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SEISMIC RISK ASSESSMENT OF HUMAN EVACUATIONS IN BUILDINGS

A. Poulos(1), S. Castro(2), J. C. De la Llera(3), J. Mitrani-Reiser(4)

(1) Research assistant, National Research Center for Integrated Natural Disaster Management CONICYT/FONDAP/15110017, alan.poulos@cigiden.cl
(2) Research assistant, National Research Center for Integrated Natural Disaster Management CONICYT/FONDAP/15110017, sebastian.castro@cigiden.cl
(3) Professor, Pontificia Universidad Católica de Chile, jcllera@ing.puc.cl
(4) Professor, Johns Hopkins University, jmitrani@jhu.edu

Abstract

Major earthquakes may require people to evacuate immediately from buildings as recently observed in the 2015 M_w 8.3 Illapel earthquake in Chile. The building may suffer damage, thus affecting the evacuation process. Perhaps due to its apparent complexity, this interaction has not been taken into account when computing seismic risk variables that are intrinsically coupled, such as evacuation times and number of injured people. This limitation can be addressed by simulating the evacuation processes and the physical damage together using agent-based modelling. The evacuation of the building emerges from a set of rules that govern the interaction between agents and with their (damaged) physical surrounding. This research focuses first on modeling evacuations when no physical damage occurs, and uses real evacuation drills performed in a K-12 school and an office building as validation. The comparison was carried out under a low level of uncertainty in the initial conditions of the occupants, i.e., their initial positions and pre-evacuation times were relatively well known, resulting in prediction errors in total evacuation time of only 5.9% and 5.7% for the school and office building, respectively. The evacuation model is then extended to consider building damage and used in an integrated methodology to evaluate the seismic risk of building occupants. This assessment was divided into five steps: (i) seismic hazard, (ii) structural response, (iii) building damage, (iv) evacuation, and (v) risk assessment. First, probabilistic seismic hazard analysis was used to compute the frequency of different levels of local earthquake intensity, characterized herein by the spectral acceleration at the fundamental period of the structure. Ground motions accelerograms matching these intensities were then used in dynamic analyses of the inelastic structure to compute the building response. Story drifts and floor accelerations of the building were related to the damage of non-structural components (e.g., ceilings and partition walls) using appropriate fragility curves. The estimated damage state of the building was used to feed an agent-based evacuation model and assess the evacuation response of the building occupants in this new environment. The outputs of the model are probability distributions of different performance measures and losses, such as evacuation times and number of injured people. These results can better inform decision making processes to mitigate the consequences that future earthquakes will have on buildings and their inhabitants, as well as provide useful information in modeling other larger scale city evacuation scenarios.

Keywords: evacuation; seismic risk; agent-based modeling; damage and evacuation interaction

1. Introduction

Major earthquakes may require people to evacuate immediately from buildings as recently observed in the 2015 M_w 8.3 Illapel earthquake in Chile. These evacuations can be carried out to protect people from other consequential hazards, such as fires, landslides, and tsunamis, or because their structures are significantly damaged. During evacuation building occupants are exposed to floor acceleration and physical damage of the building, which affects their immediate evacuation response. These effects are commonly not modeled, and are not considered when assessing the associated seismic risk of building occupants.

Several models have been previously used to simulate human evacuation based on a variety of methodologies [1]. Evacuation models can first be classified depending on their resolution. Some models have a macroscopic scale since the smallest unit that can be modeled is the flow itself, as it is the case of models based on fluid-dynamics (e.g., [2]). These models have produced reasonable results for high crowd densities, but are of limited value for densities smaller than 4 persons per m^2 [3]. Microscopic scale models represent each person as a distinct unit, and are therefore better suited to simulate heterogeneous populations. The latter kind of model can be further subdivided into discrete and continuous space problems, depending on how they consider the domain in which the individuals move. The most widely used microscopic discrete technique to simulate human evacuation are cellular automata models (e.g., [4]), which divide the space in a grid, normally a two-dimensional tessellation using a regular polygon. Evacuees can only be located at the center of cells, which has the disadvantage that they have unnatural emergent behaviors in high crowd densities, such as individuals stopping and waiting for a space to clear up [4]. A commonly used microscopic continuous approach is the social force model first introduced in [5], which models pedestrians subjected to forces as particles following Newton's second law of motion. The forces represent effects such as: the desire to move to a destination; the collision avoidance with other pedestrians; the preservation of a minimum distance from obstacles; and the attraction to other agents.

Agent-based models (ABMs) are microscopic dynamic models that build systems on the basis of autonomous agents, which act and interact using simple predefined rules. They have the advantage of being able to include heterogeneity, randomness, and interactions at the agent level with relative ease. Therefore, they can be used to model the interaction between evacuating people and with their damaged physical environment. ABMs can also be combined with other evacuation models, such as the social force model or a cellular automata model.

As stated before, the integration of earthquake induced building damage with the evacuation of people is commonly not modeled. Some few exceptions are the works of Liu et al. [6], which developed an ABM to simulate the evacuation of a three story building following the 1994 M_W 6.7 Northridge earthquake; Li et al [7], that modeled emergency evacuation using a cellular automata model coupled with the collapse of a building due to the 1999 M_W 7.6 Chi-Chi earthquake in Taiwan; and Xiao et al [8], which studied the evacuation procedure of a building during the 2014 M_W 6.1 Ludian (China) earthquake using the social force model to define the motion of pedestrians.

On the other hand, earthquake engineering has recently been shifting its design philosophy to one that is performance-based. This enables stakeholders to better understand and select performance levels of structures, and requires the designer to quantify more accurately the seismic risk of the structure. In this sense, the Pacific Earthquake Engineering Research Center (PEER) has developed a probability-based framework for Performance-Based Earthquake Engineering (PBEE) [9], which enables risk assessment of physical systems.

This study presents a seismic risk assessment methodology for building occupants that considers evacuation processes, and is based on the PEER framework. It defers from previous works on earthquake-induced evacuations since it considers earthquake generation as a stochastic process instead of assessing the response to a single ground motion. The study focuses first on modeling evacuation when no physical damage occurs, and uses real evacuation drills performed in a K-12 school and an office building as validation. The proposed evacuation model has a microscopic scale, continuous space, and is agent-based. The model is then extended to consider building damage during earthquakes and used in an integrated methodology to evaluate the seismic risk of building occupants. The assessment starts by using probabilistic seismic hazard analysis (PSHA) to compute the hazard at the location of the building. The physical response of the building to different levels of earthquake intensity is calculated using a nonlinear dynamic structural model. The physical damage of non-structural components is then assessed probabilistically using fragility curves. Finally, the buildings' response and physical damage is used as the environment for agent-based evacuation simulations of the building. The output variables that are studied here are total evacuation time and number of injured people. The results are presented as probability distributions of these variables over a specific time window, from which other simpler risk measures such as expected annual losses can be derived. The methodology is exemplified using a real four story reinforced concrete office building located in the city of Santiago, Chile.

2. Evacuation modeling

The *environment* where the evacuation takes place can be represented by a set of disjoint polygons that represent static obstacles (e.g., walls and furniture). Additional vertices are added to the map that represent building exits and stairs. Agents are represented by circles that move outside of the polygons. The goal of the agents is to reach an exit by navigating through the building avoiding static obstacles and other agents. Before the simulation starts, a roadmap containing the minimum distances, d_j, from the building exits to each vertex in the map is constructed using Dijkstra's algorithm. The simulations start by positioning the agents in the map, and sampling their preferred speeds and pre-evacuation times from predefined probability distributions. If no specific information is available the initial agent position can be sampled uniformly, the speed distribution can be chosen from empirical data [10], and the pre-evacuation time distribution can be estimated using evacuation drills [11]. Then, at each time step, all agents select a single convex vertex to follow from the precomputed roadmap such that the distance to the exit is minimized, i.e.

$$c = \underset{j \in \mathcal{S}}{\operatorname{argmin}} \left(d_j + \|\mathbf{p} + \mathbf{r}_j\| \right) \tag{1}$$

where $\mathbf{p}$ is the position of the agent; $\mathcal{S}$ is the set of all the vertices that are visible to the agent; $\mathbf{r}_j$ is the position of vertex j; and $\|\cdot\|$ denotes the Euclidean norm. The preferred speed of the agents, $\mathbf{v}_\mathrm{p}$, is then set as a vector that points to vertex c and that has a magnitude equal to the maximum speed:

$$\mathbf{v}_\mathrm{p} = \frac{(\mathbf{r}_c - \mathbf{p})}{\|\mathbf{r}_c - \mathbf{p}\|} v_p f \tag{2}$$

where v_p is the preferred speed and f is a correction factor which reduces from 1 to 0.5 in the case of staircases. This represents the speed that an agent would have if there were no other agents near him. After all preferred velocities are constructed, the optimal reciprocal collision avoidance principle (ORCA) is used to compute new velocities $\mathbf{v}_\mathrm{n}$ that prevent agents from using the same physical space [12].

$$\mathbf{v}_\mathrm{n} = \underset{\mathbf{v} \in \mathcal{V}}{\operatorname{argmin}} \|\mathbf{v} - \mathbf{v}_\mathrm{p}\| \tag{3}$$

The new velocity of an agent is selected from the set $\mathcal{V}$ of all possible velocities that ensure that the agent will not collide with other agents and obstacles, and is the velocity that minimizes the distance to the previously computed preferred velocity. The position of the agents are then updated using the new velocity and the time step of the model, Δt:

$$\mathbf{p}^{(\mathrm{t}+1)} = \mathbf{p}^{(\mathrm{t})} + \mathbf{v}_\mathrm{n} \Delta t \tag{4}$$

The evacuation model was validated with real evacuation drills carried out in a K-12 school and an office building [11], with approximately 1500 and 200 evacuees, respectively. In both cases the evacuation was monitored using videos cameras, which were used to measure the cumulative number of evacuated people as a function of time (evacuation curve). The recordings were also used to obtain the number of evacuees that were inside each classroom of the school and in each floor of the office building. The evacuation curves were then obtained from 30 simulations of the model and are compared with the real drills in Fig. 1. Results from the model are relatively close to the real drills, with average errors of predicting the total evacuation time of 5.9%

and 5.7% for the school and office building, respectively. The variability between simulations is due to the random sampling of agent speed, and the random positioning of agents inside classrooms in the case of the school and in floors for the office building. The differences in the size of the areas were agents are randomly positioned explain the higher simulation variability observed in the office building with respect to the school (Fig. 1).

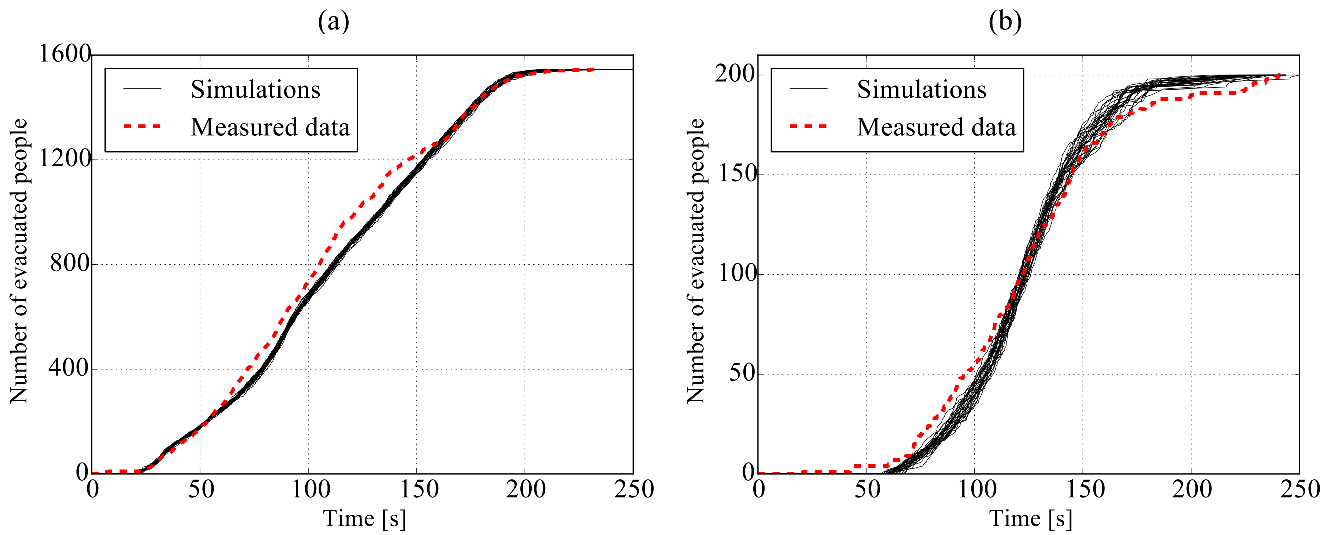

Fig. 1 – Real and simulated evacuation curves in: (a) the K-12 school, and (b) the office building.

3. Risk assessment methodology

Seismic risk assessment consists in quantifying the future effects that earthquakes will have on a system. This is achieved by simultaneously considering the likelihood of different earthquake intensities (seismic hazard) and their negative consequences on the system (vulnerability). The central equation used to assess seismic risk is:

$$\lambda_{OV}(ov) = \int_{IM} P(OV > ov|IM = im)|d\lambda_{IM}(im)| \qquad (5)$$

where OV is an output variable to be studied, which represents the response or loss of the system (e.g., economic losses, number of injured, and evacuation time); IM is the earthquake intensity at the location of the building, selected in this study as the spectral acceleration at the fundamental period of the structure; $P(OV > ov|IM = im)$ is the probability distribution of random variable OV given the occurrence of an earthquake with intensity $IM = im$, which defines the vulnerability of the system; and $\lambda_X(x)$ is the mean annual rate of an arbitrary variable X exceeding the value x, which is the inverse of the return period $T = 1/\lambda$. The mean annual rate of intensities, $\lambda_{IM}(im)$, is known as the seismic hazard curve, and is computed using PSHA [13]. This analysis adds the contributions of all seismic sources in a region, and conditions to different levels of earthquake magnitude and source-to-site distances. The link between global parameters of the earthquake (e.g., magnitude and depth) and the local intensity is given by a ground motion prediction equation (GMPE). The GMPE used in this study is that proposed by Abrahamson *et al*. for subduction zone earthquakes [14], and the seismic source parameters (i.e., geometry and Gutenberg-Richter parameters) are taken from reference [15]. The resulting hazard curve for the location of the testbed building is shown in Fig. 2a.

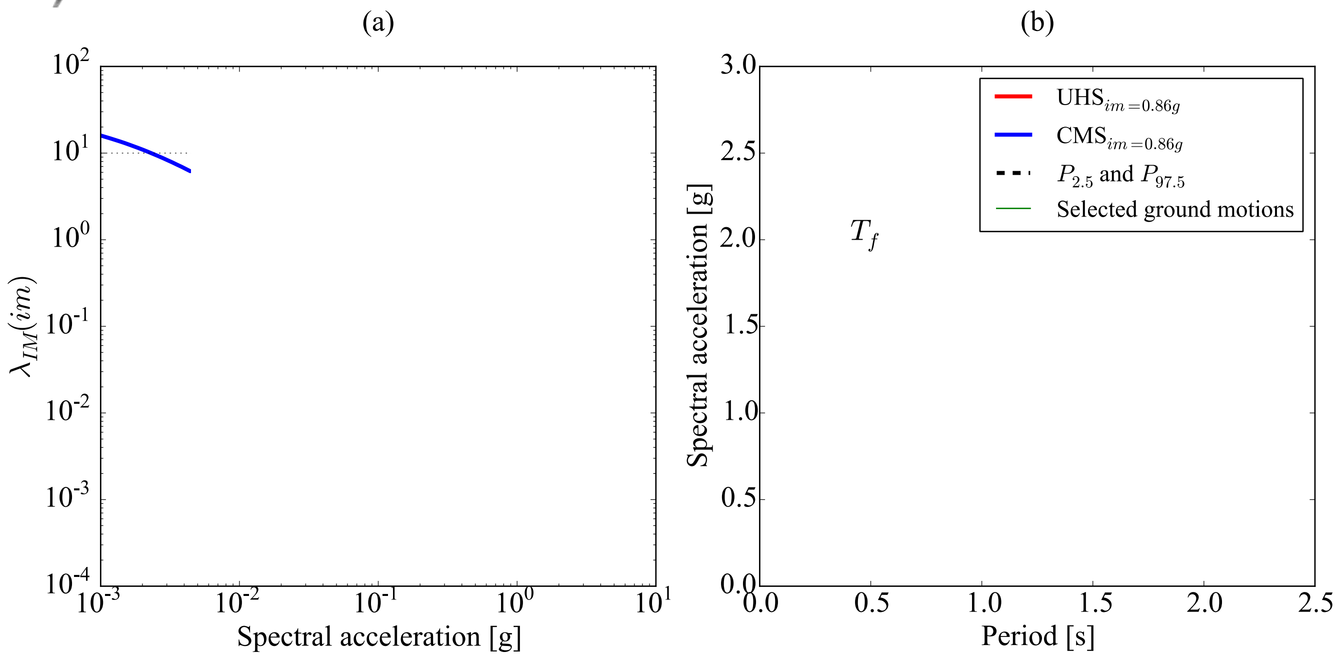

Fig. 2 – Seismic hazard at the location of the building: (a) hazard curve; and (b) conditional mean spectrum for an intensity of 0.86 g with associated 2.5th and 97.5th percentiles, and spectra from 10 selected ground motions. The gray area represents the range of periods used for matching.

Eq. (5) assumes that the system is restored to its initial state (i.e., that all building damage and component damage are repaired) before the next earthquake occurs. Therefore, this methodology does not consider aftershock sequences, since several ground motions may strike the structure in a relatively short period of time. This is consistent with the fact that aftershocks are also not considered in the seismic hazard since the earthquake recurrence model (Gutenberg-Richter law) is obtained with a declustered earthquake catalog.

The mean annual rates that are computed using Eq. (5) are not expressed in a manner that is meaningful to various stakeholder groups and decision makers [9]. To cope with this difficulty, this work computes the probability distributions of the accumulated and maximum value of the output variable from all earthquakes that occur in a certain time window. Analytical expressions and numerical simulation-based assessments of these distributions have been presented previously [11].

4. Building and human vulnerability

In order to perform seismic risk analysis, the response of building and its occupants must be assessed for each intensity measure. Fig. 3 summarizes all steps required for this vulnerability assessment in a pseudocode. First, a set of ground motions, which are scaled to the required intensity, must be selected. The response of the building to each of these ground motions is then computed using a nonlinear dynamic structural model. Several damage scenarios are sampled for each ground motion and used as inputs for evacuation simulations. Finally, the probability distribution of an output variable is estimated using all of the simulations. Some output variables depend on the occupancy level of the building, such as the number of injured people, e.g. nobody gets injured if the building is empty. If the building is assumed to be either full or empty at any given time, then the resulting exceedance probability can be adjusted simply by multiplying by the fraction of time that the building is occupied, chosen as 1/3 for the studied building. The step with the highest computational cost is to calculate the inelastic building response. Thus, the sampling is performed at two levels: first when selecting a set of ground motions, and the when sampling the physical damage. The physical response of the building for a given ground motion is deterministic, while the damage assessment and evacuation response are stochastic, and hence, they are sampled several times for a given ground motion.

Input: L intensity levels $im_1, im_2, ..., im_L$; number of ground motions to use (M); number of simulations to run (N)

Output: System vulnerability $P(OV > ov|IM)$

for $i \leftarrow 1$ to L **do**
    Compute conditional spectrum for intesity im_i
    Select M ground motions that match the spectrum
    for $j \leftarrow 1$ to M **do**
        Run dynamic structural analysis on the building using ground motion j
        for $k \leftarrow 1$ to N **do**
            Assess physical damage using fragility curves
            Run the evacuation model with the obtained damage
            Obtain the value OV_{jk} of the output variable
        end for
    end for
    Estimate the conditional probability distribution from all simulations:

$$P(OV > ov|IM = im_i) = \frac{1}{MN} \sum_{j=1}^{M} \sum_{k=1}^{N} \mathbf{1}(OV_{jk} \leq ov)$$

    Adjust $P(OV > ov|IM = im_i)$ by occupancy level when needed
end for

Fig. 3 – Vulnerability assessment pseudocode.

4.1 Ground motion selection

The intensity measure used in this study only has information of the spectral acceleration at one period (the fundamental period of the structure). The mean spectral accelerations at other periods given a certain spectral acceleration at a fixed period form a conditional mean spectrum (CMS) [16]. The CMS computed at the location of the testbed structure and its corresponding 2.5th and 97.5th percentiles are shown in Fig. 2b for an intensity level of $Sa(T_f) = 0.86$ g, with T_f being the fundamental period of the structure. These spectra were computed with the same GMPE used to compute the seismic hazard, and with the spectral acceleration correlation model proposed in reference [17]. Fig. 2b also shows the uniform hazard spectrum (UHS) for the same intensity, which represents spectral values with the same return period.

The nonlinear time history analysis requires as an input a suite of ground motion pairs (two horizontal components), whose spectral acceleration combined as a geometrical average match each intensity level. The candidate accelerograms are real Chilean ground motions recorded at sites with the same soil type as the one for the studied structure, scaled to the target intensity. The ground motions were selected for each intensity using an algorithm that matches the conditional mean and standard deviation at periods ranging from $0.2T_f$ to $2T_f$ [18]. A total of 10 ground motions were then selected for each intensity, as shown in Fig. 2b.

4.2 Building response and damage

In order to assess the physical damage generated by a ground motion, the response of the building in terms of acceleration and displacement must first be calculated. This was performed for the testbed building using a model developed in OpenSees [19], which consists of inelastic fiber based frame elements that characterize the behavior of reinforced concrete sections of the frame elements in the structure. Building diaphragms are considered infinitely rigid in their plane and with no out-of-plane stiffness. The testbed consists in a four-story reinforced concrete frame building that has a fundamental period of 0.42 s.

Once the response of the building is computed, it can be related with the damage of non-structural components using fragility curves. Two nonstructural components are considered for the testbed building: partition walls and false ceilings, which are drift- and acceleration-sensitive, respectively. The selected fragility curves used for different damage states of partition walls and false ceilings are lognormal distributions with the parameters shown in Table 1. Parameter x_m is the median of the distribution, and σ is the standard deviation of the associated normal distribution. The damage state of a component for a given intensity is uncertain, and the probability associated with being in a damage state is given by the fragility curves. However, assessing the response of building occupants requires running a finite amount of evacuation simulations. Thus, a single damage scenario was sampled for each evacuation simulation.

Table 1 – Fragility curve parameters of non-structural components.

Component	Damage state	x_m	σ
Partition walls	Moderate	0.67%	0.39
	Collapse	1.05%	0.52
False ceilings	Moderate	1.01 g	0.051
	Collapse	2.04 g	0.200

4.3 Human response

The model described in section 2 is extended here to consider building evacuation during earthquake events. Earthquakes affect the evacuation of people by inducing floor acceleration and by damaging the building. Certain levels of floor acceleration impede movement and may even result in losing stability. This is considered by calculating in real time the floor acceleration that each agent is subjected to, and assigning agent speed as zero if it is greater than a threshold value set to 0.1 g, defined as the acceleration at which people have trouble standing up [20]. Simulating the real-time effect that the building damage has on people is a complex task since there is almost no quantitative literature on the subject. Therefore, the assumptions needed for the ABM are exclusively based on intuition, and some degree of past experience, but they require future validations using experimental data. The real-time damage of non-structural components is used to modify two agent variables: health and stress; values for both variables range between 0 and 1, with health starting at 1 and stress at 0. Let us assume that agents have three behavioral regimes determined by their stress level: normal, rational, and panic. All agents start the simulation in normal regime, and any increase in stress of an agent shifts its regime to rational. When an agent enters the rational regime, it starts evacuating (if it had not started before) and increases its preferred speed. The stress limits between rational and panic regimes are assigned randomly for each agent using a standard uniform distribution $U(0, 1)$. Furthermore, it is assumed that if an agent sees moderate damage or the collapse of a building component, its stress increases by 0.05 and 0.2, respectively. Also if a component (e.g., ceiling) collapses on an agent, its stress increases by 0.5 and its health factor is reduced by 0.5. It is also assumed that agents in panic regime seeing collapse of a building component have a 50% probability to block and stop moving during a random interval between 5 to 10 seconds (uniformly distributed).

Therefore, the correction factor used in Eq. (2) to adjust the preferred speed can be extended to consider various factors:

$$f = f_s\, f_a\, f_r\, f_d\, f_h \tag{6}$$

where f_s reduces the speed of agents on a staircase (f_s = 0.5); f_a is zero when the floor acceleration exceeds a threshold value (0.1 g in this study); factor f_r increases the speed if the agent is in rational or panic regime (f_r = 0.5); f_d reduces the speed of agents walking over debris (for collapsed non-structural components: f_d = 0.5 for partition walls, and f_d = 0.7 for suspended ceilings); and factor f_h = 0.25+0.75h accounts for speed reduction of the agent depending on its health h.

Fig. 4 illustrates the effect that building damage has on evacuating agents by showing four snapshots of a section of the fourth floor during a single simulation. The damage states of partition walls and ceilings are shown using different colors. The input ground motion used to assess building damage has intensity Sa(T_f) = 0.77 g and its north-south component is shown in the same Figure. At first, all agents are randomly positioned throughout the building. At t = 15 s some agents have already started evacuating, but the majority still remain in their positions. At t = 30 s the ground motion intensity has increased and generated significant damage in partition walls, which made agents start evacuating. Finally, after the peak ground acceleration has passed (t = 45 s), all building damage has already occurred, most of the agents are near the staircase and the floor is nearly empty.

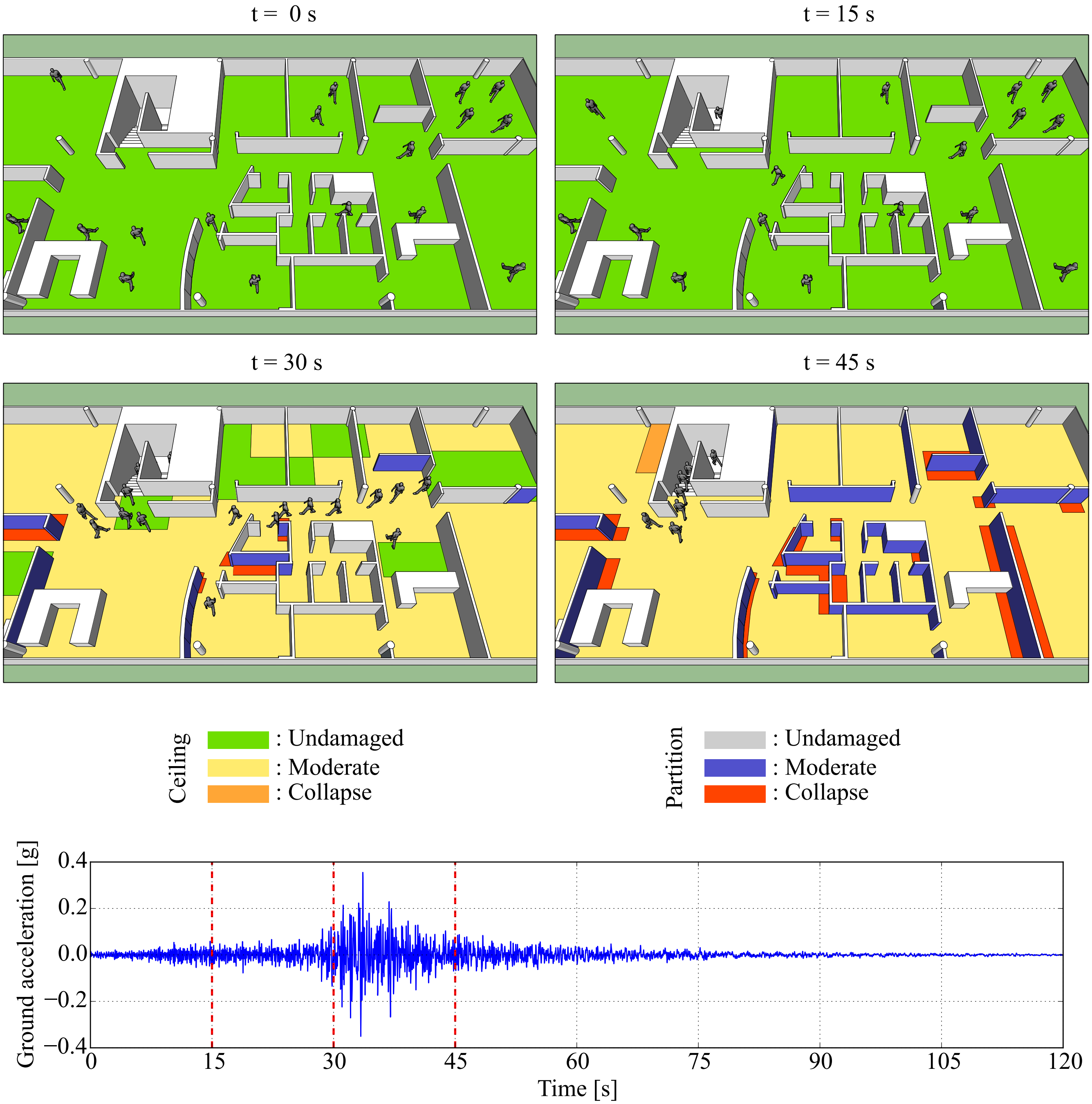

Fig. 4 – Evacuation simulation with physical damage.

5. Results

The risk assessment methodology was applied to the testbed building to compute distributions of two output variables: number of injured agents and total evacuation time. The number of injured people was estimated as the total number of agents that were hit by falling non-structural components of the building according to the simulation results. This analysis does not provide any insight of the severity of the injuries; it only provides an estimation of the number of people that are physically affected by the earthquake. Total evacuation time is defined as the time between the start of an evacuation and the moment in which the last person exits the building.

The number of intensity levels used for the analysis were L=12 with values ranging between 0.05 g and 1.04 g. The minimum intensity was selected as the maximum value that results in no injured people for all simulations. A total of M=10 ground motion were scaled to each intensity level (see Fig. 3). For each ground motion, a total of N=20 damage assessments and evacuation simulations were carried out. All evacuation simulation considered 200 agents, which were randomly positioned throughout the building plan following a uniform distribution. Fig. 5a shows the cumulative distribution functions (CDFs) of the accumulated number of injured people from all evacuations that occur in certain time windows. Since this variable is discrete, the CDFs are step functions. The CDFs of maximum total evacuation time, i.e. the maximum evacuation time of the last person that evacuates the building from all evacuations in a time window, are presented in Fig. 5b. As expected, the probability distributions show that the accumulated number of injured people and the maximum evacuation time increase when widening the time window. For example, if a time window of 5 years is selected, the probability that more than 5 people will get injured is approximately 5%. The same probability increases to 10% and 60% when selecting a time window of 10 and 50 years, respectively (Fig. 5a). It is important to note that the distribution of maximum evacuation time is affected by the arbitrary selection of the minimum intensity that will trigger evacuations (assumed as 0.05 g in this study). This is because the maximum evacuation time is assigned as zero when there are no earthquakes that triggers evacuation in a certain time window, and hence this random variable has a mixed probability distribution, with a non-zero probability of being zero and continuous probability density function for positive values. The probability that no evacuation will occur in a time window can then be deduced directly from Fig. 5b, e.g., approximately 10% in 5 years and 63% in 1 year.

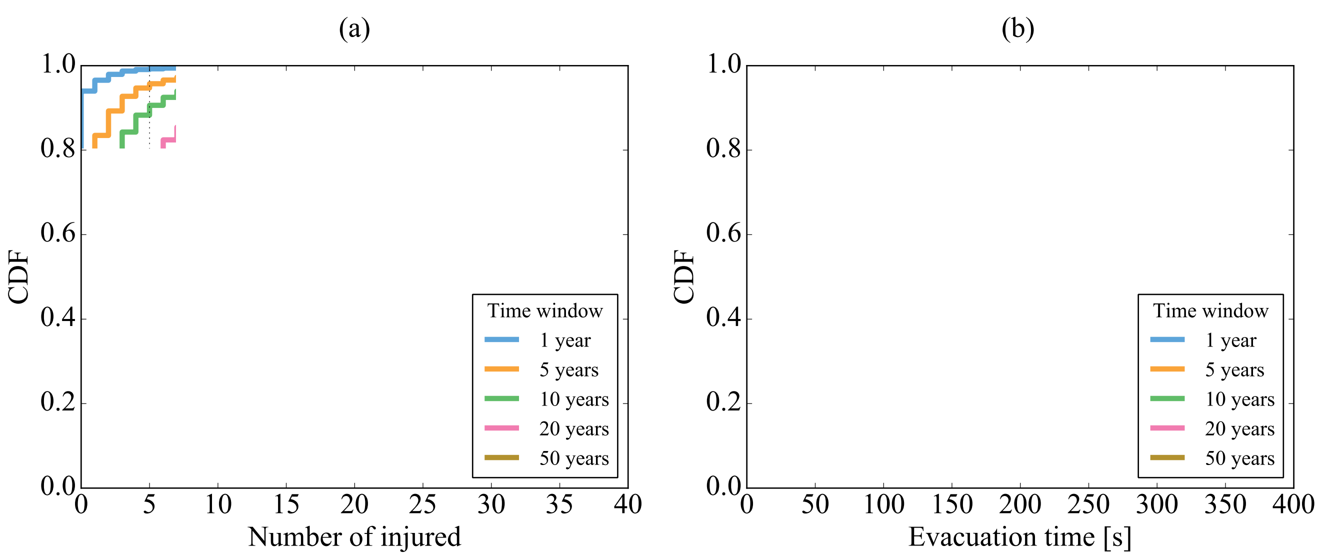

Fig. 5 – Cumulative distribution functions of (a) accumulated number of injured people, and (b) maximum evacuation time, of all evacuations that occur in different time windows.

A summary of the expected values and standard deviations of the calculated distributions are shown in Table 2. Mean values of accumulated injured are directly proportional to the considered time window, with small differences occurring due to the use of finite Monte Carlo simulations. The mean value for a time window of one year is known as the expected annual loss, and is a common result of seismic risk analyses. The results of this work are more general since it provides the complete distribution, not only its expected value. Even though these results are valid for the specific building used in this work, the same methodology can be applied to other buildings. The results in terms of number of injured can provide valuable information to emergency managers and the insurance industry. Similarly, the maximum evacuation time curves can be used by emergency managers at the moment of designing the emergency plan of a building.

Table 2 – Estimated mean and standard deviation (in parenthesis) of the output variable distributions for the testbed building.

Time window (years)	Accumulated number of injured people	Maximum evacuation time (s)
1	0.18 (1.10)	131 (46.4)
5	0.88 (2.43)	190 (40.9)
10	1.76 (3.43)	211 (30.8)
20	3.51 (4.85)	227 (29.9)
50	8.79 (7.68)	247 (33.8)

6. Conclusion

Earthquakes may generate significant floor accelerations and produce physical damage in buildings, affecting their occupants. This work proposes a probabilistic methodology to assess the seismic risk of occupants, considering their evacuation behavior inside the building. First, an agent-based evacuation model was successfully validated by the use of evacuation drills in two different buildings with different amounts of people. The evacuation model was then integrated with the building response and the physical damage to simulate earthquake scenarios, and used in a probabilistic framework to compute the seismic risk of building occupants. As a way of exemplifying the methodology, a four-story reinforced concrete frame building was used as a testbed, resulting in probability distributions of output variables for different time windows. For example, for a time window of 50 years in this building, the expected accumulated number of injured people is about 8.79 and the maximum evacuation time is 247 s.

The proposed methodology enables risk assessment of any other variable that can be derived from the evacuation model, e.g., number of people subjected to a certain level of floor acceleration, average agent speed, and even number of deaths if the severity of injuries is qualified. Moreover, the evacuation history of each agent can be used to assess long-term physical and psychological impacts, such as post-traumatic stress disorder. All these human variables represent direct effects that earthquakes have on people and are not usually considered when designing infrastructure. Thus, models as the one presented herein can better inform emergency managers and help their decision making process, thus helping in preparing and mitigating the eventually critical consequences on building inhabitants as structures are subjected to extreme earthquake events or alike. However, the model can still be improved in several ways, such as considering structural failure and changing evacuation routes due to blockage of stairs. Furthermore, reliable computations of human variables are limited to our current state of knowledge on how people are affected by earthquakes. Therefore, more quantitative research should be carried out in this field to improve these models and enable better assessments of the actual human seismic risk.

7. Acknowledgements

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8. References

[1] Zheng X, Zhong T, Liu M (2009): Modeling crowd evacuation of a building based on seven methodological approaches. *Building and Environment*, **44** (3), 437-445.

[2] Helbing D (1992): A Fluid-Dynamic Model for the Movement of Pedestrians. *Complex Systems*, **6**, 391-415.

[3] Hughes RL (2002): A continuum theory for the flow of pedestrians. *Transportation Research Part B: Methodological*, **36** (6), 507-535.

[4] Pelechano N, Malkawi A (2008): Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches. *Automation in construction*, **17** (4), 377-385.

[5] Helbing D, Molnar P (1995): Social force model for pedestrian dynamics. *Physical review E*, **51** (5), 4282-4286.

[6] Liu Z, Jacques CC, Szyniszewski S, Guest JK, Schafer BW, Igusa T, Mitrani-Reiser J (2015): Agent-based simulation of building evacuation after an earthquake: coupling human behavior with structural response. *Natural Hazards Review*, **17** (1), 04015019.

[7] Li S, Zhai C, Xie L (2015): Occupant evacuation and casualty estimation in a building under earthquake using cellular automata. *Physica A: Statistical Mechanics and its Applications*, **424**, 152-167.

[8] Xiao M-L, Chen Y, Yan M-J, Ye, L-Y, Liu B-Y (2016): Simulation of household evacuation in the 2014 Ludian earthquake. *Bulletin of Earthquake Engineering*, **14** (6), 1757-1769.

[9] Moehle J, Deierlein GG (2004): A framework methodology for performance-based earthquake engineering. *13th World conference on earthquake engineering*, Vancouver, Canada, 3812-3814.

[10] Rinne T, Tillander K, Grönberg P (2010): Data collection and analysis of evacuation situations. Research Notes 2562. VTT Technical Research Centre of Finland, Espoo, Finland.

[11] Poulos A (2014): Risk model of human evacuation under earthquake loads. Master's Thesis, Pontifical Catholic University of Chile. Retrieved from https://repositorio.uc.cl/handle/11534/15624

[12] Van Den Berg J, Guy SJ, Lin M, Manocha D (2011): Reciprocal n-body collision avoidance. In: *Robotics Research* (pp. 3-19). Springer.

[13] Cornell CA (1968): Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, **58** (5), 1583-1606.

[14] Abrahamson N, Gregor N, Addo K (2015): BC Hydro ground motion prediction equations for subduction earthquakes. *Earthquake Spectra*, **32** (1), 23-44.

[15] Alvarez M (2001): Assessment and prediction of seismic damage in conventional structures and with vibration control systems: a numerical implementation [in Spanish]. Master's Thesis, Pontifical Catholic University of Chile.

[16] Baker JW (2011): Conditional mean spectrum: Tool for ground-motion selection. *Journal of Structural Engineering*, **137** (3), 322-331.

[17] Baker JW, Jayaram N (2008): Correlation of spectral acceleration values from NGA ground motion models. *Earthquake Spectra*, **24** (1), 299-317.

[18] Jayaram N, Lin T, Baker JW (2011): A computationally efficient ground-motion selection algorithm for matching a target response spectrum mean and variance. *Earthquake Spectra*, **27** (3), 797-815.

[19] McKenna F, Fenves G, Scott M, Jeremic B (2000): Open system for earthquake engineering simulation (OpenSees). Pacific earthquake engineering research center, University of California, Berkeley, CA.

[20] Kusky T, Kusky TM (2008): *Earthquakes: plate tectonics and earthquake hazards*. New York, NY: Infobase Publishing.