Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
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doi: 10.3850/GRF-25280825_isgsr-059-P379-cd

Seismic Microzonationand Integrated Vulnerability Assessment of Seoul using Geotechnical and Social Indicators

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Seoul, as one of the world's most densely populated cities, is increasingly vulnerable to seismic risks due to its aging infrastructure and concentrated population. This study presents a GIS-based seismic vulnerability assessment integrating geotechnical and social indicators to provide a robust framework for disaster preparedness and risk mitigation. Geotechnical datainclude stratigraphy and SPT measurements that were pre-processed to develop shear wave velocity (Vs) profiles and estimate bedrock depth (H). Social indicatorsencompass the spatial distribution of old adults and young children'spopulations as well as structurally vulnerable buildings. To ensure comparability across datasets, normalization and Principal Component Analysis (PCA) were employed, assigning weights to each indicator based on variance contribution. The resulting seismic vulnerability index was classified into five grades, ranging from very low to very high vulnerability.

The analysis identifies high-priority zones, particularly in urban centers and northeastern regions, where the confluence of deep alluvial deposits, low Vs values, and high densities of old buildings and elderly populations exacerbates seismic vulnerability. Conversely, low-risk zones, primarily in southeastern areas, are characterized by modern infrastructure compliant with updated seismic design standardsand more favorable geotechnical conditions. This study emphasizes the importance of integrating structural and demographic factors in urban seismic risk assessments. The developed methodology offers actionable insights for urban planners and policymakers to prioritize seismic retrofitting and infrastructure investments. Adaptable to other urban regions, this approach sets the foundation for incorporating real-time data to enhance the robustness of future seismic vulnerability assessments.

Keywords: Seismic microzonation, Seismic Vulnerability Assessment, Geotechnical Indicators, Seismic Resilience.

1. Introduction

Seoul, as one of the most densely populated cities globally, is increasingly vulnerable to seismic events due to its aging infrastructure and dense population distribution. This study develops a seismic vulnerability map by integrating geotechnical and social indicators, offering a practical framework for disaster preparedness and risk reduction.

Seoul (605.5 km²) is characterized by diverse geological and topographical conditions, with significant urban density near the Han River basin. This study aims to evaluate seismic vulnerability using geotechnical and social datasets and combine these indicators using multivariate methods for a grid-based vulnerability map.

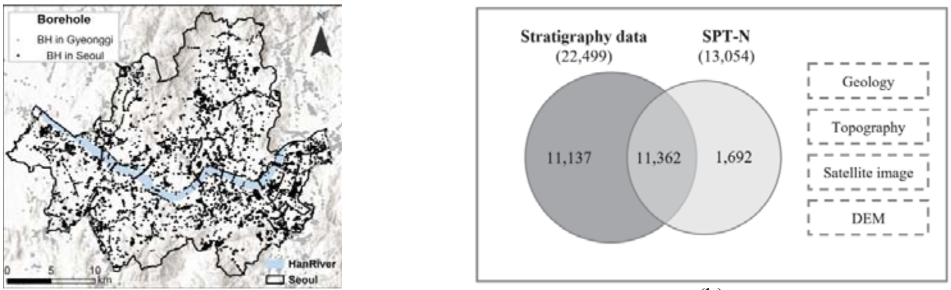
2.Geotechnical vulnerability indicators

2.1.*Data collection*

Extensive site investigation data were obtained from the National Geotechnical Information Database System (MOLIT 2019). The dataset includes stratigraphy information (22,499 sites) and SPT measurements (13,054 sites), with both data types available at 11,362 locations. Topographic data were derived using a Digital Elevation Model (DEM) from the National Spatial Data Infrastructure Portal (2022). The spatial distribution of boreholes and an integrated geotechnical database are summarized in Fig. 1.

2.2.*Data preprocessing*

Unlike standardized social indicators, geotechnical data required extensive preprocessing to evaluate key site effect parameters, such as the depth of bedrock (defined as a layer with Vs > 760 m/s) and the time-averaged Vs of the soil profile (Lee et al., 2024). These parameters are integral to the site classification system outlined in the Korean Seismic Design Standard (KDS 17 10 00:2018). Accurate identification of these parameters is critical for determining the spatial distribution of seismic vulnerability.



(a) (b)

Fig. 1. (a) Borehole distribution and (b) integrated geotechnical database

2.2.1.*Development of V_S profiles using SPT data*

The preprocessing workflow for the SPT dataset (Fig. 2a), as outlined by Lee et al. (2024), involved systematic data refinement. Profiles with incomplete or erroneous measurements were excluded to ensure data integrity. For penetration depths less than 30 cm, N valueswere extrapolated to 30 cm in accordance with the guidelines (MOLIT 2012). The corrected N values were then employed to compute Vs using Eq. (1) from Sun et al. (2013).

$$V_S = 65.64 \times N^{0.407} (m/s)(1)$$

For cases where bedrock depth was unavailable, extrapolation of the Vs profile was performed until a target velocity of 760 m/s, bedrock threshold, was achieved by Eq. (2) from Sun et al. (2007).

$$V_S(z_d) = e_0 \times (z_d^2 - z^2) + e_1 \times (z_d - z) + V_{S,z}(2)$$

The parameters include e_0=- 0.403, e_1=30.875 (shape factors), z (depth at N=50), z_d (depth below z), and $V_{s,z}$ (shear wave velocity at depth z).Post-processing resulted in a reduction of borehole profiles by 56.7%, decreasing from 13,054 to 7,369, ensuring the dataset's suitability for subsequent geotechnical analysis.

2.2.2. *Development of Vs profiles using stratigraphy data*

Stratigraphy data were simplified into seven soil groups, and representative Vs values for each group were assigned (Fig. 2b). Erroneous profiles with negative values or classification discrepancies were removed. After processing, the number of valid profiles decreased by 27.1%, from 11,137 to 8,125. Spatial outliers, comprising approximately 10% of the dataset, were removed using Local Moran's I and cross-validation techniques.

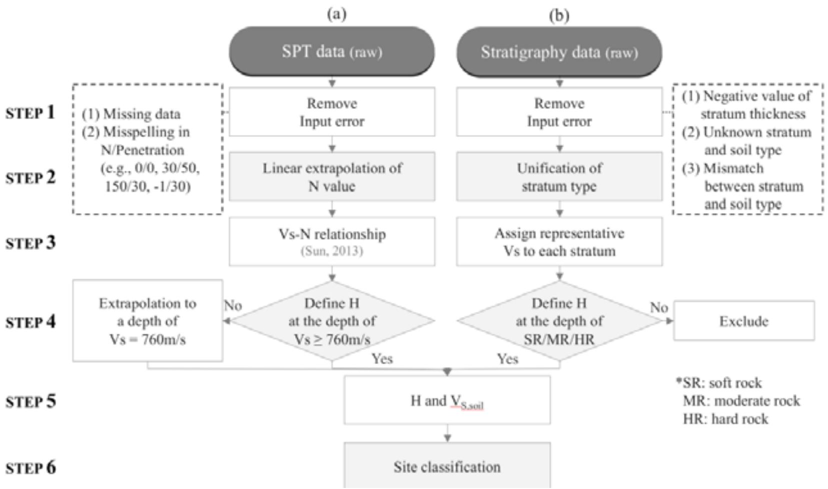
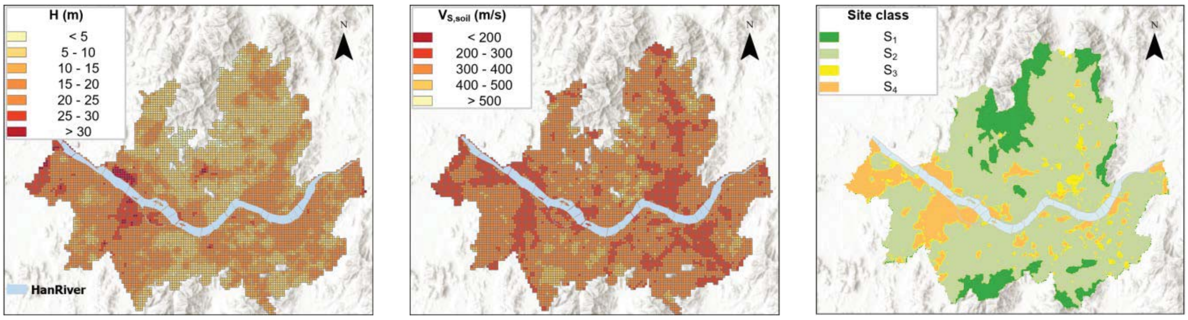


Fig. 2.Data preprocessing workflow: (a) SPT data and (b) stratigraphy data, adapted from Lee et al. (2024)

2.3.*Site structure and classification*

The zonation map of H (Fig. 3a) reveals that bedrock is predominantly located at significant depths, exceeding 30 meters, in the southern regions adjacent to the Han River basin. $V_{S,soil}$ values generally surpass 500 m/s in the northern mountainous areas, whereas regions along the Han River exhibit lower values, often below 300 m/s (Fig. 3b). The site classification map (Fig. 3c) highlights stable zones (S_1) in the norther while less stable areas (S_4), characterized by deep alluvial deposits and low $V_{S,soil}$, are concentrated along the southwestern portion of the Han River basin.



(a) (b) (a)

Fig. 3. Geostatistical analysis of site parameters: (a) H, (b) $V_{S,soil}$ and (c)seismic site classification

3. Social Vulnerability Indicators

3.1.*Vulnerable populations (older adults and young children)*

Social vulnerability to seismic events has been extensively studied, highlighting the importance of demographic and spatial factors in risk assessment (Cutter et al., 2003). Social vulnerability indicators were derived from Seoul Open Data Plaza (2024), utilizing daily population data obtained through public big data and telecommunications analysis. The platform provides hourly population distribution data at a 250m grid scale for specific dates each month. To account for residential populations, nighttime population data (23:00) were used as the primary dataset.

Vulnerable groups were identified based on their limited mobility and decision-making capacity during emergencies, focusing on older adults (65+ years) and young children (<10 years). These groups are considered particularly susceptible to seismic risks due to their increased reliance on external assistance during disaster scenarios.

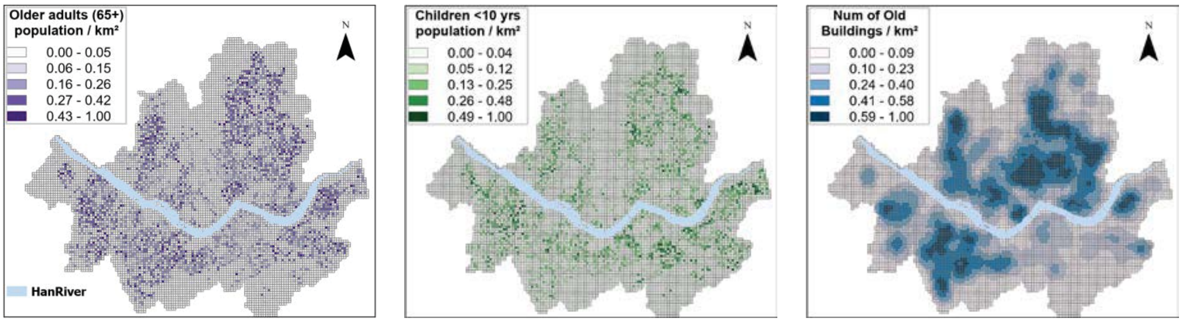
In Fig. 4a, high densities of older adults are concentrated in specific areas, often corresponding to aging residential zones. These regions may exhibit heightened vulnerability due to mobility constraints and reliance on external support during emergencies. Conversely, young children are more sparsely distributed, with high-density zones (Fig. 4b) aligning with newer developments, suburban areas, or regions characterized by schools and family-oriented infrastructure.

3.2.*Vulnerable structures (old buildings)*

Mandatory seismic design standards for private buildings in South Korea were introduced in 1988. For this study, structurally vulnerable buildings were identified based on their construction year, specifically targeting those with usage approvals issued prior to 1994. The building registry data, provided as polygon geometries, were analyzed using centroid-based point density evaluation. These datasets were sourced from the GIS-based building registry maintained by the V-WORLD platform (2024).

High densities of structurally vulnerable buildings are observed in central and historically older districts, particularly Jongno and Gangbuk(Fig. 4c). These areas are more susceptible to structural failure during seismic events, as they often lack updated construction standards, including seismic retrofitting.

To ensure comparability, all indicators were normalized to a 0–1 scale for comparability and integration. This preprocessing step facilitates the effective integration of social indicators with geotechnical data for vulnerability assessment.



(a) (b) (c)

Fig. 4. Normalized densities of (a) older adult population, (b) child population, and (c) structurally vulnerable buildings

4. Integrated vulnerability assessment

4.1. Weight allocation using PCA

Principal Component Analysis (PCA) was utilized to integrate geotechnical and social indicators with varying units and scales, reducing dimensionality while preserving variance contributions. This method assigns weights to indicators based on their contribution to overall seismic vulnerability(Lee and Oh, 2022).PCA identifies the most significant contributors to seismic vulnerability, with structurally vulnerable building density accounting for 49.8% of the variance. Geotechnical factors, including bedrock depth (20.8%) and shear wave velocity (15.2%), also play substantial roles, while social factors such as old adults (12.4%) and young children population density (1.8%) contribute to a lesser extent.

4.2. Development of the integrated seismic vulnerability

An integrated vulnerability map for Seoul was developed by calculating a composite vulnerability index for each 250m grid cell. The vulnerability grades were categorized into five distinct levels using equal intervals: Very low (1), Low (2), Moderate (3), High (4), and Veryhigh (5) vulnerability.

The map illustrates areas with varying degrees of seismic vulnerability (Fig. 5). High-priority zones, such as urban centers and northeastern regions, demonstrate a high concentration of structurally vulnerable buildings and densely populated elderly communities. These areas face increased seismic vulnerability due to unfavorable geotechnical conditions, such as deep bedrock and lower Vs values, which significantly increase their vulnerability. Conversely, low-risk zones, primarily situated in southeastern regions, benefit from modern infrastructure designed to meet updated seismic standards. Although geotechnical conditions, such as mid-depth bedrock and relatively lower Vs values, are not ideal, they do not significantly affect the overall seismic vulnerability in these zones.This comprehensive analysis underscores the robustness and reliability of the integrated vulnerability assessment, offering an accurate depiction of seismic vulnerability patterns across Seoul.

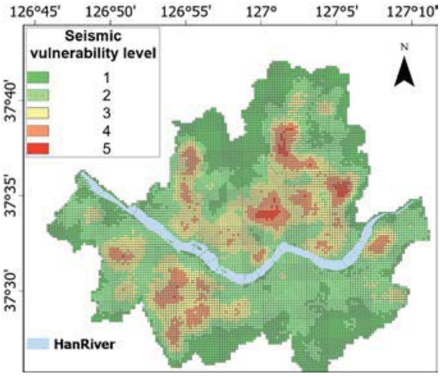


Fig. 5. Integrated seismic vulnerability

5. Conclusions

This study developed a GIS-based seismic vulnerability map for Seoul by integrating geotechnical and social indicators. The findings highlight the significant role of structurally vulnerable building density and unfavorable geotechnical conditions in determining seismic vulnerability.The map offers actionable insights for prioritizing seismic retrofitting and urban planning, aiding policymakers in zoning regulations and infrastructure investments to mitigate seismic impacts. Future research should expand the scope of vulnerability indicators and incorporate seismic probability to advance from vulnerability assessment to comprehensive seismic risk evaluation, potentially adapting the methodology for other urban regions worldwide.

Acknowledgment

This research was supported by MOIS (2022-MOIS62-001(RS-2022-ND640011)) and The Seoul Institute (2025-BR-12).

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