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Max Wyss

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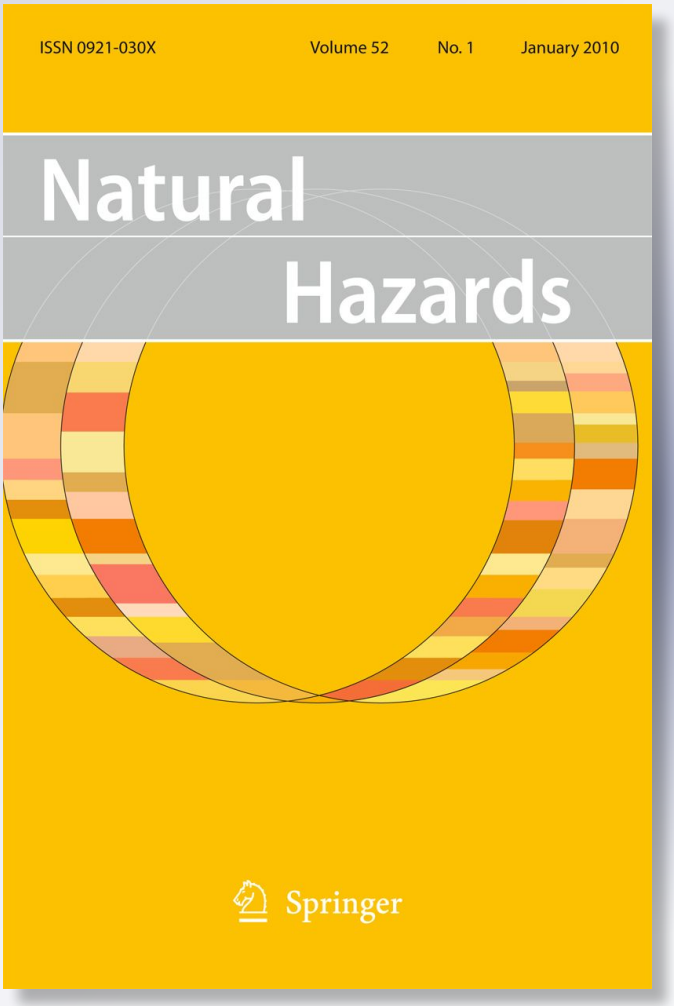

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ORIGINAL PAPER

The earthquake closet: rendering early-warning useful

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Abstract Early-warning of imminently approaching strong shaking that could have fatal consequences is a research field that has made great progress. However, its potential to save lives has a serious Achilles heel: The time for getting to safety is 5 to 10 s only, in those cities that need warnings most. Occupants of the upper floors cannot get out of their buildings and narrow streets are not a safe place in strong earthquakes. The official advice, to crawl under a table, protects from falling objects only, but not from collapsing buildings. Thus, only about 10 % of a city's population can benefit from early-warnings, unless they have access to an earthquake protection unit that is strong enough to improve their chances of survival and not being injured by factors of 1,000 to 30,000. The purpose of this paper is to generate discussion on how to use early-warning to improve the safety for occupants of buildings exposed to strong earthquake shaking.

Keywords Early warning · Earthquake safety · Earthquake risk mitigation · Reducing fatalities in earthquakes

1 Introduction

In earthquake early-warning (EEW) research, methods have been developed by which the location and ultimate size of an earthquake rupture can be estimated within seconds of its initiation and before its rupture has finished (e.g. Allen and Kanamori 2003; Festa et al. 2008; Tsuboi et al. 2002). Based on smart, self-organizing sensor networks (e.g. Fischer and Kühnlenz 2008; Heglmeier et al 2008) warnings can be transmitted at an early time to industrial users and the population of large cities near faults that are in the process of rupturing in an earthquake.

M. Wyss (✉)
World Agency for Planetary Monitoring and Earthquake Risk Reduction, 2 rue de Jargonnant, 1207 Geneva, Switzerland
e-mail: wapmerr@maxwyss.com

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The only large city for which early-warnings for residents can be useful is Mexico City. It is built on lake-fill where amplitudes of seismic waves are amplified, thus distant earthquakes affect it much stronger than normal. Although it is located more than 300 km from the source of great earthquakes along the Pacific cost, buildings collapse due to strong shaking because of poor the soil conditions. In this case, the large amplitude waves take about 1 min to arrive in the city. Sensors placed along the cost will have recorded the event shortly after its beginning, the population can be warned of the approaching strong shaking, and people can save themselves by escaping to open spaces such as parks. In cities built on rock and consolidated sediments there is no need for early warning, in case of earthquakes at distances of more than about 50 km because most buildings do not collapse.

The cities in which residents need early warning are those located closer than 50 km from a fault that is capable of generating major or large earthquakes. Istanbul (13 million inhabitants) is located at a distance of about 40 km from a segment of the North Anatolian fault that is capable of a magnitude 7.5 earthquake (e.g. Kuvvet et al. 2002), and San Francisco (1 million inhabitants) is separated only by its Bay from the Hayward fault, capable of magnitude 6.5 earthquakes (Working Group 2003). These two faults are ranked among the most probable locations for earthquakes near major population centers during the next decades. When these faults will rupture, the warning times will be not more than 10 and 5 s, respectively.

Who are the users of EEW systems? Firstly operators of industrial facilities may be able to shut down critical and dangerous processes in seconds and rapid transportation system that may be able to stop trains. The problems they face in successfully using a warning with short lead-time have been summarized by Nishenko et al. (2009).

The importance of making EEW useful for residents of large cities has been emphasized by many authors, including in an official policy statement by the United Nations (http://www.unisdr.org/preventionweb/files/3612_GlobalSurveyofEarlyWarningSystems.pdf). The reason for hoping the EEW will become useful for individuals is that urban growth has led to the recognition of the importance of early warning systems as one means of mitigating the potential human and economic losses resulting from natural disasters (Fleming et al. 2009). The need to focus on urban residents has been expressed as follows: "A new generation of early warning systems being decentralized and people-centered [is being developed]" (Zschau and Gasparini 2009). Shimoyama et al. (2009) describe the Japanese effort to supply citizens with EEW in detail. This effort to serve the public has been recognized internationally (e.g.Allen 2009; Cua 2008). In Istanbul low cost sensors of the SOSEWIN-prototype have been installed in the Ataköy district in apartment buildings with the intention to supply residents with devises that sound an alarm when strong shaking is registered (Kühnlenz et al. 2009; Vinci et al. 2009; Köhler et al. 2009).

The foregoing examples show that urban residents are targeted as users with the aim to save their lives. The widely distributed recommendation of a drop-cover-hold protection method (Fig. 1, right) may be effective against falling furniture. However, for the very serious damage addressed in this article (Fig. 1, left) it has no chance whatsoever to save life or protect from injury.

In this article, we examine the extent to which a resident user is able to benefit from EEW. We estimate that only about 10 % of the population could benefit from an early-warning with the typical short lead time available. Assuming the number of floors in large cities in earthquake-prone regions is on average five, only 20 % of the population resides on the ground floor from where they could exit within 10 s. Although running outside is generally not recommended, it is discussed here as an alternative because it can save lives in some cases. For example in Chile (M8.8, February 2010, Spence and So (2011)), in the

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Fig. 1 Drop, cover, and hold (*above*) may protect against falling furniture and fixtures. To suggest it would have helped in the El Asnam, Morocco, school (*left above*), or in Bam, Iran (*left below*), would be cynical

case of single and two story buildings that collapse completely, as in Bam, Iran (M6.6, December 2003), and in the case of Mexico City where early warning affords enough time. Assuming that approximately half the streets are too narrow for safety in an earthquake, only 10 % of the population could get to safety in large cities, after they have received an early-warning by smart expert systems.

The chance to survive an earthquake depends upon the building's ability to withstand strong shaking, the position of the occupants in the building, and their familiarity with measures to protect themselves. To decrease the casualty rates in upper floors of residential buildings, we propose installations of earthquake protection units (EPU) that can be reached in a few seconds on each floor. One could call this the professional version of the amateur approach of drop-cover-and-hold.

2 Time available for warning

The distances of well known faults capable of large earthquakes are listed for ten major cities in Table 1. The magnitudes listed (*M*) are those that the respective nearby faults are estimated to be capable of. In those cases where a historical earthquake is known to have happened on the fault in question, the year of occurrence is given in parentheses. The travel times of the S-waves (Table 1) are shorter than the time it takes to issue an early warning (estimated at about 15 s). Therefore, the P-wave itself has to be used as the early warning and residents have hardly enough time to reach the safety of their earthquake closet before the strongest shaking arrives.

The minimum population of the cities listed is also given in Table 1, along with the estimated resulting casualties (fatalities plus injured) in case of the earthquake hypothesized in this table. These values are approximate and should be taken only as order of magnitude estimates. The installation of earthquake closets could reduce these casualty numbers substantially.

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Table 1 Expected travel times for the destructive S-waves from faults capable of large earthquakes to major cities nearby

City	*M*	Distance (km)	S travel time (s)	Population (millions)	Casualties Fat + Inj
Odawara + Hadano	(1923) 7.9	10	3	0.4	2,000
Tehran	7	25	7	11	190,000
Istanbul	7.5	40	11	12	216,000
Manila	7.5	28	8	11	273,000
Lima	8.5	20	6	8.2	168,000
Caracas	7.5	25	7	2	33,000
Messina	(1908) 7.2	10	3	0.2	18,000
Algers	(1716) 7.0	15	9	2.2	65,000
Wellington	7.5	20	6	0.2	2,000
San Francisco	6.5	20	6	0.8	500

An approximate estimate of the number of casualties to be expected, based in the listed population and the building stock as currently contained in the data base of QLARM (Trendafiloski et al. 2011), is given in the last column

3 Earthquake protection unit

3.1 Concept and quantitative estimate of benefit

We define an EPU as a part of the building with greater resistance to strong shaking than the rest. The EPU might be a separate room or part of an existing room. One can envisage a range of structural strengths and costs, resulting in a range of improved chances of surviving in a damaged or collapsing building. If the EPU resistance is much higher than the resistance of the building's principal load bearing system, then the benefit is significant. To assess approximately the possible benefit, we considered:

- EPU in: (1) modern reinforced concrete high-rise residential buildings, and (2) traditional residential masonry buildings.
- Casualties pertinent to structural damage only.

In the first case, we assumed that an EPU of a resistance corresponding to vulnerability class F of the European Macroseismic Scale (Grünthal 1998) is placed in a building that belongs to vulnerability class D. Using the casualty matrices applicable to buildings of the appropriate vulnerability class, we estimate the increase in the probability of a person inside the EPU to survive, or escape injuries, from the ratio of the respective fatality and patient rates. With these assumptions, the EPU is most effective to prevent fatalities at intensity IX, where the chance to survive is more than 5,000 times better inside the unit. The probability of ending up as a patient inside the unit is about 100 times less than outside, in the range of intensity IX to X.

The benefit is higher when the principal load bearing system is of vulnerability class B and the EPU of class E (case 2). Thus, the chances of survival, or being not injured, are 30,000 and 150 times better, respectively, for intensity VIII. At intensity IX and X, the probability to survive inside the EPU is about 3,000 better than outside.

We calculated the casualty rates using the loss estimation module (Trendafiloski et al. 2009) in the computer tool QLARM (http://qlarm.ethz.ch). The contribution of the

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nonstructural damage (damage to partition walls, glass, overturning of furniture) to the casualty potential is not considered in the above calculation. In the 2003 M6.3 Northern Miyagi earthquake in Japan, 51 % of the injuries were attributed to objects falling and furniture overturning (Sato et al. 2006). The EPUs we propose prevent all injuries of this type. Thus, we estimate that the total chance of escaping injuries is about a factor of two larger than calculated in the previous section.

3.2 Types of EPUs

In general, the type of EPU may vary greatly from case to case, however one can group them considering the following:

- Material of construction: reinforced concrete, steel, plastic, or wood.
- Occupancy characteristics: individual or collective protection.
- Implementation: in existing or newly constructed buildings.

Two EPU examples are discussed bellow.

The earthquake closet belongs to the EPU group for individual (single family) protection. Few prototypes are already registered in US and Japan, such as the one with patent number US 6,349,508 B1 (2002). We envision the earthquake closet as a small strong room that will not collapse, even if the floor above it comes crashing down on it. The dimensions should be large enough to accommodate a family of four to five persons. The structure of the earthquake closet may vary from case to case and it depends on whether it is implemented in an existing or in a new building. We propose that a closet could be built in a part of the apartment, where the overall building structure offers the strongest resistance to collapse. A construction using steel might be most favorable, but strong plastic molds might be used alternatively. One side of the closet could be left open to allow fast entrance and to keep the space inside the closet available for daily use.

Tornado shelters and safe rooms are commercially available and their characteristics, as well as prices, can be found on several web sites. Although their purpose and hence construction is somewhat different from the shelter we have in mind, it is clear that the infrastructure to construct earthquake shelters exists and an affordable unit could easily be brought on the market.

Earthquake shelters in the higher floors of apartment buildings may be especially useful in highly earthquake-prone mega-cities in which the collective protection of the occupants is a top priority. This kind of protection would be achieved in new buildings by constructing a strong-tower, consisting of the elevator shaft, the staircase, plus earthquake shelters; one on every floor (Fig. 2). The earthquake shelter shaft would consist of reinforced concrete shear walls. We propose that the shelter be isolated from the main building structure. Thus, the principal load bearing system would absorb the earthquake forces and the shelter would provide an environment of increased safety. The inside walls of the shelter might be padded and several intake vents for air might be placed strategically. If there is a door, it should be constructed in such a way that it cannot jam, but can be dismounted, in case the shelter is severely deformed in the earthquake.

The survival gear stored in the shelter should include water, food, emergency crank-radio and transmitter, breathing filters to protect from inhaling dust, a first aid kit, a chemical toilet, tools, warm clothing, and a small library.

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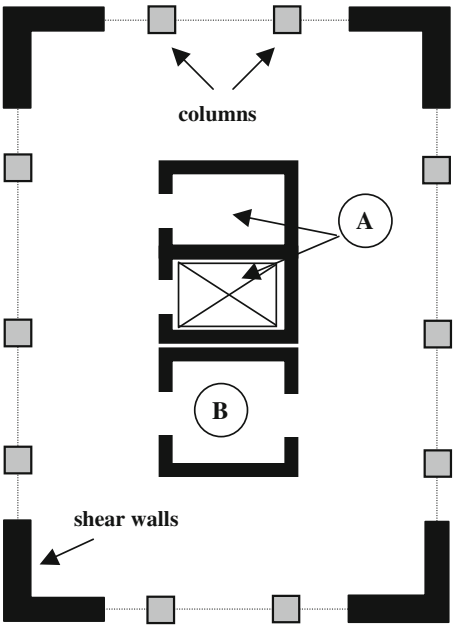

Fig. 2 Conceptual floor plan of a reinforced, concrete dual system building (frames + shear walls). *A Vertical* communication shaft consisting of an elevator (marked with *crossed rectangle*) and stairs. *B* Shelter shaft

3.3 Implementation

A few decades ago, nobody wore seatbelts in cars, now it is the law to wear them and lives are saved. It may be the same with earthquake shelters in cities near major faults. At first, the idea is bound to meet with resistance from some interest groups. The most ready acceptance may come from homeowners who value their lives and may build a simple structure in an existing bathroom or in the corner of a larger room. An awareness campaign, followed by access to workshops and training programs, where the techniques of building a small closet in a single or double residence will be taught, may serve the needs of self-reliant homeowners. The raising of awareness and the training of how to behave in an earthquake that goes along with the proposed protection unit is in itself an important element in reducing casualties. However, to lead people to believe that the amateurish drop-cover-and-hold approach would save their lives in a very strong earthquake is not a good idea. People's chances to survive a disastrous earthquake could be improved by convincing them that they need the professional approach of a strong closet into which they can rush for cover.

The owners of office buildings may find that it will be more cost-effective to install earthquake closets on each floor, rather than risk litigation by the families of employees that may be killed in an earthquake at the workplace, once earthquake closets become accepted as a means of protecting the population from the consequences of earthquakes.

Developing a most resistant design and choosing the best suited materials will require some discussion among engineers. The cost-benefit ratio is an aspect that will have to be investigated in detail. Ready-made earthquake closets should be developed that can be installed in an apartment.

The question of what weight lies above a planned closet and what support the closet has from below will have to be investigated in multi-floor buildings. Construction companies

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and consultants may specialize in this skill, so the cost of such an analysis may not be overwhelming.

The cost of an earthquake closet may vary from country to country and depend on the type of material. For developing countries, the cost may range from 1,000 to 4,000 €, if the closet is added to an existing building. The EUROCODE8 (2004) design of the proposed earthquake shaft shelter would apply an elastic spectrum at least 50 % higher than the spectrum for the design of the rest of the structure. Thus, our approximate estimation is that such structures may increase the cost of a new apartment building in South-Eastern Europe by 10–15 %.

The usefulness of installing earthquake shelters and the type of construction will vary as a function of the development of a country. In highly developed countries with enforced building codes, the need for earthquake-closets may be moderate, but the economic strength of owners of buildings may allow them to implement a device that will decrease the chance of becoming an earthquake casualty by factors of 1,000–30,000 without much hesitation. In countries with poor construction and no enforcement of building codes, poverty may be such that funds are not available, even for the cheapest type of closets. In emerging countries, with a mix of modern and outdated buildings, the usefulness of earthquake shelters may be highest because recent constructions are often almost as unsafe as old buildings.

In awareness campaigns, people should be taught to dash into their closets at the slightest shaking. All earthquakes emit Primary and Secondary waves. The amplitudes of the P-waves are approximately 10 times smaller than those of the later arriving S-waves. Hence the P-waves provide early warnings of several seconds. During the P-wave shaking, it is easily possible to walk to the closet from any location in an apartment because the amplitudes are not large enough to knock people off their feet. If the shaking does not come from a large earthquake there is no harm done by the short trip to the earthquake closet. The minimal effort required for this is bound to increase tolerance for false alarms. If all one has to do when feeling a P-wave, or receiving an early warning, is to cross a room or two to reach the closet, one is far more willing to accept false alarms, than if one would have to run down several flights of stairs and away from the building to reach safety.

Early-warning by experts and authorities, using smart networks of measuring devices and computers, is not useless, although it cannot save most of the population. Turning off dangerous processes in nuclear power and chemical plants, to stop sensitive equipment, and to slow fast trains all will benefit from early-warnings by professionals.

4 Conclusions

While advances in locating an earthquake rapidly, and in estimating its magnitude even before the rupture is finished, is spectacular and scientifically exciting, the proximity of capable faults to cities limits early-warning times for many cities so severely that only 10 % of the population may benefit. As a remedy, we propose that earthquake-closets should be installed on floors above the ground floor of apartments, office buildings, and residences. These constructions will take little space, about 2–10 m^2, will remain intact, even if the building containing them is heavily damaged, and increase the chances of surviving by several orders of magnitude. By teaching the owners of earthquake-closets to dash to safety in case they feel shaking due to a primary wave, they may reach safety, using Mother Nature's own early-warning signal.

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