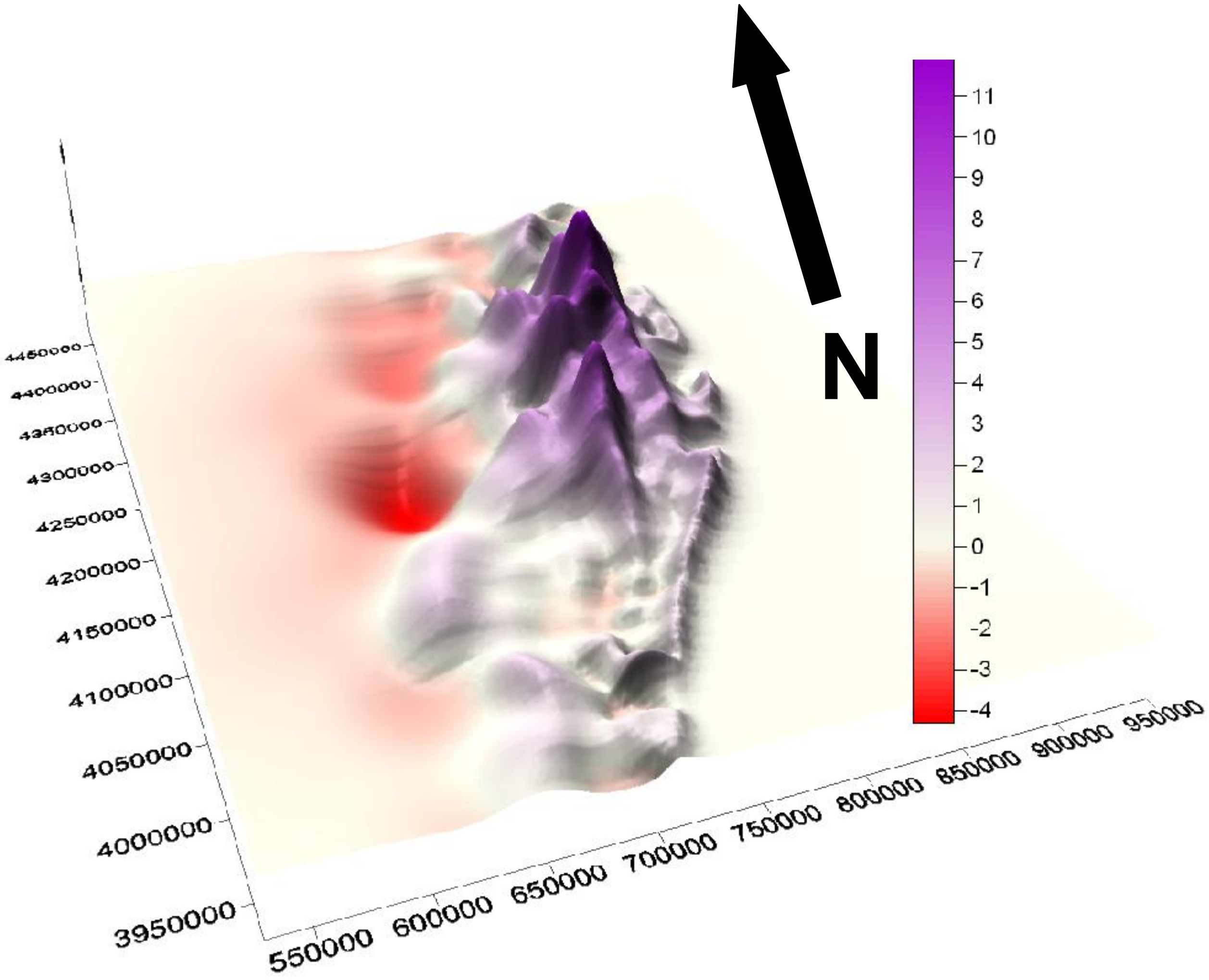
The Tohoku Tsunami

An Event That Should Have Been Expected and Could Have Been Worse

Philip Watts
Woody Epstein

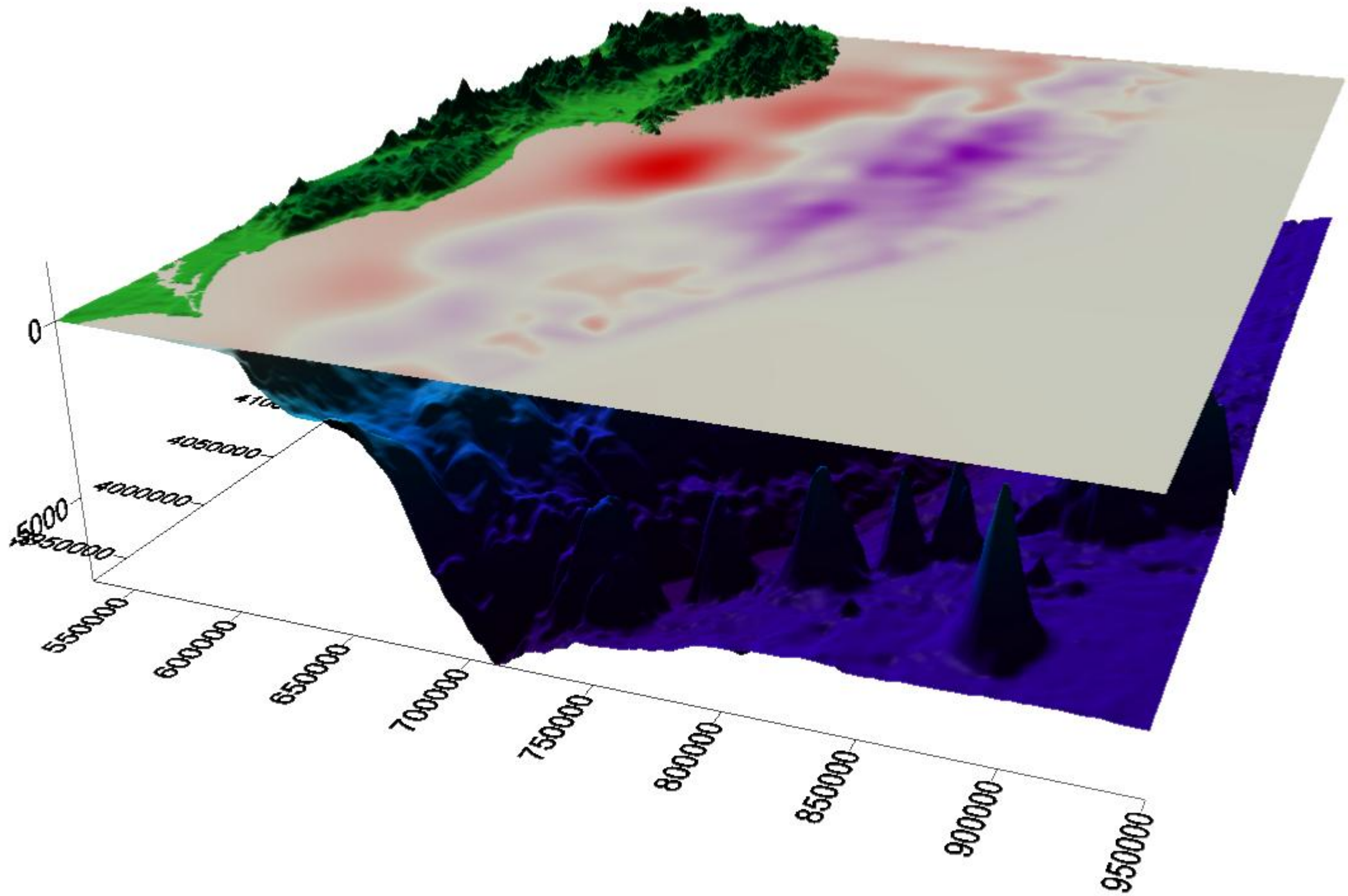
Lloyd's Register
applied *fluids* engineering

2011 Tohoku Tsunami, Japan



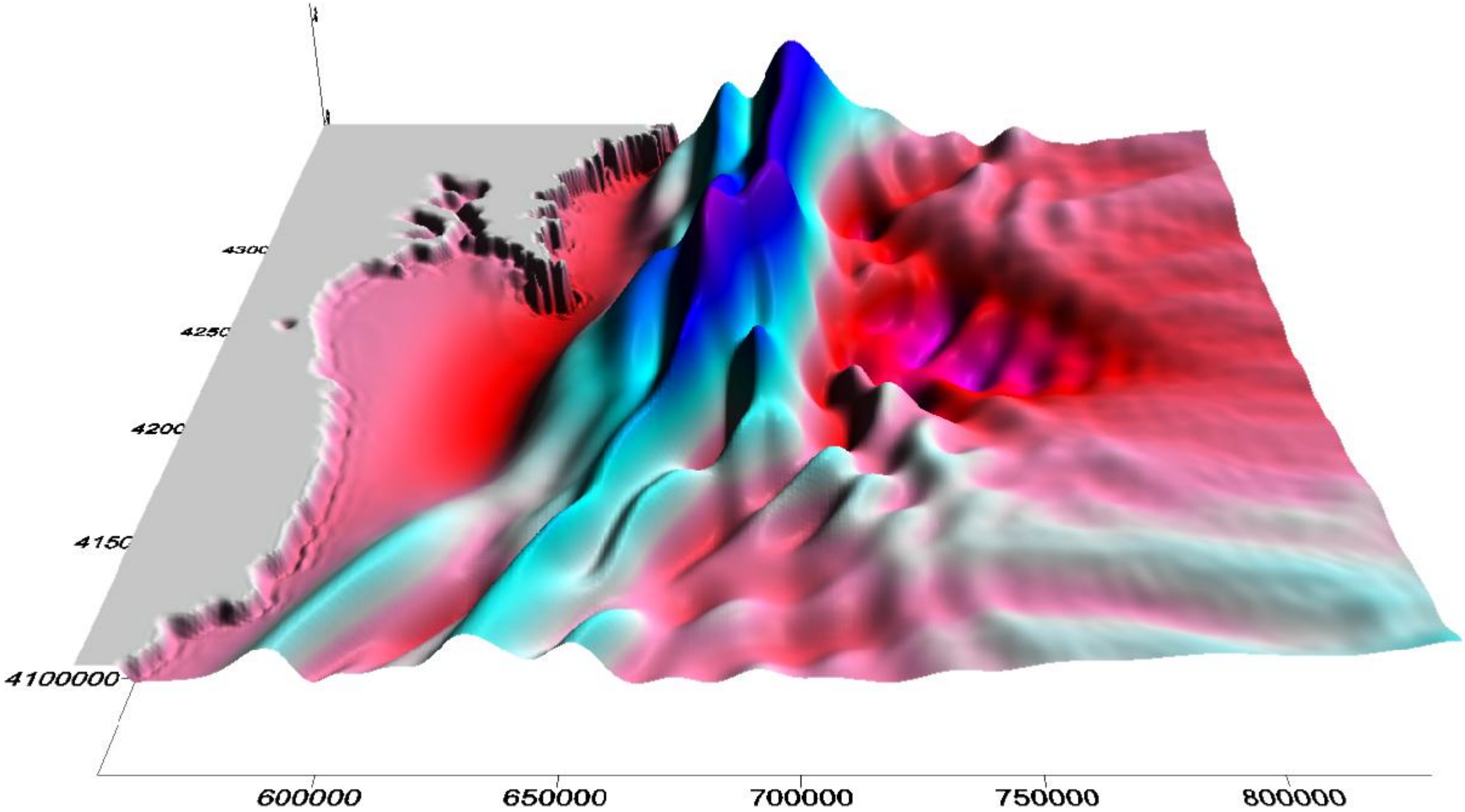
Coseismic Displacement Found by Researchers at Caltech from Multiple Inversion Techniques

2011 Tohoku Tsunami, Japan



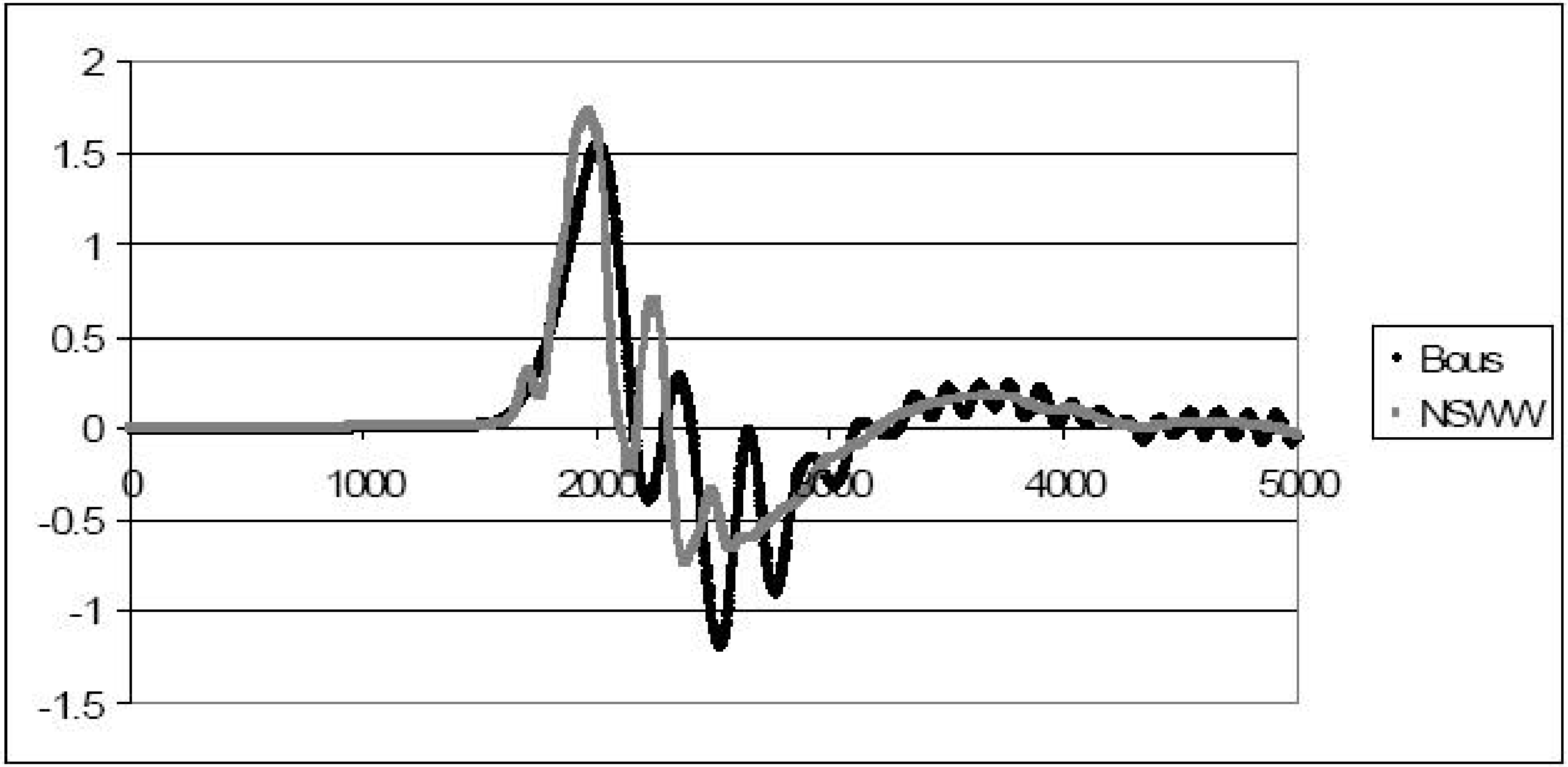
The coseismic displacement is filtered somewhat by the water depth.

2011 Tohoku Tsunami, Japan



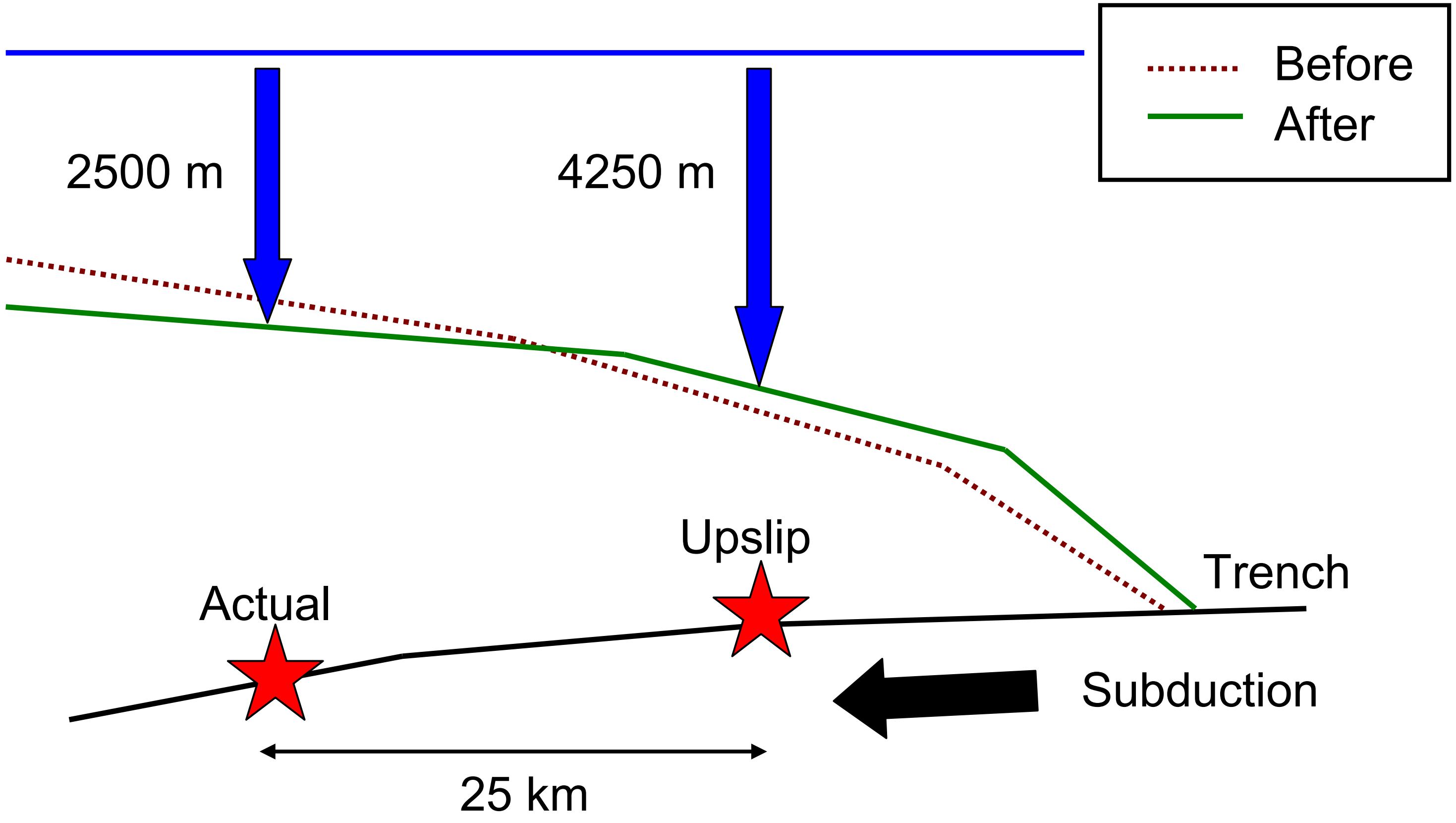
View of tsunami propagation 830 seconds after the earthquake began.

2011 Tohoku Tsunami, Japan



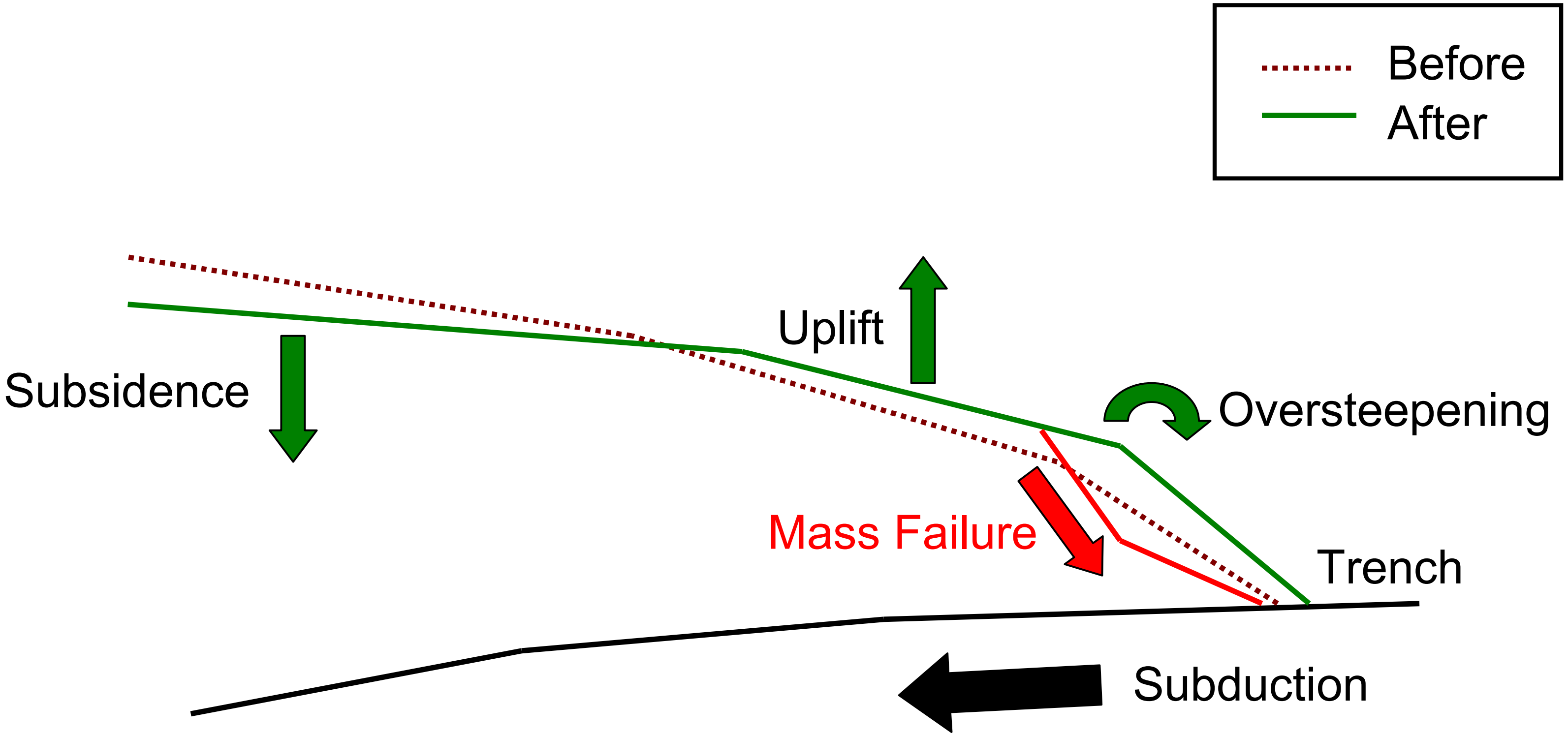
Wave dispersion makes a measurable difference at the nearest DART buoy.

2011 Tohoku Tsunami, Japan



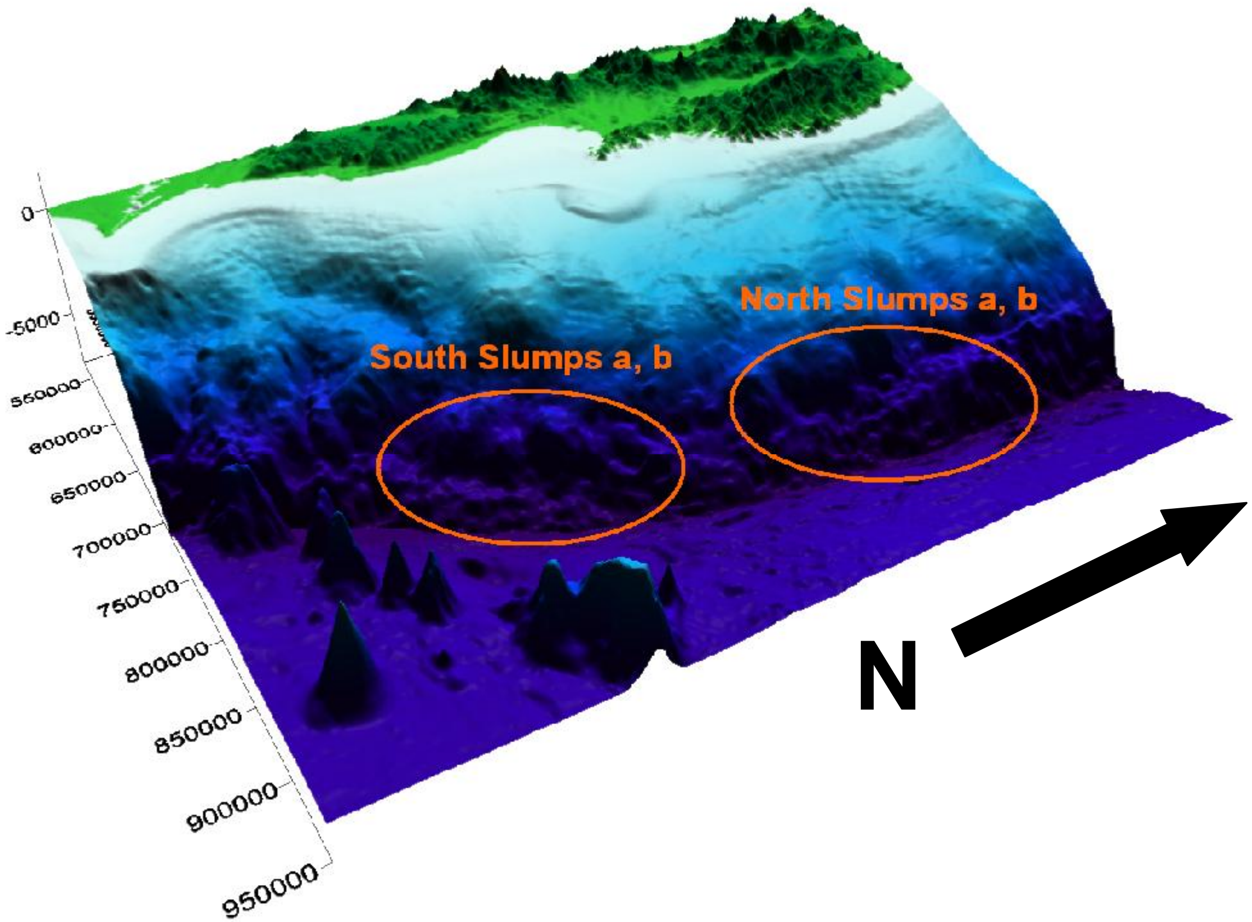
Green's Law: The tsunami amplitude could have increased by 15% or more.

2011 Tohoku Tsunami, Japan



Thesis: a submarine landslide mass failure should be expected at the trench due to oversteepening. Preliminary investigations have provided support.

2011 Tohoku Tsunami, Japan



Examples of apparent slumping along the Sanriku margin trench.

2011 Tohoku Tsunami, Japan

Nonlinearity, dispersion, and wave breaking are needed to capture this in a simulation. Thus, Boussinesq Wave modeling.

Probabilistic Tsunami Hazard Simulation of Fukushima Daiichi

Using Geowave and PerfectWave

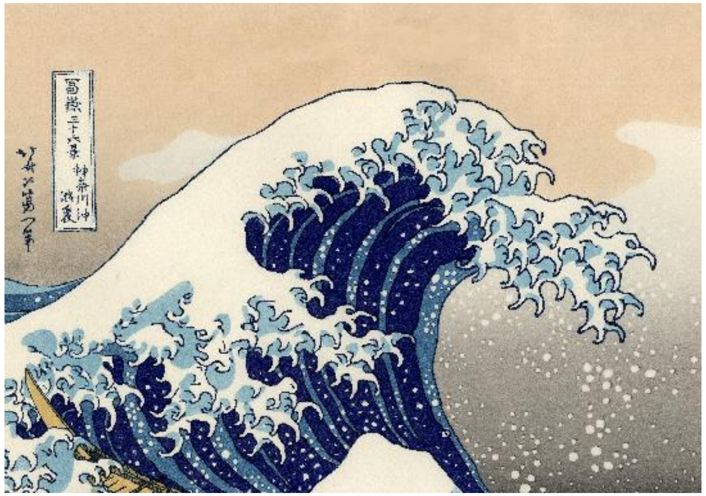
Philip Watts
Woody Epstein

Tsunamis Studied

Geowave

- Multiple tsunami sources of any kind
- Fully nonlinear wave propagation
- Fully dispersive wave propagation
- Multiple wave dissipation algorithms
- Wave breaking coefficient and tracking
- Dry land runup and inundation validated
- Captures edge wave interactions
- Many simulation grid files output

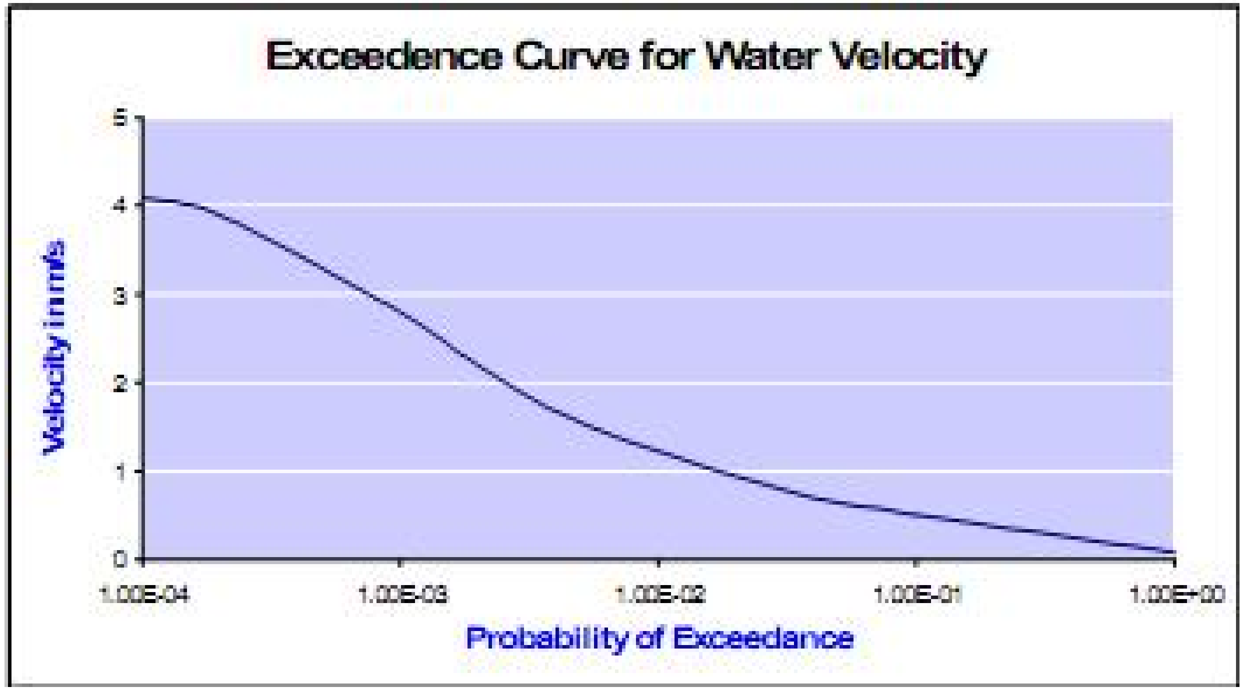
~PerfectWave®~



- produces probability distribution functions for earthquake tsunami, landslide tsunami, and volcanic tsunami to occurrence frequencies as low as 1/1,000,000 per year.

- resolves and focuses the tremendous uncertainty surrounding the largest, rarest, and most hazardous tsunamis, realistically converging on reasonable results for extreme events.

- provides probability distribution functions of tsunami amplitudes and tsunami wavelengths at the source regions, producing exceedance curves for chosen tsunami hazard levels, and setting up deterministic simulations of known frequency.



Exceedance curve for tsunami water velocity in m/s

Many Japanese Nuclear Plants Are Exposed

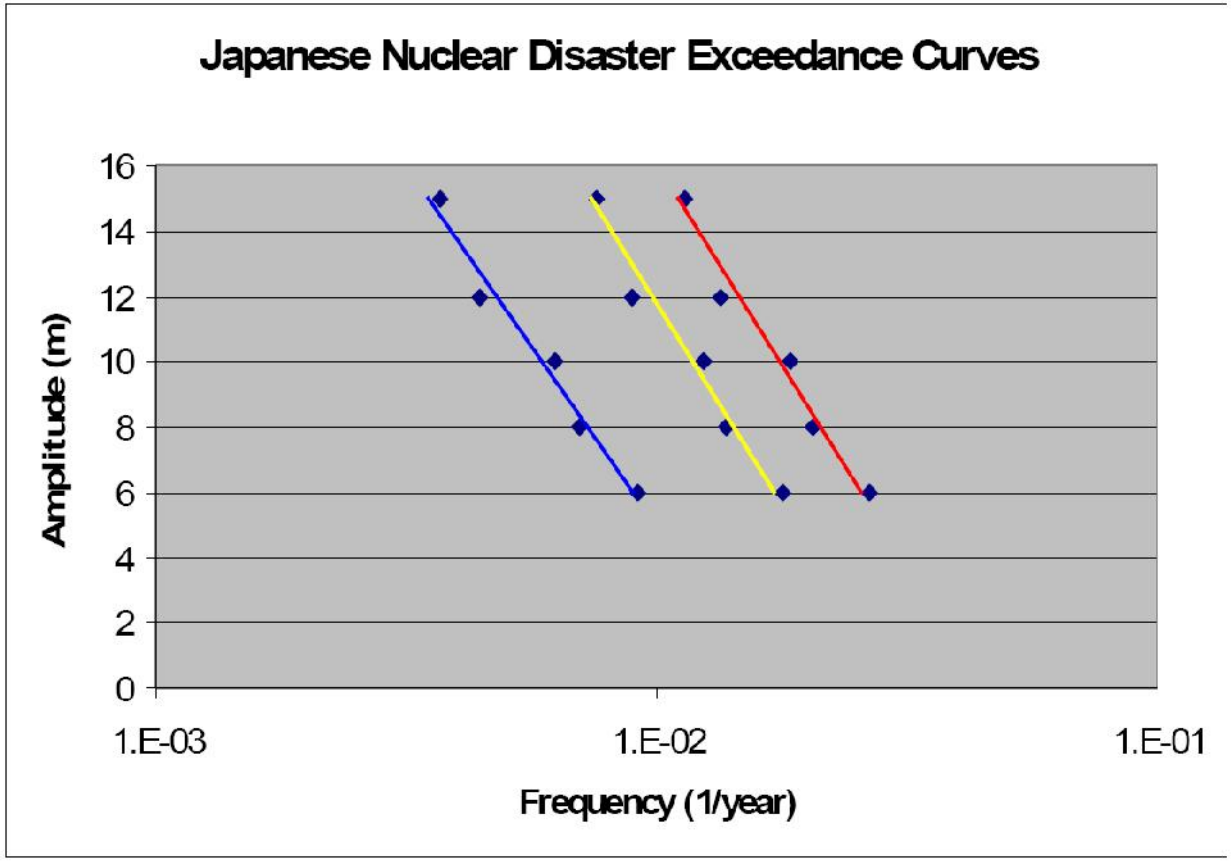
1. Kashiwazaki
2. Tomari
3. Higashidori
4. Tokai
5. Sendai
6. Genkai
7. Shimane
8. Takahama
9. Ohi
10. Mihama
11. Tsuruga

Year	EQ Magnitude	Runup (m)
1611	8.1	25
1677	8.1	6.0
1793	8.3	4.5
1843	8.4	4.5
1896	7.6	38
1933	8.4	29
1952	8.1	6.5
1968	8.2	6.0
2003	8.3	3.9

Catastrophic tsunamis strike Japan every 40 years on average, including many along the Sanriku coast (above), while many nuclear power plants are exposed with safety systems 20-40 feet above sea level.

A Tsunami Impact on an NPP Repeats Every 70 Years

Mean frequency of exceedance curve (yellow) with one standard deviation uncertainty (red and blue) for the occurrence of any nuclear disaster in Japan.



Assumes historical tsunami frequency

Assumes independent and uniform

Assumes 0.3, 0.5, 0.7 probabilities

Tsunami Uncertainty is a Profound Challenge

- Is the location of the most hazardous local fault even known?
- What is the largest possible earthquake magnitude on a fault?
- What seismic coupling and slip patch can be expected here?
- Does the earthquake depth and rake reproduce surface features?
- How frequent are the most hazardous landslide tsunamis?
- Are they frequent enough to exceed core damage frequency?
- What is the most hazardous mode of submarine mass failure?
- Will earthquake and landslide tsunamis combine amplitudes?
- How can effective warnings be issued for landslide tsunamis?
- Does a given landslide tsunami model reproduce known data?
- Will volcano collapse create a large transoceanic tsunami?
- When can the volcano collapse be expected to take place?
- Is this a tsunami simulation that requires wave dispersion?
- Does maximum run-up occur here because of edge waves?

Probabilistic Tsunami Hazard Assessment PDFs (1)

Earthquake PTHA

Parameter	Calculation	Distribution
Gutenberg-Richter slope b	Randomization	Uniform
Gutenberg-Richter minimum M	Randomization	Uniform
Moment Magnitude Mw	Determine EQ Size	CDF
Fault Length Correlation	Randomization	Lognormal
Rupture Area Correlation	Randomization	Lognormal
Tsunami Amplitude Correlation	Randomization	Lognormal
Water Depth Green's Law	Modulate Ampl.	Uniform
Seismic Coupling Ratio	Modulate Ampl.	Uniform
Earthquake Hypocenter Depth	Modulate Ampl.	Uniform
Amplitude Transfer Function	Modulate Ampl.	Lognormal
Earthquake Tsunami Period	Randomization	Uniform

Probabilistic Tsunami Hazard Assessment PDFs (2)

Landslide PTHA

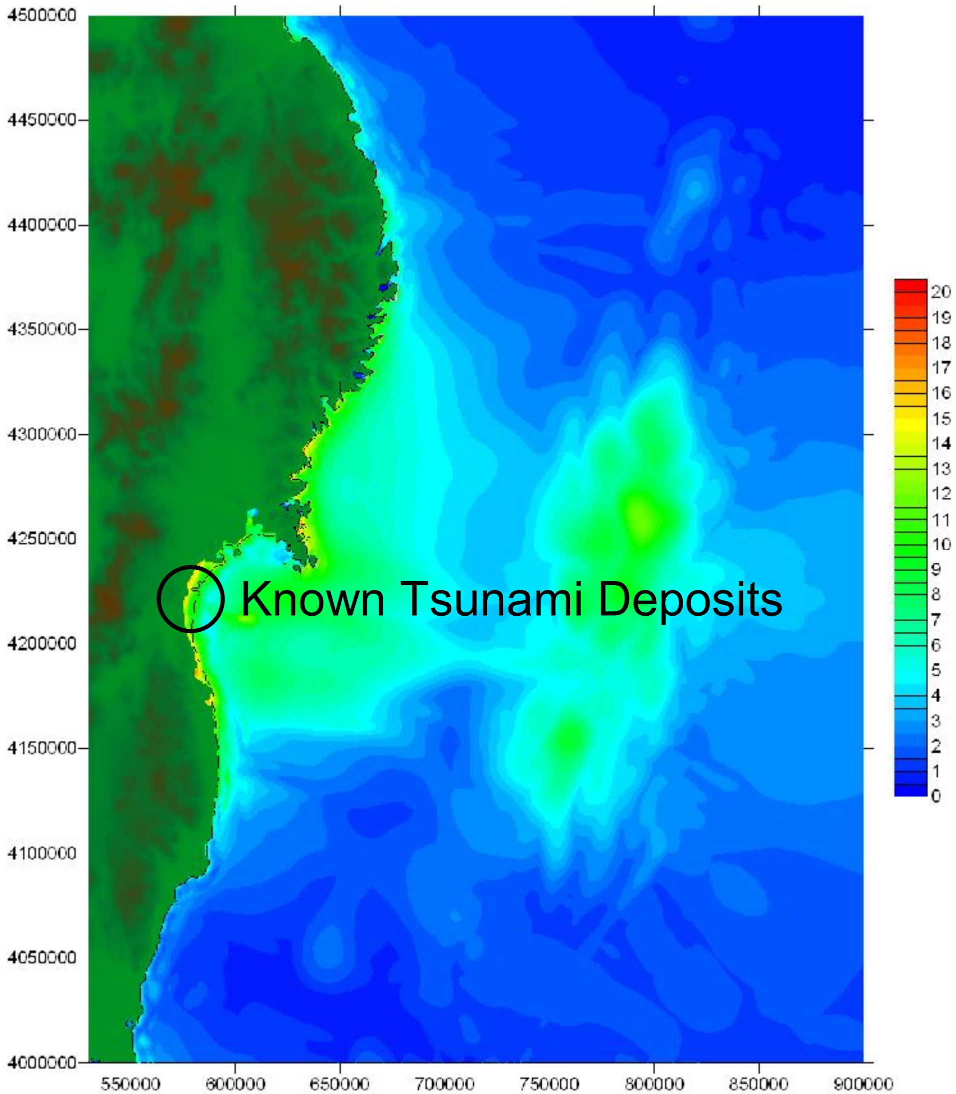
Parameter	Calculation	Distribution
Mass Failure Distance from EQ	Peak Acceleration	Uniform
Expected Sedimentation Rate	Pore Pressure	Exponential
Yearly Sedimentation Rate	Pore Pressure	Exponential
Pore Water Diffusivity	Pore Pressure	Uniform
Artesian Water Pressure	Pore Pressure	Uniform
Peak Horizontal Acceleration	Slope Stability	Lognormal
Local Failure Plane Slope	Slope Stability	Exponential
Sediment Cohesion	Slope Stability	Uniform
Sediment Friction Angle	Slope Stability	Uniform
Water Depth Above Mass Failure	Randomization	Uniform
Mass Failure Length Along Slope	Randomization	Uniform
Mass Failure Width Across Slope	Randomization	Uniform
Amplitude Transfer Function	Modulate Ampl.	Lognormal
Landslide Tsunami Period	Randomization	Uniform

Frequency of Exceedance Results from PTHA

Runup (m)	North #	South #	Total # >	Log n	Freq. (yrs)
8-9	5	14	182	-2.439	274
9-10	21	12	163	-2.487	306
10-11	15	12	130	-2.585	385
11-12	16	11	103	-2.686	485
12-13	15	4	76	-2.818	658
13-14	10	5	57	-2.943	877
14-15	4	2	42	-3.076	1,190
15-16	9	0	36	-3.143	1,389
16-17	3	2	27	-3.268	1,852
17-18	9	0	22	-3.357	2,273
>18	10	3	13	-3.585	3,846

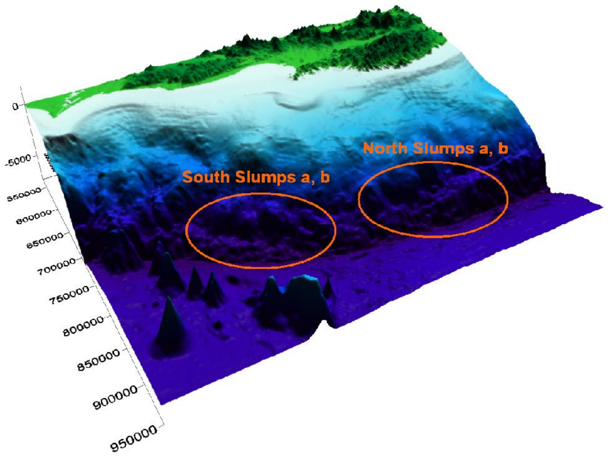
PTHA results suggest an event similar to the Tohoku tsunami should be exceeded every 1190 years.

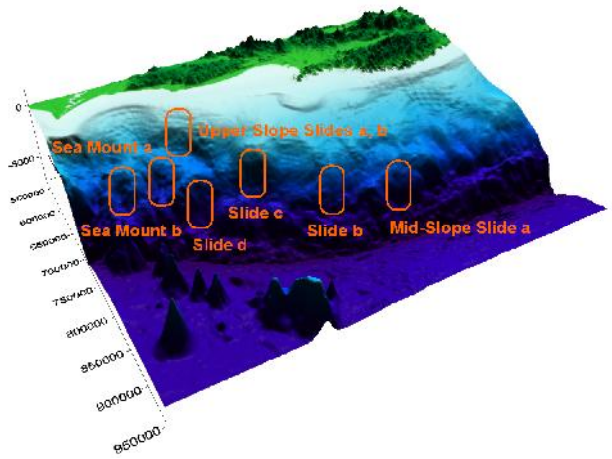
Geological evidence supports a recurrence frequency of 1.0e-03

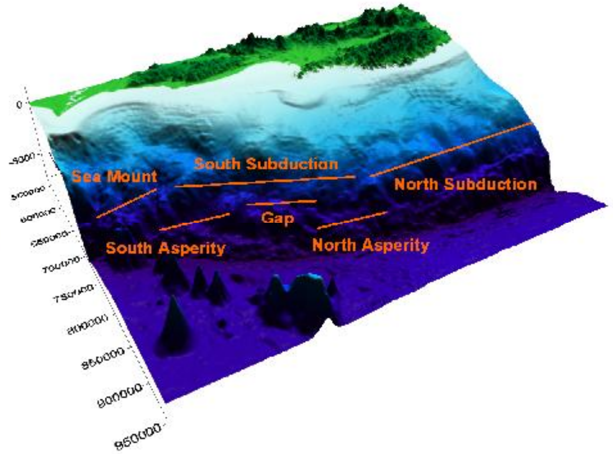


Large EQs along the Japan Trench seem to occur every 1000 years, on the average.

Tsunami Source Regions and Data for Fukushima

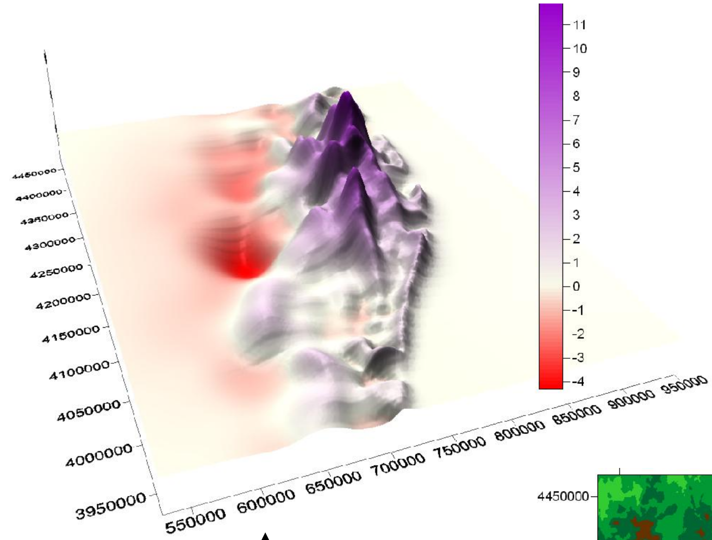


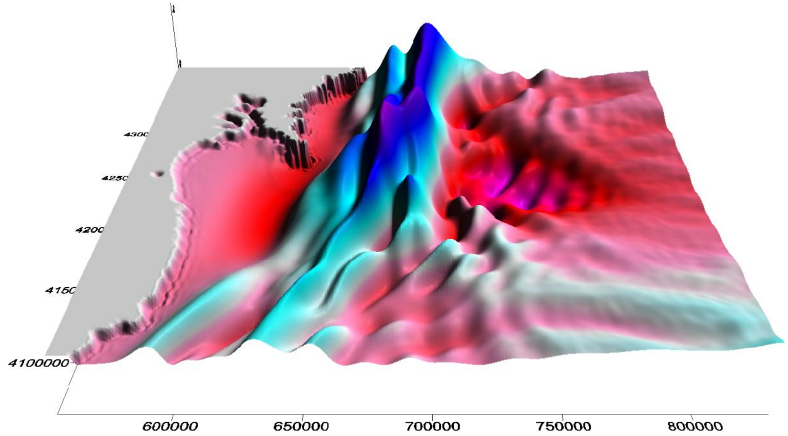




1. Topography:	Japanese government
2. Bathymetry:	ETOPO1 or GEBCO
3. Power Plant:	Google Earth and TEPCO
4. Earthquake:	USGS
5. Tsunami:	NGDC
6. Landslide:	scientific literature
7. Sediment:	scientific literature
8. Tectonic:	scientific literature

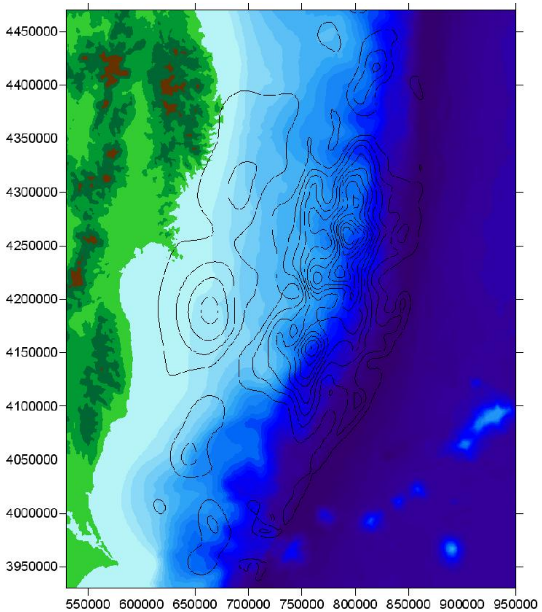
Tsunami Scenario Simulations of Tohoku Tsunami (1)



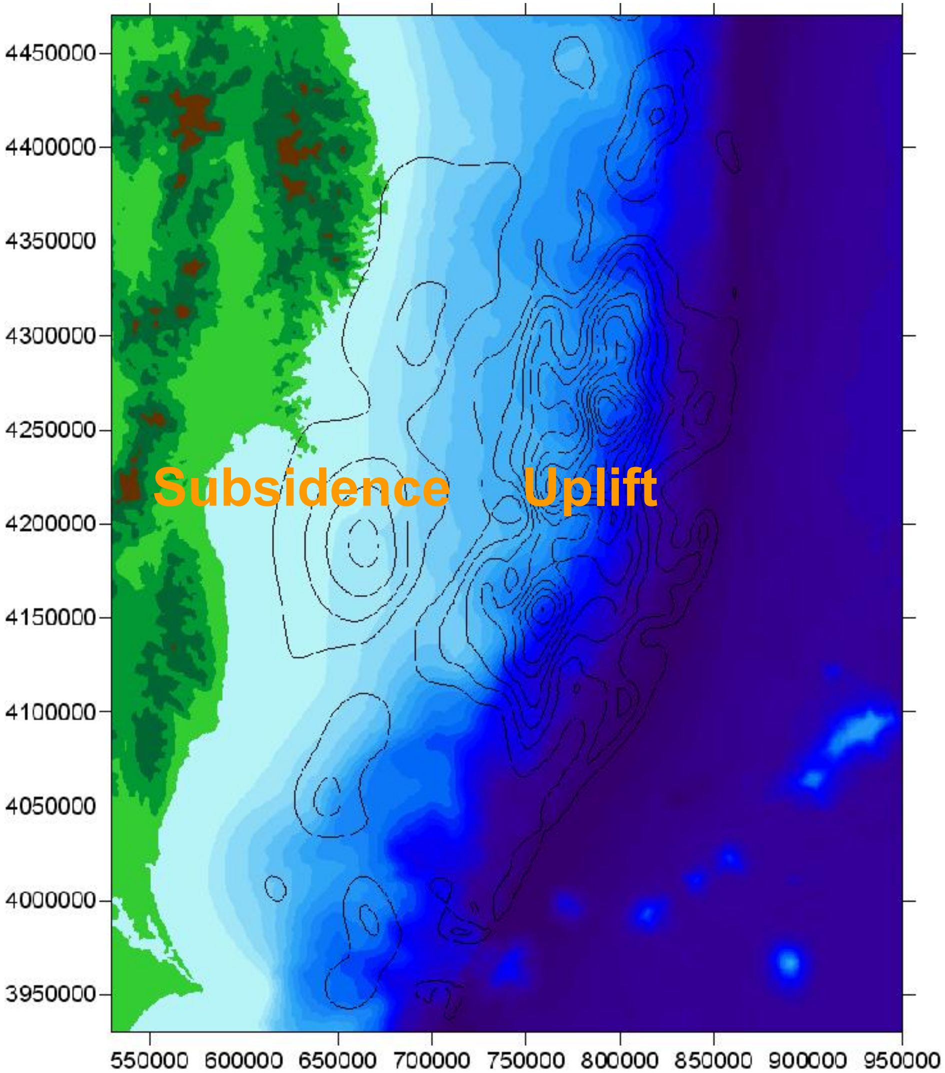


Geowave Snapshot at 830 s

Caltech Vertical Coseismic Displacement

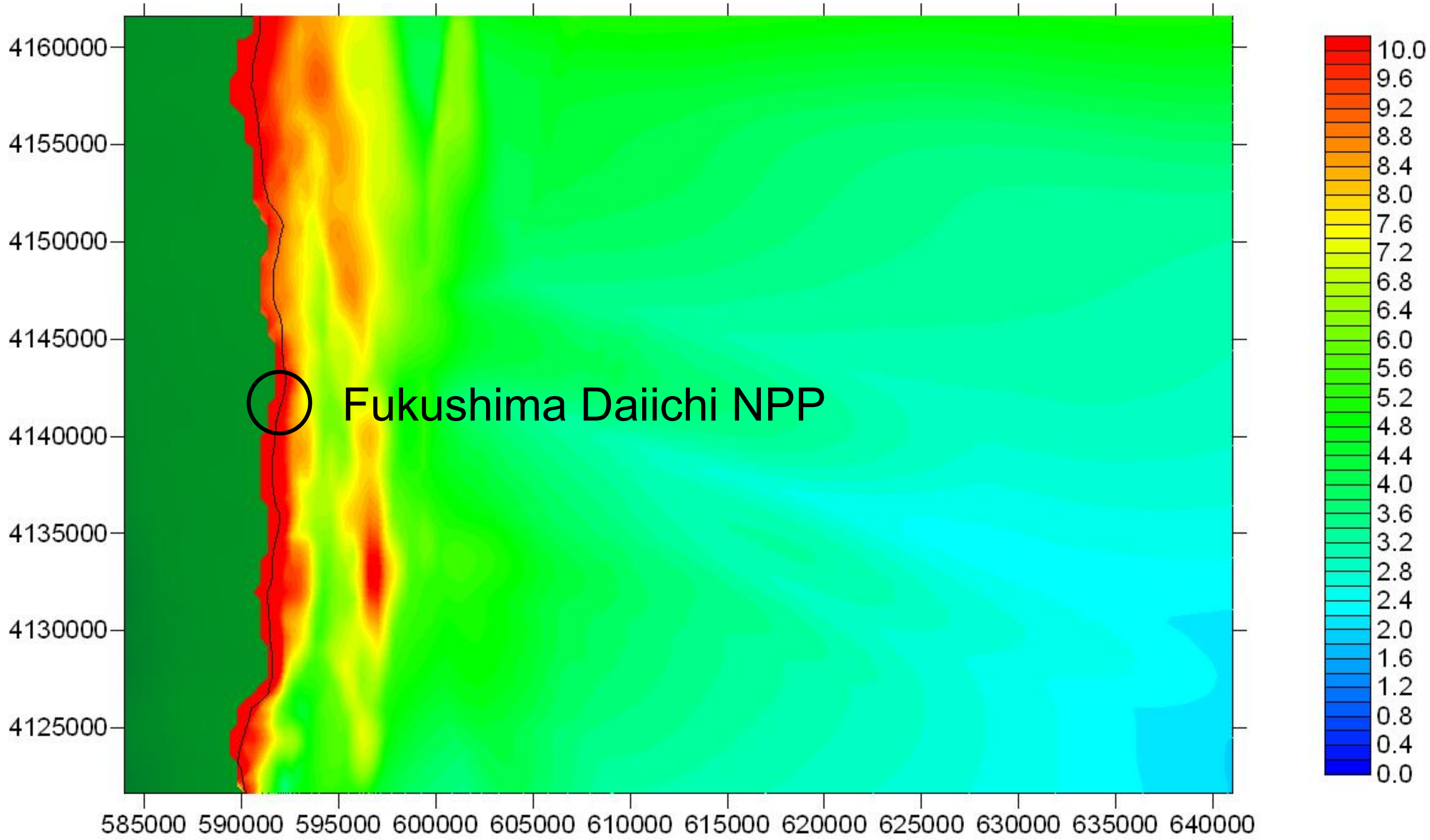


Tsunami Scenario Simulations of Tohoku Tsunami (2)



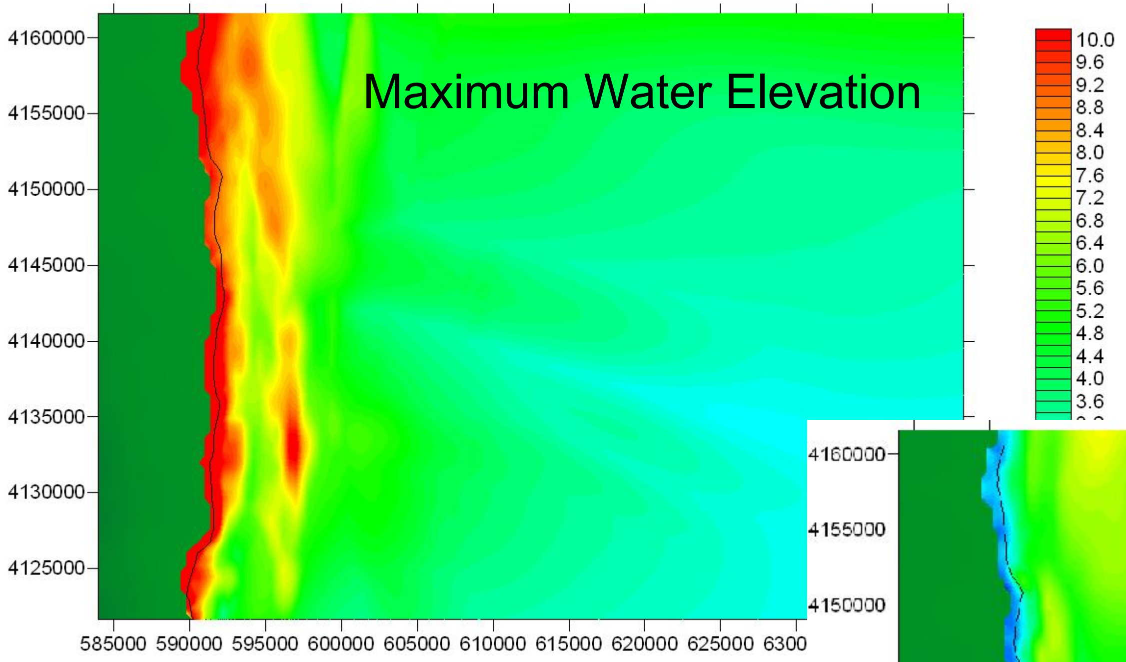
Regions of Subsidence and Uplift Superposed on the 1000 m Uniform UTM Geowave Simulation Grid

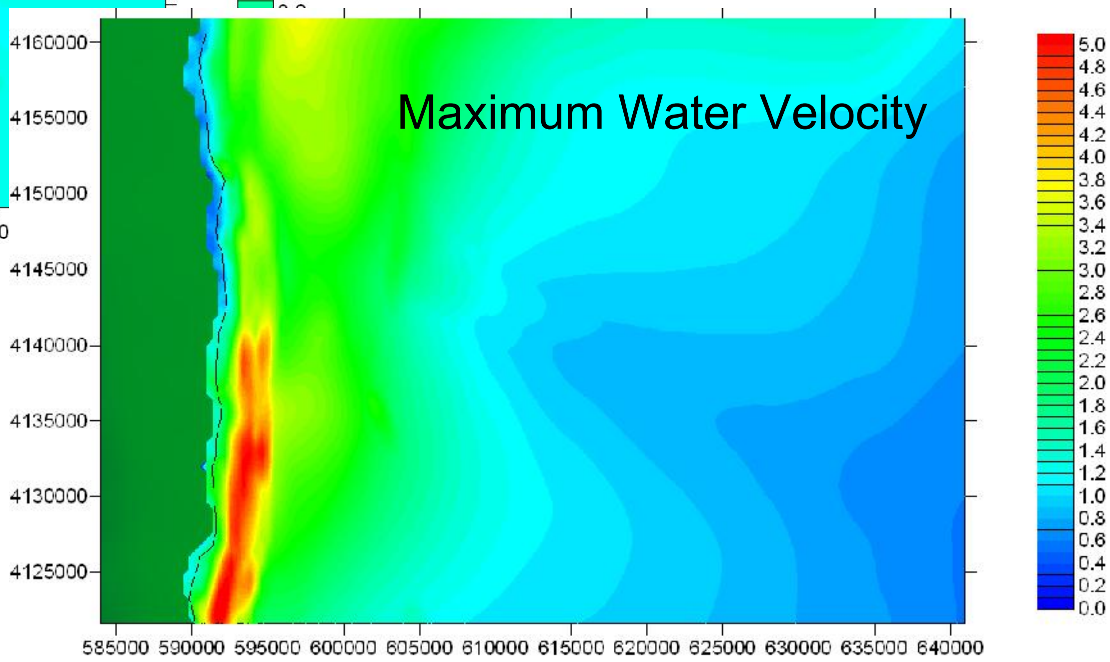
Tsunami Scenario Simulations of Tohoku Tsunami (3)



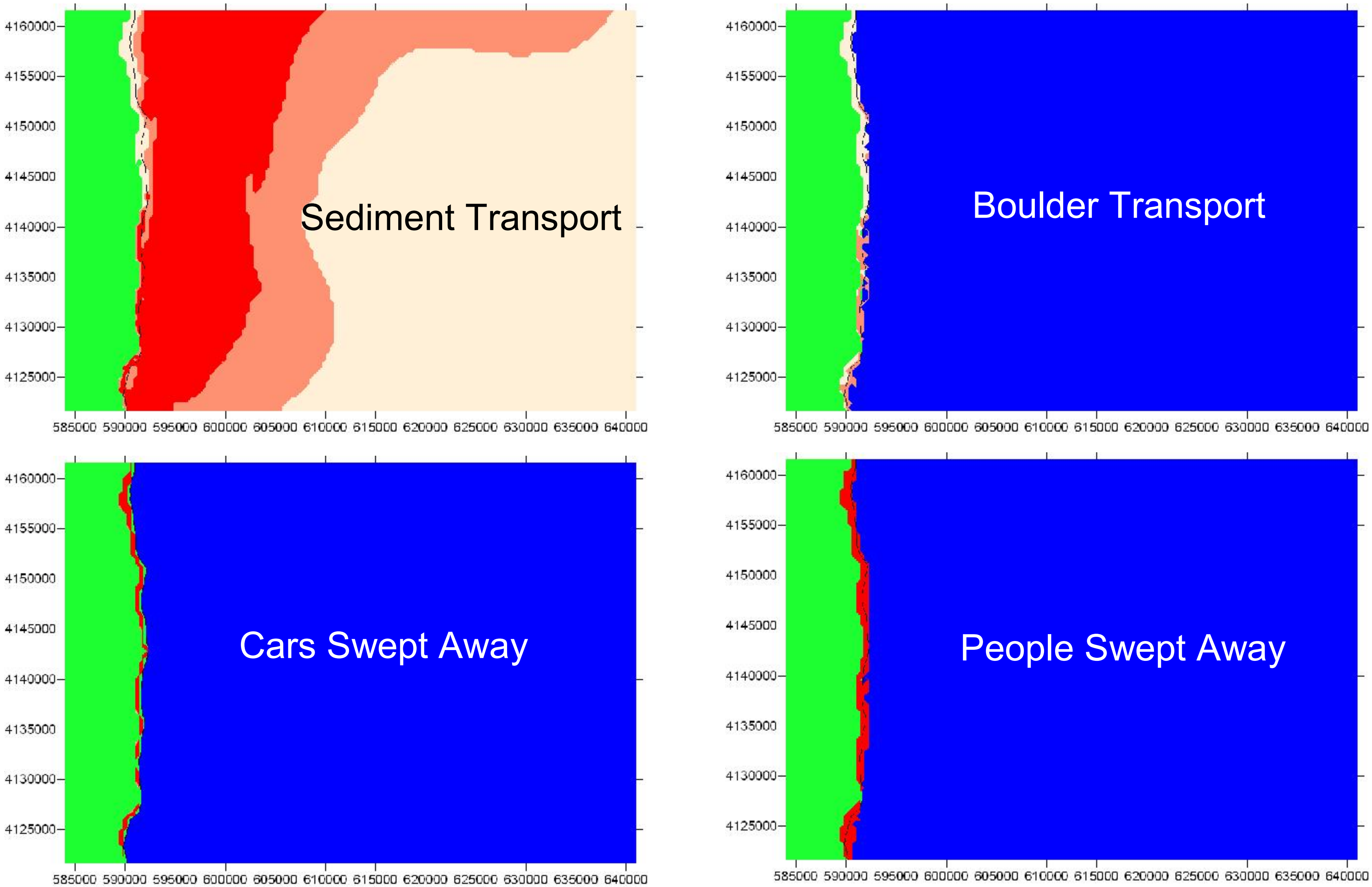
Runup elevation at the Fukushima Daiichi site matches observations there.

Primary Simulation Results near Fukushima Daiichi





Tsunami Hazard Concerns for NPP in Japan (1)



Tsunami Hazard Concerns for NPP in Japan (2)

- Water run-up height
- Water pressure
- Water velocity
- Water breaking force
- Water impact and shock
- Water spray height
- Water missiles (rocks, boats, cars)
- Water debris blocking roads
- Water blockage impeding flow
- Water loss causing intake failure

The Steps for PTHA and PRA Integration

Using Geowave and PerfectWave

Philip Watts
Woody Epstein

Lloyd's Register

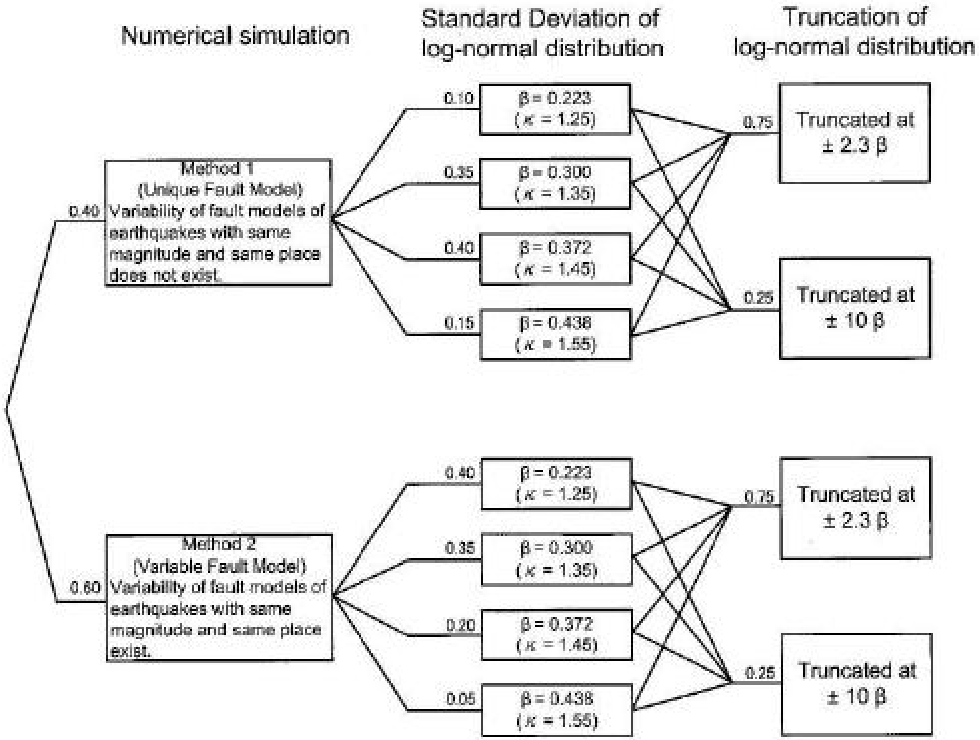
applied fluids engineering

Steps for NPP Tsunami PRA

A tsunami PRA is exactly the same as a seismic PRA. But there is one change: we make several tsunami hazard assessments in place of just one seismic hazard assessment, peak ground acceleration (PGA):

1. Create exceedance curves for hazards of interest;
2. create basic events or split fractions corresponding to hazard levels and types;
3. create tsunami hazard initiating events.
4. make a tsunami event tree;
5. link this tree to similar trees to the seismic PRA events trees;
6. then we calculate CDF and LERF which result from tsunami initiating events.

The “Logic Tree Approach”



The “Logic Tree Approach” allows generation of probability weights for the different hazard curves in a family of curves. It does this by first creating a logic tree where the nodes are choices of simulation parameter values or assumptions and the branches are <value, probability> pairs which sum to 1 at each node. In this way several simulations can be specified which will generate a family of weighted hazard curves for each hazard.

Top Ten NPP Tsunami Hazards

1. Water run-up height;
2. Water pressure;
3. Water velocity;
4. Water breaking force;
5. Water impact and shock;
6. Water spray height;
7. Water missiles, such as rocks, boats, automobiles;
8. Water debris blocking roads and walkways;
9. Water blockage impeding flow;
10. Water loss causing intake failure.

Hazard Curve Generation by Simulations

1. Choose hazards for analysis.
2. Full case studies of all historical and known events.
3. Proper Bayesian PDF of historical and known events.
4. Surveys of experts regarding NPP tsunami hazards.
5. Create the logic tree for specifying simulations.
6. For each simulation specified and for all hazards:
   a) Preparation of earthquake tsunami models.
   b) Preparation of landslide tsunami models.
   c) Preparation of tsunami models.
   d) Full PTHA of earthquake tsunami sources, including events of 1.0e-6.
   e) Full PTHA of landslide tsunami sources, including events of 1.0e-6.
   f) Full PTHA of volcano tsunami sources, including events of 1.0e-6.
   g) Numerical simulations from sources to NPP site.
   h) Create tsunami hazard maps.
   i) Use hazard maps to indicate where past large tsunami may have happened, and then do geological studies to discover if such events did indeed happen (simulation driven geological investigation).
   j) Integration of hazard map probabilities to form the cumulative density function for each hazard.
   k) Weight each hazard curve by the probability indicated by the logic tree branch.

Hazard and Fragility Calculations

for tsunami hazards (tsunami height, force, impact, debris, etc.):

- Create initiating events which correspond to hazard ranges.
- Import the family of hazard curves generated by the simulations. A family of curves, rather than a single one, is required to reflect the full uncertainty in the hazard specification.
  - The logic tree branches assign a probability, or weight, to each simulation curve as being the correct curve. The sum of the curve probabilities must add to 1.
  - Make a list of hazard values for which exceedence frequency data is available. The same hazard values are used for all hazard curves entered.
  - For each curve, an ordered pair of hazard values and exceedence frequencies is created.
- Calculate initiating events
- Create a list of component data. The following data is needed, at a minimum:
  - The median hazard for a component, which is the strength of the hazard at which the component has a 50% chance of failure on the median fragility curve.
  - The Beta R value, which is a measure of the randomness in the fragility estimate.
  - Beta U value, which is a measure of the modeling uncertainty in the assessed fragility curve.
  - The specification of where each component fragility curve should be cutoff (i.e., assigned to zero failure probability for all smaller hazards). Sometimes the HCLPF (High (>95%) Confidence of a Low (<5%) Failure Probability) hazard value is used as the cutoff point for the current fragility family. The value of zero indicates that no cutoff will be used, or sometimes a failure fraction greater than zero below which all calculated failure fractions will be set equal to zero.
- Calculate component fragilities.
- In this way we can calculate the frequency of hazard initiating events and failure frequencies of components or structures given hazards of a certain level (the fragilities).

Integration with the PRA (1)

We use these calculations to calculate the probability for each important hazard. For example, for tsunami height we can say that the probability of 15m is 1e-04, for 10m 1e-03, for 5m 5.0e-03, and so on.

Then from the fragility analysis we know the failure of systems and components GIVEN the tsunami heights. Then from the PRA model we generate new values for core damage frequency (CDF), large early release frequency (LERF), etc

Integration with the PRA (2)

1. Overlay NPP systems and structures onto the tsunami hazard maps.
2. Create damage models for systems and structures from the fragility analysis.
3. Using the same steps as in a seismic PRA, create the tsunami PRA: initiating event frequencies, component failures and integrate into seismic PRA type of model.
4. Identify building location characteristics of the NPP site which can amplify or mitigate actual tsunami run-up height and possible flooding pathways and equipment affected and augment the PRA model.
5. Identify NPP outcomes and sequences which lead to CDF, LERF, etc..
6. Calculate the PRA model.