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Towards creating a combined database for earthquake pedestrians' evacuation models

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Abstract. Earthquake risk assessment at urban scale is actually based on site hazard, buildings vulnerability and exposition, but does not consider human behaviours during both the event and the evacuation. Nevertheless, human interactions in such conditions become one of the most influencing element for inhabitants safety. Hence, an important issue is understanding how people interact with other individuals and with the environment modified by the earthquake. The development of evacuation software in earthquake conditions needs investigations about these aspects. In fact, actual data about earthquake evacuation behaviours are very poor. This work starts from this request and proposes an innovative database for earthquake evacuation models according to literature suggestions. A wide number of videotapes concerning real events from all over the World is analysed in order to provide human behaviours and motion quantities, and to integrate previous results. The database firstly includes the step-by-step evacuation behaviours that are activated during the process. Secondly, motion quantities (speed, acceleration, and distance from obstacles) are provided. The analysis of real emergency conditions evidences particular phenomena. Main results demonstrate how people prefer moving with an average speed of about 2.3÷3 m/s. Finally, fundamental diagrams of pedestrians' dynamics in earthquake emergency conditions show how, density values being equals, speeds and flows are higher than previous studies (in particular: fire evacuation and evacuation drill). These data can be used as input parameters for defining and developing new evacuation models, but also for existent models validation.

Highlights.

- We analyze videotapes of real earthquake evacuations.
- We integrate previous databases on human evacuation behaviours.
- We inquire motion quantities in evacuation.
- We define fundamental diagrams of pedestrians' dynamics in emergency condition.
- We compare results with other evacuation types.

Keyword. earthquake evacuation; applied social sciences; agent-based model; behavioural model; social force model

1 Introduction

Understanding human behaviours and defining behavioural rules in emergency conditions are essential issues in human safety assessment. Similar analyses introduce the importance of the "human" factor in the scenario and trace the bases for proposals about emergency management strategies. The most significant way to provide these results is the use of emergency and evacuation simulation software: their number has rapidly increased during the last years and demonstrates a wide range of powerful applications (Kuligowski and Peacock, 2005; Zheng et al., 2009; Helbing and Johansson, 2010), for different emergencies (Uno and Kashiyama, 2008; Zheng et al., 2009; Zhang and Yao, 2010; Hori, 2011; Song et al., 2013; D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a) and in both indoor (Filippidis et al., 2006; Korhonen and Hostikka, 2010; Alizadeh, 2011; Chu et al., 2012; Pereira et al., 2013; Sarshar et al., 2013; D'Orazio, Spalazzi, et al., 2014b; Lovreglio et al., 2014) and outdoor (Hori, 2011; Nishino et al., 2012; Osaragi, 2012; D'Orazio et al., 2013; Murray-Tuite and Wolshon, 2013; Wijerathne et al., 2013) scenarios. In order to develop these software tools, qualitative and quantitative data on human behaviours are strongly and urgently needed. All the different emergency typologies (i.e.: fire, earthquake, flood, terrorist attack) require a series of investigations that include the definition of related emergency databases (Fahy and Proulx, 2001; Purser and Bensilum, 2001; Shi et al., 2009; Kobes et al., 2010a) and chronological evacuation schemes (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a). Qualitative investigations involve human behaviours and they are performed by analyzing the step-by-step actions carried out by evacuating pedestrians, including their statistical significance (Purser and Bensilum, 2001; Helbing et al., 2002; Yang et al., 2011; D'Orazio, Spalazzi, et al., 2014a). These analyses lead to distinguish the evacuation phases (Alexander, 1990; Riad et al., 1999; Averill et al., 2005; Shen, 2006; Kobes et al., 2010a, 2010b; D'Orazio and Bernardini, 2014; D'Orazio, Spalazzi, et al., 2014a): a pre-movement phase and a motion phase (including building exiting and safe areas reaching) are generally evidenced. The quantitative motion analyses involve the determination of motion parameters (e.g.: walking speeds, individuals evacuation paths) and they are preferably performed through analyses on evacuation videotapes (Hoogendoorn, 2003; Liu et al., 2009; Hori, 2011; Yang et al., 2011; D'Orazio and Bernardini, 2014; D'Orazio, Spalazzi, et al., 2014a; Ronchi et al., 2014) by using different motion tracing techniques (Teknomo et al., 2001; Li et al., 2012; Boltes and Seyfried, 2014). Evacuation phases are generally characterized by different behaviours and numerical quantities (Alexander, 1990; Helbing and Johansson, 2010; Kobes et al., 2010a, 2010b; D'Orazio, Spalazzi, et al., 2014a). Table 1 resumes the main qualitative and quantitative data that have to be analyzed according to previous works (Fahy and Proulx, 2001; Helbing et al., 2002; Shi et al., 2009; D'Orazio, Spalazzi, et al., 2014a): these quantities should contribute to the definition of evacuation databases. Nowadays, most studies deal with human behaviour analysis in fire evacuations or big structure evacuations (Johnson et al., 1994; Muir et al., 1996; Riad et al., 1999; Shields and Boyce, 2000; Fahy and Proulx, 2001; Helbing et al., 2002; Averill et al., 2005; Chu et al., 2006; Shen, 2006; Mawson, 2007; Dederichs and Larusdottir, 2010; Nilsson et al., 2010): behavioural aspects and evacuation quantities, such as delay times and motion speeds, are deeply investigated. Analyses has been involved real accidents (Canter, 1980; Proulx, 2002a; Averill et al., 2005; Mcconnell et al., 2010), evacuation simulations in virtual reality (Ren et al., 2008; Vilar et al., 2012), evacuation experiments in different locations, such as retail stores (Shields and Boyce, 2000), hotels (Kobes et al., 2010a), cinemas and theatres (Nilsson and Johansson, 2009), schools (Zhang et al., 2008; D'Orazio and Bernardini, 2014), flats (Proulx, 1995), care homes (Gwynne, Galea, Parke, et al., 2003), means of transportations (Johnson et al., 1994; Gwynne, Galea, Lyster, et al., 2003). Pre-movement phase and egress choices are also investigated in relation to social attachment, attachment to things and known exits positions (Mawson, 2007; Augustijn-Beckers et al., 2010; Kobes et al., 2010a, 2010b; D'Orazio et al., 2015). Disabled individuals' behaviours have also been collected in other experiments (Proulx, 2002b; Lena et al., 2010). Relations between pedestrians' flow rate, people density and motion speeds (Hankin and Wright, 1958; Predtechenskii and Milinskii, 1978; Mori and Tsukaguchi, 1987; Weidmann, 1993; Seyfried et al., 2005; Johansson and Helbing, 2008) are provided: these works usually involve both normal and evacuation experiments conditions, and different approaches in quantities measurement (Johansson and Helbing, 2008; Steffen and Seyfried, 2010; Courbon and Leclercq, 2011; Burghardt et al., 2013). Besides, retrieval of related fundamental diagrams of pedestrians' dynamics (Seyfried et al., 2005) allow quick models to be defined for describing motion process from a fluid dynamics point of view (Henderson, 1971; Seyfried et al., 2006; Johansson and Helbing, 2008; Steffen and Seyfried, 2010; Transportation Research Board, 2011) also in evacuation conditions (Lämmel et al., 2008; Kunwar et al., 2014).

Table 1. Suggested data that contribute to an evacuation characterization according to previous works (Fahy and Proulx, 2001; Schadschneider et al., 2009; Shi et al., 2009; D'Orazio, Spalazzi, et al., 2014a): these aspects should be considered if evacuation databases want to be provided. For each analyzed data, its type (quantitative when involves physical quantities; qualitative when involve pure behavioural aspects) and a short description is provided.

Evacuation Data	**Type [main unit of measure]**	**Short description**
delay times	quantitative [s]	time of reaction to the event; pre-movement time characterization
walking speeds	quantitative [m/s]	in different conditions of crowdedness and path
occupant characteristics	quantitative and qualitative	differences in actions, reactions, specific parameters
evacuation behaviours	qualitative	series of actions during evacuations
evacuation path obstruction	quantitative (e.g.: density [people/m^2]) and qualitative	influence of environmental conditions on queue delays or block egress
exit and path choice decisions	quantitative (e.g.: flow [people/(m*s)]) and qualitative	influence of environmental conditions and other people positions on travel paths and travel times

On the contrary, a limited number of works investigates other kinds of emergencies, and, in particular, earthquake evacuations (James, 1968; Takuma, 1972; Boileau et al., 1978; Arnold et al., 1982; Turner et al., 1986; Alexander, 1990; Grünthal, 1998; Hori, 2011; Osaragi, 2012; Prati et al., 2012; D'Orazio, Quagliarini, et al., 2014a). Nevertheless, the importance of human behaviours in earthquake emergencies is generally evidenced (Takuma, 1972; Alexander, 1990; Ainuddin and Routray, 2012; Yang and Wu, 2012; Amini Hosseini et al., 2014; D'Orazio, Spalazzi, et al., 2014a; Mishima et al., 2014). During both the earthquake and the first post-event evacuation phase, people adopt different choices with the aim to remain in safe conditions, to avoid dangerous zones, to be close to other pedestrians, to gain safe areas. These phenomena are more influent in urban scenarios, where man-environment interactions are strongly influenced by environmental modifications due to the earthquake (Goretti and Sarli, 2006; Ferlito and Pizza, 2011; D'Orazio, Spalazzi, et al., 2014a). For this reason, tools for earthquake emergency and evacuation analysis is actually more and more needed and also the number of related simulator is increasing (Hashemi and Alesheikh, 2010; Hori, 2011; Liu et al., 2011; Ye et al., 2011; Osaragi, 2012; D'Orazio, Quagliarini, et al., 2014a). Traditional evaluations on site hazard (Klügel, 2008; Panza et al., 2012), buildings and infrastructure vulnerability (Palacios Molina, 2004; Federal

Emergency Management Agency, 2009; Zanini et al., 2012) and exposure (Chen et al., 1997; Mouroux and Brun, 2006) will be soon merged with simulators analyses in order to develop a sort of integrated "risk maps" for pre-disaster interventions and disaster management. This means the adoption of an approach comparable to the fire safety engineering one (Shi et al., 2009). Acquiring and organizing data on humans behaviours and evacuation motion quantities represent the first bases for the development of simulations tools (D'Orazio, Quagliarini, et al., 2014a). Despite of the request to gain these data, the amount of present studies is limited (James, 1968; Takuma, 1972; Boileau et al., 1978; Arnold et al., 1982; Turner et al., 1986; Alexander, 1990; Grünthal, 1998; Yang et al., 2011; Osaragi, 2012; Prati et al., 2012; Yang and Wu, 2012). These works could be evaluated by principally distinguishing the performed methodologies and the surrounding scenario. Table 2 provides their characterization by addressing their strengthens and weaknesses. Some additional references concerning other fundamental pedestrians' behavioural studies are included in order to evidence some interesting evaluation techniques. Only few works try to classify human behaviours and to organize a chronological scheme of the evacuation process (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a). They often extract data from questionnaires related to case studies (Miyamoto et al., 2011; Prati et al., 2012). The analysis of real earthquake evacuations is rarely performed (Helbing et al., 2002; Yang et al., 2011; Yang and Wu, 2012), even though it concerns potentially unbiased data (Yang et al., 2011; Yang and Wu, 2012). The importance of analyses on real earthquake is also underlined by the presence of differences between the real evacuation and the simulated ones (Yang et al., 2011). In general terms (D'Orazio, Spalazzi, et al., 2014a), results show that some behaviours are common to other kind of evacuations and some others are instead specific of earthquake evacuation. In particular, previous works evidence the existence of a lower limit in the perception of earthquake (Grünthal, 1998), the panic conditions characterization (Alexander, 1990; Grünthal, 1998; D'Orazio, Spalazzi, et al., 2014a), the "pre-movement" phase (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a), the presence of cohesion bonds between individuals (Alexander, 1990; Prati et al., 2012; D'Orazio, Spalazzi, et al., 2014a), the 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. Decision-making behaviours of individuals attempting to reach home on foot in the wake of a devastating earthquake is also investigated (Osaragi, 2012). Finally, the quantitative analysis of evacuation motion is rarely inquired, and mainly involves only walking speeds (Hori, 2011; D'Orazio, Spalazzi, et al., 2014a).

However, the actual development of emergency tools and simulators implies the urgency of expanding these early results: behavioural aspects should be codified by enlarging the reference sample. Deeper investigations on motion quantities are also needed. This work starts from these requests and tries to define a sort of evacuation database by analyzing a large database of real videotapes concerning earthquake evacuation from all over the World. The attention is also focused on evacuations in urban scenarios. Besides, human behaviours are codified and results are combined with the one of previous studies (D'Orazio, Spalazzi, et al., 2014a). Motion quantities, such as walking speeds, accelerations and distances from obstacles, are investigated by providing average values and data distributions. In addition, fundamental diagrams in emergency conditions are retrieved. A comparison with previous works results is then proposed (Lakoba et al., 2005; Hori, 2011; Yang et al., 2011; D'Orazio, Spalazzi, et al., 2014a).

Table 2. Critical evaluation of previous works about human behaviours in evacuations. Indoor (IN) and outdoor (OU) scenarios are included. Results are distinguished between quantitative (QT) and qualitative (QL).

Conditions	Scenario	Database	Techniques	Results	Strong points	Limits	References
Earthquake	IN + OU	real events	videotapes analysis	QT+QL	analysis of events from all over the world; definition of a simulation model; chronological organization of human behaviours; distinction between behaviours: common to other evacuations and peculiar; analysis including environmental modifications	small or very small analyzed sample dimension; no fundamental diagrams definition; statistical significance of behaviours; camera correction for ground shaking can be needed	(Hori, 2011; D'Orazio, Spalazzi, et al., 2014a)
	IN	real events	videotapes analysis	QT+QL	evidencing differences between evacuation drill and real evacuation behaviours; scenario involving high densities buildings	limitation of analysis to a single earthquake and in indoor conditions; no fundamental diagrams definition	(Arnold et al., 1982; Yang et al., 2011)
	IN + OU	real events	videotapes analysis	QL	evidencing the unbiased characters of analysis on real event; description of human behaviours and environmental	only qualitative analysis; limited to a single earthquake	(Yang and Wu, 2012)

					phenomena; analysis including environmental modifications		
	IN + OU	real events	direct authors observations; questionnaire /interview	QL	chronological organization and distinction of evacuation phases; analysis including environmental modifications	experienced observers needed; answers in "a posteriori" questionnaires can be influenced by perception and memory	(Alexander, 1990; Prati et al., 2012)
	IN + OU	real events	world wide observations	QL	real world analyses; fuzzy approach in describing human behaviours	limited to human perception and probability of people participation to the evacuation	(Grünthal, 1998)
	OU	hypothetical case studies	questionnaire	QL	"what if" results and scenario making evaluation; large samples by using a quick method	differences between real-life and hypothetical situations; possible limitation to case studies	(Miyamoto et al., 2011)
Fire and large buildings evacuation	OU	real events	videotapes analysis and questionnaire	QT+QL	single pedestrians' behaviours analysis of real events; definition of a simulation model	not directly usable for earthquake events	(Helbing et al., 2002, 2007)
	IN	evacuation drill	videotapes analysis	QT+QL	fundamental diagram definition; focuses on pre-movement activities, social attachment, attachment to belongings, evacuation choices, interaction with evacuation signs and devices; possibility to easily include experiments with disabled	differences between real-life and hypothetical situations; motion quantities influenced by the no-danger conditions	(Proulx, 2002b; Kobes et al., 2010b; Lena et al., 2010; Ronchi et al., 2014; D'Orazio et al., 2015)
	IN	virtual reality	direct analysis	QT+QL	large samples by using a quick method; tests many different scenarios	differences between real-life and hypothetical situations; differences between real-world and virtual environment behaviours	(Ren et al., 2008; Vilar et al., 2012)
Normal conditions	IN+OU	real scenario	videotapes analysis	QT+QL	best practices for evaluating motion quantities; definition of fundamental diagrams	results are not applicable to emergency conditions	(Hoogendoorn, 2003; Liu et al., 2009; Steffen and Seyfried, 2010; Zhang et al., 2011)

The definition of similar databases will allow emergency earthquake evacuation simulators to be developed on experimental bases, such as the one based on multi-agent methodologies (Crooks et al., 2008; Helbing and Bialetti, 2012; D'Orazio et al., 2013; D'Orazio, Spalazzi, et al., 2014a). At the same time, the database could be used for models validations and case-studies verifications (D'Orazio, Quagliarini, et al., 2014a). This approach was also adopted by previous works such as the ones about crowd motion and evacuations in case of fire (Helbing et al., 2002).

2 Phases, videotapes dataset characterization and analysis methods

2.1 Phases

This work is organized in the following main phases (the corresponding paragraph, in which relative results are explained, is indicated in brackets, in italics):

- analyzing videotapes in order to detect evacuation behaviours (*Earthquake evacuation behaviours database*);
- organizing noticed behaviours in a database by integrating previous results (*Earthquake evacuation behaviours database*);
- analyzing videotapes in order to describe evacuation motion quantities (*Earthquake evacuation motion quantities database*).

2.2 Videotapes dataset characterization

Previous collections of videotapes involving real earthquake evacuations (Yang and Wu, 2012; D'Orazio, Spalazzi, et al., 2014a) are merged in order to obtain a larger dataset of real events from all over the World, so as to consider the existence of different responses related to event because of cultural and social background (Boileau et al., 1978; Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a). Each videotape of the two datasets is divided in "scenes": each "scene" has similar evacuation conditions (D'Orazio, Spalazzi, et al., 2014a) and involves only an evacuation. Such as, some videotapes could contain more than one "scene" (e.g.: indoors and outdoors evacuations). The two initial datasets are combed and "scenes" are excluded at least in presence of one of the following aspects: no individuals on the scene; no possibility to detect evacuating pedestrians during the whole procedure; variations in tape speeds; presence of deleted frames; framing problems (e.g.: videotapes from mobile cameras or in inadequate illuminance conditions). Videotapes with at least one "scene" are included into the final dataset. The final dataset is analyzed in order to detect both behavioural aspects and motion quantities (D'Orazio, Spalazzi, et al., 2014a).

The final dataset (available at drive.google.com/folderview?id=0B91jqaXLKo5LTFlqbnplS0tJLTQ&usp=sharing) involves over 70 "scenes" of outdoor and indoor scenarios. According to previous analogous works (Yang and Wu, 2012; D'Orazio, Spalazzi, et al., 2014a), "scenes" refer to perceptible earthquakes (magnitude higher than a 5th degree in the Richter Seismic Scale or IV degree in EMS-98 scale (Musson et al., 2009)), with both known and confirmed geographical localization and date. Events from mass-media channel, civil defence or government agencies, or present in more than one different videos, including CCTV videotapes (Yang and Wu, 2012), are preferred. USGS database available at http://earthquake.usgs.gov is used to obtain general magnitude data for each event. The presence of cohesion bonds between pedestrians are detected or supposed such as in previous studies (D'Orazio, Spalazzi, et al., 2014a). According to earlier analyses (D'Orazio, Spalazzi, et al., 2014a), Fig. 1 summarizes the general dataset characteristics about earthquake magnitude (Fig. 1.a), year of occurrence (Fig. 1.b), geographical distribution (Fig. 1.c), evacuation conditions concerning both number of visible evacuating pedestrians (Fig. 1.d) and environmental factors (Fig. 1.e). In particular, the distinction between low (≤ 10 pedestrians) and high (> 10 pedestrians) number of visible evacuating pedestrians follows the previous work definition (D'Orazio, Spalazzi, et al., 2014a). Videotapes are numbered and, in the following, the dataset reference numbers are written in curly brackets.

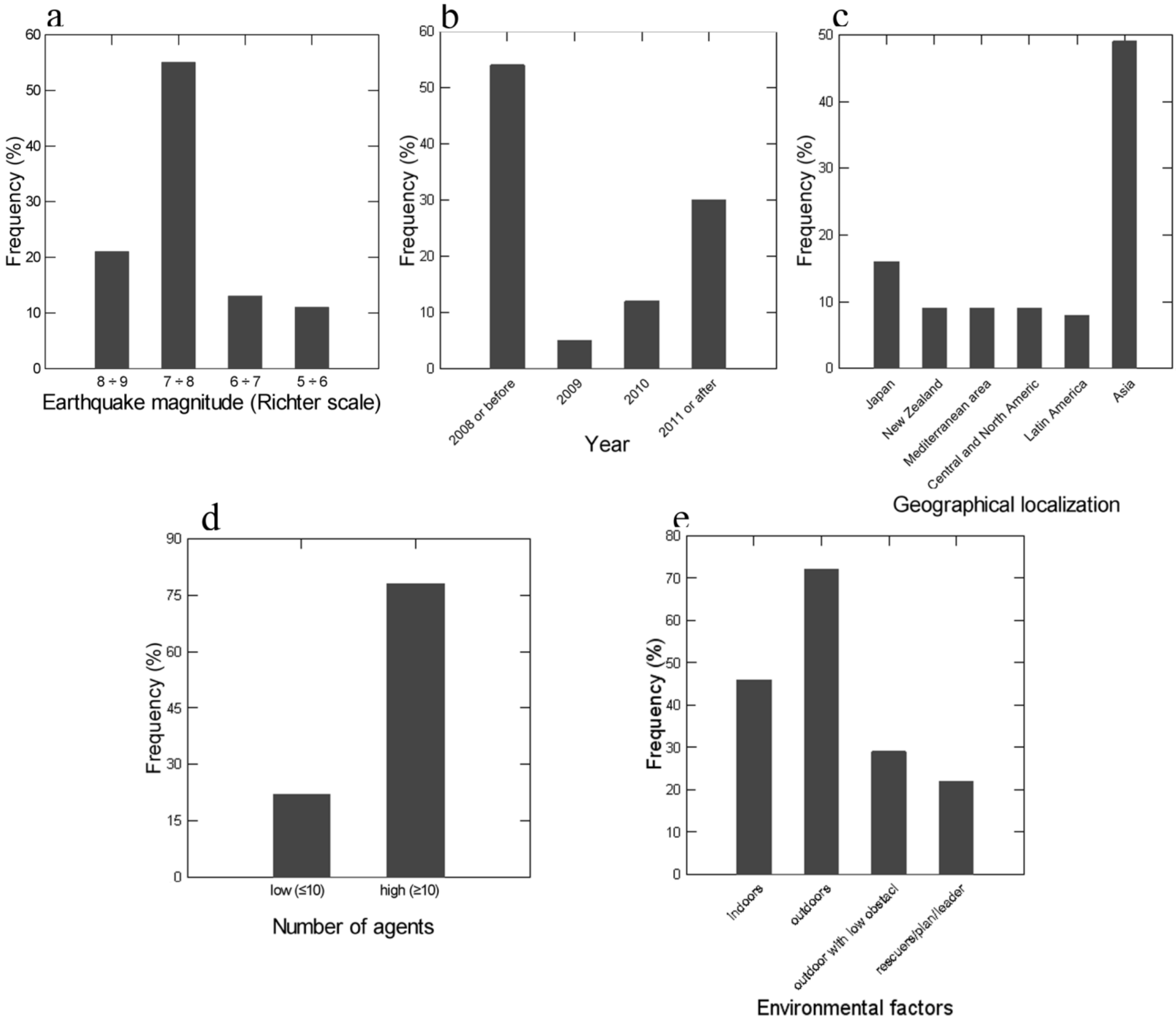

Fig. 1. Percentage distribution of analyzed videotapes "scenes" concerning: a-earthquake magnitude; b-year of occurrence; c-geographical localization (where Asia excludes Japan); d-number of agents, or rather pedestrians (low: ≤ 10 pedestrians; high: > 10 pedestrians) (D'Orazio, Spalazzi, et al., 2014a); e-different factors that characterize the environment.

2.3 **Analysis methods**

The dataset described in Fig. 1 was investigated in order to collect behavioural and quantitative data about the evacuation procedure. This paragraph describes the used methods for the different analyses.

2.3.1 Behavioural analysis

The behavioural investigation is performed according to our previous works (D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a): it allows actions and attitudes that a pedestrian carries out during the evacuation procedure in relation to both the environment and other people to be defined. The presence of behaviours evidenced by previous works is inquired (Takuma, 1972; Alexander, 1990; Helbing et al., 2002; Lakoba et al., 2005; Mawson, 2007; D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a). Besides, the presence of other characteristic behavioural patterns is inquired. According to previous approaches (D'Orazio, Spalazzi, et al., 2014a), each behaviour

is associated to the specific evacuation conditions shown in Fig. 1.e. According to previous methodology (D'Orazio, Spalazzi, et al., 2014a), a behaviour that is present at least in the 30% of the related cases will be inserted in the earthquake evacuation behavioural database. Moreover, behaviours are classified as "common to other kinds of evacuation" and "specific of this case" (D'Orazio, Spalazzi, et al., 2014a). A more detailed description is offered in our previous works (D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a).
Results are offered at paragraph 3.1. Noticed behaviours in evacuation are organized in the related database in a chronological order. The different evacuation phases are distinguished: pre-movement time (at paragraph 3.1.1); motion toward the evacuation target (at paragraph 3.1.2); safe area reaching (at paragraph 3.1.3). Short descriptions and comparisons to previous results are provided.

2.3.2 Quantitative analysis: SAD analysis

The SAD (Speed Acceleration Distances) analysis involves quantitative aspects of motion: the assessment includes values about instantaneous speeds, instantaneous accelerations, distances between the individual and the obstacles (both other pedestrians and environmental elements) during motion. Results are offered at paragraph 3.2.1. Different tracking systems for data collection of microscopic pedestrian traffic flow are provided from literature (Teknomo et al., 2001). In our study, the manual method is chosen because of the videotapes characteristics such as the not uniform backgrounds to human motion or the images resolution. This method is also chosen by other analogous works (Yang et al., 2011; D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a).
Videotapes performed by fixed cameras are investigated. Firstly, analyzable "scenes" of the final dataset are divided by considering the following cases according to paragraph 2.2: outdoor; indoor with a low number of individuals; indoor with a high number of individuals. Our dataset involves more than 2500 items in 15 "scenes".
Analyses of the "scenes" are performed by using the open source image analysis software "Tracker" (Brown and Christian, 2011; D'Orazio, Spalazzi, et al., 2014a). Fig. 2 summarizes the main steps. Firstly, the Tracker *perspective* filter[1] is applied on the original videotape (Fig. 2.a) in order to correct the distorted floor shape in the input frames to a straight-on plane shape in the output frames: it allows having a planar tracking of pedestrians' motion. The videotapes dimensions are also calibrated[2] by using objects with known dimensions (e.g.: chairs, doors), and a general approximation of 10cm is used in length measures for both calibration and individuals' tracking (D'Orazio, Spalazzi, et al., 2014a). The correction and calibration results are shown in Fig. 2.b. In addiction, when the cameras shaking due to the earthquake not allows a correct detection of the "scene", a particular image processing filter is adopted by applying the Deshaker v.3.0 plug-in[3] in VirtualDub v1.10.4[4]. Secondly, each pedestrian in the videotapes is associated to a point mass, pointed at hip level (D'Orazio, Spalazzi, et al., 2014a), as shown in Fig.2.c. The Canny algorithm for the edges detection is applied (Yang et al., 2011) in Fig.2.c in order to highlight the contours of the scene elements. Each individual's positions tracking allows instantaneous values of speed and distances between the inquired individuals and both other pedestrians in the same evacuation flow and environmental obstacles to be assessed. Instantaneous accelerations are calculated as speed variations. Individual's positions are defined in a range between about 0.25s and 0.625s according to previous approaches (Burghardt et al., 2013), during the whole pedestrian's evacuation process. The 0.25s value is related to the presence of many videotapes with a frame rate equal to 4 frames per second.

Fig. 2. Elaboration of a videotape frame for quantitative analysis {68}: a-the initial frame in perspective view, b-perspective correction and calibration through Tracker, c-final frame with trajectories of a pedestrian, where black dots on the trajectory represent the position at the individual's hip level and the final circle denotes the current frame position.

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[1] https://www.cabrillo.edu/~dbrown/tracker/help/video_filters.html (last access: 17/07/2014)

[2] https://www.cabrillo.edu/~dbrown/tracker/help/gettingstarted.html#scale (last access: 17/07/2014)

[3] http://www.guthspot.se/video/deshaker.htm (last access: 04/06/2014)

[4] http://www.virtualdub.org (last access: 04/06/2014)

According to the aforementioned length measures rules and to previous methodologies (D'Orazio, Spalazzi, et al., 2014a), positions and distances are calculated with an approximation of about 10 cm. Fig. 3 graphically resumes the proposed method for the individual's mass point positioning. The individual's position is marked at the hip level in order to detect a significant barycentric point. The marker position could change in different frames because of the individuals' breadth, so a related positioning error could be introduced. The mass point will be always putted inside the individual's silhouette, and for this reason a maximum error could be quantified by assuming an average hip breadth ≤40cm (Korhonen and Hostikka, 2010)[5]. Anyway, the Tracker *perspective* filter allows different planes for motion detection to be defined: each plane is characterized by an uniform height from the ground, as schematized in Fig. 3.a. For this reason, the individual's marker can be placed every time in an unique plane: as previously defined, the chosen plane is placed at the hip level. Fig. 3.b shows an example of application {68}. In this way, the 2D mapping is performed by considering hip plane, as shown by the individuals' tracking example in Fig. 3.c. The positioning procedure mainly influences the speeds values. When we mark an individual in the course of the motion time, we maintain a short distance between two consecutive points: an average percentage difference in detected speed of about 1.8% is retrieved between constant differences in positioning of 10cm and 15cm.

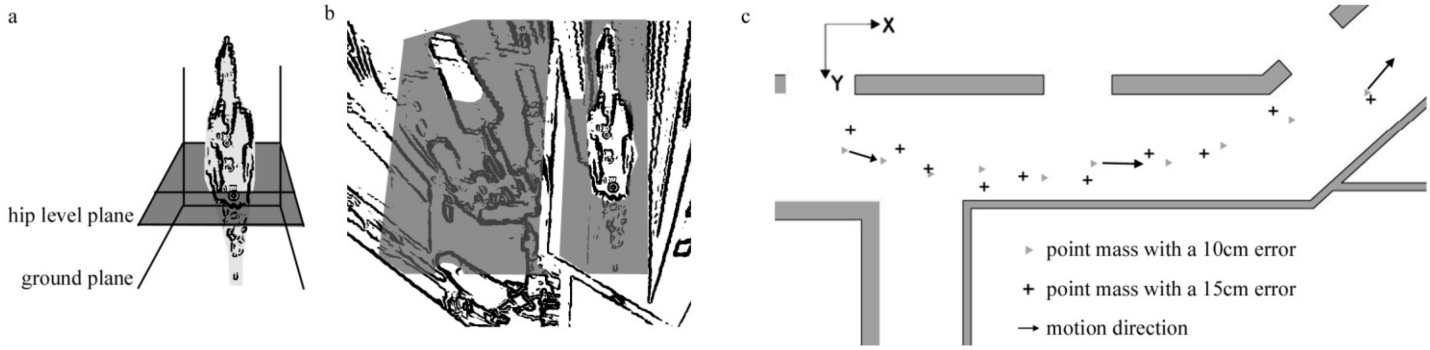

Fig. 3. Mass point tracking: a-the Tracking perspective filter to detect planes with uniform height from the ground and to identify the man (light grey figure) hip level plane (dark grey surface); b-Tracking perspective filter applied in the example {68} with hip level plan identified (dark grey); c-the hip plan is chosen and the map of 2D plan evacuation environment including individuals positions with the different approximation errors is provided {68}.

The evacuation end is fixed when the individual definitively stops him/her evacuation (he/she gains an exit door in indoors or stops in outdoors) or is no longer framed by the camera (D'Orazio, Spalazzi, et al., 2014a). Distances between individuals and obstacles are evaluated only for outdoor conditions, while distances between individuals in the same evacuation flow are measured for each scene Distances are evaluated between visible elements (D'Orazio, Spalazzi, et al., 2014a). In particular, distances from walls are measured along the perpendicular line between each individual and the obstacles.

Finally, data from "scenes" of each case are analyzed together. For each evaluated quantity, the average value, the minimum and maximum values, the median, the arithmetic mean and the standard deviation σ are provided. Statistical tests on our experimental data (jointly ranking of statistical tests: Kolmogorov-Smirnov, Anderson-Darling, Chi-square) are proposed. Data are resumed in histograms and the related distributions are provided. The number of classes in histograms is chosen following the Sturges' rule (Scott, 2009). At the same time, we controlled that each class should include at least 3 values. A comparison between our experimental results and main previous works outcomes about evacuations in both earthquake and other cases is provided (Fahy and Proulx, 2001; Lakoba et al., 2005; Shi et al., 2009; Hori, 2011; D'Orazio, Spalazzi, et al., 2014a).

2.3.3 Quantitative analysis: fundamental diagrams definition

Fundamental diagrams of pedestrians' dynamics allow quick relationships between the main motion quantities to be established, such as flow, density and velocity (Johansson and Helbing, 2008; Schadschneider et al., 2009). According to previous works (Zhang et al., 2011; Zhang, 2012), different approaches could be adopted to calculate these parameters. Analyses about pedestrian trajectories of single file movement (Seyfried et al., 2010) are similar to the one of the vehicular traffic case (Kerner, 2004). Many studies evidenced the presence of variations in analyses results due to

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[5] http://msis.jsc.nasa.gov/sections/section03.htm#_3.2_GENERAL_ANTHROPOMETRICS (last access: 28/10/2014)

different measurement methods (Fruin, 1971; Predtechenskii and Milinskii, 1978; Helbing et al., 2007). A detailed summary of the main four measurement methods has been provided (Zhang, 2012), and the related influence on the fundamental diagram is analyzed in order to evaluate which one leads to the smallest fluctuations. For our analysis, we adopted the "Method A" described in previous researches (Zhang et al., 2011; Zhang, 2012). A cross-section along the motion path is chosen and analyzed over a fixed period of time Δt [s]. The time t_i and the velocity v_i are evaluated for each pedestrian passing the chosen cross-section directly. Mean values of flow and velocity are calculated over time. Equation 1 synthesizes the flow over time $<J>_{\Delta t}$ [people/s] and Equation 2 refers to the mean velocity $<v>_{\Delta t}$ (Zhang et al., 2011; Zhang, 2012):

$$\langle J\rangle_{\Delta t}=\frac{N_{\Delta t}}{t_{N_{\Delta t}}-t_{1_{\Delta t}}} \tag{1}$$

$$\langle v\rangle_{\Delta t}=\frac{1}{N_{\Delta t}}\sum_{i=1}^{N_{\Delta t}}v_i\left(t\right) \tag{2}$$

where $N_{\Delta t}$ is the number of persons passing the cross-section during Δt; $t_{1\Delta t}$ and $t_{N\Delta t}$ [s] are the times when the first and the last pedestrians pass the cross-section in Δt; $v_i(t)$ [m/s] is the velocity of each pedestrian *i*. The Δt value should be chosen in relation to environmental conditions and the regularity of pedestrians' flow (Johansson and Helbing, 2008; Burghardt et al., 2013). In fact, a maximum limit could be fixed at about 5s (Burghardt et al., 2013) in normal conditions, but when speeds are higher, such as in real evacuation conditions, Δt should be smaller (and so <5s). According to Equation 3, $v_i(t)$ is evaluated by using the displacement of pedestrian i in a small time interval $\Delta t'$ around *t*:

$$v_i\left(t\right)=\frac{\left\|\vec{x}_i\left(t+\Delta t'/2\right)-\vec{x}_i\left(t-\Delta t'/2\right)\right\|}{\Delta t'} \tag{3}$$

where the $\Delta t'$ value should be compared to the possibility of effective motion detection (e.g.: 1 frame in the videotape). Equation 4 defines the estimation of pedestrian density $<\rho>_{\Delta t}$ [people/m^2]:

$$\langle \rho\rangle_{\Delta t}=\frac{\langle J\rangle_{\Delta t}}{\langle v\rangle_{\Delta t}\cdot b} \tag{4}$$

where *b* [m] is the cross-section width.

This method is applied to two real evacuation "scenes" of indoor spaces {57, 68} with the purpose of investigating the fundamental diagrams of pedestrians' dynamics (Schadschneider et al., 2009) in effective earthquake emergency conditions. The selected scenarios refer to the May 12, 2008, 06:43:15 UTC, Wenchuan earthquake, VI degree[6] in Modified Mercalli Intensity[7] (Yang and Wu, 2012). They both concern unidirectional pedestrians' flows in the Chengdu Shuangliu International Airport, Chengdu, Sichuan {57} and a Chinese internet café of Xi'an, Shaanxi {68}. More than 250 evacuating individuals are noticed in the videotapes. Scenarios are shown in Fig. 4 and Fig. 5. Spaces dimensions are retrieved according to the paragraph 2.3.2 methods by using the analysis software "Tracker" (Brown and Christian, 2011; D'Orazio, Spalazzi, et al., 2014a). Consequently, the manual method is chosen for the individuals tracking (Yang et al., 2011; D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a) and so for evaluating x_i. The chosen cross-sections are graphically evidenced in Fig. 4 and Fig. 5 scenes by dashed lines. Both scenarios concern indoor evacuation with a high number of individuals (D'Orazio, Spalazzi, et al., 2014a): indoor conditions allow an effective bound connected to physical environmental elements for the cross section to be chosen. At the same time, a constant flow is observed during time.

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[6] http://earthquake.usgs.gov/earthquakes/dyfi/archives.php?query=sichuan+2008-05-12&search_archives=Search+Archives (last access: 03/10/2014)

http://earthquake.usgs.gov/earthquakes/dyfi/events/us/2008ryba/us/index.html (last access: 03/10/2014)

[7] http://earthquake.usgs.gov/learn/topics/mercalli.php (last access: 03/10/2014)

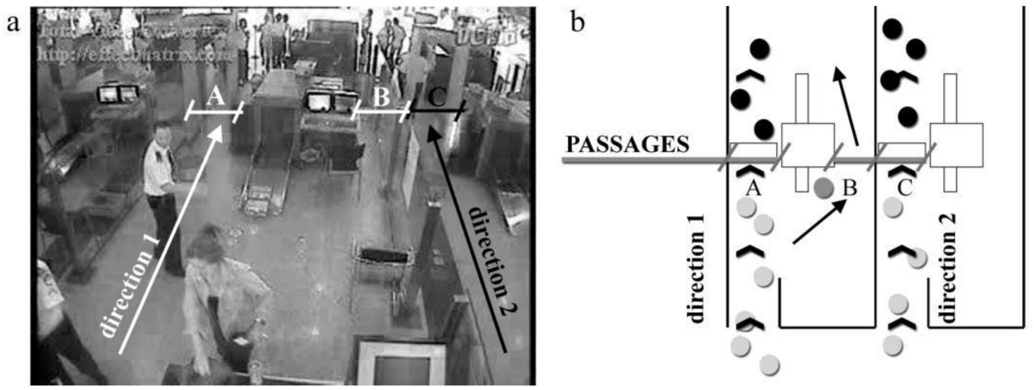

Fig. 4. Analyzed scenarios for the fundamental diagram analysis of the airport scenario {57}: a-a camera view; b-related plan representation. Identification of evacuation directions (1 in white and 2 in black) and passages (A, B and C) are provided; changes in motion along direction 1-passage B are identified on the left by long black arrows.

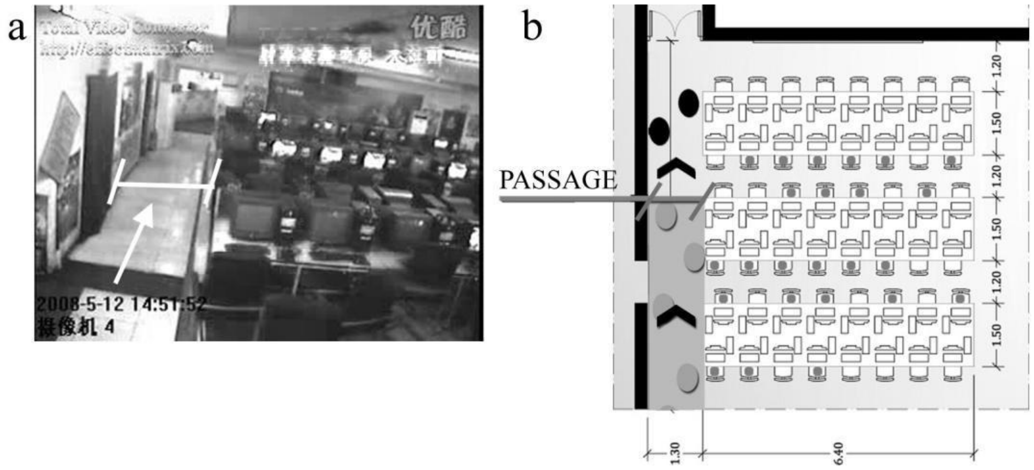

Fig. 5. Analyzed scenarios for the fundamental diagram analysis of the internet café scenario {68}: a-a camera view evidencing passage and detected flow direction; b-related plan representation with spaces dimensions, passage and direction marks, seated individuals' starting positions (grey dots).

The frame time is equal to 0.067s for both the videotapes. According to further works (Johansson and Helbing, 2008; Burghardt et al., 2013) and previous evaluations, we fix Δt=2.68s (40 frames), with the possibility to have an accurate measurement because of a continuous pedestrians' flow. At the same time, in both cases, we fix $\Delta t'$=0.067s (1 frame) (Zhang et al., 2011; Zhang, 2012).

In the airport scenario {57}, data for the diagrams definition involve the whole number of pedestrians along direction 1-passage A and direction 2-passage C, because of environmental conditions similarity, as shown in Fig. 5.

Results are offered at paragraph 3.2.2.The speed-density and flow-density diagrams are plotted and compared to the main previous works outcomes (Hankin and Wright, 1958; Predtechenskii and Milinskii, 1978; Mori and Tsukaguchi, 1987; Weidmann, 1993; Seyfried et al., 2005; Johansson and Helbing, 2008). In addiction, a proposal for the speed-density relationship in earthquake emergency conditions is offered on the bases of the revisited Kladek formula (Bruno and Venuti, 2008; Lämmel et al., 2008). The Kladek formula is chosen because of its continuity and compact direct form, and so its suitability for practical use. The relation accuracy is evaluated through the average value of the absolute percentage differences between experimental results and the predicted ones $e_{exp,pred}$ [%], as shown in Equation 5:

$$e_{exp,pred} = \left| \frac{v_{\rho,exp} - v_{\rho,pred}}{v_{\rho,exp}} \right| \cdot 100 \tag{5}$$

where v_ρ [m/s] is the speed value for a certain density ρ, and $_{exp}$ refers to experimental value, while $_{pred}$ refers to the value predicted by the proposed formula.

3 Results and discussion

3.1 Earthquake evacuation behaviours database

This first part of the work involves the analysis of real evacuation videotapes according to the methodologies defined at paragraph 2.3.1. The analysis of real evacuation videotapes allows us to trace a list of noticed behaviours in earthquake evacuation. We decide to organize the detected behaviours by using the proposals of previous researches (Takuma, 1972; Alexander, 1990; Shi et al., 2009; D'Orazio, Spalazzi, et al., 2014a). In particular, our analyses evidence the presence of typical evacuation stages: pre-movement phase, motion toward the evacuation target, safe area reaching. The pre-movement phase starts with the earthquake occurrence and ends when people decide to abandon their initial positions (Kobes et al., 2010a; D'Orazio et al., 2015). During this phase, the environmental could dynamically be modified by the earthquake, with the buildings damages and ruins formation. The motion phase follows the pre-movement phase: people decide to move in order to reach an evacuation target (in both indoors or outdoors) (Lakoba et al., 2005; Helbing and Johansson, 2010; D'Orazio, Spalazzi, et al., 2014a). While moving in the environment, individuals could interact also with generated ruins. The safe area reaching is gained when the individual arrives in a safe positions and decides to complete his/her motion because of favourable surrounding conditions. Generally, safe positions correspond to large places in urban scenarios, with a low damage level (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a). We expose the noticed behaviours by following these phases: Table 3 summarizes the related organization of noticed behaviours with the purpose of developing the behavioural database. For each evacuation phase, the noticed behaviours are characterized by 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 (*person* or *environment*) influencing the activation of mechanism. We compare and combine the retrieved results with previous ones, and in particular with our preceding earthquake investigations (D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a).

Table 3. Summary of noticed behaviours: *Environment* concerns buildings, obstacles, safe areas, evacuation paths, earthquake characteristics, ruins, presence of rescuers/evacuation plans. *Pedestrian* refers to social relationships between individuals. Behaviours distinguished by * are common to other evacuation kinds and also involved in social force model definition (Helbing et al., 2002; Lakoba et al., 2005; Hou et al., 2014).

Evacuation stage	Behaviour	Type of evacuation considered	Total number of video	Frequency (%)	Relationship in activation of behaviour
Pre-movement phase	Social attachment and information exchange*	all	71	51	pedestrian
	Attachment to things effect*	indoor	33	45	environment
	Response to sensible events	all	71	51	environment
Motion toward the evacuation target	Attraction towards safe areas*	all	71	87	environment
	Preferred path definitions	outdoor	71	74	environment + pedestrian
	Fear of buildings	outdoor	53	74	environment
	Not keeping a "safety distance" from "low obstacles"	outdoor with "low obstacles"	22	86	environment
	Repulsive mechanisms to avoid physical contact*	all	71	75	environment + pedestrian
	Attraction for group bonds*	all	71	65	pedestrian
	Formation of evacuation groups	outdoor	53	87	pedestrian
	"Herd Behaviour" and influence of "collective" velocity*	all	71	61	pedestrian
	Increased guide effect for presence of rescuers or evacuation plans	presence of rescuers / evacuation procedure/ leader	17	59	environment
	Leader effect*	presence of rescuers/ evacuation procedure / leader	17	83	pedestrian
	Panic conditions	all	71	35	environment + pedestrian
	Interruption of outdoor evacuation for high ground shaking	outdoor	53	38	environment

Safe area reaching	Safe areas definition	outdoor	54	74	environment + pedestrian
	Influence of not immediate danger feelings or panic conditions	outdoor	71	77	environment + pedestrian

In the following, evacuations stages are distinguished, and each behaviour (in italics in round brackets) is supported by examples of videotapes in which is present (i.e. the database reference numbers are written in braces).

3.1.1 Pre-movement phase

The pre-movement phase is characterized by phenomena similar to the ones of other evacuation types (e.g.: fire evacuation) (Purser and Bensilum, 2001; Mawson, 2007; Nilsson and Johansson, 2009; Kobes et al., 2010a; D'Orazio, Quagliarini, et al., 2014b) {2, 5, 11, 31, 40, 42, 44, 53, 58}. People exchange information with the purpose to evaluate the level of danger (*Social attachment and information exchange*) {26, 42}. Information exchange also occurs during the whole evacuation, especially in Latin Countries {27} (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a). Social attachment phenomena evidence how people wait or search for other people such as their friends or relatives or other people they know {1, 53, 59, 42}, especially during the pre-movement phase (Alexander, 1990; Mawson, 2007; Yang et al., 2011; Yang and Wu, 2012; D'Orazio, Spalazzi, et al., 2014a). People long to retrieve their belongings {10, 43, 52, 53, 61, 65, 68}, as also shown in other evacuation kinds (Riad et al., 1999; Prati et al., 2012; Yang and Wu, 2012; D'Orazio and Bernardini, 2014; D'Orazio et al., 2015) (*Attachment to things effect*). Fig. 6 {65} shows an individual (black arrow) that hesitates nearby the initial position (Fig.6.a), and spends time for collecting her handbag (Fig.6.b): when belongings are retrieved (Fig.6.c), the evacuation starts. This action lasts about 20s and involves a coming-and-going behaviour during the pre-movement time. This time-wasting behaviour could not be associated to safety procedures (D'Orazio, Spalazzi, et al., 2014a; D'Orazio et al., 2015).

Fig. 6. "Attachment to things effect" {65} with coming-and-going behaviour: a-starting position at earthquake occurrence (+0s); b-retrieving belongings (+15); c-evacuation starting (+20s). The individual (rectangle) spends time in order to recovering a handbag (black figure).

The *attachment to things effect* can also imply the return to the initial position (and so into the building) after the first emergency moments (Prati et al., 2012). Fig. 7 {43} shows an individual (black arrow) that initially adopts the same behaviour, but decides to return at the initial position after the evacuation (Fig.7.c): in this case, it is supposed that the individual (rectangle) remains in unsafe conditions for about 150s. Fig. 7.c also shows how other pedestrians adopt a similar behaviour (arrows). These behaviours involve milling phenomena: they are noticed also in other evacuation kinds and can also lead some people to not participate to evacuation (Averill et al., 2005; Proulx, 2008; D'Orazio et al., 2015).

Fig. 7. "Attachment to things effect" {43} with milling behaviour and return inside the building; frames are numbered by time and +0s is the videotape start: a-collecting some belongings and evacuation starting (+17s); b-returning after evacuation and gaining the initial position in order to collect other things (+148s); c-moving towards the building exit (+163s). The individual (rectangle) spends time in order to recovering a handbag (black figure).

Unlike other kinds of evacuation, a lower limit for evacuation procedure activation can be defined and people are influenced by earthquake perception (Alexander, 1990; Grünthal, 1998; D'Orazio, Spalazzi, et al., 2014a) (*Response to sensible event*). In fact, individuals participation in evacuation is mainly connected to earthquake intensity, described by the EMS98 scale (Grünthal, 1998). In particular, the evacuation is generally needed for sensible events (earthquake with a magnitude higher than a 5th degree in the Richter Seismic Scale - IV degree in EMS-98 scale), also according to paragraph 2.3.1. Besides, earthquake perception and floor shaking {40} influences the evacuation starting from both the individuals' and group's point of view {5, 6, 23, 31} (Takuma, 1972; Boileau et al., 1978; Turner et al., 1986; Alexander, 1990; Prati et al., 2012; D'Orazio, Spalazzi, et al., 2014a). Hence, geographical (magnitude of common events) and cultural (cultural background of population) aspects on behaviours is evidenced {23, 27, 31, 58} (Boileau et al., 1978; Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a). The response also includes safety procedures (mainly "drop-cover-hold on" procedures {31, 45}) influencing the pre-movement time length (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a), especially in indoor conditions: people can remain in a safe position during the earthquake duration and also for a little time after it. Finally, when the event is particularly strong or unusual, individuals prefer to start immediately their evacuation also during the earthquake itself {24, 53} (Alexander, 1990; Yang and Wu, 2012; D'Orazio, Spalazzi, et al., 2014a).

3.1.2 Motion toward the evacuation target

After the pre-movement phase, people moving toward the evacuation target (Helbing et al., 2002; Helbing and Johansson, 2010) (*Attraction towards safe areas*) are influenced by many environmental factors and by the presence of other individuals. In an indoor scenario, the final target is exiting from the building.

The outdoor scenario offers the most significant aspect in motion definition. Accordingly to other evacuation kinds (Helbing et al., 2002), people move to areas that can be considered "safe" for their geometry, level of damage and social factors (*Attraction towards safe areas*) (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a). Evacuating pedestrians generally gain the evacuation targets through the widest and clearest of dust and rubbles paths {9, 23, 29, 57}, especially in a close urban fabric {24} (Takuma, 1972; Alexander, 1990; D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a) (*Preferred path definitions*). This choice can be mainly associated to repulsive phenomena during motion.

A first repulsion level is connected with the environment and is peculiar of earthquake evacuation {3, 11, 19, 24, 25, 40, 49, 66}: people run out of buildings, maintain a "safety distance" from them, and avoid paths with rubbles and ruins (Takuma, 1972; Arnold et al., 1982; Alexander, 1990; Lakoba et al., 2005; D'Orazio, Spalazzi, et al., 2014a) (*Fear of buildings*). This behaviour is more sensible in relation to high buildings {15, 21, 28, 31, 64} (Alexander, 1990): Fig. 8 shows pedestrians moving along the centre of the street. On the contrary, "low obstacles" (one floor buildings, low walls, enclosures, benches, street furniture, shelters) generally do not provoke a similar repulsive phenomena but become attractors for pedestrians' motion, especially during the earthquake {8, 17, 27, 32, 49, 56, 71} (D'Orazio, Spalazzi, et al., 2014a) (*Not keeping of a "safety distance" from "low obstacles"*).

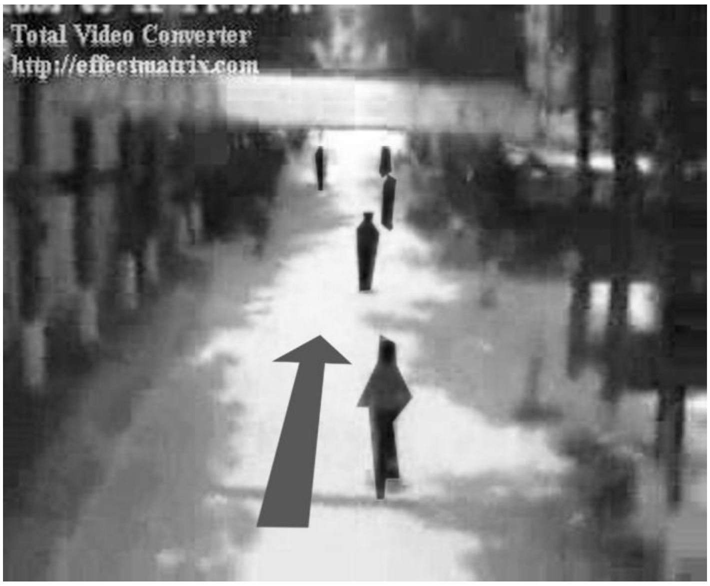

Fig. 8. Fear of building example {64}: pedestrians (black figures) prefer to run along the centre of the street; the arrow identifies the evacuation direction.

The second repulsion aspect is connected to the effective motion phenomenon, as also shown in other types of evacuations (Helbing et al., 2002): people modify their trajectories in order to avoid the collision with environmental objects and other pedestrians {15, 24, 35, 48, 50, 61, 67} (*Repulsive mechanisms to avoid physical contact*). Pushes and friction phenomena in case of physical contact are present, especially in panic conditions and high pedestrians' density {24, 45} (Alexander, 1990; Helbing et al., 2002; Lakoba et al., 2005; D'Orazio, Spalazzi, et al., 2014a).

Pedestrians sharing a cohesion tie prefer to remain close during the evacuation in both outdoor and indoor conditions (Alexander, 1990; Helbing et al., 2002; Mawson, 2007; Prati et al., 2012; D'Orazio, Spalazzi, et al., 2014a), as also shown in other evacuations {1, 2, 4, 6, 9, 16, 33, 41, 48, 59, 65, 70} (*Attraction for group bonds*). Different bonds are evidenced (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a): familiar bonds, when individuals belong to the same family or clan; evacuation target bonds, when individuals in the same environment share the same evacuation path or target. These phenomena demonstrate how the social attachment persists also during the motion stage (Mawson, 2007). People can gather during the evacuation while sharing the same evacuation paths {1, 10, 17, 21, 45}. At the same time, the main pedestrians flow becomes an attractor for individuals in terms of evacuation direction and speed {21, 45} (Alexander, 1990; Lakoba et al., 2005; Yang and Wu, 2012; D'Orazio, Spalazzi, et al., 2014a) (*"Herd Behaviour" and influence of "collective" velocity*, *Formation of evacuation groups*).

An effective improvement in evacuation is noticed in presence of known evacuation procedures and plans or officers and rescuers supporting the individuals {3, 5, 25, 31, 49, 58, 68} (D'Orazio, Spalazzi, et al., 2014a) (*Increased guide effect for presence of rescuers or evacuation plans*). Befitting behaviours are performed by pedestrians, in terms of both regular and orderly flows and evacuation speeds, in particular when a rescuer or a qualified and recognized staff member is involved {5, 25, 26, 32, 39, 59, 49, 70} (Alexander, 1990; Pelechano and Badler, 2006; Yang et al., 2011; D'Orazio, Spalazzi, et al., 2014a; Koo et al., 2014). In this case, the rescuer becomes the evacuation leader, similarly to other evacuation kinds (Zarboutis and Marmaras, 2004; Pelechano and Badler, 2006; Ji and Gao, 2007; Hou et al., 2014; Koo et al., 2014) (*Leader effect*).

Finally, environmental conditions, including both ruins formation, ground shaking and earthquake magnitude, influence the space perception and the evacuation procedure. According to previous results (Alexander, 1990; Grünthal, 1998; D'Orazio, Spalazzi, et al., 2014a), panic conditions can be described as a sort of "helplessness level" that brings people to remain near the same place and to gather around this position {14, 23, 27, 35, 41, 49, 55, 61, 63, 70} (*Panic conditions*). This phenomenon also drives people to follow other pedestrians' choices and to adequate their velocity to the others' one (Lakoba et al., 2005; D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a). In addiction, if ground highly shakes during the outdoor motion, the slowing down or the interruption of evacuation are noticed {2, 5, 17, 24, 38, 42, 45, 66, 71} (Alexander, 1990; Grünthal, 1998; Yang et al., 2011; D'Orazio, Spalazzi, et al., 2014a) (*Interruption of outdoor evacuation for high ground shaking*).

3.1.3 Safe area reaching

The evacuation end occurs in an outdoor safe area. Targets in outdoor evacuation are wide spaces in urban fabric {6, 10, 13, 17, 25, 31, 32, 34, 46, 49, 57, 62}, such as squares, large avenues, wide crossroads. The nearest safe area is generally preferred (D'Orazio, Quagliarini, et al., 2014a; D'Orazio, Spalazzi, et al., 2014a). These areas are "safe" because of 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, absence of ruins), social requirements (place of meeting for more pedestrians, sufficient space for each evacuating pedestrian (Mawson, 2007), point of information exchanging (Turner et al., 1986; Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a)).

However, when local conditions of danger are not well-rendered or panic conditions are concurrent, people can decide to interrupt their evacuation also because they are discouraged to abandon safe and well-know places (e.g.: areas closest to home) {14, 31, 32, 50, 57, 64} (Alexander, 1990; D'Orazio, Spalazzi, et al., 2014a): (*Influence of not immediate danger feelings or panic conditions*).

3.2 **Earthquake evacuation motion quantities database**

3.2.1 SAD analysis

Videotapes are organized according to the environmental conditions defined at paragraph 2.3.2: outdoor, indoor with a low number of individuals (≤10 pedestrians) (D'Orazio, Spalazzi, et al., 2014a), indoor with a high number of individuals (>10 pedestrians) (D'Orazio, Spalazzi, et al., 2014a). Videotapes are divided in "scenes": for each "scene", the sample dimension (number of tracked positions of points of mass), starting and ending times of evaluation, average values and standard deviations concerning instantaneous speeds, accelerations and distances between the individual and other pedestrians or obstacles are provided. Data related to each distinguished environmental conditions are jointly analyzed as described at paragraph 2.3.2. No disabled individuals appear in the scenes, thus no evaluation about this issue was possible. At the same time, an age characterization of the sample was not still possible because of the lack of data and the avoidance of erroneous hypothesis.

Table 4 resumes basic statistics for instantaneous speed in either the three environmental conditions. Fig. 9 shows instantaneous speed distributions and related curves: the normal distribution can surely represent both the scenarios, but a log-normal curve could be suggested for the one concerning the indoor evacuation with a low number of individuals (Fig. 9.c). Our data involve speeds, and so the modulus of the velocity: so, negative values are not acceptable. The log-normal distribution support is R_0^+, so this distribution is able to describe only positive speeds. An average value of 2.68m/s represents the whole speed sample. Previous work results (Hori, 2011) evidence a general higher average speed value (4.05m/s) with a higher related standard deviation (1.34m/s). On the other side, maximum values are similar. However, this prior study involves a small dataset and related measurements seem to be affected by ground motion because of no camera shaking correction is shown. On the contrary, our previous results (2.6m/s) are generally confirmed (D'Orazio, Spalazzi, et al., 2014a). In addiction, the speed trend during the time demonstrates higher values in the first evacuation moments (D'Orazio, Spalazzi, et al., 2014a). Concerning a comparison in indoor scenarios, the existing databases (mainly for fire evacuation) (Fahy and Proulx, 2001; Shi et al., 2009) report speed values that are up to 50% lower than the one of the earthquake case. This means that fleeing pedestrians generally own a certain degree of hurry, according to social force model suggestions (Lakoba et al., 2005). In particular, the simulators that are based on the social force model approach (Helbing and Johansson, 2010) should consider as incorrect the common value (about 1.5m/s) assigned to an isolated pedestrian (Helbing et al., 2002; Lakoba et al., 2005).

Table 4. Basic statistics for instantaneous speed.

Environmental conditions	Outdoor	Indoor with a high number of individuals	Indoor with a low number of individuals
Sample dimension	2014	254	118
Minimum [m/s]	0.71	0.58	0.28
Maximum [m/s]	6.06	5.97	4.84
Median [m/s]	2.97	2.30	2.58
Arithmetic Mean [m/s]	2.95	2.56	2.54
St. Deviation [m/s]	0.83	1.14	0.85

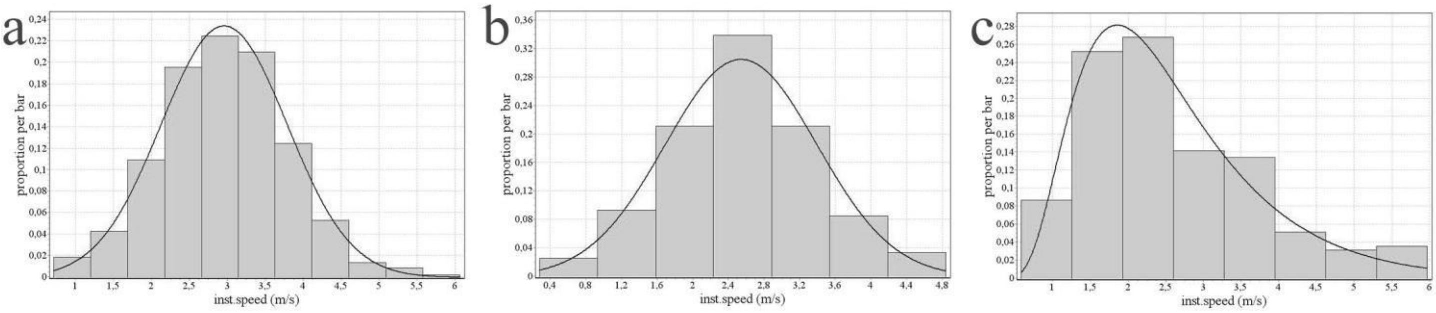

Fig. 9. Instantaneous speed distributions and related curves in: a-outdoor; b-indoor with a low number of individuals; c-indoor with a high number of individuals. A normal curve can be associated to distributions in a and b; a log-normal curve is associated to distribution c.

Table 5 summarizes basic statistics for instantaneous acceleration in the three environmental conditions. Values are positive and negative in order to distinguish accelerations and decelerations: the same trend for both of them is retrieved. In fact, Fig. 10 graphically shows symmetric distributions with a normal curve representation. Besides, the mean, the mode and the median are close to 0m/s^2. Although interactions modify the pedestrians' preferred motion speed (Helbing et al., 2002), these average values could demonstrate how people prefer to maintain a constant speed during the evacuation, also according to the principle of least-effort (Zipf, 1950) expressed by previous works and applications (Karamouzas et al., 2009; Guy et al., 2010). Maximum values have a modulus higher than literature limit of 0.3g (≈2.94m/s^2) (Lakoba et al., 2005), but the associated 5th and 95th percentile are similar to this value. The lack of previous studies on earthquake evacuation accelerations does not allow deeper comparisons to be performed. However, Fig.10.c seems to graphically confirm the presence of upper bounds in acceleration module, connected to the limit values of detected data classes.

Table 5. Basic statistics for instantaneous acceleration.

Environmental conditions	**Outdoor**	**Indoor with a high number of individuals**	**Indoor with a low number of individuals**
Sample dimension	1857	220	100
Minimum [m/s^2]	-4.70	-3.85	-3.40
Maximum [m/s^2]	4.70	3.74	4.41
Median [m/s^2]	-0.42	0.38	0.19
Arithmetic Mean [m/s^2]	-0.37	0.31	0.20
St. Deviation [m/s^2]	1.59	1.62	1.76

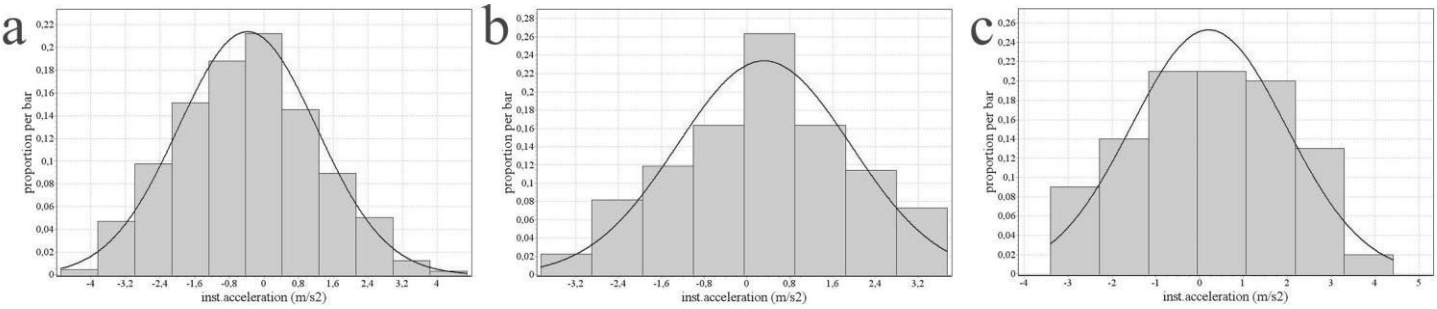

Fig. 10. Instantaneous acceleration distributions and related curves in: a-outdoor; b-indoor with a low number of individuals; c-indoor with a high number of individuals. A normal curve can be associated to each distribution.

Interactions between individuals and between individuals and environment are investigated through distances during motion. These evaluations could allow the probable evacuation path area used by pedestrians and a related average pedestrians' density to be defined. This way, the used area would be smaller than the total one because of the probable distances from boundaries and an average density could be calculated through each pedestrian's area and the distances between individuals. Table 6 summarizes basic statistics for instantaneous distances between individuals involved in the same evacuation flow, in either the three environmental conditions. The average distance for the three cases is equal to 1.70m: this value confirms previous results (D'Orazio, Spalazzi, et al., 2014a). Naturally, distances are calculated between individuals' mass points: for this reason, distances considering also the pedestrian's radius (about 0.35m) are about 1m. Previous studies on distances for the activation of interaction phenomena (Lakoba et al., 2005) suggest a perception limit equal to 3m. An effective high drop of reciprocal distances frequency is noticed around this limit value, as evidenced by the associated 95th percentile of each distribution (≈3m) (*Repulsive mechanisms to avoid physical contact*, *Attraction for group bonds*). Fig. 11 resumes opposite distances conditions. Minimum values allow a physical contact between people (Lakoba et al., 2005; Helbing and Johansson, 2010) in case of either *Social attachment* phenomena (Fig. 11.a), *Formation of evacuation groups* (especially at bottlenecks) and milling behaviours {52} (Fig. 11.b). The minimum distance value is the pedestrians' radius (≈0.35m (Lakoba et al., 2005) and however >0.20m (Korhonen and Hostikka, 2010)). At the same time, maximum values concern aspects of individuals' insertion along compact evacuation flows (*"Herd Behaviour" and influence of "collective" velocity*, *Formation of evacuation groups*) (Fig. 11.c). Fig. 12 graphically shows this tendency, and evidences the different distribution curves for each case: a beta distribution for the outdoor case (Fig. 12.a) and the indoor case with a high number of individuals (Fig. 12.b); a Wakeby distribution for the indoor case with a low number of individuals (Fig. 12.c). These distributions should be trimmed at the minimum pedestrians' radius because of considering no individuals' overlapping. However, average results could be influenced by environmental conditions, especially by spaces dimensions and cohesive bonds between individuals (*Attraction for group bonds*). Fig. 12.c seems to graphically evidence this result in indoor evacuations involving a low number of individuals. These relations should be investigated in a specific way in order to quantify the related influence on distance and pedestrians' density.

Table 6. Basic statistics for instantaneous distances between individuals.

Environmental conditions	**Outdoor**	**Indoor with a high number of individuals**	**Indoor with a low number of individuals**
Sample dimension	1382	125	52
Minimum [m]	0.44	0.35	0.38
Maximum [m]	5.24	5.12	2.88
Median [m]	1.90	1.66	1.27
Arithmetic Mean [m]	1.96	1.82	1.31
St. Deviation [m]	0.79	0.94	0.65

Fig. 11. Opposite distances conditions: a-physical contact due to panic conditions and social attachment phenomena (rectangle); b-physical contact due to evacuation group formation at bottleneck (dark grey individuals are moving along the black arrow direction) and milling behaviour (the person marked by grey line is turning back in order to collect personal belongings; the grey arrow specifies the direction); c-pedestrians (dark grey figures) are moving (the arrow marks their direction) towards a larger group (grey area with horizontal lines).

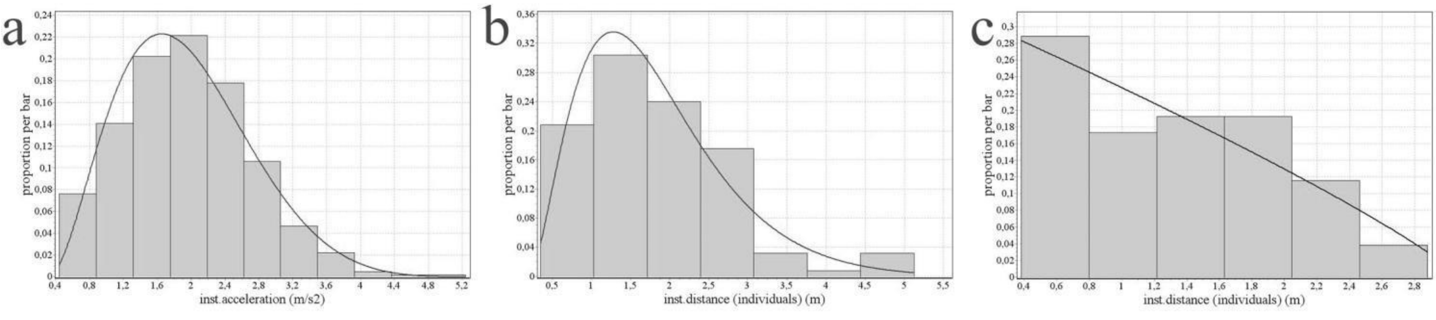

Fig. 12. Distributions of instantaneous distances between individuals in the same evacuation flow and related curves in: a-outdoor; b-indoor with a low number of individuals; c-indoor with a high number of individuals. Beta distributions can be associated to cases a and b; a Wakeby distribution is associated to case c.

Finally, Table 7 summarizes basic statistics for instantaneous distances between individuals and obstacles (environmental elements including buildings) in outdoor conditions. Unlike indoor conditions, outdoor evacuations allow people to freely choice their distance towards obstacles due to repulsion phenomena (including the *Fear of buildings*). An effective high drop (lack of values) of distances frequency over the supposed limit for obstacles repulsion (Lakoba et al., 2005) is noticed, as also shown by the associated 90th and 95th percentile (≈3m) and the maximum value. Fig. 13 graphically synthesises this trend and displays how a Weibull (3P) distribution could represent the dataset. As previously noticed, this distribution should be trimmed at the minimum pedestrians' radius because of considering no overlapping between individuals' and obstacles. Once again, as for distances between individuals, evaluations about the incidence of environmental conditions and individuals' bonds should be deeper investigated.

Table 7. Basic statistics for instantaneous distances between individuals and obstacles.

Environmental conditions	**Outdoor**
Sample dimension	629
Minimum [m]	0.44
Maximum [m]	3.49
Median [m]	2.51
Arithmetic Mean [m]	2.37
St. Deviation [m]	0.66

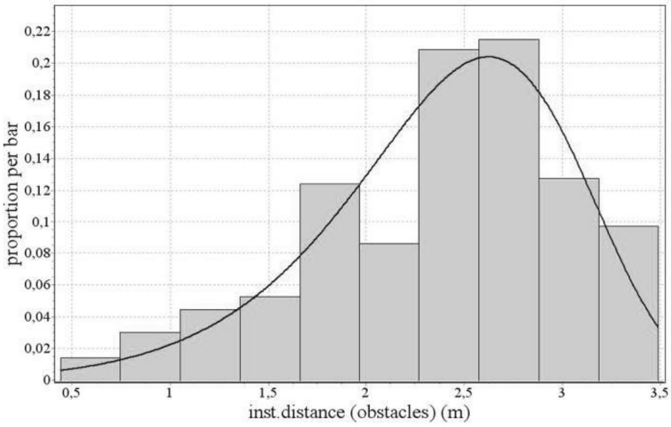

Fig. 13. Distributions of instantaneous distances between individuals and obstacles in outdoor conditions and related Weibull (3P) distribution.

3.2.2 Fundamental diagrams definition

The joint analysis of flows in the two considered videotapes {57, 68} allows us to trace the fundamental diagrams of pedestrians' dynamics in earthquake emergency conditions for indoor scenarios with a high number of individuals (Zhang, 2012). The related diagrams.csv file is offered at https://drive.google.com/file/d/0B91jqaXLKo5LY2hCT3ZuYXNCdFE/view?usp=sharing. Fig. 14 offers a comparison between our speed-density diagram (reported as "this study" and represented by +) and previous literature results, while Fig. 15 concerns the flow-density diagram.

In general terms, earlier studies for diagrams definition involve (Hankin and Wright, 1958; Predtechenskii and Milinskii, 1978; Mori and Tsukaguchi, 1987; Weidmann, 1993; Seyfried et al., 2006; Johansson and Helbing, 2008) normal motion conditions or evacuation experiments. On the contrary, our study focuses on real evacuation scenarios in earthquake conditions. In addiction, the requirement of comparable data connected to the same environmental conditions is generally solved by previous approaches through the investigation on a single physical scenario (Seyfried et al., 2005; Johansson and Helbing, 2008). This study takes advantage of two scenarios connected to the same conditions (unidirectional flow through a small passage). Furthermore, the adopted analysis method (Zhang et al., 2011; Zhang, 2012) also allows the passage dimension through the b factor in Equation 4 to be considered. Finally, the actual choice of two inspected case-studies is only limited by the poor number of available videotapes where adequate quantitative investigations are feasible.

According to behavioural comparisons (Yang et al., 2011), results referred to normal (or evacuation experiments) conditions (Hankin and Wright, 1958; Predtechenskii and Milinskii, 1978; Mori and Tsukaguchi, 1987; Weidmann, 1993; Seyfried et al., 2006; Johansson and Helbing, 2008) and real world evacuation (this study analysis) are distinguished by fundamental differences. Mainly, speeds in our analyses are higher because of the related emergency conditions (Yang et al., 2011; Chen et al., 2012; Zhang, 2012). Other causes of results differences could be ascribed to cultural and social background (Chattaraj et al., 2013; D'Orazio, Spalazzi, et al., 2014a), environment configurations including real and laboratory conditions (Yang et al., 2011; Zhang, 2012). However, the diagrams in both evacuation and normal conditions show a similar trends, especially for strictly unidirectional flows (Hankin and Wright, 1958; Mori and Tsukaguchi, 1987). A cross comparison with instantaneous speed data about indoor scenarios with a high number of individuals in Table 3 highlights the convergence to the associated 75th percentile value (≈3.3m/s) as the limit value for small pedestrians' densities. Limits in measured pedestrians' density (5.3persons/m^2) are close to the maximum pedestrians' density (5.4persons/m^2) proposed by simulation models (Lakoba et al., 2005) and to previous literature data (Hankin and Wright, 1958; Weidmann, 1993).

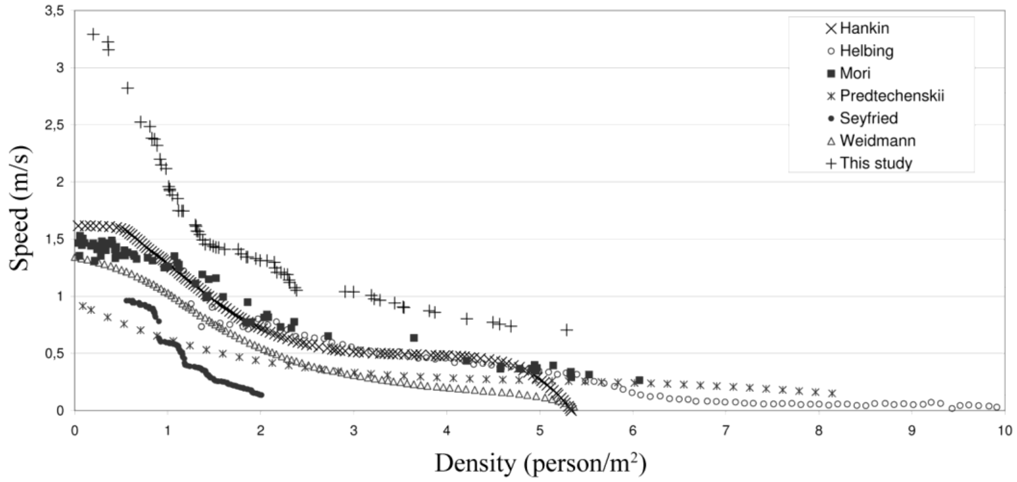

Fig. 14. Speed-density relationships in previous works and this study (symbol: +).

Concerning flow-density diagrams in Fig. 15, the absence of a final flow decrease for high densities is influenced by the related small decrease in evacuation speeds: previous works involving also evacuation simulations seem to show a similar tendency (Predtechenskii and Milinskii, 1978; Mori and Tsukaguchi, 1987).
However, the tendency in speed and flow does not denote a critical density value: in fact, the upper limit of our evaluations is influenced by the analyzed real evacuations conditions. Moreover, it should be possible that, in emergency phenomena, critical conditions are connected to densities higher than the ones supposed by previous models (Lakoba et al., 2005).

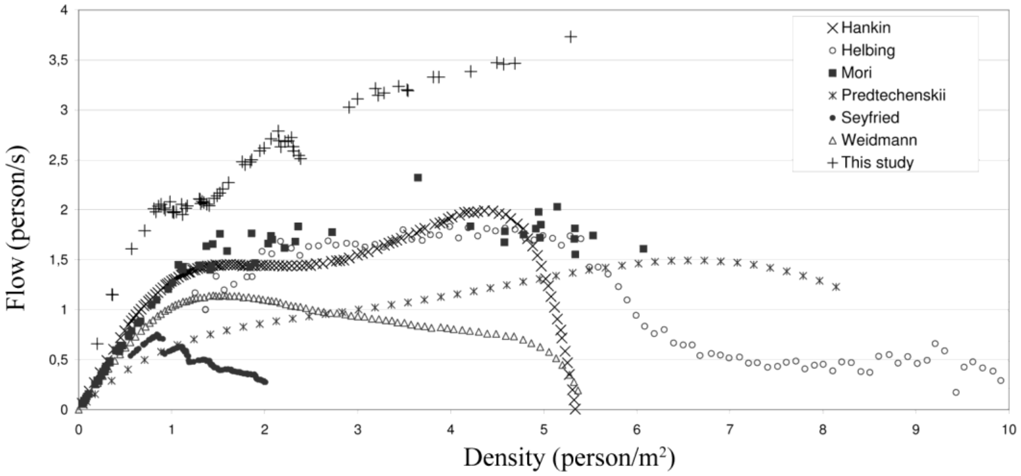

Fig. 15. Flow-density relationships in previous works and this study (symbol: +).

Finally, the speed-density relation is proposed on the bases of the revisited Kladek formula (Bruno and Venuti, 2008; Lämmel et al., 2008). Fig. 16 shows the experimental values and our proposed formula graph. The revisited Kladek formula allows speed value $v_{F,hi}(\rho)$ (m/s) to be assigned in function of four variables: the free-flow speed $v_{F,hf}$(m/s); a free parameter (form factor) γ (person/m^2), that is a fitting parameter for the experimental distribution; the pedestrians' density ρ and the maximum pedestrians' density for the study ρ_{max} (person/m^2). This expression outcomes a sigmoid function similar to the ones in Fig. 14 referring to previous studies (Hankin and Wright, 1958; Predtechenskii and

Milinskii, 1978; Mori and Tsukaguchi, 1987; Weidmann, 1993; Seyfried et al., 2006; Johansson and Helbing, 2008), as also shown in Fig. 16 by the Hankin's experimental curve (Hankin and Wright, 1958). This function is characterized by null speed for the ρ_{max} value. Fig. 14 demonstrates that our maximum experimental density does not correspond to null speed: this remark mainly implies needed modifications in Kladek formula. However, the proposed formulation is connected to the retrieved limit in data density, as previously stated. Equation 6 offers our theoretical proposal of speed-density relation in earthquake evacuation emergency conditions:

$$v_{F,hi}(\rho)=\left(v_{F,hf}-v_{\min}\right)\cdot\left\{1-\exp\left[-k\cdot\left(\frac{1}{\rho}-\frac{1}{\rho_{\max}}\right)\right]\right\}+v_{\min} \qquad \text{if } 0\le\rho\le\rho_{\max} \tag{6}$$

where the introduction of v_{min} (m/s) defines the minimum experimental speed at ρ_{max} . This proposed formulation can be currently adopted for the density range [0; ρ_{max}] pedestrians/m^2: according to the experimental results, ρ_{max}=5.3pedestrians/m^2.

Our formulation effectively suggests a vertical translation of the Kladek formula and considers $v_{F,hi}(\rho_{max})= v_{min}$ according to experimental results. A similar approach could be found also in previous simplified density-speed correlation such as the Q-model (Lämmel et al., 2008).

Finally, Equation 7 inserts the related numerical values, based on our experimental activities, in Equation 6:

$$v_{F,hi}(\rho)=\left(3.29m/s-0.71m/s\right)\cdot\left\{1-\exp\left[-0.8\cdot\left(\frac{1}{\rho}-\frac{1}{5.30\,pedestrians/m^2}\right)\right]\right\}+0.71m/s \tag{7}$$

$$\text{if } 0\le\rho\le 5.3\,pedestrians/m^2$$

We actually chose k=0.8: this form factor allows the absolute average difference between experimental and expected values (<10%) to be minimised. Moreover, this average difference including the sign is equal to about +9%, so the proposed formula really lightly underrates the speed values (we are erring on the side of caution).

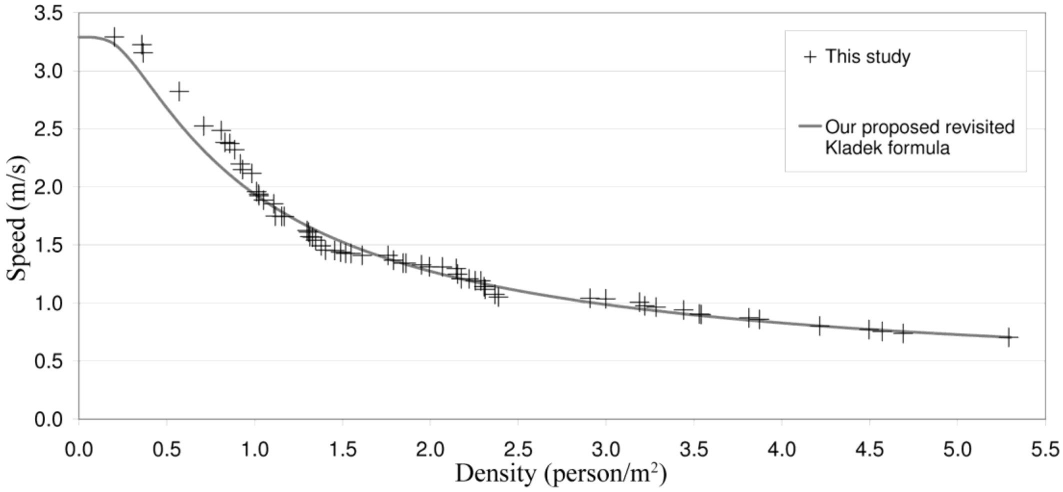

Fig. 16. Speed-density relationships: our study experimental values (symbol: +) is compared to our related proposal of revisited Kladek formula (continuous line).

4 Conclusions

Understanding and quantifying human behaviours and choices motivations in emergency evacuations are one of the most important issues in the development of tools and strategies for emergency management and planning. The basic level of knowledge is represented by the collection and organization of data concerning human behaviours. The best way to collect similar records is the unbiased analysis of real events. Despite the large number of studies about evacuation behaviours, the earthquake evacuation is not yet really inquired from this point of view. This work is aimed at filling this lack. We try to provide a complete and unitary (although surely not still exhaustive) database concerning qualitative and quantitative aspects of earthquake evacuation with an effective statistical relevance. The retrieved database would be valuable in developing, evaluating and validating different kind of emergency earthquake evacuation simulators.

A large sample of videotapes concerning real events from all over the World is analysed. Collected data concerning both behavioural and quantitative aspects are organized and compared to previous works outcomes. Analyses firstly provide the codification of behavioural pattern during the evacuation phases. Behaviours common to other kind of evacuations and behaviours peculiar of earthquake evacuation are distinguished. Behavioural analysis outcomes would be essential for characterizing rules in simulation models. In particular, interactions between man and environment would be useful for defining agent-based models.

About quantitative aspects of motion, a detailed examination of main motion quantities (speed, acceleration and distances during the evacuation) is proposed and discussed by distinguishing different scenario conditions. In addiction, fundamental diagrams of pedestrians' dynamics in earthquake emergency conditions are retrieved for the first time. Average speeds are higher than the ones of other evacuations, while distances from obstacles underline the importance of repulsion phenomena between individuals and environmental obstacles (especially buildings). Related evacuation simulators should take into account these phenomena for the motion rules characterization. Simplified design procedures of buildings and urban spaces configuration could be based on fundamental diagrams evaluations.

The actual sample offers a significant overview on the earthquake evacuation phenomenon, but our future activities would enlarge the sample dimension and inquire specific issues such as: the effective influences of geographical and cultural background on emergency behaviours; the characterization of disabled people evacuation; the variations of motion quantities and behaviours in relation to the individuals' age; the correlation between evacuation data and the earthquake scale (including both macroseismic scales and the different Richter scales).

Obtained results also underline our experimental methodology capability: this method can be also applied to define emergency databases for other kind of evacuation (e.g.: flood). Finally, database outcomes would be soon used for simulators definitions and validations. Case-studies should be investigated for complete simulators verifications and tests.

This work really represents the first needed step of an innovative frontier in evacuation simulation and disaster management. Developed simulation software would be valuable for analyzing possible evacuation procedures and projecting urban planning strategies and emergency management procedures. The use of a large number of simulations would evidence how people behave in relation to possible environmental post-earthquake scenarios. In fact, simulators previsions would really permit to introduce the "human factor" in the earthquake risk assessment investigation, and to inquire the interferences between the evacuation procedures, the environment and its modifications. Results about evacuation time, pedestrians' flows and paths could be overlapped to scenario losses maps in order to operatively define a set of prevention and management strategies. Moreover, evacuation plans could be tested and so community resilience aspects could be inquired: the results should suggest observations to communication strategies and information campaigns for the population.

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