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LOSS ESTIMATION MODULE IN THE SECOND GENERATION SOFTWARE QLARM

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ABSTRACT

Currently, we are constructing our second-generation loss estimation tool QLARM (earth**Q**uake **L**oss **A**ssessment for **R**esponse and **M**itigation) and upgrading the input database to be used in real-time and scenario mode. Our tool and database are open to all scientific users. The estimates include: (1) total number of fatalities and injured, (2) casualties by settlement, (3) percent of buildings in five damage grades, and (4) a map showing mean damage by settlement. The QLARM worldwide database of the elements-at-risk consists of city models constructed with the following parameters: (1) Soil amplification factors. (2) Distribution of building stock and population into vulnerability classes of the European Macroseismic Scale (EMS-98). We calculate damage and losses using vulnerability curves, regionally based collapse models, and casualty matrices pertinent to EMS-98 vulnerability classes as a function of the seismic intensity. We calibrate our tool for different countries and regions worldwide considering macroseismic, damage, and loss data from past events. Thus, we calculate human losses for past earthquakes correctly to within a factor of 2, on average. Recently, we used QLARM to estimate expected human losses for the metropolitan area of Lima in case of a hypothetical earthquake of magnitude 8 in the immediate vicinity offshore of Lima.

1. INTRODUCTION

We have six years of experience in distributing loss estimates by email in near-real-time for any earthquake with $M \geq 6$ worldwide. This service is free and open to anyone. Our loss estimates reach the consumers in 30 minutes (median) after the earthquake in question (Wyss and Zibzibadze, 2009). In 95% of the cases, we have been able to differentiate disastrous from inconsequential earthquakes, but we have also issued a few incorrect estimates for various reasons. Our struggle to reduce the influence of error sources will go on for years to come.

Currently, we are constructing our second-generation loss estimation tool QLARM (http://qlarm.ethz.ch) in collaboration with the Swiss Seismological Service (SED-ETH, Zurich) and we are upgrading our database of elements-at-risk to be used in real-time or scenario mode. Our steps in estimating earthquake-related human losses are the following. A) We need to know the epicenter (position) of the earthquake, its depth, and magnitude. B) From these parameters, we calculate the ground shaking for settlements in our database as a function of distance from the epicenter, using global and regional attenuation laws. C) If possible, we would like to know the soil conditions in each settlement, because some soils amplify the strong ground motion. D) To calculate what damage the ground motion causes, we need to know the distribution of buildings into classes of resistance to ground shaking. E) For estimating the effect of collapsed and damaged buildings on people, we need to know the distribution of people into the building classes and the casualty matrix. F) We also need to know the population for each settlement, in order to convert the percentages from the casualty matrix into numbers of people killed and injured in each settlement. G) Finally, it is also desirable to have accurate information about when people are in what buildings, as a function of the time of day, and as a function of the seasons. In developing countries, the focus of our efforts, it is rare that all pieces of information listed above are available and complete. Therefore, we built a strategy to construct the database and loss estimation tool based on partial information.

The results of our calculations include the following. i) The expected percentage of buildings in each of five damage states in each settlement, ii) the mean damage state in each settlement, iii) the numbers of fatalities and injured, with error estimates, in each settlement.

Recently we used QLARM to estimate human losses in Lima. Peru had enough historic earthquakes for which intensities, fatalities and injured were reported, such that we were able to calibrate our computer tool. Therefore, we feel confident that our loss estimates for future earthquakes are reasonably reliable, within the large margins of uncertainties that are associated with a scenario exercise like this.

2. QLARM DATABASE

Focusing on developing countries, we construct (Trendafiloski et al., 2009: 1) *point city models* for the cases where only summary data for the entire city are available; and, 2) *discrete city models* where data regarding city sub-divisions (districts) are available. The city models are available for all settlements (urban and rural) regardless of size. The parameters we introduce in the QLARM database are the following: 1) soil amplification factors; 2) distributions of building stock and population into vulnerability classes; and 3) the most recent population numbers by settlement or district.

We use two approaches to estimate soil amplification: (a) *local approach* based on the existing data regarding soil properties, microzonation, and geological maps to derive the amplification factor for each discrete city model; (b) *global approach* based on Vs30 values derived from topographic slopes (Allen and Wald, 2007). An average Vs30 value is then calculated from the values on the grid of data (Global Vs30 Map Server of the USGS) at a certain radius of each settlement and converted into an amplification factor. We assign the vulnerability classes to different building types considering the vulnerability table given by the European Macroseismic Scale EMS-98 (Grunthal, 1998). We construct the building and population distributions using the percentage of the number of buildings and population belonging to a particular vulnerability class 'Eqn 1'

$$\mathrm{DB}(\mathrm{VC}) = \frac{\mathrm{NB}(\in \mathrm{VC})}{\mathrm{NB}} \qquad \mathrm{DP}(\mathrm{VC}) = \frac{\mathrm{NP}(\in \mathrm{VC})}{\mathrm{NP}} \qquad (1)$$

where DB(VC) is the distribution of buildings in a particular vulnerability class (VC) [in %]; DP(VC) is the distribution of population in a particular vulnerability class [in %]; $\mathrm{NB}(\in \mathrm{VC})$ is the number of buildings belonging to particular vulnerability class; $\mathrm{NP}(\in \mathrm{VC})$ is the number of people occupying a particular vulnerability class; NB is the total number of buildings; NP is the total population.

We construct the QLARM population database using national census data and the online sources World Gazetteer and Geonames. In addition, we updated the database contained in QUAKELOSS (Shakhramanian et al., 2000, 2001) to estimated current values for small settlements. Regarding building exposure, we used various sources of information hereafter ordered by the quality of the data provided: (1) National census data. (2) Opinion of local experts. (3) World Housing Encyclopedia and PAGER database. (4) Existing QUAKELOSS database.

Once the parameters of the elements-at-risk and soil amplification are estimated, we geo-reference them to the centroid of the adopted city model (point or discrete). The distributions of buildings and population we use are different in three city size classes: 1) large cities (more then 20,000 inhabitants); 2) medium cities (2,000-20,000 inhabitants); and, 3) small (rural) settlements (less then 2,000 inhabitants). The city size classes are country or region-specific. We use the population numbers in parentheses as given by the UN Statistics Division as defaults. In addition to the spatial characteristics, the population distribution varies as a function of time. Thus, in our models we incorporate simplified daily population dynamics as suggested by Coburn and Spence (2002).

3. QLARM LOSS ESTIMATION MODULE

The characteristics of the QLARM loss estimation module are the following: (1) Calculation of the human losses due to expected damage caused by ground shaking. We do not consider other types of seismic hazard such as tsunamis, landslides or earthquake-related fires; (2) The seismic demand is expressed in terms of (a) macroseismic (seismic intensity) or (b) instrumental (PGA/PGV) parameters; (3) We adopt the damage grade scale as given by EMS-98 (D_0 – no damage; D_1 – slight damage; D_2 – moderate damage; D_3 – heavy damage; D_4 – very heavy damage; D_5 – destruction). (4) The injury severity scale is as given by HAZUS (2003) (C_1 – non-injured; C_2 – slightly injured; C_3 – moderately injured; C_4 – seriously injured; C_5 – dying or dead).

3.1. Damage estimation

The building damage in QLARM is calculated using the European Macroseismic Method (Giovinazzi, 2005). The vulnerability models are pertinent to EMS-98 vulnerability classes A to E and correlate the mean damage grade μ_D ($0 \le \mu_D \le 5$) with the seismic intensity (I) and the vulnerability index (V_I) 'Eqn 2'.

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25\,V_I - 13.1}{2.3}\right)\right] \tag{2}$$

The parameter V_I defines the membership of the particular building type in a specific vulnerability class. The membership is not deterministic and defines the most probable class and its plausible and ultimate bounds. The probabilities of occurrence of damage grade D_i for seismic intensity I_J (percentage of buildings of damage grade D_i) are then beta-distributed (Giovinazzi, 2005) considering the ranges of the mean damage grade. Thus, we create a damage probability matrix for a particular vulnerability class.

The values of the vulnerability indices for the EMS-98 vulnerability classes (Giovinazzi, 2005) are defined in the following ranges (Table 1): (1) $\mathbf{V_o}$ is the most probable value of the vulnerability index V_I for a specific building type (considered as a centroid of the membership function). (2) [$\mathbf{V}^-$; $\mathbf{V}^+$] are the bounds of the plausible range of the vulnerability index V_I for a specific building type (obtained as the 0.5-cut of the membership function). (3) [$\mathbf{V}_{min}$; $\mathbf{V}_{max}$] are the upper and lower bounds of the possible values of the vulnerability index V_I for a specific building type.

Table 1 Values of the vulnerability indices for EMS-98 vulnerability classes

Vuln. class	$\mathbf{V_{min}}$	$\mathbf{V^-}$	$\mathbf{V_o}$	$\mathbf{V^+}$	$\mathbf{V_{max}}$
A	0.78	0.86	0.9	0.94	1.02
B	0.62	0.7	0.74	0.78	0.86
C	0.46	0.54	0.58	0.62	0.7
D	0.3	0.38	0.42	0.46	0.54
E	0.14	0.22	0.26	0.3	0.38

3.2. Estimation of human losses

We estimate the human losses using the casualty event-tree model proposed by Stojanovski and Dong (1994). The probability of occurrence of casualty state C_k (k=1,5) for seismic load I_J is therefore calculated as a product of the damage probabilities for seismic load I_J and the casualty probabilities for damage grade D_i 'Eqn 3'

$$P(C_1 I_J) = \sum_{i=1}^{3} P(D_i I_J)\,P(D_i C_1) + P(D_{NC} I_J)P(D_{NC} C_1) + P(D_C I_J)P(D_C C_1)\,|_{J=1,n}$$

$$
\begin{aligned}
P(C_2 I_J) &= \sum_{i=1}^{3} P(D_i I_J)\,P(D_i C_2) + P(D_{NC} I_J)P(D_{NC} C_2) + P(D_C I_J)P(D_C C_2)\,|_{J=1,n} \\
P(C_3 I_J) &= \sum_{i=1}^{3} P(D_i I_J)\,P(D_i C_3) + P(D_{NC} I_J)P(D_{NC} C_3) + P(D_C I_J)P(D_C C_3)\,|_{J=1,n} \qquad (3) \\
P(C_4 I_J) &= \sum_{i=1}^{3} P(D_i I_J)\,P(D_i C_4) + P(D_{NC} I_J)P(D_{NC} C_4) + P(D_C I_J)P(D_C C_4)\,|_{J=1,n} \\
P(C_5 I_J) &= \sum_{i=1}^{3} P(D_i I_J)\,P(D_i C_5) + P(D_{NC} I_J)P(D_{NC} C_5) + P(D_C I_J)P(D_C C_5)\,|_{J=1,n}
\end{aligned}
$$

$$
P(D_C I_J) = k_C(I_J)\left[P(D_4 I_J) + P(D_5 I_J)\right] \qquad P(D_{NC} I_J) = \left(1 - k_C(I_J)\right)\left[P(D_4 I_J) + P(D_5 I_J)\right]
$$

where $P(D_i I_J)$ is the probability of occurrence of damage grades i = 1 to 3 for seismic intensity I_J; $P(D_{NC} I_J)$ is the probability of having no collapse among the buildings with damage grades 4 and 5; $P(D_C I_J)$ is the probability of having collapse among the buildings with damage grades 4 and 5; $k_C(I_J)$ is the collapse model; $P(D_i C_k)$ is the probability of having casualty state C_k due to damage grade D_i.

The collapse model $k_C(I_J)$ determines the percent of collapsed buildings as a function of seismic intensity I_J out of the ones with damage grades 4 and 5. As a first approximation, we define discrete collapse models for vulnerability classes A to E for nine regions worldwide 'Fig. 1' using the collapse rates for 26 countries worldwide, provided by the World Housing Encyclopedia (www.world-housing.net). The casualty probabilities compose the casualty matrices pertinent to vulnerability classes A to E. As default values we use the HAZUS 2002 indoor casualty rates for building types corresponding to EMS-98 vulnerability classes (Table 2), which we are modifying based on observed fatality and injured rates (Wyss and Trendafiloski, 2009).

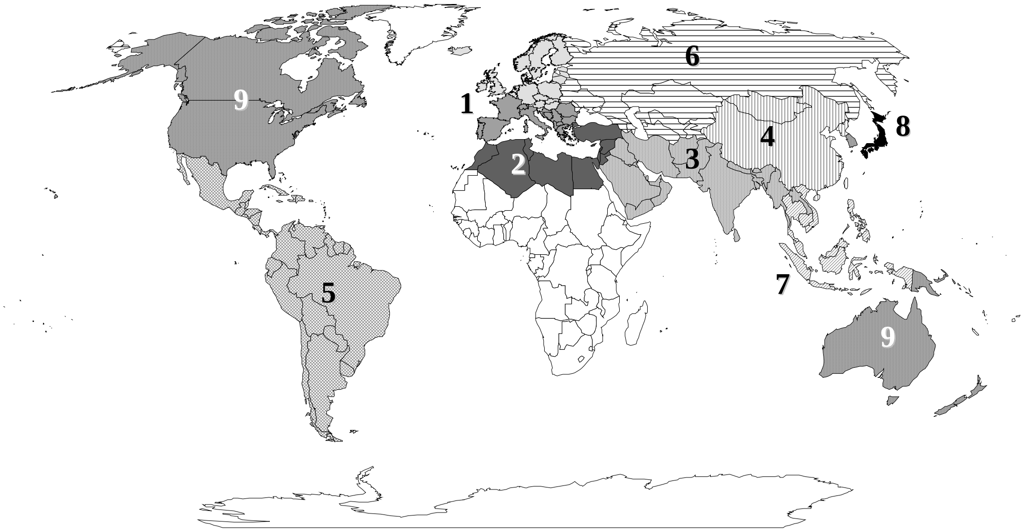

Figure 1 Worldwide regions with different collapse models
1 – Europe (1a Northern and Central Europe; 1b Southern Europe); 2 – South-Eastern Mediterranean and Northern Africa; 3 – Middle-East, Southern and South-Eastern Asia; 4 – China region; 5 - Central and Southern America; 6 - Russia and Former Soviet Countries in Central Asia; 7 – South-Eastern Asia; 8 – Japan; 9 - Northern America, Australia, New Zealand.

Table 2 Casualty matrix pertinent to vulnerability classes A and B based on HAZUS casualty rates for unreinforced masonry building type

Casualty state	Damage grade					
	D_0	D_1	D_2	D_3	$D_4 + D_5$ (no collapse)	$D_4 + D_5$ (collapse)
C_1	1	0.9995	0.99248	0.97796	0.8796	0.25
C_2	0	0.0005	0.0035	0.02	0.1	0.4
C_3	0	0	0.004	0.002	0.02	0.2
C_4	0	0	0.00001	0.00002	0.0002	0.05
C_5	0	0	0.00001	0.00002	0.0002	0.1

4. CALIBRATION AND VALIDATION OF THE LOSS ESTIMATING TOOL

We calibrate the loss estimation model in four steps. (1) *Calibration of the attenuation law.* Calculation of the ground motion is the first step. So far, we have incorporated in QLARM the following relationships: (A) Intensity prediction - Shebalin (1968), Ambraseys (1985) and Fäh (2003). (B) Ground motion prediction (PGA/PGV) - Huo and Hu (1992), Ambraseys et al. (1996), Boore, Joyner and Fumal (1997), Youngs et al. (1997). The results of the calibration are parameters of the attenuation law that give the best fit to the macroseismic observations from past events. (2) *Calibration of the city models.* In this step we use the technique of redistribution of buildings and population into vulnerability classes (Trendafiloski et al., 2009). We reassign the vulnerability classes to particular building types considering: the damage data from past events, vulnerability modifiers (Giovinazzi, 2005) in case of data with higher resolution including structural details and expert judgment. (3) *Calibration of the collapse models.* We use observed collapse rates from past earthquakes to adjust the global collapse models for particular countries and to account for local building properties. (4) *Calibration of the casualty matrices.* The ratio (R) fatalities / injured depends on the resistance of the built environment and on the intensity of shaking. In the industrialized world, the median R for earthquakes since 1970 is 50. In the developing world, the median R is 2.5 (Wyss and Trendafiloski, 2009). Thus we propose to use this ratio to adjust the casualty matrices pertinent to developing countries in Southern Asia where very low values of the ratio R are observed (R < 1) for seismic intensities larger then 9.

We perform the calibration step by step in the order given above. After every step, we validate the estimates against the observed human losses. Considering the uncertainty of the input parameters in the domain of our interest, developing countries, we calibrate our tool to calculate human losses for past earthquakes correctly to within a factor of 2, approximately, unless the number of fatalities are small, in which case our estimates usually come to within 100 of the reported number. For example, we verified our tool for India before estimating possible future losses in the Himalayas, using 16 earthquakes (Wyss, 2005). The prediction of losses in a possible earthquake in Kashmir, published before the October 2005 Kashmir event, was correct to within a factor of 2.4 (Wyss, 2006). Examples of loss estimates better than a factor of 2 in real-time include the M8 Wenchuan, 2008 (Wyss et al., 2009), and the M6.3 L'Aquila, 2009 earthquakes (both published in real-time at www.wapmerr.org). For several countries we have calibrated QLARM, using Utsu's (2002) catalog, completed for recent years from the list of significant earthquakes posted by the US Geological Survey on http://neic.usgs.gov/neis/epic/. For example, for Peru (Wyss et al., 2008) there were 6 and for Iran 37 good quality events available for calibration that resulted in agreement of estimates with observation to factors near two.

5. LOSS SCENARIOS FOR LIMA

Recently, we calculated expected human losses in Lima in case of a hypothetical catastrophic earthquake in the immediate vicinity offshore of Lima. The basic earthquake source parameters were magnitude 8, at 33 km depth, and 15 km offshore of the beach of Lima (Wyss et al., 2009).

5.1. Lima city model

We modeled the city of Lima as consisting of 43 districts in which the population is known. For each district, we calculated an average amplification factor for the strong ground motion, based on a microzonation map with known soil types. The information regarding building properties for the 43 districts of Lima was extracted from the 2005 Census of Peru. It contained: (1) number of buildings per occupancy type; and (2) number of buildings per building type based on the type of exterior walls. This information is not perfect from the engineering point of view, but it helped to account for the differences of building properties in Lima districts and to refine the city model. We concluded that the population in vulnerability class A is fairly evenly distributed in the districts; it generally deviates from the average by one to two percent only. For vulnerability class C, the variation is larger (10 percent) and reaches over 20% for three districts.

5.2. Calibration of QLARM for Peru

For the case of Peru, we used Shebalin's (1968) attenuation law 'Eqn 4' to calculate the decrease of the intensity away from the source.

$$I = AM - B \log \sqrt{(r^2 + h^2)} + C \qquad (4)$$

where M is magnitude; r is epicentral distance; h is hypocetral depth; A, B and C are parameters of the attenuation law.

We gathered intensity values reported in past earthquakes in the country and calculate attenuation parameters that give the best fit to the macroseismic data. Figure 2 shows an example of a match between calculated and observed intensities.

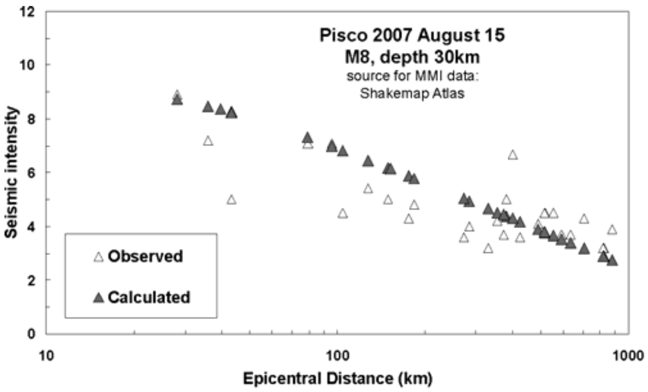

Figure 2 Comparison of observed and calculated intensities (A=1.5, B=4.5 and C=4.0) as a function of distance from the epicenter for the M8 earthquake of 2007 that occurred in the Lima/Pisco region. The observed intensities are in MMI scale.

In a second step, we calibrated the Lima city model 'Fig. 3' considering the performance of buildings during the 2007 Pisco earthquake and the collapse models pertinent to Central and South America as given by the World Housing Encyclopedia.

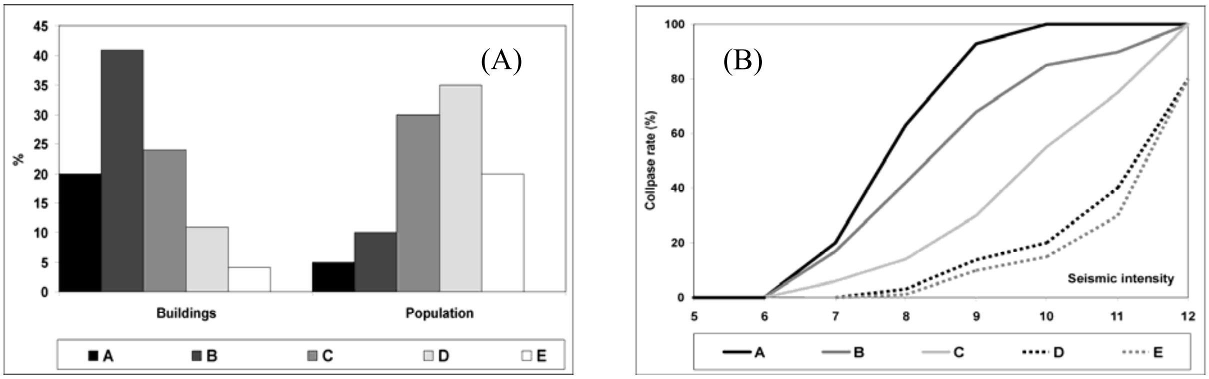

Figure 3 Calibrated city model of Lima, (A) Calibrated distributions of buildings and population, (B) Collapse models for Central and South America.

The calibrated tool was validated against six recent Peruvian earthquakes since 1990 (Wyss et al., 2009). Based on the comparison (Table 3) of observed with calculated casualties (fatalities plus injured), we conclude that QLARM estimates losses correctly within the criteria given in Chapter 4, if the parameters of the earthquakes are well known.

Table 3 Peruvian earthquakes used as QLARM calibration events. Observed casualties are compared to mean estimates which have error of approximately ±40%.

Year	Month	Day	Lon	Lat	Depth (km)	Mag	Fatalities		Injured	
							Obs	Calc	Obs	Calc
1990	5	30	-77.23	-6.02	24	6.5(6.6)	135	80	800	610
1991	4	5	-77.09	-5.98	20	6.8	53	50	252	550
1996	2	21	-79.57	-9.62	33	6.6(7.5)	12	0	56	50
1996	11	12	-75.68	-14.99	33	7.3(7.8)	15	45	700	300
2001	6	23	-73.64	-16.26	33	8.2	139	360	2687	2100
2007	8	15	-76.51	-13.32	41	7.5(8.0)	360*	310	1090	3070

** Without fatalities in the San Clemente church and the Embassy hotel*

5.3. Expected damage and human losses in Lima

For the adopted hypothetical M8 earthquake we expect that 30% of the residential building stock in Lima might be very heavily damaged or collapsed (Wyss et al., 2009).

The range of average total fatalities in our scenarios is about 6,000 to 25,000 expected in Lima. For all of these estimates, an uncertainty of about 40% has to be applied, so the range is even larger. For the worst case (occupancy rate 80% at night instead of the 50% assumed) the numbers of total fatalities would be about 9,000 to 40,000 in Lima.

The range of injured for an occupancy rate of 50% is estimated at 66,000 to 230,000. The total number of injured in the worst case (occupancy rate 80%) is therefore estimated as 128,000 to 432,000. Given that this is an average number that has a 40% error margin, the number of injured could conceivably exceed half a million.

6. DISCUSSION

Although we have successfully estimated losses due to earthquakes worldwide for the last 7 years, significant improvements in our accuracy will be achieved by the use of our second-generation loss estimation tool

QLARM. The new calculation module, the methods, and the databases focus on the area of our interest – developing countries, in which only approximate information on building stock and population exists. Averaging is an important element in achieving approximately correct loss estimates with QLARM. With the limited information available, we cannot calculate damage or losses to a single, specific building. However, the errors in soil conditions and vulnerability of single buildings will average out, if we estimate the sum of the losses in a large number of buildings. Thus, our approach and strategy to model cities with incomplete information is applicable when creating city models for developing countries. It is this part of the world that needs most assistance with estimating losses due to earthquakes in real time, as well as in scenario mode.

The QLARM database and the damage estimation method use vulnerability classes rather than specific building types. Our observation is that distributions in terms of vulnerability classes can be used as input for estimating future losses, although the resolution of the data decreases when they are inferred from building types (Trendafiloski et al., 2009). Carefully calibrated, our loss estimation tool QLARM calculates human losses for past earthquakes correctly to within a factor of 2, on average. Thus, we expect that it will reasonably estimate the losses that may be sustained in future earthquakes.

QLARM was recently used to calculate casualty potential due to future earthquakes in the vicinity of Lima. The tool was calibrated using six earthquakes in Peru since 1990 for which we have observations regarding damage and losses. We propose to calibrate our city models using earthquakes in a time-window of the past 10 to 15 years. We concluded that an earthquake of magnitude 8 in the vicinity of Lima would probably cause more than 10,000 fatalities. If a great earthquake ruptures the plate boundary outboard of Lima, but its points of greatest energy release are not close to Lima, then the disaster could be an order of magnitude smaller. The number of injured would, however, not be reduced dramatically, if the major energy release were farther away. One would still have to expect more than 100,000 injured people and with the energy release close to Lima, 200,000 injured may need medical attention. Although these numbers of casualties are frightening, the percentage of the population killed and injured is moderate. For the M8+ scenarios, the percentages killed and injured are 0.2 to 0.3% and 2 to 3%, depending on the distance of the main energy release. This percentage is less severe than in earthquakes in Pakistan (M7.6, 2005) and Iran (Bam M6.6, 2003), but much worse than in earthquakes in the industrialized world.

To improve our services we propose to upgrade QLARM by including estimates regarding functionality of medical facilities in the affected region. Therefore we initiated methods of calculating post-disaster functionality and capacity of medical facilities based on their structural and functional vulnerability. This requires construction of a database of medical facilities worldwide, which we have begun to compile.

QLARM is still in a developing phase. However, taking part in the current initiative Global Earthquake Model, we will have an opportunity to compare QLARM estimates with the estimates of other similar tools.

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