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Digital Stress-Testing of Urban Transport Resilience: Analyzing Systemic Isolation against Megathrust Tsunamis in Southern Java

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ABSTRACT

Sustainable urban mobility is defined not only by efficiency but by its resilience to catastrophic disruptions. The coastal district of Palabuhanratu, Indonesia, faces a critical vulnerability where its transportation network is bisected by major rivers, posing a severe risk during a potential Megathrust Tsunami (Mw 8.8). This study uses digital technologies for urban infrastructure analysis to evaluate transport system failure modes. Utilizing a quantitative approach based on Graph Theory and Anisotropic Least-Cost Distance (LCD) simulation, we stress-tested the road network under a specific "Bridge Failure Scenario" within a strict 22-minute evacuation window. The simulation reveals "Spatial Separation," where the collapse of the Cimandiri and Citarik bridges isolates 19 villages, creating a systemic disconnection from safe zones. The results quantify a critical failure in the transport and mobility system, showing a 23–38 minute time deficit for the isolated population. Furthermore, the analysis reveals extreme inequality in vehicular mobility, with the Gini Coefficient spiking to 0.995, indicating a near-total collapse of motorized access relative to pedestrian modes. The study concludes that the current urban infrastructure lacks the necessary redundancy. To support sustainable disaster management, we recommend integrating digital twin simulations into spatial planning and prioritizing decentralized tactical redundancy to strengthen coastal mobility systems' resilience.

Keywords: Accessibility Inequality (Gini Coefficient), Disaster Risk Reduction, Megathrust Tsunami Evacuation, Resilient Infrastructure, Spatial Separation Analysis, & Urban Transport Resilience

1. Introduction

The southern coast of Java faces a critical geostrategic threat from the seismic gap in the Megathrust segment, which could generate an Mw 8.8 earthquake and a subsequent massive tsunami (Widiyantoro et al., 2020). In such near-field scenarios, civil defense efficacy depends on the population's ability to mobilize rapidly within a severely constrained time window. Previous models for the Palabuhanratu district indicate that the golden time for evacuation is approximately 22 minutes (Indira & Manessa, 2023). While significant efforts have improved mitigation strategies, from community-based eco-actions (Tarigan et al., 2025) to time-based accessibility evaluations (Sudibyo et al., 2025), most existing studies assume a deterministic scenario: evacuation infrastructure remains intact (business-as-usual) immediately after the earthquake shock.

This assumption presents a dangerous "optimism bias" in disaster planning. In reality, transportation infrastructure, particularly bridges, represents the most fragile component of a network during catastrophic

events. The failure of critical "chokepoints" can instantly alter a city's topology, rendering pre-calculated optimal routes obsolete (Mattsson & Jenelius, 2015; Sorrentino & Giresini, 2024). In Palabuhanratu, major rivers (Cimandiri and Citarik) heavily bisect the topography, creating a systemic dependency on a few key bridges. If these critical links fail due to seismic impact or debris, the region risks "systemic isolation" that current static models fail to quantify.

Recent studies have highlighted "deep uncertainty" in coastal adaptation, emphasizing the need for flexible planning for unpredictable infrastructure failures (Shan et al., 2025). Network-based equity analyses also show that infrastructure disruptions disproportionately affect vulnerable populations, potentially trapping them in zones of "accessibility poverty" (Karner et al., 2024). While our previous work evaluated time scarcity under static conditions (Sudibyo et al., 2025), a significant gap remains in understanding how physical infrastructure degradation, specifically bridge collapse, affects the survivability and spatial equity of the evacuation system.

This study addresses this gap by performing a "digital stress-test" on Palabuhanratu's evacuation network. Unlike conventional route mapping, we simulate a Bridge Failure Scenario (Disrupted State) using Graph Theory and Anisotropic Least-Cost Distance (LCD) modeling. The objective is to quantify the systemic impact of critical infrastructure failure on reachability and to diagnose the resulting spatial inequality (Gini Coefficient). By shifting the focus from "how fast can they run" to "is there a road left to run on," this research provides a more rigorous basis for sustainable urban infrastructure planning in disaster-prone coastal areas.

To address this gap in sustainable urban infrastructure planning, the main scientific contribution of this study lies in the integration of three dimensions that are traditionally analyzed separately: (1) near-field tsunami hazard scenarios, (2) dynamic infrastructure failure simulations, and (3) transport equity evaluation. Specifically, the novelty of this research is articulated through the following key aspects:

1. First, Advancing the Urban Resilience Paradigm: This study shifts the evaluative focus of urban transport from static structural robustness to dynamic functional performance under degraded conditions. By applying a digital stress test through deterministic bridge-failure scenarios, the study provides empirical evidence of systemic collapse, which occurs when a lack of network redundancy fails to support sudden evacuation demand.
2. Second, Methodological Innovation in Transport Equity: The study introduces a Network-Based Equity Evaluation approach that recontextualizes economic metrics, namely the Gini Coefficient and Lorenz curve, to quantify survival inequality during crises. This provides a more precise, dynamic measure of urban spatial disparity than conventional static accessibility analyses.
3. Third, Validating Sufficiency in Extreme Time Scarcity: The study reinforces the theoretical foundation of sufficiency in sustainable transport planning. It shows that under extreme time scarcity (i.e., a 22-minute golden time), guaranteeing a minimum accessibility threshold for vulnerable populations matters far more than achieving average spatial equality. Consequently, it highlights how infrastructure failures can instantly plunge specific urban clusters into severe accessibility poverty.

By framing these aspects together and building on the reproducible RR-Gini-Gini screening pipeline previously detailed in Sudibyo et al. (2025), this manuscript operationalizes a digital stress-testing lens that explicitly interrogates network fragility via bridge-failure perturbations. Specifically, we (i) identify candidate bridge elements on an OSM-derived road graph using centrality diagnostics and local verification, (ii) apply deterministic full-removal and partial-capacity operators to generate a scenario matrix of single and compound failures, and (iii) recompute mode-specific least-time paths and RR-Gini-Gini* metrics under ETA budgets of 22, 18, and 15 minutes while probing robustness to pre-movement delay and walking-speed sweeps. This extension preserves the core modeling logic of (Sudibyo et al., 2025) while isolating how structural chokepoints transform hazard into inequitable access outcomes, thereby complementing the siting experiments and ETA logic previously reported.

2. Methods

2.1 Digital Twin Construction and Data Acquisition

To simulate urban transport dynamics under catastrophic stress, we built a digital twin of the Palabuhanratu coastal district (6°58' 40.8" - 7°01' 01.2"), a region with a dendritic road topology bisected by the Cimandiri and Citarik rivers. The spatial framework integrates multi-source data. We extracted the road network topology from OpenStreetMap (OSM) using the Python-based OSMnx library to generate a non-planar directed graph $G = (V, E)$ that represents the transport infrastructure (Boeing, 2017). Unlike static geometric models, this graph retains critical metadata, such as road classification and bridge tags (bridge=yes), essential for failure simulation. To capture realistic terrain impedance, we integrated the National Digital Elevation Model (DEMNAS) at a spatial resolution of 0.27 arcseconds (~8 meters), enabling precise slope calculation at the node level. We acquired population distribution data from the WorldPop Global Project at 100m resolution, enabling mapping of evacuation demand points (cap P sub i) at a granular hamlet scale (WorldPop, 2020).

The analysis adopts the network-based evacuation and equity pipeline as detailed in (Sudibyo et al., 2025); in brief, multi-modal least-time paths are computed on an OSM-derived directed road graph restricted to nodes inside a COMCOT h_{max} inundation mask, and village-level reachability (RR) together with the Gini and hazard-weighted Gini summarize access. The implementation relies on the open-source Python libraries OSMnx and NetworkX. The following subsection focuses on the extension introduced here: explicitly representing and applying bridge-failure operators to the base graph.

2.2 Hazard Model and Time Hard-Constraint Acquisition

The study adopts a "worst-case" hazard scenario based on rupture of the Sunda Strait Megathrust segment with Mw 8.8. Hydrodynamic modeling using the COMCOT (Cornell Multi-grid Coupled Tsunami Model) system indicates that the first tsunami wave arrival (ETA) at the coastline occurs 22 minutes post-earthquake (Wang, 2009). This 22-minute window serves as the critical "hard constraint" or time budget (T_{limit}) for the simulation; any population node requiring >22 minutes to reach a designated safe zone is classified as a fatality or non-survivor (Indira & Manessa, 2023).

2.3 Digital Stress-Testing: The Bridge Failure Scenario

Moving beyond conventional static accessibility analysis, this research introduces a dynamic "stress-test" to evaluate infrastructure fragility. We developed two distinct simulation scenarios:

1. Baseline Scenario (Intact Network): Assuming all road segments and bridges function normally ($G_{baseline}$).
2. Disrupted Scenario (Bridge Failure): Simulating the structural collapse of critical chokepoints. Using network topology modification algorithms, we permanently removed the edges (E_{bridge}) representing the Cimandiri and Citarik Bridges from the graph ($G_{disrupted} = G_{baseline} - E_{bridge}$) to mimic the impact of seismic shock or debris blockage. This scenario tests the system's topological vulnerability and its capacity to absorb shock without total collapse (Mattsson & Jenelius, 2015).

2.4 Anisotropic Evacuation Simulation

Evacuation travel times were computed using an Anisotropic Least-Cost Distance (LCD) model, which acknowledges that terrain physically constrains human mobility. Walking speeds (W) were not assumed constant but were modulated by terrain slope (S) using Tobler's Hiking Function, as validated in pedestrian evacuation studies (Wood et al., 2018):

$$W = 6 \cdot \exp(-3.5 \cdot |S + 0.05|) \quad (1)$$

The simulation utilized the Multi-Source Dijkstra Algorithm to calculate the minimum travel time (T_{travel}) from every population node to the nearest designated assembly point (Tsunami Evacuation Area /TEA) under both baseline and disrupted network topologies.

To account for realistic evacuation behavior and potential congestion as highlighted in recent disaster modeling critiques, the 22-minute survival threshold (T_{limit}) inherently incorporates a fixed pre-movement delay.

Drawing from local early warning standard operating procedures, we integrated a 14-minute offset (7 minutes for warning dissemination and 7 minutes for preparation), effectively constraining the physical travel window to 8 minutes. To proxy post-earthquake traffic congestion without a dynamic agent-based model, we conservatively capped baseline vehicular speed at 25 km/h.

2.5 Equity Metrics

To quantify the socio-spatial impact of infrastructure failure, we calculated two key metrics for each scenario:

1. Overall Reachability (RR): The aggregate percentage of the population capable of reaching safety within the 22-minute window.
2. Gini Coefficient of Accessibility: Adapted from econometrics to measure the inequality of evacuation times across the 26 villages. A Gini coefficient approaching 1.0 indicates extreme inequality, where specific zones monopolize access while others are trapped in "accessibility poverty" (Karner et al., 2024).

2.6 Bridge-failure modeling: overview

This section formalizes bridge failures as deterministic topological perturbations of the evacuation routing network. The formulation extends the RR–Gini–Gini* screening framework adopted in the baseline study by explicitly modeling the loss of critical river-crossing links and quantifying the resulting changes in reachability and inequality. RR, Gini, and Gini* follow the baseline formulation; we do not repeat their mathematical definitions here, and this section focuses on the additional operators introduced to represent structural disruption.

2.6.1 Conceptual framing: bridge failure as network perturbation

Let the evacuation transport system be represented by a directed graph:

$$G = (N, E), \quad (2)$$

where N denotes nodes (road intersections, access points, and TEA connectors) and E denotes directed edges with travel-time costs τ_e . A bridge failure is conceptualized as a localized but systemically significant perturbation that removes one or more edges corresponding to a physical river crossing. Rather than modeling distributed degradation across the network, the approach isolates discrete structural losses that plausibly dominate evacuation performance under near-field tsunami conditions. Accordingly, bridge failures are treated as scenario-based, deterministic interventions applied to the baseline graph G , yielding a perturbed graph

$$G^{(s)} = (N, E \setminus E_{fail}^{(s)}), \quad (3)$$

Where $E_{fail}^{(s)} \subset E$ denotes the set of edges removed under scenario s .

2.6.2 Geometric specification of failed bridges

Each failed bridge is defined by a geographic point. $pk = (xk, yk)$ representing the mid-span location of a river crossing. These points are specified in a global geographic coordinate system (WGS 84) and subsequently projected into the working planar coordinate reference system used for routing analysis. The point representation serves two purposes:

1. to anchor failure scenarios to physically realistic locations, and
2. to enable unambiguous association between failed structures and network elements through spatial proximity.

Let $E_{(pk)}$ denote the set of candidate edges whose geometries lie within a tolerance buffer $Br_{(pk)}$ of radius r . The failed-edge set associated with bridge k is then defined as

$$E_k = \arg \min_{e \in E_{(pk)}} d(pk, e), \quad (4)$$

where $d(\cdot)$ denotes the Euclidean distance between the point and the edge geometry. For bidirectional road segments, both directed edges corresponding to the same physical span are included in E_k .

2.6.3 Failure typology and scenario construction

Failure scenarios target critical chokepoints identified through centrality diagnostics. Specifically, we simulate the removal of the Cimandiri Bridge (primary failure at $7.01^\circ S, 106.56^\circ E$) and the Citarik Bridge (secondary failure at $6.99^\circ S, 106.60^\circ E$). The scenario set includes:

1. Primary failures correspond to crossings whose removal is anticipated to induce large-scale fragmentation or isolation of substantial at-risk populations.
2. Secondary failures correspond to crossings whose removal produces localized accessibility degradation without full network disconnection.

This typology does not encode structural damage severity; rather, it functions as an analytical device for organizing stress-test scenarios and interpreting results. Failure scenarios are constructed as finite combinations of individual bridge failures. In this study, the scenario set includes:

$$S = \{\emptyset, \{k_1\}, \{k_2\}, \{k_1, k_2\}\}, \quad (5)$$

where $\emptyset$ denotes the baseline (no failure) and K_1, K_2 denote the selected primary and secondary bridge failures, respectively.

2.6.4 Deterministic edge-removal operator

For each scenario $s \in S$, the perturbed graph $G^{(s)}$ is obtained by applying a deterministic edge-removal operator:

$$R(G, s) = \left(N, E \setminus \bigcup_{k \in s} E_k \right) \quad (6)$$

We assume no partial-capacity or probabilistic degradation. The removal represents complete loss of traversability across the affected bridge, consistent with worst-case structural failure immediately following strong ground motion. This formulation ensures that any path in $G^{(s)}$ does not traverse the failed crossing, thereby enforcing topological separation across the river channel.

The simulation adopts a binary failure state (full functionality vs. total collapse) rather than a probabilistic model. This deterministic approach tests network sensitivity and identifies critical tipping points of systemic isolation. By assuming a complete loss of traversability immediately after strong ground motion, the model quantifies the maximum impact of bridge failure without the confounding variables of partial structural capacity, which would require detailed structural data outside the research scope. This alignment with 'worst-case scenario' planning is essential for identifying critical vulnerabilities in coastal urban infrastructure.

2.6.5 Routing and reachability under failure scenarios

For each perturbed graph $G^{(s)}$ Recompute least-time evacuation paths using the same routing procedure as in the baseline framework. Let $D \subset N$ denote the set of TEA destination nodes. The minimum travel time from origin node i to safety under scenario s is given by:

$$t_i^{(s)} = \min_{d \in D} \text{dist}_{G^{(s)}}(i, d), \quad (7)$$

where $\text{dist}_{G^{(s)}}$ denotes the shortest-path distance with respect to travel time. An origin is considered reachable under scenario s and ETA threshold T if

$$t_i^{(s)} \leq T \quad (8)$$

Origins for which no directed path exists in $G^{(s)}$ are assigned $t_i^{(s)} = +\infty$ Moreover, classified as non-reachable. Village-level reachability rates $RR_v^{(s)}$, overall reachability, in $RR^{(s)}$ Moreover, inequality metrics (Gini and hazard-weighted Gini*) are computed identically to the baseline formulation, enabling direct comparison between baseline and failure scenarios.

2.6.6 Scenario evaluation matrix

All failure scenarios are evaluated across:

- evacuation modes (walking and driving),
- ETA thresholds $T \in \{22, 18, 15\}$ minutes and
- inundation masks consistent with the baseline analysis.

For each configuration, reported outputs include: (i) overall reachability. $RR^{(s)}$, (ii) village-level $RR_v^{(s)}$, (iii) Gini and Gini* (with bootstrap confidence intervals), and (iv) the proportion of origins rendered completely isolated by topological disconnection. While the digital stress-test computes a wide range of scenario configurations, sweeping across vehicle speeds (5 to 60 km/h) and time constraints (15 to 60 minutes), the primary comparative results are anchored to the empirically validated 22-minute threshold. The broader scenario permutations are synthesized within a temporal sensitivity analysis to validate the robustness of the system's failure modes.

3. Results and Discussion

3.1 Topological Transformation and Spatial Separation

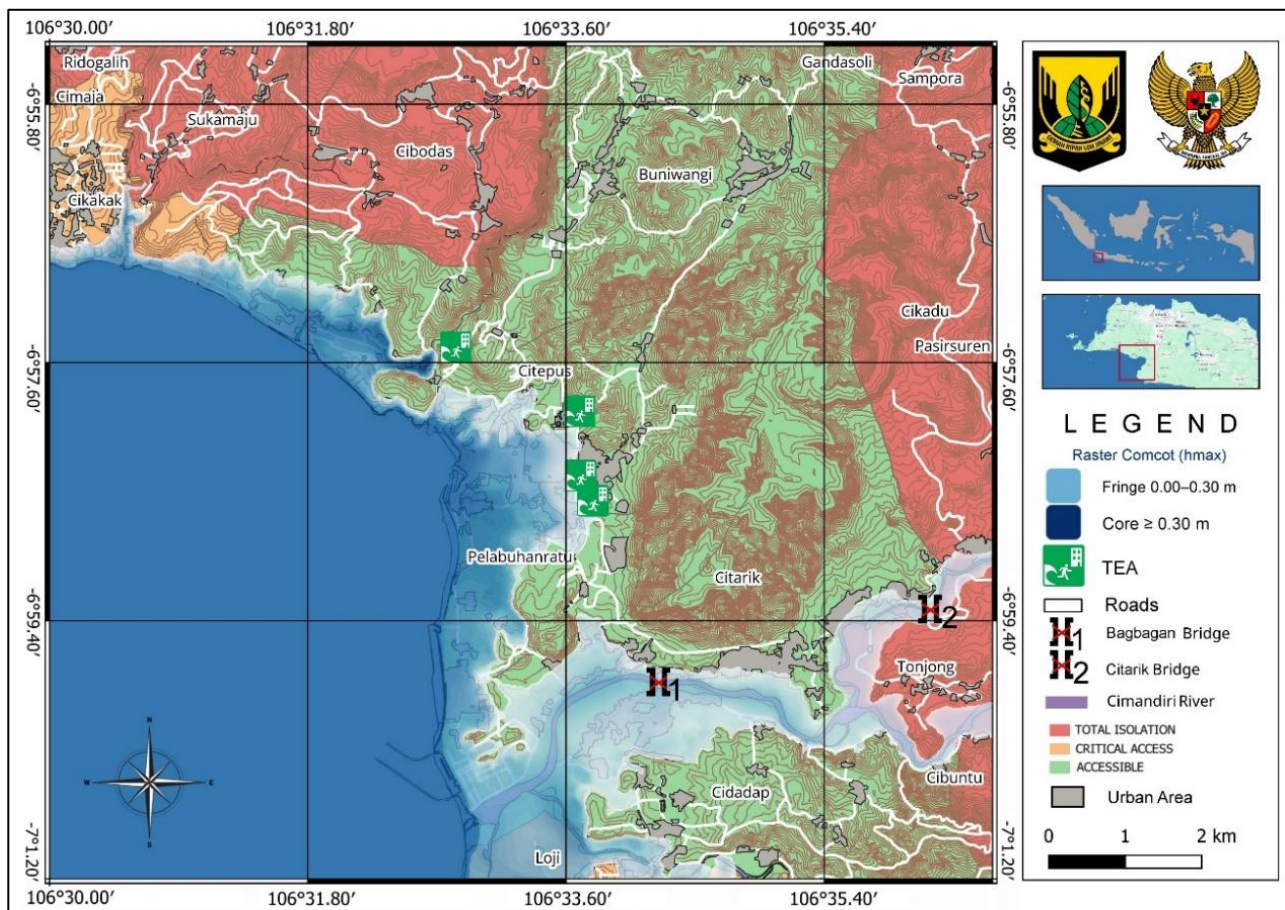


Figure 1. Spatial Separation Map (Disrupted Scenario).

Red crosses on top of the bridge symbol mark failed bridges, dividing Safe (Green) and Isolated (Red) zones. We processed visualizations in QGIS and Python (GeoPandas, OSMnx) by integrating COMCOT tsunami rasters, OpenStreetMap networks, and 100m WorldPop grids. We calculated travel times and Reachability Ratios (RR) using anisotropic least-cost distance (LCD) routing, accounting for slope variations and topological network degradation.

The digital stress-test reveals a fundamental fragility in the district's transport topology. Under the Baseline Scenario, the road network functions as a cohesive graph, with the Cimandiri and Citarik bridges as the primary

connectors between the administrative center and the peripheral coastal settlements. However, the Disrupted Scenario simulation (bridge failure) triggers a catastrophic topological transformation referred to as "Spatial Separation" (Mattsson & Jenelius, 2015).

As visualized in Figure 1, the inundation zone ($H_{max} > 0.3$ m) acts as an absolute physical barrier when combined with the loss of critical edges. Severing the Cimandiri link effectively bifurcates the study area into two distinct clusters. The Eastern Sector retains connectivity to highland safe zones, maintaining a relatively high survival probability. In stark contrast, the Western Sector, comprising 19 villages including Cikakak and Cimaja, becomes topologically isolated from the command center and regional logistical hubs. This confirms that without the bridges, the river barriers create "dead zones" where evacuation via the primary road network becomes mathematically impossible (Makinoshima et al., 2025; Mattsson & Jenelius, 2015).

To provide transparent quantitative traceability of this spatial separation, Table 1 summarizes the most critically impacted administrative units within the Western Sector. It details the estimated populations that lose all vehicular access (Reachability Ratio = 0) immediately after the infrastructure collapse.

3.2 Systemic Time Deficit

This physical separation creates a severe temporal deficit against the hard constraint of the tsunami arrival time ($ETA = 22$ minutes) established in previous hydrodynamic studies (Indira & Manessa, 2023). The simulation quantifies a "Systemic Time Deficit" ranging from 23 to 38 minutes for the isolated population. While the Overall Reachability (RR) for the pedestrian network remains relatively stable (dropping marginally from 0.316 to 0.302), the vehicular network collapses. For the population trapped in the Western Sector, the recalculated travel time (T_{travel}) surges to over 60 minutes, far exceeding the 22-minute survival threshold (Sudibyo et al., 2025). This finding challenges the "car-centric" assumption in current mitigation plans, demonstrating that in a bridge-failure scenario, vehicles become stranded assets rather than life-saving tools.

The systemic time deficit caused by sudden bridge failures aligns closely with recent international studies on network disruptions. Darvishan and Lim (2021) showed that multiple, spatially distinct road disruptions dynamically shift trapped vehicles, rapidly evolving stalled traffic bottlenecks at intermediate nodes. This supports our finding that losing the Cimandiri and Citarik bridges creates insurmountable spatial barriers rather than mere delays. Furthermore, coupled simulations of the 2024 Noto Peninsula Earthquake by Aikawa et al. (2026) proved that physical road blockages and debris directly increase tsunami encounter rates, highlighting that static evacuation strategies that ignore infrastructure collapse are highly fatally flawed.

3.3 The Inequality of Survival: Vehicular vs. Pedestrian Resilience

A critical contribution of this study is quantifying "Inequality in Survival" using the Gini Coefficient. As Table 2 shows, infrastructure failure impacts are not evenly distributed across transport modes.

Table 2. Comparative Analysis of Network Resilience Metrics (Baseline vs. Disrupted).

Evacuation Mode	Scenario	Reachability Ratio (RR)	ΔRR	Gini Coefficient	$\Delta Gini$	System Status
Walk	Baseline	0.316	-1.40%	0.217	-0.002	Degraded
	Disrupted	0.302		0.215		
Drive	Baseline	0.24	-1.09%	0.207	+0.788	Collapsed
	Disrupted	0.229		0.995		

Note: Values are derived from the computational simulation on the weighted directional graph $G(V, E)$. RR (Overall Reachability): Calculated as the percentage of population nodes (P_i) capable of reaching a safe zone within the hard time constraint ($T_{travel} \leq 22$ minutes). Gini Coefficient: Measures inequality in evacuation time distribution across 26 villages, where 0 represents perfect equality, and 1 represents maximum inequality. Status: "Collapsed".

The results first reproduce baseline RR–Gini–Gini indicators for the existing TEA configuration and ETA windows (as established in Sudibyo et al., 2025), and then quantify the incremental impacts of the bridge-failure scenario matrix (single and compound removals, and capacity-reduction sweeps) on reachability, inequality, and spatial patterns of time-to-safety.

The pedestrian network shows high resilience ($Gini \approx 0.215$ in both scenarios), attributed to flexible walking paths that can use informal routes or smaller suspension bridges unaffected by the main bridge collapse. Conversely, the vehicular network exhibits an extreme spike in inequality, with the Gini Coefficient rising from 0.207 in the baseline to 0.995 in the disrupted scenario. This near-perfect inequality ($Gini \approx 1.0$) indicates a "Winner-Takes-All" structural failure, where residents in the Eastern Sector monopolize access. At the same time, the Western Sector faces total logistical exclusion (Karner et al., 2024). This creates "accessibility poverty," where survival depends solely on proximity to the river (Karner et al., 2024).

The analytical interpretation of this modal disparity lies in the networks' fundamental topology. The vehicular transport system in the study area exhibits a 'dendritic' (tree-like) topology, characterized by a severe lack of redundant loops. Consequently, the main arterial bridges act as absolute chokepoints; once severed, the network fragments into isolated subgraphs, triggering a systemic collapse. Conversely, the pedestrian network shows significantly higher spatial 'permeability'. Pedestrians can maneuver through a denser web of informal paths, narrow alleys, agricultural borders, and local suspension bridges that are largely unaffected by the failure of the main highway infrastructure. This topological flexibility explains why the pedestrian mode degrades but remains functionally resilient, whereas the rigid vehicular mode fails systemically.

The extreme modal disparity observed in this study—specifically, the vehicular Gini coefficient spiking to 0.995—is corroborated by behavioral and empirical traffic engineering literature. Wang et al. (2016) statistically demonstrated that driver mortality increases exponentially as the percentage of car-dependent evacuees rises, severely degrading road network performance. This vehicular collapse is further exacerbated by human routing behavior during mass panic; Takabatake et al. (2020) showed that evacuating drivers abandon shortest-path logic and preferentially route toward wider main roads, which act as the primary catalyst for massive coastal traffic jams. Consequently, Palabuhanratu's rigid, dendritic topology forces all vehicles onto these main arterials, ensuring total gridlock. Empirical radar data from Staes et al. (2021) support this, confirming that mass evacuation bottlenecks reduce roadway flow capacity by over 50% compared with normal daily traffic conditions.

3.4 Sensitivity Analysis and Policy Implications

To interpret the Temporal Sensitivity Heatmap (Figure 2) more clearly, the data reveals two critical phenomena regarding urban transport resilience under disrupted conditions. First, it exposes an 'evacuation speed illusion'. The heatmap shows that even if vehicular speed is hypothetically increased to an optimistic 40 km/h during panic conditions, the Reachability Ratio (RR) at the 22-minute threshold remains critically low at 0.44 (44%). This shows that when key chokepoints fail and force massive detours, increasing vehicle speed cannot compensate for the loss of connectivity; the barrier is strictly topological, not kinematic. Second, the matrix mathematically quantifies a severe 'systemic time deficit'. The heatmap indicates that acceptable survival rates (the green zones where $RR > 0.80$) are only achieved if the evacuation time window is extended to 45–60 minutes. Given the absolute physical constraint of a 22-minute tsunami arrival, the isolated population in the Western Sector faces an insurmountable time deficit of 23 to 38 minutes.

The robustness of these findings was verified through a multi-parametric sensitivity sweep (Figure 2), which demonstrates that the vehicular system's collapse persists across a wide range of vehicle speeds (5–40 km/h). This confirms that the failure is fundamentally topological, as established in the previous section, and cannot be mitigated by marginal improvements in traffic flow or vehicle speed.

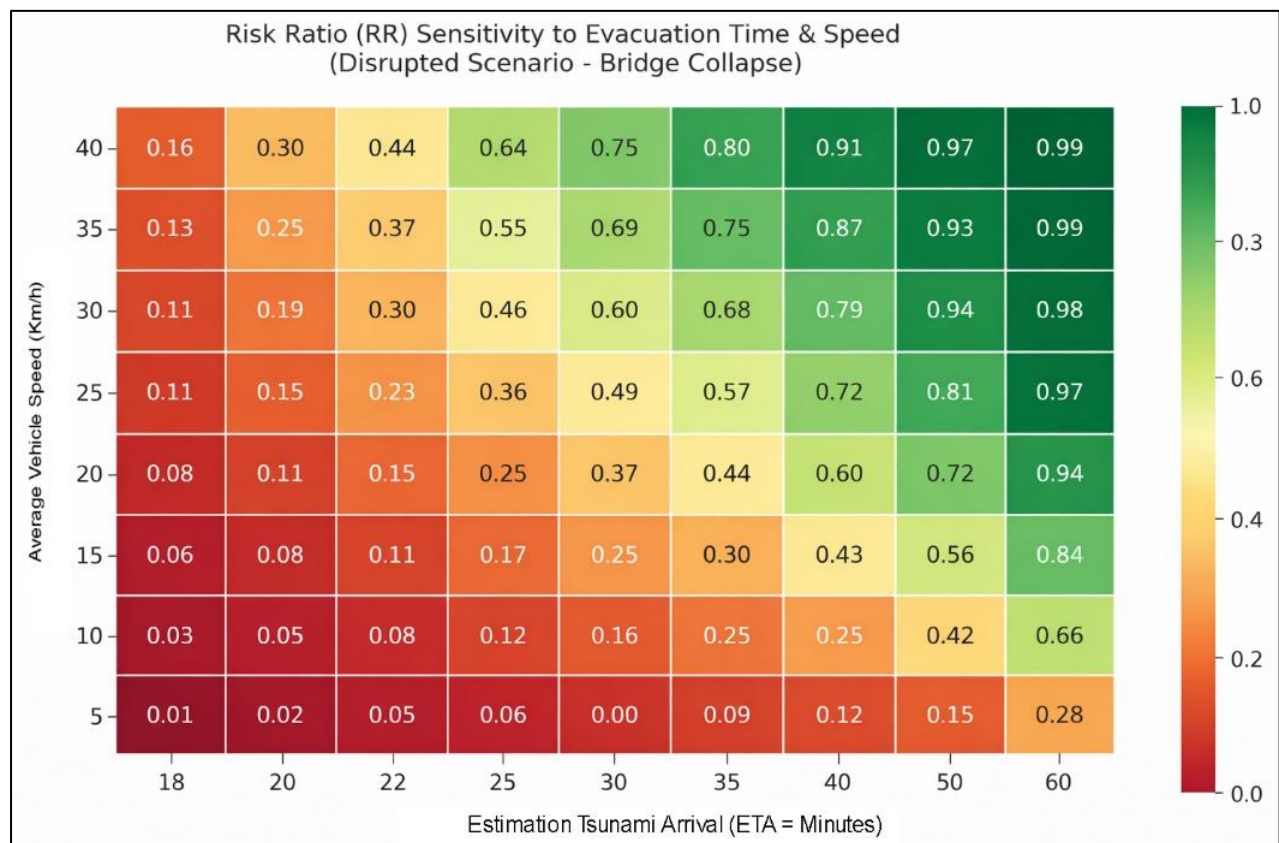


Figure 2. Temporal Sensitivity Heatmap.

The dominance of red zones indicates that increasing speed (Y-axis) does not significantly improve reachability when the time window (X-axis) is constrained to 22 minutes. The data for this temporal sensitivity heatmap were generated through a multi-parametric computational stress test simulating the disrupted vehicular network. The Reachability Ratio (RR) was dynamically recalculated across a matrix of varying average vehicle speeds (5–60 km/h) and theoretical tsunami arrival times (22 minutes). The underlying distance parameters were derived from the Anisotropic Least-Cost Distance (LCD) routing model applied to the severed network topology. We visualized the resulting matrix using Python's Seaborn library to quantify and illustrate the systemic time deficit.

This severe topological fragility necessitates a paradigm shift in urban planning and Disaster Risk Reduction (DRR). Because horizontal evacuation becomes mathematically impossible for the trapped Western Sector within the 22-minute golden time, policies focusing merely on traffic management are inadequate. Urban infrastructure planning must pivot toward decentralized tactical redundancy. This involves shifting from centralized municipal hubs to pre-positioned logistical centers in high-risk zones, prioritizing in-situ vertical evacuation structures (Temporary Evacuation Shelters) to eliminate reliance on long-distance river crossings, and retrofitting non-vehicular corridors to support light micro-mobility rescue operations.

The mathematical impossibility of horizontal evacuation within the 22-minute window for the trapped Western Sector necessitates a critical shift toward decentralized tactical redundancy. Qüense et al. (2022) observed similar constraints in Chilean coastal cities, noting that unregulated urban sprawl drastically limits evacuation efficiency and makes Vertical Evacuation Shelters (VES) the only viable alternative in flat, dense areas. The strategic placement of these shelters is paramount; Mostafizi et al. (2019) showed computationally that the percentage of people who successfully evacuate vertically drops exponentially as the shelter moves farther from the population centroid, directly affecting total mortality rates. Finally, Chang et al. (2024) mathematically showed that blind compliance with centralized "nearest shelter" policies creates fatal bottlenecks when critical infrastructure is damaged, reinforcing the push for localized, autonomous emergency hubs.

4. Conclusion

This digital stress-testing study provides compelling evidence that Palabuhanratu's coastal urban transport system is critically fragile under infrastructure failure (Sudibyo et al., 2025). The simulation yields three key findings: (1) The deterministic failure of critical bridges triggers 'Spatial Separation', isolating 19 villages and creating a systemic time deficit of 23 to 38 minutes; (2) There is an extreme modal disparity, where the pedestrian network retains functional resilience, while the vehicular network suffers a total collapse with the Gini Coefficient spiking to 0.995; (3) Car-centric evacuation doctrines are fundamentally flawed in dendritic coastal topologies characterized by sparse network redundancy (Makinoshima et al., 2025). To ensure sustainable urban mobility and disaster resilience, policy-makers must implement the following strategic and tactical interventions:

1. Decentralized Logistical Hubs: Establishing autonomous emergency stockpiles and medical facilities in vulnerable sectors (e.g., Cikakak and Cisolok) to sustain the population during critical isolation.
2. In-situ Vertical Evacuation: Prioritizing the construction of localized Temporary Evacuation Shelters (TES) or vertical structures to eliminate reliance on severed horizontal routes.
3. Non-Vehicular Corridor Retrofitting: Strengthening informal pedestrian paths and local suspension bridges to accommodate light micro-mobility rescue operations.
4. Integration of Digital Stress-Testing: Adopting the computational graph approach demonstrated in this study into formal spatial planning processes to identify and mitigate "deep uncertainty" risks in future infrastructure development (Fan et al., 2021; Shan et al., 2025).

5. Limitations and Future Research

While the macroscopic shortest-path approach effectively diagnoses topological vulnerabilities, its main limitation is its reliance on a deterministic bridge-failure assumption. By treating infrastructure collapse as a binary state (fully functional versus destroyed), this study serves as a worst-case stress test to identify tipping points of systemic isolation. However, this deterministic approach inherently oversimplifies the complex spectrum of structural damage. In reality, seismic impacts produce variable damage states governed by structural fragility models that map the probability of failure against ground-acceleration intensity. Relying solely on deterministic removal may overestimate the absolute loss of connectivity while overlooking partial capacity reductions, such as a bridge suffering structural warping that renders it impassable for heavy vehicles but still viable for pedestrian evacuation. Consequently, future research should build upon this framework by employing probabilistic structural fragility curves to simulate a range of partial degradation states. Furthermore, integrating Agent-Based Modeling (ABM) would capture dynamic traffic interactions and micro-level human behaviors under these varied probabilistic conditions (Takabatake et al., 2025).

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7. Conflict of Interest

The authors declare no conflict of interest.

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