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# A stranded-crowd model (SCM) for performance-based design of stadium egress

Qingsong Zhang[a,*], Mao Liu[a], Caihong Wu[b], Guomin Zhao[a]

[a]*Research Center of Urban Public Safety, Nankai University, Tianjin 300071, PR China*
[b]*Tianjin Fire Research Institute of MPS, Tianjin 300381, PR China*

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**Abstract**

Stadium disasters statistic analysis indicated that egress congestion is the major cause of crowd stampede trampling and crushing incidents. In this paper a *stranded-crowd model* (SCM) for stadium egress is put forward with previous works. The empirical relation between density and velocity of crowd movement have been summarized, and then the crowd-flow rate as a function of density deduced. The paper presents experimental results for this model under emergency conditions and discusses the following observations: the data show egress stranded number of crowd for different time ranges and various relations of flow rate and density can be calculated; furthermore, comparing the results of different egress width with the same formula for the movement in a stadium straight passage. This comparison shows an unexpected conformance between the egress width and stranded number of panic crowd. Based on the results, SCM shows great value in dealing with stadium, especially 2008 Beijing Olympic stadium, egress performance design, selecting and optimizing of routes and so on.


*Keywords:* Stranded crowd; Performance-based design; Stadium egress; Crowd-flow rates; Evacuation

## 1. Introduction

Stadia have facilitated large crowds since their inception. Large population densities create potential for significant numbers of casualties and deaths should an untoward incident occur. Stadium disasters are rare, however they have resulted in approximately 3000 physical casualties over the last decade worldwide [1]. Individual incidents involve large numbers of casualties and hence have a greater impact on the community than less sensational incidents that occur more frequently such as car crashes [2].

In all, 34 incidents have been analyzed, which contributed to the resulting injuries and fatalities in stadium from 1902 to 2005 [1,3]. The major stadium incident types are stampede trampling and crushing, about 79% of total stadium incidents, which result in 90% fatalities (Figs. 1 and 2). The disasters of stampede trampling and crushing resulting from egress issues have 10 incidents and the numbers of casualties are 2177 during crowd escape and evacuation procedure under emergency. The incident characteristic is high density stranded crowd around narrow egress zone. Therefore, the stranded-crowd model (SCM) for stadium egress performance safety design was introduced.

With modern design techniques, the size and facilities of these stadia, especially the Olympic stadia, have evolved and changed dramatically. For 2008 Beijing Olympic competitions from [4], 37 venues will be used, of which 32 venues in Beijing, and 5 venues outside Beijing. The Qingdao International Sailing Center, Tianjin Stadium, and Qinhuangdao Stadium will be newly constructed while Shenyang Wulihe Stadium and Shanghai Stadium are the existing ones to be renovated. Olympic stadia capacities range from less than 40,000–100,000. ‘‘Venue safety’’ is the most important issue of ‘‘safety olympics’’, which is the dependable guarantee and safety countermeasure of ‘‘green olympics, high-tech olympics and people’s olympics’’.

The rest of the paper proceeds by first describing the basal parameter relationship of SCM. Second, the model is

*Corresponding author. Tel.: +862223504894; fax: +862223507765.
*E-mail address:* nkzqsong@yahoo.com.cn (Q. Zhang).

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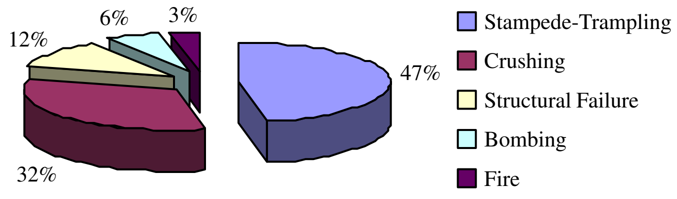


Fig. 1. The analysis of stadium-incident type.

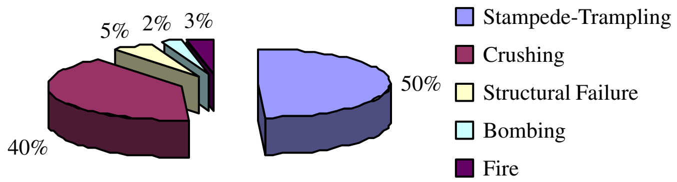


Fig. 2. The analysis of stadium-incident fatalities.

described in detail. Then, the procedure of how to incorporate the application of SCM to stadium egress analysis is presented. After that, we have a discussion with different egress width and different time interval through a real example. Finally, a conclusion is drawn to summarize the paper.

## 2. The relationship of basal variable in SCM

One of the most important areas in the field of ''Life Safety'' is the escape movement of individuals in emergency situations. It is not yet possible to accurately model very complex psychological reactions, such as panic and confusion, but many parameters can be simulated, especially in the case of crowd movement. These basic parameters include velocity, crowd density and crowd-flow rate, based upon certain assumptions. And the relationship of velocity, crowd density and crowd flow rate is the foundation of SCM. These three parameters are related by the fundamental equation [5]

$$f = vD, \tag{1}$$

where $f$ (flow rate) is specifically the number of people that pass some reference profile in a unit of time and a unit of meter width, e.g. 2.0 persons/s m; $v$ (velocity) is simply the distance covered by a moving person in a unit of time, e.g. 1.0 m/s and $D$ (density) is the number of people in a unit area of a walkway, e.g. 2.0 persons/m$^2$.

### 2.1. Relationship of velocity and density

The principles of pedestrian flow also stresses that speed is dependent on density. A number of researchers have examined the influence of population density and the dimensions of the enclosure upon the rate of locomotion of evacuees [6]. Much of the technical details concerning the contributions of Togawa [7], Fruin [8], Predtechenskii and Milinskii [9], Ando et al. [10], Paul [11], Daamen and Hoogendoorn [12], Nelson and Maclennan [13], Lo et al. [14], Liu et al. [15], Still [17] etc. The previous field surveys concentrated on the flow of pedestrians, the size and shape of individuals's bodies, queuing, and flow speed in relation to passage width.

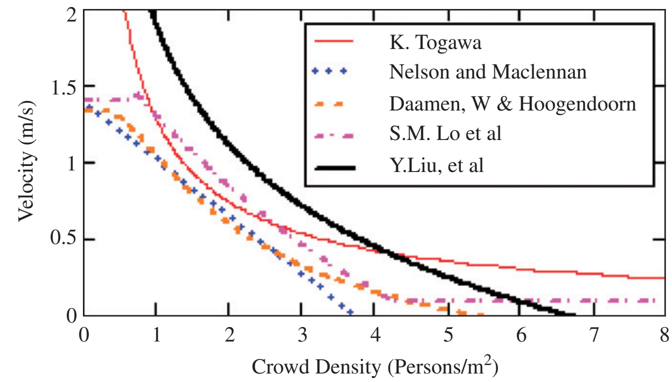


Fig. 3. Relationship of crowd density and velocity.

The relation between velocity and density in SFPE has been studied by many researchers such as Nelson and Maclennan [13], Poyner et al. [16], Hoskin [1] etc. and there are only little differences, so we use Nelson and Maclennan's formula as example, others are the same.

The modern stadium has crowd densities in excess of the Fruin observations and therefore the application of Level of Service needs to be examined Still [17]. From the Green Guide [18] we have the limit of 4 persons/m$^2$ set as a safe density for a moving crowd. At densities of about 4 persons/m$^2$, congestion builds up, but slow forward movement is still possible, and renders the maximum density 7.4 persons/m$^2$. Under extreme conditions, densities of 15 persons/m$^2$ have been observed.

The empirical relationships between crowd density and crowd velocity are summarized in Fig. 3.

Fig. 3 shown that higher crowd density, which leads to interaction between individuals, will reduce individual walking speed, but the changes are different based on various researchers.

### 2.2. Relationship of crowd-flow rate and density

With Eq. (1) the relationship of crowd-flow rate and density can be concluded based on the relationship of velocity and density (Fig. 3), a summary of crowd-flow rate from some of these studies is shown in Fig. 4.

It is noticeable from Fig. 4 that there are distinct differences amongst the various calculation methods and observations. This is not unusual and is to be expected, as people do not always behave in the same way. The differences are possibly indicative of different crowds exhibiting different behavior patterns. All are based on observational data and therefore valid.