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Agent-based model for earthquake pedestrians' evacuation in urban outdoor scenarios: Behavioural patterns definition and evacuation paths choice

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ABSTRACT

The assessment of seismic risk at urban scale does not actually consider aspects related to human behaviours, unlike other kind of events; moreover, the simulation of phases of pedestrian evacuation and motion in earthquake evacuation is a rarely inquired issue. From this point of view, this work proposes an innovative approach to earthquake evacuation, presenting an agent based model to describe phases and rules of motion for pedestrians. The model is based on the analysis of videotapes concerning real events. Results firstly show a scheme of chronological organisation of experimentally noticed behaviours activated during an earthquake evacuation. Secondly, the related behavioural agent-based model is presented by using the i^* language and posing attention to relationships between pedestrians and environment. A particular attention is given to the relationships in evacuation paths choice depending on configuration of environment and damage distribution after earthquake. Additionally, experimental values of distance between people and evacuation average speed in the first phases of outdoor motion are provided. The mathematical definitions for the model and the software implementation of the model will be implemented.

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1. Introduction

The evaluation of seismic risk R at building or urban scale can be defined using three pillars: hazard H, vulnerability V and exposed elements E (Ambraseys, 1983), as showed in the following equation:

$$R = R(H, V, E) \quad (1)$$

Notations are reported in Appendix A. A large number of studies approach the definition and evaluation of H parameter (Klügel, 2008; Panza et al., 2012); some of them also refer to researches about soil nature (Meletti et al., 2008; Orozova and Suhadolc, 1999; Semih Yücemen, 1993), while others propose applications to specific areas (Jiménez and Posadas, 2006; Panza and Romanelli, 2001). Other studies analyse V parameter (Calvi et al., 2006; Palacios Molina, 2004), with structural analysis for different buildings (Barbat et al., 1996; Giovinazzi and Lagomarsino, 2001; Grimaz et al., 1997), and definition of methodologies for loss estimation including various aspects (Federal Emergency Management Agency, 2009; Mouroux and Brun, 2006a, 2006b). The exposure parameter E (Chen et al., 1997; Mouroux and Brun, 2006a) concerns human presence in a scenario, or the historical and artistic value of buildings.

Several studies deal with human behaviour analysis in evacuation cases, but only few of them concern post-earthquake evacuation, and none of them define a link with the evaluation of E. In order to provide a more accurate evaluation of E, it should be also taken account of human behaviour during the earthquake and the first evacuation phase.

The majority of aforementioned studies are about fire evacuation or big structure evacuation (Averill et al., 2005; Chu et al., 2006; Dederichs and Larusdottir, 2010; Fahy and Proulx, 2001; Helbing et al., 2002; Johnson et al., 1994; Mawson, 2007; Muir et al., 1996; Nilsson and Johansson, 2009; Nilsson et al., 2010; Pietrantoni and Prati, 2003; Riad et al., 1999; Shen, 2006; Shields and Boyce, 2000; Zheng et al., 2009). They investigate "pre-movement" phase (Chu et al., 2006; Johnson et al., 1994; Nilsson and Johansson, 2009; Nilsson et al., 2010; Shen, 2006; Shields and Boyce, 2000; Zheng et al., 2009), phenomena of social attachment[1]

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[1] This phenomenon could be summarized as pedestrians' waiting for other known people both during the evacuation starting and the effective motion, in order to be reunited with family or clan members and friends.

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(Mawson, 2007) and attachment to objects[2] (Riad et al., 1999), "memory effects"[3] (Helbing et al., 2002; Lakoba and Finkelstein, 2005), "Herd Behaviour"[4] (Helbing et al., 2002). They pointed out that panic situations are usually due to the presence of particular conditions especially in psychological perception of environment and dangers (Auf Der Heide, 2004; Averill et al., 2005; Pietrantoni and Prati, 2003). They also notice a maximum of distance that provokes activation of interaction mechanisms between people and between people and obstacles[5] (Lakoba and Finkelstein, 2005).

Only few works deal with earthquake evacuations (Alexander, 1990; Arnold et al., 1982; Boileau et al., 1978; Grünthal, 1998; Hori, 2011; James, 1968; Osaragi, 2012; Prati et al., 2012; Takuma, 1972; Turner et al., 1986). Regarding behaviours in case of earthquake, inferior limit in perception of seism and limit for panic conditions are defined using EMS-98 intensity scale (Grünthal, 1998). These studies evidence the presence of "pre-movement" phase, cohesion bonds (Alexander, 1990; Prati et al., 2012), the influence of geographical background in behaviours (Alexander, 1990; Boileau et al., 1978), and the so called "fear of buildings" (Alexander, 1990; Arnold et al., 1982; Takuma, 1972), with frightened people that prefer to run out of buildings during the earthquake (Alexander, 1990). The decision-making and behaviour of individuals attempting to reach home on foot in the wake of a devastating earthquake is also inquired (Osaragi, 2012). Average speeds in first evacuation phases in real events are investigated (Hori, 2011).

A large number of models simulating human behaviour and motion both in normal and evacuation conditions is present (Helbing and Johansson, 2010; Helbing et al., 2002; Heliövaara et al., 2012; Hori, 2011; Hughes, 2002; Lakoba and Finkelstein, 2005; Langston et al., 2006; Osaragi, 2004; Pelechano and Malkawi, 2008; Schadschneider, 2001; Smith et al., 2009; Zanlungo et al., 2012), such as the Social Force model (Helbing and Johansson, 2010; Helbing et al., 2002; Lakoba and Finkelstein, 2005; Zanlungo et al., 2011). The Social Force model approaches analysis of real cases (normal and evacuation condition) to define a motion law for pedestrians. However that model has never been applied to post-earthquake evacuation for its limitation essentially due to initial inquires of authors (Helbing et al., 2002), which did not investigate this event and related human behaviours.

The aim of our work is to provide and implement a model that take advantages of the Social Force model and makes it capable to describe pedestrians' motion in post-earthquake evacuation. This can be accomplished in two steps: the definition of the behavioural theoretical model and the operative integration on the Social Force model.

This paper offers a first step for our work. The behavioural theoretical model is based on an experimental inquiry about human behaviour in post-earthquake evacuations using videotape analysis related to real events. This approach was adopted also to previous studies (Helbing et al., 2002; Hori, 2011). Qualitative and quantitative aspects of pedestrian motion are investigated. Behaviours are organised in order to have a scheme of the relationships that are activated during the evacuation procedure. These data are utilised to define a behavioural flowchart capable to describe the evacuation process, and to introduce corrections and integrations to Social Force model. In the following part of our work, the mathematical definition of motion law and the simulation software implementation will be provided.

The adoption of an agent-based approach (Manenti and Manzoni, 2011) is strictly connect to the possibility, on one side, to define interaction between various agents present in the scenario (the same interaction between pedestrians and between pedestrians and environment suggested by the Social Force model (Helbing and Johansson, 2010; Helbing et al., 2002)), and, on the other hand, to independently modelling each agent, and in particular the one describing a general pedestrian.

2. Phases, database definition, and methods for database analysis

2.1. Phases

From a general point of view, our definition of an agent-Based model for Post-Earthquake pedestrians' evacuation in urban outdoor scenarios concerns the following steps:

- Videotape analysis to define behaviours activated in post-earthquake evacuation and organisation of them in order of activation.
- Definition of the behavioural model including intentional model, behavioural flowchart and criteria of motion and of path choice.
- Operative definition of quantities concerning criteria of motion and of path choice, including motion law.
- Implementation of the model in a simulation software in order to validate the proposed model.
- Validation of the model through the related software, comparing average speed values, path choice, and distance between people during evacuation.

This paper regards the first steps of our work, and it is divided in the following phases (the corresponding paragraph, in which relative results are explained, is indicated in brackets, in italics):

- Quantitative and qualitative analysis of a selected videotapes database, about both pre-movement time and motion; definition of a list of noticed behaviours and their organisation in a chronological order of activation (*Noticed behaviours*).
- Definition of actors involved in evacuation, of interaction among pedestrians and between pedestrians and environment (obstacles, buildings, ...), with related organisation of noticed behaviours into a intentional model, using i^* as modelling language (*Intentional model*).
- Description of the series of actions, behaviours and choices acted by a single pedestrian during the evacuation (*Behavioural flowchart*).
- Characterisation in physical terms of criteria used by a pedestrian for his choices and his motion (*Criteria of motion*).

These steps are developed in order to correct and integrate to the Social Force model. A solving equation for pedestrian motion will be obtained on these bases.

2.2. Database definition

Fig. 1 proposes a general overview of the analysed videotape database, distinguishing different essential statistical information: magnitude of the earthquake (Fig. 1A), percentage of events per year (Fig. 1B), geographical distribution (Fig. 1C), number of visible people in the scene (Fig. 1D) and particular condition in evacuation (Fig. 1E).

[2] That is pedestrians' collecting belongings and other things they care for.

[3] This could be summarized as people in evacuation conditions that choose well-known paths.

[4] That is, a convergence of pedestrians' behaviors and choices when they are in group conditions.

[5] Elements (both people and obstacles) are taken into account for pedestrian's evaluations only if they are placed closer than the activation distance from the pedestrian.

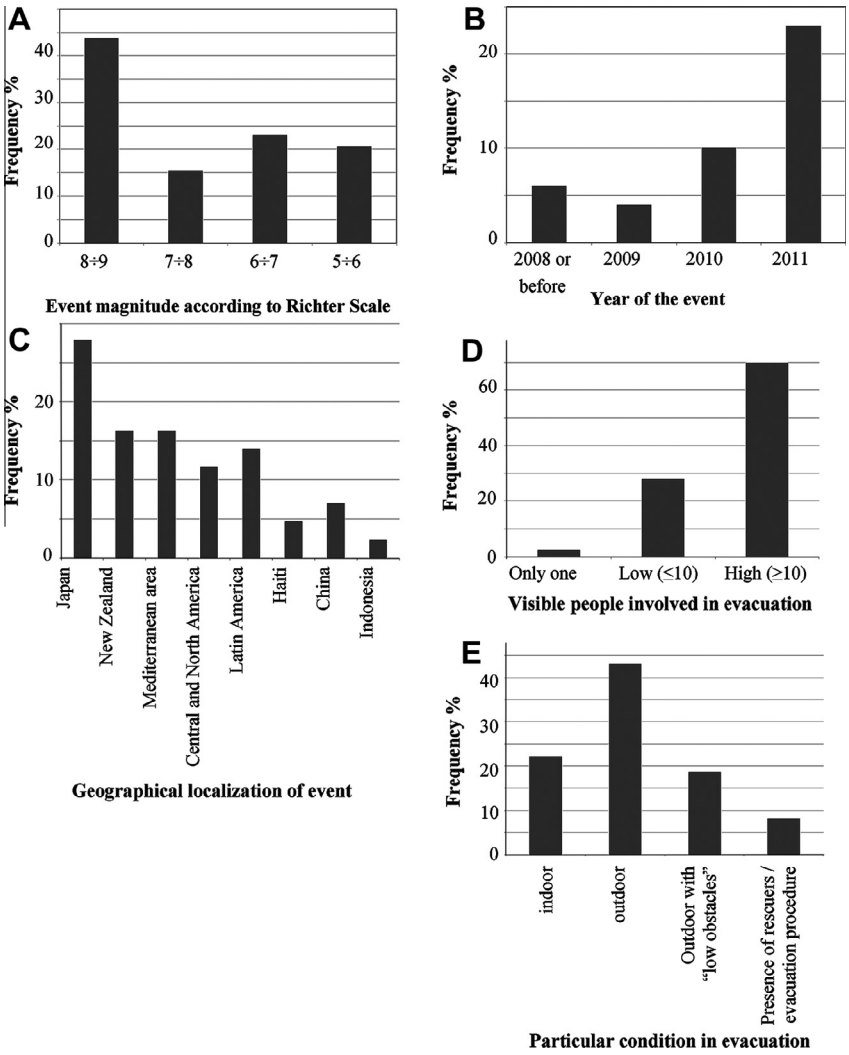

Fig. 1. Percentage distribution of analysed videotapes; "low obstacle" are, for example, trees, street furniture, shelter.

The analysed database consists of about 50 videotapes of real post-earthquake evacuation in outdoor public space (streets, squares...) or in indoors/private wide spaces connected directly to outdoors ones (wide halls, private gardens...). Videotapes are numerated and available at https://www.sugarsync.com/pf/D0452061_63556241_693560. Videotapes refer to perceptible seismic events with a magnitude higher than a 5th degree in the Richter Seismic Scale (IV degree in EMS-98 scale or equivalent degree in other seismic scales) from all over the World. USGS database available at http://earthquake.usgs.gov is used to obtain general magnitude data for each event with known localisation both in space and time. However, events from mass-media channel, civil defence or government agencies, or present in more than one different videos, are preferred. Only videotapes with a confirmed geographical localisation, date and seismic intensity of events are selected.

The analysis is extended to videotapes from all over the World, considering in this way the existence of different responses to event due to cultural and social background (Alexander, 1990; Boileau et al., 1978).

In addiction, the presence of ties between pedestrians (such as family ties) that participate to evacuation is considered: when possible, these bonds are supposed by studying behaviour before escaping, otherwise by supposing them by seeing a certain development of their evacuations.

2.3. Methods for database analysis

About behavioural inquiry, "Evacuation behaviours" are defined by the set of actions and attitudes of individuals during evacuation motion. They include attitudes towards environment and other people also in reference to the different conditions defined in Fig. 1E. Noticed behaviours must be present at least in the 30% of cases and are distinguished in: "common evacuation behaviours", if already noticed in previous studies (also in reference to other kind of evacuation); "peculiar evacuation behaviours", if specifically connected with post-earthquake evacuation.

About numerical inquiry of motion, some videotapes performed by fixed cameras are chosen for the estimation of values about people time reaction to earthquake, average speed and distance between people during motion. The open source image analysis software "Tracker" (Brown and Christian, 2011) is used for these analysis. Each pedestrian is associated to a point mass, pointed at hip level. Positions are defined at least every 5 s during the whole pedestrian evacuation period. For the evaluation of the distance between member of the same evacuation, distances lower than 3 m (that is the supposed maximum distance between people for the activation of interaction phenomena (Lakoba and Finkelstein, 2005)) are measured with an approximation of 10 cm; an evaluation of the related average distance for each evacuation step is done, and, at the end, sample mean of these values and related

standard deviation are calculated. People response to earthquake in terms of time is evaluated in case of indoor evacuation. In this case, people are considered out of scene when they gain an exit door or they are no longer viewed in camera. Earthquake description is offered from qualitative or quantitative phenomena detected from video cameras, such as using the displacement of a pendulum-shaped object.

2.4. Language used for model representation

For the operative representation of the model, i* language (Yu et al., 2011; Yu, 2009) is chosen. It is based on intentional characteristics of the agent and allows us to trace intentional and social notions (actor, goal, softgoal, plan, resource) and dependencies among them (dependencies among actors, goal decomposition ...). i* is a graphical modelling language. Moreover, attention is focused on the organisation of a behavioural flowchart of chronological pedestrian possible choices and actions.

3. Results and discussion

3.1. Noticed behaviours

Behavioural patterns in evacuations are observed and organised in order of activation, offering at the end the organisation of a list of noticed behaviours, divided by kind and reporting relative frequencies.

Behaviours are discussed below. For each behaviour, in the following, related videos (i.e. the database reference numbers are written in braces) and keywords (in italics in round brackets) are indicated.

First of all, different kinds of earthquake push people to adopt different evacuation procedures both indoor and outdoor (*Response to sensible events*). Evacuation phases, decision to evacuate, pre-movement phases and reaction time strictly depend on the perceived danger of the event {2,4,5,11,16,31,40,41,42} and on cultural background (Alexander, 1990; Boileau et al., 1978; Grünthal, 1998; Prati et al., 2012; Takuma, 1972; Turner et al., 1986).

Fig. 2 shows the importance of information exchange during the quake itself {42}, especially in groups of small dimensions or sharing cohesive bounds. Initially, people exchange information and valuate together the level of danger; when there are many people involved in communication, the number of people evacuating the room grows. To describe seism evolution during evacuation, ground shaking is represented using the displacement of a pendulum-shape object: this effect influences danger perception in people.

Communication during the whole evacuation, but especially during the first phase, is very important particularly in Latin Countries: here verbal communication is the principal way to exchange information {26,42} (Alexander, 1990).

Fig. 3 shows that time employed by people to gain a safe position or to reach the exit is connected with seism perception and floor shaking {40}: for high floor shaking people prefer to gain safe position instead of exit doors.

Fig. 4 shows the presence of different reactions to seism due to geographical and cultural background, confirming conclusions of previous studies about incidence of this factor in human behaviours in perception of seismic events and related hazard {5,6,23,31} (Alexander, 1990; Boileau et al., 1978; Prati et al., 2012; Takuma, 1972; Turner et al., 1986). Fig. 5A shows following screenshot of a chaotic indoor evacuation in Haiti {23}, while Fig. 5B shows the ordinate procedure in Japan {31}. While at Haiti scared people decide to reach the exit during the quake, in Japanese case people adopt the "DROP-COVER-HOLD ON" procedures, exit from buildings in groups and converge to precise areas. The geographical area, in which the event happens, becomes very significant because cultural background of population itself (Alexander, 1990; Turner et al., 1986), and of the magnitude of common events. This magnitude represents a sort of maximum value for ordinary events and events of magnitude higher than this value are perceived as unusual.

After the decision to start the evacuation procedure, pedestrians are essentially attracted by safe areas (*Attraction towards safe areas*, *Safe areas identification and preferred path definitions*), according

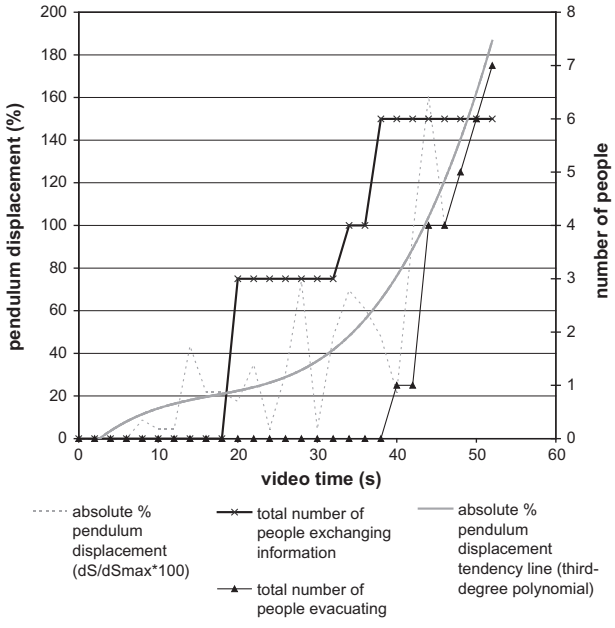

Fig. 2. Analysis of pre-movement phases in a Chilean office evacuation (27/02/2010, magnitude Richter Scale 8.8) {42} related to information exchange in a small group; after 52 s, it is definitively not possible to have information for the switch-off of the camera.

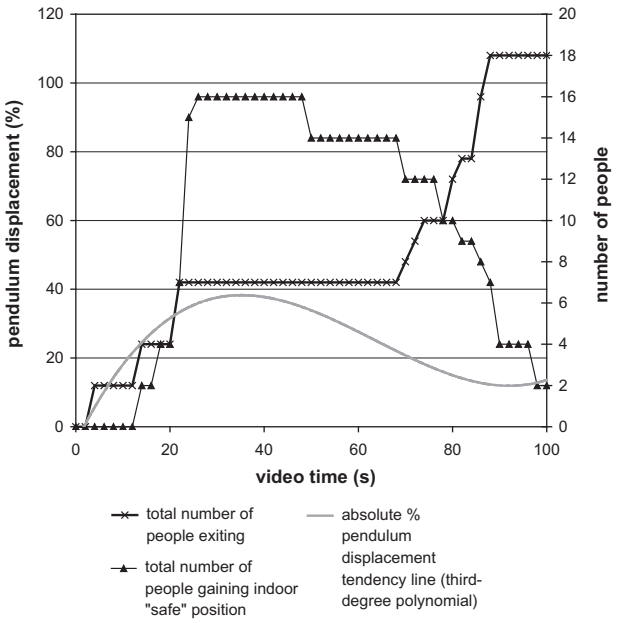

Fig. 3. Analysis of pre-movement phases in an indoor evacuation of a Chilean restaurant (27/02/2010, magnitude Richter Scale 8.8) {40}.

Fig. 4. Comparison between evacuation procedures: A-Haiti earthquake of 2010{23}; B-Fukushima earthquake in 2011 {31}.

Fig. 5. The choice of the clearest paths {24} in presence of rubble and in night evacuation, with lack of visibility due to low environment illuminance (frame from www.youreporter.it).

also to previous studies (Helbing et al., 2002). Fig. 5 shows the moment of valuation of the evacuation path for a single pedestrian, with the choice of the widest and clearest of dust and rubble paths {9,19,23,24,29}, especially in a close urban fabric, according also to previous studies (Alexander, 1990). The individual decides to avoid area with rubble moving to the bottom of image. Moreover, when the possibility to see details is lower, decision times become longer {24}.

Fig. 6 shows that targets in outdoor evacuation are generally the nearest wide spaces in urban fabric {6,10,13,17,25,31,32,34}, such as squares, large avenue, but also crossroad. These areas are considered "safe" for their geometry (distance from buildings, low height of building/width of overlooking public space ratio in comparison with the rest of the surrounding urban fabric), their level of damage (lack of visible damage, rubble and dust) and social factors (place of meeting for more pedestrians, possibility to have sufficient space for each person {10,17} (Mawson, 2007), point of information exchanging (Alexander, 1990; Turner et al., 1986).

Cohesive bounds and "herd behaviour" influence are important phenomena in both post-earthquake evacuation (*"Herd Behaviour" and influence of "collective" velocity*, *Attraction for group bounds*, *Formation of evacuation groups*) and choice of evacuation paths and safe areas. According to previous studies, a group of pedestrians that share a cohesion bound (familiar bounds, clan bounds, evacuation target bounds) prefers to remain connected and close during the evacuation. Fig. 7 shows a typical behaviour for group of pedestrians in which members share group bounds. The individual, which hastens in evacuation in respect to other people, stops himself and decides to come back or waiting for them with almost the same probability {1}.

Fig. 8 qualitatively shows the addiction of individuals in a principal direction of evacuation {21}.

It is possible to see that the possibility for other pedestrians to follow a large number of agents directed to a certain safe area/partial evacuation target is higher than the probability to choose a different evacuation path, demonstrating, in other terms, the group motion bases of this phenomena {10,21}.

Attractive phenomena seem to be function of the kind of bound between two pedestrians: distance values become smaller between two pedestrians with a cohesion bound, to avoid dispersion of members of the same group in the space during evacuation procedures. From the quantitative analysis of videotape {21}, it is noticed a value of 1.8 m for the average distance between mass points of individuals with the same evacuation target, with a standard deviation of 0.1 m; this mean value refers to whole visible evacuation procedure. Considering a radius of pedestrian of 0.35 m (Lakoba and Finkelstein, 2005), we can obtain an effective distance of 0.5 m.

Fig. 9 shows a case in which surrounding conditions during evacuation influences human behaviour: when situation about perceived danger and damage generation becomes stabilized, people are discouraged to abandon safe and well-know places {14,31}, as, for instance, areas that are closest to home, stopping evacuation procedures. This effect, according to precedent studies (Alexander, 1990), could be connected with two aspects: the first is a sort of "helplessness level" that drives people to remain near the same place and gather around this position, especially when conditions of danger are not evident or in panic conditions (*Influence of not immediate danger feelings and panic conditions*); the second is connected with interruption of outdoor motion during earthquake in case of events of particularly high magnitude and ground shaking (*Interruption of outdoor evacuation for high ground shaking*).

Fig. 6. Post-earthquake evacuation in Turkey (left) {34} and Japan (right) {31}; arrows show the direction of evacuation motion. On the left it is possible also to see the concurrence towards the same areas of a groups of pedestrians, one for each arrow.

Fig. 7. Visual example of cohesive behaviour {1}: the man indicated by the white arrow starts his evacuation before other members of his "group", and so decides to stop evacuation procedure waiting for two people indicated by black arrows.

During motion, pedestrians are aimed by a series of interactions with other pedestrians and with environment, essentially to avoid physical contact with this elements, like suggested also in previous studies (Helbing et al., 2002; Lakoba and Finkelstein, 2005) (*Repulsive mechanisms to avoid physical contact*). Conclusions of other works are considered (Alexander, 1990) (*"Safety distance" from "high obstacles"*). Moreover, in post-earthquake case, some obstacles remain fixed elements, but others can be generated during time, such as rubble or dust (Alexander, 1990): they provoke a repulsive effect only when present in the scenario itself. These conclusions are connected with the ones related to safe areas definition (Figs. 5 and 6).

Not all kinds of obstacle provoke a similar repulsive phenomena. Fig. 10 shows that trees, such as other some low obstacles (e.g.: one floor buildings, low walls, enclosures, benches, street furniture, sheds), do not provoke repulsive effects to people {8, 17, 27, 32} (*Not keeping of a "safety distance" from "low obstacles"*). On the contrary, they are attractor for pedestrians' motion: people can move towards them looking for protection, or also lean against these obstacles, especially during the quake.

Fig. 8. Visual addiction of individuals in the principal direction of evacuation, marked qualitatively with the bigger arrow; each individual has his direction marked qualitatively with the smaller arrows {21}.

Fig. 9. The initial position is marked by the single circle on the left, the final one by the two concentric circles on the right; the evacuation direction is given by the arrow. The final point is near the initial one, but in a safe position: people seem to stop here for not immediate danger feelings {31}.

Table 1 shows the statistical influence of trees and streets furniture in outdoor evacuation {32}: the majority of visible and distinguishing people are attracted by these elements during evacuation.

Finally, it is noticed an effective improvement of evacuation phases in presence of evacuation procedures and plans or officers and rescuers supporting pedestrians (*Increased guide effect*) {3,5,25,31}. Fig. 11 shows various aspects of this improvement: reference to suggested evacuation directions given by rescuers, activation of protecting behaviours (such as "DROP-COVER-HOLD ON" procedures) for instructions given by officers, convergence of individuals to precise areas in a faster way in presence of evacuation procedure. This improvement influences reaction and decision times, assumption of correct behaviours and regularisation of evacuation procedures; at the same time emergency plans and presence of officers and qualified rescuers {5} become reassuring elements of reference during outdoor motion.Fig. 12A schematically shows velocity vectors, from a semi-quantitative point of view (V4, V3, V1 in increasing order of modulus), while Fig. 12B shows average speed of a group of pedestrian in relationship to distance from building exit {21}. Speeds are higher during the first phases of evacuation, like exit and removal from buildings {15,21,28,31}; on the other side, if evacuation procedures start during the quake, motion is influenced by ground shaking: for high values of ground shaking, naturally, people slow down or stop the evacuation itself (*interruption of outdoor evacuation for high ground shaking*).

Table 2 shows the results of the numerical analysis using "Tracker" for videotapes {1,2,3,21} in both indoor and outdoor motion. According also to experimental results of other real cases analysis (Hori, 2011), maximum measured value is about 4.0 m/s; related outdoor average speed in post-earthquake evacuation is calculated in 2.1 m/s {21}; notwithstanding the value is referred to the single analysed videotape, this data confirms previous studies.

Finally Tables 3 and 4 show a synthesis of noticed behaviour. Behaviours are distinguished between the common ones with other evacuation (Table 3) and the typical ones (Table 4). For each behaviour, the position in the activation order, the keyword, the type of evacuation identified by conditions of reference, the related number of examined videotapes, the statistical frequency referred to the number of examined videotapes, the elements (*pedestrian* or *environment*) that influence the activation of mechanism are provided.

"Behaviours common also to other evacuation" in Table 3 are the ones present in other events, such as fire evacuations; they are also evidenced in the Social Force model (Helbing et al., 2002; Helbing et al., 2000; Lakoba and Finkelstein, 2005), and demonstrate an high statistical frequency. After the decision to evacuate and the choice of the evacuation target, these behaviours are always active during the evacuation procedure, in both indoor and outdoor conditions.

"Peculiar mechanisms in post-earthquake evacuation" in Table 4 are the ones noticed only for this kind of events because connected to seism scenarios. Their frequency depends on specific conditions of the scenario itself, and they can be organised in a main chronological order, with the possibility to repeat activation of mechanisms during evacuation.

The distinction of reference elements in choices and valuations for pedestrians (*environment* and *pedestrian*) outlines the use of an agent-based approach for the model implementation.

3.2. Intentional model

Noticed behaviours, organised in order of activation and in relation to subject of activation, become the bases for the description of a behavioural agent-based model to simulate post-earthquake evacuation. A model to describe relationships between pedestrian and the scenario and decisions taken by the pedestrian himself during the evacuation procedure is developed. An agent-based approach, capable to define interactions between actors involved in evacuation, is used.

As previously described, the steps of work concern the characterisation of actors involved in evacuation and the definitions of the behavioural agent-based model, with relationship between actors.

Concerning the definition of actors, videotapes analysis suggests that a pedestrian in his amount of decisions refers to other pedestrians and to the physical scenario (building, rubbles, dust, seism parameter, environmental parameters...). It is so natural to define two actors: *Pedestrian* and *Environment*.

Fig. 13 shows the general graphical model of relationships between the two kind of actors, expressed in i^* language: it illustrates resources and actions involved in evacuation by pedestrians, and, consequently, relationships between the two actors.

The representation in Fig. 13 is explained below; in round brackets, examples concerning specific point of the aforementioned figure are recalled.

Two kind of *agent* are defined; they are actors with a physical manifestations, or rather human individual (*Agent i* and *Agent j*)

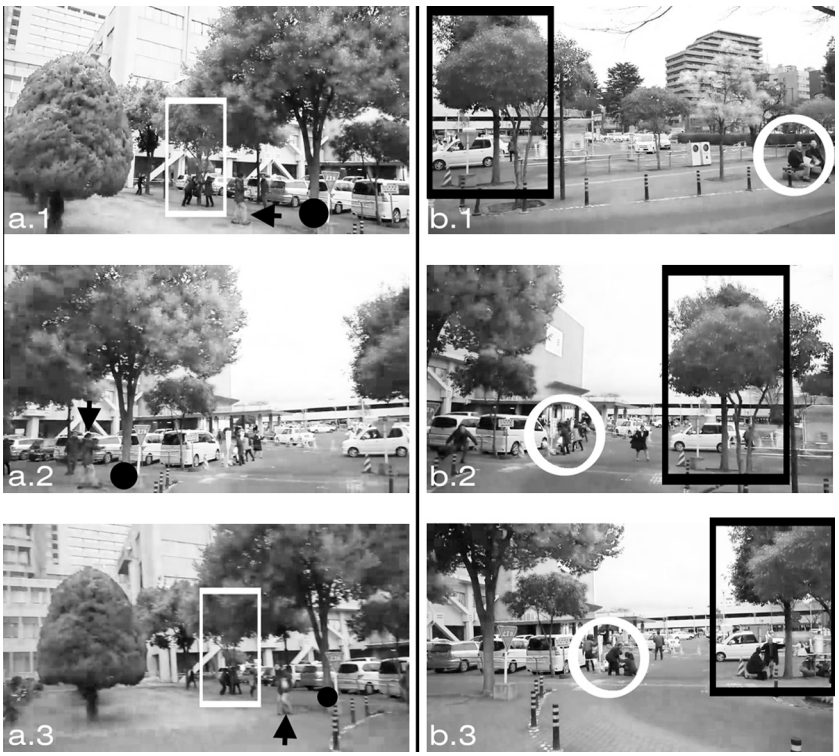

Fig. 10. Chronological sequences of an evacuation denoting absence of repulsion between pedestrian and "low obstacles" {32}: A-pedestrian (black arrow) is attracted during motion by a tree (black point), while a group prefers to remain under a tree (white rectangle) during the whole event; B-pedestrians remains near street furniture (white circles), while a tree is the partial evacuation target for some groups of them (black rectangle).

Table 1
Example of the influence of street furniture and trees on evacuation target in the first phases of outdoor evacuation {32}.

Location	Japan	
Earthquake magnitude (Richter scale)	8,9	
Valuation elements	*Street furniture, trees*	
	Total number	%
Visible and distinguishable people	27	100,0
People reaching valuation elements	22	81,5

and environmental entities such buildings and rubbles (*environment*). His characteristics are not easily transferable to other individuals. For example, *Environment* is defined through characteristics of the scenario: position of safe areas, fundamental seism data (EMS magnitude), position of buildings and relative seismic vulnerability, morphological description of urban spaces. It involves aspects related to EMS and building vulnerability studies (Barbat et al., 1996; Calvi et al., 2006; Federal Emergency Management Agency, 2009; Giovinazzi and Lagomarsino, 2001; Grimaz et al., 1997; Grünthal, 1998; Klügel, 2008; Mouroux and Brun, 2006b; Palacios Molina, 2004; Panza et al., 2012) and refers to modifications in the initial scenario because of seism, introducing the possibility of having formation of ruins and rubble during evacuation time.

Moreover, an agent has dependencies that apply despite the roles he plays. Considering *Agent i* and *Agent j*, they refers to the same rule, which is *Pedestrian*. The rule *pedestrian* is an abstract characterisation of the behaviour of a social actor within some specialized context or domain of endeavour. The dependencies associated with a role apply regardless of the agent who plays the role. The connection between *agent* and *pedestrian* is given by a "plays association", which is used between an agent and a role, with an agent playing a role. The identity of the agent who plays a role should have no effect on the responsibilities of that role, and similarly, aspects of an agent should be unaffected by the roles he plays. First of all, such agents represent pedestrians involved in evacuation procedure; each of them is characterised by different resources.

Actors, and so both *pedestrian* and *environment*, desire the provision of some entity, physical or informational, that are called resources. This type of elements assumes there are no open issues or questions concerning how the entity will be achieved. For example, it could be also possible to distinguish *pedestrians* in different types using the "kind of agent" resource: child, adult, pedestrian with disability (A). Kind of agent characterises also specific numerical values essentially in average speed in motion, radius of pedestrian, mass of pedestrian (Helbing et al., 2002; Lakoba and Finkelstein, 2005) (B).

A *pedestrian* makes decisions based on scenarios, obstacles avoidance, positions of other people, necessity to join groups behaviours, own desired speed, driving terms. He is aimed by different goals. A goal represents an intentional desire of an actor, or rather one of his behaviours. The specifics of how the goal is to be satisfied are not described by the goal; this can be described through task decomposition. The actor wants to accomplish this specific task, performed in a particular way. A description of the specifics of the task may be described by decomposing the task into further sub-elements. At the same time, a task is connected with resources from himself, or from *environment*, or from another *pedestrian* (*Agent j*).

Tasks and goals are reachable using also resources. Elements are connected using general dependencies. A general dependency is the intentional connection between more elements: the "*dependee*" that is the actor who is depended upon on a dependency relationship; the "*depender*" that is the depending actor on a dependency relationship; the "*dependum*" that is the element around which a dependency relationship centres.

Fig. 11. Influence of guidance elements in evacuation: the direction of motion suggested (black arrow) by rescuers (in black) is the effective one (grey arrow) for pedestrian (in gray in B), both in outdoor {31} (Japan, A) and indoors conditions{3} (Chile, B); people, inside white contours, follows rescuers verbal orders activating safety procedures during the quake {5} (Japan, C); workers converge rapidly in precise areas {25}, described in figure by evidenced circles, faraway as possible from buildings, crouched on the ground, waiting for the end of the event (Japan, D; frame from www.youreporter.it)).

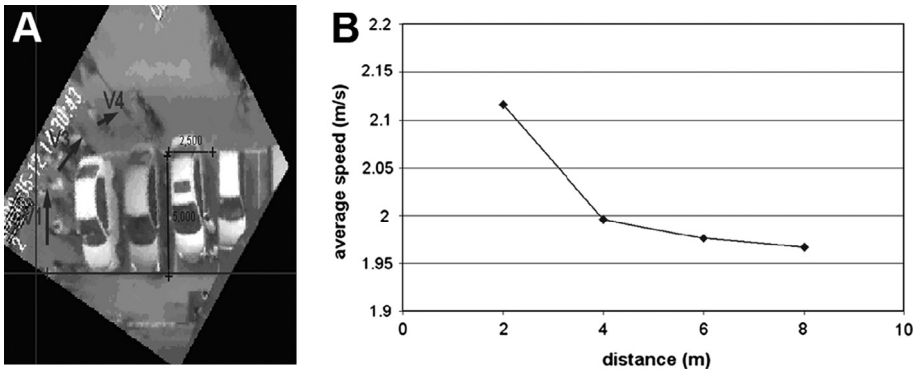

Fig. 12. Speeds are higher during the first phases of evacuation, like exit and removal from buildings {21}: (A) semi-quantitative representation of velocities V4, V3, V1 of a pedestrian, increasing order of modulus (V4 < V3 < V1) using Tracker; (B) average speed for 15 pedestrians in relationship to distance from the building exit.

Table 2
Synthesis of speed values in videotapes analysed with Tracker referring to videotape and number of analysed pedestrians.

VIDEOTAPE	Number of pedestrians	Average speed (m/s)	Standard deviation (m/s)
1	10	3.2	0.6
2	6	2.5	0.6
3	8	2.4	0.4
21	15	2.1	0.3

For example (C), a *pedestrian* gains the "response to sensible event" goal valuating the event, that is using the "evaluation of event" task, and so the goal depends on the task. At the same time, this task evaluation depends from *environment* resources, such as "duration of seism" and "magnitude of seism".

It is also possible to have contemporary dependencies. It is a dependency between more elements that are evaluated all at the same time.

For example (D), to reach the "pedestrian influence" task, it is necessary the contemporary evaluation of different goals: "repulsive mechanisms to avoid physical contact", "attraction for group bounds", "formation of evacuation group" and "Herd Behaviour" and influence of "collective" velocity.

3.3. Behavioural flowchart

As written before, Fig. 13 shows intentional aspects of the model; these aspects are connected with chronological order of activation of behaviours for the single *Pedestrian* subject of evaluation, or rather the *Agent i*. At the same time, it is necessary to define the model relating to the chronological series of action and choices that a *pedestrian* faces during his evacuation procedure, obtaining an operative behavioural flowchart.

Fig. 14 shows the behavioural flowchart for this *pedestrian*, using the chronological organisation of the same noticed behaviours expressed in Table 3.

The intentional model in Fig. 13 and the behavioural flowchart in Fig. 14 are the bases for the creation of an agent-based software simulating post-earthquake evacuation. In fact, the intentional model defines characteristics of agent implemented in the simulation software, while the flowchart permits to organise the series of

Table 3
Noticed behaviours common to other kind of evacuation: frequency is calculated on total number of videotape based on "Type of evacuation considered" column. Concerning "Relationship in activation of behaviour", *Environment* includes buildings, obstacles, safe areas, paths, description of seism, rubble and dusts, rescuers and evacuation plans. *Pedestrian* refers to social relationship between people during evacuation.

Kind of behaviours	Order of activation	Related behaviours	Type of evacuation considered	Total number of video	Frequency (%)	Relationship in activation of behaviour
Behaviours common for a large number of evacuation	3	Attraction towards safe areas	All	43	84	Environment
	3	"Herd Behaviour" and influence of "collective" velocity	All	43	65	Pedestrian
	3	Repulsive mechanisms to avoid physical contact	All	43	84	Environment + pedestrian
	3	Attraction for group bounds	All	43	84	Pedestrian

Table 4
Noticed behaviours typical of post-earthquake evacuation; in addiction to characteristics of Table 3, it is possible to define a fundamental chronological order in activation of behaviours, as suggested in "Order of activation" column. It can be possible to have more than one mechanism activated at the same time for overlapping of object of evaluation.

Kind of behaviours	Order of activation	Related behaviours	Type of evacuation considered	Total number of video	Frequency (%)	Relationship in activation of behaviour
Peculiar mechanism in post-earthquake evacuation	1	Response to sensible events	All	43	67	Environment
	2	Safe areas identification and preferred path definitions	Outdoor	37	81	Environment + pedestrian
	3	"Safety distance" from "high obstacles"	Outdoor	37	92	Environment
	3	Not keeping a "safety distance" from "low obstacles"	Outdoor with "low obstacles"	16	81	Environment
	3	Formation of evacuation groups	Outdoor	37	81	Pedestrian
	3	Increased guide effect	Presence of rescuers/ evacuation procedure	7	86	Environment
	4	Influence of not immediate danger feelings and panic conditions	Outdoor	37	57	Environment + pedestrian
	4	Interruption of outdoor evacuation for high ground shaking	Outdoor	37	35	Environment

actions and decisions taken by pedestrian during the procedure. For some tasks in the flowchart it is necessary to define criteria in decisions.

3.4. Criteria for pedestrian motion and choices

Three fundamental parameters are discussed in order to numerically describe people decisions in motion:

- probability of path use;
- "choice-of-path" delay;
- motion law.

3.4.1. Probability of path use

The probability of path use is graphically individuated by the relative block in Fig. 13. The probability $Pc(s,e)$ to reach a certain safe area s using a certain evacuation path e in the whole number of possible safe areas S_i and evacuation paths E_i usable by the pedestrian depends on a series of factor: path illuminance, obstruction and obstacles, geometric values including width of the path and highness of buildings, distance between choice point and safe area, presence of rescuers or other pedestrians. Fig. 15 shows schematically phases of valuation in a related flowchart.

Eq. (2) proposes the relationship between these parameters usable by a pedestrian for his choice:

$$P_c(s,e) = f\left(\frac{E_e}{E^{\max}}, \frac{R_{W/H,s}}{R^{\max}_{W/H,s}}, \frac{R_{W/H,e}}{R^{\max}_{W/H,e}}, \frac{d_s^{\min}}{d_{s,e}}, \frac{(A_e - A_{r,e})}{(A_e - A_{r,e})^{\max}}, \frac{\bar{W}_e}{\bar{W}^{\max}}, \frac{n_e}{N}, O_e, M_e\right) \tag{2}$$

Notations are reported in Appendix A. The value of each parameter is normalised by the maximum value for the whole number of evacuation paths that are selectable by the pedestrian. O_e term will be higher in presence of rescuers that recommend to use the path e (or their presence along the path itself), or if the path e is known as an evacuation path (for presence of known evacuation plans); weights including information exchange between pedestrians are also considerated. Memory effects are supposed according to previous studies (Lakoba and Finkelstein, 2005); this parameter takes into account the presence of well-known roads between the selectable one, and will be higher when the road is highly known. Examining different e, s combinations in the whole number of possible ones, the chosen combination between path/safe area will be the one with the higher $Pc(s,e)$ value, as shown in the following equation:

$$\begin{cases} \max P_c(s,e) \\ s \in S_i \subseteq S^* \wedge e \in E_i \subseteq E^* \end{cases} \tag{3}$$

This maximisation is due to the choice of such as the "good possible evacuation path". $Pc(s,e)$ is considered as a monotonically increasing function with independent parameters, and it is variable from 0 to 1.

3.4.2. "Choice-of-path" delay.

The choice of direction of evacuation, or rather of each intermediate evacuation target, is an action that could also take a significant time. Eq. (4) shows factors connected with this time evaluation:

$$T(s,e) = f(T_k, E, O_e, P_e) \tag{4}$$

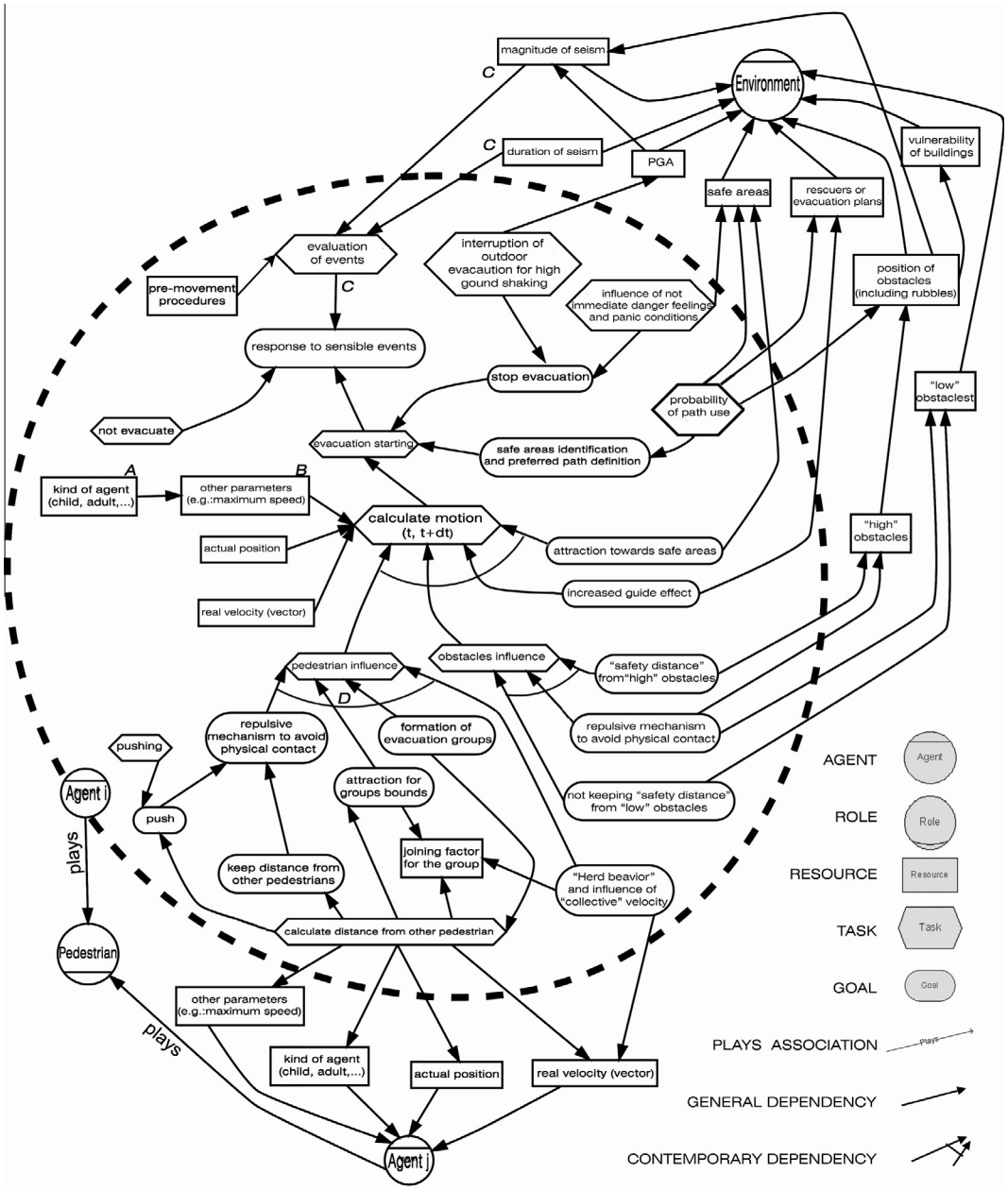

Fig. 13. Representation of the model in i* language, with representation of the interactions expressed by behavioural inquiry; it represents characteristics of *pedestrian*, which blocks are all inside the dashed line, in dependency also to *environment* (top right) and other *pedestrian* (bottom left).

Notations are reported in Appendix A. Pre-movement time (acquiring information on valuating distances, exchanging information with other pedestrians, waiting for other pedestrians, using information offered by rescuers or evacuation plans), incidence of environment illuminance, presence of rescuers or evacuation plan are considered. Moreover, the *Formation of evacuation groups* phenomena is taken into account, involving the "herd behaviours" activation: in order to reduce their decision time, people seems to follow other pedestrians behaviours and choices. It is reasonably supposed that a *pedestrian* prefers to follow the quickest choice, or rather to use the path characterised by the minimum value of $T(s,e)$, as shown in the following equation:

$$\begin{cases} \min T(s,e) \\ s \in S_i \subseteq S^* \wedge e \in E_i \subseteq E^* \end{cases} \tag{5}$$

3.4.3. Motion law. The definition of the velocity $\vec{v}_i(t)$ in pedestrian motion given by the Social Force model is adopted (Helbing et al., 2002; Lakoba and Finkelstein, 2005). Eq. (6) resumes terms involved in the relative relationship:

$$\vec{v}_i(t) = f(\vec{O}_g, \vec{F}_{rep}, \vec{F}_{attr}) \tag{6}$$

All notations are reported in Appendix A. Eq. (7) synthesizes the criterion for this term (Helbing et al., 2002; Lakoba and Finkelstein, 2005) based on distances between subjects of evaluation; modifications to original formulation are proposed:

$$\begin{cases} \vec{v}_i(t) = f(\vec{O}_g, \vec{F}_{rep,j}, \vec{F}_{rep,w}, \vec{F}_{attr,gr}) \Longleftrightarrow & i = 0 \\ \vec{F}_{rep,j} = f(\vec{p}_i, \vec{p}_j) \neq 0 \Longleftrightarrow & \|\vec{p}_i - \vec{p}_j\| \leqslant D_{\min,j} \\ \vec{F}_{rep,w} = f(\vec{p}_i, \vec{p}_w) \neq 0 \Longleftrightarrow & \|\vec{p}_i - \vec{p}_w\| \leqslant D_{\min,W} \\ \vec{F}_{attr,gr} = f(\vec{p}_i, \vec{p}_{gr_i}) \neq 0 \Longleftrightarrow & j \in gr_i \wedge \|\vec{p}_i - \vec{p}_j\| \leqslant D_{\min,gr} \end{cases} \tag{7}$$

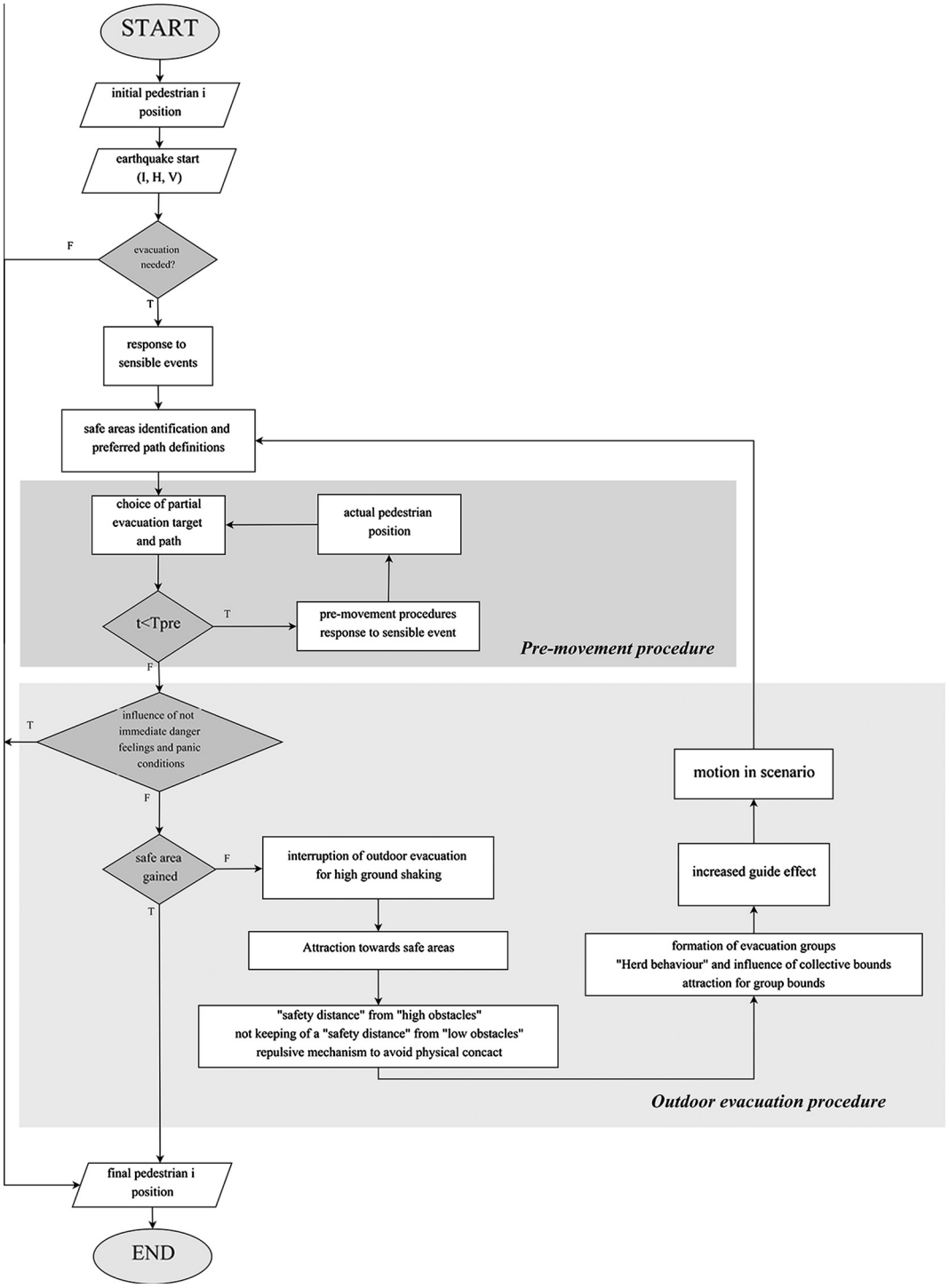

Fig. 14. General flowchart for "*pedestrian*" *i* evacuation; pre-movement procedure and outdoor evacuation procedure phases are evidenced.

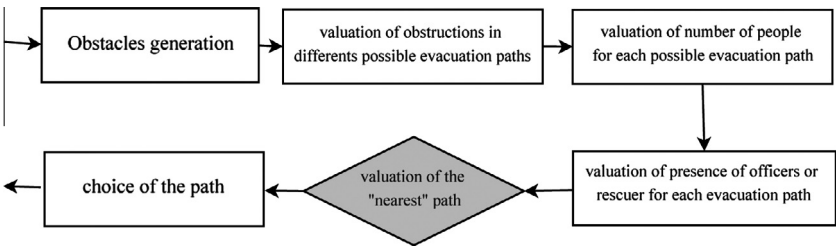

Fig. 15. Flowchart of evacuation paths choice; an evaluation of factors presented in Eq. (2) is done for each possible evacuation paths usable by the pedestrian *i*.

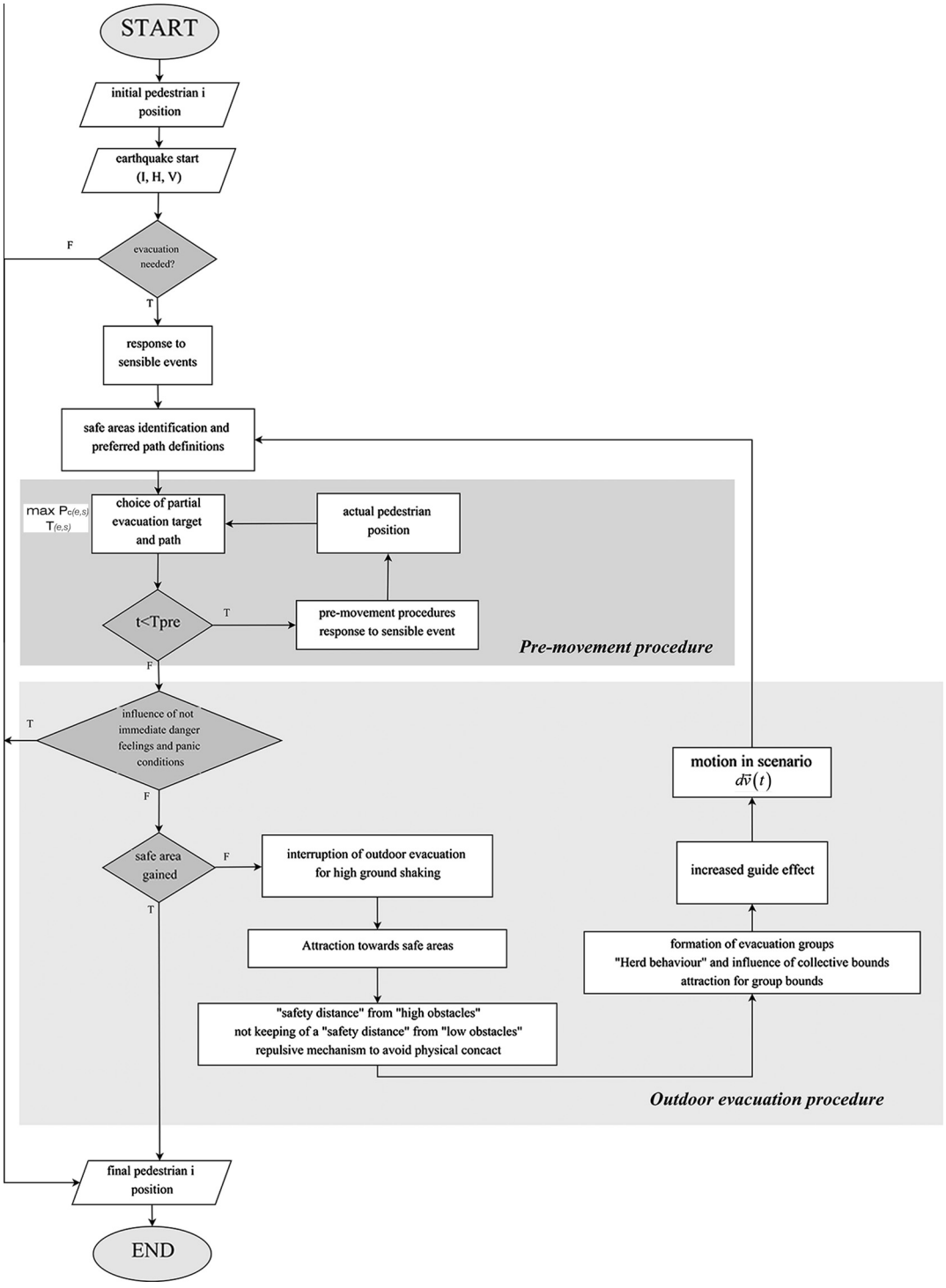

Fig. 16. General flowchart for "*pedestrian*" *i* evacuation with insertion of moment for evaluation of criteria of motion.

The attractive force is supposed to be generated between the position of the pedestrian *i* and the geometric centre of *i*'s group ($p_{gr\ i}$). *i*'s group is composed by the *j* pedestrians that are placed in a radius of $D_{\min,gr}$ from *i* and that shares the similar group bound with *i*. Eq. (8) shows this influence of a pedestrian *j* that belongs to the *i*'s group in relationship to distance between *j* and *i*:

$$\forall j | d_{ij} < D_{\min,gr}, \text{if } j \in gr_i \Rightarrow \vec{p}_{gr_i}(t_n) = f(\vec{p}_j(t_n)) \quad (8)$$

As shown also in Eq. (7), a similar structures is given to repulsive forces, with different activation limits ($D_{min,j}$, $D_{min,W}$): only the elements that are closer than a certain distance provoke repulsive phenomena.

Finally, Fig. 16 shows the insertion of the aforementioned criteria in the behavioural flowchart for a *pedestrian i*, to define the moment of evaluation for each aforementioned parameter.

However, the mathematical translation of criteria will be de-

fined in the following part of our work. In a particular way, the motion law (that is represented in Fig. 16 by "motion in scenario" block) is translated using the Social force model one. In this way, pedestrian motion can be described as the result of a system of forces involving relationship between the pedestrian itself and the surrounding scenario, obtaining the value of pedestrian *i* velocity $\vec{v}_i(t)$ for each step of motion. Moreover, the Social Force Solving equation is corrected and integrated by results of analysis and definition of behavioural model.

4. Conclusions

In this first part of our study, the exposition parameter in seismic risk evaluation is approached involving study of behaviours adopted by pedestrian in evacuation phases.

Videotape analysis of real earthquake evacuations provides a series of behavioural pattern common in the total amount of cases; it is possible to organise these noticed behaviours in chronological order of activation. This kind of analysis could be also used for other kind of events.

A related agent-based behavioural model is defined: it represents interaction and relationship between evacuating pedestrians and the environment in which they move. The agent-based model is chosen for its possibility to express characteristics of actors and relationships between them; the behavioural model is described using i∗language. At the same time, a behavioural flowchart representing the series of pedestrian actions during evacuation is offered.

Moreover, criteria in pedestrian motion and decisions are defined starting from empirical analysis.

Finally, obtained results include the capability in using this methodology: this method can be also applied to define behavioural model for other kind of evacuation of human activity based on experimental analysis of behaviours.

The following part of our work will show the operative definition of criteria of motion and the software program development. The Social Force Model equation is corrected and integrated to the studied case in order to numerically describe the pedestrian motion. Moreover, the agent-based simulation software is developed and validate.

Appendix A. Notations

Symbol	Measure	Description
A_e	m^2	total area of evacuation path e
$A_{r,e}$	m^2	total area of ruins on evacuation path e
$(A_e - A_{r,e})^{max}$	m^2	maximum value of difference between total area of evacuation path e and total area of ruins on evacuation path e
$D_{min,gr}$	m	maximum distance for group attraction
$D_{min,j}$	m	maximum distance of activation for repulsive forces between two pedestrians
$D_{min,W}$	m	maximum distance of activation for repulsive forces between pedestrian and obstacle
$d_{s,e}$	m	geometric distance between the pedestrian and the considered safe area s using the evacuation path e
d_s^{min}	m	minimum value of geometric distance between the pedestrian and the nearest safe area using the shortest evacuation path
dS	m	measured pendulum displacement at evaluation moment
dS_{max}	m	maximum measured pendulum displacement in evaluation
E	–	seismic exposure, related to the presence and the "value" of buildings and other objects and to the possible consequences on human life
E_e	lux	illuminance of path e
E_i	–	paths available for the pedestrian i
E^{max}	lux	maximum value of illuminance considering the whole number of evacuation paths usable by the pedestrian (including phenomena connected with density of dusts)
E^*	–	total number of paths in the scenario
e	–	evacuation path
$\vec{F}_{attr,gr}$	(modulus) N	attractive forces
$\vec{F}_{rep,j}, \vec{F}_{rep,w}$	(modulus) N	repulsive force between pedestrians and between pedestrians and obstacle
gr_i	–	group sharing a cohesion bound with the pedestrian i
H	–	seismic hazard, related to the possibility of future seismic actions
i, j	–	pedestrian subject of valuation, other pedestrian in valuation
M_e	–	parameter of influence about memory effects connected to the use of the evacuation path e
N	–	total number of pedestrians utilising the whole number of possible paths that are visible by the pedestrian i
n_e	–	number of visible pedestrian using the selected path e
O_e	–	parameter of influence about presence of officers, rescuers or specific signals in the evacuation path e
$\vec{O}_g(t)$	(modulus) N	drive-to-target force
$P_c(e, s)$	–	possibility to reach a certain safe area s using a certain evacuation path e
P_e	–	presence of other pedestrians in the evacuation path e
$\vec{p}_{gr_i}$	–	position of the geometric centre of the i's group
$\vec{p}_i$	–	position of the pedestrian i interested by the valuation

(*continued on next page*)

Appendix A. (*continued*)

Symbol	Measure	Description
$\vec{p}_j$	–	position of the pedestrian j
$\vec{p}_w$	–	position of the obstacle w
R	–	seismic risk, related to the number of people killed or injured, the damage to property, and the impact on economic activity due to the occurrence of the disastrous event
$R_{W/H,e}$	–	wide of path e / height of buildings on the paths e ratio
$R^{\max}_{W/H,e}$	–	maximum value of wide of path e / height of buildings on the paths e ratio
$R_{W/H,s}$	–	wide of safe area s / height of buildings on the safe area s ratio
$R^{\max}_{W/H,s}$	–	maximum value of wide of safe area s / height of buildings on the safe area s ratio
S_i	–	safe areas available for the pedestrian i
S^*	–	total number of safe areas in the scenario
s	–	safe area
$T(e, s)$	s	"choice-of-path" time
T_k	s	"choice-of-path" pre-movement time
V	–	seismic vulnerability, related to the "weakness" of the buildings and other objects
$\vec{v}_i\ (t)$	m/s	actual velocity of the pedestrian
$\bar{W}_e$	m	average wide of the selected path e considering ruins
$\bar{W}^{\max}$	m	maximum average wide of usable paths considering ruins

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