SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure

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Abstract

The era of earthquake risk and loss estimation basically began with the seminal paper on hazard by Allin Cornell in the year 1968 (Cornell, 1968). Following the 1971 San Fernando earthquake, the first studies placed strong emphasis on the prediction of human losses (number of casualties and injured) and to foresee the needs in terms of health care and shelters in the immediate aftermath of a strong event. In contrast to the early risk modeling efforts, the later studies have focused on the disruption of the serviceability of roads, telecommunications and other important lifeline systems. In the 1990’s the National Institute of Building Sciences (NIBS) developed a tool (HAZUS®99) for the Federal Emergency Management Agency (FEMA), where the goal was to incorporate the best quantitative methodology in the earthquake loss estimates.

Herein, the current version of the open-source risk and loss estimation software SELENA v4.1 is presented. While using the spectral displacement-based approach (capacity spectrum method), this fully self-contained tool analytically computes the degree of damage on specific building typologies as well as the connected economic losses and number of casualties. The earthquake ground shaking estimates for SELENA v4.1 can be calculated or provided on
three different ways: deterministic, probabilistic or based on near-real-time data. The main
distinguishing feature of SELENA compared to other risk estimation software tools is that it
is implemented in a ‘Logic Tree’ computation scheme which accounts for uncertainties of
any input (e.g., scenario earthquake parameters, ground-motion prediction equations, soil
models) or inventory data (e.g., building typology, capacity curves and fragility functions).
The data used in the analysis is assigned with a decimal weighting factor defining the weight
of the respective branch of the Logic Tree. The weighting of the input parameters accounts
for the epistemic and aleatoric uncertainties that will always follow the necessary
parameterization of the different types of input data.
Like previous SELENA versions, SELENA v4.1 is coded in MATLAB which allows an easy
dissemination among the scientific-technical community. Furthermore, any user has access
to the source code in order to adapt, improve or refine the tool according to his particular
needs. The handling of SELENA’s current version and the provision of input data is
customized to an academic environment which might support decision-makers of local, state
and regional governmental agencies in estimating possible losses from future earthquakes.

1. Introduction

Seismic risk estimation is based on the need to quantify the expectations of ground shaking
and the corresponding performance of structures. Based on such investigations and efforts
construction techniques have improved over time, and appropriate countermeasures can be
taken. The scientific field of seismic risk and loss assessment is a growing research area
which traditionally has been either based on macroseismic intensity or peak ground
acceleration (PGA). In recent years different risk assessment methodologies have been
developed which are incorporated in a considerable number of different software (Crowley
et al., 2004; McGuire, 2004; Oliveira et al., 2006).
Unfortunately, it is a large damaging earthquake of all which is able to verify or refute the
estimated seismic scenario, the chosen methodology and the defined assumptions. But still
this creates a fruitful situation when we are able to calibrate our models and input
parameters on this experience and results of different risk estimation methods can be compared with each other. In general nearly all available risk and loss assessment studies defined individual scenario earthquakes as a main basis for planning (ATC, 1996a; Algermissen et al., 1988; CDMG, 1982a, 1982b, 1987, 1988, 1990, 1995; CUSEPP, 1985; Dames and Moore, 1996; EQE, 1997; Harlan and Lindbergh, 1988; NOAA, 1973). All these studies use already existing knowledge of regional geology and seismic activity to generate maps with estimated intensities $I$ or ground motion accelerations $a$. This, in combination with other types of input data (e.g., building stock, population density), is used to calculate the extent of damages to structures and life-lines as well as the impacts on population. Some of these studies additionally address potential secondary hazards such as fire, flood, and hazardous materials release. Earthquake scenarios of this type have been employed by governmental institutions and public utilities to prepare for and to mitigate the degree of damage from future events. Thus it appears that the typical loss study has been focused on a single event, applied in the long-term pre-event period, and utilized primarily by those concerned with seismic safety planning and disaster management.

In this respect, the Federal Emergency Management Agency (FEMA 366, 2001, 2008) initiated a study on seismic risk estimation for all regions of the United States using the national loss estimation tool HAZUS®99 and HAZUS®MH, respectively. The study’s main task was to analyze and compare the seismic risk across regions in the U.S. which have different hazard levels, characterized by different population density or physical building vulnerability.

The advent of high-speed computing, satellite telemetry and Geographic Information Systems (GIS) made it possible to electronically generate loss estimates for multiple earthquake scenarios, to provide a nearly unlimited mapping capability, and perhaps most important, to develop estimates for a current earthquake event in near real-time given its source parameters, i.e. magnitude and location, are provided.
Currently, a number of different computer tools able to estimate the seismic risk using different methodologies are available. Table 1 lists some of them and briefly describes their main principles and outputs.

A very powerful approach being attractive from a scientific-technical perspective is the HAZUS software (HAZUS®99, HAZUS®MH MR2) which was developed by the National Institute of Building Sciences (NIBS) for the Federal Emergency Management Agency (FEMA, 2001, 2003). The HAZUS tool is built upon the integrated geographic information system platform ArcGIS (ESRI, 2004) and can be considered as a software extension to ArcGIS. HAZUS is directly integrated with the national and regional databases on building stock and demography data of the United States (FEMA 366, 2008). This enables any larger community in the United States to simulate earthquake risk scenarios with a minimum effort since most of the necessary data is already prepared. The basic methodology behind HAZUS represented the starting point for the development of alternative tools (see Table 1) in order to compute seismic risk and loss estimates as well as initiated numerous application studies (i.e. Kircher, 2003; Wang et al., 2005; Kircher et al., 2006; Nielson and DesRoches, 2007; Rojas et al., 2007). The fact that HAZUS is tailored so intimately to U.S. situations which makes it very difficult to be applied to other environments or geographical regions, has recently activated the development of GIS-based methodologies which facilitate the application of HAZUS to other parts of the world (Hansen and Bausch, 2006).

Aware of the importance of a proper seismic risk estimation, the International Centre for Geohazards ICG, through NORSAR (Norway) and the University of Alicante (Spain), has developed a software tool running under MATLAB (The MathWorks, Inc.) in order to compute seismic risk of urban areas using the capacity-spectrum method. The tool named SELENA (SEismic Loss Estimation using a logic tree Approach) is open for any user-defined data and thus can be applied to any part of the world. The user has to supply a
number of input files which contain the necessary input data (e.g., building inventory data, demographical data, definition of seismic scenario etc.) in a simple ASCII format. A more detailed description of the type of input data will be given below. It should be explicitly stated that the core of the HAZUS methodology (FEMA, 1999, 2003) was adopted for SELENA. However, one of the main differences between both tools is that SELENA works independent of any Geographic Information System, while HAZUS is connected to the ArcGIS software (ESRI, Inc.). In addition, a Logic Tree-computation scheme has been implemented in SELENA which allows the user to define weighted input parameters and thus being able to properly account for epistemic uncertainties. Consequently, any type of output is provided with corresponding confidence levels.

2. Technical components of the SELENA-tool

2.1 Basic procedure

The current version of SELENA (Molina et al., 2009) allows for three analysis types which are differing in the way the seismic impact is described. In general, spectral ordinates of seismic ground motion at different reference periods have to be provided for each geographical unit (i.e. census tract), in order to allow the construction of a design spectra following a selectable seismic code provision, i.e. spectral ordinates (PGA, $S_a$) at reference periods $T = 0.01, 0.3$ and $1.0$ s for IBC-2006 (International Code Council, 2006), and $T = 0.01$ s (PGA) for Eurocode 8 (CEN, 2002) as well as for Indian seismic building code IS 1893 (Part 1) : 2002 (BIS, 2002).

Once the seismic ground motion in each geographical unit is defined, the computation of physical damage to the building stock, the total economic loss related to these damages, and the number of casualties, i.e. the number of injured people and fatalities, is conducted.
Damage results are given in terms of cumulative probabilities $P$ of being in, or exceeding one particular damage state $ds$ following the classification scheme given by HAZUS-MH (FEMA, 2003) into none, slight, moderate, extensive and complete damage. Absolute numbers of damaged buildings or the damaged building (floor) area in $[m^2]$ are calculated by combining damage probabilities for each building type with the inventory data of the building stock. Figure 1 exemplarily illustrates the sequence of SELENA for a deterministic analysis and shows which input layers are required for the different program outputs.

Since the described methodology of risk assessment is based on statistical data, the level of resolution is of utmost importance. Since a resolution of the damage outputs on the level of individual buildings would require huge computation efforts, SELENA as most other risk estimation software tools considers the geographical unit (GEOUNIT) as the smallest area unit. In practice, this unit is related to building blocks or city districts. The decision on the extent of each geographical unit has to be made considering different aspects such as having equal soil conditions, constant surface topography or a homogeneous level of building quality within the demarcated area.

### 2.2 Specification of the seismic input (demand)

A key point in any seismic risk assessment is the provision of seismic ground motion. In SELENA v4.1 this can be done by:

- the provision of spectral ordinates (e.g., PGA, $S_a$ at 0.3 and 1.0 seconds) taken out from probabilistic shaking maps) and assigned to the geographical units (probabilistic analysis),
- the definition of deterministic scenario earthquakes (e.g. historical or user-defined events) and adequate/suitable ground-motion prediction equations in order to compute the spectral ordinates in each geographical unit (deterministic analysis),
- provision of spectral amplitudes of recorded ground motion at the locations of seismic (strong-motion) stations (analysis with near-real-time data).

The first results of each analysis type consist in the provision of seismic ground motion amplitudes at the center of each geographical unit. Thereby it has to be considered that these amplitudes can either represent the motion on rock conditions (deterministic and probabilistic analysis) or already include amplification effects of local (near-surface) subsoil conditions (analysis with near-real-time data). Based on these acceleration values SELENA generates an elastic response spectrum (damping factor $\xi = 5\%$) following a selectable seismic code provision. Currently, the provisions of the U.S. seismic code IBC-2006 (International Code Council, 2006), Eurocode 8 – Type 1 and Type 2 (CEN, 2002) and Indian seismic building code IS 1893 (Part 1) : 2002 (BIS, 2002) with their soil amplification factors are incorporated. Figure 2 schematically depicts the shape of a design response spectra in the $T$-$S_a$-domain.

2.3 Structural performance under seismic action

The core methodology of SELENA was adopted from the HAZUS-MH software whose basic approach in order to identify the level of structural damage under a given seismic impact is the capacity-spectrum method (FEMA, 1996). During the last years, several modifications and extensions of this powerful and efficient technique have been developed. Two of these procedures are incorporated in SELENA v4.1:
- Procedure 1: The conventional Capacity Spectrum Method as proposed in ATC-40 (Applied Technology Council ATC, 1996b)
To apply any of the available capacity spectrum methods, both seismic demand and the capacity curve have to be transformed into the spectral acceleration-spectral displacement ($S_a$-$S_d$) domain (Figure 3). Thereby, seismic demand is represented by the elastic response spectrum while the capacity curve reflects the building’s lateral displacement $\delta$ as a function of a horizontal force $V$ applied to the structure. Beside a number of factors, building capacity curves mainly depend on the building type (working materials and construction), number of stories (height), and also from its region reflecting local building regulations as well as local construction practice and quality.

The main task of the capacity-spectrum method is to find that point on the capacity curve consistent with the seismic demand being reduced for nonlinear effects. Since each point on the capacity curve represents a certain state of structural damage and thus reflects an increase in structural damping as the damages accumulate, the performance point can only be found iteratively. As Figure 3 illustrates, the performance point finally is characterized by a spectral acceleration $S_a$ and spectral displacement $S_d$ (and establishing the basis for assigning discrete damage probabilities $P$).

Once the performance point and its corresponding spectral displacement $S_d$ are found, structural vulnerability (fragility) functions for each damage state $d$s are required to assign damage probabilities $P$ (Figure 4). These represent cumulative probabilities of a certain building type of being in or exceeding one of the different damage states $d$s dependent on spectral displacement $S_d$. Figure 4 shows a set of fragility functions for a random model building type as described by HAZUS-MH (FEMA, 2003). The differences between the intersection points of two neighboring fragility functions for a given spectral displacement are discrete damage probabilities (Figure 5) which establish the basis for the calculation of...
absolute damage values. Generally, fragility functions are provided in dependence on building typology and level of seismic code design reflecting the general quality of construction practice. The fragility functions given by HAZUS-MH (FEMA, 2003) are described by the following form:

$$P[ds|\bar{S}_d] = \Phi \left[ \frac{1}{\beta_{ds}} \cdot \ln \left( \frac{S_d}{\bar{S}_{d,ds}} \right) \right]$$

(1)

in which:

- $\bar{S}_{d,ds}$ - median value of spectral displacement at which the building reaches the threshold of damage state $ds$,
- $\beta_{ds}$ - standard deviation of the natural logarithm of spectral displacement for damage state $ds$,
- $\Phi$ - standard normal cumulative distribution function.

2.4 Risk and loss assessment based on statistical inventory data

Seismic risk results are essentially represented by the total extent of physical damage an earthquake scenario likely to occur may produce to the building stock. Within SELENA v4.1 the extent of structural damage can either be quantified in the number of buildings or building floor area affected by a certain damage state $ds$. Based on the damage results, both economic losses and number of casualties are calculated. The first requires a suitable economic model, which provides realistic costs for the repair or replacement of damaged or collapsed buildings and which then allows the appraisal of the total amount of loss in each geographical unit.
The computation of economic losses caused by direct structural damage and which are required for building repair and in case of complete damage or collapse for replacement is done in the following way adopting the methodology described by FEMA (2003):

\[
L_{\text{loss}} = CI \cdot \sum_{i=1}^{\text{oct}} \sum_{j=1}^{\text{mbt}} \sum_{k=1}^{\text{ds}} A_{i,j} \cdot P_{j,k} \cdot C_{i,j,k}
\]

in which:

1. **CI** - regional cost multiplier accounting for the geographic cost variations between the different geographical units,
2. **FA\_{i,j}** - built area of occupancy type (oct) \(i\) and model building type (mbt) \(j\) (in \(m^2\))
3. **P\_{j,k}** - damage probability for model building type \(j\) to experience structural damage of damage state \(ds\ k\) (slight, moderate, extensive or complete),
4. **C\_{i,j,k}** - cost of repair or replacement for each occupancy type \(i\) and model building type \(j\) suffering structural damage state \(k\) in input currency per floor area, e.g. \(\$/m^2\).

To determine the estimated number of casualties (i.e. injured people and fatalities) which are mainly caused by the total or partial collapse of buildings, reliable statistical data on the study area’s demography is required. This does not only consist of population statistics, like e.g. total number of inhabitants per district, but also in average numbers of people staying in buildings of different type or occupancy and percentages of people staying outdoors or indoors at different times of the day.

SELENA’s current version 4.1 facilitates the computation of casualty numbers using two different methodologies. During the preparation of input files, the user can explicitly choose whether the HAZUS approach (FEMA, 2003) or the basic approach following Coburn and Spence (2002) will be applied.
The computation of the estimated number of casualties $K_{i,j}$ of severity level $i$ based on the basic approach is based on the following equation:

$$K_{i,j} = \sum_{j=1}^{mb} \sum_{k=1}^{d} CR_{j,k} \cdot P_{j,k}^* \cdot pop_{j}$$

in which:

1. $i$ - injury severity level ranging from light injuries ($i = 1$), hospitalized injuries ($i = 2$), life threatening injuries ($i = 3$) to deaths ($i = 4$), see FEMA (2003),
2. $CR_{j,k}$ - casualty rate of each severity level $i$ for model building type $j$ and damage state $k$,
3. $P_{j,k}^*$ - damage probability for model building type $j$ to experience structural damage of damage state $ds k$ (slight, moderate, extensive, complete or complete with collapse),
4. $pop_{j}$ - average number of people occupying model building type $j$.

Irrespective of the methodology chosen, casualty numbers are computed for three different day time scenarios (night time, day time, commuting time). Thus, extreme cases of occupancy are covered which are strongly dependent on the time of the day. These scenarios are expected to generate the highest casualty numbers for the population at home (night time), the population at work or educational facilities (day time), and the population during rush hour (commuting time).

2.5 Accounting for uncertainties by a ‘Logic Tree’ approach

The main difference between SELENA and other risk estimation software tools, as e.g. HAZUS-MH (FEMA, 2003) lies in the fact that uncertainties of any input type can be accounted for by a ‘Logic Tree’ approach. The diversification of each input type thereby
increases the number of branches of the logic tree and thus computation runs as well as computation time. Such logic tree methodologies have been widely used in seismic hazard computation in order to capture epistemic uncertainties which are connected to knowledge deficits of the input data (Scherbaum et al., 2005; Bommer et al., 2006). Through the assignment of a decimal weighting factor to each branch, risk results are multiplied by their corresponding weights and are fitted to a normal distribution. The weighting factor (0.0-1.0) reflects the confidence with which any particular parameter is used. The sum of weighting factors of all branches for any parameter must naturally be 1.0, and the weights should reflect the scientist’s best judgment on the reliability and spread of possible values. As any such specialized software, the results always critically depend on the expertise of the operating scientist or engineer.

The logic tree approach leads to the computation of median values as well as 16%-respectively 84%-fractile values for each output type. An exemplary illustration of the logic tree computation scheme for the deterministic analysis is given in Figure 6. Uncertainties of the earthquake source, the applied ground-motion prediction relations (attenuation laws), the subsoil model, the vulnerability of the building stock, and economic loss model are considered.

3. Implementation of the risk estimation method in MATLAB

3.1 Why MATLAB?

Like previous versions, SELENA v4.1 is coded in MATLAB since it provides a suitable scientific and technical computing environment for the purpose and required computation needs of SELENA. Further reasons for choosing the MATLAB platform are its dissemination and prevalence among the scientific community and its plain computing
language making it more attractive to a large number of potential users. Thereby it allows
the user to access SELENA’s source code and to adapt, improve or refine the tool to his
own needs.

3.2 Program structure

Following the previously described methodology to compute damages and losses, the
flowchart in Figure 7 demonstrates the main sequence of SELENA v4.1.

The whole computation process of SELENA v4.1 is subdivided into 33 separate m-script
files (format *.m) which are consecutively accessed during the program sequence. Their
respective functions and tasks are briefly described in Table 2. The main reason for
subdividing the code into separate script files was to allow the user an easier inspection of
the code and thus to implement own changes or amendments.

In general, the execution of SELENA requires less interactive action by the user. Most of
the required information has to be prepared in the forefront and provided in the form of
input files (paragraph 3.3). After starting the program, the user has to make decisions
interactively on:

- the type of analysis (deterministic, probabilistic, or (near-)real-time data)
- the source directory of the different input files.

An exemplary illustration of the prompting windows consecutively popping up after
starting the program sequence in MATLAB is given in Figure 8.

Besides a number of programming tools implemented in MATLAB, SELENA v4.1 reverts
to the wavelet, mapping and statistics toolboxes which have to be installed by the user. It
will be a matter of future development to reprogram the SELENA code such that the
toolboxes will not be required.

3.3 Preparation of input files

Most of the input files required by SELENA have to be prepared in ASCII-format and
provided as plain text files (*.txt) in the same (source) directory as the different m-scripts.
A variety of input files containing the data of an exemplary case study are included in the
SELENA-package which can be received through the NORSAR webpage free of charge
(www.norsar.no/seismology/selena.htm). It is supposed that any user simply modifies
these files according to his own data. Figure 9 exemplarily illustrates the format of some
input files which are required as txt-files.

As it was already addressed, the main difference between the three analysis types consists in
the way the seismic ground motion parameters are provided or calculated. Table 3 lists the
different input files necessary for the provision of seismic ground motion parameters. The
remaining input files are common for all analysis types (Table 4). While most of them have
to be provided as text files (*.txt), some need to be provided in MATLAB-format
(*.mat). The latter especially applies for files containing fixed parameter values (variables),
e.g. ubcampfact.mat, which will normally not be modified by the user, and files which
include the spectral acceleration and displacement values of the single capacity curves to be
provided by the user himself.

3.4 Computation duration
As already stated, a major computation component of SELENA is working iteratively in order to determine the performance point of a building type under a given seismic demand (capacity spectrum method). Consequently, this has serious effects on the computation time especially when the amount of input data (diversification of building types, size of the studied region i.e. number of geographical units) is increasing. Additionally, the number of branches defined for the Logic Tree methodology should also kept in certain limits since this also affects the computation time (Lang et al., 2008a).

In order to get an idea of SELENA’s computation duration and velocity, the risk and loss assessment calculation for Oslo (Norway) took 190 minutes on a standard PC. The study area covering the whole Oslo municipality with an area of 226 km² and around 550 000 inhabitants was divided in 84 different geographical units. The building stock consisted of nearly 71 500 single buildings which were classified into 15 different model building types and 23 different occupancy types. The Logic Tree comprised 108 branches formed by 3 different scenario earthquake sources, 2 regarded ground-motion prediction equations (attenuation relations), 3 different soil models, 3 different levels of building quality, and 2 different economic models. Consequently the computation of one branch lasted 102 seconds (Molina and Lindholm, 2005).

3.5 Managing the results, program outputs

After running one of the three analysis types which are incorporated in SELENA v4.1, a considerable number of output files is generated and written in a sub-directory. How many of these output files are written mainly depends on the defined number of Logic Tree branches as well as the analysis type. An overview and brief description of the output files is given in Table 5. It should be noted that in some cases differences both in the name of
the output files and in the units of the results exist whether the user requests the output
dependent on the number of damaged buildings or damaged area.

All output files are given in plain ASCII text format (.txt). The data contained in the
output files is in delimited format separated by tabulators, such that it can be imported into
any program or converted into any user-defined format. Since most of the results are
referring to the geographic location of the minimum geographical units, the main interest
of the user presumably lies in plotting the results with Geographical Information Systems,
as e.g., ArcView, ArcGIS, MapInfo. Figure 10 exemplary illustrates selected results taken
from a comprehensive risk assessment study for Oslo, Norway (Molina and Lindholm,
2005). Predicted physical damages (in the five different damage states) for one particular
building type (URML – unreinforced masonry, low-rise) are plotted as column bars on the
level of geographical units. The damage results are underlain with predicted seismic
ground-motion values (PGA) considering soil amplification effects for the assumed
deterministic earthquake scenario (M 6.0). The illustration of results is done with the
Google Earth-based software tool RISE (Risk Illustrator for SELENA; Lang et al., 2008b;

4. Conclusions and further development

It should be noticed that the presented tool for seismic risk and loss assessment SELENA
v4.1 is an ongoing development and thus will undergo a number of changes and
extensions. In order to be able to do this, the authors depend on the users’ feedback and
suggestions.
Since the applied methodologies for assigning damage probabilities, damage extent and loss are scientifically substantiated and accepted by the scientific community further developments will mainly concentrate on the following aspects:

1. Provision of alternatives for the user regarding the incorporation of further scientific developments and innovations, e.g., capacity spectrum methods, type of design spectra, etc.

2. Improvement of the graphic user interface.

3. Modification of output files following the structure and requested data format of commercial (e.g., ArcView, MapInfo) as well as open-source Geographic Information Systems (e.g., Google Earth, GRASS GIS) in order to simplify the graphical illustration of results.

4. Initiation of a database and web-forum for possible users of SELENA accommodating all types of input data for different parts of the world such as capacity curves and vulnerability functions for different model building types, national economic loss models for building stock or statistical data on the demography.

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### Table 1.

*Overview of available risk and loss estimation software tools and characterized*

<table>
<thead>
<tr>
<th>Tool</th>
<th>Type of analysis</th>
<th>Damage estimation based on</th>
<th>Calculation of</th>
<th>GIS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>spectral</td>
<td>damage to buildings</td>
<td>damage to life-lines</td>
</tr>
<tr>
<td>EPEDAT (Eguchi et al., 1997)</td>
<td>deterministic</td>
<td>spectral</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>HAZUS-MH (FEMA, 2003)</td>
<td>deterministic, probabilistic</td>
<td>spectral</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>KOERILOSS (Erdik and Aydinoğlu, 2002)</td>
<td>deterministic</td>
<td>intensity, spectral</td>
<td>●</td>
<td>–</td>
</tr>
<tr>
<td>LNECLOSS (Campos Costa et al., 2006)</td>
<td>deterministic</td>
<td>spectral</td>
<td>●</td>
<td>–</td>
</tr>
<tr>
<td>MAEViz (MAE; Spencer et al., 2008)</td>
<td>deterministic, probabilistic</td>
<td>spectral</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>MDLA (Mitrani-Reiser, 2007; Muto et al., 2008)</td>
<td>deterministic, probabilistic</td>
<td>intensity, structural</td>
<td>●</td>
<td>–</td>
</tr>
<tr>
<td>System</td>
<td>Type</td>
<td>Parameters</td>
<td>Time</td>
<td>Intensity</td>
</tr>
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<td>NHEMATIS</td>
<td>deterministic intensity</td>
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<td>●</td>
<td>–</td>
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<tr>
<td>(Webb, 1999)</td>
<td>spectral parameters $\lambda$–$\lambda$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PACT (ATC-58)</td>
<td>deterministic intensity</td>
<td>●</td>
<td>–</td>
<td>●</td>
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<tr>
<td>(Naeim et al., 2007)</td>
<td>and time-based analysis</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>(probabilistic)</td>
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<td></td>
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<tr>
<td>QUAKELOSS</td>
<td>real-time intensity</td>
<td>●</td>
<td>–</td>
<td>●</td>
</tr>
<tr>
<td>(Wyss, 2005)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(USGS; Luco, 2007)</td>
<td>probabilistic parameters $\lambda$–$\lambda$</td>
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<td></td>
<td></td>
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<tr>
<td>SELENA</td>
<td>deterministic, spectral</td>
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<td>–</td>
<td>●</td>
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<tr>
<td>(Molina et al., 2008)</td>
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<tr>
<td></td>
<td>near-real-time</td>
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</tbody>
</table>

Annotations:

$^5$ spectral ground motion parameters, i.e. spectral acceleration $S_a$, spectral displacement $S_d$
Table 2.

*Description of SELENA’s m-scripts and their different tasks in order of being called by the program sequence*

<table>
<thead>
<tr>
<th>m-script</th>
<th>Description</th>
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<tbody>
<tr>
<td>selena.m</td>
<td>core file of the software (calling for startwin.m)</td>
</tr>
<tr>
<td>startwin.m</td>
<td>initialization of the window environment in order to choose between a probabilistic, a deterministic or an analysis based on real-time data</td>
</tr>
<tr>
<td>dettool.m</td>
<td>function file (called by startwin.m) to initialize the window environment for a deterministic analysis</td>
</tr>
<tr>
<td>probtool.m</td>
<td>function file (called by startwin.m) to initialize the window environment for a probabilistic analysis</td>
</tr>
<tr>
<td>realtool.m</td>
<td>function file (called by startwin.m) to initialize the window environment for an analysis with real-time data (grid pattern shaking scenario)</td>
</tr>
<tr>
<td>computetool.m</td>
<td>function file (called by dettool.m) which starts the main processes of a seismic risk computation for a deterministic earthquake</td>
</tr>
<tr>
<td>computetoolp.m</td>
<td>function file (called by probtool.m) which starts the main processes of a seismic risk computation based on a probabilistic shake map</td>
</tr>
<tr>
<td>computetoolr.m</td>
<td>function file (called by realtool.m) which starts the main processes of a seismic risk computation based on real-time data</td>
</tr>
<tr>
<td>gmotion.m</td>
<td>function file which gets the ground motion at the center of each geographical unit from a deterministic earthquake (numerous attenuation relationships are provided, while new attenuation relations can be easily implemented) and computes ground motion amplification using the factors as e.g. given in IBC-2006 (called by computetool.m)</td>
</tr>
<tr>
<td>att_sub.m</td>
<td>function file with attenuation relationships from different authors which provides the ground motion values (units of $[g]$) for PGA, Sa at 0.3s and Sa at 1.0s (called by gmotion.m) (adaptation of the NPRISK subroutine) (some of the relations implemented don’t have coefficients for a 0.3 s attenuation function)</td>
</tr>
<tr>
<td>dtorry.m</td>
<td>function file used to compute the closest distance from a point (latitude, longitude) to a segment (lat1, lon1)-(lat2, lon2) (called by gmotion.m)</td>
</tr>
</tbody>
</table>
| gmotionp.m     | function file which amplifies the ground motion at the center of each geographical...
<table>
<thead>
<tr>
<th>m-script</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>gridtogeounit.m</td>
<td>function file selecting the concerning nodes of the grid pattern, making a statistical evaluation of their ground-motion ordinates (mean value, standard deviation), and assigning them to the centers of the geographical units (called by computetoolr.m)</td>
</tr>
<tr>
<td>damagep.m</td>
<td>function file which computes the probability of damage for the building stock using the capacity spectrum method (called by computetool.m, computetoolp.m, and computetoolr.m)</td>
</tr>
<tr>
<td>spectralshape.m</td>
<td>computation of spectral ground-motion ordinates following different code provisions, e.g., IBC-2006 (called by damagep.m)</td>
</tr>
<tr>
<td>csm.m</td>
<td>performance point calculation based on the ‘traditional’ Capacity Spectrum Method following ATC-40 (Procedure A) (called by damagep.m)</td>
</tr>
<tr>
<td>madrs.m</td>
<td>performance point calculation by using the Modified Capacity Spectrum Method (MADRS) following FEMA 440/ATC-55 (called by damagep.m)</td>
</tr>
<tr>
<td>areaincapcurv.m</td>
<td>function file which compares the areas under the capacity curve while doing the bilinearization (called by csm.m and madrs.m)</td>
</tr>
<tr>
<td>curveintersect.m</td>
<td>function file which finds the intersection points of two curves in the X-Y plane (called by csm.m and madrs.m)</td>
</tr>
<tr>
<td>local_parseinputs.m</td>
<td>script used by curveintersect.m</td>
</tr>
<tr>
<td>mminvinterp.m</td>
<td>1-D inverse interpolation (called by curveintersect.m)</td>
</tr>
<tr>
<td>interpl.m</td>
<td>1-D interpolation (modified from the original matlab script).</td>
</tr>
<tr>
<td>squaredam.m</td>
<td>function file which computes the absolute square meters of damaged built area for each model building type in each geographical unit (called by computetool.m, computetoolp.m, and computetoolr.m)</td>
</tr>
<tr>
<td>numdam.m</td>
<td>function file which computes the absolute number of damaged buildings for each model building type in each geographical unit (called by computetool.m, computetoolp.m, and computetoolr.m)</td>
</tr>
<tr>
<td>losssqm.m</td>
<td>function file which computes the total economic losses due to structural damage (called by computetool.m, computetoolp.m, and computetoolr.m)</td>
</tr>
<tr>
<td>m-script</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>tree.m</td>
<td>function file used to fit the damage estimation results coming from each branch of the logic tree to a normal distribution function; computes median (mean) value and 16% and 84% fractiles (called by computetool.m, computetoolp.m, and computetoolr.m)</td>
</tr>
<tr>
<td>treeloss.m</td>
<td>function file used to fit the economic loss results coming from each branch of the logic tree to a normal distribution function; computes median (mean) value and 16% and 84% fractiles (called by computetool.m, computetoolp.m, computetoolr.m)</td>
</tr>
<tr>
<td>fitnorm.m</td>
<td>function file to compute the mean and the variance from a set of data and the confidence intervals assuming Normal (mu, sigma) distribution; confidence intervals are obtained using the T-Student distribution for a chosen alpha (0.16 and 0.84) (16% and 84% fractiles) (for different alpha please change the value in the function callback) (called by tree.m and treeloss.m)</td>
</tr>
<tr>
<td>wfigmngr1.m</td>
<td>function file to manage SELENA windows</td>
</tr>
<tr>
<td>wfighelp1.m</td>
<td>function file to manage SELENA help in main window</td>
</tr>
<tr>
<td>wfigobj1.m</td>
<td>function file to manage objects in windows</td>
</tr>
<tr>
<td>humanloss.m</td>
<td>function file to compute the number of human casualties (called by computetool.m, computetoolp.m, and computetoolr.m)</td>
</tr>
<tr>
<td>humanlosshz.m</td>
<td>function file to compute the number of human casualties according to the HAZUS-methodology (called by computetool.m, computetoolp.m, and computetoolr.m)</td>
</tr>
</tbody>
</table>
Table 3.

**Required input files dependent on the three different analysis types**

<table>
<thead>
<tr>
<th>Analysis type</th>
<th>Input file</th>
<th>Content</th>
<th>Related sub-files</th>
</tr>
</thead>
<tbody>
<tr>
<td>deterministic</td>
<td>earthquake.txt</td>
<td>source parameters of the scenario earthquake(s) and their weights for the Logic Tree</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>attenuation.txt</td>
<td>empirical ground-motion prediction equations (attenuation laws) to be used and their weights (a considerable number of attenuation laws is contained in att_sub.m)</td>
<td>-</td>
</tr>
<tr>
<td>probabilistic</td>
<td>shakefiles.txt</td>
<td>link to those sub-files containing ground motion values (for rock) at the center of each geographical units and weights for the Logic Tree</td>
<td>shakecenter1.txt</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>shakecenteri.txt</td>
</tr>
<tr>
<td>real-time</td>
<td>realtimefile.txt</td>
<td>link to the sub-file containing the real-time ground motion information at geo-referenced coordinates in the study area</td>
<td>realtimegrid.txt</td>
</tr>
</tbody>
</table>
### Required input files which are common for all analysis types

<table>
<thead>
<tr>
<th>Input file</th>
<th>Content</th>
<th>Related sub-files</th>
</tr>
</thead>
<tbody>
<tr>
<td>soilfiles.txt</td>
<td>link to those sub-files containing soil type information at the center of each geographical unit and weights for the Logic Tree</td>
<td>soilcenter1.txt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>soilcenteri.txt</td>
</tr>
<tr>
<td>ubcampfact.mat</td>
<td>containing NEHRP soil amplification factors as given in IBC-2006 (called by gmotion.m)</td>
<td>–</td>
</tr>
<tr>
<td>ec8t1.mat</td>
<td>containing soil amplification factors for Eurocode 8 Type 1 spectra (called by gmotion.m)</td>
<td>–</td>
</tr>
<tr>
<td>ec8t2.mat</td>
<td>containing soil amplification factors for Eurocode 8 Type 2 spectra (called by gmotion.m)</td>
<td>–</td>
</tr>
<tr>
<td>IS1893_1.mat</td>
<td>containing soil amplification factors for Indian code spectra (called by gmotion.m)</td>
<td>–</td>
</tr>
<tr>
<td>header.txt</td>
<td>necessary header in order to create the damage output files which then can be plotted with any GIS</td>
<td>–</td>
</tr>
<tr>
<td>headerocc.txt</td>
<td>file providing the necessary header for the input files occupying the built area (in square meters) according to their occupancy in each geographical unit for the different model building types i.</td>
<td>–</td>
</tr>
<tr>
<td>vulnerfiles.txt</td>
<td>link to those sub-files containing capacity and fragility curve parameters and weights for the Logic Tree</td>
<td>capacity1.txt; fragility1.txt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>capacityi.txt; fragilityi.txt</td>
</tr>
<tr>
<td>capacityi.txt</td>
<td>link to those sub-files in *.mat-format containing the single capacity curves (values of spectral acceleration and spectral displacement) of the model building types</td>
<td>eg. cap_mbt2.mat</td>
</tr>
<tr>
<td>effdamping.mat</td>
<td>containing coefficients ‘A’ to ‘F’ dependent on post-elastic stiffness $\alpha$ (Table 6-1 in FEMA 440) in order to</td>
<td>–</td>
</tr>
</tbody>
</table>
calculate the effective damping $\beta_{\text{eff}}$ based on a stiffness degrading inelastic model (called by \texttt{madrs.m})

effperiod.mat' containing coefficients ‘G’ to ‘L’ dependent on post-elastic stiffness $\alpha$ (Table 6-2 in FEMA 440) in order to calculate the effective period $T_{\text{eff}}$ based on a stiffness degrading inelastic model (called by \texttt{madrs.m})

ocupmbti.txt built area (in square meters) for each model building type $i$ according to occupancy type in each geographical unit

builtarea.txt total built area of each model building type (in square meters) in each geographical unit

numbuild.txt total number of buildings of each model building type in each geographical unit

ecfiles.txt link to those files containing the economic values for the repair or replacement of the different model building types and occupancy types for each of the four damage states ($\text{slight, moderate, extensive, complete}$) and weights for the Logic Tree

population.txt people distribution in each geographical unit at different hours and occupancy types

poptime.txt percentages of people (in decimal numbers) staying indoors in one of the four occupancy classes or outdoors depending on the time of the day

ocupmbtp.txt percentages of the different model building types in one of the four occupancy classes

injuryi.txt casualty rates of severity $i$ (in percentages) for the different damage states $k$ ($\text{slight, moderate, extensive, complete, or complete with collapse}$)

indcasratei.txt Indoor casualty rates (in percentages) for the different
damage states \( i \) (slight, moderate, extensive, complete, or complete with collapse)

\texttt{outcasratei.txt} Outdoor casualty rates (in percentages) for the different damage states \( i \) (moderate, extensive and complete)

\texttt{occmbtpi.txt} Distribution of population (in percentages normalized to 1.0) in each geographical unit and each model building type for the different occupancy classes \( i \) (Residential, Commercial, Educational, Industrial and Hotel)

\texttt{cpfile.txt} Input file which decides on the performance point computation method, whether the damage results will be presented as damaged area or number of damaged buildings and the human loss estimation method

Annotation:

* the different variable input files in MATLAB-format (*.mat) usually need not to be modified by the user
Table 5.

Description of output files and units of results dependent on user-requested output type

<table>
<thead>
<tr>
<th>Output file</th>
<th>Description</th>
<th>User-requested output type</th>
</tr>
</thead>
<tbody>
<tr>
<td>gmotionscen\texti.txt</td>
<td>files containing ground motion ordinates with/without soil amplification, and amplification factors $S_{AV}$ and $S_{AV}[g]$, $S_{AS}$ and $S_{AS}[g]$, $F_{A}$ and $F_{V}$ [–]</td>
<td>damaged area damaged buildings</td>
</tr>
<tr>
<td>dout\texti.txt</td>
<td>damage probability for each branch of the logic tree probabilities</td>
<td></td>
</tr>
<tr>
<td>medianct.txt, 16prctilect.txt, 84prctilect.txt</td>
<td>statistical values of building damage [\mu^2]</td>
<td>numbers</td>
</tr>
<tr>
<td>sqmctdout\texti.txt</td>
<td>damage results corresponding to the branch of the logic tree [\mu^2]</td>
<td>n.a.</td>
</tr>
<tr>
<td>nobctdout\texti.txt</td>
<td>damage results corresponding to the branch of the logic tree n.a.</td>
<td>numbers</td>
</tr>
<tr>
<td>lossl6prctile.txt, lossmedian.txt, loss84prctile.txt</td>
<td>statistical values of economic loss user-defined currency</td>
<td></td>
</tr>
<tr>
<td>eclossesi.txt</td>
<td>results corresponding to the branch of the logic tree containing the economic losses user-defined currency (e.g., US-Dollars, Euro)</td>
<td></td>
</tr>
<tr>
<td>totalinjur16.txt</td>
<td>statistical values of injured persons cumulative number of injured persons</td>
<td></td>
</tr>
<tr>
<td>totalinjurmean.txt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>totalinjur84.txt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hilyinjur16pr.txt</td>
<td>statistical values of injured persons number of injured persons</td>
<td></td>
</tr>
<tr>
<td>hilyinjurmean.txt</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
hlbyinjur84pr.txt
(disaggregated by injury type)

totalinjur.txt
cumulative number of human casualties
numbers of persons (cumulative)
corresponding to the branch of the logic tree

hlbyinjur.txt
number of human casualties corresponding to
number of persons (disaggregated by injury type)
the branch of the logic tree

ltreewght.txt
weight of the damage results (excluding the
weights
branches of economic losses)

endwght.txt
final weight of the economic results (including
weights
all possible branches)

Annotation:

* decided by SELENA after reading the input file cpfile.txt
Figure 4 revised

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The figure illustrates the fragility function for various damage states. The horizontal axis represents the spectral displacement $S_d$, and the vertical axis represents the damage probability $P(ds | S_d)$. The damage states include 'none', 'slight', 'moderate', 'extensive', and 'complete'. The expected spectral displacement $d_p$ is indicated on the graph.
parameters of the scenario earthquake:

ground-motion prediction relation:

subsoil model

capacity curves and fragility functions (vulnerability):

economic model:
Figure captions:

1 Fig. 1. Principle flowchart of a deterministic analysis using the SELENA tool.
2
3 Fig. 2. Standard shape of the design response spectrum. ‘Corner’ periods $T_B$, $T_C$, and $T_D$ are either
4 described by formula relations (IBC-2006) or given as tabular values (Eurocode 8 or IS 1893).
5
6 Fig. 3. Estimating the performance point, i.e. the expected spectral displacement $d_p$ of the respective
7 building under an estimated seismic demand.
8
9 Fig. 4. The expected displacement (obtained by the capacity spectrum method) is overlaid with
10 fragility curves for the different damage states $d_s$ in order to determine the discrete damage
11 probabilities (cf. Fig. 5).
12
13 Fig. 5. Discrete damage probabilities for each damage state $d_s$.
14
15 Fig. 6. Principle of the ‘Logic Tree’ structure. Each branch will be weighted in order to compute the
16 expected values and confidence levels.
17
18 Fig. 7. Flowchart of SELENA v4.1.
19
20 Fig. 8. Prompting windows of SELENA within the MATLAB environment (here for a
21 deterministic analysis).
22
23 Fig. 9. Exemplary selection of input files in txt-format opened in an ordinary text editor.
24
25 Fig. 10. Illustration of risk results which were calculated with SELENA for the city of Oslo,
26 Norway using the Google Earth-based tool RISE (Lang et al., 2008b; Lang and Gutiérrez,
27 submitted).