

EVALUATION OF UNDERGROUND SPACE FOR TSUNAMI EVACUATION SAFETY WITH ROUTE OBSTACLES BY AGENT-BASED SIMULATION

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ABSTRACT: In the Great East Japan Earthquake 2011, a massive tsunami that exceeded predictions caused extensive flooding damage over a widespread area. As a result, the managers of underground facilities in areas at risk of tsunami arrival prepare and publish evacuation safety plans detailing measures that will ensure smooth and rapid evacuations from their facilities in the event of a tsunami. However, when attempting to verify whether all affected persons can evacuate safely in the case of a major earthquake-related tsunami, it is necessary to consider various route obstacles that may result when the disaster first strikes. This study quantitatively evaluates the safety of an evacuation guidance plan created for a large underground facility in preparation for the flooding that would result from earthquake-related tsunamis and examines the effects of evacuation route obstacles via simulations. The main findings are as follows: By comparing the results with the evacuation safety plan prepared by the facility management company and the results of simulation of each scenario including accidents, we could evaluate safety impacts quantitatively. In some scenarios, the evacuation completion time was delayed by more than 1.5 times compared to the scenario by the management company due to the high concentration of evacuees on the stairs caused by obstacles in the evacuation route. The scenarios in this study showed that evacuation time impacts were more severe in cases involving blocked corridors than in cases involving blocked stairways.

Keywords: Evacuation simulation, Large-scale underground mall, Flooding, Evacuation guidance plan, Tsunami

1. INTRODUCTION

In Japan, many large cities have constructed extensive underground facilities in areas below sea level, and such spaces now cover widespread areas. These developments have resulted in a need for social and economic risk management plans to prevent or minimize human casualties and damage to infrastructure in underground facilities such as subways in the event of large-scale flooding caused by torrential rains and earthquake-related tsunamis.

For example, in the Great East Japan Earthquake that occurred on March 11, 2011, a massive tsunami that exceeded predictions caused extensive flooding damage over a widespread area, thereby forcing a fundamental review of previous disaster prevention measures [1].

The resulting Act on Development of Areas Resilient to Tsunami Disasters 2011 requires the managers of underground facilities such as basement shopping malls, etc., in areas designated as Tsunami Disaster Prevention Zones to prepare and publish evacuation safety plans detailing measures that will ensure smooth and rapid evacuations from their facilities in the event of a tsunami.

However, when attempting to verify whether all affected persons can evacuate safely in the case of a major earthquake-related tsunami, it is necessary to consider various route obstacles that may result when the disaster first strikes. For example, evacuation

routes may be blocked by falling shelves or damage to glass windows, walls, or ceiling materials, which would affect evacuation safety and efficiency.

With the above points in mind, it is crucially important to prepare alternative evacuation routes in anticipation of cases where the optimal evacuation routes are no longer available during a disaster.

On the other hand, evacuation routes are often determined empirically, and various conditions impose limitations on the ability of facility managers to evaluate their evacuation safety plans. To assist such efforts, multi-agent simulation systems, which are increasingly being used to evaluate the evacuation safety of buildings, can quickly be adapted to predict the evacuation properties of underground facilities under various conditions [2].

For example, using a multi-agent crowd simulator, Yamada et al. (2013) reported on human behaviors during the evacuation of an underground facility directly connected to an anonymous terminal station after an earthquake disaster [3]. However, that study did not consider inflows from connected underground malls that may host numerous commercial facilities. Separately, Kiyono et al. (2001) and Nakamura et al. (2018) conducted detailed traffic surveys of actual underground malls and used the collected data to conduct evacuation simulations [4,5]. However, these studies did not consider flood damages that would result from tsunamis or torrential rains.

In other studies, Takizawa (2015) and Goda

(2014) estimated the evacuation capacity of connected buildings in their target areas and the number of pedestrians during rush hour periods for a large-scale underground shopping mall. They then used that information in basic simulations of vertical evacuations to the connected buildings under assumed flooding conditions. Their results showed severe evacuee congestion on certain staircases, which delayed evacuation completion times, and that the number of evacuees would exceed the capacities of some connected buildings [6,7].

Yamamoto (2019) proposed a mathematical programming problem to minimize the evacuation completion time of an underground shopping mall in Osaka City, along with a workflow to convert general geometric spatial data into graphical data. Ultimately, the accuracy of the proposed method was confirmed by multi-agent simulations [8].

However, the abovementioned studies did not evaluate evacuation cases using surface-level exits and specific evacuation safety plans prepared by facility management companies.

It is said that the probability of the Nankai Trough Earthquake, which scale is M 8-9, occurring within the next 30 years is 70–80% [9]. Therefore, it is considered urgent to specifically evaluate and improve the evacuation plans that have been prepared.

We evaluated the basic safety of the evacuation plan prepared by the management company using simulations; however, we did not analyze the effects

of route obstacles [10].

In another study that considers evacuation routes, to verify the evacuation safety of buildings in the event of a major earthquake, Yasufuku (2017) proposed an evacuation analysis method that uses a multi-agent system to consider multiple path obstructions caused by damage to non-structural materials [11]. Many of the studies on obstacles relate to proposed models [12-14], and few have discussed how real evacuation plans are affected by the occurrence of obstacles.

Accordingly, the significance of this study is, firstly, to quantitatively evaluate the safety of the evacuation guidance plan of a large underground facility prepared by the facility management company in anticipation of the flooding hazards that can result from Nankai Trough earthquake-related tsunamis, secondly, to examine how the evacuation plan may be affected by the occurrence of route obstacles via simulations.

2. RESEARCH SITE

2.1 Underground Mall

Our research site is an underground mall (Whity Umeda) located near JR Osaka Station in Osaka City, Japan, which is part of an even larger underground complex called the Osaka Umeda Underground Mall. The underground mall is connected to the main

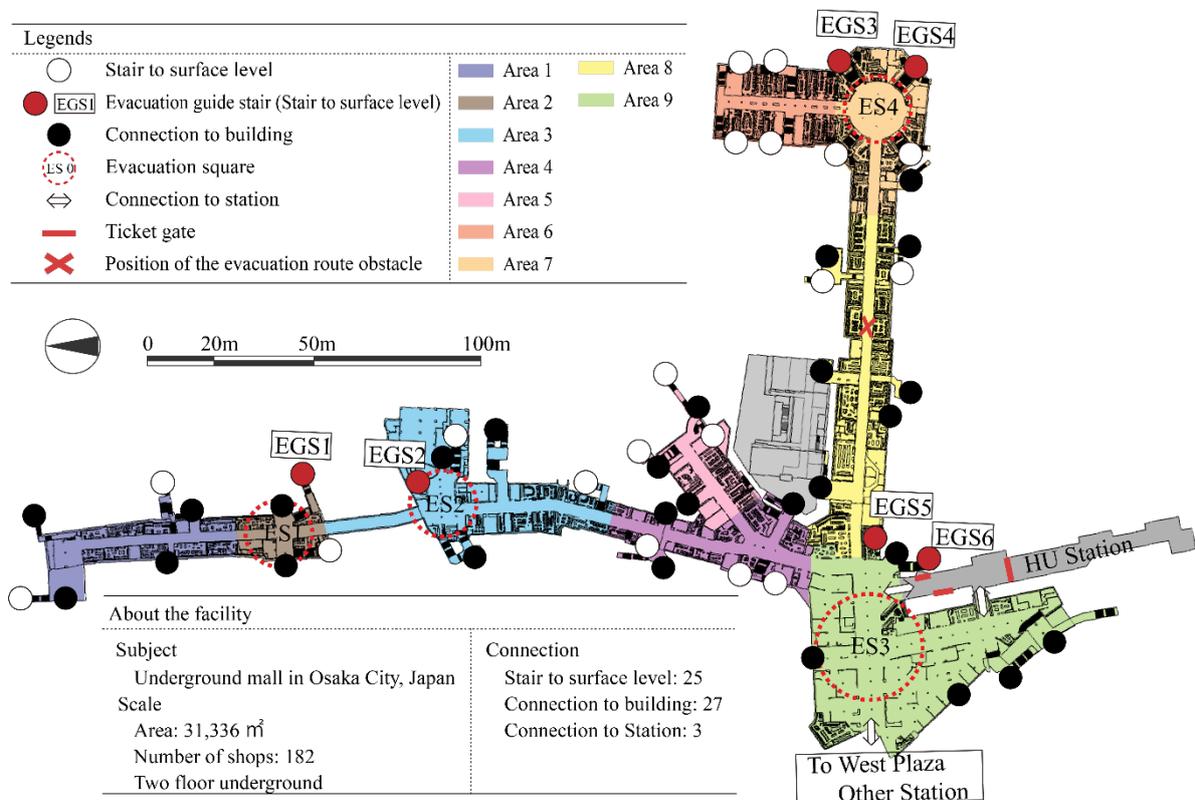


Fig. 1 Floorplan of underground mall [10]

stations of two Osaka Metro Co., Ltd. subway lines and serves approximately 400,000 daily users, which is the highest number of all the underground malls and underpasses in Osaka City. However, in the event of the long-predicted Nankai Trough Earthquake, the area around this underground mall is expected to be inundated by floodwater up to two meters deep [15].

Figure 1 shows the floor plan and outline of the subject facility, which has a 31,336 m² total floor area, two basement levels, 25 stairways to the surface level, 27 building connections, and 182 stores and restaurants. The nine areas in Fig. 1 show how the floor area was divided by the facility management company to estimate the number of people in the underground mall.

2.2 Evacuation Safety Plan

The evacuation safety plan prepared and published by the facility management company has been revised several times to improve evacuation safety and efficiency [16]. According to the newest version, the evacuation locations in the event of a tsunami disaster include the surface area to the east of the underground shopping mall that is outside the expected flooding zone and the second or higher floors of mall-connected buildings. The primary routes to these evacuation sites are, in principle, via the nearest evacuation stairways.

However, the Osaka City Underground Flooding Prevention Council has estimated that the maximum number of people that could be evacuated from the target underground mall and surrounding stations to the second and higher floors of connecting buildings at 18:00 on weekdays at approximately 1,700 people, which would make it difficult to evacuate all the affected visitors and commuters to connecting buildings [17].

As for the guidance method, although the facility evacuation safety plan states that when the plan is in effect, evacuees are to be led to the nearest safe stairways and persons outside are to be prevented from entering the underground mall, the plan does not provide a detailed description of the evacuation guidance method.

However, according to a facility management company official interviewed in conjunction with this study, even though the evacuation safety plan does not contain a specific evacuation guidance method, it is expected that the evacuation will proceed by the Evacuation Timeline that was prepared in the event of a major earthquake.

In that timeline, evacuation to connecting buildings is not anticipated because the estimated number of people that can be accommodated in those buildings is likely to be too small about the number of people in the mall requiring evacuation. Therefore, in principle, the tsunami evacuation will proceed based on horizontal movements that lead people to

the east side of the underground mall, which is outside the anticipated flooding area.

Figure 2 shows the depth of anticipated flooding in the vicinity of JR Osaka Station, including the underground mall, in the event of a major Nankai Trough earthquake. The target line for horizontal evacuation is the area more than 300 m east of Shin-Mido-Suji street, which is indicated by the black dotted line in the figure.

Here, it should be noted that physically challenged and injured persons who have difficulty walking will be evacuated to connected buildings, but this matter is outside the scope of this paper.

One of the purposes of the timeline under consideration here is to simplify evacuation guidance. This is because such guidance is primarily expected to be provided by personnel who normally perform daily security and facility management duties, and the number of such persons is limited.

This, in turn, imposes a limit on their ability to check the safety of the evacuation stairways, including those to surface level, in a limited amount of time. After considering stairway widths, access to the horizontal evacuation target line, the underground mall structure, and available human resources, the number of evacuation guidance stairways (EGSs) in the timeline was limited to six (Table 1).

Once an evacuation has been announced, evacuees are first expected to gather and wait at the four evacuation squares (ESs), established by the facility management company, shown by the red

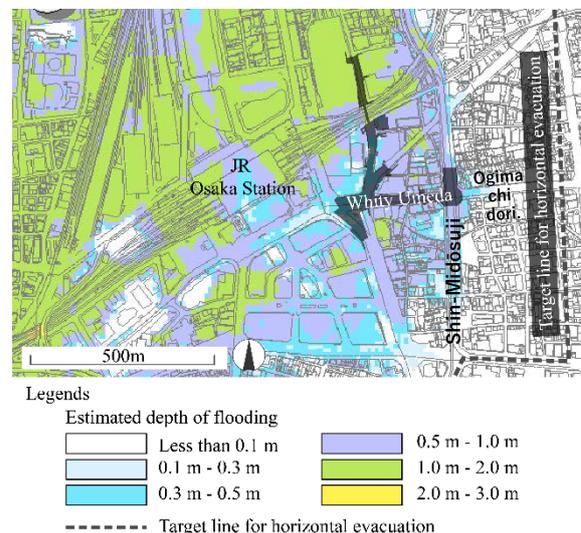


Fig. 2 Map of assumption of flooding [10,17]

Note: This figure was added and modified by the author from the figure in Ref. 17.

Table 1 Width of each EGS

	EGS1	EGS2	EGS3	EGS4	EGS5	EGS6
Width (mm)	3000	1800	5400	5400	1850	3585

dotted circles in Fig. 1. Then, after facility management personnel have confirmed the safety of the evacuation stairways and the surface level exits, they will be directed to evacuate to the EGS sequentially while following the specific evacuation instructions provided.

2.3 Evacuation Timeline

Figure 3 shows the specific steps in the Evacuation Timeline. After a disaster occurs, evacuees will first act to protect themselves (Act 01).

Next, they are expected to move to the nearest ES while following instructions provided by store staff members and public address system announcements given by underground mall facility managers (Act 02). Simultaneously, facility managers will confirm the safety of the EGSs and divide the areas with ropes to prevent the evacuation flow from crossing into Area 9 (Fig. 4). This is to ensure smooth evacuation guidance in Area 9, where the largest concentration of evacuees is expected.

Next, the managers place staff members at each ES to handle crowd control. Because it will take management staffers approximately eight minutes to confirm the safety of each EGS and its surface area exit after the disaster starts, the evacuation to surface level will begin when this process is complete. The evacuees will then be guided from each ES to the surface level exits via the EGSs.

More specifically, evacuees in ES1 and ES2 will use EGS1 and EGS2, respectively (Act 05), while evacuees in ES3 and ES4 will use EGS3 and EGS4 (Act 06). Evacuees in ES3 on the south side, which will be divided by ropes, will use EGS5 and EGS6 (Act 07) (Fig. 4).

Evacuee inflows are expected from the West Plaza and Higashi Umeda station (HU station), which are connected to Area 9. West Plaza inflowing evacuees (Act 03) will be directed to follow the path of Act 06 evacuees, and evacuees from HU station (Acts 04, 08, and 09) will follow the path of Act 07 evacuees.

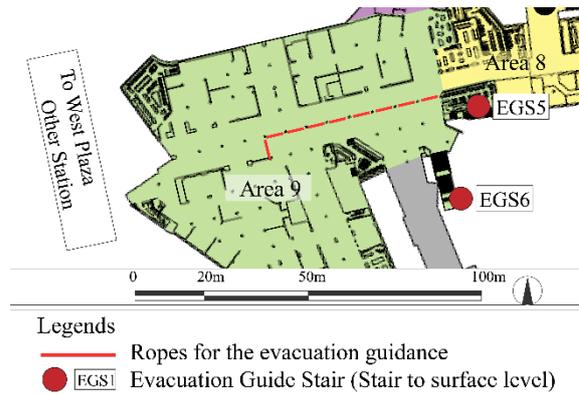


Fig. 4 The position of the ropes separating Area 9 (ES3) [10]

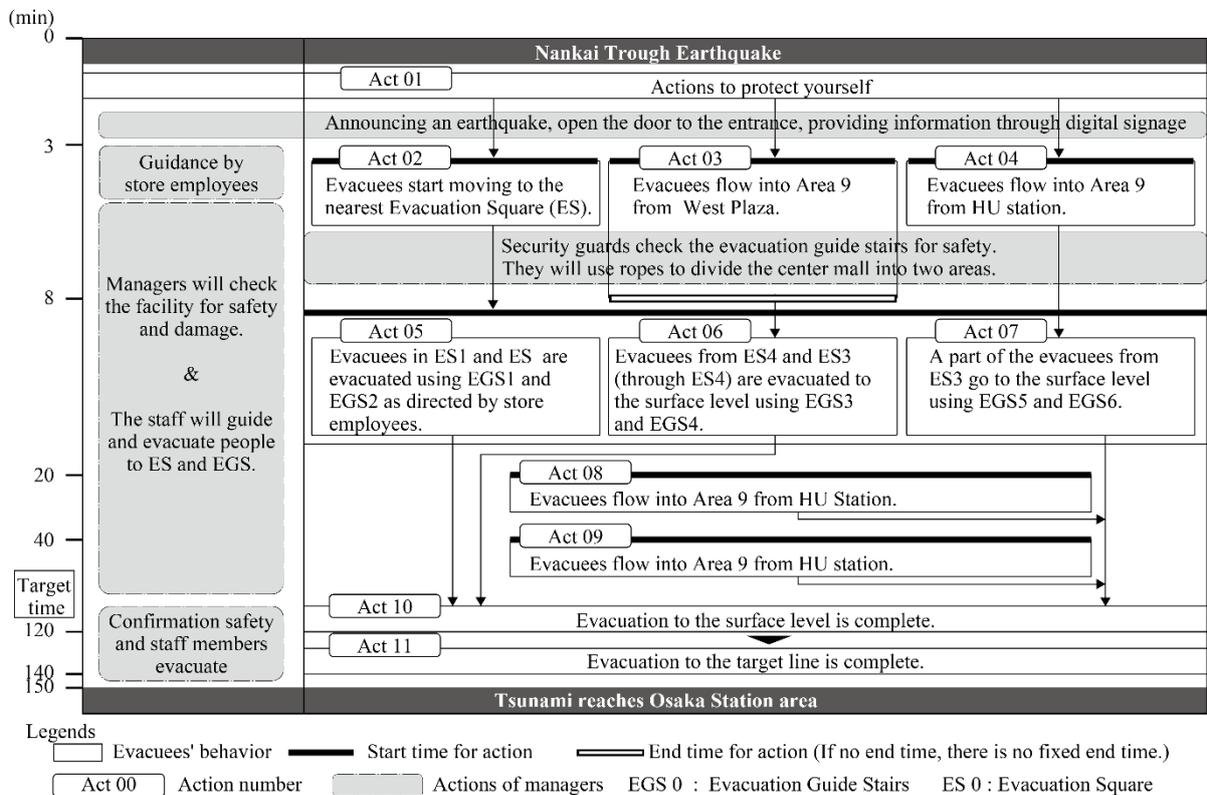


Fig. 3 Evacuation timeline flowchart

After evacuees arrive on the surface (Act 10), they will be instructed to horizontally evacuate (walk) until they pass the target line into areas where flooding is not expected (Act 11). In this study, the evacuation simulation concludes with Act 10. Since the expected arrival time of a tsunami in the JR Osaka Station area is estimated to be 150 minutes after the Nankai Trough Earthquake occurrence, the target time for Act 11 completion is 140 minutes.

The distance from the furthest EGS to the target line for horizontal evacuation is about 500 meters, which is the distance an average person can normally be expected to walk in about 10 minutes. However, considering the enhanced need for safety and the potential for confusion on the surface due to the earthquake, we assume that the travel time will be about 20 minutes. Therefore, the target time to complete the Act 10 evacuation is 120 minutes after the earthquake occurrence.

3. SIMULATION SOFTWARE

Pathfinder simulation software (Thunderhead Engineering Consultants, Inc., Manhattan, KS) is used in this study [18-19]. Pathfinder is an agent-based simulation software that can create model structures with two-dimensional navigational geometry. This navigational geometry is based on stimulating the flow of motions in a room and is suitable for reproducing complex shapes.

In the simulation, navigation geometries are grouped by rooms, and adjacent rooms are connected by doors and stairways. To assign individual behaviors to each occupant, attributes called profiles are used. When setting up an individual profile, various characteristics such as body size, movement speed, and collision behavior can be defined.

Behavioral patterns can also be used to define various instructions to the occupants. Thus, occupants can be classified by profiles and behavior patterns.

3.1 Simulation Algorithm

When an occupant in the simulation moves to a specific destination, the process involves three steps: path planning, path generation, and path following.

Path planning is the process of determining the path to a destination. Each occupant has cost information for local and global targets and the expected waiting times. Since the shortest route is not necessarily the fastest, cost calculations are made for each occupant's route to their destination. In other words, by calculating the route to the room exit and the route to the destination after exiting the room separately, the optimum route can be selected based on cost. In addition, the door queue cost is also calculated, after which a path to that door that the occupant can follow is generated.

For the reasons of page space, the detailed

information on the technical cost calculation for path planning is not provided here, but please refer to "4.1.2. Door Choice" in the Pathfinder Technical Reference Manual [19] for details.

The next step is path generation, once a local target is selected by path planning, a path to the target is needed. To produce it, the Pathfinder application uses the A* search algorithm and a triangulated navigation mesh [20]. The resulting path is represented by a series of points on the triangular edges of the mesh. For the occupants to move smoothly along the resulting path, they proceed to points on the mesh called waypoints (Fig. 5) [21].

Path following is conducted using a combination of inverse steering [22] and collision handling algorithms. These algorithms enable occupants to deviate from the path to avoid obstacles while still heading in the correct direction toward their goal [19]. The inverse steering method evaluates several discrete directions of movement based on the cost factors between the old and new paths.

Potential new paths are calculated by various cost factors, including velocity, acceleration, and waiting time until the path with the lowest cost factor is identified and set as the alternative path. While moving, each occupant tries to maintain a predetermined behavior pattern regarding distance from walls and other occupants, walking speed, obstacle avoidance, and turning.

In this experiment, referring to the evacuation safety verification method supported by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the maximum walking speed was set to 1.0 m/s for level surfaces, and 0.45 m/s was set as the maximum speed for traveling up stairways [23]. For the other required path selection parameters, the initial Pathfinder software values were used. For more details, please refer to the Pathfinder Technical Reference Manual [19].

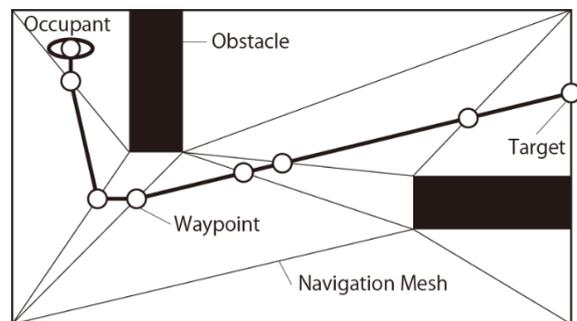


Fig. 5 An occupant's path and a waypoint on the mesh

3.2 Simulation Data

The underground mall data modeled in our simulation was created from the overall floor plan of the facility, the floor plans of each store, and stairway

data provided by the facility management company.

The input data was the number of people in the facility, which was calculated from a pedestrian-traffic volume survey conducted by the facility management company. That pedestrian-traffic volume survey was conducted on two weekdays and two holidays in 2020, and the average survey value of those days was selected as the traffic volume. The number of visitors and commuters was calculated by dividing the underground mall into nine areas based on the points surveyed in the pedestrian-traffic volume survey, as shown in Fig. 1.

The input data for the number of evacuees were taken at 18:00 on weekdays when the number of people in the underground mall is normally the highest, and the initial positions of each evacuee were randomly assigned, as shown in Fig. 6.

Table 2 shows the input values for each area and the inflow numbers of evacuees used in the simulation. The primary evacuee inflows are

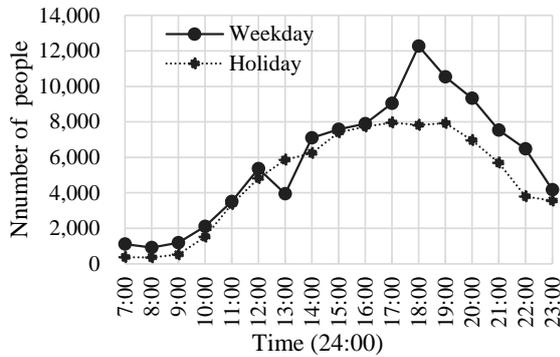


Fig. 6 Numbers of the underground mall visitors by the time [10]

Table 2 Number of people in simulation (Weekday/18:00) [10]

	Area 1	158
	Area 2	73
	Area 3	1,089
	Area 4	1,149
	Area 5	1,122
	Area 6	577
	Area 7	517
	Area 8	764
	Area 9	6,823
	total	12,272
	on the platform	114
Number of People inflow from HU Station	1st inflow (after 20 min)	647
	2nd inflow (after 40 min)	1,296
	total	2,057
Number of People inflow from West Plaza (in 5 minutes)		3,898

expected to come from two locations.

The first is the inflow from the HU station, which is expected to come in two waves. The primary wave (beginning 20 minutes after the earthquake) is assumed to be people temporarily stopped in the station concourse and platforms, and the second wave (beginning 40 minutes after the earthquake) will consist of passengers evacuating from trains that stopped between stations after the earthquake.

The second inflow, which will be people from the West Plaza connected to Area 9, is calculated based on the number of people staying in the plaza and the number of people coming from the stations. This inflow is assumed to consist of about 3,898 people in five minutes. West Plaza is connected to many of Osaka City's major stations, including Metro and private railway terminal stations, as well as large department stores, making it a major crossway of the extended Osaka underground mall area.

3.3 Evacuation Route Obstructions

Figure 3 shows Scenario 0, which is the baseline of the Evacuation Timeline. The following two conditions are considered in each of the five scenarios shown below: situations in which the EGSs cannot be used due to a blocking obstacle such as a collapsed ceiling, and situations in which the corridors that serve as evacuation routes cannot be used because they are partially blocked. Scenarios 1 through 5 are set as shown below:

- Scenario 0 (S0): Evacuation Timeline baseline (no incident)
- Scenario 1 (S1): EGS4 blocked by an obstacle
- Scenario 2 (S2): Route in Area 8 partially blocked by an obstacle
- Scenario 3 (S3): Route in Area 8 blocked by an obstacle
- Scenario 4 (S4): EGS5 blocked by an obstacle
- Scenario 5 (S5): EGS6 blocked by an obstacle

The Area 8 corridor width is about 5000 mm, and in Scenario 2, it is assumed that the 500 × 3500 mm area is no longer passable (Fig. 1).

4. RESULTS AND DISCUSSION

Table 3 shows the evacuation completion time, average evacuation time, and average congestion time for each scenario. The evacuation completion time indicates the time when the last evacuee exited the facility. The average evacuation time indicates the average time it took for each evacuee to exit the facility, while the average congestion time indicates the average of the total time during which the walking speed of each evacuee was less than 0.25 m/s.

Table 3 shows that, in completion time comparisons, S0 and S4 were almost the same; S1 and

S2 increased 8% and 13% over S0, respectively; while S3 and S5 increased significantly to 62% and 56% over S0, respectively. However, for all scenarios, the evacuations were completed within the target evacuation time of 120 minutes after the earthquake occurrence.

Both the average evacuation time and the average congestion time generally showed the same trends as the evacuation completion time, but for S5, the ratio of increase in the evacuation average time was smaller than the increase ratio in the evacuation completion time. When compared to S0, S3 showed an increase of more than three times in the average congestion time.

Figure 7 shows the number of evacuees in the facility by time for each scenario, respectively. The slope in the figures indicates the evacuation efficiency, with a steeper slope indicating a more efficient evacuation. These figures indicate that some evacuation routes suffered more unavailability impacts than others. For example, compared with S0, the largest impact on evacuation efficiency is seen in S3, and the slope in Fig. 7 becomes shallower shortly after the start of evacuation.

Figure 8 shows the cumulative number of evacuees by EGSs for each scenario, respectively. In Figure 8, in S3, evacuee congestion occurs in the vicinity of EGS5 and EGS6. Hence, to distribute the evacuees more efficiently, it might be advisable to direct a portion of the EGS5 and EGS6 evacuees to EGS1 and EGS2. In the case of S4, where EGS5 was not available, the Fig. 7 slope was almost unaffected. In contrast, in the case of S5, where EGS6 was not available, the Fig. 7 slope rapidly became shallow around 2000 seconds after the disaster onset.

From the number of evacuees processed via EGS5 and EGS6, EGS6, which is 3585 mm wide, was able to provide a sufficient throughflow. In contrast, EGS5, which is the narrowest of the evacuation stairways (1850 mm), was considered to have insufficient flow capacity for S4 and S5, as shown in Fig. 8. Therefore, if EGS6 becomes unavailable, a flexible response such as redirecting evacuees to EGS3 and EGS4 will be required.

Comparing S2 (where the corridor is partially blocked) and S3 (where the corridor is completely closed), the S3 evacuation completion time was 1.4 times longer. In the simulation, the evacuation efficiency rates of EGS3 and EGS4 were strongly affected by the flow rate congestion that resulted from a bottleneck at the end of the corridor connecting Area 9 to Area 8.

Therefore, when only half the corridor width is available, the evacuation efficiency of EGS3 and EGS4 is approximately 50%. In S2, the final evacuees were in the direction of EGS3 and EGS4, so if the passageway flow rate of Area 8 is reduced due to a larger blockage area, the impact is expected to be more severe.

Table 3 Results of the evacuation simulation each scenario

	Completed time for evacuation		Average time for evacuation		Average time for congestion	
	(sec)	/S0 (%)	(sec)	/S0 (%)	(sec)	/S0 (%)
Scenario 0 (S0)	2,875	—	1,248	—	436	—
Scenario 1 (S1)	3,092	108	1,606	129	761	175
Scenario 2 (S2)	3,254	113	1,597	128	766	176
Scenario 3 (S3)	4,666	162	2,029	163	1,343	308
Scenario 4 (S4)	2,875	100	1,356	109	536	123
Scenario 5 (S5)	4,475	156	1,590	127	767	176

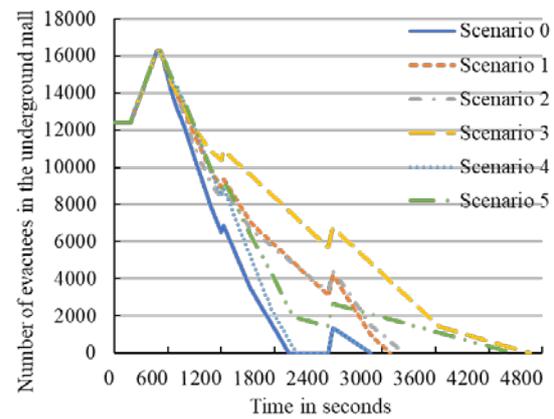


Fig. 7 Number of evacuees in the facility by time for each scenario

5. CONCLUSIONS

This study was conducted to quantitatively evaluate the safety of evacuation plans for the inundation hazards in large underground spaces that might result from earthquake-related tsunamis and to examine the effects of evacuation route obstacles. The main findings are as follows:

1. By comparing the results with the evacuation safety plan prepared by the facility management company and the results of simulation of each scenario including accidents, we could evaluate safety impacts quantitatively.
2. In Scenarios 3 and 5, the evacuation completion time was delayed by more than 1.5 times compared to Scenario 0 due to the high concentration of evacuees on the stairs caused by obstacles in the evacuation route.
3. When considering evacuation route obstructions, the impact on evacuation efficiency differed depending on the stairways and corridors that

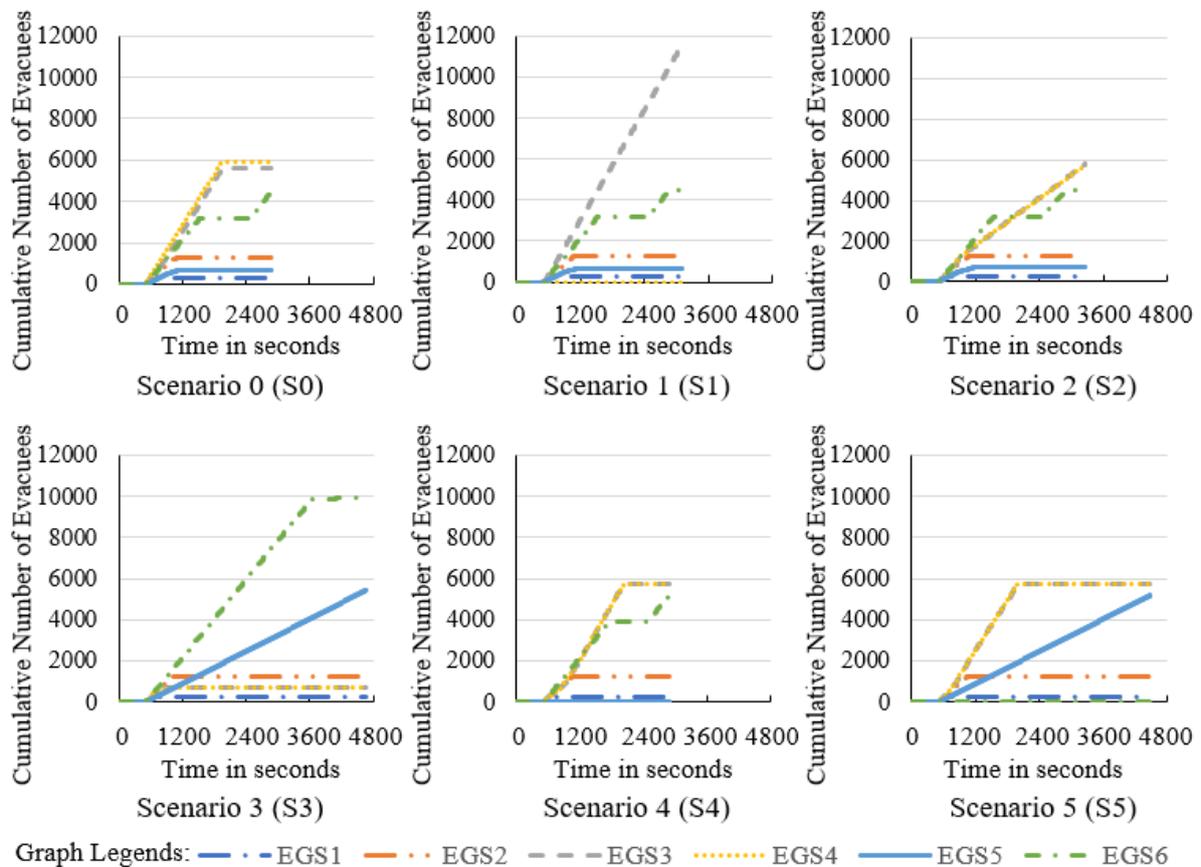


Fig. 8 Number of evacuees by stairways in each scenario

became unavailable. The scenarios in this study showed that impacts on evacuation time were more severe in cases involving closed corridors than in cases of closed stairways.

When considering evacuation route obstacles, we found that the impact on the evacuation guidance plan differed significantly depending on which stairways and corridors became unavailable. Therefore, when route obstacles appear, it is imperative to consider redirecting evacuees away from congested stairways and towards other stairways to improve evacuation safety.

However, in this experiment, the most severe impact was seen in the scenario in which the corridor was blocked, thus indicating that the possibility of blocked corridors requires more attention, primarily because of the number of stairways to which evacuees can be redirected will be limited.

6. ACKNOWLEDGMENTS

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