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INTEGRATED GIS AND DIGITAL TWIN-BASED FRAMEWORK FOR SCENARIO-BASED SEISMIC VULNERABILITY ASSESSMENT OF URBAN BUILDINGS: CONCEPTUAL ARCHITECTURE AND CASE STUDY OF TASHKENT

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Abstract

Urban areas located in seismically active regions are exposed to complex multi-factor risks arising from the interaction between seismic hazards and structural characteristics of the built environment. This study proposes an integrated analytical framework for scenario-based seismic vulnerability assessment of urban buildings that combines structural engineering analysis, multivariate regression modeling, geospatial information systems, and digital twin concepts, formulated here as a conceptual architecture that links structural databases, probabilistic simulations, and GIS visualization in an updateable decision-support loop. The methodology incorporates a structured building inventory including geometric, material, structural, and condition-related parameters to calculate a quantitative vulnerability index for each building under defined seismic loading scenarios. The proposed model was applied to a representative sample of buildings in Tashkent, where vulnerability levels were classified using a five-tier risk scale. Results demonstrate that the calculated vulnerability index effectively captures the combined influence of structural attributes and allows identification of buildings with elevated seismic susceptibility. Spatial visualization within a GIS environment revealed pronounced heterogeneity of risk distribution, highlighting localized clusters of structurally vulnerable buildings. The findings confirm that integrating engineering-based evaluation with data-driven modeling significantly improves predictive accuracy compared to traditional deterministic assessment approaches. The developed framework represents a scalable and transferable decision-support tool suitable for urban resilience

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planning, seismic risk mitigation, and prioritization of structural strengthening measures in earthquake-prone regions.

Keywords: Seismic risk assessment, urban infrastructure, structural vulnerability, GIS modelling, digital twin, regression analysis, earthquake resilience.

INTRODUCTION

Seismic risk is an increasingly critical issue for urban territories located in tectonically active zones. The ability of urban infrastructure to withstand seismic events is determined not only by geological and seismic characteristics but also by the resilience of the built environment. The consequences of seismic events can span from structural collapse to widespread socio-economic disruptions. This necessitates a comprehensive, multidisciplinary approach to evaluating and mitigating these risks. In recent decades, the convergence of civil engineering, geoinformatics, and data science has enabled the development of more sophisticated frameworks for seismic risk assessment (Boje et al., 2020; Gürdür Broo et al., 2022). These frameworks are no longer limited to static analyses but incorporate real-time monitoring, probabilistic modeling, and dynamic simulation.

Urban territories located in seismically active regions are increasingly exposed to complex and multidimensional risks resulting from the interaction between natural seismic hazards and the characteristics of the built environment. Rapid urbanization, population growth, and the expansion of critical infrastructure have significantly increased the potential consequences of seismic events (Lei et al., 2023; Weil et al., 2023). In densely developed cities, even earthquakes of moderate intensity may lead to substantial structural damage, disruption of essential services, and long-term socio-economic losses. Therefore, the assessment of seismic risk has become a fundamental task in modern civil engineering, urban planning, and disaster risk management.

Seismic risk is not determined solely by the magnitude or frequency of earthquakes. The vulnerability of buildings, infrastructure systems, and urban layouts plays a decisive role in shaping potential damage scenarios. Aging building stock, outdated construction practices, and insufficient seismic upgrading further aggravate the problem, particularly in cities with long development histories. As a result, there is a growing need for comprehensive assessment frameworks capable of addressing the complexity of urban systems under seismic loading (Guo et al., 2024; Heresi & Miranda, 2022; Macatulad & Biljecki, 2024; Wang et al., 2024).

The originality of this research lies in developing a unified framework that integrates structural inventory, probabilistic vulnerability modeling, GIS, and Digital Twin technology for dynamic seismic risk assessment and decision

support. Its regional applicability is demonstrated through a scenario-based assessment of Tashkent, combining GIS with national seismic regulations and EMS-98 to classify buildings by structural characteristics, age, height, material, and condition under defined earthquake scenarios (Jahangir et al., 2025; Kookalani et al., 2026; Sianko et al., 2023; Zhai et al., 2026).

The integration of geospatial analysis with regulatory-based vulnerability assessment allows identification of spatially concentrated high-risk zones within the urban territory. Such scenario modeling improves predictive accuracy of potential earthquake consequences and supports prioritization of structural retrofitting, urban resilience planning, and civil protection strategies in seismically active regions.

METHODOLOGY

Technical inventory of urban structures

The Technical passportization of urban buildings is a fundamental procedure for assessing the seismic safety of urban environments (Alemdar, 2025; Douglas et al., 2024; Guardiola-Villora et al., 2023; Oleng et al., 2025). To address the complexity of urban seismic risk, assessment methodologies must be structured in a clear and logical sequence (Ghaffarian, 2025; Rosvold & Buhaug, 2021; Tulaganov et al., 2021). This sequence should ensure a consistent transition from general risk concepts to detailed engineering analysis and, ultimately, to practical implementation.

$$R_{urban} = \frac{1}{N} \sum_{i=1}^N I_f(i) \quad (1)$$

Spatial information for the buildings and urban zones was obtained from municipal cadastral maps and existing GIS layers of the city's building stock and infrastructure, which were harmonized within a common coordinate system for analysis. The sampling procedure focused on ensuring coverage of the main structural typologies and construction periods rather than on statistical representativeness in a probabilistic sense. Buildings were selected to represent typical combinations of height, material, configuration, and condition that are characteristic of the urban fabric, enabling scenario-based interpretation of model behaviour across a realistic range of vulnerability drivers.

The inventory covers the principal built-up districts of Tashkent, representing the city's dominant structural patterns. Data quality was ensured through consistency checks, removal of incomplete records, and expert review. Buildings with missing key attributes were excluded. A purposive engineering sampling approach was used to capture representative combinations of structural

system, material, height, construction period, and condition, ensuring coverage of the main regional vulnerability characteristics.

A comprehensive structural database is established through systematic collection, verification, and standardization of building attributes. The inventory includes structural system typology, primary construction material, number of stories, construction year, geometric irregularities, maintenance condition, and retrofitting history.

Let each building be represented by a feature vector:

$$x_b = [S_b, M_b, H_b, Y_b, Q_b, R_b, I_b] \quad (2)$$

Where;

S_b — structural system type

M_b — material class

H_b — height/stories

Y_b — construction year

Q_b — condition index

R_b — retrofit indicator

I_b — irregularity indicator

A fragmented approach, in which individual components of risk are analyzed independently, limits the applicability of results for urban planning and decision-making.

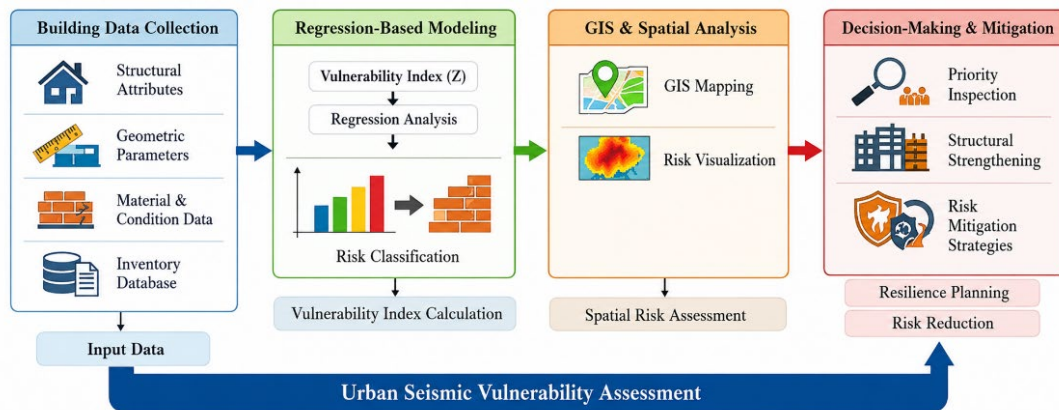


Figure 1: Integrated seismic vulnerability assessment framework for urban buildings

Within this (Figure 1) framework, technical inventory and structural vulnerability assessment constitute the core analytical stages. These stages provide the necessary link between theoretical seismic risk concepts and applied engineering evaluation, enabling the integration of empirical data, analytical models, and digital tools within a unified assessment process.

Table 1: Simulation Tools for Urban Seismic Risk Assessment

Tool	Description	Use Case
HAZUS	FEMA's loss estimation tool	Earthquake impact modeling
CAPRA	Probabilistic risk platform	Urban risk estimation
OpenQuake	Seismic hazard modeling	Scenario-based loss mapping
InaSAFE	Disaster impact tool	Planning emergency services

A technical building inventory is fundamental to city-scale seismic risk assessment, providing data on structural system, materials, height, construction period, condition, and retrofitting. Beyond documentation, it enables quantitative analysis of building typologies, spatial distribution, and vulnerable structures, forming the basis for large-scale urban risk assessment.

In many cities, incomplete or outdated building records require supplementary data from field surveys, archives, and geospatial sources. Digital inventories support efficient large-scale spatial analysis. Structural vulnerability depends on factors such as structural system, materials, construction quality, design, and seismic code compliance, causing buildings to perform differently under similar earthquake conditions. Structures with similar mechanical properties are grouped into classes, allowing statistical representation of expected damage behavior. This grouping significantly reduces computational complexity while preserving structural realism at the urban scale.

Probabilistic classification may also be implemented:

$$VC_b = \operatorname{argmax}P(VC = k \mid x_b) \quad (3)$$

Vulnerability assessment enables the classification of buildings into groups with comparable seismic performance. Such classification forms the basis for estimating expected damage levels, potential economic losses, and functional disruptions under different earthquake scenarios. At the urban scale, vulnerability mapping provides valuable insight into the spatial distribution of risk and allows

for the identification of priority areas where mitigation and retrofitting measures are most urgently required.

Building inventory and data collection

The seismic vulnerability assessment is based on a structured inventory of urban buildings compiled from technical passport records, regulatory documentation, and field verification. The inventory covers multistory residential and public buildings across Tashkent, representing the city's main structural types and construction periods. For the regression analysis, representative buildings were selected to capture variations in structural system, height, materials, and condition. Each building was described by geometric and structural attributes, construction year, condition, retrofit status, and irregularity indicators. Data consistency was verified through cross-checking of records and expert review.

Probabilistic Simulation Module

Uncertainty in seismic input, structural parameters, and material properties is propagated through stochastic simulation. Monte Carlo sampling is employed to evaluate failure probability;

$$P_f = \frac{1}{N} \sum_{i=1}^N I_f(i) \quad (4)$$

Where;

N — number of simulations

If(i) — indicator of structural failure in simulation i

Adaptive sampling strategies are used to ensure convergence while minimizing computational cost. This probabilistic framework captures variability in structural performance that deterministic methods cannot represent.

It is essential to recognize that vulnerability assessment must be adapted to local construction practices and regulatory conditions. The direct application of generalized vulnerability models without regional calibration may lead to inaccurate or misleading results. Therefore, vulnerability classification should be aligned with national design standards, historical construction practices, and observed damage patterns from past seismic events.

Spatial Risk Mapping

Building-level risk indices are aggregated spatially within a geographic information system. The spatial risk indicator for a region is computed as:

$$RI_{zone} = \frac{\sum w_b RI_b}{\sum w_b} \quad (5)$$

Where;

RI_b — risk index of building

w_b — weighting factor (population, area, importance)

Spatial clustering identifies vulnerability hotspots where structural risk is concentrated. These results are integrated into a Digital Twin environment that combines structural databases, probabilistic models, GIS visualization, and monitoring data into a dynamic virtual representation of the urban infrastructure.

The architecture operates as a bidirectional information loop consisting of three functional layers:

1. Data Layer — consolidates structural inventory records, GIS spatial datasets, hazard parameters, and monitoring inputs.
2. Modeling Layer — executes probabilistic simulations, vulnerability analysis, and risk calculations under varying seismic scenarios.
3. Interface Layer — provides interactive visualization dashboards and decision-support outputs for planners and engineers.

In the present study, this digital twin environment is introduced as a conceptual architecture that defines how structural inventory data, probabilistic simulation results, and GIS-based risk layers can be organized within an updateable decision-support system. The Tashkent case study demonstrates the operation of the data and modeling components and their integration with GIS visualization, while full real-time synchronization and implementation of all monitoring interfaces are identified as future development steps.

Linear Regression–Based Vulnerability Assessment Model.

To quantify structural vulnerability at the building level under a defined seismic scenario, a predictive model based on multivariate linear regression was developed. The model evaluates the influence of geometric, structural, and material attributes on the seismic vulnerability index.

Each building is represented by a feature vector:

$$X=[x_1,x_2,x_3,\dots,x_n] \quad (7)$$

where the attributes include building length, total area, height, structural system type, construction material, number of stories, structural configuration, construction period, maintenance condition, and retrofitting status.

The vulnerability index is computed using the linear regression model:

$$Z = XW \quad (8)$$

For transparency, the regression equation can be written explicitly as;

$$\begin{aligned} Z = & \beta_0 + \beta_1 \cdot \text{Height} + \beta_2 \cdot \text{Number of stories} + \beta_3 \cdot \text{Structural system type} \\ & + \beta_4 \cdot \text{Material class} + \beta_5 \cdot \text{Building area} + \beta_6 \\ & \cdot \text{Construction period} + \beta_7 \cdot \text{Maintenance condition index} + \beta_8 \\ & \cdot \text{Retrofit indicator} + \beta_9 \cdot \text{Geometric irregularity indicator} \end{aligned}$$

where the coefficients β_i represent the contribution of each attribute to the vulnerability index. Positive coefficients for deterioration-related variables (older construction periods, weaker maintenance condition, absence of retrofit, presence of irregularity) increase Z , indicating higher vulnerability, whereas favourable conditions (recent construction, good maintenance, presence of seismic strengthening measures, regular configuration) are associated with lower Z values.

Where;

X — matrix of building attributes;

W — vector of weight coefficients determined through normal equation estimation;

Z — predicted seismic vulnerability indicator.

The weight coefficients are obtained by minimizing the least squares error:

$$W = (X^T X)^{-1} X^T Y \quad (9)$$

where Y represents observed or calibrated vulnerability values derived from seismic performance data and regulatory thresholds.

This approach enables evaluation of the relative contribution of each structural parameter to the overall vulnerability level. The model produces a continuous vulnerability score for each building, which can subsequently be classified into discrete risk categories. For the scenario simulation, a seismic intensity corresponding to a magnitude of 6.5 was adopted and normalized for

integration into the regression framework. This allows consistent comparison of buildings under identical seismic loading conditions.

The regression-based vulnerability index was calibrated on a representative set of urban buildings characterized by structural, geometric, and condition-related attributes. The model specification and parameter values were selected to ensure consistency with established seismic design regulations, observed damage tendencies in the region, and expert engineering judgment, rather than to exhaustively report all possible statistical diagnostics.

Vulnerability Level Classification Scale.

To interpret the calculated vulnerability indicator Z , a five-level classification scale was introduced. The intervals are defined as follows:

- Level 1 (Very Low Risk): $Z < 1.5$
- Level 2 (Low Risk): $1.5 \leq Z < 2.5$
- Level 3 (Moderate Risk): $2.5 \leq Z < 3.5$
- Level 4 (High Risk): $3.5 \leq Z < 4.5$
- Level 5 (Very High Risk): $Z \geq 4.5$

Each level is associated with a corresponding visualization color code to facilitate GIS-based spatial interpretation of seismic risk distribution. This classification system provides a structured basis for prioritizing detailed structural assessment, retrofitting interventions, and urban seismic risk mitigation planning.

RESEARCH METHODOLOGY

The obtained results demonstrate that integrating structural engineering parameters with data-driven predictive modeling substantially improves the reliability of seismic vulnerability assessment at the urban scale. Unlike conventional deterministic approaches that rely primarily on generalized structural typologies, the proposed regression-based method incorporates multidimensional building attributes, allowing a more realistic representation of structural behavior under seismic loading conditions.

The spatial analysis showed that seismic vulnerability is unevenly distributed across the city, with localized high-risk clusters driven by differences in construction materials, structural systems, maintenance, and building age. These results highlight the importance of accounting for local building characteristics rather than relying on citywide averages. Integrating GIS visualization with predictive modeling improves interpretation by converting numerical results into spatial decision-support tools, helping planners prioritize

inspections, retrofitting, and risk mitigation measures while supporting urban resilience planning.

Another important outcome of this study is the demonstration that combining engineering-based assessment with digital modeling technologies creates a scalable analytical framework suitable for complex urban systems. The developed methodology can be adapted to other seismically active regions by recalibrating structural parameters, regional building practices, and local regulatory requirements. This adaptability indicates that the proposed framework represents a transferable analytical tool rather than a location-specific case study.

It should be noted that, in this initial application, the digital twin component is implemented at the level of an analytical and visualization framework linking structural inventory, regression-based vulnerability estimation, probabilistic interpretation, and GIS-based mapping, rather than as a fully operational real-time monitoring system.

Despite its advantages, several limitations should be acknowledged. The predictive accuracy of the model depends on the completeness and reliability of structural inventory data. In many urban territories, technical documentation may be outdated or incomplete, which introduces uncertainty into vulnerability estimation. Future research should therefore focus on integrating real-time monitoring data, remote sensing inputs, and automated data acquisition systems to enhance model robustness and reduce uncertainty.

Overall, the results confirm that the proposed integrated methodology provides a scientifically grounded and practically applicable approach for assessing urban seismic vulnerability, supporting evidence-based decision-making, and improving the resilience of built environments exposed to seismic hazards.

Scenario-Based Seismic Vulnerability Assessment.

The developed regression-based model was applied to a sample dataset consisting of fifteen representative buildings characterized by ten structural and geometric attributes. This sample size was chosen to provide a clear illustration of how the vulnerability index differentiates buildings with contrasting structural systems, material classes, height ranges, construction periods, and maintenance conditions within the considered urban context. For the detailed scenario-based regression demonstration, a sample of fifteen representative buildings was used to illustrate how the vulnerability index differentiates objects with different structural and condition-related characteristics. Using the calibrated weight coefficients, vulnerability index values were computed for each building under a simulated seismic scenario corresponding to intensity level 6.5. The calculated indicator **Z** reflects the integrated influence of structural configuration, material properties, geometric parameters, and technical condition on seismic performance.

In this study, Table 2 defines the classification scale used to interpret the calculated vulnerability index Z. To support the results more transparently, Table 3 presents anonymized building-level model outputs for the fifteen representative objects analyzed under the 6.5 scenario. Higher values of Z indicate increased susceptibility to seismic damage, while lower values represent more stable structural behavior.

Table 2: Classification of Buildings According to Seismic Vulnerability Index

Vulnerability Level	Color Code	Vulnerability Index (Z) Range	Color
Level 1	Green	0 – 1.5	
Level 2	Light Green	1.5 – 2.5	
Level 3	Yellow	2.5 – 3.5	
Level 4	Orange	3.5 – 4.5	
Level 5	Red	> 4.5	

Table 3. Anonymized building-level scenario results for the representative sample

ID	Structural profile	Dominant vulnerability driver	Z	Level	Recommended action
B01	RC frame, 4 stories	recent construction / good condition	1.25	Level 1 (Very low)	Routine monitoring
B02	RC frame, 5 stories	Good maintenance condition	1.42	Level 1 (Very low)	Routine monitoring
B03	RC frame, 6 stories	Moderate height effect	1.63	Level 2 (Low)	Periodic inspection
B04	Masonry, 2 stories	Older material class	1.81	Level 2 (Low)	Periodic inspection
B05	RC frame, 7 stories	height and plan configuration	2.05	Level 2 (Low)	Screening inspection
B06	Masonry, 3 stories	maintenance condition	2.22	Level 2 (Low)	Screening inspection
B07	RC frame, 8 stories	geometric irregularity	2.38	Level 2 (Low)	Screening inspection
B08	Panel building, 5 stories	construction period	2.46	Level 2 (Low)	Screening inspection
B09	Masonry, 4 stories	material and age effects	2.71	Level 3 (Moderate)	Detailed inspection

ID	Structural profile	Dominant vulnerability driver	Z	Level	Recommended action
B10	RC frame, 9 stories	height and irregularity	2.8 4	Level 3 (Moderate)	Detailed inspection
B11	Panel building, 6 stories	maintenance condition	3.0 7	Level 3 (Moderate)	Detailed inspection
B12	Masonry, 4 stories	absence of retrofit measures	3.2 6	Level 3 (Moderate)	Detailed inspection
B13	RC frame, 10 stories	irregular configuration	3.4 1	Level 3 (Moderate)	Detailed inspection
B14	Masonry, 5 stories	age, condition, and material	3.6 2	Level 4 (High)	Engineering assessment
B15	Mixed system, 7 stories	Irregularity and lack of retrofit	3.8 8	Level 4 (High)	Priority strengthening review

The individual building names and coordinates are anonymized in Table 3 to avoid disclosing exact object locations, while preserving the analytical value of the calculated vulnerability results. The behaviour of the calibrated model was examined by comparing predicted vulnerability levels with the structural characteristics and spatial patterns of the analyzed buildings. Objects classified in higher vulnerability categories predominantly correspond to older construction periods, less favourable material classes, weaker maintenance conditions, irregular configurations, and absence of retrofit measures, and they form spatial clusters rather than appearing randomly across the study area. This agreement between model outputs, engineering expectations, and GIS-based risk patterns indicates that the regression-based index provides a consistent and practically meaningful representation of seismic vulnerability for the considered scenario.

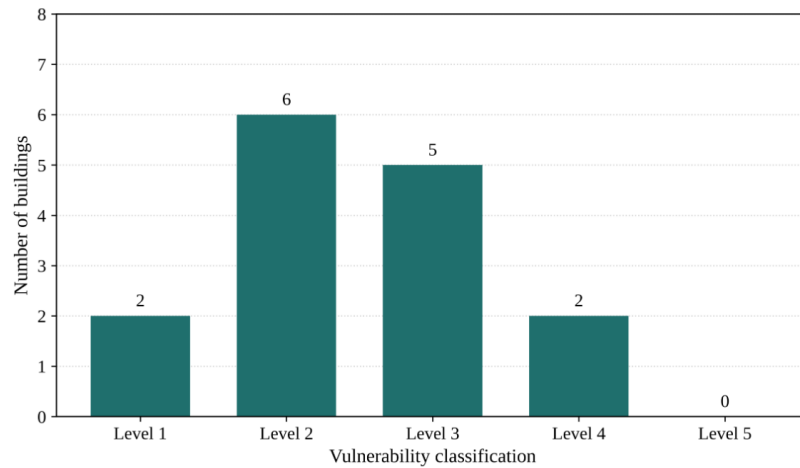


Figure 2. Distribution of buildings by seismic vulnerability level under the scenario seismic loading

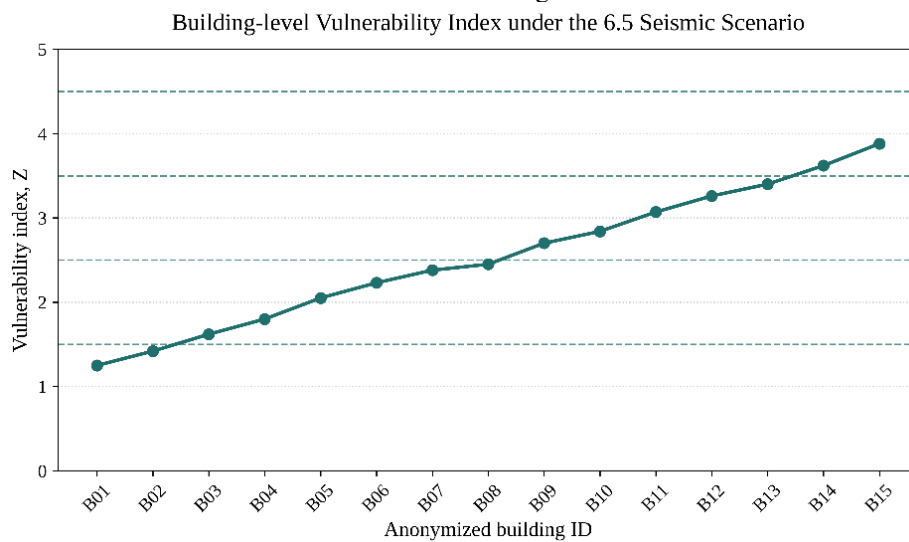


Figure 3. Building-level vulnerability index profile for the anonymized representative sample

As shown in Figures 2 and 3, most buildings fall within low-to-moderate vulnerability levels, with none classified as very highly vulnerable. The continuous vulnerability index (Z) distinguishes buildings within similar structural groups, highlighting localized weaknesses that may affect seismic performance during stronger earthquakes.

Spatial Visualization of Vulnerability Distribution.

The calculated indices were further integrated into a GIS environment to enable spatial interpretation of seismic risk distribution. Figure 4 illustrates the geographic allocation of buildings according to their vulnerability classification levels. The visualization reveals spatial heterogeneity of seismic risk, highlighting zones where structural vulnerability is concentrated rather than uniformly distributed across the study area.

From a practical implementation perspective, the framework can be deployed as a city-scale decision-support tool in which regularly updated technical passport data are fed into the regression-based vulnerability index, the resulting risk levels are visualized in the municipal GIS system, and the Digital Twin architecture is used to explore alternative retrofitting, evacuation, and resource allocation scenarios without interrupting real-world operations.



Figure 4. GIS-based visualization of building seismic vulnerability levels for Tashkent under scenario seismic loading

Such spatial analysis allows identification of priority areas requiring detailed structural inspection, retrofitting measures, and risk mitigation planning. The integration of predictive modeling with geospatial visualization significantly enhances interpretability of results and supports evidence-based decision-making in urban seismic risk management.

The reliability of the proposed vulnerability index was assessed qualitatively by comparing model outputs with expert judgment and established regional damage patterns. Buildings classified as highly vulnerable were generally older masonry structures with poor maintenance, irregular configurations, and no retrofitting, while newer reinforced concrete buildings in better condition consistently showed lower vulnerability. These results agree with engineering expectations and previous seismic risk studies, providing indirect validation of the model despite the absence of large historical damage datasets or extensive field validation. Although a formal uncertainty analysis is beyond the scope of this study, imperfect documentation and variability in structural

condition are recognized as key sources of uncertainty. The observed trends, higher vulnerability for older masonry buildings and lower vulnerability for newer reinforced concrete structures—are consistent with regional earthquake damage patterns and established typology-based vulnerability models. This agreement indicates that, despite data limitations, the proposed regression-based index is consistent with accepted seismic vulnerability concepts.

Findings and Practical Implications.

The expanded scenario analysis provides four main findings that strengthen the empirical contribution of the study. Compared with conventional approaches based on generalized building typologies or single-parameter screening, the proposed regression-based framework offers two key advantages. It combines multiple building attributes, structural system, material, geometry, construction period, condition, and retrofit status into a single vulnerability index, enabling more accurate differentiation between buildings. In addition, integration with GIS and Digital Twin technologies converts numerical results into spatial decision-support information, helping planners identify priority areas and optimize strengthening strategies. From an urban planning perspective, the proposed framework supports zoning, land-use planning, and development control by identifying areas that require stricter planning standards or strengthening measures. Integrating the vulnerability index into GIS enables seismic risk to be incorporated into local plans, emergency preparedness, and resilience strategies, making the framework both an engineering assessment and an urban planning tool.

The regression-based vulnerability index provides a consistent building-level ranking, distinguishing buildings of similar typology based on age, condition, geometric irregularity, and retrofit status. The results show that seismic vulnerability is governed by multiple factors rather than a single structural attribute, supporting the use of a multidimensional inventory over simplified typology-based screening.

The normalized contribution plot in Figure 5 supports this interpretation by showing the normalized contribution of the main input parameters to the vulnerability score. The largest effects are associated with maintenance condition and construction period, followed by geometric irregularity and material type. The normalized contributions indicate the relative importance of each variable in the vulnerability index. Structural condition and construction period have the greatest influence, followed by geometric irregularity and material type, while geometric parameters such as area and height have comparatively smaller effects. The regression model assigns higher vulnerability scores to buildings with poor maintenance, older construction, and geometric irregularities, while better-

maintained, newer, and structurally regular buildings receive lower scores. This confirms that the model behaves consistently with engineering expectations.

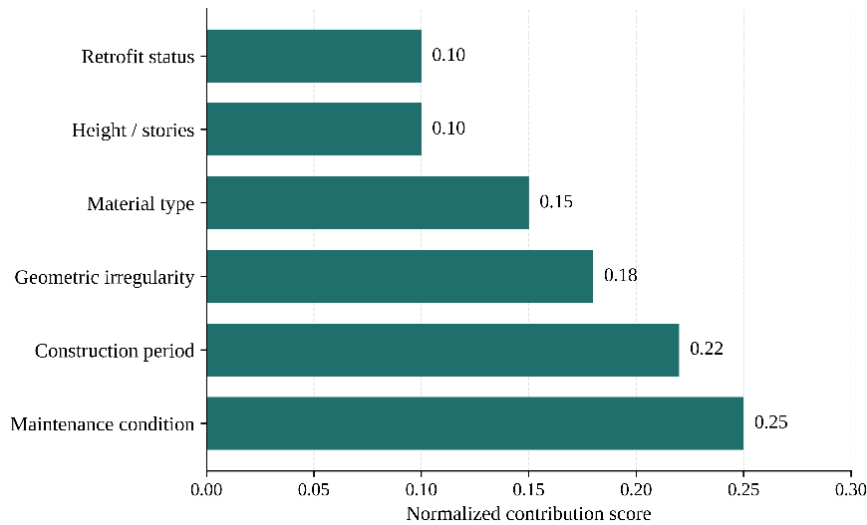


Figure 5. Normalized contribution of key structural and condition-related parameters to the vulnerability score

Third, the GIS analysis shows that vulnerability is spatially clustered, enabling priority districts to be identified for inspection and mitigation. Fourth, the Digital Twin framework supports continuous updates, allowing new building and monitoring data to be incorporated without repeating the entire assessment process.

Table 4: Number Summary of additional findings derived from the scenario-based assessment.

Analytical finding	Evidence from the scenario-based assessment	Practical implication
Building-level differentiation	The calculated vulnerability index Z assigns each building to a risk level and allows comparison of buildings with different geometric and structural attributes	Supports ranking of buildings for detailed engineering inspection and strengthening programs
Dominance of low-to-moderate categories	The analyzed sample is mainly represented by low-to-moderate vulnerability levels, while very high vulnerability is not observed in the considered scenario	Indicates that general structural performance is acceptable, but selected vulnerable buildings still require attention

Analytical finding	Evidence from the scenario-based assessment	Practical implication
Influence of structural condition and configuration	Higher vulnerability is associated with weaker maintenance condition, older construction period, irregular geometry, less favorable material type, and lack of retrofit measures	Confirms the need to include technical passportization and structural condition data in seismic risk models
Spatial clustering of vulnerability	GIS visualization reveals localized concentrations of elevated vulnerability rather than uniform risk distribution across the study area	Enables identification of priority urban zones for inspection, retrofitting, evacuation planning, and resource allocation.
Digital twin applicability	The framework links inventory data, regression-based calculation, probabilistic interpretation, and GIS visualization in one updatable system	Provides a scalable tool for future monitoring, model recalibration, and evidence-based urban resilience planning

The current implementation is limited by the size and completeness of the structural inventory, the use of a single normalized seismic scenario, and the lack of large-scale statistical calibration, which constrain uncertainty analysis and broader generalization. Nevertheless, the framework goes beyond producing a vulnerability score by generating spatially interpretable results, identifying key vulnerability drivers, and supporting the prioritization of seismic mitigation measures in Tashkent and other earthquake-prone cities.

CONCLUSION

This study developed an integrated framework for scenario-based seismic vulnerability assessment of urban buildings that combines structural engineering analysis, probabilistic modeling, geospatial technologies, and digital twin concepts. The proposed methodology enables systematic evaluation of building performance under seismic loading by incorporating multidimensional structural attributes and predictive modeling techniques.

The results demonstrate that regression-based vulnerability estimation provides a reliable quantitative indicator reflecting the combined influence of structural configuration, materials, geometry, and technical condition. The classification system derived from the calculated vulnerability index allows buildings to be grouped into standardized risk levels, facilitating interpretation and practical decision-making.

Spatial integration of calculated indicators within a GIS environment revealed pronounced heterogeneity in vulnerability distribution across the analyzed urban area. This confirms that seismic risk is strongly influenced by localized structural characteristics and cannot be accurately represented by generalized or averaged indicators. The spatial visualization approach therefore

provides a powerful tool for identifying priority zones requiring structural strengthening, inspection, or preventive mitigation measures.

The proposed framework extends beyond a single case study and provides a scalable approach that can be adapted to other earthquake-prone regions through regional calibration of structural parameters and regulatory conditions. By integrating engineering assessment with digital modeling and GIS, it transforms seismic risk evaluation into a dynamic decision-support tool for urban resilience and disaster risk reduction. Its vulnerability index is based on standard structural attributes, making the model reproducible and transferable to other cities after calibration. Future work should expand the structural database, incorporate real-time monitoring and machine learning, and develop a fully operational urban Digital Twin. Larger datasets will also enable more comprehensive validation, regression diagnostics, and improved predictive accuracy while maintaining practical interpretability.

REFERENCES

- Alemdar, K. D. (2025). Seismic risk assessment of transportation networks for the impending Istanbul earthquake with GIS-based MCDM approach. *Natural Hazards* 2025 121:9, 121(9), 10085–10123. <https://doi.org/10.1007/S11069-025-07199-Y>
- Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114, 103179. <https://doi.org/10.1016/J.AUTCON.2020.103179>
- Douglas, J., Crowley, H., Silva, V., Marzocchi, W., Danciu, L., & Pinho, R. (2024). Methods for evaluating the significance and importance of differences amongst probabilistic seismic hazard results for engineering and risk analyses: a review and insights. *Bulletin of Earthquake Engineering* 2024 22:6, 22(6), 2769–2796. <https://doi.org/10.1007/S10518-024-01896-Y>
- Ghaffarian, S. (2025). Rethinking digital twin: Introducing digital risk twin for disaster risk management. *Npj Natural Hazards* 2025 2:1, 2(1), 79-. <https://doi.org/10.1038/s44304-025-00135-x>
- Guardiola-Víllora, A., Molina, S., & D'Ayala, D. (2023). Performance based probabilistic seismic risk assessment for urban heritage. An example in Pla del Remei Area (Valencia). *Bulletin of Earthquake Engineering* 2023 21:10, 21(10), 4951–4991. <https://doi.org/10.1007/S10518-023-01721-Y>
- Guo, H., Feng, R., Dong, Y., & Gardoni, P. (2024). Life-cycle seismic resilience prediction of sea-crossing bridge piers exposed to chloride-induced corrosion in marine environments. *Structural Safety*, 111, 102523. <https://doi.org/10.1016/J.STRUSAFE.2024.102523>
- Gürdür Broo, D., Bravo-Haro, M., & Schooling, J. (2022). Design and implementation of a smart infrastructure digital twin. *Automation in Construction*, 136, 104171. <https://doi.org/10.1016/J.AUTCON.2022.104171>
- Heresi, P., & Miranda, E. (2022). Structure-to-structure damage correlation for scenario-based regional seismic risk assessment. *Structural Safety*, 95, 102155.

- <https://doi.org/10.1016/J.STRUSAFE.2021.102155>
- Jahangir, M. F., Kamari, A., & Schultz, C. P. L. (2025). Unified and interoperable digital twin models for emergency evacuation using building simulation identity cards. *Automation in Construction*, 175, 106225. <https://doi.org/10.1016/J.AUTCON.2025.106225>
- Kookalani, S., Green, S., Luo, P., Alavi, H., Parn, E., Sun, Z., & Brilakis, I. (2026). Mapping digital twin applications in infrastructure and the built environment across research types, methods, sectors, phases, and scales. *Automation in Construction*, 182, 106778. <https://doi.org/10.1016/J.AUTCON.2026.106778>
- Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. *Automation in Construction*, 147, 104716. <https://doi.org/10.1016/J.AUTCON.2022.104716>
- Macatulad, E., & Biljecki, F. (2024). Continuing from the Sendai Framework midterm: Opportunities for urban digital twins in disaster risk management. *International Journal of Disaster Risk Reduction*, 102, 104310. <https://doi.org/10.1016/J.IJDRR.2024.104310>
- Oleng, M., Ozdemir, Z., & Pilakoutas, K. (2025). Stochastic event-based probabilistic earthquake risk assessment framework for Uganda: towards informing the National Policy for Disaster preparedness and management. *Bulletin of Earthquake Engineering* 2025 23:4, 23(4), 1371–1406. <https://doi.org/10.1007/S10518-025-02103-2>
- Rosvold, E. L., & Buhaug, H. (2021). GDIS, a global dataset of geocoded disaster locations. *Scientific Data* 2021 8:1, 8(1), 61-. <https://doi.org/10.1038/s41597-021-00846-6>
- Sianko, I., Ozdemir, Z., Hajirasouliha, I., & Pilakoutas, K. (2023). Probabilistic seismic risk assessment framework: case study Adapazari, Turkey. *Bulletin of Earthquake Engineering* 2023 21:7, 21(7), 3133–3162. <https://doi.org/10.1007/S10518-023-01674-2>
- Tulaganov, B. A., Khodzhaev, A., Schwarz, J., & Abrahamczyk, L. (2021). Assessment of seismic vulnerability of buildings and structures by using European standards. *Turkish Journal of Computer and Mathematics Education*, 12(7), 323–330.
- Wang, Y., Yue, Q., Lu, X., Gu, D., Xu, Z., Tian, Y., & Zhang, S. (2024). Digital twin approach for enhancing urban resilience: A cycle between virtual space and the real world. *Resilient Cities and Structures*, 3(2), 34–45. <https://doi.org/10.1016/J.RCNS.2024.06.002>
- Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities. *Sustainable Cities and Society*, 99, 104862. <https://doi.org/10.1016/J.SCS.2023.104862>
- Zhai, G., Yao, Z., Wang, D., Zhang, A. A., Spencer, B. F., & Xu, Y. (2026). Autonomous post-earthquake structural assessment based on bidirectional graphics-based digital twin (Bi-GBDT) with physical and visual realism. *Advanced Engineering Informatics*, 69, 103971. <https://doi.org/10.1016/J.AEI.2025.103971>

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