Advances of Some Recent Mechanical Models on Emergency Evacuation

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Abstract: Since the rapid development of the society, the living area of human beings has become much wider and more complicated. Over the past decades, crowd evacuation of public places has always been a hot topic in terms of public security studies. From the early twentieth century, emergency evacuation models have emerged, developing from statistic methods to mathematical models and recently, computer simulation models. In this paper, the classic mechanical models from the very beginning are reviewed. Utilizing the available literatures, we compare the nouveau models with the classic ones and highlight their advances. The key observation is that the consideration of individual and collective behaviours of the crowd and the appropriate scale of the model should have significant influences on the modeling performances. Finally, the Smoothed Particle Hydrodynamics models are introduced as a recent advance, which takes into consideration both the individual and collective behaviours of the crowd.

Keywords: Evacuation models, numerical simulation, SPH.

1. INTRODUCTION

Emergency evacuation has under the spotlight over the last few decades, as the rate of development of social civilization skyrocketed. Since the victory of Second World War, owing to abrupt increase in population, it has become more frequent for a considerable number of people to gather in a relatively small area. Hence, the safety issues that are brought about by the growing complexity of building construction make it especially important to study the concept of emergency evacuation. In general, there are two major types of evacuation models: the macroscopic models and microscopic models. Since the 1980s, with the help of digital computer simulation technology, numerous emergency evacuation models have been developed, especially in the field of network emergency evacuation modeling, which has over 20 models either complete or under development [1].

Nowadays, people require a more emulational model that better represents a realistic situation of evacuation. Hence, the consolidation of basic modeling methods becomes a trend: we combine the macroscopic and microscopic simulation models (SPH, Smoothed Particle Hydrodynamics model) [2] with the fine and coarse network space division methods [3]. In addition, agent-based models [4, 5], which highlight the influence of psychological effects [6], interactions between individuals [7], information sharing [8], pre-evacuation time [9, 10] and collective phenomena [11, 12] predominates the development of emergency evacuation models. Besides, the GIS (Geographic Information System)-based modeling technology [13] advances in the field of risk mapping methods [14].

In the following sections, we will review a number of classic models. In Sec. 3, the advances of recently developed models will be discussed. In Sec. 4, we discuss some practical applications of these aforementioned models and introduce a new model using the SPH theory, which absorbs the key aspects of said models. Lastly, some concluding remarks are provided in Sec.5.

2. CLASSIC MODELS

2.1. Overview of Basic Models

2.1.1. Macroscopic Models

The most representative macroscopic model is the hydrodynamic model, which applies the characteristics of fluids to the crowd flow model and uses a partial differential equation to describe the time-varying crowd density and velocity. Hughes applied the flowing continuum model to reproduce the comportments of a diverse group of pedestrians [15]. In order to understand the high-density flow evacuation mechanism, Hughes has elicited the equations of motion governing the two-dimensional flow of pedestrians, which are derived for flows of both single and multiple pedestrian types [16]. In general, the macroscopic models employ the concept of continuum mediums to obtain the possible descriptions of gradient. Personal behaviour is usually too difficult to be considered in these models.

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E-ISSN: 2409-9848/14

2.1.2. Microscopic Models

While macroscopic models ignore the differences between each pedestrian, microscopic models are based on individual difference. Based on this, on account of the space partition method, the whole catalogue can be classified into two subclasses: continuous models and discrete models, amongst which the Social Force model is the most representative of the former and Cellular Automata model (CA) is that of the latter.

Helbing [17] first proposed the concept of the social force model based on Newtonian mechanics, which describes a repulsive force between a pedestrian and an intruder. The intruder could be another pedestrian or an obstacle. When “invaded”, the pedestrian tends to avoid the collision between himself and the intruder, which affects his velocity. Helbing [18] assessed the features of escape panic, which are essentially crash, crush, treat, and viewable range. After simulating an escape from a smoke-filled room, he found out that uncoordinated motion in crowds would result in panic and jamming; in emergency situations, the increase of evacuation velocity and lack of patience would cause jamming and reduce the evacuation efficiency; herding behaviours are instinctual and exist extensively during evacuations of a high-density crowd.

CA models exhibit non-linear speed transitions and self-organized criticality that are present in actual shock waves [19]. Pedestrians’ movements are extremely flexible and their walking speeds and accelerations are frequently adjusted [20]. This model discretizes both time and space and performs synchronous calculations. High-dimension is also a characteristic of CA models.

2.2. Limits of Classic Models

Macroscopic models are applicable for high-density crowds in which individuals are fairly similar, which is why the models are adapted to simulate the overcrowding situations, en account of its base of continuum. Its simulation precision is outstanding. However, when the crowd density is low, hydrodynamic models are not the best choice. Furthermore, the fluid mechanics equation is not straightforward to understand nor flexible to apply [21], which becomes a huge obstacle of the application of this genre of evacuation models.

Microscopic models are sometimes suitable for relatively low-density crowd. Social force model is already complicated to understand, yet large calculation quantity makes it impossibly more difficult to apply, especially in large-scale evacuation situations. CA has a high speed of simulation, however, it lacks of consideration of interactions between agents and difference between individuals. It is hard to reproduce collective phenomena and self-organized phenomena. CA is neither flexible nor conductive to different solutions when given similar stimuli.

3. OVERVIEW OF THE ADVANCES OF NEWLY APPEARED EVACUATION MODELS

3.1. Optimized Models Based on Classic Models

Hu [22] developed the classic Social Force model and optimized its algorithm in using the static force grid and locality principle to overcome the aforesaid drawbacks, which reduces the complexity in replacing the dimension, n-2. by n. At the same time, it is more realistic to reproduce the performance of pedestrians.

Kong [23] applied the queuing theory to Social Force model in order to have an academic view of the queuing phenomena during evacuation under fire condition, which determines the most appropriate width of exit of different buildings.

Lu [24] proposed a new crowd evacuation model combining the characteristics of agent behaviours and Cellular Automata model. The new model includes mainly four sub-models: agent’s response of fire alarm model, agent’s evacuation speed model, group movement model and exit selection model. This model, which integrates different agent behaviour, agent’s reaction time and group movement, makes the classic CA model more realistic.

Chen [25] proposed a model that corrects the oscillation problem of the speed of pedestrians of Social Force model, in importing an impact index of relative speeds between pedestrians that measures or quantizes the impact between agents. That is to say that this advanced model strengthens the agent’s subjective initiative during simulation. However, the import of impact index is a rapier, on the one side, it reduces the collision between agents and solves the problem of oscillation of speed. On the other hand, it aggravates congestion during evacuation. As a result, for every simulation, we have to find the best index so as to avoid its drawback.

Cao [27] proposed an Agent-CA crowd evacuation model based on multi-agent and Cellular Automata technology according to the behaviour characteristics and rules of evacuation. It realizes the individual differences through the design of evacuation behaviour strategy as evolution rules, for the sake of the reflection of individual character, mental effect and physical strength during evacuation.

Hughes [26] proposed the idea of “thinking fluids”, which develops the classic hydrodynamic model in the field of crowd motion. He took the capacity to think of a crowd into consideration; for example, pedestrians would judge their destinations and their process of reaching their goals. They would estimate the remaining time and distance to get to the destination, which makes the advanced model more realistic.

3.2. Other Recent Models

Peter [28] proposed the first computer model ‘SIMULEX’ that takes advantage of the relation between walking velocity and inter-person distance. In the field of simulation of escape movement of thousands of agents through large-scale and geometrically complex spaces, this model has an outstanding performance.

Heï geas [11] presented a physically based interacting particles model, focusing on global collective phenomenon, such as flowing and jamming. It associates diverse dynamic actors *via* elementary non-linear dynamic interactions, which allows the reproduction of complex and various dynamic behaviours.

Shi [29] suggested a new concept of evacuation route calculation system, which combines geometry (visualized but difficulty to extract paths) model and logical model (simple and used for calculation). Based on the basic search algorithms, it considers the timeline of evacuation. In spite of spatial information, it also takes non-spatial information into consideration. The use of the adaptive search tree makes the train of thought of this system even more clear.

Hoberka [30] developed MASSVAC as a macro-simulation model, originally for hurricane evacuations. It applies both macroscopic level and microscopic level of analysis. The former provides the maximum evacuation time estimation under different conditions, and the latter simulates a small network in detail, which shows candidacy for traffic congestion.

Church [14] presented an optimization model: critical cluster model, which can be used to identify small areas or neighbourhoods where there is a high ratio of population to exit capacity. This model can map event-risk and recognize the potential for an evacuation problem by integrating the concept of emergency planning zones (EPZ) and using the geographical information system (GIS) which was used to define the road network, population and area being evacuated.

Han [31] developed a one-destination model for evacuation-traffic distribution and assignment. This easy-implanted model is suitable for the countywide and large-scale evacuation cases and reduces the overall evacuation time by more than 60 percent, which makes up blanks of the attention to the location flexibility.

Shen [9] presented an evacuation simulation model (ESM) for simulating evacuation in building fires, as a network model consisting of stocks connected by flows. This coarse network model simplifies inputs and makes the running time during simulation shorter, in comparison to classic network models. It is also capable of tracing the occupants. By setting different pre-movement time based on the building occupancy and determining the tenable duration for the compartment, the simulation model becomes more realistic.

Lo [32, 33] described a special-grid evacuation model (SGEM), which takes advantage of a flow function generated by a gas-lattice model and resembles the fine network approach. This model records the geometrical location and velocity vector of each individual at each time step, and also the trajectory and the evacuation pattern.

Cepolina [12] proposed a phased movement model used mainly for identifying the egress times and routes, which is able to reproduce the capacity drop phenomenon. Hence, it can assess the evacuation time by taking into account the bottlenecks under oversaturated conditions. This model contributes to the simulation of the egress dynamics by a given Route-Alarm Time schedule plan. In completing the model, a bouncing ball conception is introduced.

Pelechano [8] developed an agent-based model in adding individualism into Helbing’s model. Agents here have different local motions depending on their roles: trained personnel, leaders and followers. Communications between each individual are available and the author even uses a 3D viewer. This model has contributed to improving evacuation rates.

Pan [4] proposed a multi-agent based model that considers non-adaptive crowd behaviours from three levels: the individual, the interactions among individuals, and the groups from both the macroscopic regard and microscopic view.

4. DISCUSSIONS AND REFLECTIONS

4.1. Contributions to the Guidance of Emergency Evacuation

Evacuation capacity is an important index to decide the quality of a building or the reasonable structural arrangement of an area. The target of emergency evacuation models is to guide the architects, designers, and all the other decision makers of public services and facilities to set the best standards and reduce the probability of accidents.

4.1.1. Location of Bottlenecks

Bottlenecks appear usually at the locations where the stampede accidents occur frequently. Thus, finding the congestion points is an important job for public security. Chen [34] used an MGcc-based model to evaluate bottlenecks of stairs and corridors in a metro station. Moreover, some current emergency models visualise the trajectories of each individuals so as to find the bottleneck. The physically-based particle model of Heï geas [11], the SGEM model of Lo [32] and the multi-agent based framework of Pan [4] are used to record the trajectories of agents and the locate the bottlenecks building group or inside a building.

4.1.2. Optimization of Interior Structure of Buildings

The interior structure of buildings is usually a determining factor of the result of emergency evacuations. To find out whether the interior structure of a building is rational or not is very important not only for designers but also for decision makers of public affairs. Some current emergency evacuation models contribute to determining the best locations of communal facilities, like the best place for escalators in an underground station [22], the most appropriate width of exits (because the capacity evacuation is generally not a linear function of the width of exits [36]) or the most reasonable number of open exits in a building [35], as well as the design of staircases at a mall. In addition, it may be useful to put a column before the exits to avoid blockages. The objective in common of all the applications of emergency evacuation models is to optimize the function of a building and at the same time, reduce the cost.

4.1.3. Strategies of Guidance of Evacuation

With the help of computer simulation programs, we found some strategies to guide the evacuees to reach to the safe place as within the shortest and also get the largest number of agents away from danger. The computer model SIMULEX is capable of assessing the optimal route to exit [28], with the agent-based model, Pelechano [8] figuring out an optimal percentage of trained people among all the evacuees to make the evacuation time the shortest possible.

4.2. Smoothed Particle Hydrodynamics Model

4.2.1. Theory of SPH Model

Smoothed Particle Hydrodynamics is an advanced model of classic hydrodynamic model and classic social force model, in which the former was used to solve the astrophysical problems in open three-dimension space, and the latter is used to describe interactions between agents [2]. The main idea of SPH is that the gradient of one physical quantity of a point is defined by the influence of particles all around this point; meanwhile, it is also possible to define the individual behaviour of each particle. SPH model considers the flow of pedestrians as fluid in a macroscopic view, and at the same time, disposes the each individual separately by a microscopic method. Essentially, this model combines the advantages of both macroscopic and microscopic models.

4.2.2. Superiorities and Potential Applications

Recently we developed an open-source program *sphturb*, realizing the simulation of virtual evacuation situations by employing the SPH model [37-39]. Not only crowd collective phenomena can be explained or considered by the whole computer simulation system, but also interactions between each individual and obstacles can be treated. That is why SPH model is not in restraint of crowd size, density, categories or any other factors. The universality and imitation make the model more attractive to future applications.

With the help of this model, we are aiming to obtain a more realistic and accurate simulation result compared with the real world. We will then do the optimization of interior construction of a building in order to affirm the shortest evacuation time under emergency situations; it is also possible to introduce and determine the phased pre-evacuation time to different areas in order to make the right guidance to emergency evacuations.

5. CONCLUSION

The simulation of emergency evacuation is developing with a rapid speed to satisfy the increasingly strict demands. Classic models are limited for further studies, with drawbacks like the complexity and the limitations of their suitable occasions. Most of the current emergency models supply their shortcomings in a certain aspect and make the simulation more realistic and ready to apply in real situations. The appearance of SPH model has broken the barrier between macroscopic models and microscopic models, and opens a new perspective for evacuation simulation.

ACKNOWLEDGEMENTS

This work is supported by National Natural Science Foundation of China (11202013, 51420105008).

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Received on 23-10-2014 Accepted on 05-11-2014 Published on 19-11-2014

DOI: http://dx.doi.org/10.15377/2409-9848.2014.01.01.4