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An agent-based model for earthquake pedestrians' evacuation simulation in urban scenarios

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Abstract

The earthquake risk assessment approach actually ignores human behaviors during earthquake. Nevertheless, simulating pedestrians' motion could be useful to introduce "human" interactions with post-earthquake scenarios. This work proposes an agent-based model for evacuation simulation based on the analysis of videotapes concerning real events. Modifications to the social force model are provided in order to describe typical behaviors. A simulation software is developed for model validation. Tests mainly involve speeds and distances between individuals. The model could be integrated in tools for the analysis of probable pedestrians' choices in different scenarios, and checking solutions for reducing man-environment interferences during the evacuation process.

1. Introduction

The earthquake risk assessment at urban scale is actually based on the definition (Ambraseys (1983)) of three parameters: the site hazard H (Klügel, 2008), the buildings vulnerability V (Federal Emergency Management Agency (2009)) and the exposition E (Chen et al. (1997)). In particular, the exposition parameter E defines only the number of individuals in the scenario and the presence of buildings with historical and artistic value, but does not

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consider human behaviors during both the event and the following evacuation. Nevertheless, human behaviors and by interactions between people and post-event environment represent one of the most influencing element in the inhabitants safety definition. Understanding, defining and simulating human behaviors and rules for pedestrians' motion in these emergency conditions become essential in order to really introduce the "human" factor influence in the risk assessment. Integrated "risk maps" could be designed through the combination of evaluations related to traditional parameters and results of human behaviors analyses. Finally, the community resilience (Cutter et al. (2008)) could be evaluated by analyzing evacuation procedures effectiveness through simulations (Chen et al. (2012)).

This work approaches the problem from this point of view and proposes an earthquake evacuation simulator in order to analyze the influence of behavioral effects, and so to inquiry the E parameter. Firstly, individuals in post-earthquake evacuation move in an environment that is modified by the earthquake. The post-event scenario definition can essentially be founded on correlations between building type and vulnerability (Calvi et al. (2006)), seism intensity and possible grade of damage (Grünthal (1998)) or average damage index (Giovinazzi and Lagomarsino (2004)). In this way, consequent scenarios can be defined by estimating the probable percentage of building within a certain damage level (Federal Emergency Management Agency (2009). Nevertheless, environmental aspects and human behavioral aspects have to be contemporarily considered by a similar simulator. For these reason, two other issues are needed: human behaviors in earthquake evacuation (Alexander (1990)); pedestrians' motion simulation models (Helbing and Johansson (2010), Lakoba et al. (2005)).

A limited number of works investigate earthquake evacuations (Alexander (1990), D'Orazio et al. (2014), Yang et al. (2011)). They are often strictly connected with precise case studies or are based on hypothetical questionnaires (Miyamoto et al. (2011)). The analysis of videotapes related to real earthquake evacuation is rarely performed (D'Orazio et al. (2014), Yang et al. (2011); However, general noticed behaviors concern the inferior limit in event perception (Grünthal (1998)), "pre-movement" phase, cohesion bonds (Alexander (1990)), influence of geographical background (Alexander (1990)), and the so called "fear of buildings" (Alexander (1990)), with frightened people that prefer to run out of buildings during the earthquake. The analysis of average speeds in evacuation is provided (D'Orazio et al. (2014), Hori (2011)). Only some of these studies organize empirical data in order to define a chronological scheme of them during their evacuation process (Alexander (1990), D'Orazio et al. (2014)) and an evacuation simulation model (D'Orazio et al. (2014), Hori (2011)).

Many models can simulate human behaviors and motion in both normal and evacuation conditions by using different approaches (Zheng et al. (2009)). Models can be also distinguished by different definitions of space and time (Lakoba et al. (2005)). In particular, continuous-space models uses a continuous 2-D or 3-D environment description: individuals can move continuously in space and time, and they are guided by different motion approaches (Helbing and Johansson (2010); Hughes (2002)). The "Social Force model" (Helbing and Johansson, (2010), Lakoba et al. (2005), Parisi and Dorso (2005)) takes advantages of these powerful features and founds its motion law on the real evacuations analysis: pedestrians' motion behaviors are defined in terms of attractive and repulsive forces, that are due to the interactions between people and environment, and that lead individuals to achieve their motion goal. Parameters for introducing panic conditions are also suggested (Lakoba et al. (2005)).The Social Force model can be combined with rules-based models (Rabiaa and Foudil (2010)) and discrete models and space representation (Zheng et al. (2009)). However, the original model cannot be applied to earthquake evacuations for the lack of inquiries about this case. Finally, few studies proposes the integration of behavioral simulators in the earthquake case (Hori (2011)).

Behavioral aspects and scenario modifications are jointly considered in our simulation model. For this reason, the agent-based approach (ABM) (Macal and North (2010)) is adopted in order to describe the specific agents and to trace the interactions between them. In addiction, the ABM architecture can be easily combined with "Microscopic dynamics of pedestrian evacuation" approaches (Parisi and Dorso (2005), Zheng et al. (2009)), such as the social force model, with the purpose to produce realistic simulations (Rabiaa and Foudil (2010)).

This paper proposes an ABM model that takes advantages of the social force model for the pedestrians' motion description. Modifications to the social force model are provided in order to include earthquake evacuation behaviors noticed from experimental analysis, including interferences between man and post-earthquake environment. Both ABM and social force model approaches share the same "Lagrangian" methodology (Rabiaa and Foudil (2010)): interactions between agents produce phenomena and quantitative values that are comparable with the

experimental ones for the whole system. The validation phase is aimed by this verify. This paper offers a summary of noticed evacuation behaviors, model definition, its implementation, and first results, focusing on attractive phenomena and motion speeds. The model is proposed for evaluating probable pedestrians' choices in different scenarios, and checking solutions for reducing interferences between environment and evacuation processes.

Nomenclature

C_{ij}	cohesion parameter (N)
$d_{ij}(t_n)$	actual distance between the two pedestrian i, j
$D_{min,gr}$	maximum distance for group attraction (m)
F_{attr}	modulus of attractive force (N)
F_{rep}	modulus of repulsive force between the actual pedestrian, other pedestrians and the environment (N)
$\varepsilon(t)$	modulus of random variation of forces (N)
$v(t)$	modulus of pedestrian velocity at instant t (m/s)
m_i	pedestrian's mass (kg)
O_g	modulus of drive-to-target force (N)
$p_{gr,i}(t)$	position of the geometric centre of the i's group
$p_i(t)$	position of the pedestrian at instant
$P_{s,e}$	probability $P_{s,e}$ to reach a certain safe area s using a certain evacuation path e
t	instant of evaluation (s)
$\Theta(d_{ij}(t_n)-D_{min,gr})$	Heaviside step function related to the actual distance between i and j and the maximum value for group attraction; 0 if $d_{ij}(t_n)<D_{min,gr}$, 1 anywhere

2. Phases, model structure and validation criteria

2.1. Phases

This work is organized in the following phases (relative paragraphs are in brackets, in italic):

- evacuation behaviors definition by experimental analysis (Evacuation behaviors)
- evacuation model definition, with description of agents interactions and motion criteria (Model definition)
- model implementation in a simulation software (Software implementation)
- model validation through the software (Validation)

In the first phase, a database of about videotapes of earthquake evacuations from all over the World (available at at https://drive.google.com/?authuser=0#folders/0B91jqaXLKo5LTFlqbnplS0tJLTQ; in the text below, database reference numbers are written in brackets) is analyzed in order to provide a list of noticed "evacuation behaviors". Outdoor and indoor spaces, including both public and private ones, are analyzed. Each videotape involves a perceptible event (magnitude higher than a 5th degree in the Richter Seismic Scale - IV degree in EMS-98 scale) (Grünthal, 1998) with confirmed date, geographical localization and magnitude. Results extend the one of a previous work (D'Orazio et al. (2014)). "Evacuation behaviors" are defined by the set of actions that a pedestrian carries out during the evacuation procedure in relation to both environment and other people. Each behavior must be present at least in the 30% of cases and is classified as "common to other kinds of evacuation" and "specific of this case". A summary of videotapes numerical inquiry of motion is offered. Average speeds and distances between member of the same evacuation group are provided through the open-source image analysis software "Tracker" (Brown and Christian (2011)). Concerning average distances, only values up to 3 meters (maximum distance for interaction phenomena activation (Lakoba et al. (2005)) are taken into account (in approximation to 0.1m).

2.2. Model structure and validation criteria

The model (and the related simulation software) is ABM based, and follows the chosen "Lagrangian" approach. Interactions and dependencies between agents are expressed in the intentional model, that is represented using the i* graphical modeling language (Yu (2009)). The model is composed by two parts. The *intentional model* describes the general characteristics of the agents involved in the evacuation procedure and the relationships between them. The *motion criteria* involve the effective motion law and evacuation choices for each single agent. The motion law uses the Social Force Model approach, with integrations due to the case study. A software is implemented on these bases in order to test and validate the model. The validation consists in a comparison between software results and experimental analysis data and previous studies results. Following the adopted "Lagrangian" approach, interactions between agents have to produce phenomena and quantitative values that are similar to the experimental ones for the whole system. The validation step wants to verify this statement. A part of an Italian historical city center (Corinaldo, AN) is chosen as evacuation environment; different scenarios are obtained by varying involved people number and earthquake magnitude. Ten simulations are performed for each scenario; average values and standard deviations are calculated. Groups of individuals are evaluated in order to retrieve their "average behavior". Provided results mainly concern attractive phenomena in group motion and average speeds tendency during evacuation time.

3. Results

3.1. Evacuation behaviors

Results of the videotapes database analysis extend the ones of our previous work (D'Orazio et al. (2014)) and confirm the outcomes of previous studies (Alexander (1990), Hori (2011)). Table 1 summarizes a list of evacuation behaviors and, for each behavior, expresses a short description, the scenario condition, the statistical frequency referred to the examined videotapes with the same scenario conditions, and the related elements for activation.

Table 1. Evacuation behaviors summary: behaviors with * are common to other evacuation kinds.

Evacuation behaviors (and main reference)	Scenario condition	Frequency (%)	Reference elements
evacuation needed for sensible events with information exchange (Alexander, 1990; Grünthal, 1998)	indoor + outdoor	69	environment + pedestrian
attraction towards safe areas (Helbing and Johansson, 2010)*	indoor + outdoor	85	environment
repulsive mechanisms to avoid physical contact from obstacles and other individuals (Helbing and Johansson, 2010)*	indoor + outdoor	68	environment + pedestrian
"Herd Behavior" and influence of "collective" velocity (Helbing and Johansson, 2010)*	indoor + outdoor	65	pedestrian
attraction between members of the same evacuation group (D'Orazio et al., 2014; Helbing and Johansson, 2010)*	indoor + outdoor	84	pedestrian
motion to the nearest visible safe area, using the "clearest" path (Alexander, 1990; D'Orazio et al., 2014)	outdoor	65	environment + pedestrian
keeping a "safety distance" from buildings, rubbles and ruins (Alexander, 1990; D'Orazio et al., 2014; Lakoba et al., 2005)	outdoor	73	environment
not keeping a "safety distance" from trees, shelters and street furniture (D'Orazio et al., 2014)	outdoor with "low obstacles"	84	environment
outdoor evacuation interruption for high ground shaking (Alexander, 1990; Grünthal, 1998)	outdoor	38	environment
evacuation groups formation (D'Orazio et al., 2014; Helbing and Johansson, 2010) *	outdoor	81	pedestrian
increased guide effect for presence of rescuers or evacuation plans (D'Orazio et al., 2014)	presence of rescuers / evacuation procedure	86	rescuer

Some behaviours are also noticed by studies referring to other kind of evacuations (Helbing and Johansson (2010), Lakoba et al. (2005)), while others are peculiar of the earthquake case. A short comment is needed for the path choice depending on the surrounding environmental conditions and for attraction phenomena between the members of the same evacuation group. During his motion, a pedestrian is attracted by areas considered "safe" for their geometric characteristics, their low level of damage and social factors (Alexander (1990), D'Orazio et al. (2014)): squares, large avenue, crossroads can be partial and/or final outdoor evacuation targets. A pedestrian usually selects the widest and clearest of dust and rubble path, especially in a close urban fabric (Alexander (1990), D'Orazio et al. (2014)) {9, 19, 23, 24, 29}. Cohesion bonds can affect also this individual's path choice. In particular, an individual, in his path choice, is influenced by other pedestrians' choices: the probability to follow the path chosen by a large number of individuals is higher than the probability to use another evacuation path {10, 21}. These cohesion bonds are connected with an attractive phenomenon: pedestrians which share the same bond avoid the dispersion between them during the evacuation procedure (D'Orazio et al. (2014)). Different bond causes could be introduced (e.g.: familiar bond, simple shared evacuation target). The first individual (white arrow) in Fig. 1a hastens in evacuation in respect to other people that share with him a cohesion bound: for this reason, he stops himself and decides to waiting for the other pedestrians (black arrows), as shown in Fig. 1b. The analysis of a videotape {21} involving about 50 pedestrians shows an average distance between people in the same evacuation group (average pedestrians' density of about 0.25 person/m^2) equal to 1.8m, with a standard deviation of 0.1m.
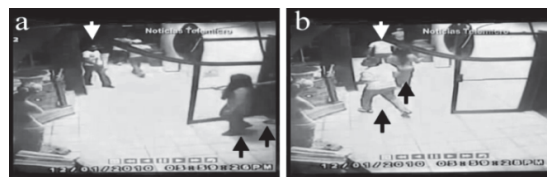

Fig. 1. visual example of "cohesion bound" in two different frames {1}.

Finally, about average speeds, the maximum measured value is about 4.0m/s; the outdoor average speed in earthquake evacuation is calculated in 2.1m/s {21}, with a standard deviation of 0.3 m/s, with an average pedestrians' density of about 0.25 person/m^2. This value is referred to the single analyzed videotape but confirms previous studies (Hori (2011)).

3.2. Model definition and motion criteria

The database analysis and the definition of *"Evacuation behaviors"* allow to trace the presence of three main agents involved in earthquake evacuation (compare to Table 1, 4th column). The *Pedestrian*, to perform his actions, refers to other *Pedestrians*, to the physical *Environment* (building, ruins, seismic parameter, environmental parameters) and to instructions of the *Rescuer*. An ABM architecture is chosen in order to simulate the earthquake evacuation process: Fig. 2 shows the "intentional model", expressed in i* language (Yu (2009)). Relationships between the agents, their relative resources, goal and tasks are represented. In the following description, the relative figure blocks are indicated in italics.

The *Environment* involves the characteristics of the physical scenario: fundamental seismic data (duration, EMS magnitude, PGA - *seism parameters*), urban fabric including the position and dimension of paths and safe areas (*path characteristics*, *safe areas*), position of trees and street furniture (*"low" obstacles*), position and vulnerability of buildings (*buildings*). Modifications in the initial scenario due to the earthquake are considered by introducing the presence of *ruins* (Grünthal (1998)). *Agent i* and *Agent j* are both playing the *Pedestrian*'s role. Each of them is characterized by different *agent parameters* (average motion speed, radius and mass (Helbing and Johansson (2010), Lakoba et al. (2005)) in order to define different *Pedestrian*'s kind (child, adult, pedestrian with disability). A *Pedestrian* interacts with the *Environment* and with the *Rescuer* when present in order to reach his chosen evacuation target (*path choice*) by maintaining a certain speed and a certain motion direction (*calculate motion*). He

decides to evacuate in some particular conditions (*decision to evacuate*). In his motion, he avoids "dangerous" obstacles, such as *ruins* and high *buildings*, and can be attracted by *"low" obstacles* (*obstacle influence*). He evaluates other *Pedestrians'* positions (*influence of other pedestrians*) and keeps a certain distance from them in order to both avoid collisions (*avoid collision*) and maintain an eventual group bound (*attraction for group bounds*). Finally, the *Rescuer* could represent the physical individuals that interact with *Pedestrians* by giving them information during the procedure, or the known evacuation plan.
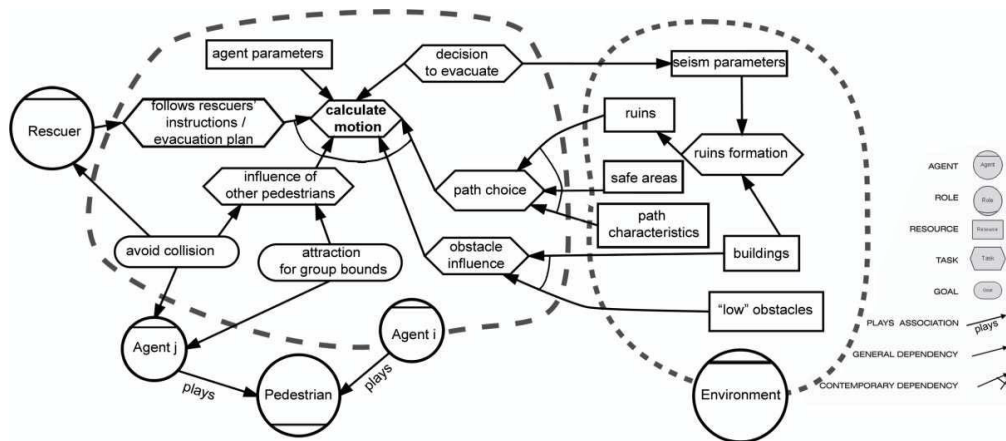

Fig. 2. the intentional model expressed by i* language.

Pedestrian's motion criteria numerically describe people decisions during evacuation, in terms of both evacuation choices and motion law. In particular, Equation 2 resumes the general motion law (Helbing and Johansson (2010), Lakoba et al. (2005)): attractive forces involves the presence of the "attraction between members of the same evacuation group" phenomenon (see Table 1) (Helbing and Johansson (2010)).

$$m_i \cdot \frac{d\vec{v}(t)}{dt} = \vec{O}_g + \sum \vec{F}_{rep} + \sum \vec{F}_{attr} + \varepsilon(t) \tag{1}$$

In fact, *Pedestrians* who share a "group bound", including the sharing of the same evacuation target, are influenced in motion by attractive phenomena. Equation 3 describes the definition of this attractive force, also according to previous studies (Helbing and Johansson (2010)). The "centroid method" is used for defining the target point of this group attraction (Bandini et al. (2013)), with the purpose to directly involve considerations about distances between *pedestrians*. The i's group (gr,i) is composed by other *Pedestrians* sharing the same "group bound" and surrounding i in a maximum radius $D_{min,gr}$=3m (Lakoba et al. (2005)). The minus sign characterizes an attraction force from i to i's group center. On the contrary, repulsive phenomena are described by vector pointing to i position (positive sign). The attractive force vector depends on the overlapping of various attractions given by possible different groups. Finally, the modulus of this force is based on the C_{ij} value: different values could be assigned for the different bond causes.

$$\vec{F}_{attr}(t_n) = \sum_{gr,i} \vec{F}_{attr,gr,i}(t_n) = \sum_{gr,i} -\Theta\left(d_{ij}(t_n) - D_{min,gr}\right) \cdot \left(C_{ij} \cdot \frac{\vec{p}_i(t_n) - \vec{p}_{gr,i}(t_n)}{\left\| \vec{p}_i(t_n) - \vec{p}_{gr,i}(t_n) \right\|} \right) \tag{2}$$

3.3. Software implementation

The model is implemented in a simulation software through the TROPOS methodology (Bresciani et al. (2004)) in TAJ environment (Paglierecci et al. (2008)), by using Alan and Java languages. A discrete representation of *Environment* is used: each squared grid cell has a dimension equal to the radius for a adult *Pedestrian* (0.35m) (Lakoba et al. (2005)). *Environment* data are imported through a BITMAP file describing urban layout and buildings characteristics. About *Pedestrian*, each individual position is updated each 0.1s by solving Equation 1 with the application of the Euler's method in a separate way for the two axes. Fig.3 shows some interfaces examples.
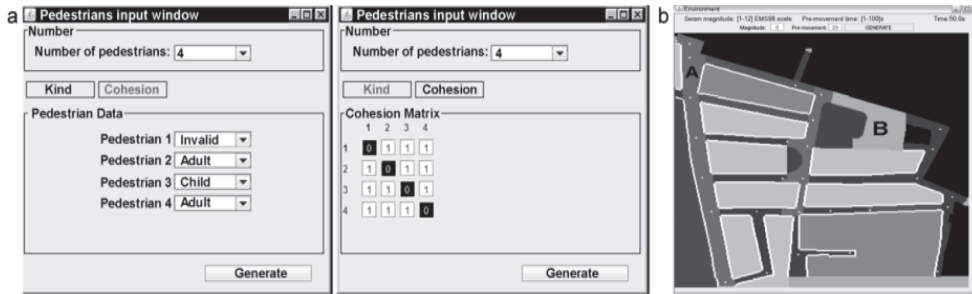

Fig. 3. (a) pedestrians' input window; (b) environment window with A-evacuation path and B-safe area.

Table 2 resumes the *Pedestrians'* characteristic parameters (Gates et al. (2006), Lakoba et al. (2005)). In particular, *hand-assisted child* parameters are connected to the presence of a child jointly to an adult. According to videotape results and previous studies (Lakoba et al. (2005)), a general maximum speed of 4.5m/s is imposed. Finally, the same C_{ij} value is assigned for both people sharing the same evacuation target and a group bond.

Table 2. Pedestrian's characterization.

Pedestrian's type	Radius (m)	Mass (kg)	Desired speed (m/s)
Adult	0.35	80	1.46
Hand-assisted child	0.45	100	1.22
Invalid	0.35	80	1.16

3.4. Validation

Validation criteria are defined in paragraph 2.2. Firstly, Fig.4 shows the influence of the cohesion parameter (up to 800N) on average values of principal group motion quantities. Fig.4a demonstrates how C_{ij} values higher than 400N generate unacceptable acceleration values: in fact, over this value, the instantaneous acceleration (continuous line) becomes higher than the literature limit of 0.2g (horizontal dashed line) (Lakoba et al. (2005)). Fig. 4b shows the relation between C_{ij} and averages distance between members of a same evacuation group (dashed line) and people in the evacuation group that are also sharing a group bound (continuous line). An average distance of about 1.7m is obtained for C_{ij}=50N, according to the experimental value. People sharing also a "group bound" prefer to stay closer because of their initial positions in outdoor motion (people exiting from the same building) (Helbing and Johansson (2010)). Fig.5a shows the correspondence between the software results and the experimental value of 1.7m for groups with a pedestrian's density of about 0.25 person/m². Moreover, according to the videotapes analysis and previous work (Alexander (1990), D'Orazio et al. (2014)), people in smaller groups prefer to maintain a lower reciprocal distance. Data for 0.20 ped/m² people is influenced by the interposition of other pedestrians between members of the same groups. Finally, Fig.5b shows trends of average instantaneous speeds in evacuation groups for different pedestrians' densities (ped/m²). According to experimental data and previous works (D'Orazio et al. (2014)), pedestrians initially move faster, in order to distance themselves from buildings and from other individuals.

The average speed for this part of the evacuation (from exiting to 8m far from building – from 0s to about 4s) is equal to 2.15m/s, with a percentage difference of 7.5% in comparison to experimental values. After these first evacuation moments, speeds decrease and become close to group average desired speed (Gates et al. (2006), Helbing and Johansson (2010)): differences in values are due to disturbs provoked by evacuation behaviors and related motion law parameters (repulsive and attractive phenomena, changes in evacuation direction, arrival of other pedestrians in the group). These phenomena are noticed for both small and wide groups, during whole evacuation.
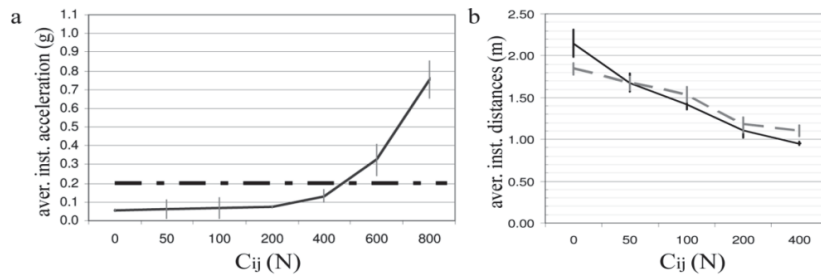

Fig. 4. (a) C_{ij} influence on average instantaneous acceleration; (b) C_{ij} influence on distance between pedestrians.
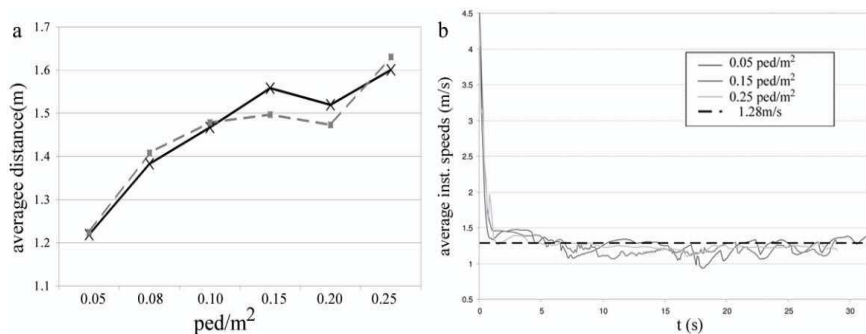

Fig. 5. (a) influence of pedestrians' density (ped/m2) on accelerations; (b) evacuation speeds trends during evacuation time.

3.5. Conclusions

This work inquires human behaviors in earthquake evacuation in order to provide a related simulation model. The final scope of a similar work is to define a series of tools for seismic risk assessment at urban scale by introducing the "human" influence and relationships between man and the post-earthquake environment. In this way, the effective level of safety of an urban aggregate should be correctly evaluated.

Firstly, the analysis of videotapes concerning real event allows to define evacuation behaviors. On these bases, an ABM approach organizes noticed behaviors and traces interactions between the evacuating pedestrians and the environment in which they move are defined. The ABM model is innovatively described by using the i* language. Motion criteria are defined: the social force model is adopted and modified in order to numerically describe typical evacuation behaviors. In particular, the definition of the attractive force between members of an evacuation groups is offered. Finally, a simulation software is implemented and a first validation is provided, stressing the attention on evacuation speeds and group phenomena and evidencing the same experimentally-noticed phenomena.

The software uses a discrete space representation, so a continuous environment description will be offered for describing the urban fabric and including also uphill road and stairways. The interaction between evacuating pedestrians and generated ruins should be inquired. Panic conditions will be introduced with the purpose to define dependencies between evacuating pedestrians. Model validation should be extended: the reconstruction of videotapes scenario will be soon offered. This model is proposed as a tool for earthquake evacuation previsions that

involves at the same time environmental modifications and human behaviours. Retrieved probable behaviors and evacuation decisions can be compared in relation to different damage scenarios. Simulation results could be analyzed with different purposes: evaluating probable pedestrians' choices in different conditions; defining risk maps at urban scale including behavioural and environmental factors such as operations on buildings vulnerability or introducing way-finding elements; checking solutions for reduction of interferences between the environment and the evacuation process; operatively define strategies for evacuation management (e.g.: evacuation plan definition, first aid phase, access for rescue teams); projecting new city parts.

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