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"Harmonization of Seismic Hazard Maps for the Western Balkan Countries"

WORKSHOP

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Overview of the Methodology and Software used for Seismic Hazard Assessment

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Mathematical Background

- The mathematical background is the so-called total probability theorem (Cornell (1968, 1971), Merz & Cornell (1973):

$$P(U>u)=\int_R \int_{m_0}^{m_{max}} P(U>u)\big|m,R)\cdot f_M(m)\cdot f_R(R)\cdot dm\cdot dR$$

P(U>u|m,R): probability that ground motion level *u* will be exceeded, given an earthquake of magnitude *m* on a source at distance *R* from the site;
$f_M(m)$: probability distribution of magnitude,
$f_R(R)$: probability distribution of site-source distance;
m_0, m_{max}: lower and upper bound of magnitude, $m_0<m<m_{max}$.

- Summation over all seismic sources gives the anual rate of ground motion exceedance:

$$\mu_u=\sum_{i=1}^{n}\mu_i(u)=\sum_{i=1}^{n}\lambda_i(m_0)\int_R\int_{m_0}^{m_{max}} P(U>u)\big|m,R)\cdot f_M(m)_i\cdot f_R(R)_i\cdot dm\cdot dR$$

$\lambda_i(\mu_0)$: the annual rate of occurrence of earthquakes of magnitude greater than m_0.

Mathematical Background

Except probability distributions of the magnitude and site-to-source distance, implementation of the PSHA also requires:

- A model to describe reliably the seismic activity rate in the region.
- A model to characterize the process that generates the ground motion.

▪ Most of the recent developments in the PSHA have been primarily concerned with introducing different probabilistic models to describe the randomness in earthquake magnitude, recurrence time, and epicentral location, in order to get more realistic descriptions for practical applications.

▪ Different approaches proposed, are distinguished on the way they model seismicity within an area: assuming the earthquake rate of occurrence being uniform throughout (source zone approach), or considering as variable (gridded seismicity: spatially smoothed, kernel methodology).

▪ Intensive efforts are made last years to derive new predictive ground motion models (PGMM) using a much more larger database (Europe-Middle East, and in USA (NGA project)).

General methodology

- Methodologies available for the calculation of seismic hazard are now well established. Generally, four different classes of earthquake source models are used (NSHM, USGS, 2008):
  1) Smoothed gridded seismicity,
  2) Uniform background source zones,
  3) Geodetically derived source zones,
  4) Faults.
- The first two models are based on the earthquake catalog and characterize the hazard from earthquakes between M5 and M6.5-7.0.
- The geodetically derived source zones are used to assess the hazard between M6.5 and the largest potential earthquake in a region.
- Faults mostly contribute to the hazard for earthquakes stronger than M6.5.

Seismicity-Derived Hazard Component

Random seismicity-derived sources (distributed seismicity) account for two types of earthquakes: 1) those that occur off known faults, and 2) moderate-size earthquakes that are not modeled on faults.

- The gridded-seismicity models are based on historical earthquakes and account for the observation that stronger earthquakes occur at near clusters of previous smaller earthquakes.
- Uniform background zones account for the possibility of future random seismicity in areas without historical seismicity and establish a floor to the seismic –hazard calculations.
- Special zones allow for local variability in seismicity characteristics within a zone (for example change in *b*-value, changes in M_{max}, depth, etc.).
- These models are combined together to account for the suite of potential earthquakes that can affect a site.

Practical implementation

- Practical application of PSHA requires a homogenous catalog of historical earthquakes, a description of possible faults and earthquake sources, the parameters describing seismicity for those faults and earthquake sources, and appropriate PGM models in region.
- Uncertainties in interpretations can be handled explicitly through multiple hypothesis, leading to uncertainties in seismic hazard.
- Seismicity models require a declustered earthquake catalog of independent events for calculation of Poissonian (time-independent) earthquake rates.
- Completeness levels have to be estimated from the earthquake catalog, and parameters of magnitude-rate distribution (*b*-values and annual seismic activity rate) are computed using a MLE method (Weichert, 1980) that accounts for variable completeness. The uncertainty in the magnitudes must be taken into account.

Practical implementation

- To calculate the hazard from a particular source, usually a doubly-truncated exponential or G-R magnitude-frequency distribution is used.
- Seismicity rate parameters (a- and b-values) are obtained from analysis of the catalog. For the gridded-seismicity models, the earthquake rates determined for cells are spatially smoothed using a two-dimensional Gaussian smoothing operator (Frankel, 1995) and/or an elliptic rupture-oriented function (Lapaine et al., 2002).
- The hazard is calculated for potential earthquakes at each grid cell. Earthquakes smaller than M6.0 might be characterized as point sources at the center of each cell, whereas earthquakes larger than M6 assume hypothetical finite vertical or dipping faults centered on the source grid. Lengths of the finite faults are determined using relations (Wells and Coppersmith) for all faulting styles taken together.

Practical implementation

Fault sources

- Faults should be specified by geometry (in 3D). Data are necessary regarding sense of the slip, dip angle, maximum depth, total length, maximum rupture length, average displacement per event, slip rate, and magnitude distribution.
- Earthquake recurrence rates for faults are based on geological measurements, geodesy, and seismicity measurements and interpretations.
- Using the fault dimensions, the maximum or characteristic magnitudes can be estimated from relationships that describe their dependence on fault length or area. These parameters, along with the fault slip rate, are needed to define the characteristic and G-R magnitude-frequency distributions.
- It seems rather difficult (at least for Albania) to provide this information, even for the faults that have generated strongest earthquakes with Mw> 6.5 in our region.

Practical implementation

Estimating Seismicity rates

- In light of the recently well established spatial variability in *b*-values, the choice is between an overall constant *b*-value, as done usually in USA (NSHM project), and large variability of *b*-values in regional zonations, which are often simply statistical variations due to the small sample sizes.
- Source zone approach requires to assess the *b*-value for small areas, due to the hypothesis of uniform seismicity within a zone. This induces undue fluctuations of *b* particularly in zones of low seismicity.
- Smoothed seismicity models generally use constant b-values for relatively large areas;

Maximum Possible Earthquake

- It is the most difficult parameter to be assessed because the database to derive it is statistically very limited. M_{max} should be relatively large (Giardini et al. 2004) to take into account large earthquakes with very long recurrence interval. M_{max} should not vary between zones, if it is believed that no fundamental differences between tectonic regions exist.

Predictive Ground Motion Models

Ground-motion prediction equations (attenuation relations) relate the source characteristics of the earthquake and propagation path of the seismic waves to the ground motion at a site.

- The predicted ground motion is typically quantified in terms of a median value (a function of magnitude, distance, style of faulting, and other factors) and a probability density function.
- Different models are in use for our region (Ambraseys et al., 2005; Akkar and Bommer , 2007; Bragato and Slejko, 2005). Several new attenuation relations are recently published (Earthquake Spectra, 2008) in the framework of NGA project. They represent significant advancements using a larger standard dataset of ground motions, and source and path parameters.
- The ground motion can be calculated for various attenuation relations, and then combined using a weighted logic tree analysis.

Uncertainty investigation

- PSHA considers only the inherent random uncertainties, termed as "aleatory" uncertainties, integrating over randomness to calculate the seismic hazard curve; this is what is meant by "annual probability of exceedance".
- Due to inadequacy or lack of available data and incomplete understanding of earthquake and ground-motion generating processes, it is difficult to specify the various input models and their parameters without any uncertainty.
- The large uncertainties in seismic hazard are not a defect of method. They result from lack of knowledge about earthquake causes, characteristics, and ground motions. PSHA only reports the effects of these uncertainties, it does not create or expand them.
- Usually, PSHA uses the logic-tree methodology to quantify the effect of these additional uncertainties, termed as "epistemic" uncertainties.

Uncertainty investigation

- To account for the effect of the epistemic uncertainties, the basis PSHA have to be performed for all the combinations of input leading to various end branches, and resulting hazard curves are assigned the corresponding weights. These can be used to define the mean or the median hazard curve, as well as the hazard curves with desired confidence intervals.

Software for PSHA

- Software to be used in the framework of BSHAP project has to provide the features presented in the above presentation. It is difficult to have all these features implemented in a single computer code.

- Nowadays, various PSHA computer codes are in use (SEISRISK III, FRISK88M^{TM}, EZ-FRISK, etc.). NSHM project (USGS) has made public its source codes (Fortran with some input and output routines in C language). OHAZ is a common production of ARSO and ISA (IGEO). The main difference between these codes stands in the way they estimate the seismic activity rate.

- SEISRISK III is based on the source zone approach, assuming seismic activity rate is constant within source zones. This hypothesis is often in open conflict with spatial distribution of the earthquake epicenters. Although SEISRISK III is product of USGS, is not in use since 1995.

Software for PSHA

- Starting from 1996 (1996, 2002 and 2008 editions) the seismic hazard maps of the USA, are compiled using gridded seismicity, also taking into account the contribution of specific faults that might generate events with M_W greater than 6.5.
- EZ-FRISK (Risk Engineering) allows the users to define their fault and area sources, and the relevant seismic parameters. It is conceived mainly for site-specific seismic hazard analysis. The gridded-site module can be used to create a seismic hazard map by performing PSHA calculations on a grid of points within a boundary.
  - Area sources assume that the rate of occurrence is uniform throughout. Therefore every location within the area has equal probability that an event will occur !
  - EZ-FRISK has also a variable-seismicity background seismic source database (USGS model for background seismicity).

Software for PSHA

- FRISK88M™ is the most sophisticated software package from Risk Engineering. This package uniquely accounts for both randomness and uncertainty. A version of FRISK88M™ is available to conduct seismic hazard mapping. FRISK88M™ does not provide the facilities to compute activity rates and slip rates fro analysis of earthquake catalogs !
- Software package from USGS (NSHM 2008):
  - powerful, but with many specific features for USA territory;
  - source code (Fortran, some functions in C) – public domain;
  - are needed some adjustments for our region, and ad-hoc programming (GNU Fortran, etc.), especially to combine results from different zones and various alternatives (logic-tree);
  - a lot of PGMM models, including the NGA models are available;
  - does not have any user friendly interface; is written for Unix-like environments (in Windows – Cygwin).

Software for PSHA

- OHAZ:
  - smoothed gridded seismicity,
  - uniform background source zones,
  - also seismic source zones approach.
  - contribution from specific faults: it is possible but not yet implemented; maybe unnecessary in our project (lack of data on the faults), but required in other regions.
  - not finished as yet (completeness periods, Tools (Combine, etc.), Help system); some improvements concerning the dynamic memory allocation, etc., are also necessary;
  - needs to extend the PGMM database (NGA models, Bragato and Slejko 2005, Akar and Bommer 2007, etc).

Thank You !