Extended Abstract (1,200-2,000 words)

■ Study Objectives

Large-scale tsunami disasters triggered by megathrust earthquakes along the Nankai Trough are anticipated to cause catastrophic human and economic losses in coastal urban areas of western Japan. In low-lying districts such as Konohana Ward in Osaka City, where certain areas lie below sea level, the time available for evacuation after a major earthquake is extremely limited. Under such circumstances, evacuation planning must ensure that residents reach safe locations before tsunami inundation occurs.

Traditional hazard maps provide two-dimensional representations of inundation depth; however, they often fail to convey the dynamic behavior of tsunami flow or the spatial relationship between buildings, roads, and evacuation sites in a way that supports quantitative planning. Moreover, while vertical evacuation (i.e., evacuation to upper floors or rooftops of reinforced concrete buildings) is widely recommended in tsunami-prone urban environments, its effectiveness has rarely been evaluated quantitatively in comparison with horizontal evacuation to designated shelters.

The primary objective of this study is to propose a rapid and efficient evacuation plan against large-scale tsunami inundation caused by a Nankai Trough megathrust earthquake through the integration of a three-dimensional (3D) urban model and network-based evacuation simulation. The study focuses on Kasugade-Kita 1-chome in Konohana Ward, Osaka City, an area including land below −1 m elevation and therefore highly vulnerable to inundation.

Specifically, this research aims to:

1. Construct a detailed 3D urban model incorporating building geometry, floor information, elevation, and road network data.
2. Quantitatively evaluate the accommodation capacity of existing designated tsunami evacuation buildings and additional candidate facilities.
3. Propose supplementary structural measures, including a tsunami evacuation tower, to compensate for capacity shortages.
4. Calculate evacuation completion times under multiple evacuation behavior scenarios, with and without capacity constraints.
5. Assess the effectiveness of distributed evacuation strategies that combine vertical and horizontal evacuation.
6. Enhance risk communication by visualizing tsunami propagation using fluid simulation within the 3D urban environment.

Through these objectives, the study seeks to establish a quantitative and spatially explicit framework for evaluating tsunami evacuation strategies in dense urban districts.

■ Contributions of the Paper

This paper makes four primary contributions to tsunami disaster mitigation research and urban evacuation planning.

First, it provides a quantitative evaluation of vertical evacuation capacity at the district scale. While many disaster management guidelines recommend vertical evacuation in reinforced concrete buildings, few studies have systematically calculated whether such buildings can accommodate the entire exposed population. By estimating rooftop capacities using standardized per-capita space requirements, this study demonstrates the potential and limitations of relying solely on designated evacuation buildings.

Second, the study introduces a capacity-constrained network-based simulation framework. Evacuation analyses often assume unlimited shelter capacity, which can lead to overly optimistic conclusions. By comparing scenarios with and without capacity constraints, this research clarifies how overcrowding may increase evacuation completion time and create the risk of secondary displacement. This approach enables a more realistic evaluation of evacuation feasibility.

Third, the paper proposes and evaluates a distributed evacuation strategy that leverages existing private reinforced concrete buildings. Rather than concentrating evacuees in a small number of officially designated shelters, distributed evacuation encourages residents to move to the nearest structurally safe building. The simulation results demonstrate that such a strategy significantly reduces overall evacuation time, particularly for vulnerable populations such as the elderly, who may face difficulties in long-distance horizontal evacuation.

Fourth, the study integrates 3D urban modeling with fluid-based tsunami visualization. By reproducing tsunami inflow using Blender's fluid simulation function within a geometrically detailed urban environment, the research enhances intuitive understanding of flood dynamics. This integration supports both technical analysis and community-based disaster risk communication.

Overall, the paper contributes a comprehensive methodological framework that combines spatial data modeling, evacuation capacity analysis, network simulation, and visual risk representation.

■ Methods and Data Used

1) Study Area

The target area is Kasugade-Kita 1-chome in Konohana Ward, Osaka City. The district includes low-lying land below sea level and is projected to experience inundation depths of 3–5 m in the event of a large Nankai Trough earthquake. According to the 2020 national census, the daytime population of the district is 1,911, which is adopted as the evacuation demand for this study.

2) 3D Urban Model Construction

A three-dimensional urban model was developed using:

- National 3D city model data (PLATEAU), including building footprints, heights, and floor information;
- Digital Road Map (DRM) data for the road network and elevation;
- Inundation depth assumptions derived from local hazard maps.

The data were imported and visualized in Blender to construct an integrated 3D representation of buildings, roads, and topography. Each building was classified by structural type (wooden or reinforced concrete) and by floor elevation relative to projected inundation depth.

3) Estimation of Evacuation Capacity

Buildings eligible as evacuation sites were selected based on the following criteria:

1. Non-wooden structure (reinforced concrete or equivalent);
2. Sufficient height above projected inundation depth;
3. Accessibility to rooftops.

Accommodation capacity was calculated based on rooftop area and a per-capita space requirement of 3.98 m^2/person (maximum recommended value in national guidelines).

The results revealed that the only officially designated tsunami evacuation building in the district could accommodate 501 people—approximately 26% of the daytime population. Additional candidate buildings provided capacity for 879 people. However, even with these facilities, 531 individuals would remain without evacuation space.

To address this shortage, a tsunami evacuation tower was proposed in Konohana Park. The proposed structure has a building area of 300 m^2, a height of 12 m, and four floors, with the rooftop and fourth floor designated as evacuation space sufficient for 531 persons.

4) Evacuation Simulation

Evacuation time was calculated using a network-based shortest-path algorithm implemented in Fortran, based on the spatial network derived from the 3D urban model.

Key assumptions include:

- Horizontal walking speed: 1.1 m/s
- Stair ascent/descent speed: 0.25 m/s
- Evacuation start time: 120 seconds after earthquake occurrence

Evacuees were distributed across buildings proportionally to floor area. Five evacuation behavior patterns were defined, combining different uses of:

- Designated evacuation buildings;
- Selected private buildings;
- The proposed evacuation tower;
- Vertical evacuation to reinforced concrete buildings.

For each pattern, two scenarios were simulated:

1. Without capacity constraints (evacuees always choose the nearest site regardless of crowding);
2. With capacity constraints (evacuees must relocate if capacity is exceeded).

In total, 15 simulation cases were analyzed by combining evacuation patterns with three candidate locations for the evacuation tower.

5) Tsunami Visualization

Tsunami propagation was reproduced using Blender's fluid simulation. The workflow included domain definition, inflow configuration, collision object assignment, simulation baking, mesh generation, and application of textures and lighting. The resulting animation visualizes tsunami inflow within the 3D-modeled district, illustrating interactions between water and buildings.

■ Results and Conclusions

1) Capacity Assessment

The analysis demonstrates that reliance solely on the officially designated evacuation building is insufficient, as it accommodates only about one-quarter of the daytime population. Even after incorporating additional private buildings, a capacity deficit remains. This highlights the structural limitation of current evacuation planning in the study district.

The proposed evacuation tower compensates for the numerical shortfall; however, simulation results suggest that physical expansion alone is not the most efficient solution.

2) Evacuation Time Analysis

Under scenarios without capacity constraints, evacuation completion times were relatively short, as evacuees simply moved to the nearest facility. However, when capacity constraints were introduced, congestion and secondary displacement increased total evacuation time in patterns relying heavily on a limited number of shelters.

The most efficient results were obtained under distributed evacuation scenarios in which:

- Residents in reinforced concrete buildings evacuated vertically to their own rooftops;
- Residents in wooden structures evacuated to the nearest reinforced concrete building or designated site.

In these scenarios, all evacuees completed evacuation in the shortest time, and capacity limits were not exceeded. The total accommodation capacity of reinforced concrete buildings (5,151 persons) far exceeded the daytime population (1,911 persons), demonstrating the substantial potential of vertical evacuation when private buildings are utilized.

3) Policy Implications

The findings indicate that:

1. Expanding designated evacuation facilities alone is insufficient;
2. Utilizing existing reinforced concrete buildings as temporary evacuation sites is highly effective;
3. Distributed evacuation reduces horizontal travel distance and physical burden, benefiting elderly and mobility-impaired individuals;
4. Capacity-constrained modeling is essential for realistic evacuation planning.

4) Visualization and Risk Communication

The 3D tsunami visualization enhances understanding of inundation height and flow behavior compared to conventional hazard maps. Such visual tools can support community awareness, stakeholder coordination, and consensus-building with private building owners regarding emergency access policies (e.g., unlocking entrances during disasters).

5) Overall Conclusion

This study demonstrates that integrating 3D urban modeling, capacity assessment, network-based evacuation simulation, and fluid-based visualization provides a robust framework for evaluating tsunami evacuation strategies.

The results strongly support the promotion of distributed evacuation strategies that actively utilize existing reinforced concrete buildings for vertical evacuation. By combining structural measures (e.g., evacuation towers) with operational and community-based strategies, urban districts vulnerable to Nankai Trough earthquakes can significantly improve evacuation efficiency and reduce the risk of casualties.

The proposed methodological framework is transferable to other coastal urban areas facing similar tsunami risks and contributes to the advancement of quantitative, data-driven disaster preparedness planning.

（1501 words）