ESTIMATION OF SEISMIC HAZARD PARAMETERS FOR POTENTIAL TSUNAMIGENIC SOURCES IN THE SOUTH CHINA SEA REGION

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OUTLINE

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- Seismic Source Characterization
- Study region and Input data
- Parameter Estimation
- Remarks
INTRODUCTION

Estimation of the seismicity (or seismic hazard) parameters of the tsunamigenic seismic sources plays important role in any tsunami hazard assessment and tsunami warning procedure.

As majority of tsunamis are generated by earthquakes, the similarity in the nature of the occurrence of these phenomena suggests to apply some well-known in seismology methods of seismic source determination and parameters estimation to the case of tsunamis.

In this presentation, we propose a statistical approach of estimation of seismicity parameters for potential tsunamigenic seismic sources, using earthquake data. An example of the use of Maximum Likelihood method to predict the $M_{\text{max}}$ and recurrence period $T(M_{\text{max}})$ for the tsunami sources in the East Vietnam Sea and some adjacent sea areas is shown.

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SEISMIC SOURCE CHARACTERIZATION

Seismic Source Characterization (SSC) refers to the component of SHA in which the locations, size and frequency of future earthquakes are estimated.

Because it is not yet possible to predict the location, size and timing of the next earthquake, seismologists attempt to determine the average rate of earthquake occurrence and use this rate as an indication of the likelihood or probability of future earthquake occurrence. The indication of rate, then, is a distinguishing feature of SHA and a key parameter to be assessed for seismic sources.
SEISMIC SOURCE CHARACTERIZATION

The 3 main elements of the SSC are:

• **Seismic source locations/geometries:** Seismic sources represent locations within the Earth’s crust that have relatively uniform seismicity characteristics. Variations in the estimates of the geometries of sources reflect uncertainties in the spatial distribution of future seismicity. The probability of activity is assessed for each seismic source. Seismicity parameters ($M_{\text{max}}$ and recurrence $T$) are specific to each seismic source.

• **Maximum earthquake magnitude ($M_{\text{max}}$):** is the largest magnitude that a seismic source is capable of generating.

• **Earthquake recurrence ($T$):** is the frequency of occurrence of earthquakes having various magnitudes. Recurrence relationships or curves are developed for each seismic source and reflect the frequency of occurrence (usually expressed on an annual basis) of magnitudes up to the maximum.
SEISMIC SOURCE CLASSIFICATION

The types of sources and the means of characterizing their earthquake behavior varies with the seismotectonic environment.

Seismic sources can be categorized into 4 basic source types (Budnitz R.J. et al., 1997).

- **Type 1**: Faults, represented as lines
- **Type 2**: Area sources enclosing concentrated zones of seismicity
- **Type 3**: Regional area sources
- **Type 4**: Background area sources

In this study, only sources of types 1 and 3 are considered.
The following tsunamigenic sources have been chosen for this study:
1) The Taiwan Sea;
2) The Manila Trench;
3) The Sulu Sea;
4) The Selebes Sea;
5) The North Banda Sea;
6) The South Banda Sea;
7) The North of East Vietnam Sea;
8) The Northwest Borneo-Palawan;
9) The West of the East Vietnam Sea;

(Nguyen et al., 2012).
A catalog of 6267 earthquakes, which consists of both historical and instrumental data up to 2007 was used for this study (IGP). Earthquakes with M≥4.0 were grouped for each source and the subcatalogs were treated for completeness and homogeneity.

<table>
<thead>
<tr>
<th>Tsunami source zone</th>
<th>Observation period</th>
<th>Number of earthquakes</th>
<th>Observed M_{max}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a. Riukiu – Taiwan</td>
<td>1965-2008</td>
<td>89</td>
<td>7.2</td>
</tr>
<tr>
<td>1b. West Taiwan</td>
<td>1964-2008</td>
<td>49</td>
<td>6.7</td>
</tr>
<tr>
<td>2a. North Manila Trench</td>
<td>1958-2006</td>
<td>36</td>
<td>8.2</td>
</tr>
<tr>
<td>2b. Central Manila Trench</td>
<td>1872-2008</td>
<td>193</td>
<td>8.0</td>
</tr>
<tr>
<td>2c. South Manila Trench</td>
<td>1974-1993</td>
<td>16</td>
<td>6.2</td>
</tr>
<tr>
<td>3. The Sulu Sea</td>
<td>1964-2006</td>
<td>95</td>
<td>7.9</td>
</tr>
<tr>
<td>4. The Seledes Sea</td>
<td>1964-2007</td>
<td>139</td>
<td>8.0</td>
</tr>
<tr>
<td>5. The South Banda Sea</td>
<td>1998-2006</td>
<td>29</td>
<td>6.3</td>
</tr>
<tr>
<td>6a. The North Banda Sea 1</td>
<td>1608-2008</td>
<td>156</td>
<td>7.6</td>
</tr>
<tr>
<td>6b. The North Banda Sea 2</td>
<td>1966-2007</td>
<td>61</td>
<td>6.5</td>
</tr>
<tr>
<td>8. Northwest Borneo-Palawan</td>
<td>1930-1995</td>
<td>7</td>
<td>6.0</td>
</tr>
<tr>
<td>9. West of the East Vietnam Sea</td>
<td>1919-2005</td>
<td>18</td>
<td>6.1</td>
</tr>
</tbody>
</table>
PARAMETERS ESTIMATION

METHOD USED

There are many statistical methods for estimating seismic hazard parameters for the seismic sources.

In this study, an example of using the Maximum Likelihood method is given. The advantage of the Maximum Likelihood procedure is that it allows incorporating as much magnitude information as possible toward the low values direction.

• Proposed by Kijko A. in 1985s.
The available earthquake catalogs usually contain two types of information: macroseismic observation of major seismic events that occurred over a period of a few hundred years, and complete instrumental data for relatively short periods of time. 

(Kijko and Sellevoll, 1992).
PARAMETERS ESTIMATION

THEORETICAL BACKGROUND

1. Extreme magnitude distribution applied to the macroseismic part of the catalog

Let us assume the Poisson occurrence of earthquakes with the activity rate $\lambda$ and the doubly truncated Gutenberg-Richter distribution $F(x)$ of earthquake magnitude $x$. The doubly truncated exponential distribution can be represented by:

$$F(x) = P(X \leq x) = \frac{A_1 - A(x)}{A_1 - A_2}; M_{\text{min}} \leq x \leq M_{\text{max}}$$

where $A_1 = \exp(-\beta M_{\text{min}})$, $A_2 = \exp(-\beta M_{\text{max}})$, $A_x = \exp(-\beta x)$; $M_{\text{max}}$ is the maximum magnitude value, $M_{\text{min}}$ is the threshold magnitude and $\beta$ is a parameter. The above assumption implies that earthquakes of magnitudes greater than $x$ can be represented by a Poisson process with mean rate of occurrence $\lambda[1-F(x)]$. 

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The probability that $X$, the largest magnitude within a period of $t$ years will be less than some specified magnitude $x$ is given by:

$$G(x|t) = P(X \leq x) = \exp\{-v_0 t \left[\frac{A_2 - A(x)}{A_2 - A_{10}}\right]\}$$

(2)

where $G$ is the distribution function, $v_0 = \lambda [1 - F(M_0)], A_{10} = \exp(-\beta M_0)$ and $M_0$ is the threshold magnitude for the extreme part of catalog, $(M_0 \geq M_{\min})$.
PARAMETERS ESTIMATION

THEORETICAL BACKGROUND

In the case discussed, the data for determination of seismic parameters are the largest earthquake magnitudes selected from the first part of the catalog, from time intervals \( t = (t_1, t_2, \ldots, t_{n_0}) \). The seismic parameters sought are \( \theta = (\beta, \lambda) \) and \( M_{\text{max}} \).

From equation (2) it follows that the maximum likelihood of \( \theta \) is (Kijko and Dessokey, 1987):

\[
L_0(\theta|X_0) = \prod_{i=1}^{n_0} g(X_{0i}, t_i | \theta)
\]

where \( g \) is the probability density function and

\[
\ln g(x, t|\theta) = \frac{A_2 - A(x)}{A_{10} - A_2} + \ln \frac{\nu_0 \beta t}{A_{10} - A_2} - \beta x
\]
2. Combination of Extreme and Complete catalogs with different threshold magnitudes

Let us assume that the second, complete part of the catalog can be divided into $s$ subcatalogs. Each of those with a time span $T_i$ is complete starting from the known threshold magnitude $M_i$, $i = 1, 2, ..., s$. Let us also assume, that the values $\left( \overline{x_j}, \overline{X_j} \right)$, $j = 1, 2, ..., n_i$ denote the lower and upper limits of the magnitude. Intervals defined in that way contain the real unknown magnitude, $n_i$ denotes the number of earthquakes in each subcatalog, and $s$ denotes the number of complete subcatalogs.
PARAMETERS ESTIMATION

THEORETICAL BACKGROUND

2. Combination of Extreme and Complete catalogs with different threshold magnitudes
PARAMETERS ESTIMATION

THEORETICAL BACKGROUND

If the size of seismic events is independent of their number, the likelihood function of \( L_i \) for each subcatalog can be written as a product of two functions:

\[
L_i(\theta | X_i) = L_i(\beta | X_i) \cdot L(\lambda | X_i)
\]  

(5)

The joint likelihood based on all data, i.e. the likelihood function for the whole span of the catalog is given by

\[
L(\theta | X) = \prod_{i=0}^{s} L_i(\theta | X_i)
\]  

(6)

The sought parameters \( \lambda \) and \( \beta \) can be obtained by solving the system of equations for \( \lambda \) and \( \beta \):

\[
\begin{align*}
\frac{\delta \ln L(\theta | X)}{\delta \lambda} &= 0 \\
\frac{\delta \ln L(\theta | X)}{\delta \beta} &= 0
\end{align*}
\]  

(7)
Seismic hazard parameters of the tsunamigenic sources in the South China Sea estimated by the Maximum Likelihood Method

<table>
<thead>
<tr>
<th>No</th>
<th>Tsunamigenic source</th>
<th>$M_{\text{max}}$</th>
<th>$T(M_{\text{max}})$ years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Riukiu – Taiwan</td>
<td>$7.7 \pm 1.60$</td>
<td>1150</td>
</tr>
<tr>
<td>1b</td>
<td>West Taiwan</td>
<td>$7.2 \pm 0.99$</td>
<td>1467</td>
</tr>
<tr>
<td>2a</td>
<td>North Manila Trench</td>
<td>$8.7 \pm 0.93$</td>
<td>2658</td>
</tr>
<tr>
<td>2b</td>
<td>Central Manila Trench</td>
<td>$8.5 \pm 0.85$</td>
<td>2864</td>
</tr>
<tr>
<td>2c</td>
<td>South Manila Trench</td>
<td>$6.7 \pm 0.28$</td>
<td>78</td>
</tr>
<tr>
<td>3</td>
<td>The Sulu Sea</td>
<td>$8.4 \pm 1.17$</td>
<td>2442</td>
</tr>
<tr>
<td>4</td>
<td>The Selebes Sea</td>
<td>$8.5 \pm 1.03$</td>
<td>2030</td>
</tr>
<tr>
<td>5</td>
<td>The South Banda Sea</td>
<td>$6.8 \pm 0.76$</td>
<td>171</td>
</tr>
<tr>
<td>6a</td>
<td>The North Banda Sea 1</td>
<td>$8.1 \pm 0.53$</td>
<td>3284</td>
</tr>
<tr>
<td>6b</td>
<td>The North Banda Sea 2</td>
<td>$7.0 \pm 0.61$</td>
<td>560</td>
</tr>
<tr>
<td>7</td>
<td>North of the East Vietnam Sea</td>
<td>$7.0 \pm 0.23$</td>
<td>283</td>
</tr>
<tr>
<td>8</td>
<td>Northwest Borneo-Palawan</td>
<td>$6.5 \pm 0.42$</td>
<td>1617</td>
</tr>
<tr>
<td>9</td>
<td>West of the East Vietnam Sea</td>
<td>$6.6 \pm 0.28$</td>
<td>976</td>
</tr>
</tbody>
</table>
**REMARKS**

1. Statistical approach can be used to estimate Maximum earthquake magnitude and Earthquake recurrence for the potential tsunamigenic sources. The results obtained depend solely on seismological data and need to be verified by other geological and geodynamic information.

2. The recurrence time $T(M_{\text{max}})$ that corresponds to the $M_{\text{max}}$ value of a tsunamigenic source can be used to predict the return period of destructive tsunamis. This approach has advantage in case when no historical tsunamis data is available.
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THANK YOU!