

Urban Seismic Vulnerability Assessment Integrating Geotechnical, Social, and Structural Indicators: A Case Study of Seoul

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ABSTRACT: Urban seismic vulnerability assessment requires integration of multiple risk factors to support disaster risk reduction in dense metropolitan areas. Seoul presents a critical case study due to its extreme urban density, extensive aging infrastructure, and complex geology that creates substantial spatial variability in site amplification effects. Traditional probabilistic seismic risk assessment approaches, while scientifically rigorous, often require extensive computational resources and specialized expertise that may be impractical for routine urban planning applications, necessitating development of compact and reproducible assessment tools for rapid prioritization of mitigation efforts. This study develops a reproducible Composite Seismic Vulnerability Index (SVI) integrating four normalized indicators: ground vulnerability from geotechnical site classification using comprehensive borehole investigation data, building vulnerability from aging structure analysis, pipeline vulnerability from utility infrastructure assessment, and social vulnerability combining elderly and young children population densities. Expert-based Analytic Hierarchy Process (AHP) with consistency ratio $CR = 0.08$ determined indicator weights, and the final SVI was classified into five vulnerability categories on a 250 m grid framework. Results identified a distinct high-priority vulnerability corridor extending from Seoul's central business district toward northeastern districts, where soft ground conditions converge with concentrated aging infrastructure and elevated vulnerable population densities, while southeastern areas demonstrated lower vulnerability due to newer construction and firmer ground conditions. The lightweight, transparent methodology provides actionable prioritization capabilities for urban planning while maintaining transferability to other metropolitan regions, supporting evidence-based decision-making for retrofitting programs, infrastructure improvements, and emergency planning optimization. The framework complements existing probabilistic hazard analyses and demonstrates practical application for municipal authorities requiring rapid vulnerability assessment capabilities with limited computational resources, providing a foundation for future integration with quantitative loss estimation and probabilistic hazard modeling for comprehensive urban seismic risk management.

KEYWORDS: seismic vulnerability assessment, urban risk analysis, composite indicators, Analytic Hierarchy Process (AHP), GIS-based modeling, disaster risk reduction, Seoul

1 INTRODUCTION

Seismic risk emerges from the interaction of hazard, exposure, and vulnerability. Seoul presents a critical case study due to its extreme urban density ($>16,000$ people/km²), extensive aging infrastructure, and complex geology featuring shallow bedrock with interlayered alluvium that creates substantial spatial variability in site amplification. These conditions result in high loss potential even for moderate seismic events.

Traditional probabilistic seismic risk assessment, while rigorous, requires extensive data and computational resources that may be impractical for routine urban planning applications. Practitioners need compact, reproducible assessment tools for rapid prioritization of retrofitting and preparedness activities where full probabilistic loss modeling is not feasible.

A systematic six-step workflow for integrated seismic risk assessment provides the comprehensive framework (Figure 1). The methodology begins with compilation of geotechnical, geological, and seismological databases (Step 1), followed by development of subsurface models incorporating site parameters and seismic motion input characteristics (Step 2). Site response analysis (Step 3) enables comprehensive seismic hazard mapping (Step 4), which is then combined with exposure and vulnerability assessment (Step 5) to produce integrated seismic risk mapping (Step 6).

This study implements Steps 1 through 5 by developing a Seismic Vulnerability Index (SVI) implemented as a weighted linear combination of four indicator groups: ground vulnerability (G), building vulnerability (B), pipeline

vulnerability (P), and social vulnerability (S). Weights are derived through expert-based Analytic Hierarchy Process (AHP) with consistency ratios ≤ 0.1 . The resulting methodology provides an operational and transparent workflow designed for city-scale vulnerability assessment, priority setting, and stakeholder communication in urban seismic risk management.

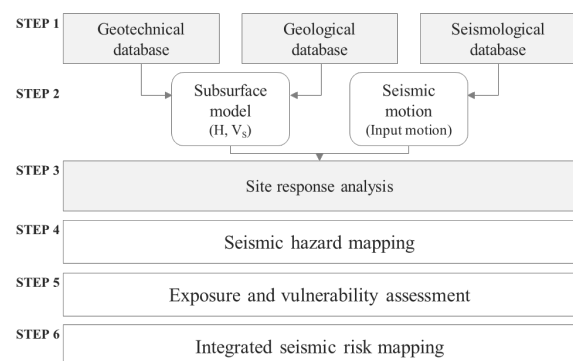


Figure 1. Workflow for computing SVI

2 DATA AND INDICATORS ANALYSIS

2.1 Geotechnical data processing and site classification

2.1.1 Data acquisition and analysis

Comprehensive geotechnical investigation data were systematically compiled from South Korea's National Geotechnical Information Database System (MOLIT 2019), representing one of the most extensive urban geotechnical datasets available for seismic vulnerability assessment. The database provides detailed stratigraphy information for 22,499 investigation sites and Standard Penetration Test (SPT) measurements for 13,054 locations across Seoul metropolitan area, with overlapping data available at 11,362 strategic locations. Additional topographic information was integrated using high-resolution Digital Elevation Model (DEM) data obtained from the National Spatial Data Infrastructure Portal (2022).

The spatial distribution of geotechnical investigation points demonstrates comprehensive coverage across Seoul's urban fabric (Figure 2), with higher density concentrations in central business districts and major development zones. This extensive dataset provides sufficient spatial resolution for regional-scale vulnerability assessment while maintaining statistical significance for grid-based interpolation procedures.

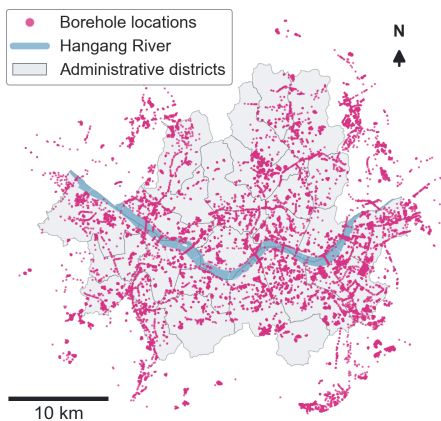


Figure 2. Spatial distribution of geotechnical investigation points

2.1.2 Parameter derivation and site classification

Geotechnical data processing required extensive computational preprocessing to extract fundamental site response parameters that directly influence seismic amplification characteristics. Unlike standardized demographic and infrastructure indicators readily available from administrative databases, geotechnical parameters necessitate specialized analysis of subsurface conditions and soil properties.

For each borehole location, two critical seismic site characterization parameters were systematically computed following established geotechnical engineering protocols: (a) depth to engineering bedrock (H), defined as the first encountered stratigraphic layer exhibiting shear wave velocity, $V_s > 760$ m/s, and (b) time-averaged shear wave velocity of the soil column ($V_{s,soil}$). Where direct shear wave velocity measurements were not available, the corrected N values were employed to compute V_s using the N- V_s correlation and representative stratigraphic values proposed by Lee et al. (2024) for Seoul metropolitan area. The data preprocessing workflow (Figure 3) illustrates the systematic approach for parameter extraction and quality control procedures applied to ensure analytical consistency across the extensive geotechnical database.

The spatial distribution of these fundamental geotechnical parameters across Seoul reveals significant heterogeneity in

subsurface conditions (Figure 4). Bedrock depth varies substantially across the metropolitan area, with deeper alluvial deposits concentrated in the Han River valley and tributary systems, while shallow bedrock conditions predominate in the surrounding upland areas. Similarly, soil shear wave velocity exhibits considerable spatial variation, with lower velocities (200-300 m/s) associated with softer alluvial deposits and higher velocities (400-500 m/s) characterizing firmer soil conditions in areas with shallow bedrock.

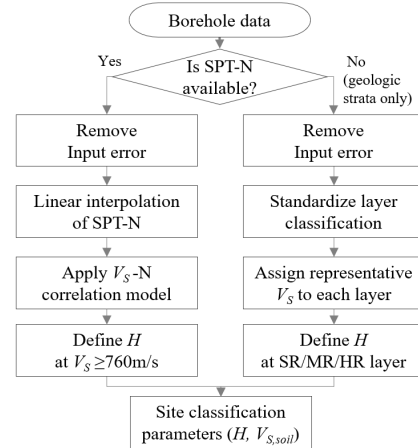


Figure 3. Geotechnical data preprocessing workflow

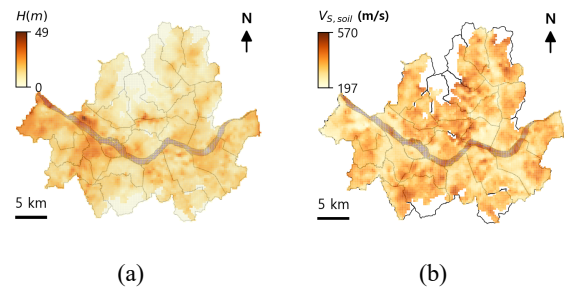


Figure 4. Spatial distribution of (a) H and (b) $V_{s,soil}$ across Seoul

These fundamental geotechnical parameters provide the foundation for systematic site classification according to the Korean Seismic Design Standard (KDS 17 10 00:2018), which categorizes geological conditions into six distinct site classes based on expected ground motion amplification potential (Table 1). The classification system integrates both bedrock depth and soil velocity characteristics to provide comprehensive assessment of site response behavior during seismic events.

Table 1. site classification system for seismic design (MOLIT 2018)

Site class	Ground type	H (m)	$V_{s,soil}$ (m/s)
S_1	Rock	1	-
S_2	Shallow deposits of stiff soils	1 – 20	> 260
S_3	Shallow deposits of soft soils		< 260
S_4	Deep deposits of stiff soil	> 20	> 180
S_5	Deep deposits of soft soil		< 180
S_6	Special soil requiring site-specific evaluation		

Site class assignments were systematically applied to a standardized 250 m grid framework using majority rule spatial interpolation, ensuring consistent coverage across the study domain while maintaining sufficient resolution for urban-scale vulnerability assessment. The resulting site classification map shown in Figure 5 demonstrates the complex spatial distribution of ground conditions across Seoul, with softer soil classes (S_4 – S_5) concentrated in alluvial valley systems where deeper deposits and lower shear wave velocities create conditions for significant ground motion amplification, while firmer site classes (S_1 – S_3) predominate in upland areas characterized by shallow bedrock and stiffer soil conditions.

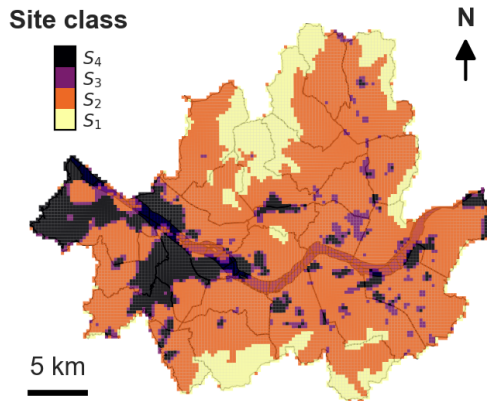


Figure 5. Site classification map (S_1 – S_6) on a 250 m grid

2.2 Vulnerability Layer Development

All vulnerability indicators were harmonized to a common 250 m grid resolution using consistent coordinate reference system to enable spatial integration and analysis. Values are expressed as area-normalized densities or dimensionless factors to ensure comparability across different data types. Missing or anomalous values were imputed using nearest neighbor median values.

Indicator normalization was performed using min-max scaling to transform all values to a standardized [0,1] range according to Equation (1):

$$I_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

where:

- I_i = normalized indicator value for grid cell i [0,1]
- x_i = original indicator value for grid cell i
- x_{\min} = minimum value across all grid cells
- x_{\max} = maximum value across all grid cells

2.2.1 Urban infrastructure indicators

Urban infrastructure vulnerability assessment incorporated comprehensive analysis of building stock and pipeline networks using centroid-based point density evaluation methods across multiple resolution scales.

Building vulnerability analysis utilized comprehensive inventory data from the Seoul Building Registry, encompassing 125,778 individual building records mapped onto 250 m grid frameworks. Critical attributes including construction type, building age, and scale characteristics (stories, height, floor area) were systematically analyzed. Building vulnerability quantifies aging gross floor area per grid cell, targeting structures with construction approvals prior to 1994 when mandatory seismic design standards were introduced in South Korea.

Structurally vulnerable buildings exceeding 30 years in age demonstrate concentrated distributions in Seoul's central districts, particularly Jongno and Gangbuk areas, where aging

structures predate modern seismic design standards (Figure 6a). These areas represent legacy urban development patterns that prioritized rapid construction over seismic safety considerations.

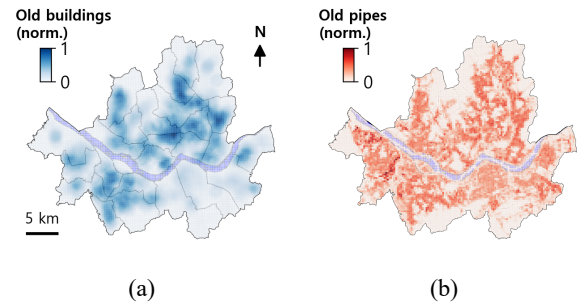


Figure 6. Normalized infrastructure vulnerability layers: (a) building vulnerability and (b) pipeline vulnerability

Critical utility infrastructure analysis encompassed 1,850,560 pipeline records representing water distribution, sewer, and district heating networks. Pipeline data were mapped using identical grid frameworks to ensure spatial consistency with building assessments. Major attributes include installation year, diameter specifications, and construction material composition. Pipeline vulnerability measures the linear density of aging infrastructure exceeding 30 years since installation for water, gas, and district heating systems.

Unlike building distributions that show clear clustering patterns, pipeline networks demonstrate relatively uniform distribution across Seoul due to extensive infrastructure installation during initial urban development phases (Figure 6b).

2.2.2 Social vulnerability indicators

Social vulnerability indicators were developed using telecommunications-based population analysis from Seoul Open Data Plaza (2024), providing high-resolution 250 m grid population distributions derived from mobile communication patterns and demographic modeling.

Residential population patterns were captured using nighttime data (23:00 hours) to represent actual dwelling locations rather than daytime workplace concentrations. This approach ensures vulnerability assessments reflect genuine community exposure during potential seismic events when populations are concentrated in residential areas.

Two primary vulnerable populations were analyzed based on emergency management research: (a) elderly adults (≥ 65 years) who face mobility constraints and require assistance during evacuations (Figure 7a), and (b) young children (≤ 7 years) who depend on adult decision-making and supervision during emergencies (Figure 7b). These groups represent populations with limited self-evacuation capabilities and heightened dependency on external support systems during seismic events.

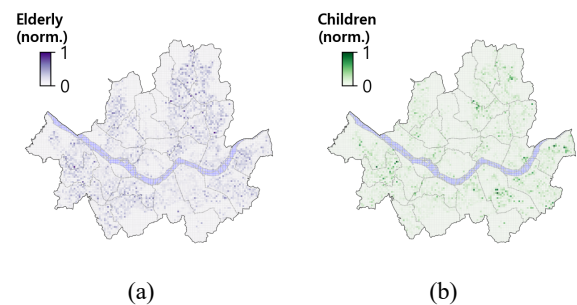


Figure 7. Normalized social vulnerability layers: (a) elderly and (b) young children population density

3 COMPOSITE INDEX DEVELOPMENT AND CLASSIFICATION

3.1 Composite Index Calculation

The composite SVI was calculated as a weighted linear combination of normalized vulnerability indicators according to Equation (2):

$$SVI = w_G \cdot G + w_B \cdot B + w_P \cdot P + w_S \cdot S \quad (2)$$

where w_G , w_B , w_P and w_S are AHP-derived weights for each vulnerability component. G, B, P, and S represent individual vulnerability indices [0,1] for ground conditions, building stock, pipeline infrastructure, and social factors respectively, and weights sum to unity ($\sum w_i = 1.0$).

3.2 AHP-Based Weight Determination

Expert-based AHP was employed to determine indicator weights through systematic pairwise comparison matrices. Domain experts in seismic engineering, urban planning, and emergency management participated in the weighting process to ensure balanced consideration of technical and practical factors.

The pairwise comparison matrix was processed to extract the principal eigenvector, which was normalized to yield final weights: w_G , w_B , w_P , w_S for ground, building, pipeline, and social vulnerability components respectively. Consistency ratio verification ($CR \leq 0.1$) ensured analytical reliability and logical consistency in expert judgments.

3.3 Vulnerability Classification and Mapping

The computed SVI values were classified into five vulnerability categories using 20% quantile thresholds: very low (0-0.2), low (0.2-0.4), moderate (0.4-0.6), high (0.6-0.8), and very high (0.8-1.0). This equal-interval classification ensures balanced spatial distribution while facilitating clear interpretation for policy applications.

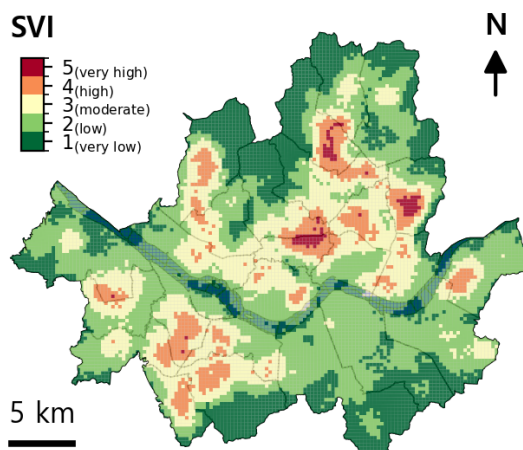


Figure 8. Integrated SVI map for Seoul metropolitan area

4 RESULTS AND DISCUSSION

4.1 Spatial Vulnerability Patterns

The SVI mapping reveals a distinct high-priority vulnerability corridor extending from Seoul's central business district toward northeastern districts (Figure 8). This corridor represents areas where multiple vulnerability factors converge: soft ground conditions (S_4 - S_5 site classes), concentrated aging building

stock, extensive pipeline networks, and elevated vulnerable population densities.

Southeastern districts demonstrate comparatively lower vulnerability due to firmer ground conditions, newer infrastructure meeting current seismic standards, and reduced pipeline density. This spatial pattern provides clear guidance for prioritizing mitigation resources and emergency preparedness efforts.

4.2 Policy Implications and Applications

The SVI framework supports targeted risk reduction strategies: (1) Building retrofitting programs should prioritize identified high-vulnerability corridors; (2) Infrastructure resilience improvements should focus on pipeline network redundancy in vulnerable areas; (3) Emergency planning should enhance evacuation capabilities in zones with concentrated vulnerable populations; (4) Resource allocation can be optimized using the transparent, quantitative vulnerability rankings.

5 CONCLUSIONS

This study successfully develops a reproducible metropolitan-scale seismic vulnerability assessment framework integrating geotechnical, structural, and social indicators. The AHP-weighted methodology ($CR = 0.08$) effectively identifies priority areas for Seoul, demonstrating a clear vulnerability corridor requiring focused mitigation efforts.

The lightweight, transparent workflow enables practical application for urban planning while maintaining scientific rigor. The framework's transferability to other metropolitan regions with comparable datasets supports broader disaster risk management applications. Future research will integrate probabilistic hazard modeling and quantitative loss estimation for comprehensive expected annual loss calculations.

6 ACKNOWLEDGEMENTS

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