Effects of the body force on the evacuation dynamics

Abstract

1. Introduction

The Social Force Model (SFM) addresses two physical forces as *essential*: the "body force" and the "sliding friction". Both are inspired by granular interactions and were claimed to be necessary for attaining the particular effects in panicking crowds [1]. The "sliding friction" actually proved to be an essential feature of the "faster-is-slower" effect, although the role of the "body force" appears, at a first instance, not so clear [2, 3, 4].

The existence of a "body force" in the context of highly dense crowds (say, 5 to $10 \, \text{people/m}^2$) is a commonsense matter [5, 6]. Researchers, however, question the numerical setting for this force in the SFM context [7]. As a matter of fact, the usual setting by Helbing prevents the overlapping among pedestrians, but it is known to accomplish artificially high force levels [1, 7, 8, 9]. The force estimates from the SFM appear to be remarkably higher with respect to the reported real life data (say, an order of magnitude). The crowd motion simulations, however, present quite realistic results [7, 8, 10]. The point seems to be that the SFM focuses on the "incoordination phenomenon" due to clogging, missing the "individualistic" perspective of single pedestrians or very small groups [1, 5, 11].

Many researchers realized that modifying the SFM may (partially) surpass the misleading parameter setting. It was proposed that the pedestrians' psychological force (say, the "social force") should be suppressed in the context of highly dense crowds [12, 13, 14, 15], or smoothly quenched according to the crowd density [16]. The authors in Refs. [17, 18] further

proposed a rigid body model in order to completely avoid the overlapping phenomenon. This perspective dismisses any connection to a "sliding friction". Conversely, other authors tried to limit the pedestrians acceleration by introducing "static friction" between the pedestrians and the floor [19]. This kind of friction, however, reduces the effective willings of the pedestrians.

A meaningful (individualistic) numerical setting appears not available yet (to our knowledge). The reason is that different numerical settings can lead to the same crowd dynamics. Actually, only a small set of dimensionless "numbers" control the crowd dynamics [20]. These are similar to those encountered in other active matter systems (Péclet number, etc.) [21]. We may hypothesize that while the dimensionless "numbers" provide some kind of control on the "incoordination phenomenon" in crowds, only a few numerical settings can attain an "individualistic" meaning.

The numerical setting for the "faster is slower" effect presented by Helbing and co-workers is somewhat cumbersome Ref. [1, 10, 20]. Although a single parameter (say, the desired velocity v_d) is numerically varied to explain the phenomenon, the researcher looses sight of the dimensionless "numbers" that truly control the crowd dynamics. The setting in Ref. [1] also misses the "faster is faster" effect reported to occur at very high pedestrian densities [10, 22]. Alternatively, the empirical fundamental diagram raises as a point of reference for the SFM control parameters [23, 10].

The fundamental diagram exhibits the flux behavior for either low dense crowds (with seldom contacts between pedestrians) and highly dense crowds (dominated by body forces and sliding friction). The latter usually experiences a flux slowing down, but other behaviors are also possible [23, 24]. In light of our previous hypothesis, we may suspect that the modeling of the "flux slowing down" within the context of the SFM will require the proper setting of the (dimensionless) controlling parameters. We examined this working hypothesis in Ref. [20], but limiting the parameter exploration to the sliding friction, disregarding the body force.

We now widen the investigation on the parameter settings to include the one associated to the body force. We will focus on the complex interplay between the body force and the sliding friction among pedestrians. Recall that the interplay dynamics is not directly controlled by the numerical setting,

but through dimensionless "numbers", where the model parameters appear mixed between each other. Thus, this step up offers a challenge to the "individualistic" meaning of the parameter's setting.

The investigation is organized as follows. We first recall the available experimental values on the body force and the sliding friction (see Section 2). Secondly, we introduce the reduced-in-units SFM and the three dimensionless numbers that control the crowd dynamics (see Section 3). We present our numerical simulations in Section 4. For the sake of clarity, this Section is separated into two major parts: the bottleneck scenario and the corridor scenario in Sections 4.1 and 4.2, respectively. Section 5 opens a detailed discussion raising from of the results in Section 4. The last Section closes the investigation with our main conclusions.

2. Experimental background

3. Theoretical background

3.1. The Social Force Model

4. Results

4.1. Bottleneck

In this section, we present the results corresponding to the bottleneck geometry. We show how the overall dynamic of the system changes depending on the k value associated to the body force in the original SFM.

Fig. 1 shows the evacuation time as a function of the pedestrian's desired velocity. The evacuation time was defined as the time until 70% of the pedestrians left the room. The different markers correspond to different k values (*i.e* different body force stiffness). The crosses correspond to the Helbing original SFM parameter, the up triangles correspond to the value measured in Ref .. and Increasing the k reduced the evacuation time, squares correspond to an absent body force and circles correspond to an extreme value of stiffness (one order of magnitude higher than the original SFM). The down triangles correspond to an intermediate value between the empirical value presented in Ref... and the chosen by Helbing in Ref...

There is a noticeable difference in the evacuation time depending on the k value of the body force. The higher the k the smaller the evacuation time,

meaning that if pedestrians are stiffer the overall speed increases (hence the evacuation time).

The Faster-is-Faster (FIF) is the phenomenon in which under certain conditions, increasing the desired velocity yields to a reduction of the evacuation time. The Faster-is-Faster is the opposite effect (the higher v_d the lower the evacuation time). Notice that the presence of the faster-is-faster (FIF) effect and the faster-is-slower are dependent on the value of k. In Fig. 1 we can see that $k = 1.2$ E5 only exhibits FIS effect for $v_d > 2$ m/s. $k = 1.2$ E6 only shows FIF effect and the explored values of k that satisfy $k \leq 6$ E4 exhibit both the FIS and the FIF effect.
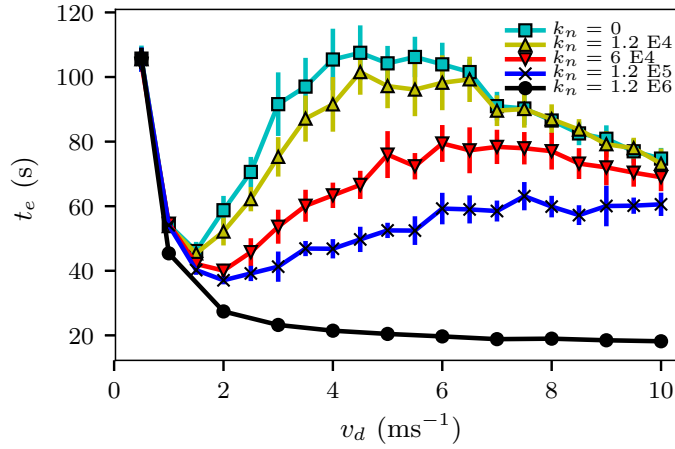
Figure 1: Mean evacuation time (s) vs. the pedestrians desired velocity (m/s) for a bottleneck. The room was 20 m x 20 m size. The door was 0.92 m width. Mean values were computed from 10 evacuation processes. 225 pedestrians were initially placed in a square lattice with a random initial velocity. Each process was finished when 158 pedestrians left the room. The different symbols indicate the k value corresponding to the body force (see the label).

Network analysis is a set of techniques that characterize the structures in a graph. We defined the graph of contacts among individuals. In this graph, each node represents a pedestrian and the link between a pair of nodes is settled if this pair of pedestrians are in physical contact (*i.e.* $r_{ij} < d_{ij}$).

Fig. 2a shows the mean degree of the contact graph as a function of the desired velocity. The degree of a node is defined as the amount of edges assigned to the node. This means, the number of pedestrians that are in contact with a given pedestrian. The mean degree is the average of the degree over all the nodes (pedestrians) and over the whole time from the stationary state until the end of the simulation.

Increasing v_d increases the mean degree in all cases. This happens because increasing v_d produces higher densities that force individuals to touch each other. For a given v_d the mean degree reduces as the k value increases. In other words, the stiffer the pedestrians the less they touch each other. We will later discuss that this phenomenon is a characteristic of the bottleneck geometry that cannot be extrapolated to the corridor geometry.

Fig. 2b shows the overlap as a function of v_d. The overlap is defined as $d_{ij} - r_{ij}$ where d_{ij} is the sum of radius of particle i and particle j and r_{ij} is the distance between both particles. In the range $v_d \geq 2$ m/s we can see that increasing v_d increases the overlap (for all the k values studied). For a given v_d, the overlap increases as the k value decreases. Reducing k means reducing the normal body force which allows a greater invasion of the personal space of the particles.

4.2. Corridor

4.3. Reduced-in-units equation of motion

5. Discussion

6. Conclusions

Acknowledgments

[1] D. Helbing, I. Farkas, and T. Vicsek. Simulating dynamical features of escape panic. *Nature*, 407:487–490, 2000.
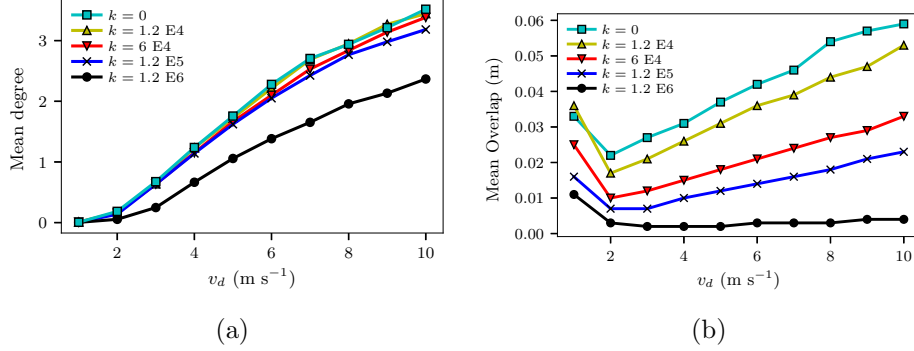
Figure 2: (a) Mean degree as a function of the pedestrians desired velocity (m/s). (b) Mean overlap as a function of the pedestrians desired velocity (m/s). Each symbol indicates the k value corresponding to the body force (see the labels). The data corresponds to a bottleneck with periodic boundary conditions (re-injecting pedestrians). The average was taken every two seconds once the crowd reaches the stationary state ($t = 20$ s) until the end of the simulation ($t = 110$ s).

[2] D. Parisi and C. Dorso. Microscopic dynamics of pedestrian evacuation. *Physica A*, 354:606–618, 2005.

[3] D. Parisi and C. Dorso. Morphological and dynamical aspects of the room evacuation process. *Physica A*, 385:343–355, 2007.

[4] G. Frank and C. Dorso. Room evacuation in the presence of an obstacle. *Physica A*, 390:2135–2145, 2011.

[5] Colin M. Henein and Tony White. Macroscopic effects of microscopic forces between agents in crowd models. *Physica A: Statistical Mechanics and its Applications*, 373:694 – 712, 2007.

[6] J. Fruin. The causes and prevention of crowd disasters. In R.A. Smith and J.F. Dickie, editors, *Engineering for Crowd Safety*. Elsevier, 1993.

[7] Taras I. Lakoba, D. J. Kaup, and Neal M. Finkelstein. Modifications of the helbing-molnr-farkas-vicsek social force model for pedestrian evolution. *SIMULATION*, 81(5):339–352, 2005.

[8] Paul A. Langston, Robert Masling, and Basel N. Asmar. Crowd dynamics discrete element multi-circle model. *Safety Science*, 44(5):395 – 417, 2006.
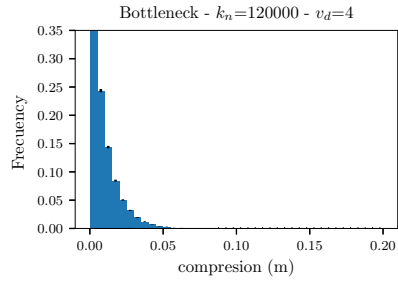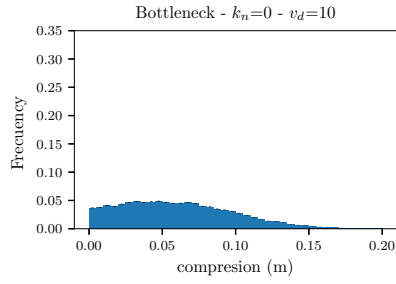
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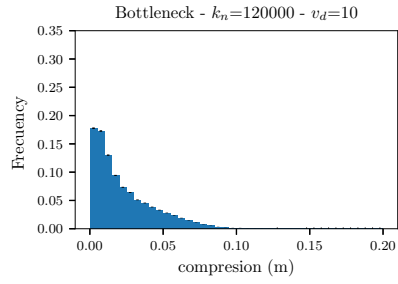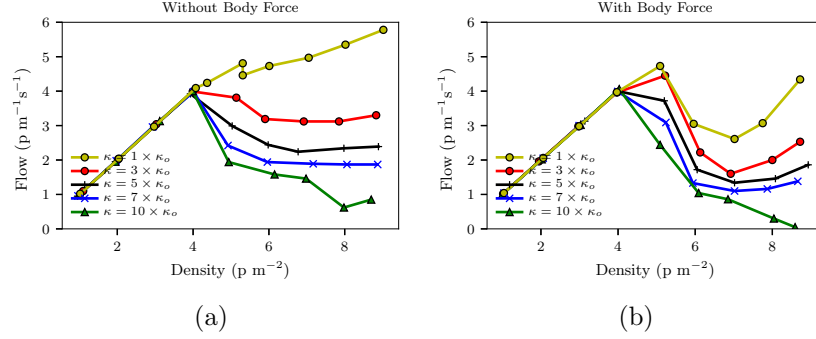
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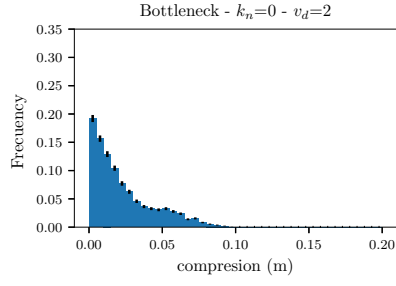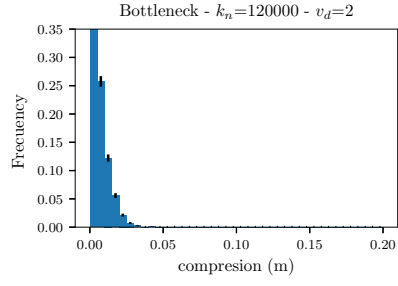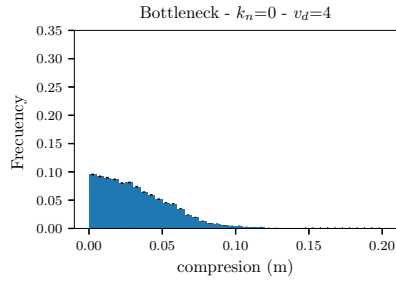
Figure 4:

[9] Peng Lin, Jian Ma, You-Ling Si, Fan-Yu Wu, Guo-Yuan Wang, and Jian-Yu Wang. A numerical study of contact force in competitive evacuation. *Chinese Physics B*, 26(10):104501, sep 2017.

[10] I. M. Sticco, F. E. Cornes, G. A. Frank, and C. O. Dorso. Beyond the faster-is-slower effect. *Phys. Rev. E*, 96:052303, Nov 2017.

[11] Rahul Narain, Abhinav Golas, Sean Curtis, and Ming C. Lin. Aggregate dynamics for dense crowd simulation. *ACM Trans. Graph.*, 28(5):122:1–122:8, December 2009.

[12] N. Pelechano, J.Allbeck, and N. Badler. Controlling individual agents in high-density crowd simulation. *Proceedings of the 2007 ACM SIG-GRAPH/Eurographics Symposium on Computer Animation*, pages 99–108, 2007.

[13] Mehdi Moussaïd, Dirk Helbing, and Guy Theraulaz. How simple rules determine pedestrian behavior and crowd disasters. *Proceedings of the National Academy of Sciences*, 108(17):6884–6888, 2011.

[14] Fernando Alonso-Marroquín, Jonathan Busch, Coraline Chiew, Celia Lozano, and Álvaro Ramírez-Gómez. Simulation of counterflow pedestrian dynamics using spheropolygons. *Phys. Rev. E*, 90:063305, Dec 2014.

[15] Arianna Bottinelli and Jesse L. Silverberg. How to: Using mode analysis to quantify, analyze, and interpret the mechanisms of high-density
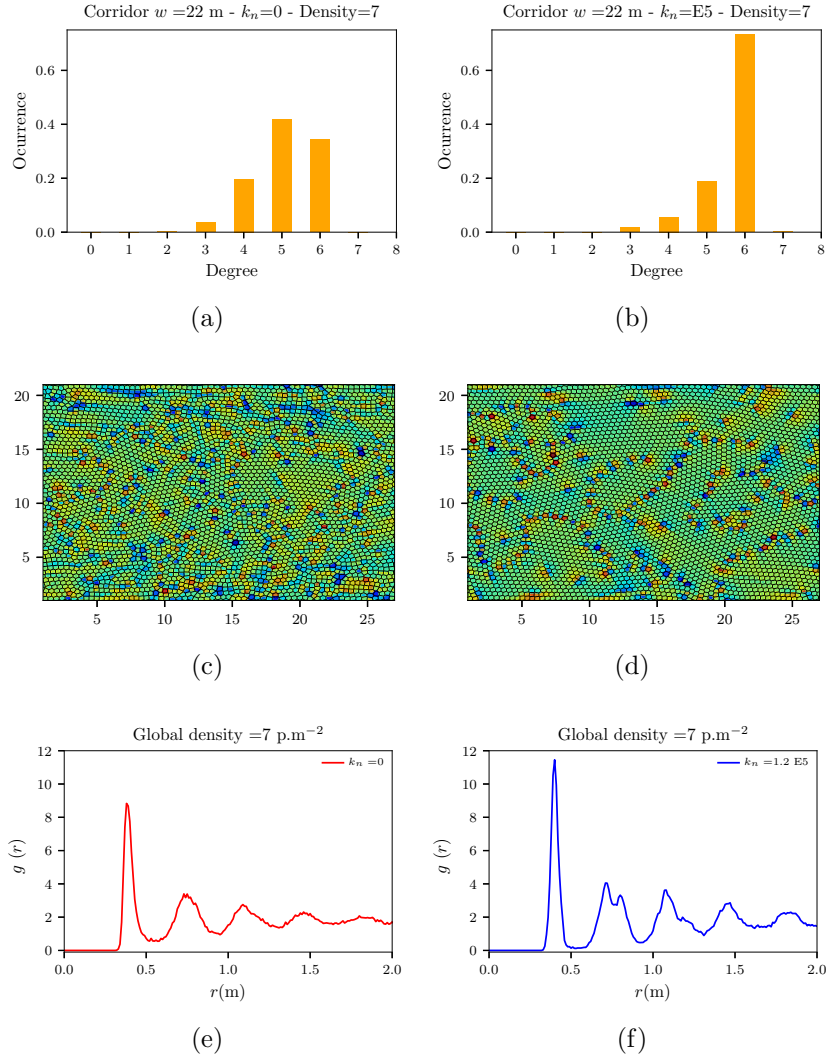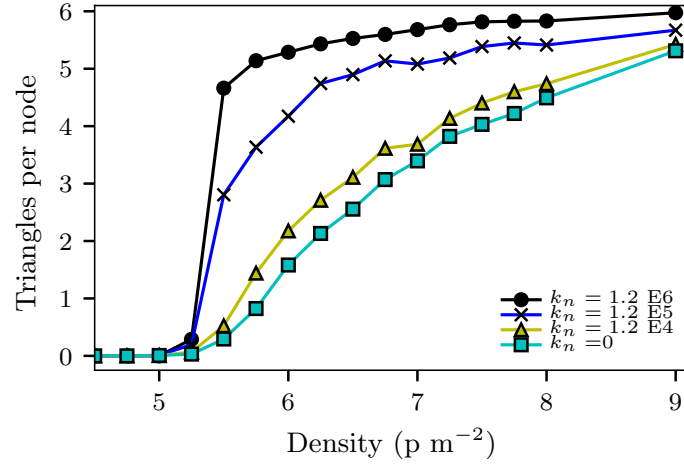
Corridor $w = 22$ m - $k_n = 0$ - Density=7

Corridor $w = 22$ m - $k_n =$E5 - Density=7

(a)

(b)

(c)

(d)

Global density $= 7$ p.m^{-2}

Global density $= 7$ p.m^{-2}

$k_n = 0$

$k_n = 1.2$ E5

(e)

(f)

Figure 5:

Figure 6:

(a)

(b)
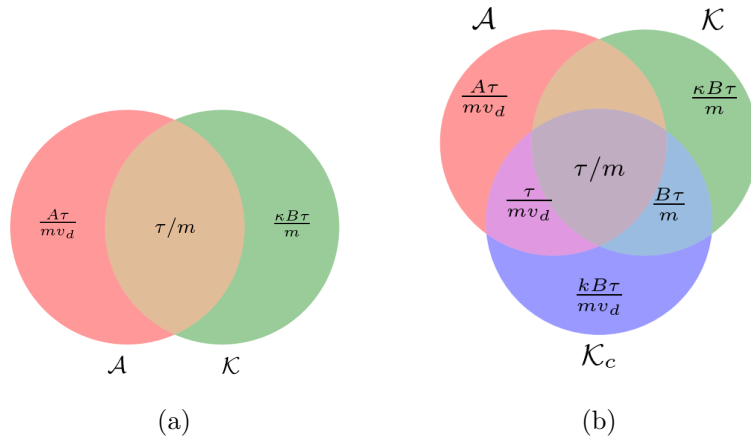
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collective motion. *Frontiers in Applied Mathematics and Statistics*, 3:26, 2017.

[16] J. Song, F. Chen, Y. Zhu, N. Zhang, W. Liu, and K. Du. Experiment calibrated simulation modeling of crowding forces in high density crowd. *IEEE Access*, 7:100162–100173, 2019.

[17] Bachar Kabalan. *Crowd dynamics : modeling pedestrian movement and associated generated forces*. Theses, Université Paris-Est, January 2016.

[18] A. Jebrane, P. Argoul, A. Hakim, and M. El Rhabi. Estimating contact forces and pressure in a dense crowd: Microscopic and macroscopic models. *Applied Mathematical Modelling*, 74:409 – 421, 2019.

[19] Litao Wang and Shifei Shen. A pedestrian dynamics model based on heuristics considering contact force information and static friction. *Transportmetrica B: Transport Dynamics*, 7(1):1117–1129, 2019.

[20] I.M. Sticco, G.A. Frank, F.E. Cornes, and C.O. Dorso. A re-examination of the role of friction in the original social force model. *Safety Science*, 121:42 – 53, 2020.

[21] Yaouen Fily, Silke Henkes, and M. Cristina Marchetti. Freezing and phase separation of self-propelled disks. *Soft Matter*, 10:2132–2140, 2014.

[22] Milad Haghani, Majid Sarvi, and Zahra Shahhoseini. When push does not come to shove: Revisiting faster is slower in collective egress of human crowds. *Transportation Research Part A: Policy and Practice*, 122:51 – 69, 2019.

[23] Dirk Helbing, Anders Johansson, and Habib Zein Al-Abideen. Dynamics of crowd disasters: An empirical study. *Phys. Rev. E*, 75:046109, Apr 2007.

[24] Rainald Lohner, Britto Muhamad, Prabhu Dambalmath, and Eberhard Haug. Fundamental diagrams for specific very high density crowds. *Collective Dynamics*, 2, 2018.