The Role of Physics-based Ground Motion Simulations for Seismic Hazard Assessment

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Probabilistic Seismic Hazard Assessment

Earthquake Source

Ground Motion Hazard Curve

Ground Motion

Peak ground acceleration

Distance

ARD Curve

M 7.6 every 25 years

San Andreas fault

r1

d1

r2

d2

r3

d3

0.5g acceleration (pga)
Seismicity Worldwide (1900-2012)
SHARE European Earthquake Catalog

Spatial distribution of Earthquake Catalogue as a function of Moment Magnitude (Mw)
Near-Source Ground Motion Data Base

\((R_{JB} \leq 20\text{km})\)

**JAPANESE**

- Records: 667

**EUROPEAN**

- Records: 198

**NGA**

- Records: 122

(Laurendeau et al. 2012)

(Akkar, 2012)

(Chiou et al., 2008)

Lack of data: \(R < 7\text{-}10\text{km}, M_w > 7\)

Need to fill this lack of data!!
Lack of data!!

- With exception of high seismicity zones, the reality is that we do not have so much data.

- Even in high seismicity zones, data near the source and for earthquakes $M > \sim 7$ are sparse.

- We put emphasis near the source where ground motions are dominated by the source effects.
What if the NPP is here?
Do we have enough data to predict it?
Near-Source (kink faults)

Or here?
Near-Source (step over faults)

Or here?
Faults are geometrically complex at all scales
We need to understand ground motion produced by them

Dawers & Anders 1995
Empirical models (GMPEs) are insufficient for the prediction of near-source ground motion for use in seismic hazard and risk assessment. That is because these GMPE are based solely on recorded data which are sparse in the near field.
- Then Hazard and risk assessment need to relay in numerical modeling to adequately assess the Hazard in the zone of interest.
- For meaningful prediction in areas where there is no data (near source, Mw > 7 and low seismicity zones), simulations have to be based on well defined physics.
The physics of Earthquake

- The physics of wave propagation are now well developed and well understood

\[ \rho \dot{v}_i = \partial_i \sigma_{ij} \]
The physics of earthquake rupture can be described as a two-step process: (1) formation of crack and (2) propagation or growth of the crack. The crack tip serves as a stress concentrator due to driving force; if the stress at the crack tip exceeds some critical value, then the crack grows unstably accompanied by a sudden slip and stress drops.

\( \tau_y = \text{Yielding stress} \)
Problem statement

Volume domain of interest
(a piece of the earth)

Fault
(a discontinuity in the earth)
Problem statement

Fault rupture
(Dynamically propagates as a running shear crack)

Tectonic loading

Stress concentration

Earthquake simulation!!
Earthquake simulation!!

Mathematical model: Elastodynamic coupled to frictional sliding (Highly non-linear problem)

\[ \rho \dot{v}_i = \partial_i \sigma_{ij} \]
\[ \dot{\sigma}_{ij} = C_{ijpq} \partial_p v_q \]
\[ \tau \leq \tau_c \]

\( \tau_c = \text{frictional strength}; \; 0 \leq \tau_c = f(\sigma_n, \dot{s}, s, \psi_1, \psi_2...) \)

Friction constitutive equation
Developments of Physics-based earthquake models

Contribute to substantial advances in our understanding of different aspects related to earthquake mechanism and near-source ground motion.
Super-shear rupture: Velocity pulses transmit large amplitude motion. Because Shear Mach waves are emanated from the rupture front.
Some phenomena identified by dynamic models

Local Super-shear rupture area: Increase with earthquake size

(Mena et al., 2012)
Some phenomena identified by dynamic models

**Surface Vs Subsurface Earthquakes:** Buried rupture can propagate higher frequency ground motion than Surface-rupturing earthquakes

![Graphs showing velocity and spectral velocity plots for Sub-Surface and Surface earthquakes](attachment:graphs.jpg)
Some phenomena identified by dynamic models

Surface Vs Subsurface Earthquakes:
Strike-slip buried rupture may produce supersaturation

(Baumann and Dalguer, 2014, BSSA)
Earthquakes with apparent supersaturation (Parkfield and Imperial Valley)

(Graizer and Kalkan, 2011)
Some phenomena identified by dynamic models

Earthquake Rupture complexity: Rupture reactivation

Gabriel et al. (2012)
Slip reactivation during Mw 9.0 2011 Tohoku

From Source slip inversion model of Lee et al (2011)

(Lee et al, 2011, GRL)

Gabriel et al. (2012)
Some phenomena identified by dynamic models

Earthquake Rupture complexity: Multi-type of ruptures

- Slip rate
- Collision of rupture fronts
- Shear stress

Two supershear rupture fronts

Back-propagating rupture

Gabriel et al. (2012)
We need to know earth structure

With current technology and seismological method we can get information from earth structure
Faults

- With current technology and seismological method we can also identify faults.

- If not, assume hypothetical faults to mitigate potential earthquakes for an expected $M_{\text{max}}$. 

Euro-Mediterranean Fault Database (SHARE)
Large Scale Validation Project Using the SCEC Broadband Ground Motion Simulation Platform

The community is preparing the models!!

Short term goal: supplement data for development of hazard models (SWUS, NGA-East)

Long term goal: develop acceptance of simulations for engineering design

Goulet et al (2014)
Validation schemes

A. Against recorded earthquake ground motions
B. Against GMPEs for generic scenarios

Validation process allows
- for development of region-specific rules (source scaling, path)
- Method refinements

Goulet et al (2014)
### Events and stations

- **Large dataset (25 EQs)**
- **Many regions & tectonic environments**
- **Span wide magnitude range (Mw 4.6 to 7.62)**
- **Variety of mechanisms**
- **Well-recorded (16 EQs with > 40 records within 200 km)**
- **Select large subset of stations (~40) that are consistent with mean and standard deviation PSa of the full dataset.**

Goulet et al (2014)

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**Table: Events and stations**

<table>
<thead>
<tr>
<th>Region</th>
<th>Event Name</th>
<th>Year</th>
<th>Mw</th>
<th># Records &lt; 200 km</th>
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<tbody>
<tr>
<td>WUS</td>
<td>Loma Prieta</td>
<td>1989</td>
<td>6.94</td>
<td>59</td>
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<td>WUS</td>
<td>Northridge</td>
<td>1994</td>
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<td>WUS</td>
<td>Landers</td>
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<td>WUS</td>
<td>Whittier Narrows</td>
<td>1987</td>
<td>5.89</td>
<td>95</td>
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<td>WUS</td>
<td>North Palm Springs</td>
<td>1986</td>
<td>6.12</td>
<td>32</td>
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<td>JAPAN</td>
<td>Tottori</td>
<td>2000</td>
<td>6.59</td>
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<td>WUS</td>
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<td>2007</td>
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<td>CENA</td>
<td>Saguenay</td>
<td>1988</td>
<td>5.81</td>
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<td>L' Aquila</td>
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<td>NEW ZEALAND</td>
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<td>6.20</td>
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<tr>
<td>NEW ZEALAND</td>
<td>Darfield</td>
<td>2010</td>
<td>7.00</td>
<td>24</td>
</tr>
</tbody>
</table>
Large Scale Validation Project

Part A:

Evaluation products

- Goodness-of-fit measures for PSA
  - Average GOF with T for all stations within an event

- Average GOF with T for all realizations (all stations)

Goulet et al (2014)
Part B: Fault and Station Geometry

Scenario: M6.6, **Strike-slip**, R=20km, SoCal

Scenario: M6.6, **Reverse**, R=20km, SoCal

(Image Source: SCEC BBP)
Large Scale Validation Project

Part B:

Scenarios from NGA-West1&2 well constrained by data at 20 and 50 km $R_{rup}$
- M5.5 REV
- M6.2 SS
- M6.6 SS & REV

50 realizations of the source, WITH randomized hypocenter location for each

Simulations for two velocity models: NorCal and SoCal

Goulet et al (2014)
Example (ShakeOut Scenario Mw7.8)
Conclusions

- We do not have another option: This approach needs to be considered in the future.

- Physics-based rupture and ground motion modeling is needed for meaningful Hazard assessment

- In the next 5-10 years, physics-based simulations are going to be the main ingredient of Hazard studies.

- This have to be done in a community level, calibrate numerical models, standardize the methodology and provide practical guidance.

- Then we need to prepare the community
Workshop:
“Best Practice of Physics-based Rupture Models for Seismic Hazard Assessment of Nuclear Installations”

Date: 18-21 November 2015
Venue: VIC, IAEA, Vienna
Important dates:
Abstract submission deadline: May 2015
Full paper submission deadline: August 2015
Registration deadline: 31st October 2015
Risk Equation

Risk = Probable Loss (lives & dollars) = Hazard × Exposure × Fragility

Faulting, shaking, landsliding, liquifaction
Extent & density of built environment
Structural vulnerability

from SCEC
Growth of Earthquake Risk

Growth of cities 2000-2015

Source: National Geographic