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EARTHQUAKE PEDESTRIANS' EVACUATION IN HISTORICAL URBAN FABRIC: AN INTEGRATED SIMULATION MODEL INCLUDING HUMAN BEHAVIORAL ASPECTS

M.D'Orazio[1], E. Quagliarini[1], G. Bernardini[1] and L. Spalazzi[2]

[1] Department of Construction, Civil Engineering and Architecture (DICEA)
Università Politecnica delle Marche, Via Brecce Bianche 60131, Ancona, Italy
e-mail: m.dorazio@univpm.it

[2] Department of Information Engineering (DII)
Università Politecnica delle Marche, Via Brecce Bianche 60131, Ancona, Italy
e-mail: l.spalazzi@univpm.it

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Abstract. *The majority of Italian historical urban fabric is placed in earthquake prone areas. Earthquake risk assessment at urban scale is actually based on site hazard, buildings vulnerability and exposition, but does not consider human behaviors during both event and evacuation. Nevertheless, interactions between man and environment in such conditions becomes one of the most influencing element for inhabitants safety: historical buildings analysis and previsions of possible post-event modifications should be combined with evaluations on the "human" factor influence, in order to define integrated "risk maps". This study approaches this problem and proposes a model for earthquake evacuation simulation. Firstly, scenario modifications due to the earthquake are inquired: possible historical buildings damages, including ruins formation, are based on EMS and building vulnerability studies. Secondly, real earthquake evacuations are analyzed in order to define human behaviors and physical quantities in motion. Two actors are defined by using a multi-agent architecture. "Environment" describes the physical scenario (urban fabric, earthquake data, modifications). "Pedestrians" (adult, child, disabled) takes decisions based on obstacles avoidance, joining group behaviors, own desired speed, driving terms; modifications to the Social Force model are provided for describing his motion law. A related software is implemented. The model considers interactions between the actors and calculates, step-by-step, direction and speed for each "Pedestrian". An Italian historical centre is used for validation. Tests involve both post-event buildings modifications and human behaviors: results are compared to empirical data, demonstrating the validity of the model. The model is proposed for evaluating probable pedestrians' choices in different scenarios, and checking solutions for reduction of interferences between human evacuation processes and built environment.*

1 INTRODUCTION

Actually, the earthquake risk assessment [1] at urban scale is based on three parameters: site hazard H [2], buildings vulnerability V [3] and exposition E [4]. This E parameter involves the human presences in the urban scenario and the historical and artistic value of buildings; on the contrary, human behaviors and pedestrians' motion during both the earthquake and the evacuation phase are not considered. Nevertheless, one of the most influencing elements in the inhabitants' safety definition is represented by these factors and, in particular, by the interactions between people and the post-event environment. Understanding and simulating rules for pedestrians' motion in this kind of evacuation could be useful to inquire the risk assessment: integrated "risk maps" could be realized through the combination of evaluations related to traditional parameters and results of human behaviors analyses. This work approaches the problem from this point of view: an earthquake pedestrians' evacuation simulator is offered in order to effectively investigate the influence of human behavioral effects. Three issues are needed for a similar activity: human behaviors in earthquake evacuation [5]; damage previsions estimation [6,7]; models for pedestrians' motion simulation [8,9].

Concerning human behavioral aspects, a limited number of studies analyses this kind of evacuation [5,10–13]. Main noticed behaviors concern the inferior limit in earthquake perception [6], the presence of a "pre-movement" phase, cohesion bonds between members of the same evacuation group [5,10], the influence of geographical background [5], and the so called "fear of buildings" [5], with frightened people that decide to keep a safety distance from buildings also during the earthquake. Some previous studies adopt the analysis of videotapes of real earthquakes [11,13,14], and motion quantities in first evacuation phases in real events are investigated [12].

The post-earthquake scenarios description essentially describes the possibility of losses and building damages depending on correlations between earthquake magnitude and vulnerability of buildings. Building vulnerability indices can be evaluated by using different quick or accurate evaluation procedures [7,15]: these approaches essentially consider the building typologies with relative integrations due to peculiar building characteristics. Macroseismic scales (i.e.: EMS 98) propose relationships between type of building (and so vulnerability indices), seism intensity and possible grade of damage based on experimental data [3,6]. Moreover, an average damage index is offered for the correspondent seismic magnitude in EMS 98 scale [15]. In this way, consequent post-earthquake scenarios (including partial or total collapse and "unfit for use" buildings) can be estimated. However, correlations between damage index and ruins area should be proposed.

The last issue effectively concerns the operative definition of the possible motion simulation model. Models simulating human behaviour and motion in both normal and evacuation conditions are distinguished by different definitions of space and time [9,16]. In particular, continuous-space model are based on a continuous representation of space and time: pedestrians move in a 2-D surface representing the environment, and they are guided by motion equations [8,12]. One of the most powerful approaches is represented by the social force model [8,9]: it uses a continuous-space representation and is based on real evacuation analyses. Motion behaviors are here described in terms of attractive and repulsive forces, that are generated by interactions between people and environment, and that lead individuals to accomplish their own motion goal. This model has never been applied to earthquake evacuations, because previous studies do not investigate this kind of event and the related human behaviours. However, only few studies provides a proposals for the integration of the two simulators in the earthquake case [12]. Finally, integrated approaches based on Social Force model and rules-based models are offered [17], and it is also possible to combine the this approach with a discrete environment representation [18,19].

This work proposes an earthquake evacuation simulation model and its software implementation. The model describes human motion by using the social force model approach; modifications are provided in order to include earthquake evacuation behaviors from experimental analysis. On the other side, environment modifications due to the earthquake are included. The model takes advantages of the chosen Multi-agent architecture [20]: this methodology allows to describe the rules of different agents in pedestrians' motion and environment modifications simulation, and also the interaction between them. The model adopts a "Lagrangian approach", or rather a "microscopic dynamic approach" [21]: the operative law is attributed to each single agent involved in the model, and the interaction between people, and between people and environment, produces the global experimental results. This paper provides the model definition, the software implementation and the first results analysis, focusing the attention on man-environment interactions and path choice algorithm.

The model and the resulting software are proposed for evaluating probable pedestrians' choices in different scenarios, and checking solutions for reduction of interferences between the environment and evacuation processes.

2 PHASES, DATABASE ANALYSIS, MODEL STRUCTURE AND VALIDATION CRITERIA

2.1 Phases

This paper is organized in four steps:

- definition of evacuation behaviors by experimental analysis (*Evacuation behaviors*);
- characterization of the theoretical multi-agent model (*Theoretical model definition*);
- software implementation (*Software implementation*);
- software test and first validation (*Validation*).

2.2 Database analysis

A database of 50 videotapes of earthquake evacuations from all over the World (available at https://drive.google.com/?tab=io&authuser=0#folders/0B91jqaXLKo5LTFlqbnplS0tJLTQ; in the text below, database reference numbers are written in curly brackets) is analyzed in order to experimentally define a list of human evacuation behaviors. Videotapes refer to both outdoors and indoors scenarios, and both public and private spaces. The whole number of events are perceptible seismic events [6] (magnitude higher than a 5th degree in the Richter Seismic Scale - IV degree in EMS-98 scale), and have a confirmed date, geographical localization and magnitude. "*Evacuation behaviors*" are defined by the set of actions that pedestrians perform during the evacuation, in relationship to both the environment and other people. These behaviors must be noticed at least in the 30% of cases; a distinction between the behaviors common to other kinds of evacuation and the ones specific of earthquake evacuation is provided. Moreover, the videotapes inquiry include the analysis of average motion speeds in the first evacuation steps; values are provided by using the open source image analysis software "Tracker" [22].

2.3 Model structure and validation criteria

Both the model and the related software are based on a multi-agent approach. Interactions between agents are expressed in the *intentional model*, that is represented using the i* graphical modeling language [20]. The operative law for each pedestrian is organized by defining the c*riteria for pedestrians' motion*. The motion law is founded on the social force model, with integrations for the earthquake case. Finally, *ruins formation criteria* are proposed in order to quantify the damages to historical buildings due to the earthquake.

The validation phase consists in a comparison between the software results and experimental analysis data and literature values. Following the adopted "Lagrangian" approach [21], interactions between agents must produce phenomena and quantitative values that are similar to the experimental ones, for the whole system. The validation step is aimed by this verification. An historical urban city center (Corinaldo, AN, Italy) is used as evacuation environment; different scenarios are obtained by varying involved people number and earthquake magnitude. Ten simulations are performed for each scenario, and average values and standard deviations are calculated. Observations concern ruins formations, chosen paths and average speeds tendency in the course of evacuation time.

3 EVACUATION BEHAVIORS

A list of evacuation behaviors is provided by the experimental videotapes analysis. Table 1 resumes the related results: each behavior is organized by expressing its kind, its chronological activation order, a short description and reference elements for its activation.

Table 1: List of noticed evacuation behaviors.

Kind	Order	Description	Reference elements
Common with other events	3	Attraction towards safe areas	Environment
	3	"Herd Behavior" and influence of "collective" velocity	Pedestrian
	3	Repulsive mechanisms to avoid physical contacts	Environment, Pedestrian
	3	Attraction between members of the same evacuation group	Pedestrian
Peculiar	1	Evacuation for sensible events with information exchange	Environment, pedestrian
	2	Motion to the nearest visible safe area, using the "clearest" path	Environment, Pedestrian
	3	Keeping a "safety distance" from buildings and ruins	Environment
	3	Not keeping a "safety distance" from trees, shelters and street furniture	Environment
	3	Evacuation groups formation	Pedestrian
	3	Increased guide effect for presence of rescuers or evacuation plans	Environment
	4	Evacuation interruption for immediate danger feelings and panic conditions	Environment, Pedestrian
	4	Evacuation interruption for high ground shaking	Environment

Figure 1 shows the typical evacuation behaviours connected with outdoor evacuation targets. Firstly, targets in outdoor evacuation are generally the nearest wide spaces in urban fabric {6, 10, 13, 17, 25, 31, 32, 34}: examples are squares, large avenue, crossroad, as shown in Figure 1-A. This "safe" areas are generally wide public spaces, with a significant distance from buildings, low height of building/width of overlooking public space ratio in comparison with the rest of the surrounding urban fabric far from buildings their geometric characteristics, and a low level of damage (including generated ruins) [5]. Moreover, the influence of social factors connected with information exchanging between pedestrians', with the possibility to have sufficient space for each person {10, 17} is noticed [5,23]. So, while high buildings and ruins provoke repulsive phenomena during motion [5], trees and streets furniture does not provoke repulsion, and they can be also attractor in outdoor evacuation: Figure 1-B evidences {32} this attraction phenomenon during the evacuation procedure.

Figure 1: Interactions in evacuations: A - left, different pedestrians' group converge towards the same area (white arrows), far from buildings (Turkey, {34}); B - right, pedestrians are attracted during motion by trees and street furniture (white circles) (Japan, {32}).

Pedestrian's choices of evacuation path {9, 19, 23, 24, 29} depend on environmental factors [5]: the individuals prefers the widest and clearest of dust and rubble path, especially in a close urban fabric. Group bounds, presence of other people long a precise path, and "herd behavior" [8] phenomena influence can also affect these choices: Figure 1 shows the related concurrence of different pedestrians' group to the same target. Finally, Table 2 shows average speeds in a group of pedestrians against distances from building {15, 21, 28, 31}; values are organized in four classes of distance: speeds are higher when individuals are exiting and running far from the building, and so they seem to converge. The maximum measured speed is about 4.0m/s and confirms literature values [12].

Table 2: Average speed for 15 pedestrians in relationship to distance from the building {21}.

Distance from building (m)	Average speed (m/s)
2	2.11
4	1.99
6	1.97
7	1.96

4 THEORETICAL MODEL DEFINITION

The analysis of *evacuation behaviors* suggests the presence of two actors involved in earthquake evacuation (see also Table 1, 4th column). *Pedestrians* refer to other *Pedestrians* and to the physical *Environment* (building, ruins, seismic parameter, environmental parameters) in order to perform their own evacuation actions. For this reason, a multi-agent approach is chosen for simulating the earthquake evacuation procedure.

4.1 Intentional model

Figure 2 shows the "Intentional model" by using the i* language [20]: relationships between *Pedestrians* and the *Environment*, their relative resources, goal and tasks are represented. In the following description, the relative blocks are marked in italics.

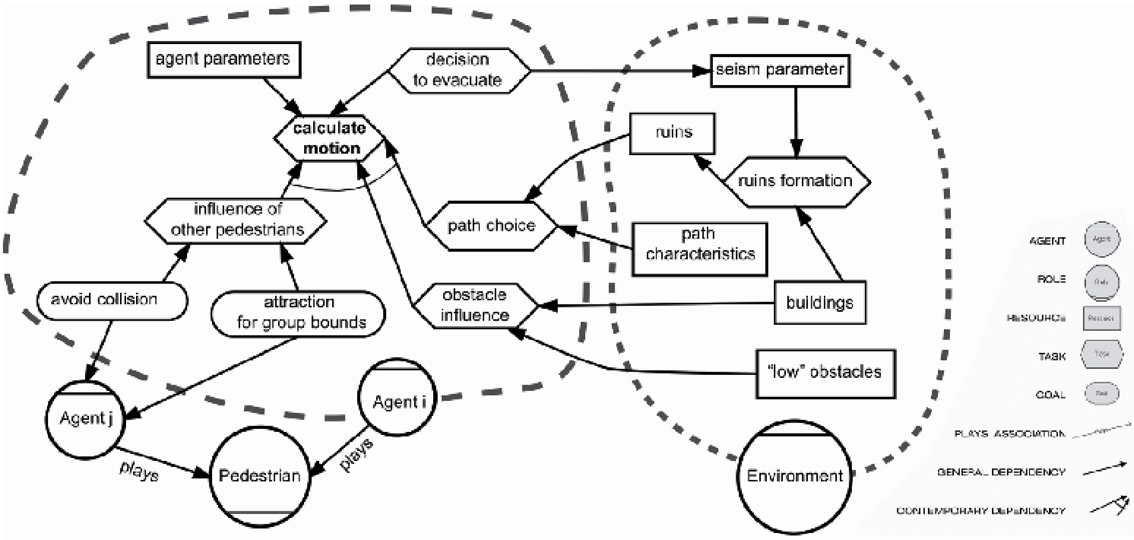

Figure 2: The intentional model using i* language.

Environment involves the characteristics of the physical scenario: urban fabric including position and dimension of paths and safe areas (*path characteristics*), fundamental seismic data (EMS magnitude, duration, PGA - *seism parameters*), position and vulnerability of buildings (*buildings*), position of street furniture and trees (*"low" obstacles*). Modifications of the initial scenario due to the earthquake concerns *ruins formation* [6].

Agent i and *Agent j* play the same *Pedestrian*'s role. *Pedestrian*'s kinds (adult, children hand-assisted by adult, pedestrian with motor disability) are characterized by different *agent parameters* (average motion speed, radius, mass [8,9]). A *Pedestrian* relates to the *Environment* during the evacuation: he decides to evacuate in function of the event magnitude (*decision to evacuate*); he avoids buildings and ruins and can be attracted by "low" obstacles (*obstacle influence*); he decides his evacuation target (*path choices*) in dependency of the surrounding conditions. He evaluates other *Pedestrians*' positions (*influence of other pedestrians*), with the purpose of keeping a distance from them that allows to avoid contacts (*avoid collision*) and maintain an eventual group bonds (*attraction for group bounds*). Both his desired speed and direction are influenced by these phenomena.

4.2 Criteria for pedestrians' motion

Criteria for motion numerically describe people decisions in evacuation, in terms of both evacuation path choice and pedestrian velocity.

In particular, parameters for the proposed path choice criterion are suggested by videotape analysis: presence of obstruction along the path, width of the path, highness of facing buildings, distance between actual position and safe area, presence of other pedestrians along the path. Equation 1 shows the proposed formula for determining the probability $P_{s,e}$ to reach a certain safe area s between the possible visible safe areas S, by using a certain evacuation path e between the possible evacuation paths E usable by the pedestrian:

$$P_{s,e} = \frac{R_{W/H,s}}{R_{W/H,s}^{\max}} \cdot \frac{R_{W/H,e}}{R_{W/H,e}^{\max}} \cdot \frac{d_{s,e}^{\min}}{d_{s,e}} \cdot \frac{\Delta A_{r,e}}{\Delta A_{r,e}^{\max}} \cdot \frac{W_e}{W_e^{\max}} \cdot \frac{n_e}{N} \tag{1}$$

where $R_{W/H}$ is the ratio between the wide of urban space and the height of facing buildings (for both e and s), $d_{s,e}$ (m) is the geometric distance between the pedestrian and the considered s using e, $\Delta A_{r,e}$ (m^2) is difference between total area of e and total area of ruins on e, W_e (m) is average path wide considering generated ruins, n_e is number of pedestrians along e, N is total number of visible pedestrians, ^{max} refers to maximum related value, ^{min} refers to minimum related value. Parameters are considered independent and variable from 0 to 1. When a denominator is null, the related term is considered equal to 1 (not influent). When there are no visible safe areas, $d_{s,e}$ is calculated in respect to the nearest variation in the path (for intersections between paths or plano-altimetric variation of the path itself). The chosen path will be the one with maximum $P_{s,e}$ value.

Equation 2 shows the general motion law [8,9,24], that calculates the pedestrian velocity at a certain instant of the motion. In order to describe the presence of the "attraction between members of the same evacuation group" phenomenon (see Table 1), the attraction forces between members of an evacuation group are introduced [8,24].

$$m_i \cdot \frac{d\vec{v}(t)}{dt} = \vec{O}_g + \sum \vec{F}_{rep} + \sum \vec{F}_{attr} + \vec{\varepsilon}(t) \tag{2}$$

where m_i (kg) is pedestrian's mass, $dv(t)$ (m/s) is the modulus of pedestrian velocity at instant t, t = instant of evaluation, O_g (N) is the modulus of drive-to-target force, F_{rep} (N) is the modulus of a repulsive force exchanged between the actual pedestrian, other pedestrians and the environment (N), F_{attr} (N) is the modulus of an attractive force (N) [24], $\varepsilon(t)$ (N) is the modulus of random variation of forces.

4.3 Criteria for ruins formation

The definition of post-event scenario, including ruins formations due to the earthquake, is proposed by using the Damage Probability Matrix approach, which adopts a statistical correlation between the macroseismic intensity and the probable damage grades [15]. Firstly, the mean damage grade is evaluated by combining the vulnerability and ductility index of the building with the earthquake EMS magnitude, according to previous studies [15]. Ruins formation are considered dependent on the mean damage grade: the EMS98 classification of damage for buildings is used [6]. The probability P_k to reach a certain EMS98 damage grade k is function of the calculated mean damage grade of the building [15]; there are six k values, starting form 0 (no damage) to 5 (total collapse) [6]. For each building, the k values are generated through a weighted sampling: sampling weights are represented by P_k. A ruins area along the evacuation paths is related to a precise damage grade k of the building itself. Moreover, the presence of local damage mechanism is considered: for this reason, each side of a building is associated to a specific damage grade k. The operative assignment between ruins area and damage grade is defined in the implementation phase.

5 SOFTWARE IMPLEMENTATION

The software implementation uses the TROPOS methodology [25]; the application is developed in TAJ environment [26] by using Alan and Java languages. A hybrid spatial approach is chosen for spatial representation. *Pedestrians* move in a continuous 2-D plane representation for motion: this fact allows to preserve the social force model features. *Envi-*

ronment modifications are represented in a 2-D grid, with dimension equal to the radius for a adult Pedestrian (0.35m) [9]. In this way, grid cells can describe an obstacle (a *building* or a *"low" obstacle*) or an evacuation *path* (in which people can effectively move). Similar approaches are present also in previous hybrid models [19]. This choice allows to simplify the ruins description algorithms, while errors in interactive forces between man and environmental elements seem to be not so influenced by the grid because to its small dimension (minor than the pedestrian dimension [9]). Each *building* grid cell, when attached to a *path* grid cell, generates a number of *ruins* grid cells that is function of the building *k* value. These *ruins* gird cells are generated perpendicularly to the *building* side, and occupy the *path*. They are obstacles: they introduce repulsive phenomena in pedestrians' motion and they cannot be crossed by the individuals. At the same time, they reduce the *path* dimension: in this way, $\Delta A_{r,e}$ and W_e can be also calculated for each *path*. Equation 3 shows the proposed association between the aforementioned six *k* damage grades (EMS98 [6]) and the number of *ruins* grid cell along the *path*. The dimension is given by the number of grid cells *n_occ* occupied by ruins; ruins grid cell are cast to integer values, when *k* is equal to 4 and 5:

$$k \begin{cases} = 0 \Rightarrow n\_occ = 0 \\ = 1 \Rightarrow n\_occ = 1 \\ = 2 \Rightarrow n\_occ = 2 \\ = 3 \Rightarrow n\_occ = 5 \\ = 4 \Rightarrow n\_occ = (\text{int})\left(\frac{h_{building}}{4} \cdot \frac{1}{0.35}\right) \\ = 5 \Rightarrow n\_occ = (\text{int})\left(\frac{h_{building}}{2} \cdot \frac{1}{0.35}\right) \end{cases} \tag{15}$$

where $h_{building}$ (m) is the height of the building. Finally, the pre-event *Environment* is inserted through a BITMAP file representing both urban layout and buildings characteristics.

Table 3 summarizes the characteristic parameters by pedestrian kind [9,27]. A maximum speed of 4.5m/s is imposed for the three pedestrian kinds, according to both videotape results and previous studies [9].

Table 3: Input parameters by pedestrian kind.

Parameter	Measure	Adult	Hand-assisted Child	Invalid
radius	m	0.35	0.45	0.35
mass	kg	80	100	80
desired speed	m/s	1.46	1.22	1.16

Figure 4 shows an example of the three main software interfaces. A part of the historic city centre of Corinaldo (Italy) is chosen for simulations.

Figure 4: Pedestrian's input interface (left), group bonds interface (middle) and Environment window (right).

6 VALIDATION

The validation phase follows the criteria expressed in paragraph 2.3. Firstly, the results of test concerning ruins formation and damage definition are provided. Figure 5 shows how the implemented algorithm, based on weighted sampling, approximates the previous studies curve [15] for a smaller number of simulation, while for more than 10 simulation, it describes the curve itself.

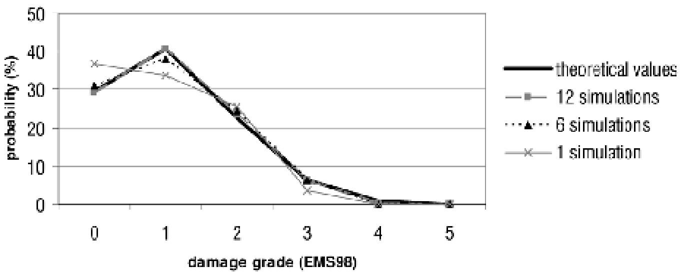

Figure 5: Damage grade distribution curves for 1, 6 and 12 simulations and theoretical values, for I=8 and Q=2.3, VI =0.58 (class C presented in the EMS98 study).

About path choice, the adopted algorithm verifies the correspondence between the $P_{s,e}$ value and the chosen path. Figure 6 shows a graphical overview of an example. The pedestrian starts his evacuation from S, deciding to reach one point between $a0$ and $a1$.

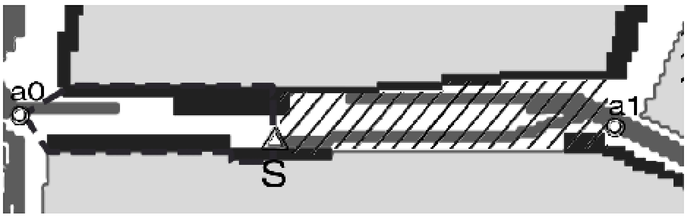

Figure 6: Choice of path for pedestrian S (triangle): buildings (light grey) reachable points (a0, a1), ruins (dark grey), areas of possible evacuation paths (different hatchings), and effective evacuation path (grey) are evidenced.

Table 4 mathematically analyses the incidence of the single parameter in the pedestrian path choice calculus; the order of values in multiplication is the same of Equation 1.

Table 4: Numerical data for path choice in Figure 6.

Usable path	Equation 1 calculus	Probability of path use
S-a1	$\frac{2}{2}\cdot\frac{1}{1}\cdot\frac{22.05m}{39.90m}\cdot\frac{148.11mq}{148.11mq}\cdot\frac{6.3m}{6.3m}\cdot\frac{3}{4}$	0.42
S-a0	$\frac{1.75}{2}\cdot\frac{1}{1}\cdot\frac{22.05m}{22.05m}\cdot\frac{64.19mq}{148.11mq}\cdot\frac{4.2m}{6.3m}\cdot\frac{1}{4}$	0.06

Finally, Figure 7 shows the evolution of average instantaneous speeds in the same evacuation group during the first evacuation phase, when people is walking away from the original building. A group of 15 pedestrians is analyzed with the aim to define their "average behaviour", by using the motion average values. Instantaneous average speeds (dashed line) are continuously provided. Speeds decrease after the initial instants, demonstrating the same experimental tendency of analyzed videotapes. The average speed for this first evacuation part (from exiting to 8m far from building) is equal to 2.15m/s. Average speeds for different distance classes (continuous line), including standard deviation, are offered in Figure 7. The percentage difference between simulation and videotape analysis result is equal to +7.5%. Differences in values are due to phenomena connected with the motion law parameters in the testing environment layout: attraction between pedestrians, repulsion between pedestrians and with obstacles, changing in evacuation direction, arrival of other pedestrians in the group. Nevertheless, similar phenomena are noticed for both small and large evacuation groups and in course of the whole evacuation procedure.

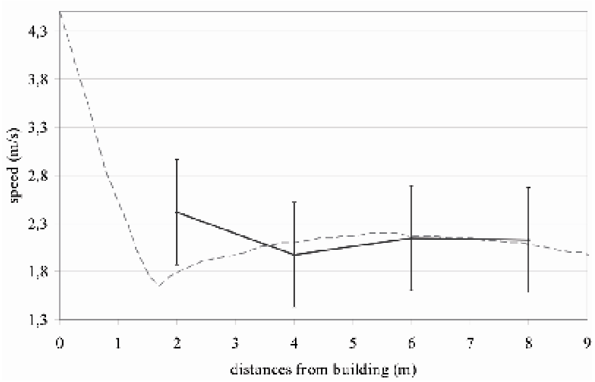

Figure 7: Pedestrians' Average values for instantaneous speed (dashed line) and sample mean speed (continuous line, including standard deviation) at discrete intervals (2m, 4m, 6m, 8m).

7 CONCLUSIONS

This paper provides an innovative approach to seismic risk assessment evaluation at urban scale, by introducing the analysis of human behavioral aspects. The "human" factor should be examined in order to fully determine the safety level of an urban scenario. In particular, a model for simulating earthquake evacuation in urban areas is provided.

Videotapes of real earthquake evacuations are analyzed with the purpose of defining a list of evacuation behaviors, and providing their activation order. A multi-agent model is organized on these bases: the attention is focused on interactions between evacuating pedestrians and the environment in which they move. The model is described by adopting the i* language. Criteria for pedestrians' motion are offered: in particular, the social force model includes modification connected to peculiar earthquake evacuation behaviors. Moreover, the experimentally-based evacuation path choice algorithm is provided. Finally, the related software is implemented and a first validation is offered: evacuation speeds and path choices are explored. Simulation results about evacuation speeds evidence the same experimental phenomena.

The model is proposed as a tool for earthquake evacuation analysis, also because his possibility to represent environmental modifications, human behaviours and related man-environment interactions. Retrieved probable behaviors and motion decisions in evacuation can be checked in relation to different damage conditions. Results could be useful for defining integrated risk maps that add evacuation data to the traditional risk assessment evaluation. Moreover, solutions for reducing interferences between human evacuation process and built environment could be proposed by analyzing the model previsions: punctual interventions on particular buildings placed in strategic evacuation points can be evaluated in order to decrease the vulnerability of both historical buildings and historical urban fabric. Similar activities could be extended to both the existing urban fabric and new city parts. Finally, different operative strategies for "human" evacuation process organization (i.e.: evacuation plan definition, first aid phase, access for rescue teams) could be compared through the simulation results.

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