TSUNAMI EVACUATION IN A MASSIVE CROWD EVENT USING AN AGENT-BASED MODEL

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INTRODUCTION

Under emergencies, individuals tend to move faster than during normal conditions, i.e., evacuation vs non-evacuation scenarios (Helbing et al., 2000; Cornes et al., 2019; Chen et al., 2018). Evacuations because of false alarms, terrorist attacks, fires, or disasters like earthquakes or tsunamis can quickly increase stress levels in people. Activities such as carnivals, festivals, sports, pilgrimages, and marches gather thousands of people in one place. For instance, on 27th October 2019, a massive demonstration occurred between the cities of Viña del Mar and Valparaíso, gathering 100.000 people in the streets of Valparaíso in Central Chile (El Desconcierto, 2019).

In the literature, open space tsunami evacuations in places such as beaches are scarce. Studies from Takabatake et al. (2018) and Lanza et al. (2021) have integrated beach users in their simulations. However, studies involving massive tsunami evacuations including socio-psychological interactions, to our knowledge, are not documented.

The main objective of this study is to assess human behavior in a hypothetical scenario such as a massive tsunami evacuation in a coastal area, using Valparaíso City as a case study. Here, two cases are implemented in an agent-based model. The first scenario attempts to reproduce the demonstration as it was, meaning people walking at a relaxed velocity, while the second case consists in a hypothetical massive tsunami evacuation. One of the specific objectives of this research is to incorporate the “tsunami evacuation stress” in the Social Force Model (SFM). For this, a method is proposed to spread the stress among agents in the crowd. Then, by comparing metrics such as evacuees per unit of time, flow/density relationship, and velocities with the case base scenario (no tsunami), the impact of the “tsunami evacuation stress” will be discussed.

METHODS

Social Force Model (SFM)

$$m_i \frac{dv_i}{dt} = f_d + \sum_{j=1}^{N} f_{ij} + \sum_{j=1}^{N} f_g \qquad (1)$$

The Social Force Model (SFM) is a continuous microscopic physics-based method extensively used in pedestrian dynamics. The SFM in the context of escape panics (Helbing et al., 2000) utilizes Newton’s motion equations to account for changes in velocity of N pedestrians over time (dv_i/dt) considering three forces: the desired force (f_d) (driving force), the social force (f_{ij}) (repulsive force), and the granular force (f_g) (repulsive force) accounting for physical contact at high densities (body force and sliding friction) in pedestrian-pedestrian or pedestrian-wall interaction as shown in Equation 1.

$$f_d = m_i \frac{v_d^i(t)\, e_d^i(t) - v^i(t)}{\tau} \qquad (2)$$

The driven force (f_d) in Equation 2 represents the willingness of pedestrian i with mass m_i to reach the desired location (i.e., safe zone or evacuation shelter) while moving in the desired direction ($e_d^i(t)$) at the desired velocity ($v_d^i(t)$). Interaction between the environment and other pedestrians induce deviations (acceleration/deceleration) from the desired velocity, moving instead, at the current velocity ($v^i(t)$). At each time step, pedestrians attempt to reach the desired velocity, here, the relaxation time (τ) is introduced to account for the pedestrian’s attitude. Helbing & Molnár (1995) suggests 0.5 s is a good approximation for the relaxation time, smaller values make individuals move in a more reactive/aggressive fashion. In this study, for the hypothetical tsunami case, a lower value of 0.4 is used to account for individuals in a hurry (evacuation).

$$f_{ij} = A_i\, e^{(rij-dij)/Bi}\, n_{ij} + k_n\, g(r_{ij} - d_{ij})\, n_{ij} + k_t\, g(r_{ij} - d_{ij})\, \Delta v_{ij}^t\, t_{ij} \qquad (3)$$

The socio-psychological force or social force (f_{ij}) accounts for the pedestrian-pedestrian and pedestrian-wall/objects interaction. In Equation 3, the social force equation for pedestrian-pedestrian interaction including both socio-psychological and physical (contact) forces. As individuals prefer to maintain a certain distance from others and walls, the personal space is represented by the pedestrian radius (r_i). The interaction is governed by a repulsive force (exponential function decay) where A_i (strength of the social interaction) and B_i (reach of the social interaction) are constant values. n_{ij} is the unit vector pointing from pedestrian j to i. If the distance between the pedestrian’s centre of mass is larger than the sum of pedestrian i and j radius ($d_{ij} > r_{ij}$) individuals do not touch each other. On the contrary, if $r_{ij} > d_{ij}$ (the sum of the pedestrian’s radius is larger than the distance between pedestrian’s centre of mass) individuals are in contact, therefore, a physical force f_g (normal and tangential) is generated. k_n is the body force coefficient, k_t is the sliding friction coefficient, and $g(r_{ij}\text{-}d_{ij})$ is a Heaviside function equal to zero when agents are not in contact, otherwise equal to the argument. Lastly, the term $\Delta v_{ij}^{t}\ t_{ij}$ is the difference in velocities between pedestrian i and j in the tangential direction t_{ij}.

$$f_g=A_{iw}\ e^{(ri\text{-}diw)/Biw}\ n_{iw}+ k_n\ g(r_i\text{-}d_{iw})\ n_{iw}+ k_t\ g(r_i\text{-}d_{iw})\ \Delta v_{iw}^{t}\ t_{iw} \tag{4}$$

In Equation 4 the social force for pedestrian-wall interaction. The repulsion is governed by the constant parameters A_{iw} and B_{iw} (strength and reach of the social interaction, respectively), the difference between any given pedestrian i radius (r_i) and the normal distance to the wall (d_{iw}), and the unit vector pointing from the wall towards the pedestrian (n_{iw}). The term $\Delta v_{iw}^{t}\ t_{iw}$ is the difference in velocities between pedestrian i and the wall in the tangential direction t_{iw}.

Agent-based model

In this study, the SFM is implemented using an Agent-based model (ABM) in NetLogo. NetLogo software utilizes a bottom-up approach for simulating complex systems. The main idea behind ABM is the capability for modelling systems or phenomena, using agents, an environment, and agent-agent/agent-environment interaction. One of the properties of complex systems is emergent phenomena. This phenomenon is the consequence of the mutual interaction between heterogenous adaptive individuals and the environment, even when using very simple rules (Wilensky & Rand, 2015).

The NetLogo environment was set as a unidirectional corridor where the crowd walk from left to right as shown in Figure 1. Agents are created in the purple vertical line and navigate throughout the environment until they reach the destination (evacuation route) represented as a vertical brown line. Boundaries (walls) are in lime color. Agents in magenta and lime colors correspond to female adults and female children. Light blue and orange colors represent males (adults and children).

Chen et al. (2018) and Sticco et al. (2021) mentioned the pedestrian mass and radius (biacromial breadth/2) follow a Gaussian distribution. In this study, to add heterogeneity to the model, a gaussian distribution is implemented for mass and radius values.

Anthropometric data was collected between April-September 2016 from Chilean workers (adults 18-65+ years old) in the Valparaíso and Metropolitan Region by Viviani et al. (2020). For kids and teenagers, data from students between 6 to 18.9 years old compiled by Gomez-Campos et al. (2019) in Maule Region from March to November of 2014 and 2015 was used to estimate the gaussian distribution of mass for children (Table 1).

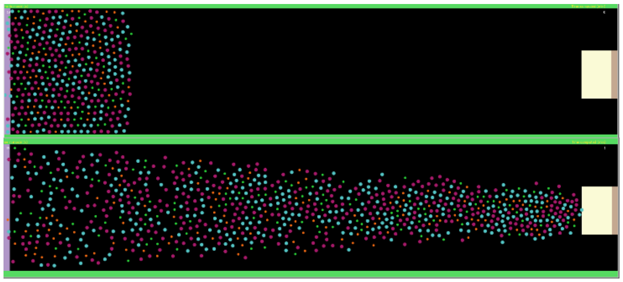

Figure 1 The SFM implemented in NetLogo. Snapshot for the no tsunami case (top) and tsunami case (bottom) at 560 ticks

Secondary data from a YouTube video was used to obtain the crowd velocity. From a drone recording with a duration of 04:01 (mm:ss) in the streets of Viña del Mar, Valparaíso's neighboring city, a velocity of 0.66 m/s (Table 1) was obtained (refer to Fredes, 2019). This velocity will be considered representative of the whole crowd moving from Viña del Mar towards Valparaíso city (the crowd was ~ 7 km long).

Table 1 Set of parameters for cases with and without tsunami

Parameter	Details	
m_i	Adults: 74.15 kg (average female and male). Female child: mean 54.6 kg SD 10.7. Male child: mean 58 kg SD 11.4	
r_i	Female: mean 0.43 m with SD 0.034. Male: mean 0.48 m with SD 0.030. Children: 0.20 m	
k_n	1.2 x 10^5 Kg/s^{-2} (from Helbing (2000))	
$v_d^i(t)$	1 m/s	Equation 6
$v^i(t)$	0.66 m/s (from Fredes, 2019)	
τ	0.5 s (Helbing (2000))	0.4 s
A_i/A_w	10 N (*) /2000 N (from Helbing (2000))	
B_i/B_w	0.13 m (*) /0.08 m (from Helbing (2000))	

(*) need further calibration

Tsunami stress propagation

The studies of Cao et al. (2021) and Cornes et al. (2019) have used sigmoid and exponential decay functions for stress variation during evacuations. This study follows a similar approach to estimate the "tsunami evacuation stress" where changes in velocity due to an increase in stress is accounted in the desired force (Equation 2). The understanding here is that stressed pedestrians tend to move faster. Hence, their desired velocities are higher when compared with non-emergency situations (case base scenario).

In this investigation, a sigmoid function that varies in the interval [0,1] where 1 represents the highest tsunami stress level and 0 is the lowest tsunami stress level, is proposed in Equation 5. The agent stress depends on the distance to the exit ($d_i^{exit}(t)$), representing a tsunami evacuation route. The longer the distance the higher the stress. The shortest the distance the lower the stress. The k value represents the slope of the sigmoid function.

$$S_i^t=\frac{1}{1+ e^{(-k^*d_i^{exit}(t))}} \tag{5}$$

In Equation 6, the piecewise function for fluctuations in the desired velocity due to the tsunami evacuation stress. For the high stress level, a maximum velocity of 5 m/s is proposed based on Helbing et al. (2000). The slow stress velocity value is from secondary data (Table 1). Intermediate stress level corresponds to Cao et al (2021). Additional research is needed in the context of tsunami evacuation for updating this value, this is a preliminary proposal.

$$v_d^i(t) = \begin{cases} 5 & \text{high stress} \\ 3 * S_i^t + 0.6 & \text{intermediate stress} \\ 0.66 & \text{low stress} \end{cases} \qquad (6)$$

PRELIMINARY RESULTS AND DISCUSSION

In Figure 2, the flux of agents measured in the yellow squared (Figure 1) for the tsunami and no tsunami case. Thicker dark red and dark blue lines represent the mean for 30 simulations of 4000 ticks for each scenario. In the tsunami case (red dashed area) because of the influence of the stress level, agents have higher desire velocity, reaching the exit sooner than agents in the no tsunami case. The number of agents between both cases varies due to fluctuations in the desired velocity, where agents in a relax state (no tsunami) exhibit a more compact shape crowd when compared with the tsunami case, where a more disperse and rounded shape is shown (Figure 1).

Further parameter calibration is needed to fix the oscillations (see light purple line for the no tsunami case). Also, from the simulations is not clear the influence of the slope k in the evacuation behavior.

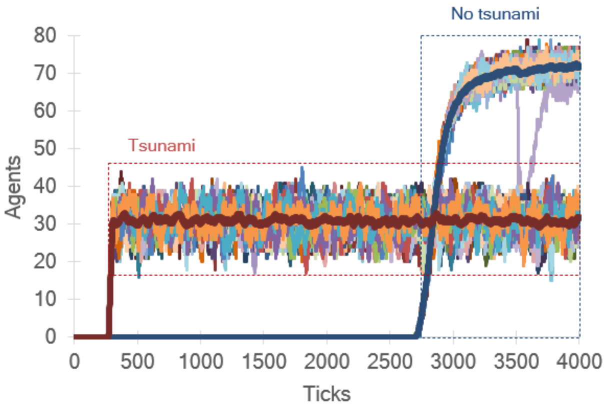

Figure 2 Flux of agents for tsunami and no tsunami case

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