SEISMIC RISK ASSESSMENT OF URBAN AREAS USING ADVANCED MODELING APPROACHES

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Abstract. Urban settlements located in seismic zones are increasingly vulnerable to devastating earthquakes, which pose significant threats to human life, infrastructure, and economic stability. Modern urbanization, combined with inadequate building practices and outdated infrastructure, amplifies the potential impacts of seismic hazards. This study presents a comprehensive overview of contemporary approaches to seismic risk assessment, including probabilistic modelling, vulnerability indexing, and scenario-based simulation using GIS and Big Data platforms. A critical comparison between international and national methodologies is provided, emphasizing practical and normative aspects. Uzbekistan serves as a case study to examine regional applications of seismic zoning, structural vulnerability assessment, and the use of simulation technologies for disaster mitigation. The paper concludes by discussing policy implications and the need for unified international standards that reflect both probabilistic uncertainty and geospatial variability in risk.

Keywords: seismic risk assessment, urban areas, structural vulnerability, probabilistic modeling, GIS-based simulation, seismic zoning, disaster risk reduction.

Introduction.

Earthquakes remain among the most destructive natural hazards, causing substantial human and economic losses worldwide. According to global risk assessments, the annual financial damage resulting from seismic events exceeds 100 billion US dollars, with developing countries experiencing the most severe consequences. These impacts arise not only from tectonic processes but also from systemic vulnerabilities such as outdated construction practices, uncontrolled urban expansion, and insufficient emergency preparedness. Urban areas are particularly exposed to seismic hazards due to high population density, aging infrastructure, and the concentration of economic activities.

Seismic risk in urban environments is generally defined by three principal components: hazard, which represents the probability and intensity of seismic events; exposure, referring to the presence of people and infrastructure within hazardous areas; and vulnerability, describing the susceptibility of structures and systems to damage during earthquakes. Contemporary research indicates that earthquake losses are often determined more by structural vulnerability than by seismic intensity alone [1-3].

The experience of Tashkent, Uzbekistan, illustrates the importance of integrating geotechnical data, structural characteristics, and spatial modeling into national planning strategies. The 1966 Tashkent earthquake, with a magnitude of 5.1 and an intensity of IX on the MSK-64 scale, destroyed more than two million square meters of housing and displaced approximately 300,000 residents. This event stimulated the development of national seismic design standards and significantly contributed to the advancement of earthquake engineering research in Uzbekistan [4].

Over the past decades, advances in probabilistic seismic hazard analysis, geographic information systems (GIS), and machine learning (ML) have significantly improved the ability to analyze and manage seismic risks. These technologies are particularly relevant for seismically active regions such as Central Asia, where complex tectonic conditions intersect with socio-economic vulnerabilities. This study examines global and regional approaches to seismic risk evaluation, focusing on methodological, technical, and regulatory aspects. Using Uzbekistan as a case study, the research highlights the role of digital tools, national regulatory developments, and urban seismic modeling in enhancing the resilience of cities.

Global and Domestic Approaches to Seismic Risk Assessment.

Seismic risk assessment has undergone significant evolution since the late 19th century, transitioning from empirical intensity scales to data-driven probabilistic frameworks. The global scientific community now recognizes that effective seismic risk management requires a multidisciplinary approach that integrates geological, structural, social, and economic data into a

coherent system of analysis. Modern international methodologies emphasize probabilistic seismic hazard analysis, spatial modelling, and integration of uncertainty into scenario-based predictions. Countries like the United States, Japan, Italy, and New Zealand have developed high-resolution tools for loss forecasting, structural fragility estimation, and urban vulnerability mapping.

In contrast, Uzbekistan and many other post-Soviet countries developed deterministic approaches rooted in Soviet engineering, focusing on macroseismic zoning and structural typology simplifications [5]. Recent regulatory updates like mark a transition toward risk-based planning, but implementation remains uneven due to technical and institutional barriers.

Table 1. Comparative analysis of domestic and foreign methods of seismic risk assessment

№.	Criteria	Domestic methods	Foreign methods
1	Level of detail	Average (by building type)	High (for specific buildings and areas)
2	Data used	Normative maps, typical vulnerabilities	Global databases, real-world scenarios
3	Accounting for uncertainties	Limited	Wide (Monte Carlo, Bayesian networks, etc.)
4	Technologies	Mainly analytical methods	Modeling, GIS, digital twins
5	Target	Integrated risk assessment	Loss forecasting, scenario planning

Table 1. demonstrates the differences in approaches to seismic risk assessment. Domestic methods predominantly use simplified data and analytical calculations, which limits the depth of analysis and forecast accuracy. International methods, on the other hand, rely on more detailed source data, probabilistic models, and digital technologies that enable scenario-based forecasts and account for a wide range of uncertainties.

Consequently, domestic approaches are more focused on aggregated assessments, while foreign methods provide more detailed and scientifically sound forecasts of the consequences of seismic events. This highlights the need to further refine national methodologies, taking into account international experience and modern technologies.

If certification has not been conducted, the assessment is performed using a consolidated building catalog, categorized by macroseismic scale type.

The economic risk assessment methodology involves calculating probable cost losses for each building separately. Structural vulnerability to secondary processes is determined through modeling, and the transition from vulnerability class to expected damage is performed using standard ratios (Table 2.). This allows for a quantitative assessment of potential financial losses and the development of measures to reduce seismic risks.

Table 2. Relationships between classes of structural vulnerability and probable structural damage

Structural damage (%)	Levels of vulnerability								
	n	s	l	lm	m	mh	h	vh	f
Range of values	< 0.1	0.1-1	1-3	3-10	10-35	35-60	60-80	80-100	100%
Average value	0	0.05	1.5	5	20	50	75	100	100%
Degree of damage	0	1	2-3	3-4	4-5	5			
	G	F	E	D	C	B	A		
Vulnerability class on the EMS scale is 98									

The conversion from probable structural damage to economic losses for Tashkent is based on an assessment of the market value of buildings and structures. Three levels of seismic zoning are used for the analysis: OSR-97, DSR, and SMR, the results of which are integrated into a GIS environment. Based on this data, earthquake scenarios are generated and the intensity distribution across the city's administrative districts is calculated.

A comprehensive assessment revealed that in the central districts (Shaykhontahur and Mirobod), the proportion of modern reinforced concrete and frame-panel buildings is higher, ensuring relative stability at earthquake intensities of up to 8. Meanwhile, in Chilanzar and Sergeli, a significant portion of the housing stock consists of Soviet-era large-panel buildings, which are sensitive to prolonged shaking. The most vulnerable remain the outlying districts—Yashnabad, Uchtepa, and Almazar—where low-rise brick and adobe buildings are common, posing a high risk for earthquakes exceeding 8.

Consequently, seismic vulnerability in Tashkent is clearly distributed by region: new microdistricts are at moderate risk, while older housing remains critical. Data integration into GIS allows for precise linking of calculations to development sites and the creation of damage scenario

maps, which provides the basis for developing strategies for strengthening buildings and improving the capital's overall seismic safety.

In seismic risk assessment, Big Data technologies enable the integration of earthquake, geology, and development data into a unified analysis system. This enables more accurate impact modeling and the identification of the most vulnerable sites. Real-time information processing improves response times and minimizes potential damage. However, using Big Data requires significant computing resources and qualified specialists. Overall, these technologies are becoming an important tool for improving the reliability of forecasts and developing seismic risk mitigation strategies.

The integration of national codes with international performance-based standards and GIS tools offers a pathway for improved resilience and scientific alignment.

Seismic hazard and risk modelling in urban contexts.

Seismic risk is composed of hazard, exposure, and vulnerability. In urban environments, complex soil-structure interactions, structural heterogeneity, and demographic concentrations exacerbate risk [11-12]. Ground motion models, including accelerograms and spectral response functions, define the dynamic input used in structural safety checks. Buildings respond according to their natural periods, and resonance effects can significantly amplify damage. Probabilistic seismic hazard analysis accounts for recurrence, location uncertainty, and intensity prediction equations to produce iso-intensity maps and expected shaking scenarios.

Scenario-based simulation is increasingly used for city-scale planning, integrating fragility functions and structural inventories to produce probabilistic damage distributions and loss curves [6-10].

Technological approaches to seismic risk assessment.

Modern seismic analysis is enhanced by Geographic Information Systems, which support spatial modelling of soil conditions, structural typologies, and demographic exposure. Big Data sources—ranging from satellite imagery and sensor networks to crowd-sourced mobile data—enable dynamic updates of vulnerability maps and post-event damage assessments.

Artificial Intelligence (AI) and machine learning models trained on structural behavior and seismic data provide real-time insights, collapse predictions, and damage classification from imagery. Digital twins offer 3D, dynamic models of urban systems, allowing planners to simulate damage scenarios, visualize economic risks, and test evacuation strategies under various hazards.

Tashkent is located in a seismically active region, with recent zoning maps classifying much of the city in intensity zones 8–9. Soft soils in some districts increase amplification risk. The

city's building stock is highly varied, including Soviet-era panel buildings, unreinforced masonry homes, and modern frame structures. Vulnerability is particularly high in older districts such as Chilanzar and Almazar.

Scenario-based GIS modelling has identified high-risk zones and potential economic losses exceeding \$7 billion in the event of a magnitude 7.5 earthquake. Up to 400,000 people could be affected. Digital twin simulations have been used to assess dynamic structural responses and horizontal displacements, revealing priority retrofitting needs for over 150,000 housing units.

Conclusion.

This paper demonstrates that seismic risk in urban environments is best addressed through integrated models combining probabilistic analysis, Big Data, and AI. The Tashkent case illustrates the value of digital twins and scenario simulation in shaping urban resilience strategy and retrofitting policy.

Recommendations include: adopting performance-based design codes, expanding risk-based zoning, mandating digital building inventories, and developing national risk platforms. Improved seismic resilience will depend on coordinated governance, open data access, interdisciplinary training, and community engagement supported by real-time analytics and international standards.

REFERENCES:

1. Rodríguez-Castellanos A., Bojórquez E., Bojórquez J., Ruiz S.E., Carvajal J., Leyva H., Payán O. Advanced intensity measures for urban seismic-risk mapping: Evidence from a megacity. International Journal of Disaster Risk Reduction. 2025, 129, 105791. https://doi.org/10.1016/j.ijdrr.2025.105791

2. Nikolić Ž, Benvenuti E, Runjić L. Seismic Risk Assessment of Urban Areas by a Hybrid Empirical-Analytical Procedure Based on Peak Ground Acceleration. Applied Sciences. 2022; 12(7):3585. https://doi.org/10.3390/app12073585

3. Zhou G., Zhu Z., Zhong J., Zheng W., Huang Y. Seismic damage mechanism of high-speed railway simply supported bridges considering spatial distribution characteristics of near-fault ground motions. Soil Dynamics and Earthquake Engineering. 2026, Vol. 200, Part B, 109864.

4. B.A. Tulaganov, S.A. Khodzhaev, Schwarz, L. Abrahamczyk Assessment of seismic vulnerability of buildings and structures by using European standards //Turkish Journal of Computer and Mathematics Education Vol.12 No.7 (2021), 323-330.

5.   Raab N. The Tashkent Earthquake of 1966: The Advantages and Disadvantages of a Natural Tragedy. Jahrbücher für Geschichte Osteuropas, 2014.

6.   Ferranti G, Greco A, Pluchino A, Rapisarda A, Scibilia A. Seismic Vulnerability Assessment at an Urban Scale by Means of Machine Learning Techniques. Buildings. 2024; 14(2):309. https://doi.org/10.3390/buildings14020309

7.   Fiamingo A, Mangione E, Abate G, Massimino MR. Seismic Risk Assessment and Sustainable Geotechnical Solutions for Building Heritage: A Case Study in Southeastern Sicily. Heritage. 2025; 8(11):485. https://doi.org/10.3390/heritage8110485

8.   Naser M.Z., Hawileh R. Developing empirical indices for structural engineering problems via machine learning. Engineering Structures. 2026, Vol. 346, Part A, 121609. https://doi.org/10.1016/j.engstruct.2025.121609.

9.   Nadi F., Hamdy O. The role of vulnerability assessment in urban planning for mitigating seismic risk. International Design Journal. 2025, 15(3), pp. 195–206.

10. Mesgar M.A.A., Jalilvand P. Vulnerability analysis of urban environments to different seismic scenarios: Residential buildings and associated population distribution modelling through integrating dasymetric mapping and GIS. Procedia Engineering. 2017, 198, pp. 454–466.

11. Crowley H., Colombi M., Crempien J., Erduran E., Lopez M., Liu H., Mayfield M., Milanesi M., Silva V. Probabilistic seismic risk assessment of buildings in large urban areas: The OpenQuake platform. Natural Hazards. 2014, 74(3), pp. 1409–1427.

12. Zhang Y., Burton H., Sun H., Shafieezadeh A. Machine learning approaches for regional seismic risk assessment of buildings. Earthquake Engineering & Structural Dynamics. 2021, 50(5), pp. 1401–1418.