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Review

A review on the performance of an obstacle near an exit on pedestrian crowd evacuation

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ABSTRACT

In a pioneering work in *Nature* journal, a counter-intuitive prediction that escape rates of people under panic conditions will be enhanced if an obstacle such as a column or a barrier is placed on the "upstream" side of an exit was demonstrated through a simulation model. However, the prediction lacked empirical verification. Despite the substantial works in this topic in the past decade, there is currently a lack of knowledge on how and to what extent the obstacle near an exit can enhance the pedestrian outflow at the bottlenecks during emergency escape.

Therefore, the aim of this paper is to present a critical review on the performance of an obstacle near an exit and identify future research directions. It is found that although there is a general consensus on the beneficial effect of an obstacle, there is a large uncertainty on the situations on which the positive effect of obstacle could be observed. In addition, verification of the model's prediction with empirical data with humans is still largely unexplored. There is no clear established relationship between the exit width, obstacle distance and obstacle size/shape. Also, quantitative understanding of the nature of the clogging transition due to obstacle is a challenging task. Further, researchers have questioned the implementation of such obstacles at bottlenecks in real life scenario. A systematic approach of optimising architectural adjustments that enhances escape dynamics of pedestrians' crowd in indoor and outdoor public spaces needs to be conducted in future.

1. Introduction

Researchers started to focus on understanding pedestrian traffic in the early seventies of the last century (Henderson, 1971; Fruin, 1971). In these earlier studies, efforts were put into determining the level of service (LOS) for pedestrian facilities. The LOS would then enable the designers to design pedestrian walking facilities. Also, studies on behavioural models of emergency situations have been conducted by sociologists/psychologists over many years (Mawson, 2007). Post 9/11 attacks in twin towers of the World Trade Centre in New York City in 2001, challenges on safety and security of pedestrians have been intensified (Johnson, 2005). Hence, recently there has been considerable attention on the development of simulation models, evacuation systems and plans for pedestrians' crowd to respond effectively to natural disasters, terrorist attacks or other emergencies (Alizadeh, 2011; Ding, 2011; Galea, 2012; Vermuyten et al., 2016).

Quick and efficient evacuation of pedestrians from the public infrastructure is critical as delay in egress by even a second or a fraction of second could influence their chance of survival (Helbing et al., 2000). Therefore, many studies on understanding pedestrian flow at bottlenecks such as exit have been conducted in the past two decades (Helbing et al., 2005; Shiwakoti et al., 2011; Jiang et al., 2014; Zhao et al., 2017; Shi et al., 2018a). In a pioneering work by Helbing et al. (2000) in *Nature* journal, a counterintuitive prediction that escape rates of people under 'panic' conditions will be enhanced if an obstacle such as a column or a barrier is asymmetrically placed on the "upstream" side of an exit (refer Fig. 1) was demonstrated through a simulation model. The term "panic" in the paper refers to the situations in which pedestrians are impatient due to high crowd density and short time for egress resulting in increased desired speed, competitive and pushing behaviour. It is hypothesised that the barrier absorbs physical pressures from a dense pedestrians' crowd and helps disrupt transiently "frozen" crowd configurations near the exit that momentarily prevent egress. This may help to prevent pushing behaviour at the exit thereby

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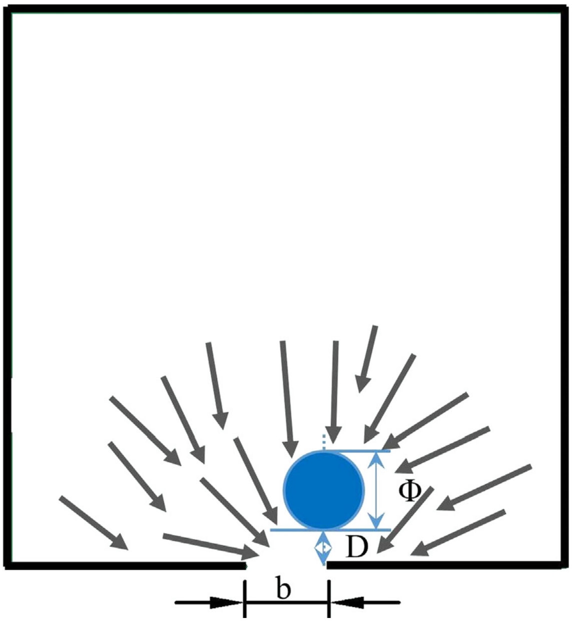

Fig. 1. A schematic diagram showing asymmetrical placement of a circular obstacle (like a column) with diameter "ø" at a distance "D" from an exit of width "b". The arrows show the pedestrians' directions towards the exit.

reducing the chance of trampling and stampede by distributing the tremendous pressure generated at the exit. However, the prediction lacked empirical verification.

Since the work of Helbing et al. (2000), many simulation and empirical studies have been conducted to examine the efficacy of obstacle (s) near an exit for the pedestrian outflow during evacuation. This counterintuitive performance of the obstacle near an exit has been the subject of interests not only for researchers on evacuation and crowd safety (Helbing et al., 2005; Shiwakoti et al., 2014a; Zhao et al., 2017), but also to researchers working on granular matters (Zelinski et al., 2009; Zuriguel et al., 2011, Alonso-Marroquin et al., 2012), architecture (Escobar and De La Rosa, 2003; Illera et al., 2010) and biological sciences (Burd et al., 2010; Zuriguel et al., 2014; Lin et al., 2017).

Despite the substantial works in this topic over a decade, there is currently a lack of knowledge on how and to what extent the obstacle near an exit can enhance the pedestrian outflow at the bottlenecks during emergency escape. In addition, there are recurring debate on the performance of these obstacles in terms of outflow and their viability in practical scenario. Therefore, the aim of this paper is to present a critical review on the performance of an obstacle on the pedestrians outflow near an exit, and identify future research directions.

The paper is organized as follows. The next section briefly explains the methodology adopted for the review. We then present the state-of-the-art on the performance of an obstacle on outflow near an exit by examining simulation and empirical studies conducted with both human and non-human entities. Finally, we discuss the debates in this topic and identify five future research directions.

2. Methodology

Through the use of "Boolean" searches of databases, literatures were obtained from electronic database including "ISI Web of Science", "Scopus" and "Google Scholar". The time period studied for literature specific to obstacle performance ranges from 2000 to 2018 as the 'obstacle effect' was first mentioned in 2000 in the *Nature* journal by Helbing et al. (2000). Only papers published in English language were considered as they are widely accessible to the readers around the world. The literature search was further augmented by relevant publications in the reference lists of the publications collected. Both qualitative and quantitative studies were considered. The initial stage of review of literature involved becoming familiar with the literature by reading the articles. Then, the literature was analysed by means of thematic analysis (Braun and Clarke, 2006) as this tool assists in the identification and exploration of major themes across the literature in a systematic manner. "Modelling/Simulation" and "Empirical Studies" were identified as two major themes. Each theme had three sub-themes on whether the studied focussed on pedestrians crowd, granular flow or animal models.

3. State-of-the-art

This section is structured into five sub-sections. The first sub-section reviews the insights from models and simulations that have been adopted to predict the obstacle performance in terms of outflow of pedestrians at bottlenecks. Then, the second sub-section describes the empirical studies with human participants. It is then followed by sections on insights from animal dynamics and granular flow respectively. Finally, a summary table highlighting the contributions and recommendations from these studies are presented.

3.1. Predictions from pedestrians' crowd simulations model

In past, many simulation studies have been conducted to replicate crowd behaviours at bottleneck (Shiwakoti et al., 2008; Vermuyten et al., 2016). Helbing et al. (2000), in a pioneering work, simulated the crowd egress behavior at bottleneck (exit) under panic situation and noted 'faster-is-slower' effect due to impatience of pedestrians. Further, they noted that 'faster-is-slower' effect can be avoided by improved outflows through suitably placed columns in front of the exits, which helps to prevent the build-up of fatal pressures. As it was only model's prediction, verification with empirical data was emphasised by the authors. This counterintuitive prediction has inspired many researchers to examine the performance of architectural adjustments near a bottleneck or an exit in the past decade.

By applying the social force model developed by Helbing et al. (2000), Escobar and De La Rosa (2003) investigated several types of architectural adjustments, including the performance of obstacles (columns) near an exit. In general, it was found that obstacles slow down the individual velocity and increase the outflow. However, beneficial effect was not noted for crowd less than 100 people. In addition, the authors noted that the column's performance depends on 'waiting room' effect near the exit. The "waiting room" effect is observed when the obstacles that act as flow regulators create a small area or room near the main exit. However, if the inflow to the "waiting room" exceeds the outflow, overcrowding would be observed. This will lead to clogging at the exit and reduce the outflow of the people. The authors suggested considering the performance of column in non-flat surface such as stairs/ramps near exit in future. Kirchner et al. (2003), through a cellular automata model of pedestrian crowd, provided quantitative evidence that introduction of sufficient friction between pedestrians and slightly asymmetric column is necessary to produce the beneficial effect of column.

Hughes (2003), discussing the application of macroscopic model in the analysis of crowd flow at annual Muslim Hajj, highlighted that suitably located barriers can increase the flow of pedestrians as compared to a situation when there are no barriers present. Hughes (2003) further noted the need to focus on transition of behavior at the macroscopic level to the microscopic level of the individual in studying the "turbulent" nature of the flow behind objects or barriers. In another microscopic simulation study by Johansson and Helbing (2005), the beneficial effect of suitably placed columns was highlighted. The authors further showed that funnel shaped or zig-zag shaped corridor near exit can also enhance the outflow of pedestrians during evacuation.

Varas et al. (2007) used cellular automata model to demonstrate that there is optimum door width relationship with the obstacle near exit. By increasing the exit width beyond the optimum, the presence of obstacles may not facilitate faster evacuation. Yanagisawa et al. (2009) developed a cellular automata model that used “friction functions” and “turning functions” to verify that obstacle decreases the conflicts at the exit by blocking pedestrians’ movements. While the “friction functions” showed that an obstacle blocked pedestrians’ movements and decreased the number of pedestrians involved in a conflict, the “turning functions” highlighted the importance of considering the position of the obstacle.

Through the simulation, Shukla (2009) demonstrated that the optimisation of the performance of the obstacles near an exit is a multi-objective problem that needs to consider several objectives (e.g., maximizing the flow, minimizing the discomfort or reducing the number of injured persons among others). Hence, it is recommended to use a multi-objective evolutionary algorithm in the simulation model to find the optimal design solutions. Later, this suggestion was adopted by Jiang et al. (2014), who used social force model and genetic algorithm to achieve maximal flow by exploring the optimal design of obstacles (considering obstacle numbers, size and positions) near the exit. It was found that by suitably placing two pillars on both sides of the exit (not in front of the exit) can maximise the escape efficiency. In addition, the escape speed and the tangential momentum were found to be negatively correlated and hence the authors suggested that focus should be in the development of layout design that would reduce tangential momentum of the escapee.

The collision avoidance strategies of evacuees near the exit with obstacle have been also investigated in the literature. For example, Frank and Dorso (2011) simulated two types of pedestrians, “strategic-managing” and “non-strategic” to examine the effect of obstacles placement near an exit. The “strategic-managing” pedestrians would change his (her) desired direction in order to avoid obstacles in the way out. In contrast, the “non-strategic” pedestrian would move directly to the exit, as if the blocking obstacles were transparent. It was found that improvement in evacuation time was dependent on the distance of the obstacle from the exit. For example, if the obstacle was very close to the exit, evacuation time was reduced for both, “non-strategic” and “strategic-managing” pedestrians, with respect to the obstacle-free situation. In contrast, if the obstacle was far away from the exit, the evacuation time for “non-strategic” and “strategic-managing” pedestrians was similar to the obstacle-free situation. The effects of obstacle position to the exit were further examined in another simulation study. Fang et al. (2012), in their preliminary numerical simulation, found that there is an effect of the obstacle size and distance from the exit on evacuation time when pedestrians with different speeds escape from a single exit.

Using an animal dynamics based microscopic simulation model, Shiwakoti et al. (2011) simulated the panic escape of pedestrian crowd with and without a column near an exit. The simulation model predicted an increase in the evacuation rate of the pedestrians with the column near the exit as compared to a scenario when the column was absent. In another simulation study, Shiwakoti and Sarvi (2013) compared the performance of a column near a middle exit and a corner exit with various horizontal offset distances from the exit. It was found that the performance of the column was dependent on the horizontal distance from the exit. At some offset distance, column reduced the outflow while at other distance, it improved the outflow. Also, the presence of a column near a cornet exit was more effective than placing a column near a middle exit. Later, Shiwakoti et al. (2014a) used different column size and horizontal offsets in their simulation and demonstrated that the performance of the obstacle dependent not only on the horizontal offset from the exit but also on the size of the obstacle. For example, the maximum flow rate for either a 1.5 m or 2 m diameter column occurred when there was a 0.5 m horizontal offset from the exit while for a 1 m diameter column the optimum offset was 0.6 m. Similar to the findings by Shiwakoti et al. (2014a), Matsuoka et al. (2015) also found that the performance of the obstacle like column depends on the size and location of the obstacle from the exit.

Recently, using differential evolution algorithm, Zhao et al. (2017) demonstrated that the performance enhancement due to an obstacle near an exit is not a result of pressure decrease in the region of exit. As noted by the authors, the enhancement in escape speed and outflow is due to a significant reduction of high density region by effective separation in space. This finding is in contrary to previous findings where it was reported that the obstacle may behave like a wave breaker to absorb the pressure in the crowd (Kirchner et al., 2003; Helbing et al., 2005; Zuriguel et al., 2011). In addition, the authors found that the panel-like obstacle is more robust and stable than the pillar-like obstacle to guarantee the enhancement of evacuation efficiency.

3.2. Experiments with human participants

To test the model’s predictions, it is critical to have empirical data. Therefore, there have been several controlled laboratory experiments to study the egress dynamics at bottlenecks (Hoogendoorn and Daamen, 2005; Kretz et al., 2006; Seyfried et al., 2009). However, there are relatively fewer empirical studies on the performance of architectural adjustments or obstacles at bottlenecks during evacuation. One of the reasons could be the ethical and safety reasons in creating experiments with human participants that replicates competitive behaviour. Therefore, the experiments with obstacles near exit are largely restricted to non-panic situations including normal condition and orderly evacuation drills (Shiwakoti and Sarvi, 2013).

Helbing et al. (2005) conducted experiments to determine the effect of an obstacle on a pushy crowd. Participants were asked to rush toward the door after an acoustical signal was given and to behave in a pushy way. The width of the door was 82 cm and a board of 45 cm width, acting as an obstacle, was placed near an exit. The obstacle increased the outflow of participants by around 30% and decreased the variation in the time gaps (of exit) by about the same amount, indicating a smoother evacuation from the room. However, the authors did not explore the effect of location of obstacle, shape and size on the outflow of the participants.

Yanagisawa et al. (2009) studied the effect of the obstacle in front of the exit at the NHK TV studio in Japan. Fifty participants, all women in their thirties and forties, passed through a 50 cm width exit with 20 cm diameter column in front of the exit. It was found that the outflow of the participants was larger (around 7% increment) when the obstacle was in front of the exit as compared to the normal evacuation where there was no obstacle near the exit. The limitations of the study were the consideration of only female participants in the experiments and lack of observations on the effect of location of obstacle, shape and size on the outflow of the participants.

In another study, Jiang et al. (2014) conducted experiments with 76 college students (21–25 years old) to study the effect of obstacle near the exit. The experiments had one obstacle, two obstacles and no-obstacle near the exit. To simulate the panic condition, the participants were divided into 10 groups, with each group receiving a score according to their escape speed for each evacuation. A prize was then awarded according to the ranking of the groups determined by their cumulative scores. It was observed that two obstacles near an exit are better than one obstacle or no obstacle near an exit. However, the study did not conduct systematic experiments to study the effect of horizontal offsets, shape and size on the outflow of the participants. Further, consideration of only young college students may not be representative sample of pedestrians’ crowd in real world.

Liu et al. (2016) conducted experiments to explore different exit designs on crowd evacuation dynamics. Fifty participants passed through a door of 1.2 m width. An obstacle, in form of a column with 1 m diameter, was placed 1 m in front of the exit. Two exit designs, one at the middle of the walls and the other at the corner, were tested. To replicate evacuation scenario, participants were instructed to run slowly. It was found that for corner exits, without obstacle was the most effective (by around 4%) scenario as compared to the middle exit. In addition, contrary to previous studies, presence of obstacle increased

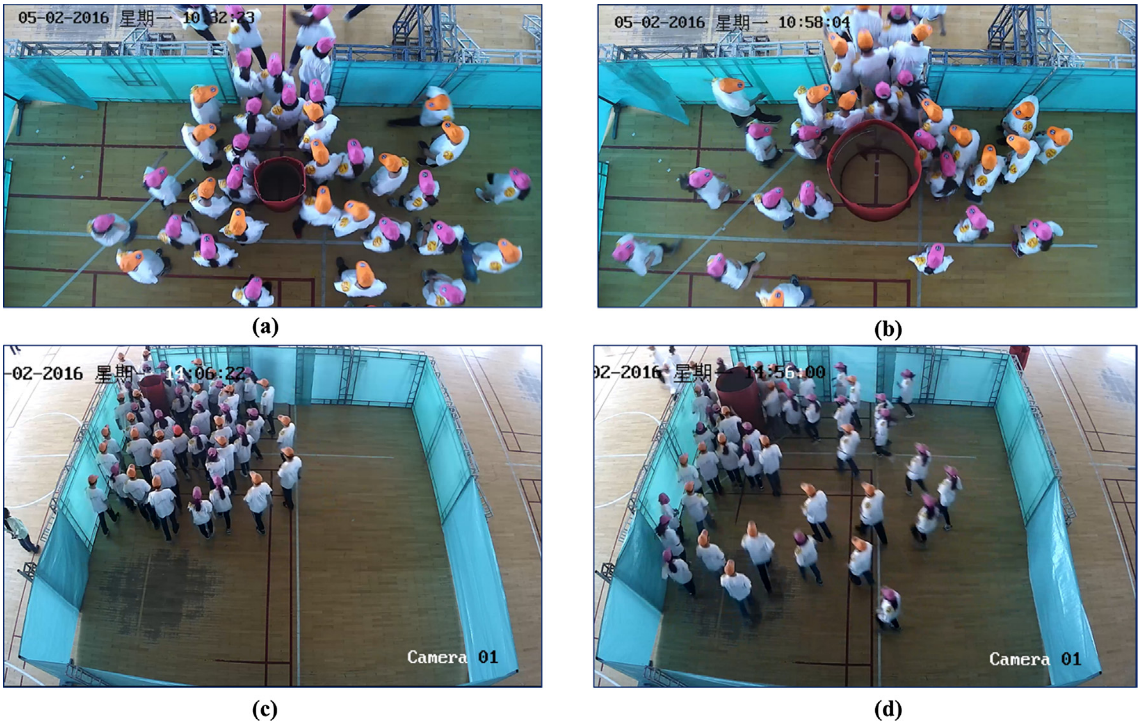

Fig. 2. Selected snapshots of controlled laboratory experiments in Shi et al. (2018b). (a): 60 cm width column placed 80 cm in front of a middle exit; (b): 100 cm width column placed 60 cm in front of a middle exit; (c): 60 cm width column placed 60 cm in front of a corner exit; (d): 100 cm width column placed 60 cm in front of a corner exit.

the egress time (by 7% and 11% respectively for middle and corner exits) as compared to the no obstacle middle exits. The findings supported the position taken by some researchers that the performance of the obstacle like column depends on the size and location of the obstacle near the exit (Frank and Dorso, 2011; Shiwakoti et al., 2014a).

Following up with the study from Liu et al. (2016), Shi et al. (2018b) recently conducted a series of controlled experiments with 50 participants to examine the effects of different architectural adjustment near an exit of 1.2 m width (Fig. 2).

Different exit location (middle exit vs. corner exit), obstacle size (0.6 m diameter vs. 1 m diameter) and obstacle distance from the exit (0.6 m, 0.8 m, 1.0 m) were considered. Therefore, a total of 14 set of experiments were conducted under normal and emergency (faster walking) situations. The middle exit without obstacle was selected as the standard design and the outflow of evacuees for other exit setups were compared to the standard design. The empirical results demonstrated that the beneficial effect of obstacle in terms of increased outflow depends on the size and position of the obstacle. For example, the architectural configuration that had corner exit with 60 cm diameter column located at 100 cm from the corner exit was 32.7% efficient in terms of outflow. In contrast, the experimental configuration that had a 60 cm diameter column and located at 60 cm from the middle exit was 10.6% inefficient in terms of outflow.

3.3. Insights from collective animal dynamics

To overcome the scarcity of empirical data under panic conditions, experiments with non-human organisms have been conducted under stressed or panic conditions especially to examine the effect of architectural features or obstacles effect near the exit. Obstacles effect at bottleneck was studied through experiments using non-human organisms such as ants (Shiwakoti et al., 2009; Shiwakoti et al., 2011; Shiwakoti and Sarvi, 2013), sheep (Zuriguel et al., 2014; Garcimartín et al., 2015) and mice (Lin et al., 2017) under panic or relatively stressed condition.

Shiwakoti et al. (2009) in their preliminary pioneering experiments with ants found that the placement of partial obstruction like a column near an exit enhanced the outflow of ants as compared to the scenario when there was no column near an exit under panic conditions. The authors further suggested exploring the use of sheep and mice for similar experiments.

Shiwakoti et al. (2010, 2011) further followed up their preliminary work and conducted a series of experiments with ants under panic conditions to observe and study how collective movement patterns are affected by the layout of the escape area or the presence of certain geometrical structures in the escaping area. From the experiments, it was found that mean escape time for ants was about 44% slower under the ostensibly more favourable conditions of an unobstructed exit as compared to the partially obstructed exit with a column. The empirical data were also compared with the prediction developed from a simulation model for both ants traffic and human traffic and the results were consistent to those empirical observations.

In another experiments with ants, Shiwakoti and Sarvi (2013) found that within a given layout of same area, the presence of partial obstruction (like column) near the middle exit or at corner exit were very effective (almost two times) in reducing the evacuation time as compared to the standard design of middle exit with no column. Although the underlying mechanisms of enhanced performance of column near an exit for ants traffic and pedestrians' traffic may be different, the fact that the beneficial effect of column observed in two species of varying body sizes and shape suggests further exploration of learning from these model organism approach (Burd et al., 2010; Shiwakoti and Sarvi, 2013; Shiwakoti et al., 2014b).

Inspired with these previous findings from non-human organisms, Zuriguel et al. (2014) and Garcimartín et al. (2015) observed the competitive behaviour of a sheep herd passing through a narrow door and evaluated the effect of increasing the door size and the performance of an obstacle placed in front of the door. The authors highlighted that the action of widening the exit or placing an obstacle before the door may have a beneficial effect in terms of reducing the clogging

Table 1
Summary of scenarios, methodologies, contributions and recommendations from the literature.

Source	Modelling & Simulations			Experiments			Scenario Conditions		Main Contributions		Recommendations
	Pedestrians	*Granular*	*Animals*	*Pedestrians*	*Granular*	*Animals*	Exit Condition	Obstacle Condition	Methodology	Key Findings	
Helbing et al. (2000)	X						● 1 m width, single, middle exit ● 1.5 m width, dual, symmetric, middle exits	● circular column, single, asymmetric placed obstacle	● social force model introducing a panic parameter	● asymmetric column near exit helps disrupt transiently “frozen” crowd configurations facilitating quick egress	● needs empirical verification of prediction
Kirchner et al. (2003)	X						● 1 cell width, single, middle exit	● squared pillar, 3*3 cells, central/ asymmetric placed obstacle	● a cellular automaton model considering the friction effect	● provided quantitative evidence that introduction of sufficient friction between pedestrians and slightly asymmetric column is necessary to produce the beneficial effect of column	● effect of size of obstacle and distance from exit needs further investigation
Escobar and De La Rosa (2003)	X						● 1 m width, single, middle/ corner exit	● barrier/V/T pillars, single, central placed obstacles ● circular column/barrier shape, dual, central placed obstacles	● improved social force model introducing the vector field solution	● obstacle effect not noted for crowd less than 100 people in a 15 m by 15 m room ● column performance depends on ‘waiting room’ effect near exit. If the inflow to the “waiting room” exceeds the outflow, column performance declines	● consideration of non-flat surface such as stairs/ramps near exit
Hughes (2003)	X						● 45 m width entrance and exit on Jamarat Bridge	● oval pillar, triple, 8 m radius, successive placed obstacles	● a continuum theory to address the flow of human crowds under different scenarios	● suitably located barriers can increase the flow of pedestrians as compared to when there are no barriers present	● focus on transition from behaviour at the macroscopic level to the microscopic level of the individual in studying the “turbulent” nature of the flow behind objects
Johansson & Helbing, (2005)	X						● 1 m width, single, middle exit	● funnel/compartment/ zig-zag shape, single, asymmetry placed obstacle	● social force model and generic algorithm to optimize the outflow	● besides pillars near exit, funnel shaped or zig-zag shaped corridor near exit can enhance the outflow of pedestrians	● only model’s prediction and thus needs empirical data
Helbing et al. (2005)				X			● 82 cm width, single, middle exit	● squared pillar, 45 cm width	● controlled experiments with human participants	● a board of 45 cm near a door of 82 cm width increased the flow by about 30% as compared to absence of board when people showed competitive behaviour (i.e. pushing allowed) ● placing an obstacle in front of the exit could avoid the clogging effect ● under normal leaving (no competitive behaviour), the outflows for rooms with and without pillars (column) will be about the same	● effect of size of obstacle & distance from exit not studied

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Table 1 (*continued*)

Source	Modelling & Simulations			Experiments			Scenario Conditions		Main Contributions		Recommendations
	Pedestrians	*Granular*	*Animals*	*Pedestrians*	*Granular*	*Animals*	Exit Condition	Obstacle Condition	Methodology	Key Findings	
Varas et al. (2007)	X						● 2 cell with, single, middle exit	● panel shape, 7 cell width, asymmetric placed 3 cell away from the exit	● a bi-dimensional cellular automaton model to simulate pedestrian evacuation	● there is optimum door width relationship with the obstacle near exit. ● increasing the exit width beyond the optimum, the presence of obstacles may not facilitate faster evacuation.	● apply the model to other types of pedestrian facilities
Shukla (2009)	X						● 1 m width, single, middle exit	● evolutionary shape/size, single/dual/triple, asymmetric placed obstacles	● social force based panic model to simulate the crowd and a multi-objective evolutionary algorithm to optimize the obstacle shape and position effects	● efficiency of obstacles placement is not a straightforward issue of maximising outflow but a multi-objective problem that should consider comfort and minimising injured pedestrians	● explore multi-objective evolutionary to find the optimal design solutions
Yanagisawa et al. (2009)	X			X			● 0.5 m width, single, middle exit	● circular column, 20 cm width, asymmetric placed obstacle	● a floor field model considering the conflicts and friction effect at bottlenecks ● controlled experiments with human participants	● observed increased pedestrian outflow as compared to no obstacle. ● obstacle decreases the conflicts at the exit by blocking the pedestrians' movement is verified by theoretical calculation using friction functions	● conflicts at exit are affected by the pedestrians' walking velocities and the angle of the pedestrians' walking direction which needs to be investigated.
Zelinski et al. (2009)					X		● 1 cm width, single, middle exit, angle changing	● circular column, 2.5/3.75/5/10 mm width	● granular experiments to examine two exits setups on the outflow	● first experimental evidence of flow maximization by oblique exits or by obstacles in granular flow that is relevant to pedestrian crowds. ● suggests the possibility of optimization of the angle of an oblique exit, as well as of the distance and diameter of a column for pedestrians' crowd	● needs empirical data verification for pedestrian crowds
Shiwakoti et al. (2010)			X			X	● 2.5 mm width, single exit, circular room ● 2.5 mm width, single, middle exit, squared room	● circular column, 5 mm width, placed 2 mm in front of the exit	● experiments using panicking ants ● a microscopic simulation model to reproduce the egress dynamics of panicking ants	● for the first time, effect of obstacle (column) near an exit is demonstrated in ants panic escape ● similar to pedestrian crowds simulation, with the presence of column near the exit, a reduction in average evacuation time by 30% as compared to the no-column scenario was observed (both experimentally and simulation) in ants' colony.	● underlying behavioural differences between human crowds and ants escape needs further scrutiny

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Table 1 (*continued*)

Source	Modelling & Simulations			Experiments			Scenario Conditions		Main Contributions		Recommendations
	Pedestrians	*Granular*	*Animals*	*Pedestrians*	*Granular*	*Animals*	Exit Condition	Obstacle Condition	Methodology	Key Findings	
Frank & Dorso (2011)	X						● 1.2 m width, single, middle exit	● circular column, 1.2 m width, central placed near the exit at three distances ● a (4 × 0.1) × 1.2 m flat panel barrier, central placed near the exit at three distances	● a social force model with human clusters to simulate pedestrian egress dynamics numerically	● obstacle very close to the exit is much efficient in terms of outflow as compared to the obstacle that is considerably away from the exit. ● The human factor, the obstacles' shape (e.g. pillar vs. panel) and size must contribute cooperatively to optimize the preservation of life in evacuation.	● consider the possible strategies that pedestrians might take in order to achieve a real evacuation in future
Zuriguel et al. (2011)					X		● 4.2 mm width, single, middle exit	● circular column, 10 mm width , central placed near the exit at different distances	● granular experiments to examine the effects of obstacle on clogging reduction	● if the position of the obstacle is properly selected near an orifice, decrease of the clogging probability of granular materials can be obtained ● obstacle induces a strong reduction of the pressure above the outlet (relevant to pedestrian crowds).	● verification of effect of obstacle size and location on pedestrians' crowd outflow is needed
Shiwakoti et al. (2011)	X		X			X	● 2.5 mm width, single exit, circular room ● 2.5 mm width, single, middle/corner exits, squared room	● circular column, 5 mm width, central placed near the exit	● ants experiments under panic situation ● a microscopic simulation model to reproduce ants egress dynamics ● extend the animal dynamic model to simulate pedestrian crowd	● the results from ants escape with/without column experiments and simulation were scaled up to pedestrian crowds' simulation and similar beneficial effects of column were observed in both entities. ● the location of exit also had an influence on the outflow of pedestrians	● verify if similar beneficial effect of column is seen on other animals (for e.g. mice, sheep) and from empirical data with human
Alonso-Marroquin et al. (2012)		X					● 6.3 d width, angle changing (five angles) hopper, single, middle exit	● circular column, ranging from 0 to 15 d width, central placed in front of the exits at difference distances	● a particle-based model and simulation of mono-disperse disks in an hourglass to represent the granular flow and examine the obstacle effects	● flow rate in a hopper with an obstacle placed before the bottleneck depends on the minimum distance between the obstacle and the hopper, and the angle of the hopper. ● velocity-density relation is in contrast with previous models without obstacles for pedestrian evacuation	● investigations on the transition from funnel flow to mass flow, and temporal periodic fluctuations in the velocity field around an obstacle
Lozano et al. (2012)					X		● 3.13/4.20/ 4.55 m width, single, middle exit	● circular column, 10 mm width, central placed in front of the exits at difference distances	● granular flow experiments to examine the effect of obstacle position and exit width on the flow and clogging in a silo	● clogging reduction caused by the obstacle is enhanced as the outlet size is increased, thereby approaching the region of "no clogging." ● implications towards pedestrian flow outflow at a bottleneck	● further experiments and simulations to characterize the pressure exerted by the granular media on the obstacle as well as its fluctuations

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Table 1 (*continued*)

Source	Modelling & Simulations			Experiments			Scenario Conditions		Main Contributions		Recommendations
	Pedestrians	*Granular*	*Animals*	*Pedestrians*	*Granular*	*Animals*	Exit Condition	Obstacle Condition	Methodology	Key Findings	
Shiwakoti and Sarvi (2013)	X					X	● 2.5 mm width, single, middle/corner exits ● 1.2 m width, single, middle/corner exit	● circular column, 5 mm width, central placed near the exit ● circular column, 1.5 m width, central placed near the exit	● ants experiments under panic condition ● a scaled animal dynamic based simulation model to represent human crowd dynamics	● experiments with panicked ants showed that the presence of partial obstruction (like column) near the middle exit or at corner exit were very effective in reducing the evacuation time ● pedestrian simulation results also showed similar findings and that the performance of obstruction dependent on the distance from the exit. At some distance, presence of column decreased the flow	● further examination of design solutions to optimise the flow in given layout considering the physical and behavioural similarities and dissimilarities among different biological entities
Shiwakoti et al. (2014a)	X		X			X	● 1.2 m width, single, middle/corner exit ● 1.2 m width, funnel shape, single, middle exit	● circular column, 1.5 m width, central placed near the exit	● compare the results from ants experiments, animal dynamic models' simulations and scaled models' simulations ● present new exit designs to reduce the turning angles	● simulation of pedestrians' crowd along with insights from ants' experiments and simulation highlights that the presence of a partial obstruction like a column near the exit is effective only for some horizontal offsets and some column diameters	● learn the extent to which convenient model organisms can substitute for humans in the study of crowd panics
Zuriguel et al. (2014)						X	● 0.77 m width, single, middle exit	● circular column, 1.14 m width, central placed 0.8 m from the exit	● use sheep to conduct collective motion experiments	● transition from clogged to unclogged states was observed by placing an obstacle before the door for a sheep herd ● findings consistent with observations from pedestrians crowd	● quantitative assessment of the relevant parameters characterizing clogging phase
Jiang et al. (2014)	X			X			● 1 m width, single, middle exit	● circular column, 0.5/0.75/1.0 m width, single/dual/triple obstacles, asymmetric placed near the exit ● rectangular pillar, 0.86 m width, single/dual obstacles	● a social force model to simulate pedestrian egress ● a genetic algorithm to optimize the size and position of obstacle ● controlled human experiments	● suitably placing two pillars on both sides but not in front of the door can maximize the escape efficiency. Simulation results are consistent with experiments with human subjects ● escape speed and the tangential momentum are found to be negatively correlated	● further study in the layout design that would reduce tangential momentum of escapee
Zuriguel et al. (2016)						X	● 0.77/0.96 m width, single, middle exit	● circular column, 1.14 m width, central placed 0.6/0.8/1.0 m away from the exit	● animal experiments using sheep herd	● additional experiments with sheep herd shows that effectiveness of the obstacle is quite sensitive to its location	● fairness of straightforward comparisons between pedestrian behavior and animal experimental observations needs careful scrutiny

(*continued on next page*)

Table 1 (*continued*)

Source	Modelling & Simulations			Experiments			Scenario Conditions		Main Contributions		Recommendations
	Pedestrians	*Granular*	*Animals*	*Pedestrians*	*Granular*	*Animals*	Exit Condition	Obstacle Condition	Methodology	Key Findings	
Liu et al. (2016)				X			• 1.2 m width, single, middle exit	• circular column, 1 m width, central placed 0.5 m away from the exit	• human experiments with 50 participants	• for corner exits, without obstacle was the most effective scenario. In addition, contrary to previous studies, presence of obstacle increases the egress time, compared to middle exits.	• additional experiments to study influence of different obstacles sizes and positions on evacuation dynamics
Lin et al. (2017)						X	• 2 cm width, single, middle exit	• circular column, 3.2 cm width, central placed 3/4/6 cm from the exit	• evacuation experiments with mice	• experiments with mice under high competitiveness show that the presence of an obstacle in front of an exit can increase or decrease the evacuation efficiency depending on the location and size of the obstacle. • the formation of clogs and arches is subject to randomness, particularly with the introduction of obstacle	• relevancy of mice experiments to pedestrians' crowd evacuation under high competitive behaviour needs careful scrutiny
Zhao et al. (2017)	X						• 1 m width, single, middle exit	• circular column, ranging from 0 to 1.5 m width, offset placed near the exit • panel barrier, ranging from 0 to 14 m width, offset placed near the exit	• social force model to simulate pedestrian motion • a differential evolutional algorithm to optimize the geometrical parameters of column-like and panel-like obstacles	• performance enhancement while placing an obstacle is not a pressure decrease in the region of exit, but a significant reduction of high density region by effective separation in space lead to the increased escape speed and evacuation outflow. • Panel-like obstacle is more robust and stable than the pillar-like obstacle to guarantee the enhancement of evacuation efficiency.	• effect of arrangements of pillars and efficiency of panel-like obstacle needs to verified with experimental data with pedestrians' crowd
Shi et al. (2018a,b)				X			• 1.2 m width, single, middle/corner exit	• circular column, 0.6/1.0 m width, central placed 0.6/0.8/1.0 m from the exit	• controlled human experiments to examine the effect of exit position, obstacle size and position on the outflow of pedestrians	• experimental evidences show that obstacles have different performance with different size and position. • suitably selected obstacle size and position can increase up to 33% outflow of pedestrians • some obstacle size and location can reduce the outflow of people up to 7%.	• the performance of obstacle should be extended to other crowd motion scenarios such as merging or diverging corridors

probability. The authors recommend that the effectiveness of those architectural adjustments can be gauged by measuring the exponent of the power law tail in the time lapse distribution. Zuriguel et al. (2016) reported additional experiments with sheep herd which shows that effectiveness of the obstacle is quite sensitive to its location. The authors, however, questioned the fairness of straightforward comparisons between pedestrian behaviour and animal experimental observations.

Recently, Lin et al. (2017) conducted a series of experiments with mice under high competitiveness with various configurations of obstacles size and distance from the exit. It was found that the obstacle in front of an exit can increase or decrease the evacuation efficiency depending on the obstacle size and location. It was observed that an obstacle with a diameter of 0.4–3 times of the exit width, and at a distance of 1–2 times of the exit width can improve the flow rate. Also, it was noted that the formation of clogs and arches near an exit is subject to randomness, particularly with the introduction of obstacle. Finally, the authors acknowledge that mice and human are different in many aspects, such as body constitution and shape, navigation capabilities, and intelligence. However, the authors believe that in some extreme instances, people may shove one another selfishly to escape, just as the mice did in their experiments.

3.4. Insights from granular flow

Inspired by previous simulation results of pedestrian crowd dynamics on the performance of obstacles near an exit, Zelinski et al. (2009) conducted experiments that involved the passing of granular materials (wood spheres) through an exit in a hopper due to vibration from a shaker. The inclination of the bottom wall could be set to different angles. For a horizontal bottom, a cylindrical column with varying diameter and varying distance from the exit was placed. The authors found that the obstacle size, distance along with inclination angle had an effect on the outflow of the granular materials. The authors claim that it was the first experimental evidence of flow maximization by oblique exits or by obstacles in granular flow. The authors believe that the findings are relevant not only to the discharge from containers (e.g., ore, coal, seeds or of pharmaceutical granulates flow for industrial application) but also towards optimization of the distance and diameter of an obstacle or column near an exit for increased pedestrians outflow.

Zuriguel et al. (2011) conducted experiments to study the effect of inserting an obstacle just above the outlet of the silo on the clogging process. They found that if the position of the obstacle is properly selected, a substantial decrease of the clogging probability can be obtained. It was concluded that the obstacle induces a strong reduction of the pressure above the outlet. The researchers suggested that this granular flow behavior could have an analogy in the flow of crowds through bottlenecks, where it has been typically assumed that the main role of a column behind an exit is to prevent straight motion of people towards the exit.

By extending the previous work by Zuriguel et al. (2011), Lozano et al. (2012) presented new measurements to analyse different outlet sizes and revealed that the effect of the obstacle is enhanced as the outlet size is increased. In addition, the effect of the obstacle position on the flow rate properties and in the geometrical features of arches was studied. Their results supported previous evidence of the pressure reduction induced by the obstacle, similar to the outflow of human crowds. Therefore, researchers suggested further experiments and simulations to characterize the pressure exerted by the granular media on the obstacle as well as its fluctuations.

Alonso-Marroquin et al. (2012) concluded through the particle-based simulation of granular flow that the flow rate in a hopper with an obstacle placed before the bottleneck was dependent primarily on the aperture (the minimum distance between the obstacle and the hopper) and the angle of the hopper. Researchers found that the flow rate across a bottleneck increased when an optimized obstacle was placed before it. The researchers also found that the velocity-density relation was in contrast with previous models without obstacles for pedestrian evacuation. These findings emphasise the need to further explore the role of obstacle size and position from the exit towards improved outflow of particles or individuals, especially with empirical data.

3.5. Summary

Table 1 shows the summary of scenarios, methodologies, key findings and recommendations from the literature that examined the performance of obstacles near an exit. Please note that the list may not be exhaustive. There are chances that we may have missed non-English literature or English literature due to limitation of search engine. However, the list does include important studies that have examined this topic over a decade. The table shows whether the study is a simulation based or experimental based approach. Further, there is a sub-classification on whether the study focussed on pedestrians, granular flow or animal dynamics for both simulation and empirical based approaches. The 'X' tick in the table shows what approach has been followed in a particular literature while blank cell shows missing approach in a particular literature. The table also shows "scenario conditions" that summarise the type of exit and obstacle considered in the study. The methodology adopted and key findings are listed under "main contributions". Finally, a column that lists recommendations from the literature is provided.

From the table, it is clear that initial studies have focussed mainly on the simulation study of pedestrians' crowd flow with an obstacle near exit. Those studies highlighted the need for empirical data which led to the empirical data collection via experiments with human participants, granular flow and collective dynamics of animal models. Yet, only limited experimental data are available to verify the model's prediction and the studies are still largely simulation based. In addition, it can be observed that there are recurring debates on the performance of the obstacles near the exit and how this strategy can be effectively implemented at bottlenecks during evacuation of pedestrians' crowd. Further, the performance of obstacles near an exit has been the subjects of interests for researchers working on granular flow for industrial application as well as collective animal dynamics. Therefore, there is a lot to learn from each other. In the next section, we provide a detailed discussion on the implications of these findings and directions for future research.

4. Discussions and conclusions

Effect of obstacles (like column) near an exit on the outflow of individuals at bottleneck has been of considerable interests to the research community working on evacuation and pedestrians' crowd safety. As such, a wide range of approaches ranging from simulation, empirical analysis, granular flow and biological sciences have been adopted in the literature. From the synthesis of the findings, we have identified five critical issues that need attention in future studies as described below. Based on these discussions, at the end, we have also presented a summary table that summarises the critical issues, key problems and future research directions (refer Table 2).

4.1. Uncertainty on obstacle performance

Although there is a general consensus on the beneficial effect of obstacle on the outflow of pedestrians near an exit, there is a large uncertainty on the situation on which the beneficial effect of column could be observed. For example, Helbing et al. (2005) observed that the asymmetric column near an exit helps disrupt transiently "frozen" crowd configurations facilitating quick egress during panic conditions, while under normal egress (i.e. without competitive behaviour), the outflows for rooms with and without pillars (column) will be about the same. In addition, Escobar and De La Rosa (2003) found that there was

Table 2
Summary of critical issues, problems and future research directions.

Critical issues	Problems	Future directions
(1) Uncertainty on obstacle performance	• A large uncertainty on the situation on which the beneficial effect of column could be observed.	• Establish relationships with obstacle distance, size and shape. • Understand the underlying mechanisms of obstacle effect that may increase or decrease the outflow of the individuals at bottlenecks.
(2) Uncertainty on insights from animal dynamics and granular flow	• Lack of understanding on the underlying behavioural mechanisms governing the beneficial effect of obstacles in entities of vastly different body sizes, physical abilities, and cognition.	• Identify the generic nature of the clogging transition and quantify the relevant parameters that control the clogging of both biological and non-biological entities.
(3) Practical implications issues	• Creation of obstacle (like column) near exit may not be perceivable or understandable to evacuee creating confusion and delay in egress. • Counterintuitive solution (obstacle near exit) may need approval from building insurance companies, and getting approval may not be straightforward for a counterintuitive solution.	• Conduct study on people's perception of obstacles near an exit/door and the functionality of doors. • Develop design solutions in consultation with relevant stakeholders including modellers, emergency managers, architects, insurance companies, human factors.
(4) Beyond obstacle performance	• Lack of studies that focus on optimal layout of escape area by considering complex architectural configurations in addition to obstacle effect.	• A systematic approach that optimises complex architectural elements like angle of turning, merging and intersecting along with obstacles is required for the optimal design of pedestrian facilities.
(5) Outdoor scenarios	• Applicability of the indoor results to outdoor scenarios, such as evacuation from public squares or intersections is less explored in the literature • Can substantial improvements in pedestrian traffic flow be achieved by placing barriers (such as column or other architectural adjustments) in the intersections or public squares?	• Scope to investigate the obstacle performance associated with the other type of movement patterns (e.g., turning, merging) for outdoor scenarios. • Scope to study pedestrian streams in outdoor intersections or public squares by controlling the temporal roundabout traffic in intersecting pedestrian streams.

no effect of obstacle for low density crowd (less than 100 people in a 15 m by 15 m room). Therefore, whether obstacle effect could be observed in normal conditions or low density conditions is questionable.

Although several simulation studies have shown that the performance of the obstacle depends on the size and distance of the obstacle from the exit, verification of the model's prediction with empirical data is largely unexplored. In addition, there is no clear established relationship between the exit width, obstacle distance and obstacle size/shape. Some simulation studies have shown that when the obstacle is at $\sqrt{3}$ E/2 distance from the exit (where E = width of the exit), there was increase in outflow of individuals due to an obstacle as compared to obstacle-free situation (Frank and Dorso, 2011). However, when the obstacle was far away from the exit (i.e. at 2E), the evacuation time was similar to the obstacle-free situation. Establishment of such relationships with obstacle distance, size and shape in future will be valuable contributions to this field.

Although there have been few experiments with human participants to study the effect of obstacle near an exit, systematic experiments with human subjects exploring the effect of obstacle size and distance from the exit is limited in the literature. Even few experiments with human participants have produced conflicting findings. For example, some researchers (Helbing et al., 2005) observed improved in outflow of pedestrians via obstacle (by around 30%) while others (Liu et al., 2016) found the decrease in outflow of pedestrians in presence of obstacle near exit (by around 11%). In addition, recent researches have highlighted the role of the shape of the obstacle in the outflow of the pedestrians (Frank and Dorso, 2011; Zhao et al., 2017). In the past, researchers were focused on the effect of column or pillar shaped obstacle, while findings from recent research suggests that the panel like obstacle is more efficient than the column or pillar shaped obstacle (Zhao et al., 2017). Such uncertainty on the obstacle effect needs careful scrutiny in future with systematic experiments with human participants.

There is also uncertainty on the understanding of the underlying mechanisms of obstacle effect that may increase or decrease the outflow of the individuals at bottlenecks. For example, previously it was reported that the obstacle behaves like a wave breaker to absorb the pressure in the crowd (Kirchner et al., 2003; Helbing et al., 2005; Zuriguel et al., 2011). However, recent research has demonstrated that a significant reduction of high density region by effective separation in space lead to the increased escape speed and evacuation outflow by obstacles rather than the reduction of the pressure in the crowd (Zhao et al., 2017). Further, it has been demonstrated that the obstacle helps in reducing the tangential momentum of the escapee as escape speed and the tangential momentum are negatively correlated (Jiang et al., 2014).

4.2. Uncertainty on insights from animal dynamics and granular flow

As the beneficial effect of obstacles at bottleneck were predicted to be more pronounced under highly competitive behaviour (Helbing et al., 2005), researchers have examined other empirical approaches to explore this issue. This is because experiments with human participants under highly competitive behaviour or panic conditions were not possible due to ethical and safety issues. Therefore, experimental studies with animal models and granular flow are on rise in the past few years. However, there are uncertainties to what extent those results from non-human entities are transferable or scalable to human situation. Although experiments with ants, sheep and mice along with granular flow have shown the beneficial effect of obstacles near exit as in human crowds, understanding the underlying behavioural mechanisms governing these phenomena in entities of vastly different body sizes, physical abilities, and cognition is limited in the existing literature. While some researchers argue that in some extreme instances, people may shove one another selfishly to escape just as in experiments with mice (Lin et al., 2017), others question fairness of straightforward comparisons between pedestrians' crowd outflow and animal experimental observations (Zuriguel et al., 2016).

Likewise, several studies on the granular flow have found beneficial effect of obstacle near exit (Zelinski et al., 2009; Zuriguel et al., 2011) while in some study, it was found that the velocity-density relation was in contrast with previous models without obstacles for pedestrian evacuation (Alonso-Marroquin et al., 2012). One way to understand the underlying mechanisms of obstacle effect among these different entities would be to understand and characterise the clogging phenomena with and without obstacle at the bottleneck (Zuriguel et al., 2014). This approach may help to understand phenomena, such as the 'faster-is-slower effect' and become a starting point for researchers working in a wide variety of situations where clogging may be problematic. Therefore in future, coordinated efforts are required to identify the generic nature of the clogging transition and quantifying the relevant parameters that control the clogging of both biological and non-biological entities.

4.3. Practical implications issues

While the previous simulation and experimental studies suggest that appropriately placed columns or pillars may provide benefits in terms of stabilizing the flow and increasing the throughput in case of high level of competition or motivation, some researchers have questioned the implementation of such columns or obstacles at bottlenecks in real life (Illera et al., 2010; Shukla, 2009). According to Illera et al. (2010), it is essential to make space intuitively perceivable, so that an evacuee can concentrate on simple, basic, understandable spatial structures during evacuation. The creation of obstacle (like column) near an exit may not be perceivable or understandable to evacuee creating confusion and delay in egress. Study focusing on people's perception of these obstacles near an exit/door and the functionality of doors is missing in the literature and can be studied in future.

While columns at the exit may decrease the architectural value and depending on their design may reduce visibility at the exit, appropriate solutions can be developed in consultation with the architects. For example, Illera et al. (2010) illuminates that from architect point of view such a structure should have some functional meaning. Therefore, building a column-shaped info-point before the exit area which is brightly lit and used by visitors to seek information could be a win-win solution. Helbing et al. (2002) illustrates with a real-life observation of a pedestrian tunnel connecting two subways in Budapest's Metro System at Deak Tér where a series of columns in the tunnel stabilizes pedestrian lanes when the density of pedestrians and the variations of their desired speed are high. Some of the other solutions proposed in the literature (for e.g. illuminated columns, telescope columns activated only in critical situations) are promising from practical implementation (Helbing et al., 2005). Having said that, the modifications of the existing structure with such counterintuitive solution (obstacle near exit) may need approval from building insurance companies, and getting approval may not be straightforward for a counterintuitive solution. Hence, in future, coordinated efforts from relevant stakeholders including modellers, emergency managers, architects, insurance companies, human factors engineers are required to develop design solutions that could enhance the safety and outflow of the individuals.

4.4. Beyond obstacle performance

The 'obstacle effect' shows that if seemingly small structural features of the physical environment can have disproportionate influence on the pedestrian escape dynamics, then there is enormous potential in the design of optimal layout of the escape area. This can have implications in the development of other design solutions for public space, major transport hubs and other public buildings for safe and efficient crowd movements. In the absence or failure of external emergency managers (such as the police or an evacuation team), the immediate environment that a crowd is interacting in at that moment are the individuals within the crowd and the layout or the geometrical structure through which they need to escape. In such worst cases, by making appropriate architectural adjustments within the escape area, there is the possibility of changing the collective movement patterns in a way that enhances the outflow and safety of the crowd (Shiwakoti et al., 2014a). Recent studies have shown that other architectural features such as turning and merging corridors form an important bottleneck in floor plans of any major public infrastructure. By selecting appropriate angles for turning or merging corridor, the negative consequences of the angled and merging corridor can be minimised (Dias et al., 2014; Shiwakoti et al., 2015; Shi et al., 2016; Severiukhina et al., 2017). Therefore, a systematic approach of optimising architectural adjustments that enhances escape dynamics of pedestrians' crowd within an escape area or a building or other public infrastructures needs to be conducted in future.

4.5. Outdoor scenarios

From the literature review, it is observed that most studies aim to study the effect of obstacle or architectural adjustments in indoor scenarios such as a room or building evacuation. However, the applicability of the results to outdoor scenarios, such as evacuation from public squares or intersections is less explored in the literature. Public spaces, such as intersections, attract huge crowds during special events. Intersections also serve as refuge points during disasters like earthquake, fire, or terrorist attacks. For example, more than a million people congregate at Sydney's Central Business District (CBD) on New Year's Eve (SBS News, 2017). There have been stampedes during such outdoor events in the past resulting in fatalities and injuries. A crowd stampede during a New Year's Eve celebration in Shanghai, China resulted in 36 fatalities and over 49 serious injuries (Wikipedia, 2018a); while a football crowd stampede in Piazza San Carlo public square in Italy led to over 1500 injuries (Wikipedia, 2018b). As intersections form a regular part of any street network, it is imperative for event managers to assess flow management of crowds during outdoor events and to be aware of ways to control the crowd if emergency situations arise. Therefore, there is potential to test the effect of such architectural adjustments in outdoor scenarios, especially at the intersection.

Outdoor scenarios such as at intersection can be quite different to indoor scenarios in terms of the extent (scale) and layout of infrastructure, the number of exits (limited in indoor scenarios), and variation in walking speed (Shiwakoti, 2010). At intersections, according to Helbing et al. (2002), one is confronted with various alternating collective patterns of motion of a temporal and unstable nature. Phases during which the intersection is crossed in the "vertical" or "horizontal" direction alternate with phases of temporary roundabout traffic. Therefore, it would be of great value if any substantial improvements in pedestrians traffic flow can be achieved by placing barriers (such as column or other architectural adjustments) in the intersection (refer Fig. 3). The concept is similar to indoor situations where putting obstacles at exits breaks up the pressure generated by panicked crowds.

Shiwakoti (2010) examined the effect of obstacles in outdoor intersections under emergency conditions via experiments with ants. Preliminary results showed that ants enhance their escape patterns by minimizing the mutual interactions at the central part of the intersection as shown in Fig. 4. The ants tend to distribute towards the nearby intersection leg instead of crossing each other at the central portion of the intersection. Shiwakoti (2010) recommended conducting further experiments and analysis to understand ants' peculiar way of avoiding

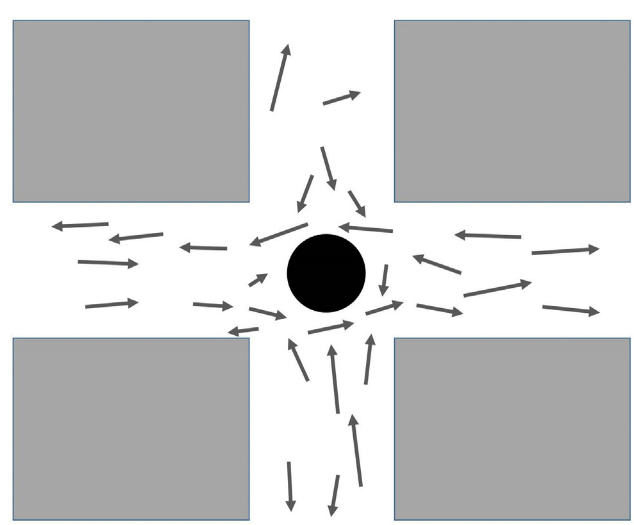

Fig. 3. Possibility of studying pedestrian streams in outdoor intersections or public squares by controlling the temporal roundabout traffic in intersecting pedestrian streams (shown by arrows) via a column (shown by filled circle).

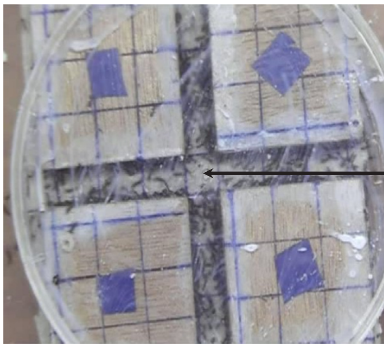

Fig. 4. Preliminary experiments showing organization of ant traffic at intersection under emergency conditions (Shiwakoti, 2010).

the conflicts, and observing the similarities and dissimilarities with pedestrians' traffic at the intersection under emergency conditions. Recently, Sun et al., (2018) investigated the impact of roundabout design (via a column) on intersecting pedestrian streams by conducting a series of experiments on pedestrians. It was observed that, although placing a roundabout at the intersection reduced the total space available and lengthened the average walking distance, the speed and volume of pedestrian stream was increased. Severiukhina et al., (2017), through their simulation, also observed that intersecting flows may significantly increase density and decrease average velocity in scenarios without obstacles. Likewise, simulation results from Jia et al., (2017) show that in a passageway without spatial obstacles, the evading and surpassing behavior will increase the evacuation time under the condition that the pedestrian number is larger than a critical value. It was also concluded that a circle-shaped obstacle performed better guiding function and a larger area of "evading region" as compared to a bar-shaped obstacle.

Therefore, the findings from these few studies demonstrate that there is a tremendous potential to test the effect of architectural adjustments to the pedestrian outflow in outdoor scenarios under emergency conditions. In future, more studies should investigate the obstacle performance associated with the other type of movement patterns (e.g., turning, merging) for outdoor scenarios.

A summary table summarising the five critical issues, key problems and future research directions as discussed above has been presented in Table 2.

In conclusion, in future we will see more study focusing on variety of scenarios at bottlenecks, potential problems, their consequences, and the outcome and effect of collective dynamics among different biological and physical systems. As such, this study will be a valuable resource to the researchers working into the topic of evacuation and crowd safety.

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