■ **Study objectives**

When residents evacuate from water-related disasters such as river floods, storm surges, and tsunamis, vertical evacuation is also important in addition to horizontal evacuation because the time spent in lowland areas should be reduced as much as possible. However, the current evacuation plans for flood disasters are based on the assumption of horizontal evacuation to shelters. In addition, although the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and local governments have clearly stated the importance of vertical evacuation, vertical evacuation behavior has not yet been quantitatively evaluated. Therefore, this study uses data from a 3D urban model (3D PLATEAU) to construct vertical–horizontal evacuation simulations, estimate the number of people temporarily accommodated by rooftop evacuation measures in the case of a large-scale storm surge and tsunami in Konohana-ku, Osaka City, and quantitatively evaluate the disparity between the two areas. The study also identifies future issues to be addressed to propose measures and develop support tools to improve residents' evacuation awareness and improve evacuation accuracy.

■ Contributions of the paper

The current disaster prevention and evacuation plans are based on evacuating people living in the entire area to the evacuation centers via horizontal movement in the evacuation target areas where the risk of flooding has increased. Therefore, the plan does not take into account the layout, area, and number of floors of the buildings in the evacuation area, and the safe floors in the buildings are still unknown. In addition, the evacuation plan is based on the assumption that all people in the evacuation area will escape to the evacuation shelters; however, in case of flooding, most of the evacuees will go to nearby high buildings or escape to the safe floors in their buildings, and a gap exists between the evacuation plan and reality.

As one of the solutions to the problems of the current evacuation planning against water-related disasters, this study proposes a vertical–horizontal evacuation model using 3D data. The scheme is as follows: 1) The number of occupants per building/floor is calculated by distributing the occupants proportionally according to the floor area and number of floors of the building. 2) Whether the building will be inundated is determined according to the maximum inundation depth data of tsunamis and storm surges in the building, and the results are compared with the height data of each building/floor (including rooftop floors). 3) If the building is RC and the floor is not inundated, the residents are assumed to not evacuate. 4) If the building is wooden or RC and the floor is inundated, the residents on that floor are assumed to evacuate to the nearest evacuation building or the nearest RC building and the rooftop that is not inundated.

This model is applied to the entire Konohana Ward of Osaka City, the number of people temporarily accommodated is estimated, and the usefulness of the rooftop evacuation policy is discussed. The issues and future development of the proposed vertical and horizontal evacuation model are also described.

■ Methods and data used

As of the end of FY2022, the MLIT has completed the conversion to open data in 34 prefectures and 123 cities, wards, towns, and villages and is gradually expanding the number of target cities for 3D data development and data expansion. This project is an expansion of spatial information, which used to be mainly in 2D, to 3D, and PLATEAU is now capable of creating 3D hazard maps. For Osaka City, which is the subject of this evaluation, 3D PLATEAU data are available for the entire area.

First, we conducted a trial calculation based on the proposed vertical and horizontal evacuation model in Kasugade-kita 1-chome, where the ward office of Konohana-ku, Osaka City is located. First, buildings that can be evacuated only to the rooftop were selected from the evacuation buildings designated by Osaka City, and the rooftop area was divided by the estimated number of evacuees to determine how much area is required for one person to evacuate (4.46 m^2). Then, all RC buildings in Kasugade-kita 1-chome were selected, and their rooftop area was determined from the building data and divided by 4.46 to estimate the number of people to be temporarily accommodated.

Next, a similar analysis was conducted for all 58 sub-districts in Konohana-ku to clarify the disparities in rooftop evacuation policies. Data from a 3D urban model (3D PLATEAU) was used for the building area and structure type of each building, as well as for the maximum inundation depth of storm surges, and data from the 2015 national census were used for the daytime and nighttime population of each sub-district in Konohana-ku.

■ Results and conclusions

Out of a daytime population of 1,777 in Kasugade-kita 1-chome, 1,116 people were found to need to evacuate in the event of a tsunami and 1,421 people were found to need to evacuate in the event of a storm surge. However, only one building in Kasugade-kita 1-chome has been designated as a tsunami evacuation building by Osaka City, and its estimated capacity is 501 people, which is significantly insufficient. Therefore, we estimated the number of people who could be temporarily accommodated if the rooftop of an RC building, which is less likely to collapse or spread fire, were used as new evacuation sites. We found 45 buildings (including tsunami evacuation buildings) with rooftop evacuation sites, and an estimated number 2,045 temporary evacuees that could be accommodated. In the event of flooding, the maximum number of people that cannot be accommodated in evacuation buildings in Kasugade-kita 1-chome is 920. If approximately 45% of the buildings have rooftop evacuation sites that can be accommodated, it is theoretically possible to temporarily evacuate all residents in this area.

Next, using the data for the locations of tsunami evacuation buildings designated by Konohana-ku and the number of evacuees, we determined whether the daytime and nighttime population of each large family unit was sufficient to accommodate the number of people in the area. We found that the evacuation buildings can accommodate more people than the daytime population in 16 out of 57 sub-districts in Konohana-ku and that the evacuation buildings can accommodate more people than the nighttime population in 15 out of 45 sub-districts with a nighttime population. That is, approximately two-thirds of the sub-districts have insufficient evacuation sites in the currently designated evacuation buildings. Approximately one-third of the large sub-divisions have high-rise residential buildings and schools; thus, the number of people in these buildings exceeds the daytime and nighttime population. Therefore, we estimated the number of temporarily housed persons by applying the vertical–horizontal evacuation model to all the surnames in Konohana-ku, Osaka City, using the method described above. The results showed that 49 of 57 sub-districts had sufficient shelter space for the daytime population and that 39 out of 45 sub-districts had sufficient shelter space for the nighttime population. In the entire Konohana Ward, it is clear that, if the rooftop of an RC structure can temporarily accommodate 100% of the population, it is possible to create a temporary evacuation site for approximately 200,000 people (approximately 2.3 times the daytime population and 3.0 times the nighttime population). If the rooftop evacuation measures proposed in this study can be realized, the feasibility of vertical and horizontal evacuation for water disasters such as tsunamis and storm surges can be increased.

However, the following issues regarding the further refinement of vertical and horizontal evacuation remain unresolved at the present stage: 1) Approximately 15% of the large residential districts in Konohana-ku lack sufficient capacity for both day and night evacuation, and these districts require horizontal evacuation beyond the boundaries of the large residential districts. 2) In addition to the evacuation of residents to buildings, the evacuation of people in transit such as on roads and railroads should also be considered. 3) In particular, in the case of a tsunami caused by an earthquake, horizontal movement might be impossible because of damage to the evacuation route or fires in houses.

The following issues also need to be addressed to improve the feasibility of the rooftop evacuation measures proposed in this study: 1) Currently, hazard maps have been published for various flood damage cases, but the existence of too many hazard maps can cause confusion about evacuation behavior because of excessive information. The hazard maps should therefore be prepared in a way that makes them easy to understand. Thus, it is necessary to simulate what evacuation actions should be taken if the building in which a person lives is shown in a hazard map and to determine a format for providing information that is easy for residents to understand. 2) Most of the rooftops that we have designated as evacuation sites are private buildings. Therefore, it is necessary to deepen cooperation between residents and local governments from a wide range of viewpoints, such as security mitigation measures in the event of a disaster and tax and building incentives for rooftop evacuation measures.
(1,485 words)