Electronic Preprint for Journal of Information Processing Vol.28

Regular Paper

Method for Deriving Evacuation Routes Considering Disaster Risk

Nagi Yoshitsugu[1,a)] Shinya Abe[1] Kayoko Yamamoto[2]

Received: February 28, 2020, Accepted: September 10, 2020

Abstract: Achieving safe evacuation is the main goal of selecting an evacuation route. General path-finding methods determine a single shortest route to one end point; however, this is insufficient for selecting evacuation routes. Central Tokyo has a dense population with many tourists, and there are many areas with high disaster risk, such as densely populated wooden houses. As a result, it is important to prepare multiple evacuation sites and routes in case the optimal ones become unavailable. At present, the safety of evacuation routes is determined empirically; however, it should also be evaluated by quantitatively comparing multiple evacuation route candidates. In this paper, we propose a method for simultaneously deriving multiple evacuation route candidates using the Physarum solver. This method also quantitatively considers disaster risk. To evaluate the safety of the evacuation routes derived by this method, we define an index called the evacuation success rate. By developing a method for obtaining multiple evacuation routes considering disaster risk and by providing an index for quantitatively evaluating the safety of the obtained evacuation routes, safe and rapid evacuation can be achieved during disasters.

Keywords: path finding, Physarum solver, evacuation route, disaster risk, safe evacuation

1. Introduction

1.1 Purpose

The Tokyo Metropolitan Government has created the Tokyo Disaster Prevention Plan, which consists of natural disaster prevention efforts [1]. These guidelines aim to achieve safe and rapid evacuation during earthquakes and achieve smooth evacuation during wind and flood disasters. To achieve safe and rapid evacuation as well as smooth evacuation, it is necessary to select evacuation routes on a quantitative basis among multiple evacuation route candidates. When an evacuation route is derived by simulation, a path-finding method is used. However, because path-finding methods identify the shortest route connecting one starting point and one end point, it is not possible to quantitatively derive multiple evacuation route candidates simultaneously while considering disaster risk.

In this paper, we propose a method for deriving evacuation routes using the Physarum solver. The Physarum solver makes it possible to set multiple end points, derive multiple evacuation routes simultaneously, and quantitatively determine the priorities of the routes without additional calculations. In this paper, we present the results of deriving evacuation routes with the proposed method using road network data from Tokyo. We demonstrate that it is possible to derive multiple evacuation routes simultaneously without additional calculations and to quantitatively compare their priorities. The method of deriving evacuation routes considering disaster risk is achieved by converting disaster risk into the parameters of the Physarum solver. By introducing a new index representing evacuation success rate, we demonstrate that the evacuation routes that consider disaster risk are superior to the evacuation routes that do not consider disaster risk.

1.2 Related Work

In this subsection, we present related studies focusing on the following topics: evacuation routes, optimization using the Physarum solver, and spatial analysis using geographic information systems (GIS). Research on the first topic includes a study by Liu et al., in which the authors developed an adaptive evacuation route algorithm that responds to condition changes by the time course of flood disasters using Dijkstra's algorithm, a shortest route search method. In addition, the authors developed a flood disaster simulation using the Disaster Management Spatial Information System (DiMSIS) [2]. Alcada-Almeida et al. proposed a GIS-based decision support system that uses a multi-objective approach to locate emergency shelters and identifies evacuation routes in urban areas [3]. Onorati et al. proposed a semi-automatic technique for knowledge acquisition and modeling of accessible evacuation routes using ontology [5]. Yamashita et al. simulated a pedestrian evacuation from a tsunami using a multi-agent system, and clarified the necessity of evacuation guidance so that evacuees would not be concentrated in a specific evacuation facility from their analysis [4]. Furthermore, Shimura et al. proposed an evacuation route search method using a multi-objective genetic algorithm (GA) [6]. In addition, Yamamoto et al. developed a method for determining an evacuation route dur-

[1] Tokyo Metropolitan Industrial Technology Research Institute, Koto, Tokyo 135–0064, Japan
[2] The University of Electro-Communications, Chofu, Tokyo 182–8585, Japan
[a)] yoshitsugu.nagi@iri-tokyo.jp

ing earthquakes by cluster analysis [7].

Research on the second topic - optimization by the Physarum solver - includes studies by Tero et al., in which the authors modeled the tubular structure of the true slime mold *Physarum polycephalum* [8] and applied it to the development of a Physarum-based network model for the Tokyo rail system [9]. Watanabe et al. also discussed the optimization of railroad networks using the Physarum solver [10]. Song et al. presented Physarum optimization for determining minimal exposure paths in wireless sensor networks [11], while Liu et al. applied Physarum optimization to solve the Steiner tree problem in networks [12]. In addition, Sun et al. reported Physarum-inspired fast algorithms for NP-hard Steiner tree problems [13]. The Physarum solver was also applied in the field of disaster prevention. Khare et al. proposed the Earthquake Clustering Network (ECN), which effectively identifies mainshocks and aftershocks present in seismic catalogs [14].

Research on the third topic - spatial analysis using GIS - includes a study by Koarai et al., in which the authors analyzed a land condition map superimposed with information of past building damage caused by earthquakes on GIS. In addition, the authors examined the relationship between foundation disasters caused by earthquakes and land conditions [15]. Asou et al. determined the optimal location for evacuation sites in the case of a disaster by means of GA using geographic information [16]. Furthermore, Inoue et al. used GIS to determine optimal locations for tourism-related facilities in urban tourist areas [17].

This study differs from previous works on evacuation routes in that it proposes a method for obtaining multiple evacuation routes to multiple evacuation sites and quantitatively assessing the evacuation success rate. The proposed method make it possible to derive safe evacuation routes from public data by focusing on the performance of the roads as evacuation routes, not on evacuees. This research is also novel in that it uses the Physarum solver to derive the evacuation route itself, and uses GIS as a tool to process input data and display the results.

2. Method

2.1 Physarum Solver

The Physarum solver [8] is an algorithm inspired by a transportation network consisting of a tubular structure of the true slime mold *Physarum polycephalum* (hereinafter referred to as slime mold). It is known that slime molds form a transportation network that excels in transport efficiency by reciprocating protoplasm through a tubular structure formed in the cell body. In the Physarum solver, the time evolution change of the protoplasm flux in each transportation tube constituting the slime mold transportation network is expressed by tube Eqs. (1), (2), and (3). By numerically solving these equations, the time evolution change of the flux in each transportation tube can be expressed. The flux decreases as the tube length increases, and increases as the conductance increases. Furthermore, the conductance increases as the flux increases, and decreases with a constant attenuation. Therefore, the flux of tubes with high conductance (i.e., passable tubes) increases with time, while the flux of tubes that are not passable attenuates.

By translating the slime mold transportation network into a road network, as presented in **Table 1**, the Physarum solver can be applied to the derivation of evacuation routes. The relationship between each variable of the Physarum solver and the road can be interpreted as illustrated in **Table 2**. "Priority" is an index showing the performance of each road as an element of the evacuation route. In normal times, length and slope affect road performance, but in the disaster, disaster risk also affects road performance in addition to these. The priority of the evacuation routes can then be compared by calculating the flux of the transportation tubes connecting the starting points as the inflow points of the protoplasm, and by calculating the end points as the outflow points of the protoplasm. In the evacuation routes, roads with a short length and high passability have increased priority.

Table 1 Road network and transport tube network of slime mold.

Road network	Transportation network of slime mold
hline Road	Link
Intersection	Node
Pedestrian	Protoplasm

Table 2 Road parameters and Physarum solver parameters.

Road	Physarum solver
Passage possibility	Conductance
Length	Tube length
Priority	Flux
Starting points	Inflow points of the protoplasm
End points	Outflow points of the protoplasm

$$\sum_i \frac{D_{ij}}{L_{ij}}(p_i - p_j) = \begin{cases} -1 & (j = 1) \\ 1 & (j = 2) \\ 0 & (\text{otherwise}) \end{cases} \tag{1}$$

$$\frac{d}{dt}D_{ij} = f(|Q_{ij}|) - D_{ij} \tag{2}$$

$$Q_{ij} = \frac{D_{ij}}{L_{ij}}(p_i - p_j) \tag{3}$$

D: conductance,
L: tube length,
p: pressure of each node,
Q: flux

2.2 Proposed Method

Evacuation routes are derived using the procedure presented in **Fig. 1**. The steps of this method are described below.

1) Extracting a road network

In our experiment, the road network is extracted using data from the Digital Map (Basic Land Information) Central Tokyo published by the Geospatial Information Authority of Japan (**Fig. 2**). Digital maps (basic land information) comprise geospatial information that integrates basic map information, digital map series, digital elevation data, and information on various attributes [18]. The digital map contains road centerline data, and the attribute information of the road centerline includes the latitude and longitude of both ends as well as the road widths (five levels). A road network is extracted from a digital map using QGIS 2.18.15. First, the length of each road is obtained using the field computer function and is exported in csv format along with the coordinates of both ends and the road widths. Next, the coordinates of both ends are listed without fogging, and serial numbers are assigned as node numbers to create a node list. Finally, the coordinates of both ends from the previous road information are rewritten with the node number of the node data to create a link list.

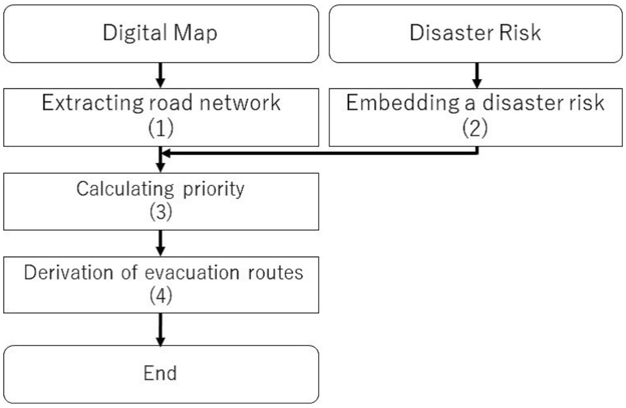

Fig. 1 Outline of proposed method.

2) Embedding disaster risk

Disaster risk information extracted from the Regional Risk Measurement Survey on Earthquakes (8th) (Tokyo Metropolitan Bureau of Urban Development) [19] is embedded in the road network data, as described above (**Fig. 3**). It is calculated from the building collapse risk, fire risk, and activity difficulty level during disaster for each area, and takes a value from 0 to 10.

3) Calculating priority

The priority of each road is obtained from the road network data using the Physarum solver. Any number of starting points and end points are selected from the node list, and the flux at these nodes is always constant. The appropriate conductance and road length are provided as initial values, and tube Eqs. (1), (2), and (3) are solved by repeated calculation. At each calculation step, pressure p, flux Q, and conductance D are updated. When considering disaster risk, the process to correct D is added at each step as shown in Eq.(4).

Digital Map
(Basic Land Information)
Central Tokyo

	A	B	C	D
1	WKT	rID	rnkWidth	length
2	LINESTRII	50310-12ξ	13m-19.5r	26.59846
3	LINESTRII	50310-12ξ	3m-5.5m未	27.78952
4	LINESTRII	50310-12ξ	3m-5.5m未	50.87434
5	LINESTRII	50310-12ξ	5.5m-13m	35.21892
6	LINESTRII	50310-12ξ	3m-5.5m未	4.556799
7	LINESTRII	50310-12ξ	3m-5.5m未	26.29062
8	LINESTRII	50310-12ξ	13m-19.5r	5.357997
9	LINESTRII	50310-12ξ	5.5m-13m	71.96756
10	LINESTRII	50310-12ξ	5.5m-13m	48.44856
11	LINESTRII	50310-12ξ	3m-5.5m未	106.1329
12	LINESTRII	50310-12ξ	3m-5.5m未	28.42429
13	LINESTRII	50310-12ξ	3m-5.5m未	103.5112
14	LINESTRII	50310-12ξ	13m-19.5r	34.33499
15	LINESTRII	50310-12ξ	13m-19.5r	56.72942

Link
(as a CSV format)

+

	A	B	C
1	nodeID	longitude	latitude
2	0	139.7823	35.73038
3	1	139.7823	35.73003
4	2	139.7831	35.73029
5	3	139.7812	35.73051
6	4	139.7812	35.73027
7	5	139.7819	35.73043
8	6	139.7807	35.73056
9	7	139.7808	35.73109
10	8	139.7802	35.73066
11	9	139.7804	35.73062
12	10	139.78	35.73069
13	11	139.7801	35.73098
14	12	139.7824	35.73112
15	13	139.7828	35.73097

Node
(as a CSV format)

Fig. 2 Extracting a road network.

	A	B	C	D
1	WKT	rID	rnkWidth	length
2	LINESTRII	50310-12ξ	13m-19.5r	26.59846
3	LINESTRII	50310-12ξ	3m-5.5m未	27.78952
4	LINESTRII	50310-12ξ	3m-5.5m未	50.87434
5	LINESTRII	50310-12ξ	5.5m-13m	35.21892
6	LINESTRII	50310-12ξ	3m-5.5m未	4.556799
7	LINESTRII	50310-12ξ	3m-5.5m未	26.29062
8	LINESTRII	50310-12ξ	13m-19.5r	5.357997
9	LINESTRII	50310-12ξ	5.5m-13m	71.96756
10	LINESTRII	50310-12ξ	5.5m-13m	48.44856
11	LINESTRII	50310-12ξ	3m-5.5m未	106.1329
12	LINESTRII	50310-12ξ	3m-5.5m未	28.42429
13	LINESTRII	50310-12ξ	3m-5.5m未	103.5112
14	LINESTRII	50310-12ξ	13m-19.5r	34.33499
15	LINESTRII	50310-12ξ	13m-19.5r	56.72942

Link
(as a CSV format)

+

WKT	no	city_name	town_nam	C_amount	C_place	C_rank
MULTIPO	1	千代田区	飯田橋１丁	0.06	3721	1
MULTIPO	2	千代田区	飯田橋２丁	0.03	4139	1
MULTIPO	3	千代田区	飯田橋３丁	0	4767	1
MULTIPO	4	千代田区	飯田橋４丁	0.06	3798	1
MULTIPO	5	千代田区	一番町	0.02	4247	1
MULTIPO	6	千代田区	岩本町１丁	0.05	3907	1
MULTIPO	7	千代田区	岩本町２丁	0.01	4481	1
MULTIPO	8	千代田区	岩本町３丁	0	4767	1
MULTIPO	9	千代田区	内神田１丁	0.05	3882	1
MULTIPO	10	千代田区	内神田２丁	0	4767	1
MULTIPO	11	千代田区	内神田３丁	0.01	4522	1
MULTIPO	12	千代田区	内幸町１丁	0	4767	1
MULTIPO	13	千代田区	内幸町２丁	0	4767	1
MULTIPO	14	千代田区	大手町１丁	0	4767	1
MULTIPO	15	千代田区	大手町２丁	0	4767	1
MULTIPO	16	千代田区	鍛冶町１丁	0	4767	1
MULTIPO	17	千代田区	鍛冶町２丁	0	4767	1
MULTIPO	18	千代田区	霞が関１丁	0	4767	1
MULTIPO	19	千代田区	霞が関２丁	0	4767	1
MULTIPO	20	千代田区	霞が関３丁	0	4704	1
MULTIPO	21	千代田区	神田相生	0	4767	1
MULTIPO	22	千代田区	神田淡路	0	4767	1
MULTIPO	23	千代田区	神田淡路	0	4767	1

Disaster Risk
(Regional Risk Measurement Survey on Earthquakes)

D	E	F	G	H	I
length	start_long	start_latitu	stop_long	stop_latitu	C_amount
61.98028	139.8031	35.71004	139.803	35.7106	0
37.82884	139.8031	35.71004	139.8026	35.71002	0
56.18986	139.8041	35.71009	139.8035	35.71006	0
4.51156	139.8071	35.71023	139.8071	35.71019	0
52.15142	139.8079	35.71045	139.8083	35.71078	0
49.42391	139.8074	35.7106	139.8079	35.71045	0
47.69035	139.8074	35.7106	139.8072	35.7102	0
44.45989	139.8074	35.7106	139.807	35.71073	0
27.5633	139.802	35.71099	139.8018	35.71107	0.12
28.88369	139.8076	35.711	139.8079	35.71091	0
46.64188	139.8076	35.711	139.8074	35.7106	0
105.4846	139.8042	35.71102	139.8046	35.71191	0
56.29858	139.8067	35.71127	139.8069	35.71175	0
89.02798	139.8067	35.71127	139.8076	35.711	0
34.00755	139.8063	35.71137	139.8067	35.71127	0

Link including
Disaster Risk
(as a CSV format)

Fig. 3 Embedding disaster risk.

Table 3 Conditions of results.

	Start	End	Route	Disaster risk	Figure
(1)	1	1	1	Not considering	Fig. 4
(2)	1	1	2	Not considering	Fig. 5
(3)	1	2	1 for each end	Not considering	Fig. 6
(4)	1	1	1	Considering	Fig. 7
(5)	1	1	2	Considering	Fig. 8
(6)	1	2	1 for each end	Considering	Fig. 9

$$D_{ijt+1} = min(1 - Dr/10, D'_{ijt+1}) \quad (4)$$

D_{ijt+1}: conductance of $t + 1$ step,
D'_{ijt+1}: temporary conductance calculated by Eq. (2),
D_r: disaster risk

4) Derivation of evacuation routes

Evacuation routes are derived using the priority described above. The average priorities of all roads' along evacuation routes is defined as the priorities of the evacuation routes. The priority value is asymptotically stable and is not reliable in the middle of the calculation; however, the magnitude relationship converges earlier and is reliable even in the middle of the calculation.

2.3 Evacuation Success Rate

To evaluate the derived evacuation routes, we define the passability of each road and the evacuation success rate of the evacuation route, as illustrated in Eqs. (5) and (6). The road passability and evacuation success rate values are not meaningful in themselves; however, the magnitude relation of these values is meaningful.

$$P_E = \prod^{roads\ on\ a\ route} P_p \quad (5)$$

$$P_p = 1 - \frac{Dr}{100} \quad (6)$$

P_E: evacuation success rate,
P_p: passability of a road,
Dr: disaster risk

3. Results

The advantages of this proposed method are (1) multiple evacuation routes to multiple goals can be derived at the same time, (2) safe routes can be obtained by consideration of the disaster risk, and (3) safety can be evaluated quantitatively. We present 6 examples to evaluate (1) qualitatively, and 4 examples to verify (2) and (3) quantitatively.

3.1 Qualitative Evaluation

We derived evacuation routes under the conditions displayed in **Table 3** using the proposed method. In this experiment, road network data around the Tokyo Skytree was used. Although the Tokyo Skytree is a popular tourist attraction, the surrounding area is densely populated with wooden houses and has a high disaster risk. The darkness of the background in the figures represents disaster risk.

As demonstrated in **Fig. 4**, when deriving one evacuation route for one starting point and one end point, the route with the highest priority agrees with the shortest route derived by the Dijkstra method [20], which is a common method for identifying the shortest path in graph theory. As illustrated in **Fig. 5**, two evacuation routes can be derived at the same time in order of priority for one starting point and one end point. Because the proposed method calculates the priority of each road, any number of evacuation routes can be derived without additional calculations. As demonstrated in **Fig. 6**, when there are one starting point and two end points, two evacuation routes for each end point can be derived simultaneously. Deriving evacuation routes using the proposed method is equivalent to correlating the starting point to the

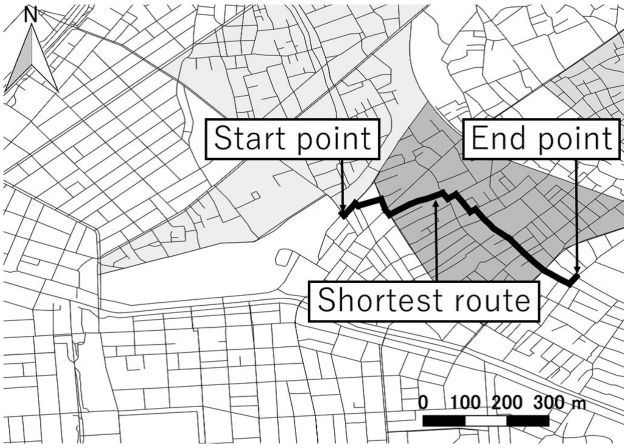

Fig. 4 Derived evacuation routes (1).

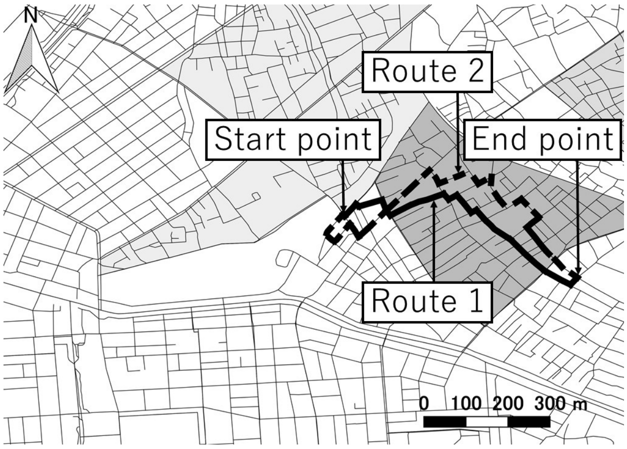

Fig. 5 Derived evacuation routes (2).

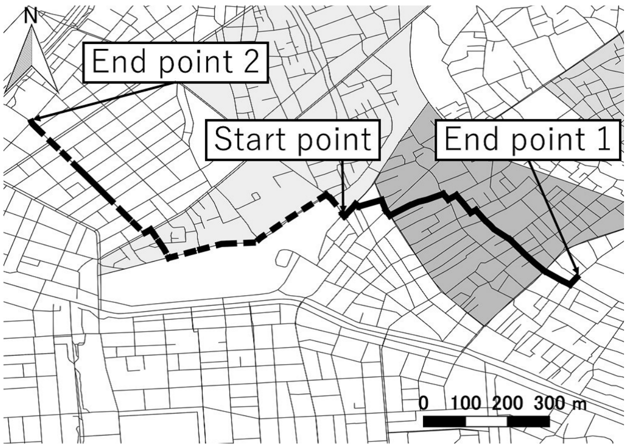

Fig. 6 Derived evacuation routes (3).

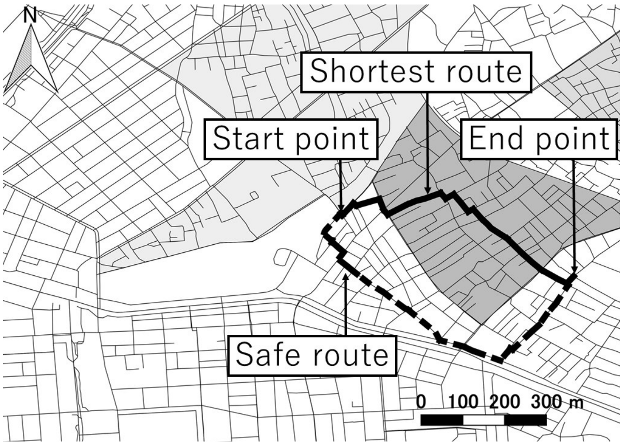

Fig. 7 Derived evacuation routes (4).

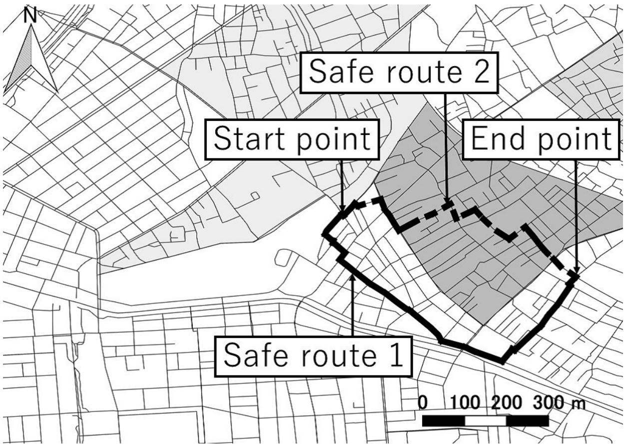

Fig. 8 Derived evacuation routes (5).

inflow point of the protoplasm and the two end points to the overflow points of the protoplasm. By arbitrarily setting the overflow rate ratio, it is possible to calculate in consideration of the capacity and safety of the evacuation sites.

As displayed in **Fig. 7**, when there is one starting point and one end point, the evacuation route considering disaster risk does not include roads in areas with high disaster risk. As illustrated in **Fig. 8**, two evacuation routes considering the disaster risk can be derived at the same time for one starting point and one end point. By obtaining multiple evacuation routes considering disaster risk before a disaster occurs, smooth evacuation can be achieved using the second safest route even if the safest route becomes unavailable. As demonstrated in **Fig. 9**, when there are one starting point and two end points, two evacuation routes considering disaster risk for each end point can be derived simultaneously.

3.2 Quantitative Evaluation

In order to evaluate the calculation time, that under each condition in Table 3 was compared with that for deriving one shortest path by the Dijkstra method [20] (**Table 4**). In the proposed method, the computational complexity cannot be obtained analytically. We implemented each method in Python 3.7.0 and used a computer which has two 2.4 GHz processors, and 64 GB memory. Calculated roads are the same under all conditions.

To verify quantitative advantages, we derived routes from a single starting point to 4 end points, which correspond with the actual evacuation sites in Koto-ku, considering the disaseter risk. Then, we compared route length and evacuation success rate of

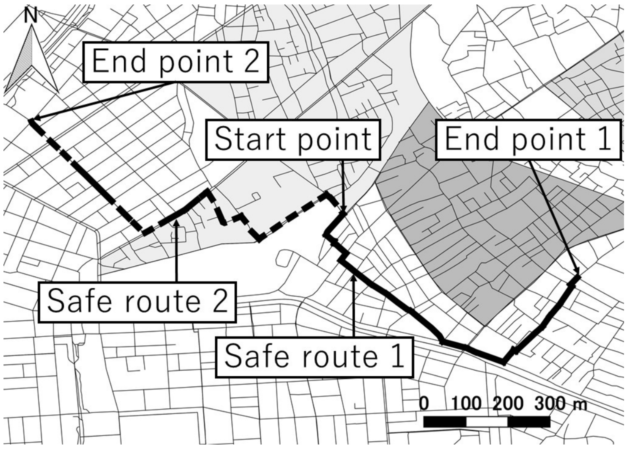

Fig. 9 Derived evacuation routes (6).

Table 4 Calculation time.

	Caluculation time
Dijkstra method	2,492 [s]
(1)	784 [s]
(2)	788 [s]
(3)	823 [s]
(4)	1,000 [s]
(5)	1,035 [s]
(6)	1,090 [s]

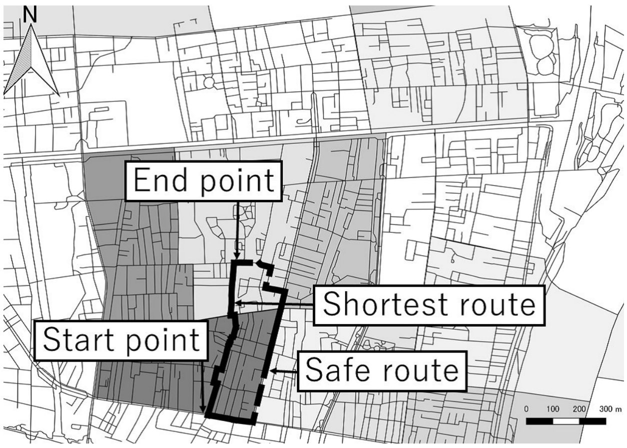

Fig. 10 Shortest route and safe route (1).

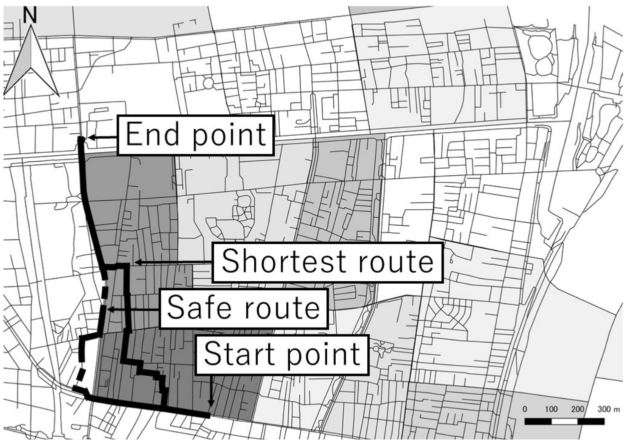

Fig. 11 Shortest route and safe route (2).

Table 5 Disaster risk and evacuation success rate.

	Evacuation success rate		Route length	
Disaster risk:	Considering	Not considering	Considering	Not considering
Fig. 7	0.91	0.21	1,043 [m]	956 [m]
Fig. 10	0.58	0.20	1,146 [m]	887 [m]
Fig. 11	0.76	0.18	1,698 [m]	1,689 [m]
Fig. 12	0.79	0.56	2,016 [m]	1,708 [m]
Fig. 13	0.55	0.43	2,103 [m]	1,698 [m]

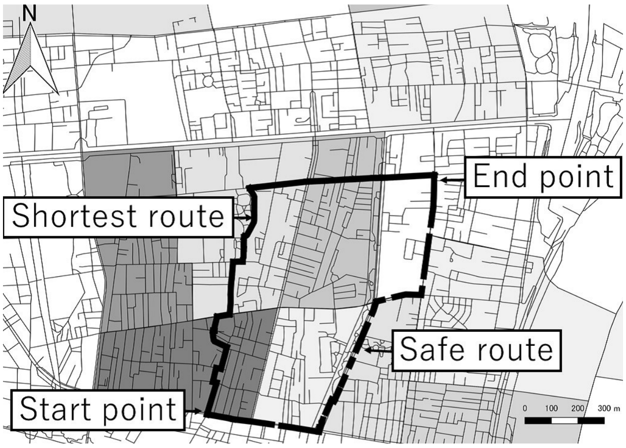

Fig. 12 Shortest route and safe route (3).

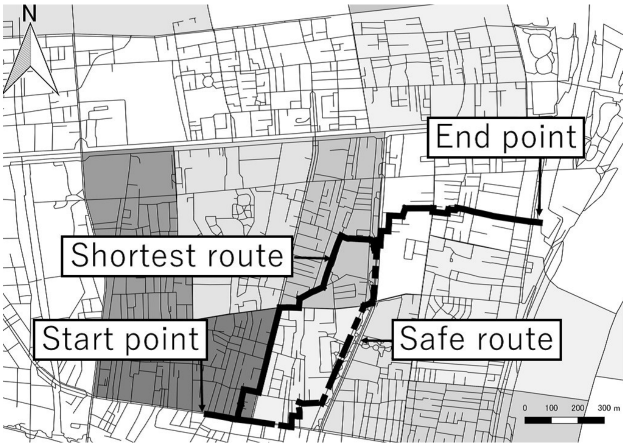

Fig. 13 Shortest route and safe route (4).

these safe routes with those of the shortest routes (**Fig. 10**, **Fig. 11**, **Fig. 12**, and **Fig. 13**). **Table 5** presents the evacuation success rate and route length of the routes that consider disaster risk and those that do not. The evacuation routes that consider disaster risk have a higher evacuation success rate than the shortest evacuation routes that do not consider disaster risk; however, the former routes are longer than the latter routes.

4. Discussion

4.1 Difference from Existing Methods

The proposed method differs from existing path-finding methods in three respects. First, multiple end points and multiple routes can be handled without additional calculation. In general, existing path-finding methods only produce one shortest route for one starting point and one end point. However, using the proposed method, if one evacuation site becomes unavailable due to a disaster, evacuation can be performed to another evacuation site. Similarly, if one evacuation route cannot be taken, another evacuation route can be used for evacuation.

The second difference between the proposed method and existing methods is that the former considers disaster risk. While it is possible to avoid high-risk areas when a disaster occurs in areas near the home or workplace, it is difficult to determine an evacuation route avoiding high-risk areas in unfamiliar locations. The proposed method thus makes it possible to achieve safe evacuation even when individuals are not familiar with a given area.

The third difference is that deriving multiple routes and considering disaster risk do not require more calculation than doing one shortest route in this proposed method. This is a large advantage over existing methods, as it enables the quantitative comparison of multiple route candidates. As a result, it becomes possible to consider the efficiency of evacuation route candidates for safe, rapid evacuation, and smooth evacuation.

4.2 Convergence of Priority

The priority value of each road is asymptotically stable and has no significance in the middle of the calculation. However, because the magnitude relationship converges early in the calculation, the priority order is meaningful even during the calculation. Therefore, in the comparison of evacuation routes, it is not necessary to wait for all priority values to converge (unless absolute values are required), and iterative calculation may be terminated before the priority order converges. Because it is possible to determine whether accuracy or calculation time should be prioritized, we can prioritize accuracy before a disaster occurs and perform calculations until convergence. However, after a disaster occurs, we can prioritize calculation time and use only priority rankings to determine the evacuation routes.

5. Conclusion and Future Research

In this study, we developed a method for deriving multiple evacuation route candidates. This method quantitatively considers disaster risk for multiple routes simultaneously using the Physarum solver. To evaluate the safety of the evacuation routes, we defined an index called the evacuation success rate. By providing a method for obtaining multiple evacuation routes considering disaster risk and an index for quantitatively evaluating the safety of the obtained evacuation routes, safe and rapid evacuation is possible during disasters.

However, there are currently three problems. The first is that the road data used is not consistent with the pedestrian space network. On a wide road, sidewalks on both sides are separate paths for pedestrians. Furthermore, underpasses and footbridges are not included in the road data. Because this study addresses pedestrian evacuation in densely populated areas, more accurate evacuation route derivation and evacuation success rate calculations will be possible if these data are obtained. Currently, pedestrian space network data can be obtained in limited areas, such as near stations; however, comprehensive data are lacking. When the necessary data become available, we would like to improve our proposed method using the data.

The second problem is that the granularity of the used disaster risk is coarser than the road network data. The disaster risk reported by the Tokyo Metropolitan Bureau of Urban Development is a value for each town; however, the disaster risk of each road will differ even in the same area. In deriving evacuation routes while avoiding areas with high disaster risk, the evacuation routes are derived so as to avoid entire areas with a high disaster risk. Therefore, the obtained evacuation routes may have more detours than necessary. In addition, there is a possibility that a road with a particularly high disaster risk may exist in an area with a low disaster risk. In future work, we would like to improve our proposed method using more detailed disaster risk data.

The third problem is that we do not consider the time factor. In actual evacuation, it is unlikely that everyone starts evacuation at the same time, and it is assumed that evacuation will be started at different times. In the proposed method, the evacuation start time can be considered by setting the right side of the Eq. (1) as a function of time. As the next step, we will work on this task.

Acknowledgments The authors would like to thank Enago (www.enago.jp) for English language review.

References

[1] Tokyo General Affairs Bureau General Disaster Prevention Department Disaster Prevention Management Division: Disaster prevention plan in Tokyo (online), available from ⟨http://www.metro.tokyo.jp/INET/KEIKAKU/2014/12/DATA/70ocp401.pdf⟩ (accessed 2018-08-13).

[2] Liu, Y., Hatayama, M. and Okada, N.: Development of an adaptive evacuation route algorithm under flood disaster, *Annuals of Disaster Prevention Research Institute*, Vol.49, pp.189–195, Kyoto University (2006).

[3] Alcada-Almeida, L., Tralhao, L., Santos, L. and Coutinho-Rodrigues, J.: A multi objective approach to locate emergency shelters and identify evacuation routes in urban areas, *Geographical Analysis*, Vol.41, No.1, pp.9–29 (2009).

[4] Yamashita, T., Matsushima, H. and Noda, I.: Exhaustive analysis with a pedestrian simulation environment for assistant of evacuation planning, *Transportation Research Procedia*, Vol.2, pp.264–272 (2014).

[5] Onorati, T., Malizia, A., Díaz, P. and Aedo, I.: Modeling an ontology on accessible evacuation routes for emergencies, *Expert Systems with Applications*, Vol.41, No.16, pp.7124–7134 (2014).

[6] Shimura, Y. and Yamamoto, K.: Method of searching for earthquake disaster evacuation routes using multi-objective GA and GIS, *Journal of Geographic Information System*, Vol.6, No.5, pp.492–525 (2014).

[7] Yamamoto, K. and Li, X.: Safety evaluation of evacuation routes in Central Tokyo assuming a large-scale evacuation in case of earthquake disasters, *Risk and Financial Management*, Vol.10, No.3, p.14 (2017).

[8] Tero, A., Kobayashi, R. and Nakagaki, T.: The mathematical model for adaptive transport network in path finding by true slime mold, *Journal of theoretical biology*, Vol.244, No.4, pp.553–564 (2006).

[9] Tero, A., Takagi, S., Saigusa, T., Ito, K., Bebber, D., Fricker, M., Yumiki, K., Kabayashi, R. and Nakagaki, T.: Rules for Biologically Inspired Adaptive Network Design, *Science*, Vol.327, No.5964, pp.439–442 (2010).

[10] Watanabe, S., Tero, A., Takamatsu, A. and Nakagaki, T.: Traffic optimization in railroad networks using an algorithm mimicking an amoeba-like organism, Physarum plasmodium, *Biosystems*, Vol.105, No.3, pp.225–232 (2011).

[11] Song, Y., Liu, L. and Ma, H.: A physarum-inspired algorithm for minimal exposure problem in wireless sensor networks, *IEEE Wireless Communications and Networking Conference* (*WCNC*), pp.2151–2156 (2012).

[12] Liu, L., Song, Y., Zhang, H., Ma, H. and Vasilakos, A.: Physarum optimization: A biology-inspired algorithm for the steiner tree problem in networks, *IEEE Trans. Computers*, Vol.64, No.3, pp.818–831 (2013).

[13] Sun, Y. and Halgamuge, S.: Fast algorithms inspired by physarum polycephalum for node weighted steiner tree problem with multiple terminals, *IEEE Congress on Evolutionary Computation* (*CEC*), pp.3254–3260 (2016).

[14] Khare, P., Nanda, S. and Vijay, R.: Clustering networks based on physarum optimization for seismic catalogs analysis, *IEEE Congress on Evolutionary Computation* (*CEC*), pp.2864–2871 (2019).

[15] Koarai, M., Satou, H. and Une, H.: GIS analysis of the relationship between earthquake-induced ground disaster and the physical characteristics of land, *Bulletin of the Geospatial Information Authority of Japan*, Vol.112, pp.115–123 (2007).

[16] Asou, T., Matsumoto, Y. and Morishita, K.: A study on the optimal location of disaster shelters using genetic algorithm, *Research Report of Faculty of Engineering*, Vol.58, pp.522–533, Yamaguchi University (2007).

[17] Inoue, M. and Yamamoto, K.: Method for evaluating the location of tourist-related public facilities using genetic algorithms and GIS, *Journal of Communication and Computer*, Vol.10, No.4, pp.496–512 (2013).

[18] National Land Research Institute, Ministry of Land, Infrastructure, Transport and Tourism: Digital Map (Basic Land Information) (online), available from ⟨http://www.gsi.go.jp/kibanjoho/kibanjoho40027.html⟩ (accessed 2019-11-27).

[19] Tokyo Metropolitan Bureau of Urban Development: Regional Risk Measurement Survey on Earthquakes (8th) (online), available from ⟨https://www.toshiseibi.metro.tokyo.lg.jp/bosai/chousa_6/home.htm⟩ (accessed 2019-11-27).

[20] Dijkstra, E.W.: A note on two problems in connexion with graphs, *Numerische Mathematik*, Vol.1, No.1, pp.269–271 (1959).

Nagi Yoshitsugu graduated from Waseda University in 2015. She received her M.S. degree from the same university in 2017. In the same year, she joined the Tokyo Metropolitan Industrial Technology Research Institute. Her research interest is evacuation route derivation methods.

Shinya Abe graduated from Iwate University in 2006. He received his M.E. degree from the same university in 2008, and his Ph.D. from The University of Electro-Communications in 2017. He joined the Tokyo Metropolitan Industrial Technology Research Institute in 2009. His current research interests are information retrieval systems and tourism information systems. He received the Student Encouragement Award of the 70th and 72nd IPSJ National Convention in 2008, in 2010. He is a member of the IPSJ and a member of IEICE, ISSJ, DBSJ, INFOSTA, JAST and STI.

Kayoko Yamamoto received her Ph.D. from Tokyo Institute of Technology in 1999. She joined Shiga Prefecture Lake Biwa Research Institute in 1998. She became an associate professor at The University of Electro-Communications in 2006, and a professor at the same university in 2019. Her research interests are spatial information science, urban/regional planning and disaster science. She has served as a member of the Science Council of Japan and a senior science and technology policy fellow at the Cabinet Office.