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Earthquake Risk Management: A Scenario Generator

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Contents

Abstract

This paper presents a software package EDGE**,** an Earthquake and Damage Generator/ Estimator for Toscana, Italy. EDGE creates samples of multidimensional distributions of damage using models of geophysical processes, seismic-geophysical data and a catalog of vulnerability of buildings in the region. The main algorithmic elements: seismic maps, geophysical formulas, and stochastic modeling, are described in detail. The work contributes to a joint research program of Dynamic Systems, and Risk Modeling and Society projects on data-based methodological support for decision making in the insurance industry against risks of natural catastrophes. The designed catalogs of expected damages can be used for actuarial calculations and optimization of the regional insurance portfolio.

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1. Introduction

The complex socio-economic development of the world has led to a dramatic increase of losses due to natural and anthropogenic catastrophes, earthquakes, floods, and nuclear accidents, etc. It has been estimated that within the next 50 years, more than a third of the world's population will live in seismically and volcanically active zones. Studies on possible scenarios of earthquakes and losses are a critical issue for decision making in insurance as a part of mitigation measures [35].

This analysis has two dimensions. On the one hand, it deals with earthquakes, which are studied in seismology. On the other hand, it is concerned with risks of damages of property, which are significant for the insurance industry.

Recently, it has become clear that strategies for insuring property against natural hazards could be based on catastrophe modeling to compensate for the lack of historical data. Therefore, researchers should base estimates of possible earthquake damages on geophysical models.

This paper continues the work started in [2], [3], [8], [9], [11]-[14]. The paper presents a data-based modeling approach aimed at supporting decisions on insurance of property in a seismically active region. The goal of the paper is to describe a tool, which realizes a methodology of estimation of possible damages due to earthquakes by using available data on the region. The described case study is devoted to the Toscana region, Italy. It should be noted though that the methodology under consideration is *invariant* with respect to a region and to data available for the region.

The proposed damage estimation methodology is based on seismic and vulnerability models. These models are supported in large capacity by data, namely, geo-tectonic structure and historical records of earthquakes in the region.

A software package named EDGE (Earthquakes and Damage Generator/Estimator) for the stochastic modeling of earthquake and damage scenarios was created. The program may be characterized as a *multi-layer* information system, which links together a geophysical model with statistical data on main seismological parameters and a catalog of the vulnerability of buildings. In the study, the geophysical model is taken in form of geographically explicit maps. The main output of EDGE is a synthetic catalog of the damage distribution, which can be directly used for the optimization of insurance coverage and calculation of premiums. Theoretically, various standard tools such as geo-information systems (GIS) may be used for realization of a part of this methodology. But in practice, they are quite heavy and therefore are very difficult to incorporate into another system.

In the literature, the seismic models have primarily been used for the explanation of mechanisms of changes in seismically active zones, which may precede strong earthquakes. A large variety of models have been suggested. One can divide them, roughly, into two categories: physical models and data-based models. Physical models describe natural processes in the Earth's crust. Most of the physical models refer to mechanical laws. The main idea of these models is to describe the relative movement of lithosphere plates due to an earthquake [6], [31]. Data-based models deal with available historical catalogs of seismic events and employ statistical approaches to generate possible scenarios of earthquakes. Unfortunately, the relative success in testing algorithms oriented on mean value calculations has not led to a real progress in the practice of predicting particular events. Seismologists agree that the results of efforts to develop a reliable earthquake prediction method over the last 30 years did not give reliable results [17]-[20], [22], [23]. In this context, the idea to combine mechanical models with data-based models seems to be productive. A step in this direction has been made in the present work. Let us emphasize that the present work does not aim to predict earthquakes. The main purpose of this study is to create tools for generating a variety of possible earthquakes, which can be embedded then into optimization models to find robust insurance decisions.

The earthquake and damage generator EDGE creates samples from multidimensional damage distributions of catastrophe losses, based on results of modeling geophysical processes, geophysical data and a model of vulnerability of buildings in the selected region. Geophysical data are given by a map of geo-tectonic structure of the region [32]. Historical data are given by a map of seismic activity in the region and a map of maximum observed macro-seismic activity (web page of Italian National Seismic Service (http://www.dstn.pcm.it/ssn/).

The EDGE software package is written in Delphi and consists of two blocks: the *earthquake scenario generator* and the *damage estimator*.

The *earthquake scenario generator* produces possible over-time distributions of epicenters of the earthquakes and their seismic parameters: magnitudes, intensities and the effected areas. There are two principal ways to generate possible earthquakes in a region. If reliable data of observations cover only short time intervals comparing with geological time responsible for the seismic process, one should use some adequate physical model of seismicity [16], [36]. Otherwise, statistical analysis of existing data is applied. In this paper, the emphasis is on the second approach. The map of seismic activity is used in the *earthquake scenario generator* for generating epicenters of the earthquakes. The map of maximum observed macro-seismic intensities and the map of the geo-tectonic structure of the region are used for the calculation of seismic parameters of the generated earthquakes. Basing on the intensity and magnitude, the *earthquake scenario generator* produces affected areas, in which the intensities of surface shaking lie within given intervals. A standard shape of an affected area is ellipsoid, whose greater axis is parallel to the nearest geological fault.

The regional property is divided into several classes according to the vulnerabilities with respect to the earthquakes. The vulnerability classes are characterized by materials, constructions and the age of buildings. For each vulnerability class, the average expected damage is determined by the statistics of the earthquakes' intensities and magnitudes. The *damage estimator* computes damage in the affected areas for each vulnerability class. In this block the study uses the geo-tectonic structure of the region and a vulnerability model. The output of the *damage estimator* can be directly used in the optimization of insurance decisions and calculation of insurance premiums [2], [3], [8], [9], [11]-[14].

EDGE uses the following geophysical and historical input data from the Toscana region: a map of maximum observed macro-seismic intensities, a map of the seismic activity (the frequencies of the occurrence of strong events), and a map of the geo-tectonic structure of the region.

In Section 2, the geophysical data used in EDGE for modeling earthquakes are characterized. Section 3 describes the employed earthquake and damage scenario generation techniques. Section 4 describes a Monte-Carlo simulation algorithm. Section 5 presents concluding remarks on the perspectives of the suggested approach.

2. Geophysical Data

2.1. Geo-Tectonic Structure

The *geo-tectonic structure* of a seismic region may be characterized by lineaments, which are in most cases the borders of the tectonic plates. As a rule, lineaments are identified with geological faults. A geological fault is a fracture zone, along which a relative movement of two neighboring sides of the surface has been registered. A fault trace is represented by the ruptures on the Earth’s surface formed as the intersection of the surface with the fault. [7]. Those faults, where displacements have been registered recently, are called *active;* they have a significant potential for further displacements. The absence of evident faults, however, does not indicate that earthquakes do not endanger the region, because there may be “hidden” faults.

2.2. Earthquake dynamics

The extent of the damage to a building from an earthquake depends on characteristics of the earthquake, on the type of ground around the epicenter and under the building, as well as on the building itself. Energy released by slippage or rupture along a fault is transmitted through the ground or, depending upon the location of the earthquake’s epicenter, through water as well. The ground shakes in response to those energy waves. A number of measures are employed to characterize the earthquake’s effects in a specific location: ground acceleration, velocity, ground displacement, wave period, wave frequency, wave length, and duration of shaking [1], [4].

2.3. Macro-seismic Intensity

The *intensity* of an earthquake on the Earth's surface is measured in points of a macro-seismic scale [27]. The seismic scale is used in two aspects: for estimation of intensities of earthquakes and for calculating the seismic vulnerability of buildings. The scale consists of two parts: descriptive (macro-seismic) and instrumental.

The instrumental part of the macro-seismic scale associates the intensities with quantitative parameters of the ground oscillations: the peak ground acceleration (PGA) and the peak ground velocity (PGV). These parameters are crucial for estimation of damage due to earthquakes; they determine the size of destruction of property in the region. The descriptive part of the scale characterizes the size of damage due to different shaking intensities. The magnitude and the intensity determine areas, in which the shaking intensities are not less than the given characteristic levels. A standard model of an affected area is an ellipse whose great axis is parallel to the nearest geological fault.

2.4. Magnitude

The *magnitude* of an earthquake is an important factor for estimation of damage. An earthquake is characterized by the release of elastic deformation energy. A part of this energy produces seismic waves that affect buildings and determine the intensity of surface shaking and, consequently, the damages. The magnitude is proportional to the logarithm of this energy.

The amplitude of seismic oscillations is positively related to the seismic energy released in the earthquake source. The first research efforts in this field were made by B. B. Golitsyn in 1900's. The first scale for the classification of earthquakes in magnitudes was suggested by C. Richter in 1935. Nowadays such scales are known as magnitude scales [27]. Three types of magnitude scales are usually distinguished. Most widely used are the scales that classify magnitudes with respect to the surface and body waves.

2.5. Seismic Activity

An important parameter of a region is its *seismic activity*, the distributions of return times for earthquakes with a given magnitude. Basing on this seismological factor, one can estimate a probability of the occurrence of an earthquake at a given location for a given expectation time. This estimation gives a basis for Monte-Carlo simulations of the occurrence of epicenters.

It is hardly possible to find the magnitude of a strongest possible earthquake at a given location using seismic observations at this location since the extreme events occur too rarely. For an initial approximation to a strongest possible seismic event one can take the strongest event observed in the past. To find better estimates one should take into consideration indirect factors and specific conditions of the earthquake occurrence at a given location.

The statistical methods for maximum possible magnitude estimation for given region and time interval require an earthquake catalog containing the events occurring within the epicentral distance with potential to affect the area under consideration. They assume that the seismicity within the area is uniform. Some of them are based on the Gutenberg–Richter frequency–magnitude relationship (see, e.g., [33]), another being based on Gumbel's extreme value distribution [29]. While the Gutenberg–Richter model makes use of all available data, the extreme values statistical approach uses only the maximum parameter under consideration per unit time.

Any statistical model is heavily based on the quality and the completeness of the catalog of earthquakes in use. Since this requirement is rarely reached, the resulting hazard parameters must be critically evaluated. This is mainly the case when the model makes use of the whole data set and to a lesser degree, when only the maximum values are used (the extreme method) [29].

It should be noticed that the application of other region's features, for example, a map of soil properties is also admissible. Soil properties cannot influence the intensity of an earthquake (its source is in the lithosphere), but a soil type clearly influences the ground acceleration and oscillation velocity and, consequently, the damages. This factor should be taken into account for a more accurate estimation of damages due to earthquakes.

The study performed in this work was based on the available data for the region under consideration. The lack of real data was compensated by using the data for regions of similar seismic features. It is supposed that the necessary real data are to be involved in the methodology as soon as they become available. For instance, completeness of a catalog of earthquakes stipulates the particular approach to be applied for determining parameters of generated model events.

The geophysical data are processed in EDGE according to the technique described in the next section.

3. Earthquake Scenario Generator

For some regions, in particular, Italy, there are maps that generalize the experience of observations during thousand of years [5], [30].

3.1. Input Data

The EDGE earthquake scenario generator is based on the following input data:

(i) a map of seismic activity zones (Figure 1);

(ii) a map of maximum observed macro-seismic intensities (Figure 2);

(iii) a map of the geo-tectonic structure of the region (Figure 3);

(iv) a catalog of earthquake magnitudes.

The maps (i), (ii) are available on the web page of Italian National Seismic Service (http://www.dstn.pcm.it/ssn/).

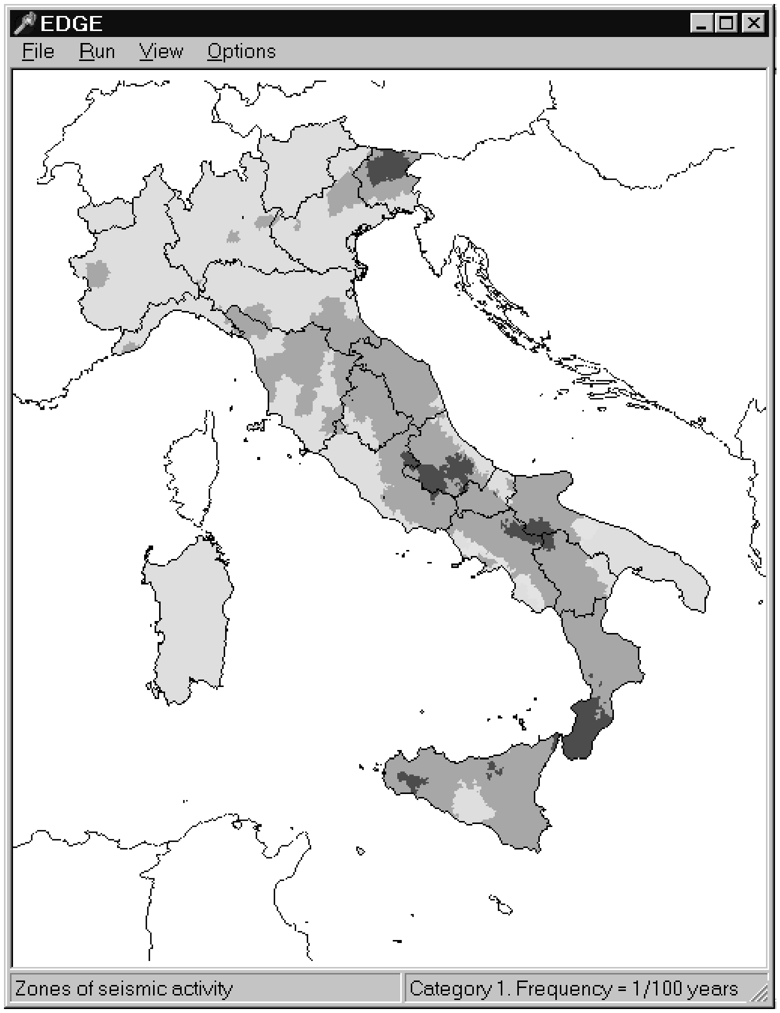

Figure 1. A map of seismic activity zones

The map of seismic activity zones in Italy is shown in Figure 1. The zones with different average return periods of strong earthquakes are shown in different colors. This map describes the frequency of the occurrence of major earthquakes. This parameter is used in calculation of the probability of the occurrence of an earthquake at a given location in Monte-Carlo simulations. In the general case, the generator uses distributions of return periods conditioned on the length of waiting times from the last earthquake in the given location (see section 4).

The map of maximum observed macro-seismic intensities is shown in Figure 2. The zones, in which different maximums of intensities were registered, are shown in different colors. The maximum observed macro-seismic intensity is an essential parameter for generating intensities of earthquakes in Monte-Carlo simulations.

The geo-tectonic structure of the region is shown in Figure 3. Different numbers mark the tectonic plates. According to the classification given in [32], the tectonic plates are divided into eight classes. Each class has its specific distribution of earthquake intensities.

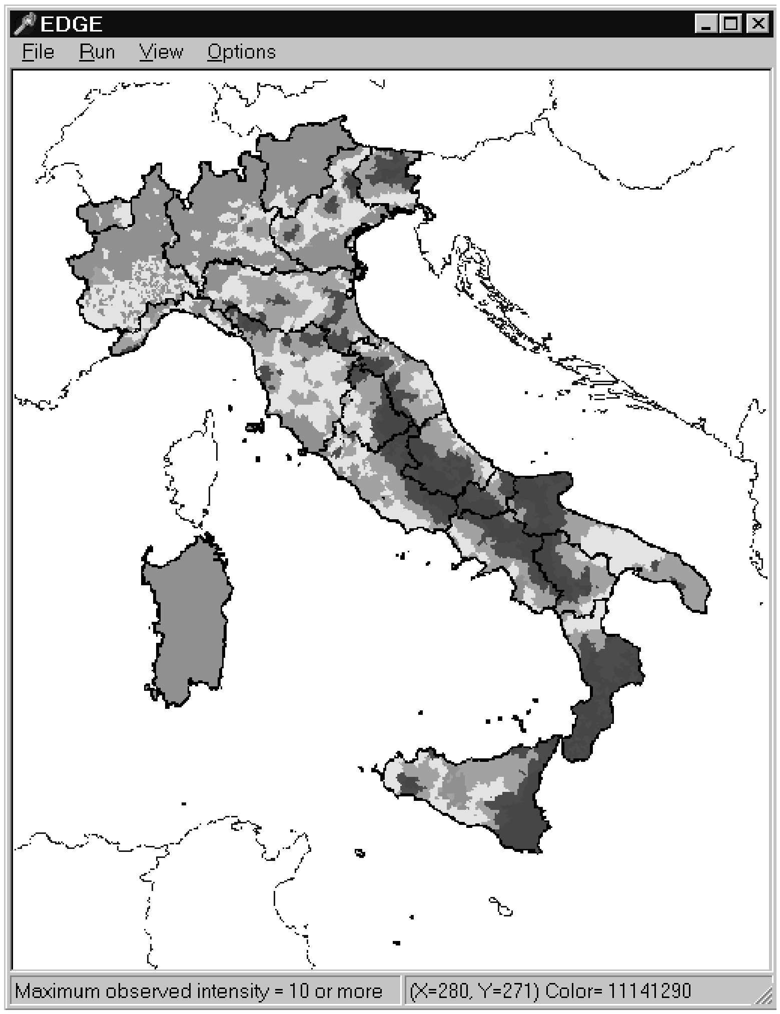

Figure 2. A Map of maximum observed macro-seismic intensity.

For the Toscana region in Italy these distributions are given by

$$F_{Io}(I) = 1 - \exp[-\alpha(I - Is)] \quad (1)$$

$$F_{Io}(I) = 1 - \exp[\exp(\alpha Is) - \exp(\alpha I)] \quad (2)$$

$$F_{Io}(I) = 1 - \exp[\exp(\alpha Is + \beta) - \exp(\alpha I + \beta)], \quad (3)$$

where $Is = 6$ (VI point of the MCS macro-seismic scale); I_o is the maximum observed macro-seismic intensity; I is the intensity. Parameters α and β depend on the class of a tectonic plate. The relations between the classes of tectonic plates, distributions of intensities, and parameters α and β are given in Table 1. In case of the Toscana region, formula (1) is not used. Parameters Is, α, and β are derived by fitting into the available data set for the region.

Let us note that the distributions similar to those given by (1)–(3) are widely used in statistical methods applied to modeling extreme events [10], [15], [37].

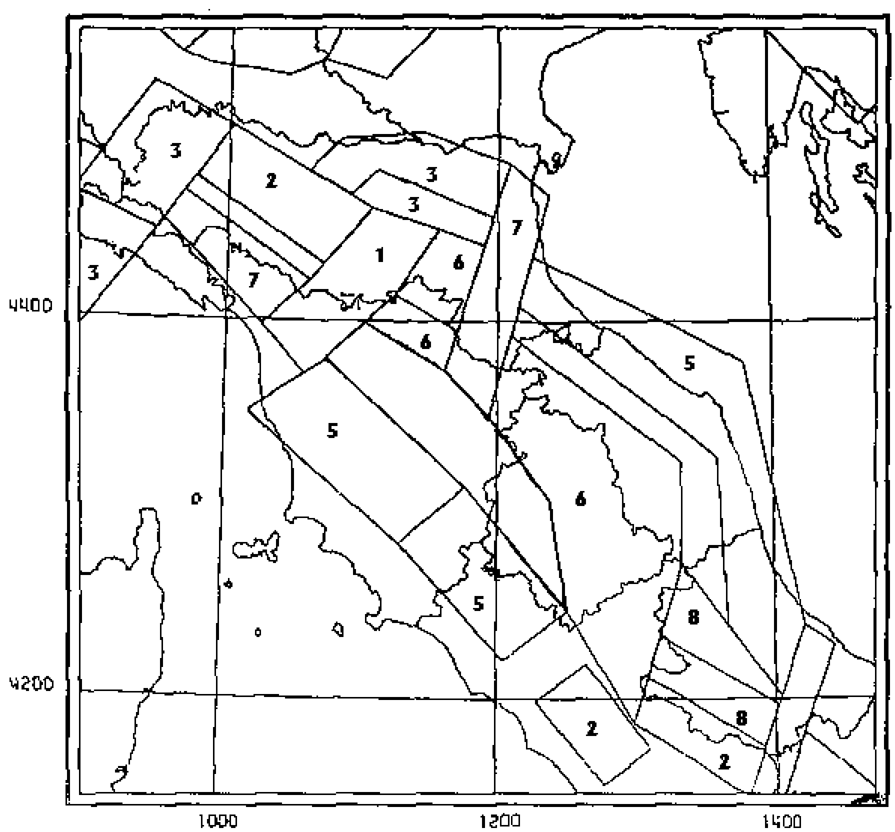

Figure 3. Geo-tectonic structure of the region.

Class of tectonic plate	α	β	Distribution of intensities
1	0.8385	-5,2678	(3)
2	0.9691	-6.6969	(3)
3	0.74447	-5.0468	(3)
4	0.17129	----	(2)
5	0.36373	-1.4810	(3)
6	0.21167	----	(2)
7	0.20078	----	(2)
8	0.05491	2.2900	(3)

Table 1. Relations between the geo-tectonic structure, intensity distribution, and parameters α and β [32].

The suggested methodology is also invariant with respect to any particular kind of distributions. Usage of the formulae mentioned above is caused by the fact that for the considered region we are given the data and empirically derived and justified relationships, which link macro-seismic intensity with vulnerability of buildings. Provided with data on another factor such as the magnitude and with other distribution laws inherit in the region, the generator could use them as well.

Basing on the distribution of intensities of earthquakes, the program EDGE generates intensities via Monte-Carlo simulation at each epicenter on a tectonic plate of a given class. The following algorithm is adopted. The distribution function $\nu = F_{Io}(I)$ associated with the tectonic plate is inverted at a randomly drawn real ν uniformly distributed between 0 and 1:

$$I = F_{Io}^{-1}(\nu)\ . \tag{4}$$

Anyway, possible magnitude of a model earthquake is selected with the use of available catalog of events. If the number of records in the catalog is not large enough, the maximum magnitude observed in the past at a considered point is taken as the magnitude of the corresponding model earthquake. Otherwise, we can use the statistical method described in [33]. This method is based only on the assumption that the Gutenberg–Richter frequency-magnitude relation below is valid:

$$\log N(M) = a^* - b^* M, \quad M_0 \le M \le M_{\max}, \tag{5}$$

where $N(M)$ is the average number of events with a magnitude no less than M in the given region for a unit of time (e.g., one year); $[M_0, M_{\max}]$ is the interval of the magnitude varying; a^*, b^* are parameters of the relation.

In accordance with (5), for the random variable *M*, the following distribution function can be written:

$$F(M) = \frac{10^{-bM_0} - 10^{-bM}}{10^{-bM_0} - 10^{-bM_{\max}}}. \quad (6)$$

Then, using the formula similar to (4) and the same value of parameter ν (such a choice provides the necessary correlation between intensities and magnitudes) we define the value *M* of model earthquake magnitude.

In the case when data available for some region are not sufficient for carrying out the procedure described above, some physical models of seismicity may be applied to obtain a synthetic earthquake catalog for the region under consideration. One of approaches to modeling seismicity is based on the block models of lithosphere dynamics [36]. In the existing block models, a seismically active region is considered as a system of absolutely rigid blocks separated by infinitely thin plane faults. The system of blocks moves as a consequence of the action of outer forces. The motion of the boundaries and the underlying medium is prescribed and plays the role of boundary conditions. Displacements of the blocks at every time moment are determined so that the system is in quasistatic equilibrium state (the sums of all forces acting on a block and their moments are equal to zero). Block interaction along the faults is viscous-elastic while the ratio of the stress to the pressure is below a certain strength level. When the level is exceeded for a part of some fault a stress-drop (a failure) occurs in accordance with the dry friction model. The failures represent earthquakes. As a result of numerical simulation a synthetic earthquake catalog is produced. Every model event from this catalog is characterized by some origin time, epicenter coordinates, depth, and magnitude. All such events occurred in a specified time interval in a specified area represent one earthquake scenario. The number of possible earthquake scenarios depends on the ratio of the length of the whole time interval taken for modeling and the length of the interval specified for scenario generation. From the viewpoint of the problem under consideration the important feature of block models is the possibility to simulate earthquake sequences on arbitrary long time intervals, so we can obtain arbitrary number of earthquake scenarios. It is evident that a model applied to a region should be adequate in the sense that it should reproduce main patterns and features which were determined empirically in real seismic flow in this region.

3.2. Affected Area due to Earthquake

Another important characteristic determined from the input data is the area affected by an earthquake. To generate an affected area, the *earthquake scenario generator* refers to a model of the isoseismals [27], [24]. An isoseismal, A_I is a domain, in which the shaking intensity is not less than a given level I. A standard model of an isoseismal is an ellipse. The affected area increases as the magnitude grows. General models of isoseismals are built on the basis of estimates of the average radii of isoseismals for well-recorded earthquakes. A relation between magnitude M, intensity I, and the affected area Q (in sq. km.) is represented in the form of a linear regression:

$$\log Q(I, M) = d_I + f_I M \ . \tag{7}$$

An example of dependence of parameters d and f on the intensity is given in Table 2. As a rule, the ratio of the axes of the isoseismals is set to 1:1.5. The main axis of an isoseismal ellipse is parallel to the nearest geological fault. An example of a system of isoseismals is shown in Figure 4. The system of isoseismal domains associated with the epicenter of an earthquake is the main output of the *earthquake generator.*

I	d_I	f_I
6	0.06	0.55
7	-1.87	0.77
8	-1.31	0.6
9	-4.52	1

Table 2. Parameters of regression

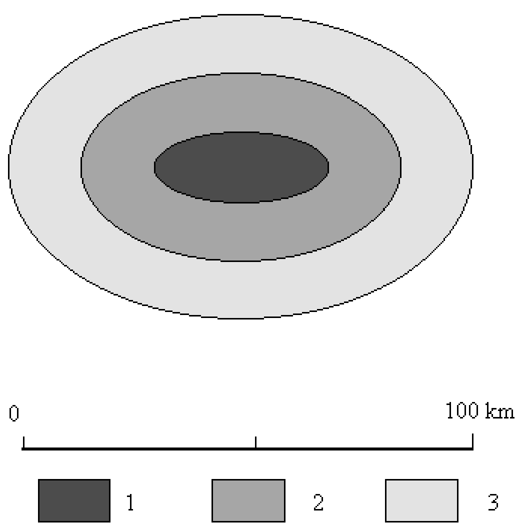

Figure 4. Isoseismal domains.
Intensity (in points of macro-seismic scale): 9– color 1; 8– color 2; 7 – color 3.

3.3. Model of Vulnerability Classes

All property in a region is usually subdivided into several categories according to its vulnerability with respect to earthquakes. Given a macro-seismic intensity, the distribution of buildings among different vulnerability classes generates a probability distribution of damage [24].

According to the classification given in [32], the vulnerability of buildings V varies over 101 classes from 0 to 100. For practical estimates, however, 11 vulnerability classes are sufficient.

The main factor that determines the local damage and average expected damage, is the acceleration of ground in the affected area. The maximum acceleration of ground y depends on intensity I. According to [32], the relation between acceleration y and intensity I is described as

$$\ln(y) = aI - b \, . \tag{8}$$

where constants a and b depend on the geo-tectonic structure of the region.

Since the intensity of an earthquake has a stochastic nature, consequently, maximal ground acceleration is a random value. The distribution functions for maximal ground acceleration have the same structure as the distribution functions for the intensities:

$$\begin{aligned} F(y) &= 1 - \exp\{-[\alpha(\ln y + b)/a - Is]\} \\ F(y) &= 1 - \exp\{\exp(\alpha Is) - \exp[(\alpha(\ln y + b)/a + \beta]\} \\ F(y) &= 1 - \exp\{\exp(\alpha Is + \beta) - \exp[\alpha(\ln y + b)/a + \beta]\} \end{aligned} \tag{9}$$

Here $Is = 6$ (VI point of the MCS macro-seismic scale); I is Intensity; parameters α and β are given in formulas (1)–(3).

The local damage d for each class of vulnerability V depends on the maximal ground acceleration and can be represented by the relation

$$d = d(y,V) = \begin{cases} 0, & y \le y_i \\ \dfrac{y - y_i}{y_c - y_i}, & y_i < y < y_c \\ 1, & y_c \le y \end{cases} , \tag{10}$$

where parameters y_i and y_c are characteristics of the region. According to [32], for the Toscana region

$$y_i = \alpha_i \exp(-\beta_i V) \, , \; y_c = \frac{1}{(\alpha_c + \beta_c V^{\gamma})} \, ,$$

where $\alpha_i = 0.08,\ \beta_i = 0.195,\ \alpha_c = 1,\ \beta_c = 0.00191,\ \gamma = 1.8$.

Taking into account relation for local damages, the EDGE *damage estimator* computes the average expected damage D_m for each vulnerability class V at each point of the region. The average expected damage is the mathematical expectation of local damage. According to [32],

$$D_m(V) = \int_0^\infty d(y,V)\, f(y) dy \ , \qquad (11)$$

where

$$f(y) = \frac{dF(y)}{dy} \ .$$

3.4. Model Structure

The input-output diagram shown on Fig. 5 illustrates the structure of the EDGE model.

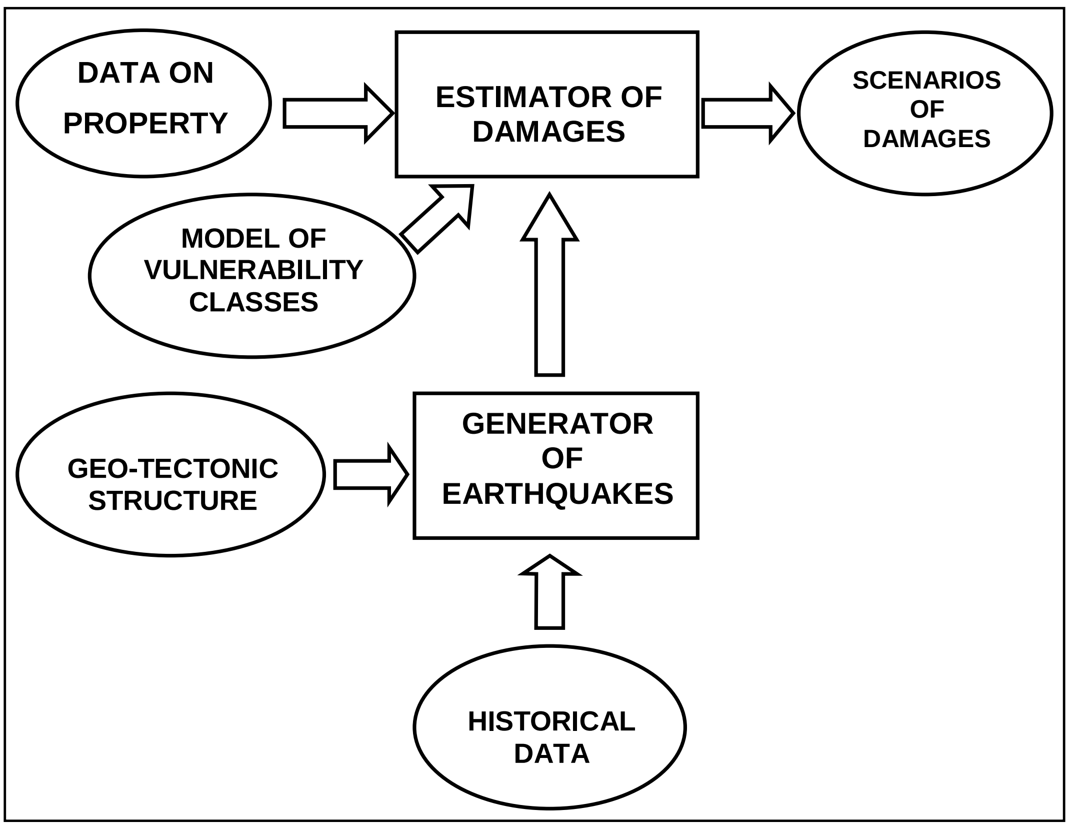

Figure 5. Flowchart of the model

The geo-tectonic structure of the region and historical data on earthquakes are the inputs for the *earthquake scenario generator*. Its outputs are earthquake scenarios. Earthquake scenarios together with the vulnerability model and the property data are the inputs for the *estimator of damages.*

In the *earthquake scenario generator* the Toscana region referred to as G in what follows is presented as a collection of small cells $G_i, i = 1,..., N$, as illustrated in Figure 6.

All parameters in a cell G_i are assumed to be constant and associated to its center r_i. A random return time is sampled according to the given probability distributions. The available data from the map of seismic activity zones provide only the frequency $B(r_i)$ (see Figure 1). Therefore, the average return period for earthquakes is found as $T(r_i) = 1/B(r_i)$. This information is used for the exponential distribution. There is also an option to introduce the following approximation. Let t be the time period over which earthquake and damage scenarios of interest are generated. The time interval $(0,t)$ is split into n subintervals of length $\Delta t = t/n$ each. The probability of the occurrence of an earthquake during the interval $(0, k\Delta t), k = 1,..., n$ is set equal to

$$P(k\Delta t, r_i) = k\Delta t / T(r_i) .$$

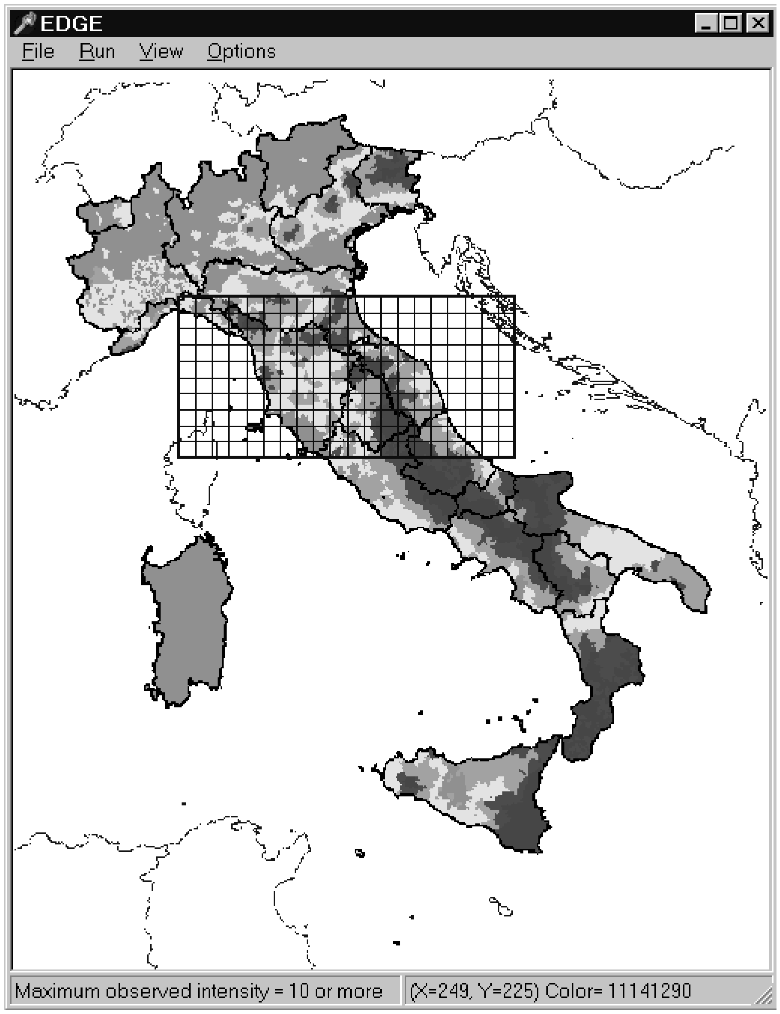

Figure 6. Region G .

Let us now define the following logical (Boolean) variable C_{ik} for every cell G_i and for every time step $k = 1,...,n$:

$$C_{ik} = C(k\Delta t, r_i) = \begin{cases} 1, & P(\Delta t, r_i) > rand(1) \\ 0, & P(\Delta t, r_i) \le rand(1) \end{cases}, \tag{12}$$

where $rand(1)$ is a real number randomly drawn from the interval $(0,1)$. Each point r_i, for which $C_{ik} = 1$, is taken as an epicenter of an earthquake in period k .

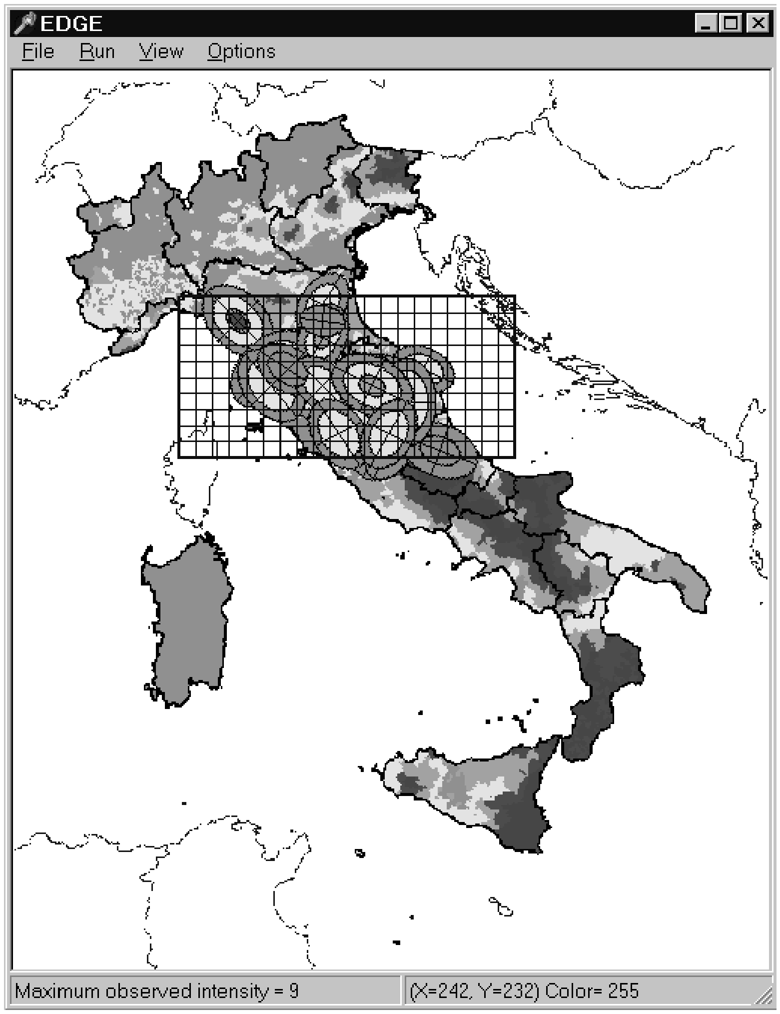

Figure 7. Generated earthquake scenarios

For each generated epicenter, the earthquake intensity, magnitude, and affected area are computed using corresponding distribution functions (1)–(3), (6), formula (7) and the geo-tectonic structure of the region. The simulated intensity *I*, magnitude *M*, and formula (7) are the basis for calculating the system of isoseismals– affected areas. For all cells in the affected area, the maximum ground acceleration is computed by formula (8). Finally, *the earthquake scenarios generator* produces a synthetic catalog of simulated scenarios of earthquakes and affected areas.

The *damage estimator* uses formula (10) to calculate local damage for each class of building vulnerability in each cell G_i and in each time period of length Δt.

EDGE repeats the described operations a large number of times and creates over-space and over time distributions of local damage. At the final stage, EDGE computes the average expected damage for each cell, each time period and each class of the vulnerability of buildings.

Figure 7 illustrates one generated Monte-Carlo scenario. The ellipses present the affected areas as a system of isoseismals. Different colors within an ellipse correspond to different intervals of intensities. The maximum intensity locates at an epicenter. The intensity decreases while the distance from an epicenter grows. In a simulation of a Monte-Carlo scenario ellipses appear sequentially in different locations.

Consider a more accurate description of the algorithm for calculating the expected damage in a given cell. For each year the value $f(y)$ given in formula (11) is computed by taking into account the geo-tectonic structure of the region. Based on the simulated record of the local damages $d(y,V)$ for any given cell, the average expected damages for all cells are computed via formula (11).

Figure 8 illustrates the aggregated result of five thousand Monte-Carlo scenarios for a given cell. The horizontal axis is time. The vertical axis shows the local average expected damage for all classes of vulnerability of buildings. The simulation results (partially seen in Figure 8) show that the evolutions of the local average expected damages are sensitive to the vulnerability but relatively slow. These preliminary model- and data-based conclusions can be helpful for actuarial calculations.

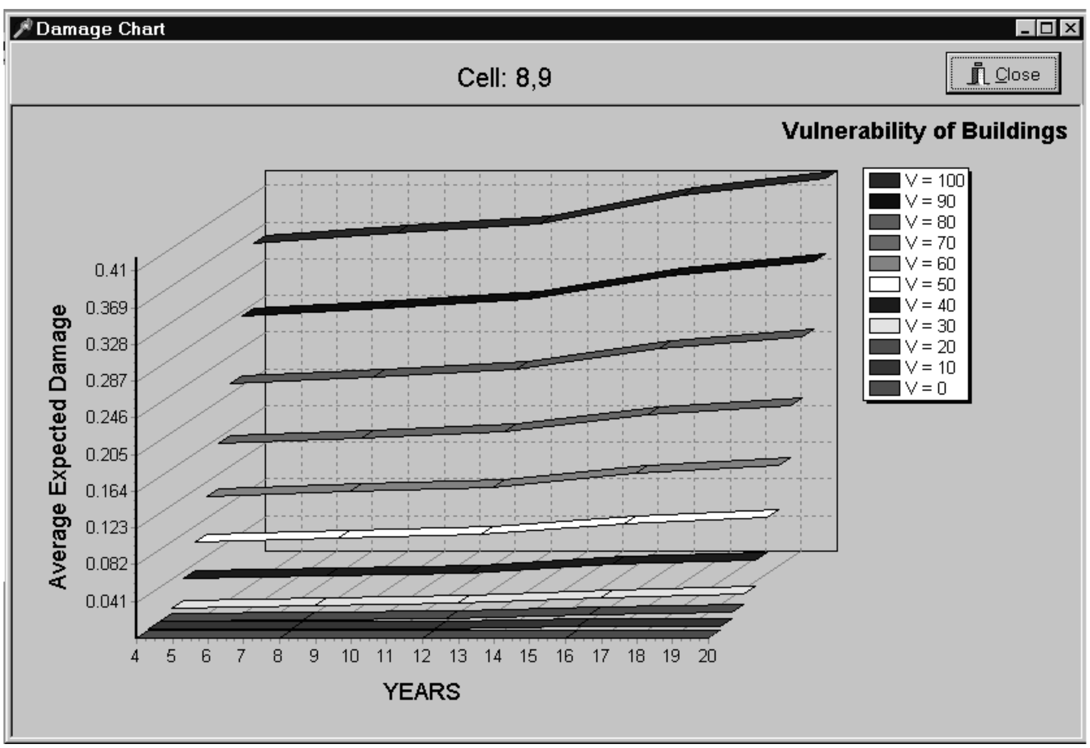

Figure 8. The average expected damage

4. EDGE Algorithm

INPUT:

A geographic region G divided into cells G_i, $i = 1,...,N$, with centres r_i.

Map 1: Zones of seismic activity in region G. Distributions of return periods for cells and waiting times from the last major earthquakes.

Map 2: Maximum observed macro-seismic intensity in region G.

Map 3: Maximum magnitudes of observed earthquakes in region G (or an earthquake catalog).

Map 4: Geo-tectonic structure of region G.

Time duration t.

Number of time steps n.

Number of Monte-Carlo simulations S.

OUTPUT:

A synthetic catalog of earthquake scenarios E.

A synthetic catalog of damages D.

A synthetic catalog of local expected damages.

An aggregate loss distribution for a given subset of cells.

ALGORITHM: first and next major earthquakes.

Set $E = \varnothing, D = \varnothing$.

For every $s = 1,...,S$ produce a Monte-Carlo scenario.

Earthquakes scenario generator (Monte-Carlo scenario)

For every $i = 1,...,N$ do the following:

Sample the return period τ_i from conditional distribution for the given waiting times. The first major earthquake occurs at time $\tau_{i^*} = \min_i \tau_i$. For cell i^* sample the return time period $\Delta\tau_{i^*}$ from unconditional distribution and compute the time for the next earthquake as $\tau_{i^{**}} = \min\{\min_{i \neq i^*} \tau_i, \tau_{i^*} + \Delta\tau_{i^*}\}$, where i^{**} is the corresponding index i. Proceeding in similar way the generator produces a sample of earthquake in a given region within a given time interval starting from the first earthquake. Find the system of isoseismal (affected area) for the event with epicenter r_i, and the associated values of local damages for each vulnerability class *V*. Namely:

Using maps on Figures 2, 3, Table 1 and formulas (1)–(3), generate the shaking intensity I^* at the epicenter.

Using Map 3 (or earthquake catalog), compute the magnitude M of the generated earthquake;

Using Map 4, orient the main axis of the isoseismals centered at r_i parallel to the nearest geological fault.

Set $E = E \cup \{(k\Delta t, l, r_i, I^*, M)\}$.

Using formula (7) and Table 2, calculate the areas of the isoseismals $A_{6,\ldots,}A_{I^*}$;

Damage estimator

Using formulas (8) and (10), for every $I = 1,\ldots,I^*$ and every $V = 0,10,\ldots,100$, compose the set $J_k^I(V) = \{(p, M, I, y, d) : G_p \in A_I\}$.

Set $D = D \cup J_k^I(V)$.

For each cell G_i, synthesize the evolution of the average expected damage using the catalogs *D* for *S* Monte-Carlo scenarios, formula (11), the map on Figure 7, and Table 1.

5. Concluding Remarks

This paper presents the multi-layer software package EDGE, an earthquake scenario generator and damage estimator for the Toscana region, Italy, and describes the underlying methodological approach. EDGE uses a large amount of geophysical, tectonic and historical data on the selected seismic region for the simulation of areas affected by randomly occurring earthquakes. EDGE can also use results of simulation of regional seismicity by means of an appropriate physical model. The simulated characteristics of affected areas and the model of vulnerability of buildings produce scenarios of local damages for each vulnerability class. EDGE can use both European and Richter macro-seismic scales, as well as magnitude scales.

EDGE can be used for supporting decision making in the regional insurance industry. It has been planned to link it to stochastic algorithms for the optimization of the insurance decision making processes. Further versions of the software will presumably take into account the impact of soil and subsoil structures, dynamical features of the seismoactive regions and other factors such as migration of earthquakes along geo-tectonic structures, clustering and seismic cycles. These data will permit to involve a larger amount of interdependencies between seismic events into the model under construction.

6. References

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