Ullrich, ISPRS Int. J. Geo-Inf. **10(7)**, 461 (2021)
10. K. B. Yavuz Kumlu, Ş. Tüdeş, Nat. Hazards **96**, 999-1018 (2019)
11. A. Kanak, İ. Arif, O. Kumaş, S. Ergün, in 2020 IEEE Int. Conf. Syst., Man, Cybern. (SMC), IEEE, 3813-3818 (2020)
12. M. Alirezaei, M. Noori, O. Tatari, K. R. Mackie, A. Elgamal, Procedia Eng. **145**, 1051-1058 (2016)
13. S. Mavroulis, E. Andreadakis, N. I. Spyrou, V. Antoniou, E. Skourtsos, P. Papadimitriou, E. Lekkas, Int. J. Disast. Risk Reduct. **37**, 101169 (2019)
14. M. P. Anand, G. S. Thirugnanam, S. B. Gnanappa, Appl. Math. **13(1)**, 97-104 (2019)
15. P. E. B. Quinay, J. M. M. Soliman, A. R. F. Fader, J. Earthq. Tsunami **14(06)**, 2050021 (2020)
16. H. Deng, Z. Ou, G. Zhang, Y. Deng, M. Tian, Sensors **21(11)**, 3851 (2021)
17. Z. Xu, H. Zhang, X. Lu, Y. Xu, Z. Zhang, Y. Li, Autom. Constr. **102**, 245-257 (2019)
18. M. Messaoudi, N. O. Nawari, Int. J. Disast. Risk Reduct. **42**, 101349 (2020)
19. Y. Zou, V. Gonzalez, J. Lim, R. Amor, B. Guo, M. Babaeian Jelodar, Proc. CIB World Build. Congr. **2019**, 17-21 (2019, June).
20. B. Liu, X. Chen, Z. Zhou, M. Tang, S. Li, Environmental Hazards and Resilience, Routledge, 91-110 (2021)
21. E. S. Park, H. C. Seo, Sustainability **13(2)**, 456 (2021)
22. H. Wang, Y. Pan, X. Luo, Autom. Constr. **103**, 41-52 (2019)
23. A. Shekargoftar, H. Taghaddos, A. Azodi, A. Nekouvaght Tak, K. Ghorab, J. Perform. Constr. Facil. **36(3)**, 04022023 (2022)
24. L. Zhao, J. Mbachu, Z. Liu, KSCE J. Civ. Eng. **26(4)**, 1505-1521 (2022)