Framework of "Optimization of Coastal Urban Building Layout Based on Tsunami Risk"

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Abstract. Tsunamis pose significant threats to South China's coastal cities, with the Manila subduction zone as the primary risk source, where 2500-year return period wave heights exceed 3m in high-risk areas. While recent studies advanced risk assessment, analyzed coastal risk, explored Pearl River Estuary terrain effects, and proposed a full-chain framework, they lack integration with building layout optimization. This study develops a layout optimization framework for these cities: it uses Liu's framework to zone areas into three risk levels (high: >3m wave/2m inundation; medium: 1–3m/0.5–2m; low: <1m/<0.5m) by integrating multi-source data, and links to evacuation research. Results propose targeted strategies: high-risk zones need strict density control and coastal green buffers; medium zones require reduced spacing and wave-resistant materials; low zones prioritize evacuation alignment. The framework bridges risk assessment and planning, providing a scientific basis for coastal resilience, though it relies on existing data.

Keywords: Tsunami risk, Coastal urban building layout, Layout optimization framework, South China coastal cities, Risk zoning

1. Introduction

Tsunamis pose persistent threats to coastal cities, driving advances in risk assessment, yet critical gaps remain in translating these insights into urban planning. Recent research has enhanced understanding of regional tsunami hazards: Deng et al. conducted targeted risk analysis for South China's coast [1]; Liu et al. quantified the Manila subduction zone's probabilistic and potential impacts on the region, highlighting high-risk areas with 2500-year return period wave heights exceeding 3m [2,3]; Yan et al. focused on the Pearl River Estuary's unique topographic influence on tsunami propagation [4]; and Liu proposed a full-chain risk assessment framework covering hazard analysis to loss estimation [5]. However, these studies primarily focus on macro-level hazard mapping—such as Hui et al.'s broad coastal risk assessment [6]—and lack integration with urban building layout optimization. Historical records, like Wang et al.'s discovery of Northern Song Dynasty tsunami traces in Hainan, confirm long-term coastal risk [7], yet few studies link this historical context to spatial planning. Additionally, while Sun & Wu addressed earthquake-tsunami observation station design [8] and Zhang et al. explored T-wave-based early warning [9], the synergy between these tools and building layout remains underexplored.

This study aims to develop a framework for optimizing coastal urban building layout based on tsunami risk, with a focus on South China. It addresses two key questions: ① How to integrate multi-source tsunami risk data—including probabilistic impacts, historical records, and observation data—into layout optimization? ② What layout strategies align with early warning systems and pedestrian evacuation needs? Methods involve risk zoning using Liu's framework [5], synthesizing data from [1,2-4,6,7], and developing strategies linked to observation/early warning [8,9] and evacuation research [10-13]. This work provides a scientific basis for resilient coastal planning, reduces potential disaster losses, and guides the integration of tsunami risk assessment into urban design.

2. Tsunami risk context for coastal cities in South China

The tsunami risk faced by coastal cities in South China is predominantly driven by the Manila subduction zone, a major tectonic boundary between the Eurasian Plate and the Philippine Sea Plate with high seismic and tsunami potential. Liu et al. conducted in-depth analyses of this zone, revealing that it has a non-negligible probability of generating large-magnitude earthquakes (up to Mw 9.0) [2,3]. Such earthquakes can trigger destructive tsunamis, with the 2500-year return period wave height reaching over 3m in high-risk coastal sections (e.g., the northern part of Guangdong Province) and inundation ranges extending 1–2 km inland in low-lying areas [2]. This risk profile is distinct from other coastal regions globally—for instance, Atillah et al.'s assessment of the Rabat and Salé coastal areas in Morocco focused on local seismic sources and smaller-scale wave impacts, highlighting the unique threat intensity and source characteristics of South China's tsunami risk [14].

Regional terrain further shapes South China's tsunami risk, with the Pearl River Estuary exhibiting particularly notable variability. Yan et al.'s hazard analysis of this estuary found that its branched waterways and shallow topography significantly alter tsunami propagation [4]. Narrow channels, such as the section between Hong Kong and Zhuhai, cause wave energy to converge, leading to a 20–30% local amplification of wave height compared to open coastal areas. In contrast, the wide upper reaches near Guangzhou dissipate wave energy through friction with the riverbed and lateral diffusion, resulting in inundation depths of less than 0.5m under a 2500-year return period [4]. Historical evidence further confirms the long-term nature of this risk: Wang et al. discovered earthquake-tsunami records from the Northern Song Dynasty in Puqian Bay, Hainan, providing geological proof of past tsunami events in the region and reinforcing the necessity of long-term risk mitigation [7].

Observation and early warning systems play a critical role in supporting effective tsunami risk management for these coastal cities. Sun & Wu emphasized that scientifically designed earthquake-tsunami and marine meteorological observation stations are essential for ensuring the accuracy of hazard data, such as real-time wave height and inundation range monitoring—data that directly underpins reliable risk assessment for building layout optimization [8]. Complementing this, Zhang et al.'s preliminary study on T-wave-based tsunami early warning indicated that this technology can provide 15–30 minutes of response time for South China's coast [9]. This window is critical for coordinating building layout with evacuation plans, as it defines the maximum allowable time for residents to move from buildings to safe areas.

Despite this clear risk context, current building layouts in South China's coastal cities suffer from significant vulnerabilities. Deng et al. noted that high-density building clusters, including residential quarters and commercial complexes, are concentrated in high-risk coastal zones—for example, the waterfront areas of Shenzhen's Nanshan District, which fall within the 2500-year return period inundation range identified by Liu et al. [1,2]. These dense layouts not only increase exposure to tsunami impacts but also lack necessary buffer zones (e.g., green spaces or wetlands) that could dissipate wave energy. Additionally, evacuation paths are often misaligned with risk levels: Pelling & Manuel-Navarrete's study of Mumbai, India—a densely populated coastal urban area—highlighted similar issues, where poor alignment between layout and evacuation needs exacerbated disaster vulnerability, a problem that also persists in South China's coastal cities [10].

3. Risk zoning & data integration for layout optimization

Risk zoning serves as the foundational link between tsunami risk assessment and coastal urban building layout optimization, and its methodology must be grounded in scientific frameworks and multi-source data to ensure reliability. This study adopts the full-chain earthquake tsunami risk assessment framework proposed by Liu, which emphasizes that risk zoning should integrate hazard intensity, exposure, and vulnerability factors—critical for translating abstract risk data into actionable spatial boundaries for urban planning [5]. Drawing on core hazard indicators (tsunami wave height and inundation depth) from this framework, South China's coastal areas are divided into three distinct risk zones using data from authoritative regional studies. High-risk zones are defined as areas where the 2500-year return period tsunami wave height exceeds 3m and inundation depth surpasses 2m; this threshold is derived from Liu et al.'s probabilistic analysis of the Manila subduction zone, which identifies such areas as facing severe destruction risks to buildings [2]. Medium-risk zones correspond to a 2500-year return period wave height of 1–3m and inundation depth of 0.5–2m, based on Liu et al.'s assessment of potential tsunami impacts from the same subduction zone—these areas are prone to moderate building damage, particularly to non-structural components [3]. Low-risk zones are categorized by wave heights below 1m and inundation depths less than 0.5m under the same return period, a standard established by Yan et al.'s targeted hazard analysis of the Pearl River Estuary, where terrain-driven wave dissipation minimizes building risk [4]. Hui et al.'s broader Chinese coastal tsunami risk assessment further validates these zoning thresholds, confirming their consistency with regional risk patterns across South China [6].

To enhance the credibility of risk zoning, multi-source data integration is essential for cross-validation and error reduction. Probabilistic hazard data form the core of this integration: Liu et al. provide detailed probabilistic disaster impact maps of the Manila subduction zone, including wave height and inundation range under different return periods, which define the baseline risk for each zone [2,3]; Hui et al. supplement this with large-scale coastal risk data, ensuring zoning does not overlook broader regional trends [6]. Historical records add a long-term perspective—Wang et al.'s discovery of Northern Song Dynasty earthquake-tsunami traces in Puqian Bay, Hainan, reveals that the bay's historical inundation extent aligns with the modern low-to-medium risk zone boundary identified in this study, confirming the stability of regional risk patterns over centuries [7]. Observation data further refine zoning accuracy: Sun & Wu's analysis of earthquake-tsunami observation stations highlights the value of real-time monitoring in capturing local variations in wave propagation—for example, nearshore stations in the Pearl River Estuary detect subtle wave height amplifications in narrow channels, allowing for micro-adjustments to zone boundaries that static probabilistic data might miss [8]. This multi-layered data synthesis ensures zoning reflects both long-term historical trends and real-time environmental dynamics.

Critical to practical layout optimization, risk zoning must also align with observation and early warning systems to bridge risk assessment and emergency response. Sun & Wu's research on observation station design emphasizes that stations should be strategically placed within each risk zone to provide continuous, high-precision data—this allows for dynamic zoning updates (e.g., adjusting inundation depth estimates after seismic events) and ensures layout strategies remain adaptive to changing risk conditions [8]. For instance, in medium-risk zones near the Pearl River Estuary, data from coastal stations can refine building setback distances by accounting for short-term wave height fluctuations. Equally important is linking zoning to early warning capabilities: Zhang et al.'s preliminary study on T-wave-based tsunami early warning indicates that South China's coast can expect 15–30 minutes of response time after a tsunami is detected [9]. This window is integrated into zoning to calculate maximum allowable evacuation distances from buildings—for high-risk zones, where evacuation urgency is greatest, the maximum distance from any building to a safe shelter is set to ensure travel time does not exceed 80% of the minimum 15-minute warning period (i.e., 12 minutes), while medium-risk zones allow for slightly longer distances (up to 24 minutes, 80% of the 30-minute maximum warning time). This alignment ensures risk zoning not only defines where buildings can be placed but also how they should be arranged to enable timely evacuation, laying the groundwork for actionable layout optimization.

4. Layout optimization strategies & evacuation synergy

Tsunami risk zones with distinct hazard intensities demand targeted building layout strategies to balance safety and urban functionality. For high-risk zones—where 2500-year return period waves exceed 3m and inundation depths surpass 2m [2]—strict density control is paramount: high-rise buildings and densely populated residential/commercial clusters must be avoided, as their collapse would amplify casualties [1]. Instead, coastal green buffers (e.g., wetlands, open green spaces) should be established along shorelines; Yang et al.'s study on low-rise structures shows that such open areas, combined with strategic openings in remaining buildings, can reduce tsunami force by dissipating wave energy, minimizing structural damage [13]. Critical facilities (e.g., hospitals, power stations) should be relocated to safer inland areas, following Liu et al.'s 5000-year return period thresholds—these stricter standards ensure resilience against extreme, low-probability events [2].

Medium-risk zones (2500-year wave height 1–3m, inundation depth 0.5–2m [3]) require a balance between risk mitigation and urban functionality. Building density should be moderately reduced, with spacing between adjacent structures set to at least 1.5 times the height of the shorter building. Leon et al.'s research on pedestrian evacuation efficiency confirms that this spacing prevents cascading damage from tsunami-borne debris and creates clear paths for residents to flee [11]. Additionally, wave-resistant materials (e.g., fiber-reinforced concrete) should be used for construction; Yang et al. note that these materials resist erosion and impact, extending structural integrity during moderate inundation [14]. Low-risk zones (wave height <1m, inundation depth <0.5m [4]) prioritize functional needs but cannot ignore residual risk: building layouts should align with evacuation routes designed via vulnerability mapping, as demonstrated in Pelling & Manuel-Navarrete's Mumbai study—this ensures even minor inundation does not block escape paths [10].

Evacuation planning and early warning systems must be fully integrated with layout design to maximize safety. Yang et al.'s analysis of 12 Chilean cities identifies urban form metrics (e.g., road network connectivity, straight evacuation paths) that directly improve evacuation efficiency [12]; these metrics should guide layout—for example, avoiding narrow alleyways in high-risk zones and ensuring main roads connect building clusters to elevated safe areas. Crucially, evacuation time from any building to a safe shelter must be less than 80% of Zhang et al.'s T-wave-based early warning window (15–30 minutes for South China) [9], leaving a buffer for delays (e.g., assisting vulnerable populations). Leon et al.'s findings further support this: optimizing building cluster spacing based on pedestrian flow rates ensures evacuations stay within this time limit [11].

Cross-regional case studies validate the framework's practicality. Atillah et al.'s Moroccan coastal assessment focuses primarily on hazard mapping without linking to actionable layout strategies, highlighting this framework's unique focus on implementation [14]. Meanwhile, Pelling & Manuel-Navarrete's Mumbai vulnerability data— which identifies misaligned evacuation paths as a key flaw —confirms that the framework's route-design principles address global coastal urban vulnerabilities, demonstrating adaptability beyond South China [10].

5. Conclusion

This study developed a framework for optimizing coastal urban building layout based on tsunami risk by integrating multi-source data and research. It synthesized tsunami risk data—including South China coastal risk analysis [1], Manila subduction zone impacts [2,3], Pearl River Estuary hazards [5], broad coastal risk assessment [6], and historical tsunami records [7]—along with observation/early warning research [8,9] and evacuation studies [10-13]). The framework divided South China's coast into three risk zones and proposed targeted layout strategies, addressing the key gap between macro-level tsunami risk assessment and practical urban building layout optimization.

Key findings reveal that the Manila subduction zone is the dominant source of tsunami risk for South China's coastal cities [2,3]; effective layout optimization must align with risk zone characteristics, early warning time windows [9], and evacuation efficiency requirements [11]; and historical records [7] further confirm the need for long-term resilience in coastal urban planning.

This study has limitations: it relies heavily on existing regional risk data [6] and does not validate proposed strategies through on-site simulations. Future research should use refined numerical models to test the framework's strategies, integrate multi-hazard considerations (e.g., typhoons and storm surges) to enhance comprehensiveness, and expand the framework to other coastal regions by adopting Atillah et al.'s [14] cross-regional comparison method, promoting broader application of tsunami-resilient urban layout principles.

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