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A Two-Stage Framework for Urban Earthquake Vulnerability Assessment: Integrating Social and Built Environment Indicators

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A Two-Stage Framework for Urban Earthquake Vulnerability Assessment:

Integrating Social and Built Environment Indicators

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Abstract

Siliguri Municipal Corporation, a Tier II city in northern West Bengal, faces severe seismic vulnerability from weak alluvial soil, dense development, and ageing buildings. The region falls under Zone VI in the revised IS 1893:2025 hazard map, placing it in the highest hazard category. This paper examines how social vulnerability and built environment vulnerability relate across the city. To trace root causes and the coupling between vulnerability components, a Social Vulnerability Index (SVI) was built for all 47 wards using census indicators. A Built Environment Vulnerability Index (BEVI) was developed for nine wards through field surveys, road mapping, and rapid visual screening that covered buildings, roads, layout, density, and open space.

Social vulnerability varies across the city, with 9 wards in the high category. Among the nine wards with both indices, wards 4, 5, and 20 were high on social vulnerability, while 16, 22, 29, and 39 were low. The built environment shows different vulnerability. 57% of the 1,499 surveyed buildings face a high probability of Grade 3 damage, and 13% a very high probability of collapse. Only 55% of roads meet the emergency width standard, and 33% fall below it.

Comparing the indices reveals compound vulnerability and mismatch. Wards 4 and 5 overlap strongly, while Ward 29 carries hidden physical vulnerability i.e., low social but medium built environment. The strongest link is between social disadvantage and post-earthquake road inaccessibility (Pearson r = 0.78). SVI can serve as a city-wide screening tool, while built environment assessment is needed for detailed diagnosis and planning.

Keywords: Social Vulnerability, Built Environment Vulnerability, Urban Planning, Disaster Risk Reduction

1 Introduction

India's earthquake risk is a huge urban problem shaped by where people live, and whether the built environment can withstand and respond to seismic shocks. Around 60 percent of India's landmass falls within moderate to severe seismic zones (Nath et al., 2015). Recent earthquakes have shown the scale of this risk. The 2001 Bhuj earthquake, with a magnitude of 7.6, caused nearly 20,000 deaths across Gujarat and adjoining areas (Jain et al., 2010). The 2015 Nepal earthquake also hit northern India, reminding Himalayan and sub-Himalayan cities of their ongoing exposure to major earthquakes.

The consequences of earthquakes are not just the structural damages to the buildings. They disrupt housing, mobility, livelihoods, public services, and recovery systems, persisting beyond the event (CRED, 2020). But the damage isn't just about the earthquake itself. A 7.6 quake can destroy one place and leave another relatively intact depending on how people live and what they've built (Blaikie et al., 1996; Wisner, 2003). The same shaking can hit two neighbourhoods in the same city very differently.

For a long time, disaster management in India was largely organised around post-disaster relief and reconstruction. The 2001 Bhuj earthquake marked an important change in this approach. By 2006, a national body took form – National Disaster Management Authority (NDMA) whose purpose to force shift from reactive disaster management towards proactive disaster risk reduction (NDMA, 2007). This shift is also consistent with the Sendai Framework for Disaster Risk Reduction, which emphasizes on understanding and reducing the underlying drivers of disaster risk (UNISDR, 2015)

This shift in perspective gains importance since exposure to disasters varies across regions. Earthquakes of similar magnitude do not cause similar levels of damage everywhere. Their effects depend on building quality, road access, land-use patterns, household resources, social networks, and the capacity of local institutions to respond (Cutter, 1996). In India, this issue has become

especially urgent in rapidly growing urban areas where development often outpaces the regulation and infrastructure provision (Wamsler, 2006).

1.1 Urban Vulnerability as a Multi-Dimensional Problem

Urban earthquake vulnerability is produced through the interaction of several systems. The *natural system* defines the seismic hazard: earthquake magnitude, expected shaking intensity, soil conditions, slope stability, and liquefaction potential. Cities cannot remove their seismic exposure, but they can understand it and plan around it. Site-specific ground conditions are therefore central to any meaningful vulnerability assessment (Papathoma-Köhle et al., 2011).

The *built system* includes buildings, roads, utility networks, open spaces, and the physical layout of the city. These components have a significant influence on both immediate damage and post-earthquake response. Buildings that are poorly constructed can collapse, resulting in casualties and obstructing access routes. Structures built without seismic design standards are particularly vulnerable (Arya, 2014). Narrow roads may become unusable because of debris falling on carriageways, making it difficult to carry out rescue and evacuation (Golla et al., 2022). Limited open space can also reduce the availability of safe evacuation areas and emergency staging grounds. These physical vulnerabilities are rarely random and reflect planning failures and socioeconomic differences within the city (Sinha & Goyal, 2004).

The *social system* covers the characteristics of residents and communities that shape their ability to prepare for and recover from earthquake. Income, education, gender, age, disability, job security, housing tenure, access to information, and social support all influence disaster outcomes (Cutter & Emrich, 2006). Low-income groups are often more vulnerable due to living in weaker buildings and informal settlements, and having fewer resources (Wisner & Uitto, 2009).

Together, these systems show why earthquake vulnerability cannot be understood through physical exposure alone. A low-income settlement with weak buildings and narrow roads faces a very different risk profile from a better-resourced neighbourhood with stronger buildings and wider

access routes. This makes integrated assessment necessary in cities where social disadvantage and physical fragility overlap in space (Rashed & Weeks, 2003)

1.2 Interaction Between Built and Social Vulnerability

Previous studies have made important contributions to understanding different dimensions of earthquake vulnerability. Building vulnerability research has examined how construction typologies respond to seismic shaking (Barbat et al., 2010; Silva & Pereira, 2014). Infrastructure studies have analysed road network vulnerability and the consequences of access disruption (Berdica, 2002; Cetin et al., 2025). Social vulnerability research has developed indices to identify populations with lower capacity to prepare for and recover from disasters (Cutter et al., 2003; A. Fekete, 2010).

Most studies still look at buildings or people separately. Very few examine how social vulnerability and poor building condition actually overlap or don't in the same parts of a city (Burton et al., 2022; Menoni & Pergalani, 1996). This is important because earthquake risk is not simply the sum of unsafe buildings and vulnerable populations. It is shaped by the way people, infrastructure, and urban form are connected.

This problem is especially serious in India's Tier-II cities. These mid-sized urban centres are growing fast, but planning and regulation often can't keep up. They also attract migrants and lower-income households who may settle in cheaper and environmentally fragile locations. Hazard-prone land, such as riverbanks, weak-soil zones, and steep slopes, is often occupied by poor households because it is less expensive and less regulated (Blaikie et al., 1996). These same households also face limited savings, insecure employment, lower education levels, and weaker access to formal services, all of which increase social vulnerability (Pelling, 2003b).

The result is a complex spatial relationship between social and built environment vulnerability. In some areas, the two overlap clearly. Socially vulnerable residents live in weak buildings, dense settlements, and poorly connected neighbourhoods. In some areas, the relationship may be less direct. A relatively better-off neighbourhood may still contain ageing or non-compliant buildings,

while a socially vulnerable neighbourhood may have moderate built environment conditions. Understanding both alignment and mismatch is therefore essential for planning (March & León, 2015).

1.3 Research Objectives and Approach

This paper examines the relationship between social vulnerability and built environment vulnerability in Siliguri Municipal Corporation, a Tier-II city in northern West Bengal located in Seismic Zone VI. Siliguri is a rapidly growing city with a significant number of ageing buildings, congested roads, and alluvial soil conditions. These conditions make it a useful setting for examining how social and physical vulnerability interact in an Indian urban context.

We did the analysis in two parts. First, we created a Social Vulnerability Index for all 47 wards (*a ward is a smallest administrative boundary in Indian cities*) using census data. This index uses census-based indicators to identify wards where residents may have lower capacity to respond and recover from earthquake impacts. Then we did a detailed Built Environment Vulnerability Index for nine selected wards where we had field data. This assessment includes field-based and spatial data on buildings, roads, layout, density, and open space to evaluate physical susceptibility to earthquake damage and post-earthquake disruption. The relationship between the two dimensions is examined only for the nine wards where both SVI and BEVI are available.

This paper has three main objectives. First, to map social vulnerability across all 47 wards of Siliguri using census data. Second, to assess physical (built environment) vulnerability in nine selected wards through field surveys. Third, to see how these two types of vulnerability relate to each other in those wards.

The framework is intended to support a two-step planning process. SVI provides a rapid city-wide screening layer, while BEVI provides a more detailed diagnostic layer for wards requiring closer physical assessment. This distinction is important for municipal decision-making in data-constrained cities, where detailed physical surveys may not be immediately possible for every ward.

The remainder of the paper is organised as follows. Section 2 presents the theoretical framework for understanding earthquake vulnerability as an interaction between social and built environment conditions. Section 3 introduces Siliguri Municipal Corporation and explains its relevance as a seismic risk case among Indian Tier-II cities. Section 4 discusses the methodology, including the construction of the city-wide SVI, the BEVI for selected wards, and the procedures used to examine concordance, mismatch, and component-wise association. Section 5 presents the results. Section 6 discusses the implications for vulnerability theory, urban planning, and disaster risk reduction. Section 7 concludes with the main contributions, limitations, and directions for future research.

2 Theoretical Framework

Earthquake vulnerability can be understood as a coupled urban condition rather than a purely built environment or social problem. Natural hazards, built environments, and social systems interact with one another in ways that shape disaster outcomes (Alberti, 2008; Mileti, 1999). In the case of earthquakes, the hazard originates from geophysical processes, but the actual level of loss depends on how exposed and vulnerable human settlements are. Vulnerability is therefore not a fixed property of a place. It is produced through the interaction of multiple systems and can change as cities expand, buildings age, infrastructure becomes strained, or social conditions shift (Cutter, 1996; Wisner, 2006). This understanding has become increasingly central to disaster risk science, which now recognises that effective risk reduction requires attention to the conditions that generate vulnerability rather than only to the hazard itself (Panwar et al., 2024).

We can’t keep looking at buildings and people in isolation. This systems perspective discourages single-sector explanations. The built environment decides how much damage occurs, while social conditions decide who suffers most and how well they recover. These two are deeply connected (Blaikie et al., 1996; Pelling, 2003a; Wisner, 2003). A building-focused assessment may identify structural fragility but miss the social conditions that shape preparedness and recovery. A social vulnerability index may identify disadvantaged populations but cannot reveal whether roads,

buildings, or open spaces are physically capable of supporting emergency response. Integrated assessment is therefore warranted.

The tricky part is that these two don't always line up neatly. In some wards, the two may clearly coincide i.e., socially vulnerable residents may live in weak buildings, dense settlements, and poorly connected neighbourhoods. In other wards, the relationship may diverge. A ward with relatively better social indicators may still contain ageing or non-compliant buildings, while a socially disadvantaged ward may have moderate physical conditions (Rashed et al., 2007). These patterns of alignment and mismatch are not only analytically interesting but they also imply different planning responses. Compound vulnerability, where high social disadvantage and high physical fragility overlap, calls for integrated intervention. Hidden physical vulnerability, where social indicators appear favourable but the built fabric remains unsafe, requires direct structural interventions and retrofitting. Socially driven vulnerability, where residents face significant disadvantage despite only moderate physical risk, needs stronger preparedness and recovery support.

3 Study Area: Siliguri Municipal Corporation, India

Siliguri Municipal Corporation, located in northern West Bengal, serves as India's gateway to the north-eastern states (Figure 1). The city occupies a narrow corridor between Nepal (northwest), Bhutan (north), and Bangladesh (south), making it strategically vital for national security and commerce. It connects India's northeastern region to the mainland and lies close to the Indo-China border via Sikkim's Nathula Pass.

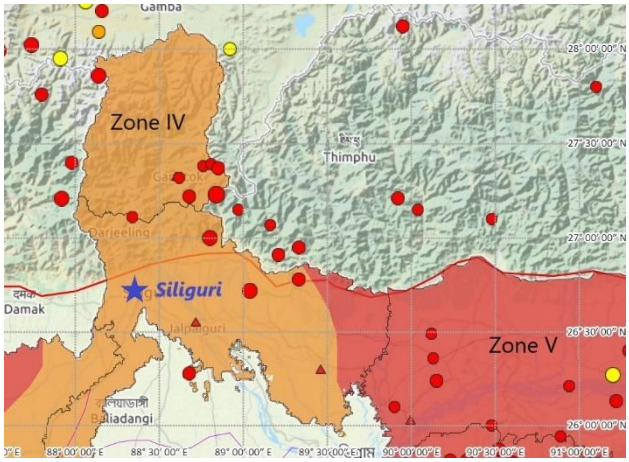


Figure 1: Location of SMC with respect to Seismic Zoning

The city spans Darjeeling and Jalpaiguri districts with 47 wards. Historically known for tea, timber, and tourism, Siliguri has transformed into a commercial hub. Population grew rapidly from <5,000 (1931) to 513,264 (2011), driven by migrants from Bihar, Uttar Pradesh, Assam, Nepal, Bhutan, and Bangladesh.

3.1 Seismic Hazard Profile of SMC

Siliguri falls within Seismic Zone VI (High Damage Risk), expected to experience MSK VIII intensity shaking (Figure 1). Major threats include the Teesta Fault (15 km north) and Main Boundary Fault at Sevoke-Sukna, which could generate devastating earthquakes. North Bengal University research identifies Siliguri as highly vulnerable to Main Boundary Fault rupture. The city experienced strong shaking during the 2011 Sikkim earthquake (M6.9) with moderate structural damage but no casualties. The 2015 Nepal earthquake (M7.8) also caused significant impacts, demonstrating ongoing seismic exposure (Khanna et al., 2012).

Siliguri rests entirely on alluvial soils with average bearing capacity of 1.6 tonnes/sq.m—below safe construction standards. Areas within 500m of Mahananda, Jorapani, and Fuleshwari Rivers have even weaker soils, creating compound flood-earthquake hazards. Informal settlements proliferate in these geologically unstable riverbank zones.

3.2 Urban Morphology in SMC

Rapid, largely unplanned urbanization has produced a mixed formal and informal built fabric with highly uneven structural quality and access conditions. A building survey of 1,499 structures across nine wards shows that the dominant construction type is concrete frame with masonry infill, accounting for 59 percent of the stock, followed by unreinforced masonry (URM) at 21 percent. The vulnerability profile is concerning, with 57 percent of buildings showing a high probability of Grade 3 damage and 13 percent showing a very high probability of collapse (Grade 5). The stock is predominantly residential and low-rise, with about 70 percent of buildings below three storeys, yet this low-rise form does not translate into safety because vertical and plan irregularities are common. Setbacks are also inadequate. The average setback is 1.4 m, below the 3 m standard, which increases the likelihood that debris will spill onto carriageways and constrain post-earthquake movement and emergency response.

Infrastructure conditions amplify these risks. A road survey covering about 170 km across the same nine wards indicates that only 55 percent of the network meets the 3.5 m minimum width needed for emergency access, while 33 percent of roads fall below 3.5 m and are likely to become impassable in a post-earthquake scenario. Full internal accessibility is achieved in only three of the nine wards, specifically Wards 16, 29, and 39. Network structure further limits resilience because the road system is predominantly tree like, with limited alternative routes and low redundancy. Open space availability is critically low at about 0.01 sq m per person against a 9 sq m standard, and three of the nine surveyed wards have no designated open spaces at all, leaving minimal capacity for evacuation, temporary sheltering, or emergency staging.

4 Methodological Approach

The methodology follows a two-layer structure. The first layer develops a city-wide Social Vulnerability Index for all 47 wards of Siliguri Municipal Corporation. The second layer uses the Built

Environment Vulnerability Index for the nine wards where detailed field and spatial data are available. The two indices are then compared only for the common ward set.

This structure is a reflection to the reality of data availability in Indian urban local bodies. Social vulnerability can be assessed across the entire city using census based and settlement related indicators. Built environment vulnerability requires more intensive field survey and spatial analysis. The study therefore uses SVI as a screening layer and BEVI as a diagnostic layer. The purpose is to examine how they align, where they diverge, and how these patterns can guide planning decisions.

4.1 Social Vulnerability Index (SVI)

The Social Vulnerability Index measures the relative capacity of ward populations to prepare for, respond to, and recover from earthquake impacts. It was developed for all 47 wards of Siliguri Municipal Corporation using thirteen indicators derived from census-based variables. These indicators capture demographic sensitivity, household resource constraints, housing and service deprivation, and settlement informality.

The final indicators included population density, female population, age factor, marginalised population, illiteracy, house ownership condition, household size, no financial savings, no toilet facility, no kitchen facility, no basic assets, disability, dilapidated houses, and slum population. These variables were selected based on literature study and effectively reflect seismic vulnerability conditions in India.

All indicators were standardised using z scores and Principal Component Analysis was applied to reduce the dimensionality of the dataset and identify the dominant underlying dimensions of social vulnerability. The suitability of the data for PCA was checked using the Kaiser Meyer Olkin measure and Bartlett's Test of Sphericity. Components with eigenvalues greater than one were retained.

The SVI was calculated as the weighted sum of the retained component scores. Component weights were derived based on the proportion of variance explained by each retained component.

The final SVI scores were classified into low, medium, and high vulnerability categories. For the further coupling analysis, SVI values were extracted for the nine wards where BEVI values are available.

4.2 Built Environment Vulnerability Index (BEVI)

The Built Environment Vulnerability Index (BEVI) assesses the physical susceptibility of urban form to earthquake damage. The methodological approach for measuring BEVI adopted in this paper follows Golla et al., (2022). Five interrelated elements for Siliguri were analysed which included buildings, roads, layout, density, and land use (Dempsey et al., 2008). These elements were classified into two components i.e., functional (buildings, roads, layout) and static (density, land use). The functional component captures direct structural damage and its cascading effects. Buildings represent primary structural vulnerability. Roads measure accessibility for emergency response. Layout assesses spatial connectivity and redundancy. Static components capture pre-existing spatial vulnerabilities that amplify disaster impacts.

4.2.1 Data Collection

Rapid Visual Screening (RVS) methodology was applied to 1,499 buildings across 9 selected wards representing varied socioeconomic and construction patterns. RVS as a tool is effective to rapidly asses the structural vulnerability of the buildings to earthquakes (Ajay Kumar et al., 2017; Arya, 2006; FEMA 154, 2015; Ningthoujam & Nanda, 2018). Road network assessment covered 170 km using GPS mapping and field verification. Open space measurement combined satellite imagery analysis with field verification.

4.2.2 RVS Procedure for Buildings

RVS followed Sinha & Goyal (Sinha & Goyal, 2004) methodology adapted for Indian conditions. Buildings received Basic Structural Hazard (BSH) scores based on typology and seismic zone, modified by structural irregularities (soft story, heavy overhang, short column, layout irregularity, pounding effect, age, height, ground settlement, prior damage) and soil conditions.

4.2.3 BEVI Components Measurement

- Buildings (BV): Ward-level aggregation of RVS scores reflecting the proportion of buildings in each damage grade.
- Roads Intrinsic Vulnerability (RI): Pre-earthquake inaccessibility because of road width <3.5m (insufficient for movement of emergency vehicles).
- Roads Extrinsic Vulnerability (RE): Post-earthquake inaccessibility due to Grade 5 building collapse debris. Collapse models estimated debris extension based on building height, setback, and road width. Network analysis identified complete/partial closures.
- Layout: Network redundancy measured by Alpha index (ratio of existing to possible circuits).
- Density (D): Built-up density (built area/total ward area) and building adjacency.
- Land Use (S): Per capita open space deficit.

BEVI Calculation

Once all six elements of the Built Environment are assessed for their vulnerability, a Built Environment Vulnerability Index (BEVI) is calculated as the weighted aggregation of the functional and static components Equation 1. The study proposes two types of BEVI: Discrete and Systemic that are calculated using Equation 2 and Equation 3.

$$\boldsymbol{BEVI = W_1(functional\ component) + W_2(static\ component)}$$

Equation 1

$$BEVI_{Discrete} = W_1[w_b(BV) + w_r(R_I) + w_l(\alpha)] + W_2[w_d(D) + w_s(S)]$$

Equation 2

$$BEVI_{Systemic} = W_1[w_b(BV) + w_r(R_E) + w_l(\alpha')] + W_2[w_d(D) + w_s(S)]$$

Equation 3

Discrete BEVI is a weighted summation of individual elements' measures in the pre-earthquake scenario and does not consider interdependencies between elements. However, the Systemic BEVI is a weighted summation of measures of elements of BEVI in the post-earthquake scenario and

considers the interdependencies between elements. Analytically put, Systemic BEVI is a measure that considers the change in accessibility and layout structure due to the collapsed buildings, while the rest of the variables are constant.

4.3 Coupling SVI and BEVI

The relationship between SVI and BEVI was examined only for the nine wards where both indices were available. This common ward set includes Wards 2, 4, 5, 16, 20, 22, 29, 39, and 42. The analysis does not compare 47 SVI values with 9 BEVI values. Instead, the 47 ward SVI is used for city wide screening, while the nine-ward subset is used for the coupling analysis.

The first step examined the aggregate association between SVI and Systemic BEVI. Pearson correlation was used to assess the direction and strength of the relationship. A simple regression was also used to examine the proportion of variation in BEVI associated with SVI within the nine-ward subset. Given the small number of wards, this analysis is treated as exploratory.

The second step used a component wise correlation matrix. Selected SVI indicators were correlated with BEVI subcomponents such as Building Vulnerability, Extrinsic Road Vulnerability, post-earthquake layout, density, open space deficit, and Systemic BEVI. This analysis identifies which social vulnerability conditions align most clearly with particular forms of built environment vulnerability. It supports interpretation of possible pathways linking social disadvantage with physical fragility.

The third step uses concordance analysis. Each ward was classified according to its SVI category and BEVI category. This produced four broad vulnerability types. High SVI with high BEVI indicates compound vulnerability. Low SVI with medium or high BEVI indicates hidden physical vulnerability. High SVI with low or medium BEVI indicates socially driven vulnerability. Low SVI with low BEVI indicates relatively lower vulnerability.

The fourth step calculated a Vulnerability Mismatch Index (VMI). The index was computed as the absolute difference between standardised BEVI and standardised SVI values as shown in Equation 4.

$$VMI = | Z_{BEVI} - Z_{SVI} |$$

Equation 4

A low value indicates that social and built environment vulnerability are closely aligned. A high value indicates divergence. The direction of mismatch was also noted. If BEVI exceeds SVI, the ward may contain hidden physical vulnerability. If SVI exceeds BEVI, social vulnerability may be higher than the built environment assessment suggests.

5 Results

5.1 Social Vulnerability

5.1.1 Principal Component Analysis

The Social Vulnerability Index was developed using thirteen ward level indicators derived from Census based variables and slum population data. Before factor extraction, all variables were standardized using z scores. Principal Component Analysis was then carried out on the correlation matrix. The diagnostic tests confirmed the suitability of the data for dimensional reduction. The overall Kaiser Meyer Olkin value was 0.766, indicating acceptable sampling adequacy, while Bartlett's Test of Sphericity was significant, with a chi square value of 458.487 and $p < 0.001$. Four components with eigenvalues greater than one were retained. Together, they explained 76.11 percent of the total variance.

Table 1: PCA diagnostics for SVI construction

Diagnostic	**Value**
KMO overall	0.766
Bartlett chi square	458.487

Bartlett df	78
Bartlett p value	< 0.001

The rotated component structure shows that the first component is the dominant axis of social vulnerability. It explains 43.22 percent of the variance after rotation and has high positive loadings on illiteracy, no savings, no assets, slum population, households without toilets, dilapidated houses, and female plus child population. This component therefore represents a broad deprivation and informality dimension.

Table 2: Retained SVI components and weights

Component	**Main interpretation**	**Variance explained (%)**	**SVI weight**
RC1	Deprivation and informality	43.22	0.568
RC2	Housing tenure and service condition	12.23	0.161
RC3	Population density	10.51	0.138
RC4	Large household size	10.15	0.133

The second component explains 12.23 percent of the variance and is mainly associated with renters and houseless households, households without kitchen facilities, and marginal workers. The third component explains 10.51 percent of the variance and is primarily associated with population density. The fourth component explains 10.15 percent of the variance and is strongly associated with large household size. The component weights used for SVI aggregation were derived from their respective shares of the retained variance.

5.1.2 Social Vulnerability Index

The final SVI was calculated as the weighted sum of the four retained rotated component scores. The scores were then scaled to a 1 to 5 range for interpretation and classified into low, medium, and high vulnerability categories using Jenks Natural Breaks.

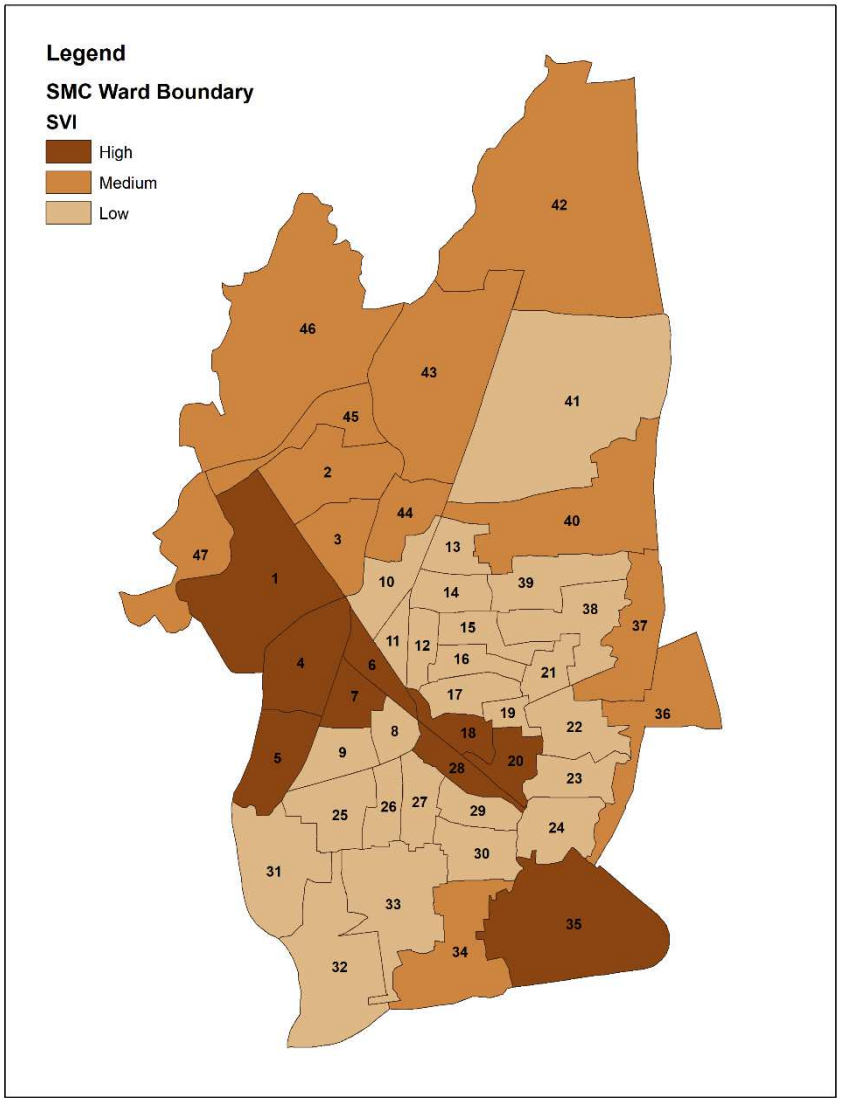


Figure 2: Social Vulnerability - Ward level

Of the 47 wards, 26 were classified as low social vulnerability, 12 as medium vulnerability, and 9 as high vulnerability as shown in Figure 2. The high vulnerability group includes Wards 1, 4, 5, 6, 7, 18, 20, 28, and 35. The medium vulnerability group includes Wards 2, 3, 34, 36, 37, 40, 42, 43, 44, 45, 46, and 47. The remaining wards fall in the low vulnerability class.

For the nine wards where BEVI data are available, three wards fall in the high SVI category: Wards 4, 5, and 20. Wards 2 and 42 fall in the medium category. Wards 16, 22, 29, and 39 fall in the low category.

Table 3: SVI values for the nine BEVI wards

Ward	SVI raw score	SVI category
2	-0.111	Medium
4	1.044	High
5	1.366	High
16	-0.909	Low
20	0.639	High
22	-0.488	Low
29	-0.639	Low
39	-0.188	Low
42	0.320	Medium

Social vulnerability in Siliguri is clearly uneven. High SVI wards are associated with deprivation, settlement informality, limited savings, weak household assets, and basic service deficits.

5.2 Built Environment Vulnerability

5.2.1 Functional Component

5.2.1.1 Buildings

Rapid Visual Screening of 1,499 buildings across nine wards revealed dominant construction typologies of concrete frame with burnt brick masonry infill (59%) and unreinforced masonry (21%). The damage grade distribution indicated that 57% of surveyed buildings face a high probability of Grade 3 damage, with 13% showing a very high probability of Grade 5 collapse (Figure 3).

Approximately 70% of Grade 5 buildings were moment resisting frames without infill walls (C1 typology).

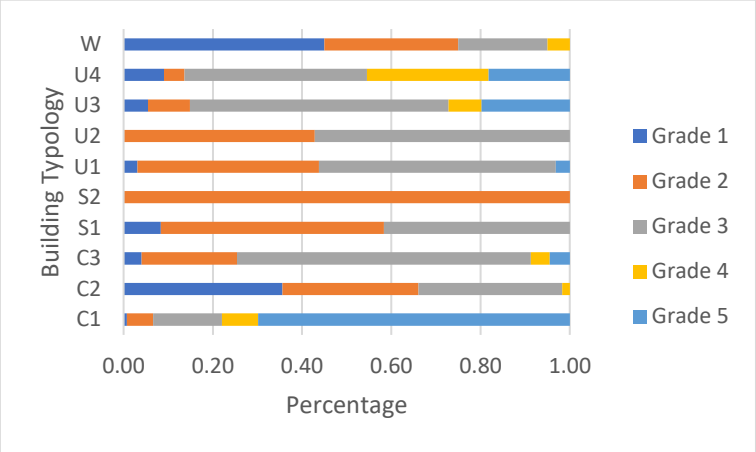


Figure 3: Building Typology Distribution and Damage Grade Assessment

Low rise development characterizes all wards, with 80% of buildings at or below three stories. Ward 20 exhibits midrise development with 33% of buildings exceeding four stories. Analysis reveals a negative correlation between building height and Grade 5 damage probability (Figure 4). Building vulnerability (BV) scores range from 2.78 to 3.22 on a scale of 1 to 5, with an average of 3.0. Five of nine wards exceed the average mark, indicating accumulated building stock vulnerability.

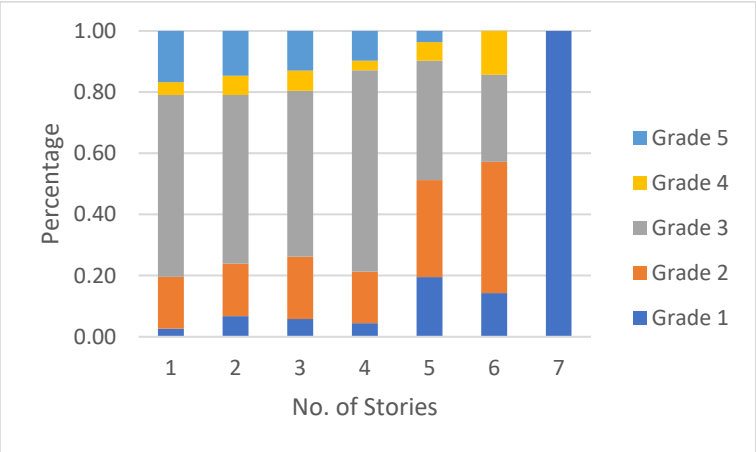


Figure 4: Building Height Distribution and Grade 5 Damage Correlation

5.2.1.2 Collapse and Debris Analysis

Collapse analysis of 199 Grade 5 buildings using a 45-degree collapse angle and 20% volume reduction factor revealed average debris spillage of 1.6 meters onto adjacent roads. The average building setback of 2.4 meters across all surveyed buildings falls below the prescribed 3-meter standard (Table 4). Grade 5 buildings register the lowest average setback of 2.1 meters. The combination of limited setbacks and substantial debris extension creates conditions for road blockages, particularly affecting single-lane roads already constrained to 3.5-meter widths.

Table 4: Average Building Setbacks by Damage Grade across Wards (meters)

Ward No.	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Average
2	3.1	2.5	2.3	3.4	2.4	2.4
4	2.2	2.7	1.6	4.4	1.2	1.8
5	2.8	2.5	1.8	2.0	1.3	1.9
16	3.9	4.2	3.5	3.7	4.1	3.8
20	3.0	3.1	2.7	4.2	3.1	3.1
22	1.9	2.0	1.9	1.5	1.8	1.9
29	2.1	2.8	1.9	4.9	1.7	2.1
39	3.1	3.1	2.8	3.4	2.7	3.0
42	3.5	3.1	2.3	1.7	2.0	2.4
Average	2.8	2.9	2.2	3.4	2.1	2.4

5.2.1.3 Road Network

A survey of 170 kilometres of road network across nine wards identified that 55% of roads meet the 3.5-meter minimum width for emergency vehicle access. Approximately 21% of total road length remains below safe width standards. Only three wards (16, 29, 39) achieve 100% network accessibility by width. Intrinsic vulnerability (RI) measurements indicate Ward 5 with the highest

vulnerability at 18.75 square kilometres of inaccessible road per square kilometre of area, followed by Ward 20 at 9.96 and Ward 4 at 5.19 (Table 5).

Table 5: Road Network Lane Details by Ward

S. No	Area (Sq.km)	Total Road Length (km)	Double Lane (km)	Single Lane (km)	Inaccessible (km)
2	0.88	22.36	3.31	15.49	3.56
4	0.78	16.85	3.58	9.22	4.05
5	0.59	18.60	4.47	3.05	11.08
16	0.26	8.60	0.47	8.13	0.00
20	0.33	10.13	1.99	4.82	3.32
22	0.53	15.93	2.28	11.84	1.82
29	0.29	8.60	2.96	5.64	0.00
39	0.59	17.27	3.11	14.16	0.00
42	4.07	51.50	11.78	28.45	11.27

Post-earthquake network modelling incorporating debris spillage from building collapse identified complete road closures on single lane segments and partial closures on double lane roads. Complete closures increased inaccessible road lengths substantially, with Ward 5 experiencing 60% network inaccessibility in the post-earthquake scenario. Extrinsic vulnerability (RE) measurements range from 1.55 to 19.96 square kilometres per square kilometre. Per capita road availability across all wards falls below the 4 to 5 meters per capita benchmark established by urban planning guidelines, with four wards registering below 1 meter per capita (Table 6).

Table 6: Intrinsic Vulnerability and Per Capita Road Availability

Ward No	Intrinsic Vulnerability (Ai/Sq. Km)	Per Capita Road Availability (m/person)
2	4.02	1.22
4	5.19	0.47

5	18.75	0.42
16	0.00	1.61
20	9.96	0.66
22	3.40	1.28
29	0.00	0.75
39	0.00	1.32
42	2.77	1.84

5.2.1.4 Layout Structure

Topological analysis using alpha and gamma indices reveals predominantly tree-like network structures throughout Siliguri. Alpha index values indicating circuit redundancy range from 0.29 to 0.59 in pre-earthquake conditions, declining to 0.18 to 0.52 post-earthquake (Table 7). Ward 42 registers the lowest alpha index of 0.29, declining to 0.18 after debris-induced closures represent an 11% reduction in circuitry. Ward 2 experiences maximum redundancy loss at 14%. Gamma indices measuring inter-nodal connectivity range from 0.48 to 0.67, indicating incomplete network integration. Ward 42, with a gamma index of 0.48, demonstrates that only 48% of the network can access every other node.

Table 7: Topological Analysis Results (Alpha and Gamma Indices)

Ward No	Pre-Earthquake Alpha	Pre-Earthquake Gamma	Post-Earthquake Alpha	Post-Earthquake Gamma
2	0.48	0.57	0.34	0.49
4	0.37	0.53	0.27	0.47
5	0.44	0.55	0.33	0.45
16	0.58	0.60	0.51	0.54
20	0.45	0.51	0.33	0.38
22	0.53	0.49	0.44	0.45

29	0.57	0.67	0.46	0.60
39	0.59	0.61	0.52	0.55
42	0.29	0.48	0.18	0.43

5.2.2 Static Component

5.2.2.1 Density

Built-up densities across surveyed wards range from 44% to 56%, remaining below the recommended guidelines of 58 to 65% (Table 8). Average building adjacency measures 1.6 meters, approximately half the recommended 3-meter separation standard. Wards 2, 5, and 20 demonstrate density vulnerability scores of 3.3, 3.0, and 3.7, respectively. Ward 39, despite the highest building density of 0.56, shows the lowest pounding vulnerability of 1.1 due to superior building spacing. Deviation from Development Control Regulations appears most pronounced in interior ward sections containing older structures.

Table 8: Built-up Density and Building Adjacency Analysis

Ward No	Built-up Density (d1)	Average Building Adjacency (m)	Built-up Adjacency (d2)	Density (D)
2	0.49	1.04	1.96	3.3
4	0.44	1.42	1.58	2.2
5	0.50	1.75	1.25	3.0
16	0.55	2.74	0.26	3.3
20	0.53	1.71	1.29	3.7
22	0.55	1.54	1.46	1.4
29	0.56	1.35	1.65	1.4
39	0.56	2.30	0.70	1.1
42	0.44	1.26	1.74	1.2

5.2.2.2 Land Use and Open Space

Satellite image classification reveals low to medium density development across Siliguri Municipal Corporation. Per capita open space availability measures 0.01 square meters municipality-wide against the 4 square meter standard. Three wards (16, 20, 39) contain no designated open spaces. Ward 5 provides only 0.2 square meters per capita, followed by Ward 29 at 0.3 square meters. Average per capita open space across nine surveyed wards reaches only 0.6 square meters (Table 9).

Table 9: Per Capita Open Space Availability by Ward

Ward No	Available Open Space (sq. m)	Population	Per Capita Open Space (sq. m)	Shortfall (sq. m)
2	17525	14327	1.2	2.8
4	15755	20745	0.8	3.2
5	3174	16369	0.2	3.8
16	0	4922	0.0	4.0
20	0	9009	0.0	4.0
22	10888	10182	1.1	2.9
29	3619	10703	0.3	3.7
39	0	12353	0.0	4.0
42	28046	19139	1.5	2.5

5.2.3 Built Environment Vulnerability Index

The Analytical Hierarchy Process survey of 12 expert professionals yielded component weightings for BEVI calculation, as shown in Figure 5.

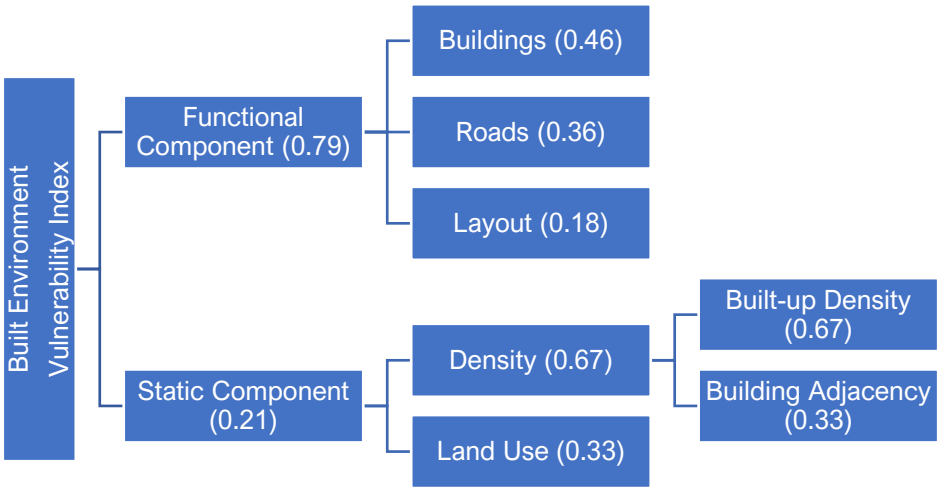


Figure 5: Weights obtained from AHP analysis

Discrete BEVI, representing pre-earthquake conditions without interdependency effects, yields scores ranging from negative 0.900 to 0.958 (Table 10). Systemic BEVI incorporating post-earthquake changes in accessibility and layout ranges from negative 0.957 to 0.904 (Table 11).

Table 10: Discrete Built Environment Vulnerability Index (BEVI Discrete)

W. No.	BV	RI	α	D	S	Functional	Static	$BEVI_D$
2	-0.765	-0.149	0.022	0.394	-1.074	-0.409	-0.091	-0.342
4	1.300	0.047	-1.056	0.159	-0.396	0.805	-0.024	0.631
5	0.612	2.273	-0.370	-0.044	0.622	1.166	0.176	0.958
16	-0.765	-0.804	1.001	-0.654	0.961	-0.821	-0.121	-0.674
20	-0.765	0.833	-0.272	-0.019	0.961	-0.003	0.304	0.062
22	-0.076	-0.247	0.512	0.086	-0.905	-0.216	-0.241	-0.222
29	1.300	-0.804	0.903	0.203	0.452	0.146	0.285	0.175
39	-1.453	-0.804	1.099	-0.383	0.961	-1.156	0.061	-0.900
42	0.612	-0.345	-1.840	0.258	-1.583	0.488	-0.350	0.312

Table 11: Systemic Built Environment Vulnerability Index (BEVI Systemic)

W. No.	BV	RE	α '	D	S	Functional	Static	$BEVI_S$
2	-0.765	-0.260	-0.310	0.394	-1.074	-0.390	-0.091	-0.327

4	1.300	0.677	-0.921	0.159	-0.396	1.008	-0.024	0.791
5	0.612	2.067	-0.398	-0.044	0.622	1.097	0.176	0.904
16	-0.765	-0.729	1.173	-0.654	0.961	-0.826	-0.121	-0.678
20	-0.765	0.839	-0.398	-0.019	0.961	0.022	0.304	0.081
22	-0.076	-0.277	0.562	0.086	-0.905	-0.236	-0.241	-0.237
29	1.300	-0.875	0.737	0.203	0.452	0.150	0.285	0.179
39	-1.453	-0.923	1.261	-0.383	0.961	-1.228	0.061	-0.957
42	0.612	-0.519	-1.707	0.258	-1.583	0.402	-0.350	0.244

Highest Systemic BEVI scores appear in Ward 5 (0.904) and Ward 4 (0.791), indicating elevated vulnerability. Lowest scores occur in Ward 39 (negative 0.957) and Ward 16 (negative 0.678). Jenks Natural Breaks classification categorizes wards into high, medium, and low vulnerability classes. Vulnerability classification demonstrates alignment with original ward selection criteria based on population density and construction patterns, validating methodological coherence.

5.3 Association between Social and Built Environment Vulnerability

The association between SVI and BEVI was examined only for the nine wards where both indices were calculated. Because the SVI was calculated for all 47 wards, while BEVI was available only for the surveyed wards. The association analysis therefore uses the common ward set: Wards 2, 4, 5, 16, 20, 22, 29, 39, and 42.

The BEVI values used here are the Systemic BEVI scores, which account for post-earthquake changes in accessibility and layout structure due to collapsed buildings. This is consistent with the BEVI framework, where Systemic BEVI differs from Discrete BEVI by including road disruption and layout changes after building collapse.

5.3.1 Overall BEVI SVI Association

The correlation between SVI and Systemic BEVI for the nine wards is positive and reasonably strong, with a Pearson correlation coefficient of 0.78. The adjusted R square value is 0.55, indicating that the social vulnerability score explains a substantial share of variation in Systemic BEVI within the surveyed ward set. Given the small sample size, this result should be interpreted as exploratory rather than predictive.

When Ward 29 is excluded, the association becomes stronger. The Pearson correlation coefficient increases to 0.89, and the adjusted R square rises to 0.75. Ward 29 therefore remains an important mismatch case. It has low social vulnerability but medium built environment vulnerability, suggesting that better social conditions do not automatically imply a safer built fabric. This supports the argument that SVI can guide preliminary screening, but it cannot replace direct built environment assessment.

5.3.2 Component-wise Association

To move beyond an aggregate BEVI SVI comparison, a component wise correlation matrix was developed between selected SVI indicators and BEVI subcomponents. This provides a clearer understanding of which social characteristics align with which forms of built environment vulnerability. The full component wise correlation matrix was computed for all thirteen SVI indicators. For readability, Table 12 reports the indicators that showed clearer theoretical relevance to the vulnerability pathways examined in this paper

Table 12: Component wise correlations between SVI indicators and BEVI components

SVI indicator	BV	RE	Alpha'	D	S	$BEVI_S$
SVI raw score	0.35	0.87	-0.69	0.30	-0.04	0.78
Illiteracy	0.43	0.77	-0.84	0.36	-0.16	0.80
Household size above 6	0.43	0.83	-0.64	0.23	-0.11	0.78

Dilapidated houses	0.49	0.76	-0.71	0.38	-0.21	0.81
Households with no toilets	0.38	0.65	-0.88	0.34	-0.25	0.72
Households with no kitchen	0.56	0.47	-0.77	0.49	-0.49	0.70
No savings	0.41	0.82	-0.79	0.33	-0.14	0.81
No assets	0.37	0.89	-0.67	0.25	0.02	0.80
Slum population	0.12	0.87	-0.63	0.29	0.08	0.65

The strongest associations are observed between social deprivation variables and RE, the post-earthquake road inaccessibility component. No assets, slum population, no savings, large household size, and illiteracy all show strong positive correlations with RE. This suggests that social vulnerability is most clearly reflected in the functional fragility of the built environment, particularly in the risk of post-earthquake accessibility disruption.

The association with overall Systemic BEVI is also strong for dilapidated houses, no savings, illiteracy, no assets, household size, and no toilet facilities. These results indicate that the relationship between social and built vulnerability is not driven by a single variable. It is produced through overlapping conditions of housing deprivation, limited household resources, service deficits, and settlement informality.

By contrast, the association between SVI indicators and open space deficit is weak or inconsistent in this dataset. Density also shows only moderate relationships with most social indicators. This implies that the built social coupling in the surveyed wards is expressed more strongly through accessibility disruption and housing condition than through static land use variables.

5.3.3 Vulnerability Mismatch Index

To identify the degree of divergence between the two indices, a Vulnerability Mismatch Index was calculated as the absolute difference between standardized BEVI and standardized SVI:

$$VMI = |Z_{BEVI} - Z_{SVI}|$$

A low VMI indicates that built and social vulnerability are aligned. A high VMI indicates divergence between the two dimensions.

Table 13: Vulnerability Mismatch Index

Ward	VMI	Direction of mismatch
4	0.09	BEVI > SVI
42	0.14	BEVI > SVI
5	0.16	SVI > BEVI
16	0.23	BEVI > SVI
2	0.25	SVI > BEVI
22	0.41	BEVI > SVI
20	0.57	SVI > BEVI
39	1.22	SVI > BEVI
29	1.33	BEVI > SVI

The mismatch analysis confirms two important patterns. First, Wards 4 and 5 are not only high vulnerability wards; they are also strongly aligned across both dimensions. Their vulnerability is therefore compound rather than sector specific. Second, Ward 29 has the highest mismatch value, with BEVI exceeding SVI. This supports its interpretation as a hidden structural risk ward.

5.3.4 Pathway Interpretation

The component wise correlations and mismatch results suggest three broad vulnerability pathways.

The first is an informality accessibility pathway. Slum population, no assets, no savings, large household size, and illiteracy are strongly associated with post-earthquake road inaccessibility. This suggests that social deprivation becomes spatially embedded through informal or constrained urban form, where narrow roads, limited setbacks, and debris related obstruction can produce accessibility collapse after an earthquake.

The second is a housing deprivation pathway. Dilapidated housing, households without toilets, households without kitchens, and no savings are associated with overall Systemic BEVI. This indicates that weak household conditions and poor housing quality are linked to higher built environment vulnerability.

The third is a hidden structural risk pathway. Ward 29 shows that low social vulnerability can coexist with medium built environment vulnerability. This pathway is important because it prevents the analysis from reducing seismic vulnerability to poverty alone. Some areas may have better household resources but still contain ageing, non-compliant, or physically vulnerable building stock.

Overall, the analysis shows that the BEVI SVI relationship is not only a matter of aggregate correlation. It is expressed through concordance, mismatch, and specific subsystem linkages. Social vulnerability is most strongly associated with systemic accessibility disruption and housing condition, while mismatch cases show where direct built environment assessment remains essential. This supports a planning approach in which SVI is used as a city-wide screening tool and BEVI as a detailed diagnostic layer for targeted seismic risk reduction.

6 Discussion

6.1 Coupling Social and Built Environment Vulnerability

The findings from Siliguri Municipal Corporation helps us understand how social problems and weak physical conditions reinforce each other on the ground. This supports the hazards-of-place

perspective (Cutter, 1996) and aligns with systems-based approaches to disaster risk (Mileti, 1999; Rashed & Weeks, 2003; Liu et al., 2007).

The city-wide SVI identifies wards where residents may have limited capacity to prepare for, respond to, and recover from earthquake impacts. The BEVI assessment, by contrast, captures the physical conditions that may intensify earthquake damage and disrupt post-earthquake response.

The positive association between SVI and Systemic BEVI within the nine common wards suggests that social disadvantage often coincides with physical fragility. However, the relationship is not uniform enough. When the two are read together, they show that social vulnerability and built environment vulnerability are related, but not necessarily mimic each other. This is the core argument of the paper.

In Siliguri, Wards 4 and 5 show a strong overlap between high SVI and high BEVI, indicating compound vulnerability. Ward 29, however, shows the opposite pattern i.e., it has low social vulnerability but medium built environment vulnerability. Here, relatively better social conditions (low SVI) hide a ticking infrastructural weakness (medium BEVI) that could rapidly reduce those social gains during a major earthquake.

6.2 SVI as a Screening Layer and BEVI as a Diagnostic Layer

The SVI serves its purpose well as a starting point. It identifies wards where residents face combinations of deprivation, informal housing, limited savings, and weaker service access. This is consistent with the broader vulnerability literature, which recognises that census-based social indices are effective tools for first-level prioritisation in data-constrained settings (Birkmann, 2006; Fekete, 2009; Roy et al., 2024). For a municipal body trying to prioritise across 47 wards with limited resources, that kind of rapid city-wide read is genuinely useful.

But the Siliguri results also show where the SVI needs to be carefully interpreted. For example, Ward 29, the SVI is low, placing it in the least vulnerable category in the city-wide screening. Yet its built

environment vulnerability is medium. Its road network has weak redundancy, its buildings carry structural risk, and debris modelling shows meaningful post-earthquake inaccessibility. Füssel (2005) cautioned that composite social indices need contextual validation before informing high-stakes planning decisions. Ward 29 is exactly the kind of case that justifies that caution. A planning decision based only on the SVI would have deprioritised this ward entirely.

Ward 20 makes the opposite point. It scores high on social vulnerability but only medium on the built environment assessment. Planning for structural retrofitting resources in this neighbourhood wouldn't be sufficient. It actually needs is stronger preparedness and household-level recovery support. This is what Wisner (2006) describes as socially driven vulnerability, where the primary constraints are not physical but rooted in household capacity and community resilience. Without the BEVI, there is no way to make that distinction from the social data alone.

The Systemic BEVI matters here more than the Discrete version. Most built environment assessments treat a city as it stands before a disaster. The Systemic BEVI goes further by modelling how building collapses change road accessibility after an earthquake. This is consistent with Berdica (2002) and Golla et al. (Golla et al., 2022) who argue that road network vulnerability must be analysed dynamically rather than as a fixed pre-event condition. In Siliguri, Ward 5 loses 60 percent of its road network in the post-earthquake scenario. That is not visible in a static structural assessment. It only gets highlighted when you account for how debris from collapsed buildings interacts with already narrow streets and insufficient setbacks.

Hence, used in sequence, these two indices give planners a much sharper picture of where compound risk sits, where physical risk is hiding behind acceptable social conditions, and where social recovery capacity is the real constraint.

6.3 Component-Level Relationships and Vulnerability Pathways

The component wise results make the SVI and BEVI relationship much clearer than the overall correlation alone. This tells us that social disadvantage is being expressed most sharply through the everyday physical form of the city.

One of the patterns that stands out is informality accessibility pathway. Slum population, no assets, no savings, large household size, and illiteracy are all strongly associated with post-earthquake road inaccessibility. This fits earlier work showing that socially vulnerable groups often live-in areas where access is already constrained by narrow roads, limited setbacks, and weak planning control (Kaiser et al., 2025; Roy et al., 2022; Wamsler, 2006). In other words, social disadvantage does not directly block a road, but it is often embedded in neighbourhoods where the road network is already fragile and likely to fail when debris falls after an earthquake. This calls for prioritise road widening, setback enforcement, and emergency access upgrades in informal and densely settled wards.

The second pathway is a housing deprivation pathway. Wards such as 4 and 5 show this clearly because their dilapidated housing, service deficits, and weak household conditions are strongly associated with higher Systemic BEVI, which fits the vulnerability logic of Pressure and Release (PAR) Model, where poor housing and limited resources combine to deepen disaster outcomes (Blaikie et al., 1996). In planning terms, these wards need housing repair, service improvement, and structural safety checks together, not as separate interventions.

The third pathway points to hidden structural risk in the city. Especially in case of SVI for Ward 29 look relatively strong, yet its built environment shows medium vulnerability because of ageing or noncompliant buildings and weak road redundancy. This pattern proves the theoretical expectation that social and physical vulnerability do not always coincide, so structural danger can remain unseen when planning focuses only on household disadvantage (Menoni & Pergalani, 1996). For practice, planners should treat such wards with caution and require structural audits and targeted retrofitting rather than assuming they are safe.

The weak association between SVI indicators and open-space deficit should also be read carefully. It does not mean open space is unimportant. In fact, the open-space shortage across the surveyed wards is a serious planning concern. It only means that in this dataset the shortage of open space is a city planning problem that is not necessarily tied to the selected social indicators. However, it still matters for evacuation, temporary shelter, and emergency staging, especially in a dense city like Siliguri where recovery space is already scarce.

6.4 Concordance, Mismatch, and Planning Typology

From the previous sections, it is clear that earthquake risk reduction cannot be addressed through a uniform intervention strategy. That is where the concordance and mismatch analysis help. Different wards show different combinations of social and built environment vulnerability.

Wards 4 and 5 are cases of compound vulnerability i.e., they combine high social disadvantage with fragile physical conditions. In these neighbourhoods, structural safety and household capacity must be strengthened together. Practical steps should include selective retrofitting, improving road access, and upgrading services alongside measures to boost household preparedness and local communication networks.

Ward 20 fits a socially driven profile. Its built fabric is not the main problem, so interventions should prioritise social preparedness with selective physical checks to confirm that no hidden structural risks exist.

Wards 22 and 29 show hidden physical vulnerability i.e., social indicators look relatively strong, yet physical risks are notable. These areas need immediate structural audits, enforcement of setback and building codes, and focused road access improvements. This makes sure that the urban managers do not miss serious hazards simply because social data look reassuring.

Wards 16 and 39 appear less vulnerable now, but that status is conditional. Ongoing monitoring is essential because growth, encroachment, and ageing buildings can quickly change risk patterns. Wards 4 and 5 represent compound vulnerability. They have high social vulnerability and high built environment vulnerability and they reinforce each other. Planning interventions therefore need to be integrated. Retrofitting unsafe buildings or widening access routes would reduce physical risk, but these measures would be incomplete without attention to household preparedness, financial capacity, and recovery support. Similarly, social programmes alone would not address the physical danger created by unsafe buildings, narrow roads, and constrained layouts.

6.5 Implications for Urban Planning and Disaster Risk Reduction

The findings point to a simple but important fact. Seismic risk planning in Indian cities cannot stay at the level of broad schemes and one size fits all action. The Siliguri case shows that social vulnerability and built environment vulnerability do not always overlap, so a blanket approach will miss both compound risk and hidden physical risk.

This is where the current programme driven approach needs to be sharper. Schemes such as Pradhan Mantri Awas Yojana Urban, Atal Mission for Rejuvenation and Urban Transformation (AMRUT), and NDMA disaster management guidelines are useful for broad coverage. But they do not by themselves identify where social and physical risk actually converge on the ground. A city like Siliguri needs interventions specific to wards and their contexts.

Accessibility should be a no compromise as part of seismic mitigation planning. A strong link exists between social deprivation and post-earthquake road inaccessibility, which means emergency access is also an equity issue (Golla et al., 2020). Wards with narrow roads, weak network redundancy, and high debris blockage risk can be cut off fast, and the impact is greater where vulnerable households already have fewer resources to cope.

Open space also needs far more attention. The shortage recorded in Siliguri is not a minor design issue, it is a serious gap in evacuation and response capacity. Without safe open areas, cities lose space for shelter, relief, and emergency operations when they are needed most.

6.6 Methodological Contribution and Limits of Interpretation

The main methodological contribution of this study lies in combining screening, diagnosis, concordance, mismatch, and pathway interpretation within one framework. The SVI provides a city-wide screening layer, while the BEVI provides a detailed physical diagnosis for selected wards. The coupling of the two indices allows the analysis to identify where social and built environment vulnerabilities align, where they diverge.

This framework overcomes two common limitations in vulnerability assessment. First, it avoids treating social vulnerability as a complete proxy for disaster risk. Second, it avoids treating built environment vulnerability as only a technical or structural problem detached from the social conditions of residents. By reading the two together, this research provides a more planning-oriented interpretation of earthquake vulnerability.

At the same time, the results should be interpreted cautiously. The coupling analysis is based on nine common wards because detailed BEVI assessment requires field and spatial data that were not carried out for all 47 wards. The correlations should therefore be read as exploratory associations, not as predictive relationships for the entire city.

The use of ward-level data also has limitations. Wards are administrative units, and they may contain internal differences in their morphological characteristics. Vulnerable pockets may exist within wards classified as low or medium vulnerability. Future research could improve this framework by applying SVI and BEVI at finer spatial scales, expanding BEVI assessment to all wards and testing the framework in other Tier-II Indian cities.

Despite these limitations, the study offers a practical approach for urban seismic risk planning. Municipal agencies often need to make decisions before complete physical survey data are available. In such contexts, SVI can guide initial prioritisation, while BEVI can confirm, refine, or correct that prioritisation through direct built environment assessment. The Siliguri case shows that this combined approach can identify both compound vulnerability and hidden physical risk, making earthquake risk reduction more targeted, transparent, and operationally useful.

7 Conclusion

Earthquake risk in Indian cities cannot be reduced to either buildings or poverty. In Siliguri, the most serious risks appear where fragile infrastructure, constrained urban form, and limited social capacity come together in the same neighbourhood. Treating these as separate problems leads to incomplete planning.

The Social Vulnerability Index works well as a first pass. It quickly flags wards where residents face deprivation, informal housing conditions, limited savings, and weaker access to services. But it cannot see what a building looks like, how wide a road is, or whether a neighbourhood would become inaccessible after a collapse. The Built Environment Vulnerability Index fills that gap. Together, the two indices tell planners not just where risk is concentrated, but why it is there and what kind of response it requires.

Wards 4 and 5 show compound vulnerability, where social disadvantage and physical fragility reinforce each other. Ward 29 shows the opposite. Its residents are relatively better off, yet its built fabric carries medium physical risk. A planning strategy built only on social screening would miss it entirely. Ward 20 sits somewhere between the two, needing stronger preparedness support rather than structural retrofitting.

The strongest connection between the two dimensions runs through post-earthquake road accessibility. Socially deprived areas tend to sit in neighbourhoods with narrow roads, minimal

setbacks, and buildings close together. After a major earthquake, debris from collapsed structures can cut off these streets entirely, delaying rescue and relief precisely where it is needed most. This is not a coincidence. It reflects how poverty and informality get written into the physical shape of a city over time.

The framework proposed has some limitations. The coupling analysis covers only nine wards, the ward scale can hide pockets of hidden risk, and census-based indicators miss community networks and local preparedness capacity. Future work should expand the physical survey to all wards, apply both indices at finer spatial scales, and test the approach in other Indian Tier-II cities.

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