SIMULATION OF OCCUPANTS EVACUATION FOR THE DISASTER PREVENTION AND MITIGATION IN AN URBAN AREA

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ABSTRACT

Economics, populations and buildings are more and more concentrated in the modern urban areas in China with the development of urbanization. While most of the urban areas are located in disaster prone areas, it is important to develop an effective response system for the occupant evacuation when a disaster occurs. This paper presents a system which is developed by the authors for the simulation and analysis of occupant evacuation and rescue commanding under disaster condition based on GIS. Information of geographical and attribute are stored in the computer to form an integrated urban disaster database. Layers including classified data can be overlaid according to the requirements to evaluate the satisfactory of the space lands for evacuation, the required evacuation time for the occupants in a specified area, or to simulate the evacuation process. Different models are introduced for different types of evacuation. The microcosmic model is applied to evacuation from small areas; the macroscopic model is applied to evacuation from main roads; the mixed model is applied to evacuation from secondary roads. The system architecture, the theoretic principles of the evacuation model and the development details of the system are presented.

KEYWORDS

Disaster prevention and mitigation, occupant evacuation, computer simulation, optimization, transportation.

1. Introduction

Populations and buildings are concentrated in the most urban areas in China, while 70% of the urban areas of China are located in the disaster prone region. With the development of urbanization and the expansion of the populations, the frequency and magnitude of disasters increase significantly, which contributes to the severe challenge that urban community safety

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system has to face (Xu et al. 2004). It is important to develop an effective response system for the occupant evacuation when a disaster occurs.

The studies on the evacuation behavior of the occupants have begun since 1970. The earlier studies were absorbed in the behavior of occupants under normal condition (Predtechenskii VM et al. 1978, Fruin JJ 1971). During the last thirty years, a lot of evacuation models have been developed to help managers to constitute emergency evacuation plans and disaster prevention layout (S.Gwynne et al. 1999). The evacuation models are divided into two types: macroscopic and microcosmic. FEgress is a macroscopic model which was developed for evacuation of large emporium underground. The position where disastrous accidents occurred is taken into account in this model but the spread of disasters is ignored while it is applied to predict occupant evacuation in an area. Other models, for example, WAYOUT, EXITT, EVACSIM and EVACNET etc. are also macroscopic models. EVASIM is a microcosmic simulation model which uses scatter event simulation means to express human behavior under catastrophic conditions. Other models, for example, EXODUS, EGRESS etc. are also microcosmic models. The evacuation routes in these microcosmic models are determined by designers of the models or by the shortest distance of routes. However, there will be uncertainly obstacles in the shortest evacuation routes under catastrophic conditions. Thus users will be unable to get correct data about evacuation time, traffic flow etc.

Several models have been developed for hurricane evacuation traffic flow analysis. It is interesting to note that many of the early models were initially developed to plan for other civil defense emergencies such as nuclear missile attacks and nuclear power plant accidents. One of these programs, NETVAC (NETwork emergency eVACuation) uses established flow relationships to estimate flow at the macro, or vehicle-group, level (Sheffi et al. 1982). It estimates queue formation, allows for dynamic route selection, and permits manipulation of the network in terms of alternative intersection controls and lane management strategies.

MASSVAC (MASS eVACuation) is also a macro-level model using traffic flow relationships in its structure (Hobeika et al. 1985). It has been used in several applications, including a test of operational strategies for hurricane evacuations in Virginia (Hobeika 2002).

DYNEV (Dynamic Network Evacuation) is a macroscopic model developed in the early 1980s in response to the concern of nuclear power plant accidents, employing principles of flow continuity and flow dynamics (KLD 1984). The model is capable of determining the impact of alternative traffic control, network capacity, and evacuation demand. It provides estimates of flow, density, and speed on each link in the network.

A more recent model of evacuation is OREMS (Oak Ridge Evacuation Modeling System) (ORNL 1995). Developed by the Center for Transportation Analysis at the Oak Ridge National Laboratory (ORNL) using the CORridor SIMulation (CORSIM) platform, OREMS was created to simulate traffic flow during various defense-oriented emergency evacuations.

Based on the analysis of the existed studies, a new occupant evacuation model, a vehicle model and a mixed model are introduced in this system. By employment of these models, the authors also developed a system for the emergency response and commanding in urban area when a hurricane occurs based on GIS technology. The system has the functions as follows: the hurricane induced influence region prediction, simulation of occupant evacuation and management commanding, traffic flow prediction, and road network evaluation and optimization of evaluation plans. All these functions provide decision-making support for the making of disaster prevention layout and emergency response plan for urban area. In the following sections, the system architecture, the evacuation models and the technical solutions are presented in details.

2. System architecture

Facing the new challenges in the field of urban community safety, we need new technologies and measures to establish an effective urban community safety system which safeguards cities' development. Disaster prevention needs to be taken into account in the layout of the construction of new urban area and in the plan of the reconstruction of old urban areas. Effective emergency plan for evacuation and harmony are required while the disastrous accidents take place as we hope minimize the loss. Therefore, managers and designers need a computer system which is able to get the correlative information, to make the layout of an urban area and emergency plan, and to simulate the projects to check them up.

Geographical information system (GIS) is new geographical tools with both the quantitative analysis and the space analysis, integrating graphics, images, attributes and special model. By employment of GIS technology users can not only obtain spatial quantitative information but also express results of numerical value analysis as spatial figures. Meanwhile, GIS holds out both numerical thought and spatial thought. Hereby, our system is developed based on GIS platform ArcGIS. ArcGIS Engine is one of the ArcGIS components which is independent of ArcGIS Desktop. The system is developed based on ArcGIS Engine. The logical framework of the system is shown in figure 1.

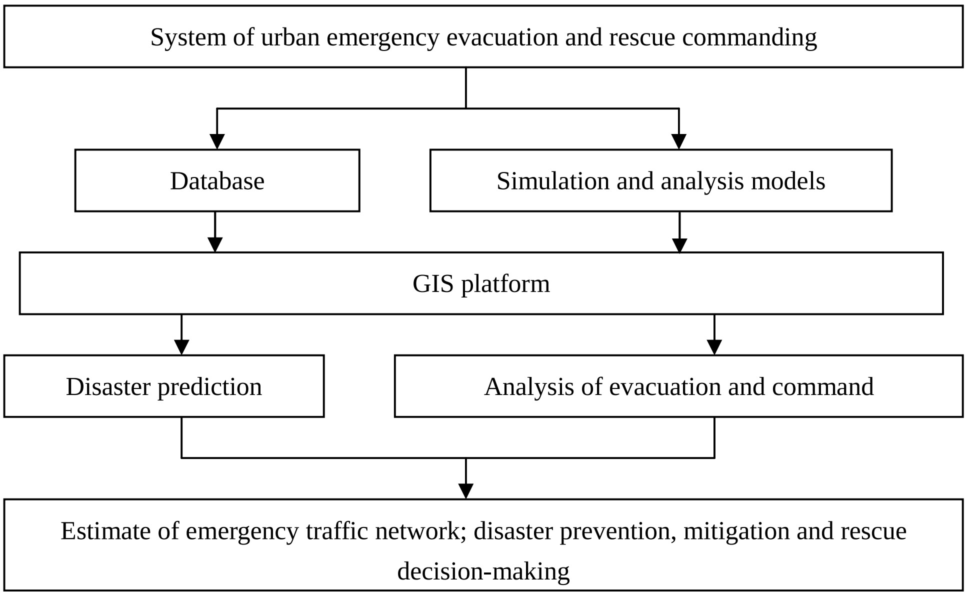

Figure 1 the logical framework of the system

The urban geographical information database, attributes database and evacuation simulation models are integrated on the GIS platform. The system unifies the functions of disasters dynamic prediction, emergency evacuation simulation and rescue commanding in a friendly interface.

Geographical, social, economic and population information of a city such as roads (name, length, surface qualities, transit ability etc.), population, building (name, function, capacity, exits etc.), storages, refuges, park, rescue organization (position, capability, type etc.) are preserved in database. Moreover, users can get safety statutes and emergency plan from database. These data are associated with digital maps. Users can edit both database and digital maps to update these data and require data what needed.

Evacuation models are the core of the theories supporting the system. Dynamic disaster prediction, data inquire, evacuation simulation, visualization of simulation results and decision-making supports are the primary functions of the system. The details are below:

Occupant evacuation and rescue commanding are divided into 3 parts: inside a small area, research focus on occupants; on secondary roads linking small area with main roads, research focus on both occupants and vehicles; on main roads, research focus on vehicles. The system is able to simulate these 3 types of scenes. As evacuation process is an ordinal process, evacuation simulation should keep order as follows: occupants evacuate from a small area; both occupants and vehicles mixed evacuate from secondary roads; occupants and vehicles divided evacuate from primary roads. The results of the former step are the initial condition of the latter step. Users may also set the initial condition according to the requirements. Users can optimize the evacuation plan and rescue commanding according to the results what simulation exported, including the difference of time when evacuation command is issued in each small area, traffic control on certain roads, changing evacuation termini, command succor vehicles etc. Rational evacuation plan is based on data about evacuation time and traffic status what are obtained from 3 steps simulation.

3. Occupant evacuation model

Evacuation models are divided into two types: macroscopic and microcosmic. The evacuated crowd is looked as a whole in macroscopic models. Macroscopic models abstract detailed ichnography to network map, considering capacity of nodes, transit capability, density of flux, velocity etc. Users may obtain evacuation time of crowd using macroscopic model. Macroscopic models don't require powerful computational capability as a result of its simple conformation so as to they suits the request of large-scale evacuation simulation. Meanwhile, macroscopic models have their defects. Some spatial information, effect between individuals and individual characteristics will lose during the model running as the models are abstract. Microcosmic models fill the gaps of macroscopic models as the models are created based on individual. The individual determine his/her actions according to the circumstance and the characteristics of his/her own. Microcosmic models require stronger computing capability than macroscopic models. The model will be awkward when there are a large amount of occupants in the scenario, especially the evacuation is carried out in a whole area of a city.

Considering the request of reality-degree, complexity and computing capability, we use different models in different types of evacuation. The microcosmic model is applied to evacuation from a small area; the macroscopic model is applied to evacuation from main roads; and the mixed model is applied to evacuation from secondary roads. The detail description is below.

Occupant evacuation model of the system is created based similar cellular automata principle. The model not only considers holistic movement characteristics and physical characteristics of field, but also regards every individual as an active factor, considering his/her actions, such as choosing exit, judging surrounding etc. The model abstracts detail space as a simulative space based on plane-space coordinates. Characters of individual action in different time and under diverse surrounding are controlled by rule-process functions. Both impact and restriction between individuals determine the transformation of the whole model space. Thereby, both the holistic characters and the individual actions are represented synchronously in the model. The model has the merit of rule-based controlling simulation directly other than the method using differential equation for transition. The factors described above which influence the actions of individuals can be divided into two types: the influences of static physical scenario and the influences of dynamic surrounding.

Firstly, geometrical configuration is the most important factor influencing individual actions. The primary action of occupants in evacuation process is to choose the shortest route to the nearest exit. Many evacuation models describe space information of structures by using concept of field. A parameter R, called *distance field*, is introduced in these models.

Any point (i, j) not occupied by obstacle in evacuation area has its distance field intensity *R*, of which value depends on the linear distance from the point to the nearest exit *L* (Xu 2003). Thus, the value *R* of the points where exits locate is 0. Agent representing occupant will move along gradient direction of the distance field intensity, namely from the position having higher value *R* to the position having lower value *R*. Most of models make *R* proportional to *L*. It is suitable only in area where not obstacles are. The influences of obstacles are taken into account in our model. The model divides evacuation area according to the conformation of the area. For example, as figure 1 shows, the whole area is divided into 3 sub-areas a, b and c. M_1 is regarded as an exit from b to a; M_{21} and M_{22} are regarded as exits from c to b. A is exit of whole area. The two black rectangles are two buildings. W_1 and W_2 are exits of the two buildings. During the evacuation period occupants escape from W_1 and W_2. Considering actual distance to the exit A, we assign *R* to every sub-area, R_a=1, R_b=2, R_c=3. Occupants escape from the sub-area having higher value *R* to the sub-area having lower value *R*. In this way, the problem individual was incapable of bypassing obstacles has been resolved.

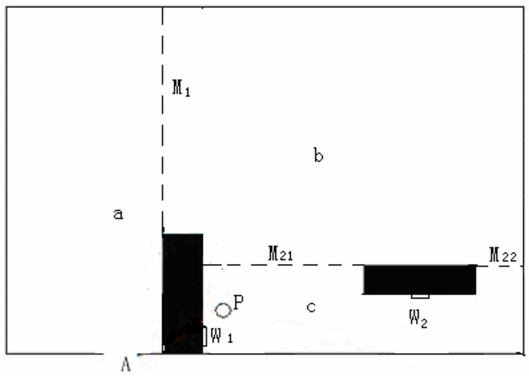

Figure 2 separation of sub-area

Secondly, there are some other factors influencing actions of occupants. For instance, the influences of dictate, command and others surrounding. These factors will change as time pass by. Therefore, another parameter *D*, called *dynamic field*, describing dynamic factors is introduced in the model. Similarly as distance field, any point (i, j) in evacuation area has a dynamic field intensity *D*, of which value depends on the attraction of the point. For example, there are two exits A and B in an evacuation area. Exit B has a clear sign but exit A doesn't. Then the value *D* of exit B is lower than exit A, namely exit B will attract more occupants in evacuation process.

4. Vehicle evacuation model

This system is designed to simulate channeling the vehicles on the main road of the city based on the hydrodynamics theory. The models of LW (Lightill & Whitham) and Payne are generally introduced in the research of traffic flow involving the way of hydrodynamics. The LW model is used in the conditions of large traffic flows and low speeds but the Payne model is opposite (Leo and Pretty 1992, Michalopoulos et al. 1984). This system simulating the channeling traffic flows of the main roads are based on the LW model because the vehicles are crowded while being evacuated.

In the LW model, supposing the traffic density (the numbers of vehicles in the unit length) of a single-way section is k, the traffic flow rate (the numbers of vehicles passing the fixed point in the unit time) is q, x is the coordinate of the distance of the highways, t is the time, so the traffic flow rate $\frac{\partial q}{\partial x}dx$ of the control unit with the length dx in the position in the section of x in coordination is equal to the deduction rate $-\frac{\partial q}{\partial x}dx$ of the vehicles in the control unit. According to this, a continuous equation can be set up:

$$\frac{\partial k}{\partial t}+\frac{\partial q}{\partial x}=0 \tag{1}$$

Supposing u is the average speed of the traffic flow, u_f is the free flow speed, q is the traffic flow volume, according to the definition of the continuous unit:

$$q=k\cdot u \tag{2}$$

u--k relation equation:

$$u(k)=u_f\cdot(1-\frac{k}{k_0}) \tag{3}$$

A macroscopic continuous model—LW model can be made combining equations (1), (2) and (3).

The road network is first abstracted into the simulated network complying with the LW model. In this model, lines represent the road segments and nodes represent the intersections and the exits for the vehicles or people of the sub-areas near the roads. The evacuation traffic flows are also simulated according to the traffic flow volumes of the main roads from the sub-roads and the maximum traffic flow volumes of the roads to the evacuation destinations. In some road sections where the traffic volumes are so high and traffic jams are likely to happen, the vehicles are controlled and decentralized in order that the routes to the evacuation destination can be properly distributed.

5. Mixed evacuation model

The mixed-run between motor vehicles and non-motor vehicles and foot passengers is a general phenomenon in the transportation of China. The non-motor vehicles and foot passengers run in low speeds and their running routes changes frequently, which affect the motor vehicles greatly. Especially in time of emergency, such as the times when the traffic volumes are very high, the mixed-run decreases the road transiting capability and the difficulty of evacuation is much larger. The following model is involved in the system.

According to the practical transportation conditions in China, some conditions of the models are supposed: 1) the mixed-run phenomenon is only available in the conditions of sub-roads with less than 2 lanes because the speeds of vehicles on the main roads are very high and are properly separated from the passengers. 2) There are no separating facilities betweens the lanes for the motor vehicles and non-motor vehicles.

Then, the motor vehicles and non-motor vehicles (including passengers) run in their own lanes and the vehicles are separated into masses automatically in the case of low traffic volumes. The non-motor vehicles and passengers may come into the lanes for motor vehicles, when the distances between the head of the K th motor vehicles masses and that of the K+1 th's are large enough for non-motor vehicles and passengers to run out safely (open section), if their volumes are very high. After a period, the passengers and non-motor vehicles leave the motor lanes, while the motor vehicles accelerate gradually and become dissipation wave. The times of the motor lanes being interrupted can be calculated as follows (Xu 1991):

$$N_0 = Q \cdot P_0 = Q \cdot e^{-\frac{Q \cdot \tau}{3600}} \qquad (4)$$

Q is the motor vehicles volumes (/h), τ is the minimum headway, P_0 is the probability of open section.

Appear of *open section* only means that there are opportunities for passengers and non-motor vehicles to come in, but they are not sure to do so unless the density of them θ is large enough. Thus, the intrude possibility of the passengers and non-motor vehicles P_b is related to θ. The road service levels for the non-motor vehicles have been evaluated in some materials as shown in table 1.

Table 1 road service levels for the non-motor vehicles (TEHECA 1998)

Grade of service level	1	2	3	4
Area occupied by vehicle (m^2/vehicle)	>9.0	7 ~ 9	5 ~ 7	<5
Status of traffic flow	Fully free	Free	Steady flow	Unsteady flow constrained
Probability of occupation P_b	0	0.25	0.5	0.75

The intrude times of the motor lanes in the whole research section N_b can be calculated as follows:

$$N_b = P_b \cdot N_0 = Q \cdot P_b \cdot e^{-\frac{Q \cdot \tau}{3600}} \qquad (5)$$

When the motor vehicles volumes are high, the traffic jams may happen and the vehicles can be described according to the *Car-Following* model. Passengers and non-motor vehicles run in their own lanes.

In the simulation, the evacuation data of the residential areas close to this road (the flow rate and evacuation time of the exit etc.), the distributions of vehicles and the traffic volumes of the entrance of this section are obtain automatically by the system after a road section is chosen. The evacuation time, vehicles and population density, the volumes of people and vehicles at the exit of this section can be calculated according to the methods above, which can be used as the original data for macroscopic evacuation of main roads.

The transportation of people on the roads involving motor vehicles for evacuation has also been considered while modeling. Using the motor vehicles to evacuate the mass of people, the densities of passengers and non-motor vehicles can be decreased and hence their disturbance to the motor vehicles is much smaller. Besides, the time spent on getting on the vehicles has also been considered.

6. Conclusion

Modern cities have higher risk of disastrous accidents due to numerous population and concentrative fortune. Congested status caused of improper design of evacuation route and exits and failing management will delay rescue work. Researches how to select correct evacuation routes, where to set signs for evacuation is proper and how to plan the evacuation time have important significance.

The results obtained from the studies show that the occupant evacuation model, the vehicle model, and the mixed model presented in this paper are suitable for the development of the emergency response and commanding system for urban area when it is attacked by a hurricane. The system is designed for the application to Santou city of China. Shantou is a coastal city in the south of China, having about 1,000,000 populations. Hurricanes affect the city every year in summer or autumn. Therefore, the system is useful for this city. Figure 3 shows an interface of the system when an evacuation simulation is performed.

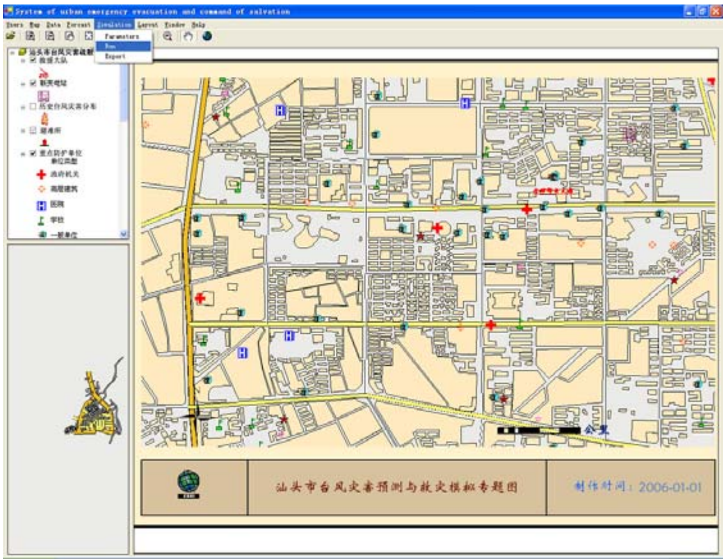

Figure 3. Interface of system

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