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Nat. Hazards Earth Syst. Sci., 17, 581–594, 2017
www.nat-hazards-earth-syst-sci.net/17/581/2017/
doi:10.5194/nhess-17-581-2017

Natural Hazards and Earth System Sciences
Open Access
EGU

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Received: 31 March 2016 – Discussion started: 10 May 2016
Revised: 23 February 2017 – Accepted: 8 March 2017 – Published: 19 April 2017

Abstract. The earthquake which struck the city of Lorca, Spain, on 11 May 2011 killed 9 people, injured over 300 and caused considerable damage, including one collapsed building. Streets near buildings were the main danger areas for people. This article proposes an dynamic ad hoc spatio-temporal method for studying individual evacuation after an earthquake. Its application to the Lorca case shows the spatial and temporal variability of individual exposure levels in the street during the hours following the shock. As yet little studied, human exposure deserves more attention, particularly in zones of moderate seismicity like the Euro-Mediterranean area. The results of this study could be helpful for enhancing the evacuation planning after an earthquake, stressing the specific dangers in the street.

1 Introduction

On 11 May 2011, exactly 2 months after the Fukushima disaster in Japan, a two-shock earthquake struck the city of Lorca, located about 60 km southwest of Murcia in southern Spain. The earthquake mainly affected the city centre, home to 60 000 of the municipality's 90 000 inhabitants (Fig. 1). The Lorca earthquake was not one of the deadliest in the Mediterranean area but did display several novel features.

The Iberian peninsula had not experienced such a deadly earthquake since 1956, when an earthquake killed 13 people in southeast Spain, near the city of Granada (Solares, 2012). In 2011, the magnitude M_w 5.2 Lorca earthquake occurred at around 18.47 h local time (16.47 h GMT), after another magnitude M_w 4.6 foreshock had occurred almost 2 h before. With an epicentre intensity of VII (EMS-98), the quake killed 9 people and injured 300. One building collapsed completely and 1164 others were severely damaged. Economic losses were estimated by Lorca municipality at EUR 1 200 million in November 2011 (Oterino et al., 2012). The casualties were caused in streets near buildings and were due not to collapsing buildings but to falling cornices, balconies and other façade elements (Martínez Moreno et al., 2012).

The shock lasted only a few seconds, developing a maximum acceleration of 0.37 g, as recorded in the city 3 km from the epicentre. It was the highest acceleration recorded in Spain since the first accelerometers were installed in the region in 1984 (Rodríguez et al., 2011). Site effects, shallow focal depth, high acceleration and the relatively high vulnerability of infrastructure seem to be the main factors explaining the damage (Díaz, 2012). They probably helped restrict damage to the city itself, as there was hardly any visible damage only a few kilometres outside the city limits. The nearest outside measuring station, located 24 km from the epicentre, actually recorded a peak acceleration of only 0.02 g, nearly 20 times less than that recorded inside the city (Oterino et al., 2012).

In Lorca, casualties mainly occurred outdoors (outside the buildings), whereas they are usually found under the ruins of damaged buildings (Coburn et al., 1992). Hence, we focus on the individuals' exposure over the time, along the main public areas. Following other recent studies, we chose to adapt the most common approach that primarily examines structural defects caused by earthquakes and how these can cause causalities (Quagliarini et al., 2016; Ferreira, et al., 2014).

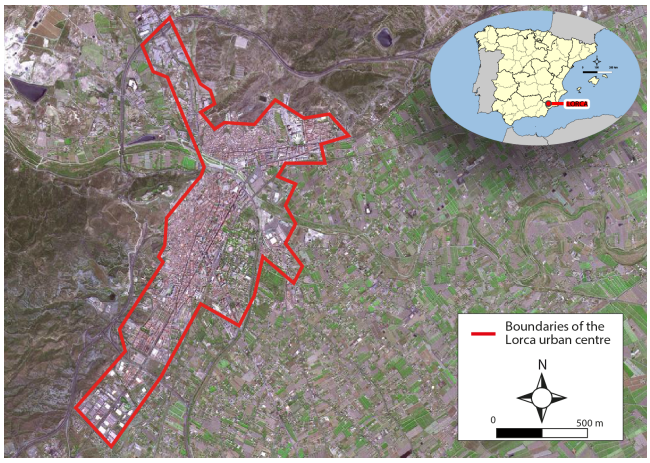

Figure 1. Location of Lorca (inset) and view of the city centre. SPOT source courtesy of the ©Instituto Geográfico Nacional de España.

2 Individual exposure to earthquakes: the state of the art

Based on the literature analysing the reasons for deaths and injuries (in Sect. 2.1), we will examine the reasons why streets may be a specific area of exposure (Sect. 2.2) and how this affects the way the social dimensions of a seismic event can be addressed compared to a more traditional vulnerability-centred approach (Sect. 2.3).

2.1 The causes of casualties during an earthquake

According to Coburn et al. (1992), 75 % of earthquake death tolls in urban environments are due to buildings collapsing, amounting to over 1.5 million fatalities between 1900 and 1992 ($N = 1\,528\,000$ deaths). This is consistent with figures in Euro-Mediterranean countries, where most deaths result from building collapse (Galindo-Zaldívar et al., 2009; Tapan et al., 2013; Alexander 2011). These observations require some qualification, however.

Collapsed buildings result in many casualties in single places. In the case of the San Giuliano di Puglia earthquake in Italy in 2002, for example, 25 out of 29 deaths were due to the collapse of a school (Vallée and Di Luccio, 2005). In the same way, the collapse of five factory buildings during the 2012 earthquakes in Italy killed 12 people. It is therefore understandable that research mainly seeks to minimise seismic impacts on buildings through earthquake-resistant construction methods. These have become widespread in earthquake-prone regions with special laws and systematic enforcement of building standards.

Europe's long history, however, has left a considerable heritage of old buildings, particularly houses in mountain and rural areas, a large number of historical city centres (Guardiola-Víllora and Basset-Salom, 2015; Moreno González and Bairán García, 2012) and many religious buildings and historical monuments (Martínez, 2012; Milani, 2013). A series of earthquakes in Turkey in the 2000s (2002, 2004, 2010, 2011) and in Italy (2009), for example, caused significant damage and the collapse of many ancient buildings. Local habits in which inhabitants self-design buildings by following local building practices and without taking earthquake-resistant building standards into account could also have been reasons for some of the damage (Ellidokuz et al., 2005; Dogangün, 2004; Celep et al., 2011; Tapan et al., 2013; Alexander, 2011). The above examples suggest that religious buildings are the least resistant to earthquakes. This was seen during recent earthquake events in Italy (Martínez, 2012; Milani, 2013) as well as during the Lorca earthquake. In the latter, 33 historical buildings suffered damage that was hard to quantify economically. Damage was visible to domes, abutments, arches and decorative features, which in several cases became skewed and lost stability (Martínez, 2012).

In addition to this type of building, and even when recent construction is subject to earthquake-resistant standards, certain unsuitable habits make buildings vulnerable. This is true, for instance, with the use of short pillars or when storeys are of different heights, especially when buildings are made of concrete blocks (Bechtoula and Ousalem, 2005; Tibaduiza et al., 2012). In consequence, even though Euro-Mediterranean countries are not located on the world's most active faults, both ancient and more recent buildings are vulnerable to shocks affecting their structure or causing façade items to fall into neighbouring streets and impact people.

Previous studies have found that crushing and asphyxiation are the most common causes of death during earthquakes (Ramirez and Peek-Asa, 2005). The analysis of specific events, however, leads to conclusions qualifying such findings.

During the Liege earthquake in Wallonia (Belgium) at around 01:49 local time on 8 November 1983, most damage resulted from the large number of falling chimneys (Camelbeek et al., 2006). Other objects such as stonework pediments and chimney covers also fell. The falling objects damaged roofs and vehicles parked alongside buildings but could have resulted in a significant death toll if the earthquake had struck during the day. The authors of the above study concluded that in Wallonia "the leading cause of death in a low-intensity earthquake is the fall of loosely fixed or weakly resistant non-structural elements placed high up: chimneys, decorative façade elements, partitions and interior dividing walls which have simply been put in place without being fixed" (Camelbeek et al., 2006).

Elsewhere, following the Darfield (South Island, New Zealand) earthquake in 2010, non-structural elements which had suffered severe damage were examined. Only two people were seriously injured in this earthquake, one of them by a falling chimney. Considering that the streets next to buildings were littered with debris, it is clear that the main factor deter-

mining the low number of casualties was that the earthquake struck at 04:35 (Dhakal, 2010).

Even if building collapse is one of the main causes of death during an earthquake, the exposure of people on streets and near buildings should also be regarded as a significant factor, especially in regions of moderate seismic activity. Some of the latest research has in fact refined the environmental characteristics people are faced with after an earthquake and drawn a distinction between internal and external damage (Quagliarini et al., 2016). In the Afyon (Turkey) earthquake in 2002, the death toll was higher indoors than outdoors, but the difference was not statistically significant (Ellidokuz et al., 2005). Other accounts of the same earthquake stressed that many non-structural elements of buildings suffered severe damage. The most frequently observed problem comes from the flimsiness of dividing walls not included in initial architectural plans and added later (Tapan et al., 2013).

In the Lorca case only one building collapsed, with nobody being injured inside (the investigations did not give us enough details for understanding why). The people injured were those struck in the street near buildings. Once again, injuries were not due to buildings collapsing but to falling cornices, balconies and other façade and roofing items (Martínez Moreno et al., 2012).

2.2 Exposure in the street

Putting people at the centre of a study requires paying close attention to the new surroundings people find themselves in the aftermath of an earthquake. A number of psychological and medical papers have listed typologies of injuries and traumas caused by earthquakes. Some have investigated the origins of injuries (Ellidokuz et al., 2005; Armenian et al., 1997; Chou et al., 2004). A few have described people's behaviour following an earthquake and examined the reasons for it by assessing perceptions of danger (Bolton, 1993; Weiss et al., 2011; Goltz et al., 1992). In Japan, where closed-circuit camera surveillance is widespread, a new line of research seeks to analyse individual behaviour during the earthquake itself and during subsequent mass evacuations (Yang et al., 2011). Such studies enable clear differences to be seen between real-life escape panic and the mimicry displayed during simulated exercises. Observational data on individual evacuation behaviour remain rare, however. It is for this reason that a number of recent initiatives have sought to create video databases. Analysing images enables behavioural models to be defined and people's movements in such situations to be more accurately quantified (Bernardini et al., 2016b).

After an earthquake such as that in Lorca, people have to adapt immediately to more or less altered surroundings. Awareness of the new situation and subsequent decision-making processes are linked to individual and collective assessments of the new environment (Weiss et al., 2011). Nevertheless, in a troubled situation (especially with disturbances to electrical and telephone networks), this is mainly done when people physically go to see what has happened, thus increasing individual mobility. Such movements may take place near weakened buildings, however, leading to increased individual exposure.

In order to analyse the exposure of individuals in the street, it is therefore necessary to understand how people move from the moment of the earthquake up to the time they reach a safe area (outside the city in the Lorca case). To this end, our study resorted to an approach proposed by time geography, which observes individuals and their daily journeys and activities over time and through space. This methodology has been developing since the 1960s to evaluate people's daily mobility at a local scale, usually an urban area (Chardonnel and Stock, 2005; Thevenin et al., 2007). In order to observe and represent people's movements in their environments as accurately as possible, we used the concept of spatio-temporal trajectories developed by time geography. This approach enables mobility to be represented as a succession of places or positions and journeys to be defined precisely in time and space. It therefore seems very suitable for analysing people's mobility during a disaster (André-Poyaud et al., 2009) and has been tested for other types of sudden event such as flash floods (Debionne et al., 2016).

Over the last decade much work has been done in order to understand warning processes and how people adapt to environments altered by sudden rises in water levels (Ruin and Lutoff, 2004; Ruin, 2007; Ruin et al., 2008; Creutin et al., 2009; Créton-Cazanave and Lutoff, 2013; Ruin et al., 2013; Calianno et al., 2013). A specific methodology for collecting and analysing data has been developed by these studies. The analysis of several flood events found that people's mobility and their location on roads and streets were determining factors in their exposure (Ruin, 2007). The fact that people are able to, have to or want to move during a flood can thus put individual lives in danger. Our question was whether this would be similar for earthquakes. We therefore applied the mobility analysis method for flash floods to the Lorca earthquake in order to examine the conditions for exposure during a seismic crisis.

Finally, to evaluate the exposure of people in the streets, it is necessary to identify the area of exposure due to debris falling from buildings. A number of exhaustive studies have used aerial photographs to analyse and digitalise disaster areas caused by earthquakes (indoors and outdoors) (Quagliarini et al., 2016). In Lorca, unfortunately, this could not be done as the streets and roads had been cleared very quickly in order to allow emergency vehicles to move around. As far as we have been able to establish, there are no pictures of debris in Lorca just after the earthquake. In addition, only one building actually collapsed during the earthquake. Other studies incorporate the area covered by debris into their analysis of people's behaviour after an earthquake (D'Orazio et al., 2014). Such work uses a large quantity of video images, however, and focuses on the actual time of

shaking and the immediate aftermath of the shock (a few minutes only).

2.3 Exposure vs. vulnerability

Our focus on the concept of exposure requires theoretical explanations of the geography of hazards.

The literature on the social approach to hazards – especially in geography – tends to concentrate on the concept of vulnerability but only rarely focuses on exposure. According to Reghezza (2006), "The approach centred on vulnerability leaves exposure with a secondary role, especially because of the difficulties in characterising the interaction between the element exposed and the event" (our translation). Our goal was to deal with these difficulties and analyse the fluctuations of human exposure in the time and space of a seismic crisis. We therefore relied on Leone's (2007) definition of exposure as a spatial and temporal co-incidence between a hazard and an individual.

To meet our goal it was necessary to take a dynamic rather than a static approach. The issue was to analyse how people become exposed after an earthquake depending on their movements and the way in which the earthquake will have altered the built environment. The alteration of the environment after an earthquake modifies individuals' behaviour. This is the reason why current predictive models of behaviour during a crisis increasingly incorporate environmental elements such as the external damage caused by the earthquake (Quagliarini et al., 2016).

Analysing exposure thus requires a dynamic approach to take into account the spatial and temporal dimensions both of people's journeys and of the threat (Chardonnel and Stock, 2005). An example of this type of dynamic approach was shown at a small historical site in Japan with 21 inhabitants. The study enabled an individual evacuation plan to be drawn up, with possible scenarios adapted to each person (with or without mobility problems) and to each dwelling (Mishima et al., 2014). In our case the temporal window we analysed corresponded to the time taken by individual respondents to evacuate the ruined city. The spatial dimension was determined by the extent of the damage, which in Lorca was concentrated in the city centre (Fig. 1) (Alfaro et al., 2011; Tibaduiza et al., 2012). This definition of the spatio-temporal window to be observed led to a more precise definition of the concept of evacuation, to wit, evacuation means leaving the area impacted by the earthquake and thus reducing exposure by increasing one's distance from buildings weakened by the earthquake. This definition was adopted to account for the specific features of our case study. When a person reached a "safe area" inside the city, he or she was temporarily safe. Before being able to reach the exterior of the city, however, a majority of respondents explained that they had to re-expose themselves to danger by passing alongside weakened buildings. Consequently, the limits of our study's time window corresponded to the evacuation of the city for each individual, which allowed us to define the temporality of what we considered to be the seismic crisis.

Works focusing on crisis periods are not new. Research undertaken in the late 1980s and early 1990s highlighted the importance of addressing seismic crisis periods (Quarantelli, 1982; Goltz et al., 1992; Bolton, 1993). These studies – mostly quantitative and based on large sample groups – tend to focus on individuals' main actions, on the damage suffered and the reasons causing people to evacuate. They have contributed statistically significant information enhancing the understanding of affected individuals' main activities, but the information is disconnected from the time and place in which the activities occurred. Only a few recent studies have analysed differences in exposure according to the activities carried out, i.e. have assessed whether the activities led to an increase or decrease in human exposure or whether they had no influence on it (Bernardini et al., 2016a). The present paper proposes a methodology for the dynamic analysis of human exposure during the moderate earthquakes that occur in the Euro-Mediterranean context.

3 Methodology for analysing dynamic exposure

This section describes the details of the present paper data collection methodology (Sect. 3.1). Two different analytical methods will also be described: a spatial analysis of exposure (Sect. 3.2) and a temporal analysis of exposure using actograms (Sect. 3.3).

In both cases, the spatio-temporal window retained for the analysis included the seismic crisis period as it occurred in Lorca city centre. Our focus will be on a sample of individuals who were inside the city when the earthquake struck until the time they were evacuated outside the city. When respondents were outside the affected area (Fig. 1), they were considered to have no longer been in a seismic crisis period and no further data on them were collected. Nevertheless, as shown below, respondents were exposed more or less constantly while inside the city, which for the purposes of this study corresponded to the crisis period.

3.1 Data

Data were collected in two stages. The first one took place 4 days after the earthquake and was a field trip to prepare the interview stage. It enabled observations on participation to be made, authorities to be contacted and visual material (photographs and videos) to be produced in the immediate post-crisis period. The second stage was made 9 months after the event to carry out interviews.

We carried out 20 interviews of Lorca residents using qualitative enquiries focusing on how people had reacted during the crisis (Ruin et al., 2013). As we already pointed out, other similar works are based on the same number of individuals

(Mishima et al., 2014). In all we interviewed 8 men and 12 women aged 24 to 80, 9 of them with dependent children.

We used snowball sampling techniques while seeking the widest possible diversity of spatial situations despite the limited number of respondents. As in other studies, respondents were required to fulfil two conditions: to be residents of Lorca and to have been present in Lorca during the earthquake (Prati et al., 2012).

The interviews enabled us to describe and map all the journeys each respondent made between the first shock (11 May 2011 at 17:05 LT, local time) and the evacuation of the city. A great deal of spatial parameters can influence people's behaviour, such as place of residence, workplace and the situation when the first and second shocks occurred. Following more conventional vulnerability parameters noted in the literature, we also attempted to obtain a diversity of respondents in terms of age and gender (Cutter et al., 2000). From this sample group we collected a database of 229 activities and 115 journeys which had occurred during the seismic crisis period.

To collect data we adapted an interview grid originally developed for the analysis of mobility behaviour during flash floods (Ruin et al., 2013). The grid was based on a chronological scale on which time is split into a succession of places or positions and journeys. For each of these we asked about a number of qualitative details linked to a precise space and time for each respondent. We thus collected addresses, timetables and details of the activities undertaken and with whom. For journeys we noted the means of transport, how and why itineraries may have been modified (such as a detour to see the state of a property) and abnormal characteristics of itineraries such as traffic jams. This grid allowed us to work with precise time schedules ("I remember calling my son at 08:14") or durations by default ("I don't know what time I got there but I usually do this trip in 15 min").

While completing the grid with the respondents, we drew a map of their itineraries, the places they went to and the places where they had experienced the earthquake (Fig. 2). Using the map during the interviews allowed people to remember the details of their journey better and to specify time schedules more precisely. It also allowed them to have better recall of the way journeys were modified by the event (e.g. avoiding streets that were blocked by debris or cut off).

3.2 Spatial analysis of exposure

In this section, we present the spatial data created and compiled (Sect. 3.2.1), the method for estimating the dimensions of exposure areas (Sect. 3.2.2) and finally the creation of the spatial database (Sect. 3.2.3).

3.2.1 GIS data (journeys and damaged buildings)

Based on the 20 individual interviews, journeys made during the time window were digitalised. With the aim of identifying

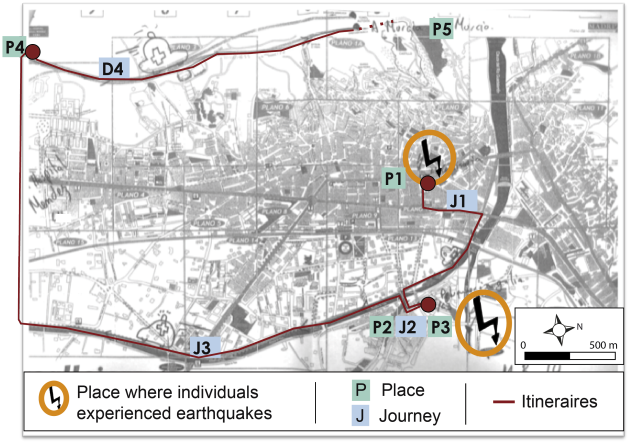

Figure 2. Example of the itinerary map drawn during one of the interviews. Base map: Lorca shopkeeper directory.

spatial consistency between individuals and hazards – and thus exposure – we merged two layers of information using GIS software. We provide details here of the two layers and the related information.

a. Individual journeys

This layer contains all the journeys performed by the 20 respondents. The digitalisation protocol described here was defined to standardise the layer.

All individuals walk in the same path: we supposed that individuals walking on the same road, in the same square or in the same open space were taking exactly the same path. This simplification offers greater data homogeneity from a spatial point of view.

Regarding entering or leaving a building, the minimum egress time from a building (initial position of evacuees) is considered 60 s. This was done so as not to exclude any inside-to-outside journeys.

b. Characterising damaged buildings

The second layer consists of the altered environment characterising the dangers due to buildings weakened by the earthquake and liable to collapse partially or totally during an aftershock.

Following the second earthquake, several teams of architects, engineers and volunteers undertook an emergency evaluation of the state of the buildings in Lorca and the surrounding area. The objective of this preliminary evaluation was to estimate buildings' safety and habitability and to detect any extremely dangerous buildings (González López, 2012).

Following each evaluation, a coloured mark was made at the entrance of buildings to indicate the degree of danger. This information was extremely valuable as it detailed the state of buildings immediately after the earthquake. Data were provided by the Servicio de Urbanismo de

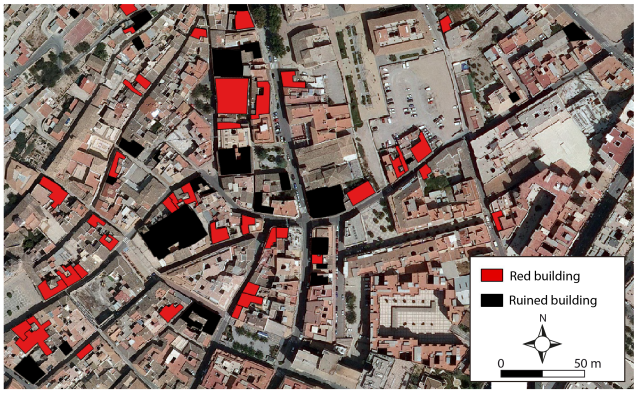

Figure 3. Sample of the selection from the maps of buildings classified red or black (ruined). Map base: PNOA images from the Instituto Geográfico Nacional. Evaluation of buildings: Servicio de Urbanismo de Planeamiento y Gestion. Production: Marc Bertran Rojo, 2014.

Planeamiento y Gestion de Lorca (SUP)[1]. A green colour indicated that residents could re-enter the building because it had not suffered significant structural damage. A yellow mark was used for buildings requiring repairs but which could possibly be occupied, the building structure showing no danger. Buildings in red were those with severe structural and non-structural problems and could not be occupied. Finally, buildings in black – also called ruined buildings – were considered beyond repair and were the first to be demolished (González López, 2012). Public access to them was therefore totally forbidden. In our analysis of individual exposure we retained buildings classified red or ruined, defined as "fragile" by the preliminary evaluation (Fig. 3). They were the ones that constituted a serious danger for people approaching them.

3.2.2 Analysis of exposure areas

Here we consider how individual exposure can be increased or decreased by people's movements near weakened buildings during the evacuation phase.

Human exposure is considered to be the spatial and temporal co-incidence between an individual and a possible hazard; we observed here how this spatio-temporal co-incidence occurred for the Lorca respondents.

An exposure situation supposes that the individuals concerned are in the vicinity of buildings that have become hazardous following the earthquake. This requires defining more precisely the distance at which people can be considered as exposed to the fall of façade elements into the street (actual contact with the façade or when they are located one to 10 m away).

[1]Servicio de Urbanismo de Planeamiento y Gestion de Lorca: the agency in charge of developing and implementing urban planning tools.

To do so, we studied the distances reached by the debris of items having fallen from a building or resulting from a complete building collapse after the earthquake.

We also studied images posted on the Internet in the days following the earthquake in order to calculate the debris area for each building classified as fragile. The images used included both photographs (35 pictures) and videos (from TV news and private sources).

The idea was to use the pictures to estimate the maximum distance reached by debris falling from buildings. The distance was defined as the furthest point from the façade where debris approximately the size of a brick ($110 \times 70 \times 230$ mm) could be observed. This size was used to set a limit and not include small pieces of debris possibly resulting from the fracturing of larger objects hitting the ground. The point from which distances were calculated was the façade of the building from which the debris came. Two examples of how the maximum impact distance was studied are given below.

Each had distinctive features but we endeavoured to collect as many reliable references as possible from which we could determine the approximate width of the impact. There was some uncertainty linked mainly to different photographic perspectives, as has already been described in the literature (Bernardini et al., 2016a). We preferred to underestimate impact distances rather than overestimate them to avoid exaggerating situations when interpreting results.

First example: a cornice (Fig. 4)

We had five photographs at our disposal for this case (two of them are shown here as examples). A reference point corresponding to a round, coloured restaurant sign present in both photos allowed us to compare the two pictures (cf. the yellow arrow in Fig. 4). We first identified the brand and model of the car (a Hyundai Tiburon) in the first photograph; this enabled us to determine its width (1.7 m according to the manufacturer), which was used as a benchmark. In the same picture the biggest pieces of debris can be seen spread over a distance similar to the size of the car in the roadway alongside the parked cars. The second picture shows that the width of the car was similar to that of the pavement (i.e. 1.7 m). Adding these three distances leads to the conclusion that the maximum impact distance was roughly 5 m.

Second example: collapsed building (Fig. 5)

We wanted to calculate the maximum impact distance of a single collapsed building. The impact area was spread across the whole breadth of the street. It was about 7 m wide, as the building collapsed into the display window of the shop across the street (Fig. 5). However, we preferred to round off the estimation at 7 m.

We implemented this method for nine buildings. Despite its approximate nature, it provided us with a rough estimate

Figure 4. An example of how maximum impact distance was calculated. The yellow arrow shows a common reference point for the two pictures (the round restaurant logo). Image **(a)** was taken a few hours after the earthquake. Image **(b)** was taken 4 days after the earthquake. Photographs: **(a)** Andrés Ribón and **(b)** Marc Bertran Rojo.

Figure 5. An example of how maximum impact distance was evaluated. Photographs: **(a)** Marc Bertran Rojo and **(b)** Google Street.

of the impact area for each case. Nevertheless, due to the small number of cases a statistically representative average could not be determined.

According to previous work of Rojo (2014), we wondered whether the height of a building could influence the façade elements impact area. However, in the nine cases observed no ratio between height and impact area was confirmed. For three- and four-storey buildings the most frequent value characterising the impact area was 6 m. In Lorca, 92 % of fragile buildings had fewer than four floors. It therefore seemed relevant to set a maximum impact area of 6 m for all buildings regardless of their height.

3.2.3 Exposure areas and exposure sections

Here impact areas as defined above are compared with people's journeys. With this in mind exposure areas were created using a 6 m buffer area around fragile buildings (red and ruined). The methodology described below describes the way such areas impact people's journeys and thus increase their exposure.

In order to estimate the extent to which people encountered exposure areas, we considered that all individuals would walk in the middle of the street. The primary reason for this choice is that safety instructions recommended keeping away from buildings and that the furthest point from buildings is the middle of the street. We also used videos and photographs taken by the population after the earthquake to check whether these instructions had been followed in Lorca. The majority of the pictures we were able collect on this subject (20 photos and videos) confirmed this type of behaviour, previously identified by Alexander (1990). The main explanation is that after the earthquake pavements were more or less cluttered with debris of all sizes, which naturally forced people to walk at a distance from buildings.

Based on our 20 interviews, 86 journeys were selected out of a total of 115 to analyse their exposure. Journeys made between the two shocks, i.e. just before the main shock, were not taken into account. We chose to work only with journeys made after the second, main shock because weakened buildings were listed only after this. Figure 6 shows how journeys were made across exposure areas to generate sections of exposure as analysed below. This operation was performed by the Intersect geoprocessing tool.

3.3 Temporal analysis of exposure using actograms

The temporal analysis of interviews was based on the use of actograms. These are a form of graphic representation widely used in medicine and biology (Thinus-Blanc and Lecas, 1985); they are also used to analyse people's daily activity schedules in time geography (Thévenin et al., 2007). Actograms are matrices in which each individual is represented by a line and each column symbolises a time step defined according to the subject of the study. Cells use a code and/or a colour to indicate the type of activity performed by

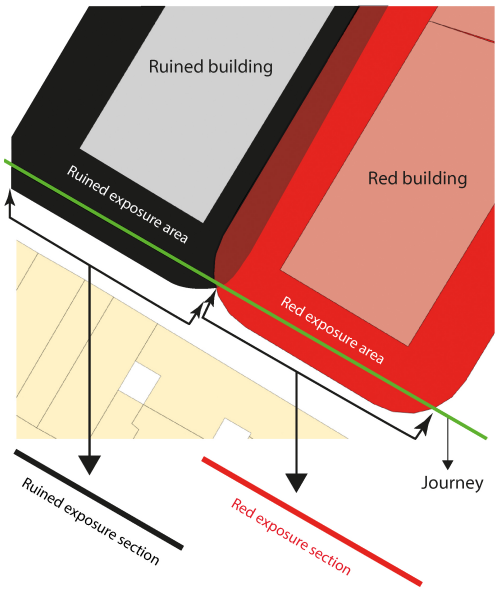

Figure 6. Exposure sections produced by the Intersect geoprocessing tool between journeys (green lines) and exposure areas around fragile buildings (ruined and red).

an individual for each time step. In the field of hazards, actograms have been used to analyse mobility during a flood crisis period (Ruin et al., 2013).

Actograms thus show a succession of activities organised from temporal information relating to a single individual. Superimposing actograms of a group of people on the same temporal scale allows columns to be read vertically and thus to see the number of individuals performing the same activity (or moving) at the same time. By adding the cells from each column the numbers of individuals moving and not moving can be obtained for each time step.

In our case, information in the actograms had a 1 min time step. We were aware that this choice could lead to bias linked to the accuracy of people's memories in a state of panic. However, given the high number of very short journeys – of around 1 min – we nevertheless opted for this very short time step.

The approach proposed here aims at defining the categories of situation that correspond to a specific exposure so as to understand better how individual exposure changes over time and space. The situational categories are not associated with precise places but rather with features of those places, especially sources of hazard. In this way we sought to model the temporal evolution of human exposure indirectly by observing people's locations in specific situations. With this aim in mind the following four situational categories were considered: inside buildings, in the street, in open spaces and outside hazardous areas (i.e. outside Lorca). These categories enabled us to determine the hazards individuals may be exposed to after an earthquake.

We depict here the four situational categories considered. The aim of this section is to provide an overview of the events' sequences through respondents' behaviour and to identify the collective reactions leading to fluctuations in human exposure.

3.3.1 Inside buildings

People are deemed to be inside buildings whatever the type (houses, blocks of flats, etc.) or associated social functions (home, workplace, at friends', etc.). When an individual comes within the "inside" category, an aftershock can generate a partial or total building collapse and directly affect the individual. As already stated, only one building collapsed during the Lorca earthquake, and there were no casualties inside.

3.3.2 In the street

Streets are outside buildings. They are almost exclusively used to travel along, but they can also be places where people meet and gather.

As most of the people injured, and all of those killed, were located on the street, the latter were clearly spaces associated with the highest exposure levels in Lorca.

3.3.3 Open spaces

Open spaces are located inside the city but, unlike the previous two, it is very difficult or even impossible for people gathering there to be at risk from a building or debris. The nature of such places varies considerably: squares, gardens and wasteland are examples. Exposure can be considered as almost nil. Sometimes, however, in order to reach or leave open spaces people need to travel across hazardous areas (streets) and walk past fragile buildings likely to become a threat in the case of an aftershock. In addition, open spaces have a limited capacity: the greater the number of people, the less safe they are. People standing on the edges of open spaces will be more exposed, as they are nearer the surrounding buildings. Finally, in some cases (for example the forecourt on Plaza de España in Lorca), a square's sides may be bordered by very high, fragile religious buildings (Martínez, 2012). Exposure there is thus greater than nil.

3.3.4 Outside hazardous areas

With the help of PNOA's aerial orthoimages and the land register, a polygon was drawn around the city. Anybody located beyond this limit was outside Lorca and out of danger wherever they were: inside a house, in the street or in an open space. This category was characterized by a complete decrease in human exposure because of the earthquake's very limited spatial impact. The limits of this area are shown in Fig. 1.

4 Results

Results are presented in two parts: the first deals with the exposure areas to consider for the evacuation phase in a post-earthquake altered environment (Sect. 4.1); the second focuses on the classification of exposure situations to see how the latter are distributed over time (Sect. 4.2).

4.1 Exposure in an urban environment after an earthquake

Our analysis of the spatial co-incidences of individual journeys and exposure areas (Sect. 3.2) gave the following results: out of 86 journeys, 32 were made through "ruined" areas and 39 through red-building-related areas at least once (any single journey is likely to have been made through several exposure areas).

Only three of the 20 respondents never travelled through any exposure areas (in italic, Table 1). In most cases journeys were made through several such areas. Regardless of the number of journeys, it was the number of times individuals were exposed that was counted, as one individual can become exposed several times during a single journey. Overall, 151 exposure sections were obtained, 49 of them ruined (black) exposure sections and 102 red exposure sections.

It was noticed that five people totalled almost 100 exposure sections between them and that one of them totalled 29. The dimensions of exposure sections varied according to façade length. Out of a total of almost 100 km of journeys in the city after the earthquake, journeys inside exposure areas covered 3.6 km (1.1 km in ruined-building exposure areas and 2.5 km in red exposure areas).

We wanted to examine whether there was a correlation between the number of added exposure sections for each individual (column 3) and the total distance walked or the number of journeys (columns 4 and 5). The aim was to define the best exposure indicator. This is shown in Table 1.

The table is in descending order according to the number of times people were exposed to fragile buildings (in this case red and ruined are not differentiated), so as to highlight the most critical situations. It shows the sections of exposure to buildings classified red, ruined and the addition of both red and ruined (columns 2, 3 and 4). It also gives the total distances for all journeys, the total number of journeys made by each individual and the distance per journey (columns 5, 6 and 7). The boldface indicates the five highest values in each column.

It can be seen that while individuals moving only a little do not usually travel through exposure areas, it is less clear that those who move the most are the most exposed. The number of journeys made does not seem to determine exposure after an earthquake. Individual (ID) 2 made only four journeys, for example, but had the second highest exposure, while ID 13 made twice as many journeys for a much lower total exposure. Distance also does not seem to be an explanatory variable of exposure. For example, the individual who travelled the furthest (ID 3) was 10 times less exposed than one who travelled less than a third as far (ID 1). When exposure after an earthquake is considered, it is also necessary to examine other factors. Due to our small sample, we did not extend our analysis to the influence of the location of buildings generating the greatest exposure.

These results require validation with a bigger sample. An in-depth analysis of activities and the reasons for journeys in a seismic crisis period also needs to be carried out in order to understand the complexity of the factors contributing to human exposure.

4.2 Fluctuations of exposure over time

Using the methodology described above (Sect. 3.3), the graph in Fig. 7 shows the location of the 20 respondents according to their exposure status as the crisis developed. Each of the graph's lines corresponds to the number of individuals present in each spatial category counted by using the actograms. The sum of the individuals present during each time period always equals 20. The red arrows indicate the time of the first and second earthquakes. The "low" line (in yellow) shows a high number of short journeys largely corresponding to those made immediately after the earthquake. They were made to enable people to leave buildings after the shock. On the same line there are several of the situations reported in the interviews. A few minutes after the foreshock some individuals went back into their homes because they thought they were out of danger. This stage is well known to psychologists and has been identified as a denial phase, in some cases affecting the perception of external reality. Such unconscious mechanisms help some people put a relatively disturbing situation into perspective and enable them to control their fears or anxieties more effectively (Páez et al., 1995; Bernardini et al., 2016a). Other individuals left buildings because of rumours of an aftershock or to see the damage done by the foreshock and even to discuss the event with people on the street.

In the second, main shock, the injuries and deaths happened when people were leaving the buildings. It also made people who had remained inside buildings leave immediately whenever possible, or several minutes later if they had others to look after (especially elderly people) or if they were panic-stricken. This phenomenon is clearly visible on the graph with a substantial decrease in the number of people inside buildings.

There is then the activity of assembling family members to plan for evacuation. Sometimes this can increase exposure for one or several family members. The assembly phenomenon can be observed with the line corresponding to the "inside" situation after the main earthquake. The people who went back into buildings after the earthquakes did so to help their close family and friends evacuate. Within a minute of the main shock a majority of people were in the streets

Table 1. This table summarises the spatial convergence between people's mobility after the second, main shock and the weakened buildings following this shock. Italic rows correspond to individuals who never travelled through an impact area. The boldface indicates the five highest values in each column.

Individual (ID)	Exposure sections: red	ruined	red and ruined	Total distance for each individual (in metres)	Number of journeys for each individual	Distance per journey (in metres)
1	17	12	**29**	4784	**8**	598
2	17	5	**22**	**5388**	4	**1347**
3	18	1	**19**	**18 292**	**7**	**2613**
4	13	1	**14**	**10 808**	**7**	**1544**
5	6	4	**10**	2457	**8**	307
6	2	7	9	**9043**	**9**	1005
7	5	3	8	**6917**	5	**1383**
8	5	3	8	813	3	271
9	6	1	7	1804	5	361
10	3	3	6	3088	4	772
11	3	3	6	4938	4	1235
12	2	2	4	3019	1	**3019**
13	2	1	3	3128	**8**	391
14	0	3	3	149	3	50
15	1	0	1	1031	2	516
16	1	0	1	2087	2	1044
17	1	0	1	405	1	405
18	*0*	*0*	*0*	*78*	*2*	*39*
19	*0*	*0*	*0*	*397*	*2*	*199*
20	*0*	*0*	*0*	*4*	*1*	*4*
TOTAL	**102**	**49**	**151**	**78 630.0**	**86**	

where fatal incidents and serious injuries occurred to 13 out of 20 people. Very rapidly (a few minutes on average) it can be seen that the number of people in open spaces increased who were a priori thus protected from potential falling objects from buildings.

Before the city was completely evacuated some individuals re-entered buildings after the second shock. However, this was immediately followed by the complete evacuation of the city. Such people had not been trying to protect family and friends but were making a last effort to organize themselves before evacuation, for example by looking for car keys or the keys to a holiday home (Prati et al., 2012; Bernardini et al., 2016a).

Movement mainly started almost 2 h after the main shock; after that the number of individuals evacuated rose regularly until 7 h after the earthquake.

Figure 7 suggests that people did not feel the need to go to open spaces after the first earthquake and preferred to stay in the street. Following the second shock, however, most of the respondents decided to get to open spaces as quickly as possible rather than stay in the street. This difference in behaviour seems to be directly linked to strength of the earthquakes.

Based on our analysis of the interviews, Fig. 8 proposes a model of mobility during a seismic crisis. The model helps show that the evacuation of the city was the outcome of a complex series of journeys with greater or lesser degrees of exposure and is a qualitative description of evacuation and mobility timing. Exposure was evaluated based on events in Lorca. Time on the y axis is specific to each individual, which means that the time it took to travel from inside to outside the city varied according to individual constraints. The model also shows two types of journey according to individual objectives: those corresponding to protection (black arrows) and those relating to evacuation (blue arrows). Protection journeys are defined as the set of movements preceding evacuation. They may consist in seeking personal protection or in seeking to protect another person or property (Creutin et al., 2009; Bernardini et al., 2016a). In Lorca this type of journey did not involve any lessening of exposure, because the people were still exposed to weakened buildings. Evacuation itself concerned journeys to get outside the impact zone (in this case the city), which had the effect of reducing exposure by increasing the distance from weakened buildings. Nevertheless, it was sometimes necessary for people to pass near weakened buildings in order to leave the city. As long as individuals stayed inside buildings, in the street or even in open spaces they may in some cases have remained exposed. According to the definition of the term we are using, exposure decreased only when people reached the exterior of the affected area. In Lorca, the street was more exposed

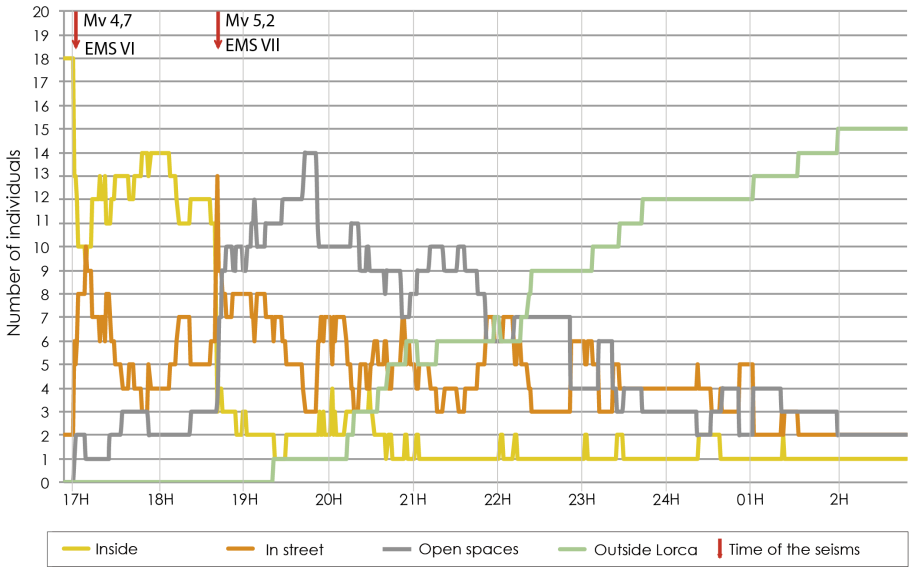

Figure 7. Evolution of the location of individuals in various categories of space during the seismic crisis (inside, in street, open spaces and outside Lorca).

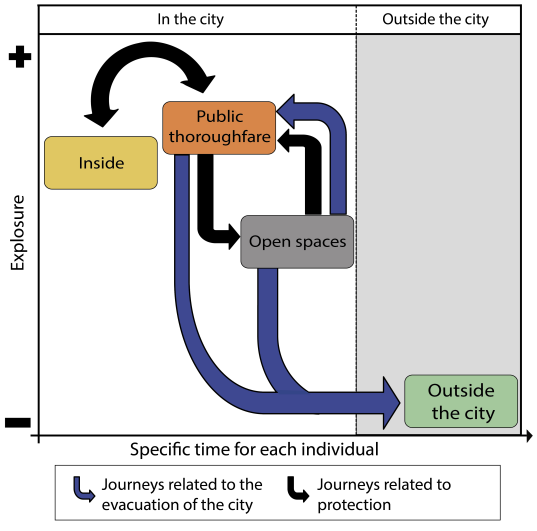

Figure 8. Conceptual model of mobility and exposure in a seismic crisis modify from (Rojo et al., 2013). A model developed from the analysis of the earthquake of 11 May 2011 in Lorca, Spain.

than the interior of buildings. Indeed, only one building collapsed during the Lorca earthquake, and there were no casualties inside. Moreover, as previously mentioned, the casualties were caused by the non-structural elements of buildings falling into the streets (Martínez Moreno et al., 2012).

5 Discussion

Initially adapted from a methodology developed for another hazard (flash floods), our approach to earthquakes shows that methodologies can be transferred from one hazard to another. The potential for doing this may be helpful in studies of earthquakes, which are less frequent in Europe than floods. Adapting methods from flash flood to earthquake studies is likely to be continued with other seismic events. The results should be comparable with those presented here for the Lorca case.

Concerning the survey, it is difficult to collect significant samples of the type of subjects that we sought to study here with a sufficient level of detail to address our initial questions because many of Lorca's inhabitants were then still living outside the city, since the city was not reconstructed. In addition, although the emotional impact had lessened over time it was still present and sometimes interfered with interviews.

Nevertheless, analysis of the 20 interviews was able to provide substantial information on journeys and their time schedules and create the opportunity to go beyond the mere analysis of interviews. Our method also enabled all the respondents' accounts to be assigned the same spatial and temporal scale and thus compared. Although the first earthquake could have played the role of warning, the behaviours observed in Lorca are comparable to other studies (Prati et al., 2012; Yang et al., 2011). In fact, similar behaviour patterns were observed either during the earthquake (e.g. flight, freezing, seeking shelter) or in the aftermath (such as returning to houses and gathering in groups). However, our small sample size makes it impossible for the proportion of each type of behaviour to be calculated in the case described here.

The Lorca earthquake highlights the fact that the exteriors of buildings are also high-exposure places and that façade elements can be serious hazards. In terms of safety, the local authorities in charge of risk management should give

appropriate recommendations, in countries of low seismicity where the risk of building collapse remains limited. For example, it could be advisable to stress suitable behaviour patterns people should adopt during and after an earthquake. Current information leaflets to improve population actions go no further than the moment a person reaches an open space. However, analysis of the Lorca event shows that people should be informed not only about what to do when an earthquake strikes but also of the best decisions to make so that the city can be evacuated while keeping potential individual exposure to a minimum. In this way, as it is already developed for other hazards like tsunamis or volcanoes eruptions, local authorities could also design preventive actions (leaflets, direction signs, evacuation routes, etc.) that would limit journeys within the city and favour wide avenues over shortcuts. Alternative actions (smartphone applications or evacuation exercises) could also be proposed so that the population would be aware before the event or informed in real time of which road is the best to evacuate safely. Like other recent studies in the same field (Bernardini et al., 2016a), Lorca shows yet again that any analysis of exposure must include the need to be able to leave urban centres safely. It is thus essential for any pertinent view of evacuation after an earthquake to take into account both individual behaviour and the status of buildings.

Earthquake-resistant building standards tend to be modified following disasters (Aribert, 2002), while seismic risk zoning maps often expand at each review (Frechet, 1978; Martin et al., 2002; SISMORESISTENTS, 2003). Ever stronger earthquakes are expected in a greater number of regions, whether in France, Italy or Spain. In the Lorca case it appears that Spanish earthquake-resistant standards had been properly implemented, since only one building collapsed. Typical Spanish building elements such as cornices, balconies and other façade elements at the top of buildings proved to be fragile and hazardous, however. Several examples of this have become topical issues for engineers and architects, while many papers have been published providing further evidence (Alfaro et al., 2011; Diez and Sanz Larrea, 2011; Martínez, 2012; Tibaduiza et al., 2012). The present study has shown that even if victims were struck at the moment the seismic shocks occurred, several factors could have converged to increase the number of casualties. Stronger aftershocks would certainly have caused a greater number of unstable façade elements to fall, with the likelihood of injuring passersby in the streets. Our considered view is that it is essential to raise the awareness of the inhabitants of areas exposed to earthquakes with regard to the hazards that threaten them during evacuation. It is also important to insure that earthquake-resistant standards of moderate seismicity countries take into account non-structural elements as they do for structural elements, as the former could kill as much as the latter. Moreover, reinforcement campaigns should be carried out to limit the potentially dangerous non-structural elements.

Data availability. Due to the confidential nature of the interviews, information about data is available upon request to the authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The authors thank the Rhône-Alpes region, research cluster no. 6, Environment (2011–2013), which funded this work. We also thank all the people we met during our field surveys and who gave their time to answer our questions. Finally many thanks to J.-L. Pinel who translated this document from French into English, and P. Fletcher who revised the modified version.

Edited by: O. Katz
Reviewed by: two anonymous referees

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