Modeling scenarios of earthquake-generated tsunamis for the Vietnam coasts

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Direct and inverse problems in seismology

- A wide set of **direct** and **inverse** problems in seismology may significantly benefit from advanced e-infrastructures and improved computational capability.

- **Aim:** allow for a physically sound and reliable assessment of **seismic** and **tsunami hazard**, and, in conjunction with geophysical data assimilation, improve the current **understanding of the Earth structure and dynamics**.
**Top Eleven Deadliest earthquakes since 2000**

All of them are “surprises” with respect to traditional probabilistic ground shaking estimates (GSHAP). Some of them also generated tsunamis. => Need for a new scenario-based approach to seismic and tsunami hazard assessment.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Magnitude</th>
<th>Initial Intensity</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sendai (Japan, 11.03.2011, M9.0)</td>
<td>∆I=3.3</td>
<td>&gt; 20,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port-au-Prince (Haiti, 12.01.2010, M7.3)</td>
<td>∆I₀ = 2.2</td>
<td>222,570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Padang (Southern Sumatra, Indonesia, 30.09.2009, M7.5)</td>
<td>∆I₀ = 1.8</td>
<td>1,117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wenchuan (Sichuan, China, 12.05.2008, M8.1)</td>
<td>∆I₀ = 3.2</td>
<td>87,587</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yogyakarta (Java, Indonesia, 26.05.2006, M6.3)</td>
<td>∆I₀ = 0.3</td>
<td>5,749</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kashmir (North India and Pakistan border region, 08.10.2005, M7.7)</td>
<td>∆I₀ = 2.3</td>
<td>86,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nias (Sumatra, Indonesia, 28.03.2005, M8.6)</td>
<td>∆I₀ = 3.3</td>
<td>1,313</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bam (Iran, 26.12.2003, M6.6)</td>
<td>∆I₀ = 0.2</td>
<td>31,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boumerdes (Algeria, 21.05.2003, M6.8)</td>
<td>∆I₀ = 2.1</td>
<td>2,266</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bhuj (Gujarat, India, 26.01.2001, M8.0)</td>
<td>∆I₀ = 2.9</td>
<td>20,085</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Possible approaches to tsunami modeling

- **Classical hydrodynamic approach**: numerical solution of Navier-Stokes equations with bottom lift condition. Partial liquid-solid coupling.

- **Modal approach**: tsunami as a low frequency gravity mode generated in a liquid layer over a solid structure (Ward, 1980; Okal, 1982; Comer, 1984; Panza et al., 2000)
Modal approach

- Considering tsunami as a gravity mode allows us to use the **modal technique** to compute complete signals; this permits very fast calculations.

- Seismic source is naturally included in computation, directly as a force, and not treated as an external condition.

- The low computational costs and the efficiency in including the source mechanism can be very helpful in **fast computation** of tsunami hazard scenarios.
New approach based on the possibility to compute synthetic tsunamigrams by the modal technique.

Starting from the available information about seismic sources and bathymetry, the off-shore expected tsunami wave is modeled, considering a wide set of scenario events.

Possibility to use extended sources

Fast computation!!
Seismotectonic map of Vietnam
Tsunami scenarios for the Vietnam’s coasts

Map of the Southern Chinese Sea, with the locations of the six selected tsunamigenic seismic sources (the red pins correspond to the epicenters), and of the seven selected receiver sites (yellow pins) along the Vietnam coasts.
Synthetic tsunamigrams computed at the different sites for Source 1 scenario

<table>
<thead>
<tr>
<th>Site</th>
<th>Khan Hoa</th>
<th>Vung Tau</th>
<th>Bac Lieu</th>
<th>Quang Ninh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td>911</td>
<td>1028</td>
<td>1160</td>
<td>1736</td>
</tr>
<tr>
<td>Tmax (min)</td>
<td>205</td>
<td>229</td>
<td>261</td>
<td>397</td>
</tr>
<tr>
<td>Tmax - Tmin (min)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Strike max (°)</td>
<td>30</td>
<td>15</td>
<td>7.5</td>
<td>60</td>
</tr>
<tr>
<td>Max(cm) M=7</td>
<td>16</td>
<td>14</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Max(cm) M=7.5</td>
<td>93</td>
<td>84</td>
<td>76</td>
<td>56</td>
</tr>
<tr>
<td>Max(cm) M=8</td>
<td>378</td>
<td>345</td>
<td>314</td>
<td>225</td>
</tr>
</tbody>
</table>
Tsunami scenarios - **Source 2**

Synthetic tsunamigrams computed at the different sites for Source 2 scenario

<table>
<thead>
<tr>
<th>Site</th>
<th>Khan Hoa</th>
<th>Bin Dinh</th>
<th>Quang Ninh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td>571</td>
<td>598</td>
<td>1214</td>
</tr>
<tr>
<td>Tmax (min)</td>
<td>150</td>
<td>156</td>
<td>312</td>
</tr>
<tr>
<td>Tmax − Tmin(min)</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Strike max (°)</td>
<td>0</td>
<td>15</td>
<td>52.5</td>
</tr>
<tr>
<td>Max(cm) M=7</td>
<td>11</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Max(cm) M=7.5</td>
<td>64</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Max(cm) M=8</td>
<td>290</td>
<td>276</td>
<td>150</td>
</tr>
</tbody>
</table>
Snapshots of the tsunami wave heights for a $M_w=8.0$ earthquake at Source 1 location.
Tsunami hazard for the Vietnam’s coasts

Distribution of the maximum positive tsunami wave heights along the Vietnam coasts computed considering the six sources with Mw=7.0
Tsunami hazard for the Vietnam’s coasts

Distribution of the maximum positive tsunami wave heights along the Vietnam coasts computed considering the seven sources defined according to historical seismicity
Tsunami hazard for the Vietnam’s coasts

Distribution of the maximum positive tsunami wave heights along the Vietnam coasts computed considering the seven sources defined based on maximum credible earthquake, including the extreme scenario of M=9.0 at Manila Trench.
Extended seismic source models

Method DWN (Pavlov, 2002)

Point source approximation

FPS and radiation pattern

Extendend source kinematic model

2-dimensional final slip distribution over a source rectangle.
Rupture front evolution is simulated kinematically from random rupture velocity field.
Synthetic tsunamigrams computed at the different sites for Source 3 scenario, considering point source approximation (continuous line) and extended source (dashed line).
Synthetic tsunamigrams computed at the different sites for Source 4 scenario, considering point source approximation (continuous line) and extended source (dashed line).
Tsunami hazard for the Vietnam’s coasts

- Events with magnitude M=8.0 (which is nearly the maximum magnitude expected in many regions of the South China domain) could generate tsunamis with amplitudes up to a few meters, in agreement with a number of historical events reported in the catalogues.

- The shoaling and other amplification phenomena due to the local morphology, could increase that amplitude, enough to cause some damages and inundations, specially if coinciding with the high tide or a sea storm.

- The low level of monitoring of the South China Sea and the high degree of anthropization of the Vietnam coasts (and their high level of vulnerability) could make the risk quite high.
Finite Fault Model: Preliminary result of the Mar 11, 2011 Mw 8.9 Earthquake Offshore Honshu, Japan (Gavin Hayes, USGS):

Cross-section of slip distribution. The strike direction of the fault plane is indicated by the black arrow and the hypocenter location is denoted by the red star. The slip amplitude are showed in color and motion direction of the hanging wall relative to the footwall is indicated by black arrows. Contours show the rupture initiation time in seconds.
Japan earthquake March 11, 2011
(few seconds of computations...)

Modeled vs Observed tsunamigrams
The tsunamis are computed for different scenarios, compatible with seismic history and seismotectonics.

Two possible source localizations adopted for the tsunami modeling:

1) **offshore**, in front of the Croatian coastlines, where many historical tsunamis occurred.

2) **inland**, associated to the historical event of 26/3/1511

**Area:**

Adriatic Basin

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**Tsunami hazard: inland sources**

Synthetic mareograms for Zone 1, $H = 10$ km (blue), 15 km (red), 25 km (green). Magnitude: $M = 6.5$.

Synthetic mareograms for Zone 6, magnitude, $M = 7.0$. Above: dip angle=45°; below: dip angle=30°. Blue line, $d = 20$ km; red line, $d = 40$ km.
Tsunami hazard: expected waves ingestion

Comparison of the coast line in quiet conditions and maximum ingestion of two scenario tsunamis A and B.
Conclusions

- The considered method, based on modal technique, makes it possible to define a set of \textit{earthquake-generated tsunami scenarios} for the Vietnam coasts, using the current knowledge of the physical process of earthquake generation and wave propagation.

- An \textit{improved computational capability} would enable us the \textit{fast computation} of increasingly realistic tsunamigrams, dealing efficiently with the \textit{complexity of the seismic sources}, and to carry out \textit{parametric studies} that may permit accounting for the related uncertainties.
Long-term international collaborations on seismic and tsunami hazard assessment are ongoing, based at the DiGeo - University of Trieste and at the ICTP-SAND Group, in the framework of various projects and scientific networks:

- **Europe**: Switzerland, Germany, Spain, Russia, CEI Countries network: Bulgaria, Croatia, Czech Republic, Hungary, Romania, Albania, Macedonia, Republic of Moldova
- **Asia**: China, India, Iran, Pakistan, Vietnam, Nepal (“Seismic hazard in Asia” Scientific Network)
- **Africa**: Morocco, Algeria, Tunisia, Libya, Egypt, Ghana (NASG - North Africa Seismological Group)
- **America**: Cuba, Chile, Argentina, Ecuador, USA

Activities: ICTP advanced schools and workshops (on a yearly basis); fellowships, scholarships and visits exchange; sharing of software and computing resources.
Main outcomes:

- **Current methods for seismic hazard assessment** are moving towards physical modelling of earthquake ground motions, mainly due to the lack of statistically representative and complete data.

- Both probabilistic and deterministic methods are essentially coming to a scenario-based approach, aiming to include a wide range of possible seismic sources into their analysis.

Agenda and Summary report:

E:\ictp\ACTIVITY\CDSAGENDA V_5 Advanced Conference on Seismic Risk Mitigation and Sustainable Development.mht