PTHA for Seaside, Oregon
… and Other Studies

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Earth and Space Sciences

17 June 2010 Scoping Meeting

for California Probabilistic Tsunami Hazard Map Projects

UC Berkeley

Tsunami Pilot Study Working Group

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David	Carlton	FEMA, Dept. of Homeland Security
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Brief History …
FEMA Initiative that Led to PTHA Development

2004: • **FEMA Workshops** ***to Update NFIP Tsunami Hazard Mapping Guidelines***
• **Final Draft Guidelines for Coastal Flood Hazard Analysis &Mapping for Pacific Coast of U.S.**

2005: Chowdhury, et al. – *Pilot Study Recommended* [*fema.gov/pdf/fhm/frm_p1tsun.pdf*]

2006: TPSWG – *Pilot Study Completed* [*pmel.noaa.gov/pubs/PDF/gonz2975/gonz2975.pdf*]

2009: González, et al. – *PTHA Methodology* [*agu.org/journals/jc/jc0911/2008JC005132/*]

2005

FOCUSED STUDY REPORTS

Tsunami Hazards

FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report

February 2005

Focused Study Leader
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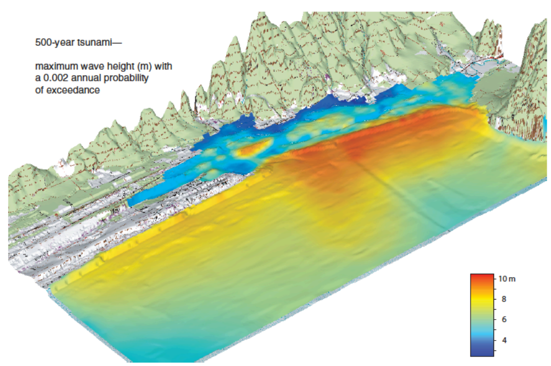
2006

Seaside, Oregon Tsunami Pilot Study— Modernization of FEMA Flood Hazard Maps

By Tsunami Pilot Study Working Group



Joint NOAA/USGS/FEMA Special Report
U.S. National Oceanic and Atmospheric Administration
U.S. Geological Survey
U.S. Federal Emergency Management Agency

NOAA USGS science for a changing world FEMA

2009

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, C11023, doi:10.1029/2008JC005132, 2009

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Probabilistic tsunami hazard assessment at Seaside, Oregon, for near- and far-field seismic sources

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[1] The first probabilistic tsunami flooding maps have been developed. The methodology, called probabilistic tsunami hazard assessment (PTHA), integrates tsunami inundation modeling with methods of probabilistic seismic hazard assessment (PSHA). Application of the methodology to Seaside, Oregon, has yielded estimates of the spatial distribution of 100- and 500-year maximum tsunami amplitudes, i.e., amplitudes with 1% and 0.2% annual probability of exceedance. The 100-year tsunami is generated most frequently by far-field sources in the Alaska-Aleutian Subduction Zone and is characterized by maximum amplitudes that do not exceed 4 m, with an inland extent of less than 500 m. In contrast, the 500-year tsunami is dominated by local sources in the Cascadia Subduction Zone and is characterized by maximum amplitudes in excess of 10 m and an inland extent of more than 1 km. The primary sources of uncertainty in these results include those associated with interevent time estimates, modeling of background sea level, and accounting for temporal changes in bathymetry and topography. Nonetheless, PTHA represents an important contribution to tsunami hazard assessment techniques; viewed in the broader context of risk analysis, PTHA provides a method for quantifying estimates of the likelihood and severity of the tsunami hazard, which can then be combined with vulnerability and exposure to yield estimates of tsunami risk.

Citation: González, F. I., et al. (2009), Probabilistic tsunami hazard assessment at Seaside, Oregon, for near- and far-field seismic sources, *J. Geophys. Res.*, *114*, C11023, doi:10.1029/2008JC005132.

1. Background and Introduction

[2] There are multiple levels of tsunami hazard assessment (THA), including studies to investigate and document the frequency and severity of prehistoric and historic tsunami events, and numerical modeling studies with varying degrees of complexity, including worst case scenario simulations and sensitivity analyses to different sources. This paper describes probabilistic tsunami hazard assessment (PTHA), a method that provides the next level of predictability for the likelihood and severity of an event, and its application to Seaside, Oregon.

[3] Risk analysis provides the broader conceptual context for PTHA. Thus the term hazard is generally understood to deal only with the physical aspects of the phenomena and, in particular, the ability of the phenomena to inflict harm. Risk, on the other hand, although defined in many ways, invariably invokes probabilistic concepts. The World Meteorological Organization [*WMO*, 2008] adopts the widely accepted definition of *Crichton* [1999], based on his "risk triangle" concept: "Risk is the probability of a loss, and this depends on three elements: hazard, vulnerability, and exposure. If any of these three elements in risk

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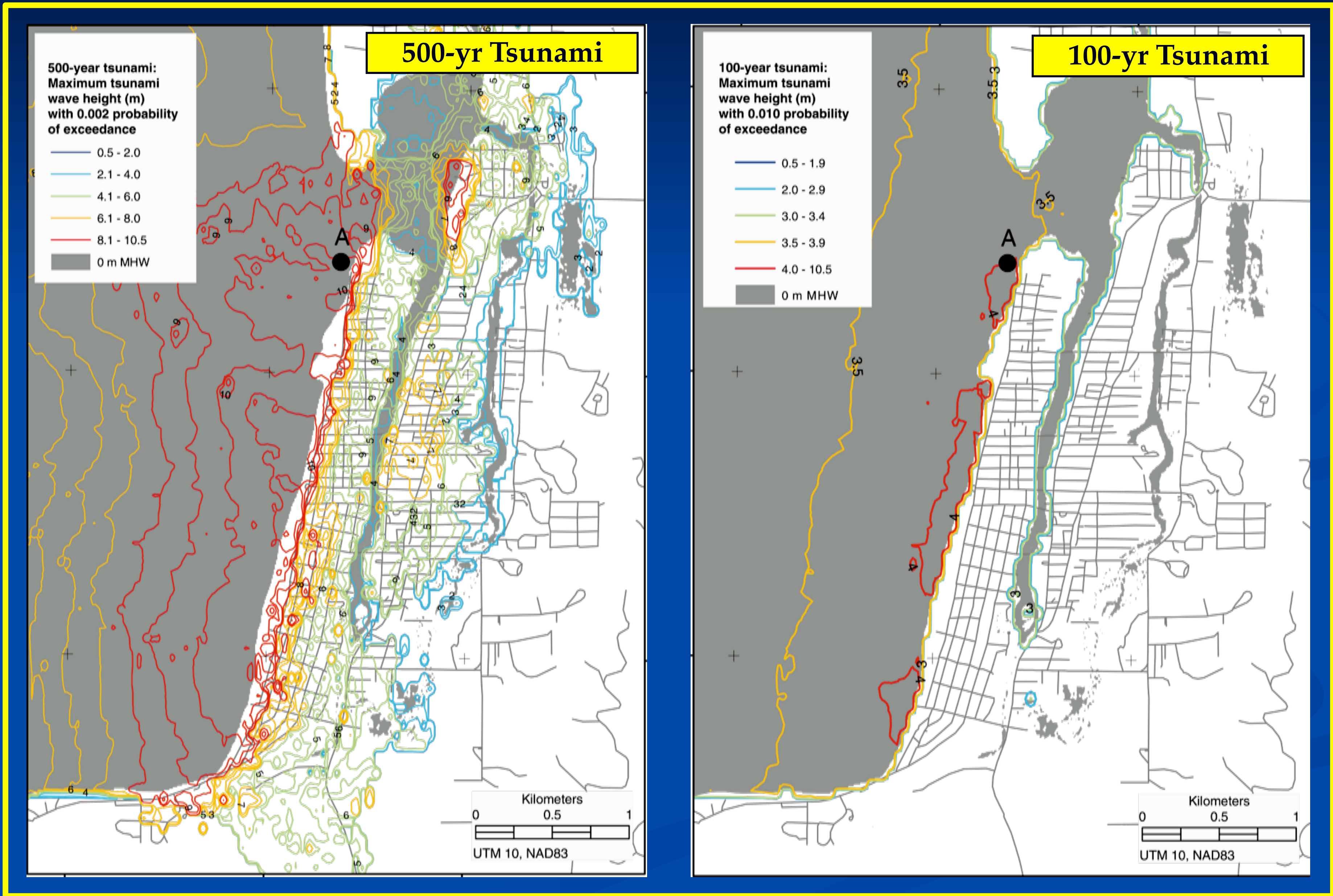
Seaside, Oregon
Maximum Flooding Levels with 0.2% and 1% Annual Probability of Exceedance



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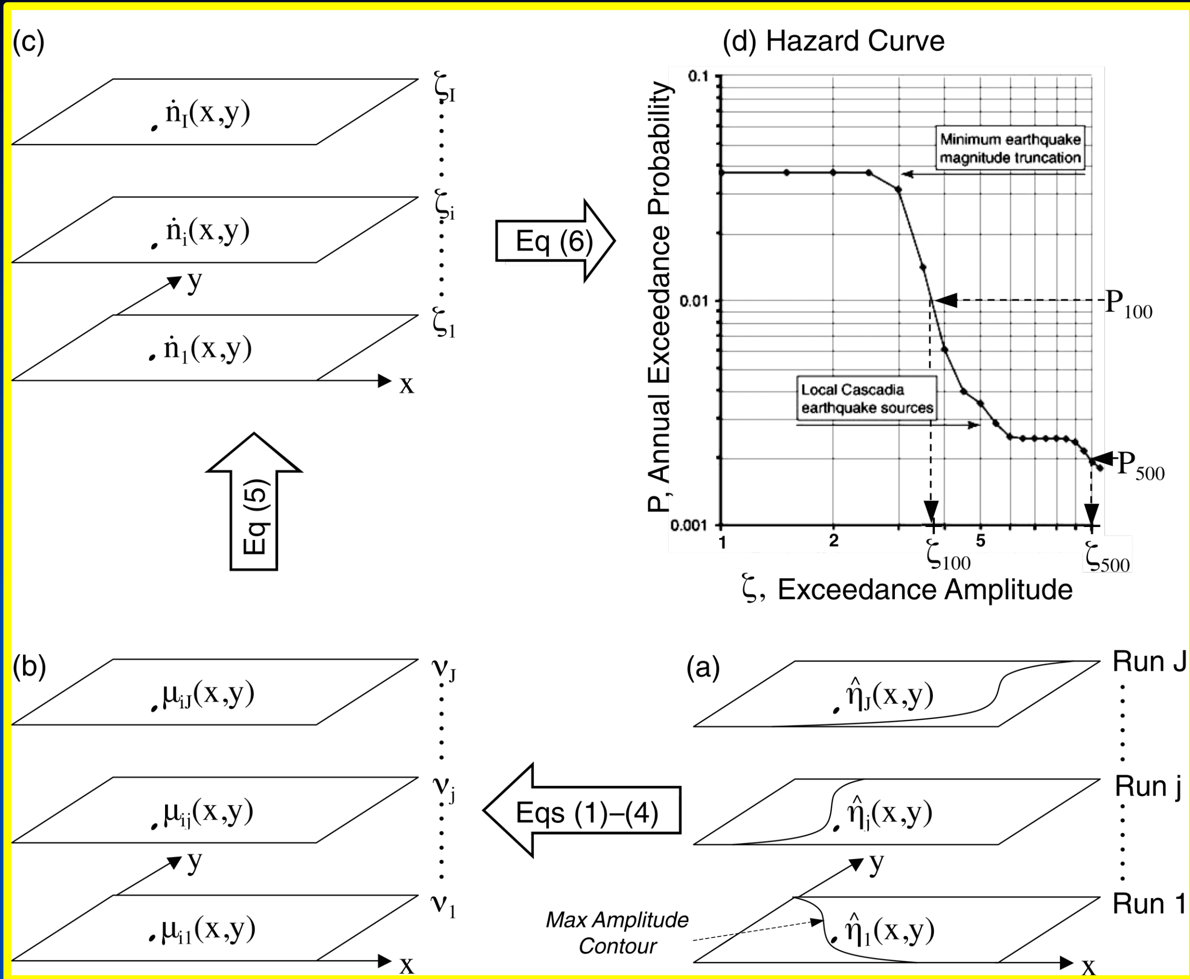
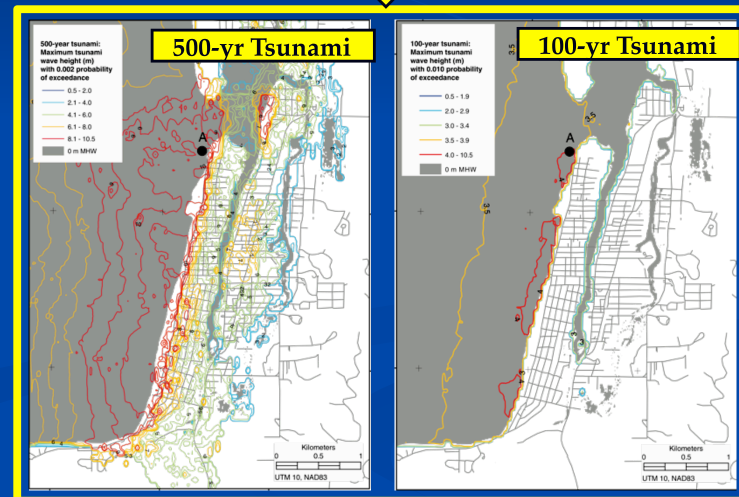
Schematic



Exceedance Value Computations

Equations (1)-(6) in González, et al. (2009).

ζ_{50} , ζ_{100} , ζ_{500} … etc.
at every point (x,y):



Sources:
- Physical Parameters
- Probability of Occurrence

Computational Grids:
- Bathymetry
- Topography

- Generation
- Propagation
- Inundation

- $\eta(x,y)$
- $u(x,y)$
- $v(x,y)$

Model Input

Model Computations

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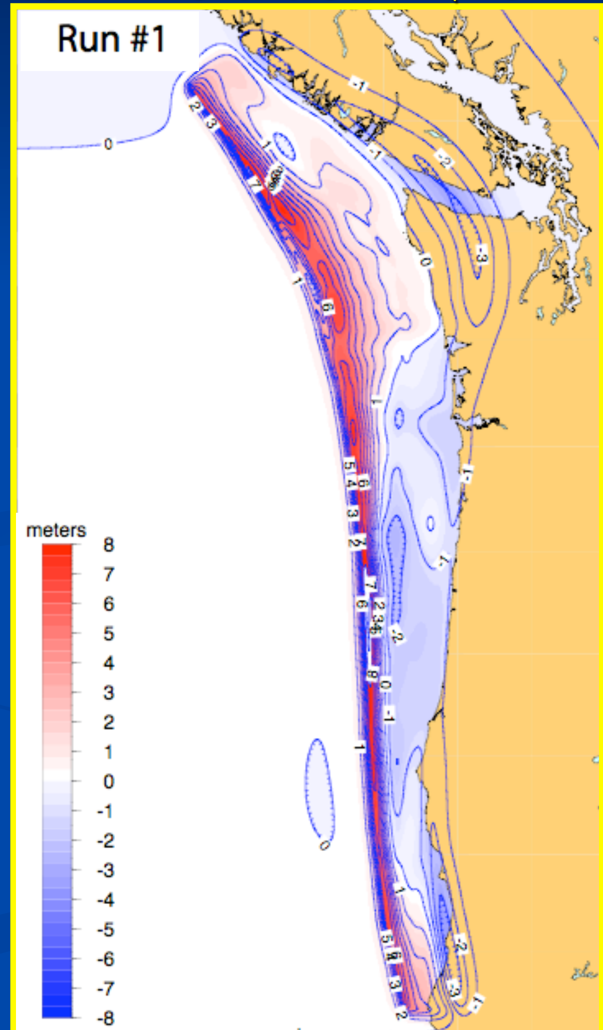
Source Specification

Table 1. Source Specification for Earthquakes Used in This Study[a]

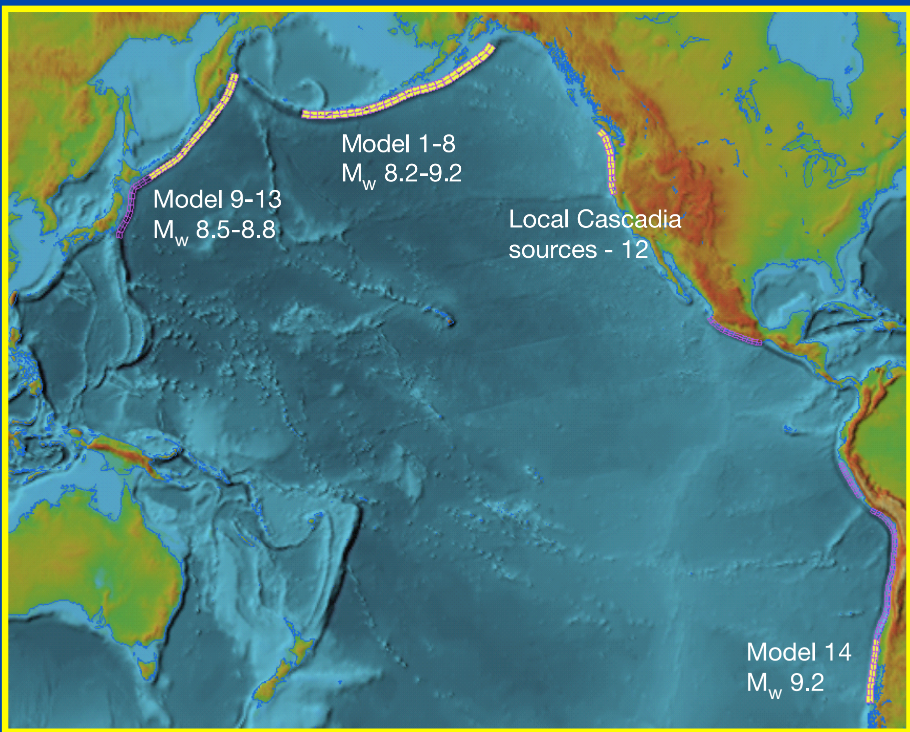
Source	Location	M	Length (km)	Width (km)	Slip (m)	T_M (y)
1	AASZ	9.2	1000	100	17.7	1,313
2	AASZ	9.2	1000[c]	100	17.7[c]	750
3	AASZ	9.2	600	100	Dist.	750
4	AASZ	9.2	1200	100	14.8[c]	1,133
5	AASZ	9.2	1200	100	14.8	750
6	AASZ	8.2	300	100	2.1	875
7	AASZ	8.2	300	100	2.1	661
8	AASZ	8.2	300	100	2.1	661
9	KmSZ	8.8	500	100	9.8	100
10	KmSZ	8.8	500	100	9.8	100
11	KrSZ	8.5	300	100	5.8	500
12	KrSZ	8.5	300	100	5.8	500
13	KrSZ	8.5	300	100	5.8	500
14	SChSZ	9.5	1100[c]	100	40.0	300
15	CSZ	9.1	1100[c]	Variable	Variable	520

(T_M is mean interevent time)

Near-Field detail (1 of 12)



All Sources: Far- & Near-field



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Far-field Earthquake Specification

- Only the largest earthquakes (that is, $M = M_{max}$) along major north Pacific Subduction Zones and the southern Chile Subduction Zone were used, primarily.
- Rationale: Even though the recurrence rate for each event is low, combining these earthquakes (along with local Cascadia earthquakes) should be sufficient to specify the tsunami at Seaside from *any source* with an average return time of 100 years and 500 years, because inclusion of smaller magnitude and more frequent earthquakes will likely not add significantly more information with which to constrain the 100-year exceedance wave heights.
- Exception: Smaller earthquakes in the Prince William Sound segment of then Aleutian -Alaska Subduction Zone, that can result in larger runup values than $M = M$max earthquakes in other subduction zones.
- Variations in slip distribution patterns will have minimal effect on far-field tsunami, so …
- Pre-computed fault plane solutions from NOAA/PMEL's FACTS database were used
- Average return times estimated for different earthquake sources, based primarily on published references
- See TPSWG, Section 5.2, for detailed discussion of earthquake parameters specification and citations of published references

Near-field Earthquake Specification

- M ~ 9 earthquakes along the Cascadia Subduction Zone will likely produce the worst-case tsunami inundation and be the defining event for the 500-year tsunami flood standard.

- National Seismic Hazard Mapping program methodology: Two equally weighted scenarios

  (1) one M = 9.0 characteristic earthquake with an average repeat time of 500 years and

  (2) a series of M = 8.3 earthquakes that fill the CSZ every 500 years, with repeat time of 110 years for occurrence anywhere in the seismic zone (Frankel *et al*., 1996; Frankel *et al*., 2002; Petersen *et al*., 2002).

- Arguably, this either/or option has been superseded with analysis of the Japan tsunami records indicating the 1700 event was M = 8.7–9.2 and ruptured approximately 1100 km (Satake *et al*., 2003).

- Coseismic displacement field calculated over fault grid developed by Fluck *et al*. (1997):

  - 105 quadrilateral elements with varying dip, strike and slip

  - Average slip equals the specified seismic moment

Near-field Earthquake Specification (cont.)

- Uncertainties: Rupture width and transition zone slip

  Satake *et al*., 2003, could not resolve between

  - "Long-Narrow" model with uniform slip in the locked zone and slip tapered to zero half-way down the transition zone and
  - "Long-Wide" model with uniform slip throughout both the locked and transition zones.

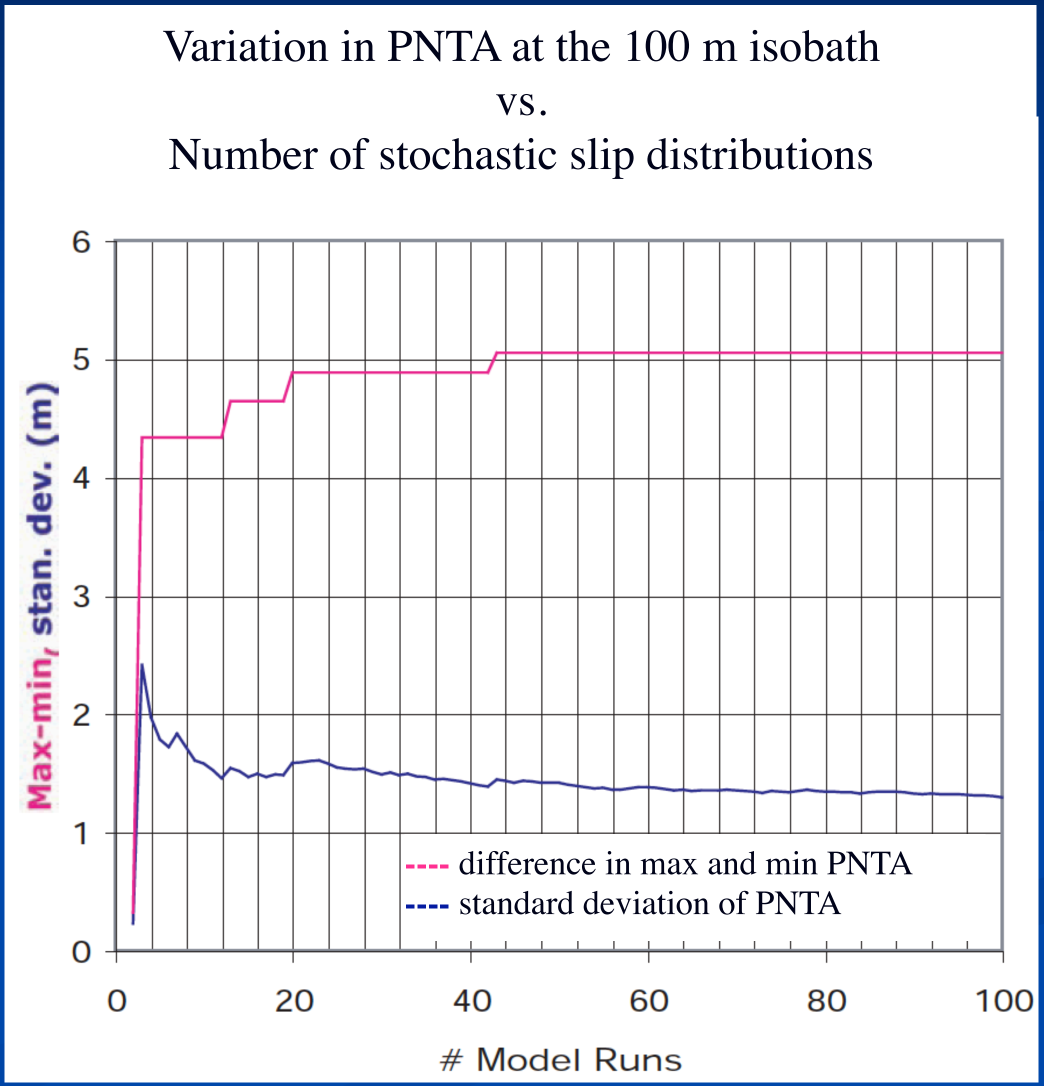
- Arguably, uncertainty in the effective width of the rupture zone is in part aleatory uncertainty in slip distribution patterns.

- So ... we used Long-Wide rupture geometry with stochastic slip realizations, in which narrow effective rupture widths occur when slip is concentrated updip.

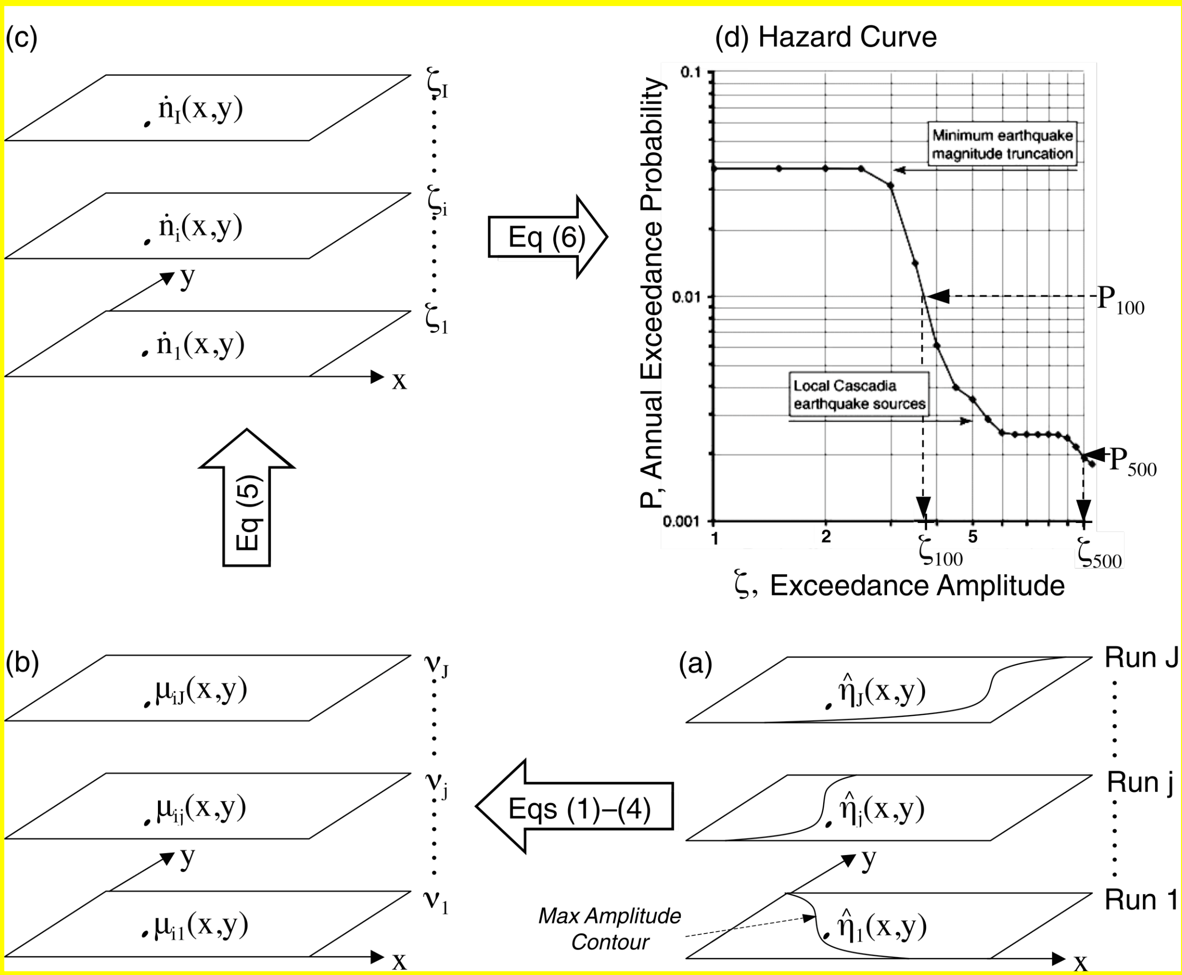
Near-field Earthquake Specification (cont.)

Question: How many model runs are adequate to capture the natural variability in runup heights caused by variations in slip distribution patterns ?

Answer: About 12.



Schematic



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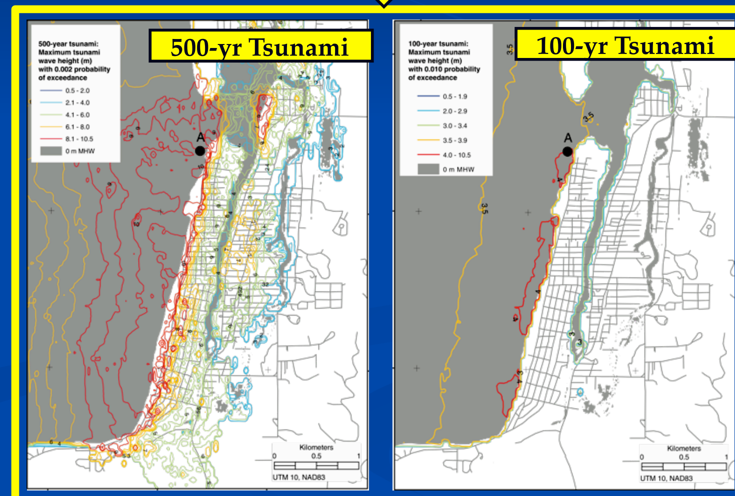

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Model Input

Model Computations

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Theory

- Poissonian probability that wave height ζ will exceed level ζ_i in time T for a source with recurrence rate μ_j

$$P_{ij}(\zeta > \zeta_i) = 1 - \exp\left(-\mu_j T\right) \qquad (1a)$$

$\mu_j = 1/T_{Mj}$ (inverse of mean interevent time)

- Combined probability for multiple sources that level ζ_i will be exceeded

$$\begin{aligned} P_i(\zeta > \zeta_i) &= 1 - \Pi_j\left(1 - P_{ij}\right) \\ &= 1 - \Pi_j \exp\left(-\mu_j T\right) = 1 - \exp(-\mu T) \qquad (1b) \end{aligned}$$

$$\mu = \sum_j \mu_j.$$

- Tidal stage uncertainty. Form the Gaussian approximation for PDF of (tsunami + tide):

$$p[\zeta(x,y)|\hat{\eta}(x,y)] = \left[\sigma(2\pi)^{1/2}\right]^{-1} \exp\left\{-[\zeta(x,y) - \zeta_0]^2/2\sigma^2\right\} \qquad (2a)$$

where $\zeta(x, y, t) = \eta(x, y, t) + \xi(t)$ for tides ξ , the series mean ζ_0 and standard deviation σ ,

with ζ_0 and σ approximated by a function of $\hat{\eta}$ and standard tidal parameters:

$$\begin{aligned} \zeta_0[\hat{\eta}(x,y)] = \hat{\eta}(x,y) + MSL + C(MHHW - MSL) \\ \cdot \exp\left\{-\alpha[\hat{\eta}(x,y)/\sigma_0]^{\beta}\right\} \qquad (2b) \end{aligned}$$

$$\sigma[\hat{\eta}(x,y)] = \sigma_0 - C'\sigma_0 \exp\left\{-\alpha'[\hat{\eta}(x,y)/\sigma_0]^{\beta'}\right\} \qquad (2c)$$

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Theory (cont.)

- Far-field sources with tidal uncertainty: The combined probability that flood level ζ_i will be exceeded by the sum of a tsunami η and the local tides ξ is

$$P_{ij} = P_{ij}\left(\zeta > \zeta_i | \hat{\eta}_j\right) = \int_{\zeta_i}^{\infty} p\left(\zeta | \hat{\eta}_j\right) d\zeta$$
$$= \tfrac{1}{2}\left\{1 - \mathrm{erf}\left[\left(\zeta_i - \zeta_{0j}\right) / \left(2^{1/2}\sigma_j\right)\right]\right\} \qquad (3a)$$

$$\zeta(x, y, t) = \eta(x, y, t) + \xi(t)$$

Multiply this by the mean earthquake recurrence rate to get the cumulative rate for the combined probability that the *j^th^ earthquake* and flood level ζ_i will *both* occur is

$$\mu_{ij} = \mu_{ij}\left(\zeta > \zeta_i | \hat{\eta}_j\right) = \nu_j P_{ij}$$
$$= \tfrac{1}{2}\nu_j\left\{1 - \mathrm{erf}\left[\left(\zeta_i - \zeta_{0j}\right) / \left(2^{1/2}\sigma_j\right)\right]\right\}. \qquad (3b)$$

$$\nu_j = 1/T_{Mj}$$

- Near-field sources with tidal and earthquake slip uncertainty: Multiple stochastic sources (12 found adequate), with constant moment magnitude and variable width and slip. Combined probability and cumulative rate for all 12 sources that flood level ζ_i will be exceeded is

$$P_{ij} = P_{ij}(\zeta > \zeta_i) = 1 - \Pi_k\left(1 - P_{ijk}\right)$$
$$= 1 - \Pi_k \tfrac{1}{2}\left\{1 + \mathrm{erf}\left[\left(\zeta_i - \zeta_{0jk}\right) / \left(2^{1/2}\sigma_{jk}\right)\right]\right\}. \qquad (4c)$$

$$\mu_{ij} = \mu_{ij}\left(\zeta > \zeta_i | \hat{\eta}_j\right) = \nu_j P_{ij}$$
$$= \nu_j\left[1 - \Pi_k \tfrac{1}{2}\left\{1 + \mathrm{erf}\left[\left(\zeta_i - \zeta_{0jk}\right) / \left(2^{1/2}\sigma_{jk}\right)\right]\right\}\right]. \qquad (4d)$$

$$\nu_j = 1/T_{Mj}$$

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Theory (cont.)

- Now specify a discreet set of exceedance levels ζ_i … say

$$\{\zeta_i\} = \{1.0,\ 1.5,\ 2.0,\ \ldots\ 10.5\}$$

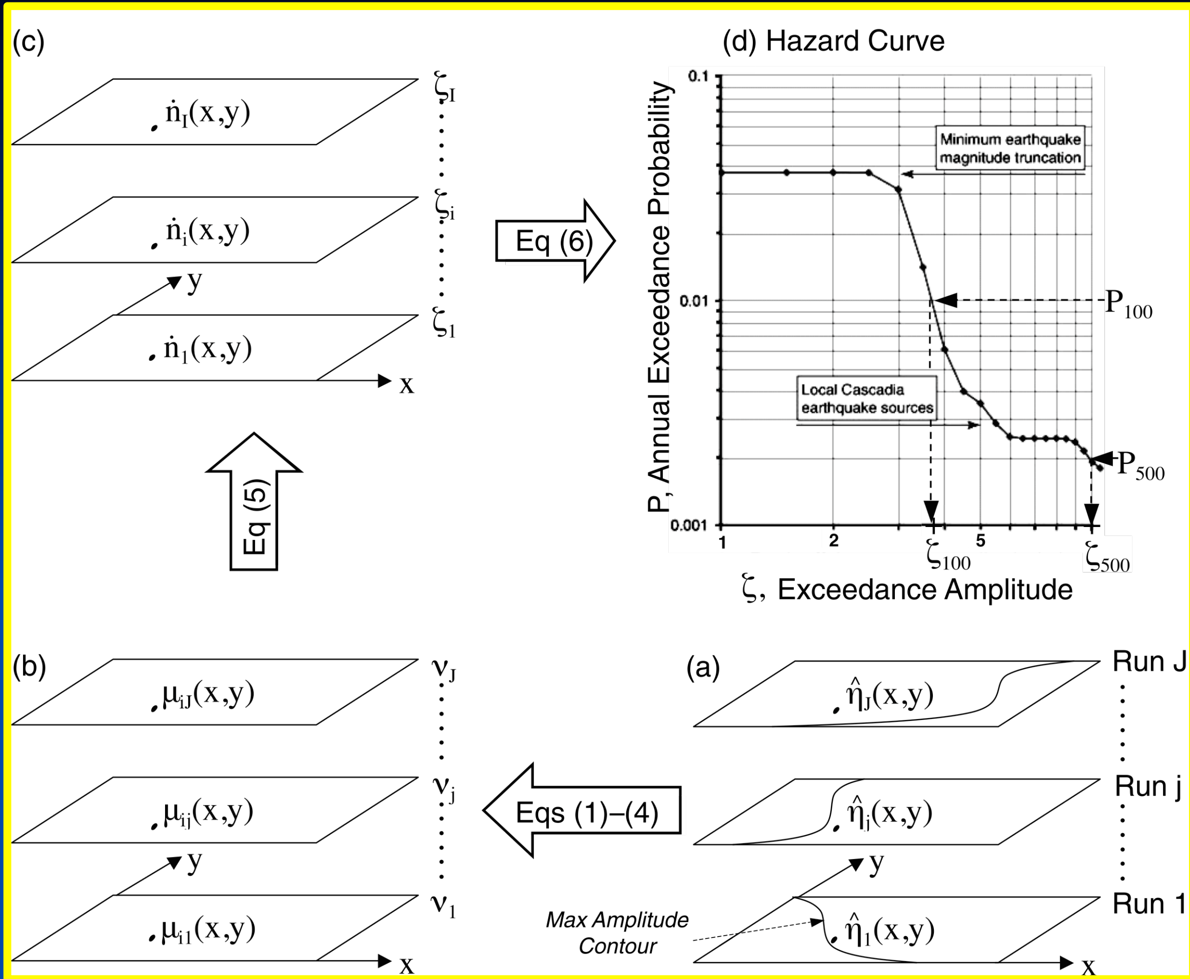
- The cumulative rate for all sources, near- and far-field is

$$\dot{n}_i(\zeta > \zeta_i) = \sum_j \mu_{ij}(\zeta > \zeta_i) \qquad (5)$$

- and for all sources, the combined probability that level ζ_i will be exceeded is

$$P_i(\zeta_i, T) = 1 - \exp(\dot{n}_i T) \qquad (6)$$

Schematic



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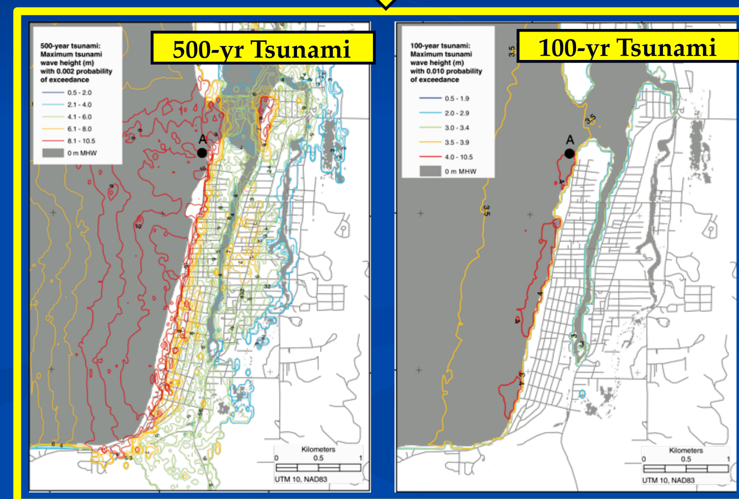

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Seaside Summary

- **PTHA methodology was developed, and estimates probability of a tsunami exceeding a given height in a given period of time (e.g. 10, 50 , 100, 500 yrs)**

- **The 500-yr Tsunami at Seaside is a local-source CSZ Tsunami:**
  Max height: *10 m*
  Max inland extent: *> 1 km*
  (And … this is likely true of the entire Pacific Northwest coast)

- **The 100-yr Tsunami at Seaside is a distant-source AASZ Tsunami:**
  Max height: *4 m*
  Max inland extent: *0.5 km (concentrated at inlet and rivers)*

- **PTHA can now be applied to most Pacific Northwest and Alaska coastal communities, using sources developed for Seaside study:**

- **Current PTHA Limitation:** ***Seismic sources only … no landslides, etc.***

… and Other Studies

- **What is Risk ?**
- **Multiple definitions exist for risk, hazard, vulnerability and exposure** *[Thywissen, 2006]*

Risk: *Probability of a loss, dependent on three elements: hazard, vulnerability, and exposure. Risk increases or decreases as any element increases or decreases. [Crichton, 1999; WMO, 2008]*

Hazard: *The physical aspects of the phenomena and the ability of the phenomena to inflict harm.*

Vulnerability: *Condition or process resulting from physical, social, economic and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard [UNDP, 2004]*

Exposure: *Inventory of people or artifacts at risk by exposure to a hazard. [UNDP, 2004]*

- **The corresponding general equation** *[WMO, 2008]* **is:**

$$\text{Risk} = \textit{function}\ (\text{Hazard} \times \text{Vulnerability} \times \text{Exposure})$$

where at least one of the three factors is *probabilistic*

- **So … PTHA provides a probabilistic Hazard Factor for Risk Analysis**

- **Tsunami Risk Analysis of Long Beach, WA , has been proposed to the NTHMP.**

F. González, UW (PTHA) N. Wood, USGS (Socioeconomic metrics) G. Crawford (Emerg. Mgt.)

"Risk" References

Crichton, D. (1999), The risk triangle, in Natural Disaster Management, edited by J. Ingleton, pp. 102 – 103, Tudor Rose, London, U. K.

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