Probabilistic Tsunami Hazard Analysis

Hong Kie Thio
URS Corp
Tsunami hazard - probabilistic

• Integration over a broad range of seismic sources with varying sizes and recurrence rates
• Formal inclusion of uncertainties through logic trees and distribution functions
• Straightforward for offshore waveheights because of linear approximation (analogous to stiff site condition)
• How do we extend probabilistic offshore waveheights to inundation (i.e. site behaviour)?
Expression of probability

• Assuming Poissonian (time-independent) process:
  – \( P = 1 - e^{-\gamma t} \), where \( P \) = probability of exceedance, \( \gamma \) = average annual rate of exceedance and \( t \) = exposure time.
  – Average Return Period (ARP) = \( 1/\text{Average Annual Rate} \)
  – Typical engineering levels:
    • 10% in 50 years -> 475 years ARP
    • 5% in 50 years -> 975 year ARP
    • 2% in 50 years -> 2475 years ARP
Probabilistic Tsunami Hazard Analysis

Aim:

• Determine the probability of exceeding a certain hazard level (e.g. wave amplitude)
• Determine the hazard level that is exceeded for a particular probability (or set of probabilities)
Tsunami Hazard Curve
Application of PTHA

- Performance Based Engineering
  - Chapter on Tsunami Loads in next iteration of ASCE 7
- Risk/Loss modeling
- Land use planning
What is the final product?

- Waveheight
- Inundation
- Flow depth - D
- Flow velocity – V (maybe at minimum flow depth)
- Momentum, momentum flux
- Drawdown, duration
- Vorticity
- Combinations of the above?
Concepts of Probability

Frequency (aleatory)
- Describes the natural (physical) variability of earthquake processes
- Typically expressed in the form of distribution functions

Judgment (epistemic)
- Expresses the uncertainty in our understanding of earthquake processes
- Included as different branches of a logic tree that each express a different opinion, or belief
What are the largest uncertainties in PTHA?

- Source models
  - Recurrence
  - $M_{\text{max}}$
  - Slip Distribution
- Digital Elevation Models
  - Near-shore Bathymetry
  - Onshore Elevations (SRTM: errors of $>10$ m)
- Numerical Models
  - Near-shore Propagation/Inundation
Aleatory: Magnitude Distribution

Truncated exponential distribution

Characteristic distribution
Slip Relations

Crustal

Magnitude-Slip Displacement Scaling for Crustal Earthquakes

Subduction

Magnitude-Slip Displacement Scaling for Subduction Interface Earthquakes

[Graphs showing linear relationships between magnitude and displacement for both crustal and subduction earthquakes with data from specified sources]
Alaska-Aleutian Subduction Zone

USGS model for PSHA:
- Coupling ~50%
- Strong segmentation
- Gutenberg-Richter relation for most segments
Further work for slip models

• Comprehensive scaling relations for subduction zone interface
  – Maximum magnitude
  – Average and maximum slip
  – Concentrate on larger (M > 6.5) events
  – Reduction in sigma?
  – By-pass magnitude scaling?

• Stochastic slip models
Source recurrence model

• Generic model
  – $M_{\text{max}}$ based on $L_{\text{max}}$
  – Recurrence rate based on plate motions

• Specific model
  – $M_{\text{max}}$, recurrence based on instrumental, historic and paleo-tsunami observations
  – Inferences from tectonic models (e.g. Marianas vs Chile type subduction)

• Increased weight on specific model depending on completeness and duration of catalog
Aleatory Uncertainty from Scenario Modeling
Benchmarking - Okushiri

- Iwanai:
  - URS - NRMSD = 28%
  - URS - ERR Max Wave Amp = 9%

- Esashi:
  - URS - NRMSD = 15%
  - URS - ERR Max Wave Amp = 30%

**Okushiri Island Runup**

- ERR Runup = 19%
Effect of Variability on Hazard Curves

Hazard curves

- No variability/σ
- σ
- σ + Dip variation
- σ + Dip + rupture

SF Bay

Cascadia

ε truncation

- ε = 0
- ε = 2
- ε = 3
- ε = 4

Average Return Period (years)

Exceedance Waveheight (meters)

Return Period (yr)

Waveheight (m)
Effect of Tides on PTHA

Astoria.OR-0

Santa.Monica.CA-0
Variability of global DEM’s
How and where do we apply our uncertainties

• Source
  – In many ways similar to seismic
  – Variability in slip and scaling are important

• Offshore
  – Straightforward in case of probabilistic exceedance amplitudes

• Onshore
  – Difficult due to strong non-linearity
  – May need to apply on the offshore waveheights and propagate in
Average return period: 975 yr
Offshore waveheight hazard

72 yr
475 yr
975 yr
2500 yr
Source disaggregation

Morro_Bay-475yr

San_Pedro-475yr
Cascadia Model

- $M_w=8.1-9.2$
- $D_{\text{max}}=2 \times D_{\text{ave}}$
- Asperities 1/3 of total rupture (x3)
- Narrow and wide models (x2)
- With and without splay (x2)
Probabilistic Inundation Maps

Morro_Bay−0.96c

ARP

Morro Bay−0.96c

ARP
Probabilistic Inundation Maps
Probabilistic Inundation Maps

Santa_Cruz-0.96c

Monterey-0.96c
Probabilistic Inundation Maps

Avila_Beach-0.96c

Pacifica-0.96c

West_Frisco-0.96c

Golden_Gate-0.96c
Probabilistic Inundation Maps

Oceanside-0.96c

San_Diego-0.96c
Conclusion

• Important to quantify uncertainties in every stage of the hazard model, including modeling uncertainties

• Aleatory variability in rupture models should be included

• Close coordination between the USGS Seismic Hazard Mapping program and NTHMP
PTHA Inundation in Hawaii
Probabilistic offshore waveheight

Exceedance waveheights: 975 yr