An emergency evacuation model for avoiding high nuclide concentration areas in nuclear accident

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Abstract. This paper proposes a nuclear accident emergency evacuation model based on nuclide concentration field and traffic flow network model. Gaussian puff model, which describes the instantaneous concentration of nuclide, is widely used to predict the diffusion of radionuclides in nuclear accidents. We adopt a modified Gaussian puff model to preserve the time characteristics of nuclide diffusion, which considers the effects of dry deposition (gravity deposition), wet deposition (rain wash), and nuclide decay on the concentration distribution. An A-star algorithm based on nuclide concentration and traffic pressure cost is proposed to formulate the optimal path planning under nuclear accident. With the expansion of the nuclide concentration field, more and more paths cannot be safely passed through, and evacuation vehicles will also cause congestion on the path. The evacuation model we proposed will regularly update the optimal route according to road traffic conditions and nuclide spatial distribution, so as to obtain an optimized evacuation strategy. This study takes a real road network around the nuclear power plant as the application scenario of evacuation simulation. The computation time of the evacuation model is short, so it can respond quickly in the event of a nuclear emergency. The results show that the evacuation strategy formulated by the model can ensure good evacuation efficiency and avoid areas with high nuclide concentrations during the evacuation process, thereby reducing the radiation exposure of personnel.

Keywords: Nuclear accident, Emergency evacuation, Path-planning, A-star algorithm, Route optimization.

1 Introduction

Nuclear power plants are currently operating around the world to meet growing energy demands. However, once a nuclear accident occurs, people in the surrounding area will be at risk of extensive radiation exposure, requiring large-scale evacuation. In the process of determining the evacuation route scheme, not only traffic conditions but also radiation risks should be considered, so that personnel are less affected by nuclear accidents. In addition, it is also necessary to ensure that the time of the evacuation process is as short as possible. Furthermore, the emergency response work is mainly divided into two parts, one is to estimate the radiation field for risk assess-

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ment, and the other is to evacuate residents to shelters as soon as possible. Generally, in the event of a nuclear accident, the area within a radius of 5-10 kilometers from the nuclear power plant is the Emergency Planning Zone (EPZ), and people in the area need to be evacuated to shelters as soon as possible

The diffusion models of nuclides in the atmosphere are similar to the diffusion of atmospheric pollutants. These models describe the physical process of atmospheric diffusion with mathematical expressions. Sorensen, J. H. et al. parameterized the dry and wet deposition of aerosols, and used hybrid stochastic particle-puff diffusion to describe three-dimensional atmospheric diffusion. It is currently capable of describing plumes at downwind distances greater than 20 km and globally[1]. Li Ke et al proposed a parameter bias transformation method combined with the Lagrange puff model for Data assimilation. They use coordinate transformations to approximate parameter deviations, improving the reliability of model predictions and parameter estimates[2]. The hazards of nuclear radiation are also worthy of research. Steinhauser, G. et al compared the environmental impact of the Chernobyl and Fukushima nuclear accidents[3]. Hasegawa, A. et al. focused on investigating the effects of radiation on health after the Fukushima nuclear accident and other health problems after the nuclear accident[4]. Ohba, T. et al. reviewed the problems of three major nuclear accidents in the past and gave suggestions for evacuation planning for future nuclear accidents[5]. In order to avoid nuclear radiation hazards caused by nuclide proliferation, many scholars are more concerned about evacuation in nuclear accidents. Pei Qiu-Yan et al proposed a path-planning method based on the minimum collective dose using the Dijkstra algorithm[6]. Urbanik, T. tried to estimate the evacuation time of the nuclear power plant[7]. Tang Zhihong et al. proposed a multi-objective evacuation route optimization method. It improves the ant colony algorithm and the road resistance model, and can solve the evacuation path with the minimum travel time and radiation dose[8]. Lakshay et al. proposed a bus-based evacuation planning model for large-scale area evacuations. Using a nuclear accident in India as an example, they showed that the model was able to provide real-time, efficient and robust results within an acceptable time frame[9]. Based on the random forest model, Yang Linyao et al. established a pedestrian exit selection model in the smoke plume planning area by comprehensively considering the exit distance, exit capacity, exit queuing scale, and nuclear power plant distance[10]. Zou Yang et al. assumed that vehicles need to pass through all nodes that need to be evacuated in a nuclear accident, and designed a method to calculate the evacuation route[11]. Tan Ke et al. proposed a nuclear evacuation scheme based on intelligent vehicle collaborative systems (IVCs), artificial systems, computational experiments, and parallel execution (ACP), as well as the planning model and algorithm of the scheme[12].

This paper proposes a nuclear accident emergency evacuation model based on nuclide concentration field and traffic flow network model. We adopt a modified Gaussian puff model to preserve the time characteristics of nuclide diffusion. An A-star algorithm based on nuclide concentration and traffic pressure cost is proposed to formulate the optimal path planning under nuclear accident. The evacuation model we proposed will regularly update the optimal route according to road traffic conditions and nuclide spatial distribution, so as to obtain an optimized evacuation strategy. In this study, the real road network around a nuclear power plant is used as the application scenario for evacuation simulation. The results show that the evacuation strategy formulated by the model can ensure good evacuation efficiency and avoid areas with high nuclide concentrations during the evacuation process, thereby reducing the radiation exposure of personnel. The structure of this paper is as follows. Section 2 presents the algorithm of the model. Section 3 presents an application example, provides a summary and discusses the limitations of the model.

2 Model Description

This section proposes an emergency evacuation model that can avoid areas with high nuclide concentrations in nuclear accident evacuation. Firstly, a modified Gaussian puff model is introduced. The results of the modified model are more consistent with the diffusion of radioactive pollutants in nuclear accidents. Then, an A-star algorithm based on nuclide concentration and traffic pressure cost is designed to formulate the optimal path planning under nuclear accidents.

2.1 Modified Gaussian Puff Model

In this paper, a modified Gaussian puff model describing the instantaneous concentration of nuclides is used to preserve the time characteristics. For the classical Gaussian puff model, the radiation source is located at the origin of the coordinate system. The direction of the ambient wind is the positive direction of the x-axis. The positive direction of the z-axis is vertically upward. Then, the radiation concentration at the space-time coordinates (x, y, z, t) is given by

$$\boldsymbol{C}(x, y, z, t) = \frac{Q}{(2\pi)^{1.5}\sigma_x\sigma_y\sigma_z} exp\left[-\frac{(x-ut)^2}{2\sigma_x{}^2}\right] exp\left(-\frac{y^2}{2\sigma_y{}^2}\right)\left\{exp\left[-\frac{(z-H)^2}{2\sigma_z{}^2}\right] + exp\left[-\frac{(z+H)^2}{2\sigma_z{}^2}\right]\right\} \quad (1)$$

Where $\boldsymbol{C}(x, y, z, t)$ is the nuclide concentration. x, y, z are locations. t is the time from the appearance of the puff to the present. Q is the source strength. u is the wind speed. $\sigma_x, \sigma_y, \sigma_z$ are dispersion coefficients, and there are many ways to get the value. This article uses the empirical formula recommended by the Chinese national standard. H is the height of the release source.

Assuming that the atmosphere is uniform and stable, in the case of atmospheric turbulence, the process of gradual deposition of radionuclides under the action of gravity is called the dry deposition process of radioactive pollutants. The height of the radionuclide is mainly determined by the settling velocity of the radionuclide particles. The settling velocity of radionuclide particles mainly depends on the influence of gravity and diffusion resistance, and the following formula can be obtained from the Stokes formula

$$V_s = \frac{\rho g D^2}{18\mu} \quad (2)$$

where V_s is the settling velocity of radioactive particles. ρ is the density of radioactive particles. g is the acceleration due to gravity. μ is the atmospheric viscosity coefficient, which can be $1.8 \times 10^{-5} Pa/s$. D is the diameter of radioactive particles, and I131 is taken as an example in this paper. The deposition of radionuclides can be regarded as the center line of the puff moving downwards, and the effective height of the source is $H - V_s t$

Precipitation will have a certain cleaning effect on radionuclide particles or aerosols. As the rainfall progresses, radionuclides are deposited on the ground. We represent this effect with a correction to the source strength.

$$Q_{wet}(t) = Qexp(-aI^b t) \tag{3}$$

In the above formula, I is the precipitation intensity in mm/h. a, b are empirical constants, which are taken according to the types of radionuclides. If the nuclide contains iodine, take $a = 8 \times 10^{-5}$, $b = 0.6$. For nuclides without iodine, $a = 1.2 \times 10^{-4}$ and $b = 0.5$.

After a nuclear accident, the released radionuclides conform to the law of decay, and the source strength correction formula is as follow

$$Q_{decay}(t) = Qexp\left(-\frac{ln\,2}{T_{1/2}}t\right) \tag{4}$$

where $T_{1/2}$ is the half-life of the radionuclide.

The final form of the Gaussian puff model considering dry deposition (gravity deposition), wet deposition (rainwater erosion) and nuclide decay is

$$\boldsymbol{C}(x,y,z,t) = \frac{Q}{(2\pi)^{1.5}\sigma_x\sigma_y\sigma_z} exp\left(-\frac{ln\,2}{T_{\frac{1}{2}}}t - aI^b t\right) exp\left\{-\left[\frac{(x-ut)^2}{2\sigma_x{}^2} + \frac{y^2}{2\sigma_y{}^2}\right]\right\} \cdot \left\{exp\left[-\frac{(z-H+V_s t)^2}{2\sigma_z{}^2}\right] + exp\left[-\frac{(z+H-V_s t)^2}{2\sigma_z{}^2}\right]\right\} \tag{5}$$

A point source that releases continuously can be viewed as releasing a transient puff over a small period of time Δt. The sum of the concentrations of multiple puffs at a point is the concentration of a continuous point source at that point. Therefore, it can be transformed into a continuous point source diffusion model according to the form of the instantaneous puff model:

$$\boldsymbol{C}'(x,y,z,t) = \sum \boldsymbol{C}(x,y,z,t) \tag{6}$$

$\boldsymbol{C}'(x,y,z,t)$ is the continuous point source concentration. $\boldsymbol{C}(x,y,z,t)$ is the instantaneous power concentration represented by Equation 5.

2.2 Evacuation Model

Some assumptions:

1. When organizing a large-scale evacuation, managers need to get people to certain locations and wait for vehicles;

2. These origins have enough vehicles to complete the evacuation. Vehicles will reach these origins and pick up pedestrians at a certain arrival rate;
3. During emergency evacuation, traffic control will be implemented on the road, and vehicles will not be restricted by traffic lights. Vehicles traveling from the previous road section immediately enter the next road section.
4. Shelter is the evacuation destination.

As most researches did, we construct an undirected graph based on roads. It consists of vertices in the map and links between vertices. The form is as follows

$$\begin{cases} G = (V, A) \\ V = \{v_i, 1 \leq i \leq n\} \\ A = \{(v_i v_j) | v_i, v_j \in V, A(i,j)\} \end{cases} \tag{7}$$

G is the road network graph of the city; V is a set of vertices belonging to G; A is a set of edges (lines connecting vertices) used to represent evacuation routes. A complete evacuation path can be expressed as a set of vertices.

Excessive traffic flow can have a negative effect on road transit times. The most commonly used function to describe road capacity is the Federal Highway Administration's road resistance function.

$$T(i,j) = T_0 \left(1 + \alpha \left(\frac{Q_{i,j}}{C}\right)^{\beta}\right) \tag{8}$$

Where T is the actual time required to pass the section. T_0 is the time required for free exercise to pass through the road section. $Q_{i,j}$ is the traffic flow. C is the maximum traffic capacity of the road section. α and β are undetermined parameters of the model, and the parameters $\alpha = 0.15$ and $\beta = 4$ are used in this paper.

We created a nuclide correction factor $I\left(\boldsymbol{C}\left(x_j, y_j, z_j, t_{o,j}\right)\right)$. The nuclide correction factor can be any monotonically increasing function of nuclide concentration that is always greater than 1. In this study, we set four risk levels according to the nuclide concentration, and the nuclide correction factor is a constant for each risk level. $t_{o,j}$ is the time to predict the nuclide concentration, we will explain it later.

The Astar algorithm is a classic pathfinding algorithm. He uses the valuation function to predict the cost of moving from the current node to the destination. In this way, a large number of unnecessary search paths can be omitted, and the efficiency is improved. The cost function $f(n)$ of the Astar algorithm is expressed as:

$$f(n) = g_I(n) + h(n) \tag{9}$$

$$g_I(n) = g_I\left(n_{parent}\right) + I(\boldsymbol{C}\left(x_n, y_n, z_n, t_{o,n}\right))T\left(n_{parent}, n\right) \tag{10}$$

$h(n)$ is the straight-line distance between node n and the shelter. $g_I(n)$ is the cost from the origin to node n, which is the accumulation of the product of the nuclide correction factor and the time of the road section. The increase of nuclide concentration will make $g_I(n)$ larger, so the calculated path will avoid the area with high nuclide concentration. In the process of computing the path, we also record the time $g(n)$ for passing the road. This is performed synchronously with calculating $g_I(n)$

without increasing the complexity of the algorithm. The specific iterative process is consistent with the classic Astar algorithm.

After calculating the path from each origin to the shelter, each origin will choose a path with the shortest evacuation time, that is, the path with the smallest $g(n)$. After the route of each origin has been determined, evacuation will continue for a period of time. The period for recalculating is T_p. In order to ensure that all departing vehicles are safe during this period, the independent variable $t_{o,j}$ in the nuclide correction factor has the following form:

$$t_{o,j} = t + g(j) + T_p + T_s \tag{11}$$

where t is the current time. $g(j)$ is the time required to travel from origin o to node j. T_s is a small value, a safety margin.

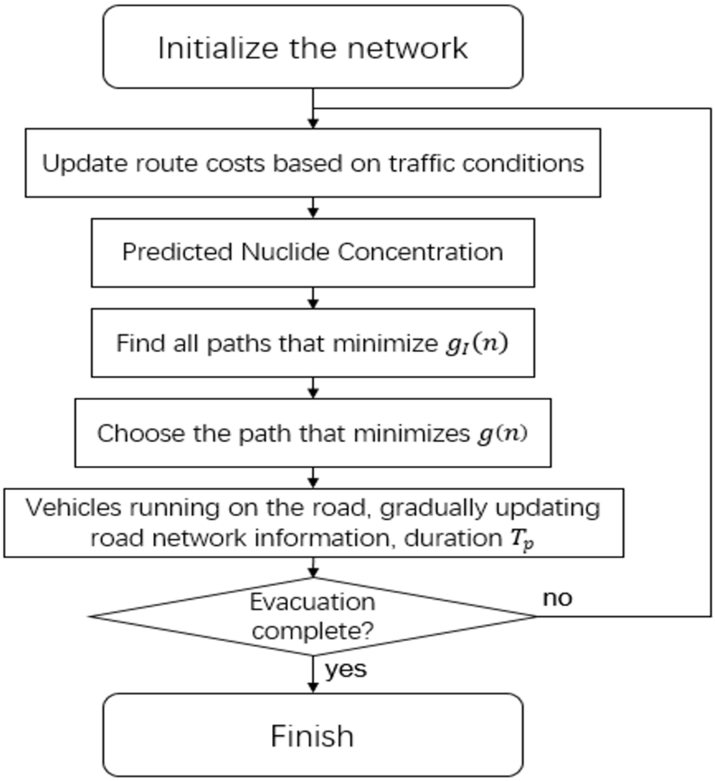

Fig. 1. Schematic diagram of the algorithm flow chart of the emergency evacuation model under nuclear accidents.

3 Application and Conclusion

Taking the Qinshan Nuclear Power Plant as the application scenario, the evacuation simulation is carried out. According to the population of Qinshan, per capita private car occupancy rate and public transportation capacity, the number of people, initial vehicles and vehicle arrival rate at each origin are set.

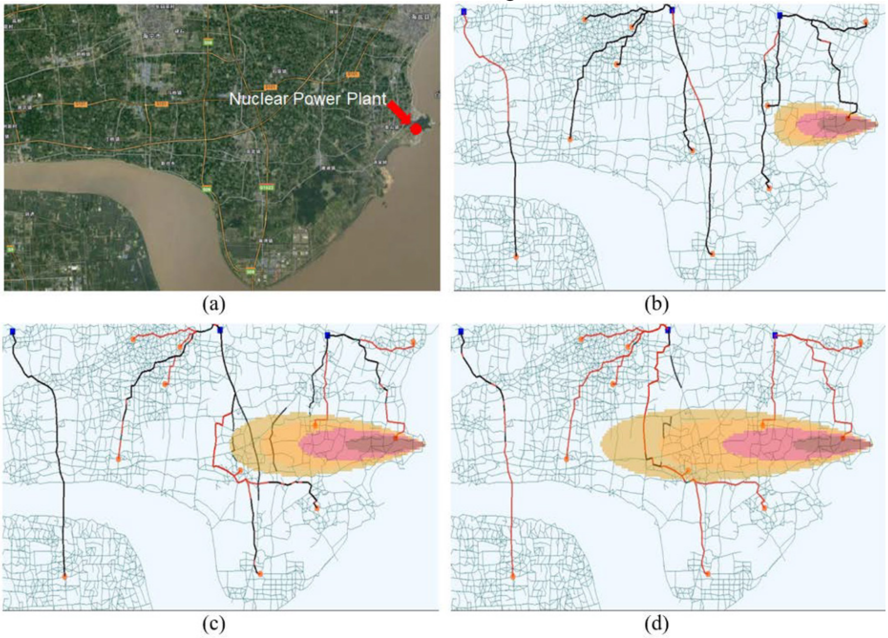

Fig. 2. (a) Satellite image of Qinshan Nuclear Power Plant and surrounding areas; (b) t=480s; (c) t=1200s; (d) t=1500s.

The red line in the figure indicates the path currently selected by the vehicle starting from the origin, and the black line indicates the vehicle on the road segment. With the spread of nuclear pollution, evacuation routes are also shifting to safe locations. This phenomenon means that our algorithm can make evacuation routes avoid areas with high nuclide concentrations. The calculation time of the model is much shorter than the simulated evacuation time, which meets the use of emergency situations.

This paper presents an emergency evacuation model in nuclear accident. The evacuation path of this model avoids the high nuclide concentration area, and the calculation time is short. However, our work still has some limitations. The value of nuclide correction factor is formulated according to the standard of a radiation work manual, which lacks sufficient scientific basis. In the model, reducing the calculation period T_p can improve the calculation accuracy and the utilization rate of the traffic road network, while increasing T_p can reduce the calculation time, which is a contradictory problem. For networks with different numbers of vertices and different ranges, it may be necessary to adjust T_p to obtain a better usage effect. In the future, more scientific nuclear risk assessment can be used to construct the expression of nuclide correction factor, or to explore a more reasonable and faster evacuation model.

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