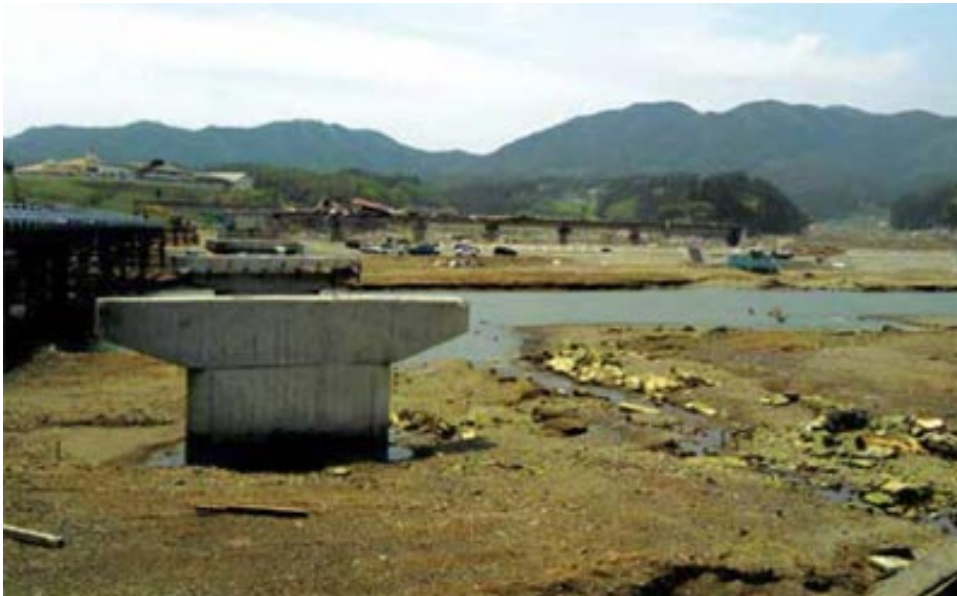


# Designing Bridges for Tsunami Hazard

Patrick Lynett,  
University of Southern  
California



With major technical  
contributions from: Hong Kie  
Thio, Michael Scott, Ian  
Buckle, Dennis Istrati, Tom  
Murphy

# Tsunami Design Guidelines for Coastal Bridges

- The project objectives center on the development of design guide specifications for the estimation of tsunami loads on highway bridges
- The work will include verification of the guidelines by model testing and comparison with observed results to calibrate the predictive capability of numerical models for analysis of tsunami loads on coastal bridges
- Final product will be a guidespec document
- Project is supported through a pooled fund with contributors from California, Oregon, Washington, Alaska, and Hawaii

# Tsunami Design Guidelines for Coastal Bridges

- Project has five major components:
  - Working Group 1: Tsunami Hazard and Mapping
    - Hong Kie Thio (co-Lead), Patrick Lynett (co-Lead)
  - Working Group 2: Tsunami Loading of Bridges
    - Members: Michael Scott (Lead), Ian Buckle, Denis Istrati
  - Working Group 3: Bridge Detailing for Tsunami Loads
    - Members: Tom Murphy (Lead)
  - Working Group 4: Geotechnical Issues (Scour and drawdown induced liquefaction)
    - Members: Tom Shantz (Lead)
  - Working Group 5: Guide Specifications for Bridge Design for Tsunami Hazard
    - Members: Tom Murphy (Lead), Ian Buckle



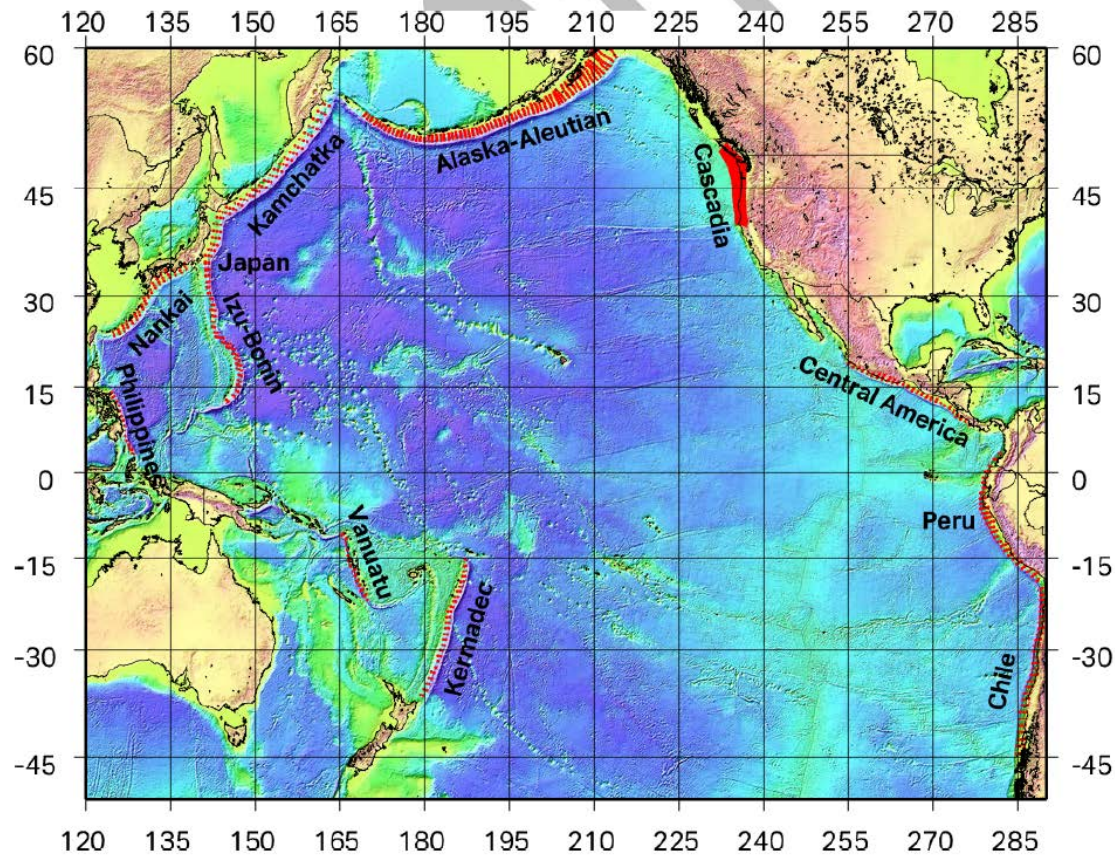
# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping
  - Development of tsunami hazard map database
    - Inventory of existing maps
    - New maps at the 1000-yr hazard level, at 10-m to 60-m resolution modeling in selected locations
  - Quantification and inclusion of uncertainties in the offshore & onshore propagation
  - Specification of Method(s) to provide the hydrodynamic information needed (max, mins, time series, etc) for design using the hazard maps as input
    - Options include using the Energy Method (ASCE7) or some Numerical Model Transect tool in the general vicinity of the structure (LEVEL 1)
    - Or detailed 2D/3D, site-specific modeling for projects requiring more precision / refinement (LEVEL 2)



# Tsunami Design Guidelines for Coastal Bridges

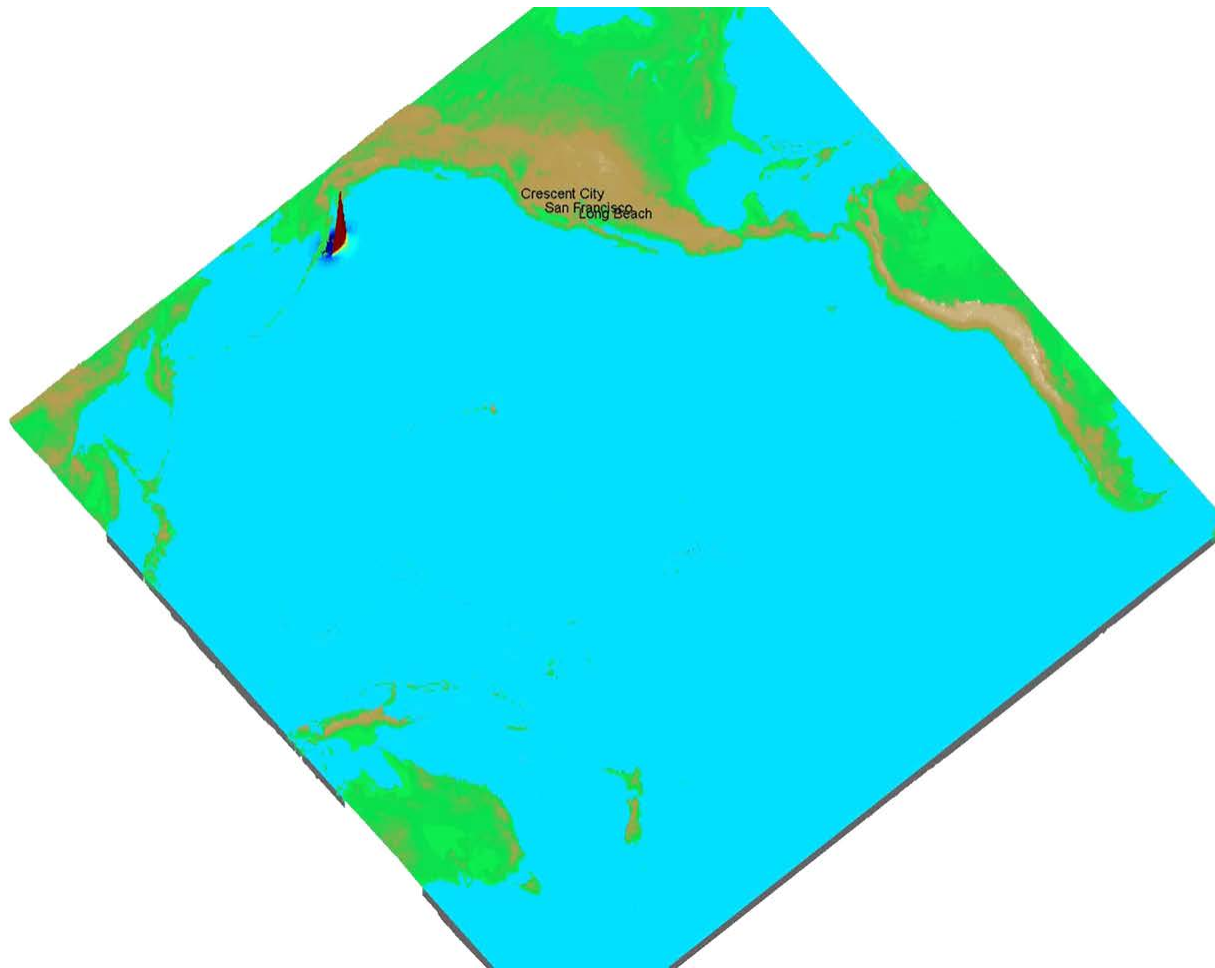
- Working Group 1: Tsunami Hazard and Mapping
  - PTHA





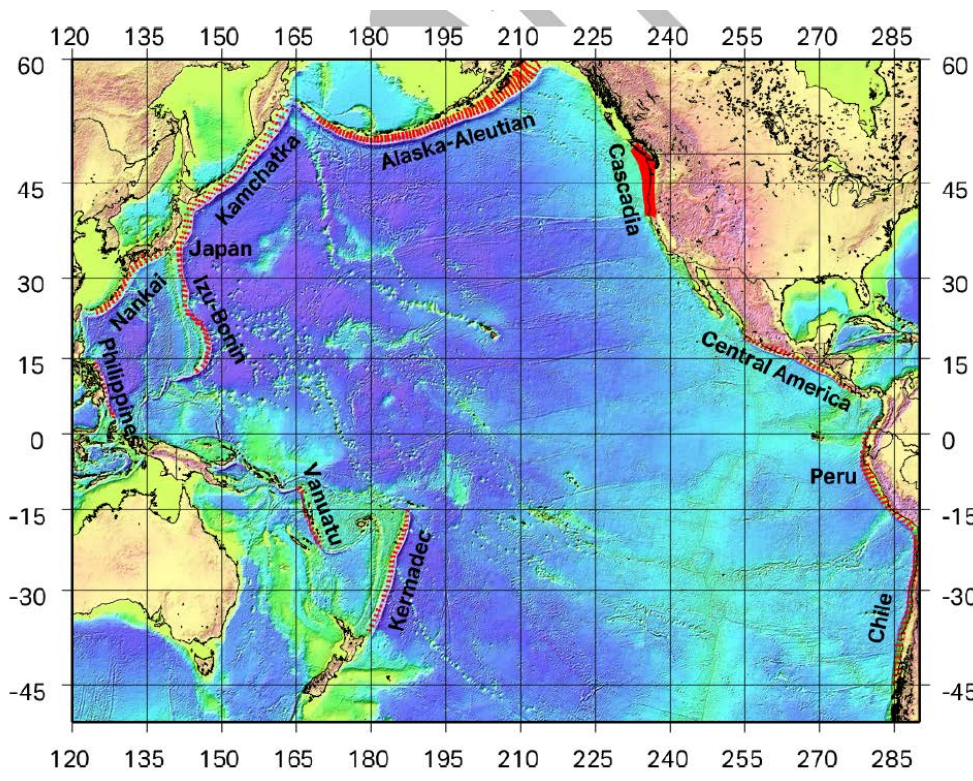
# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping
  - PTHA

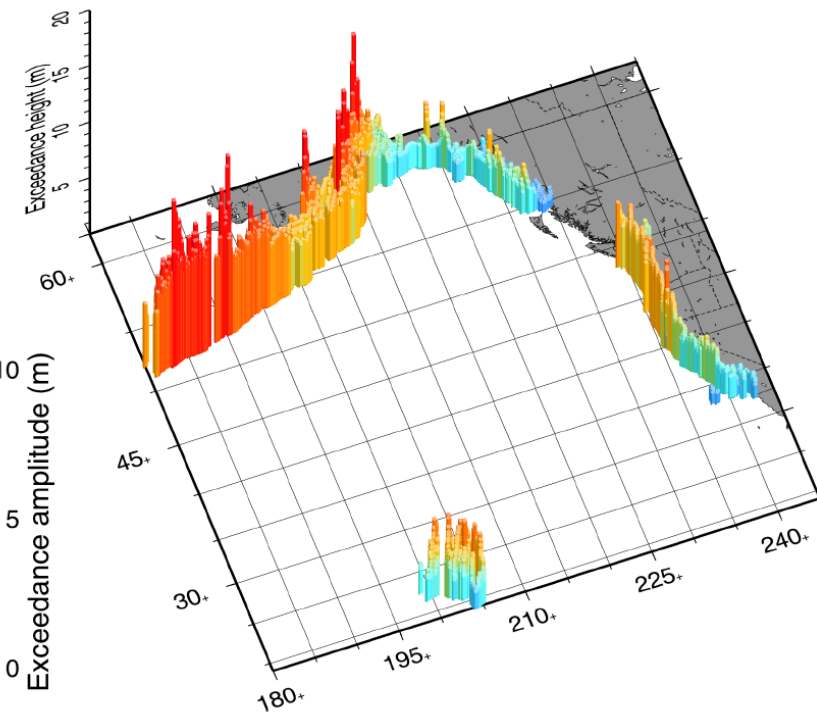


# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping
  - PTHA



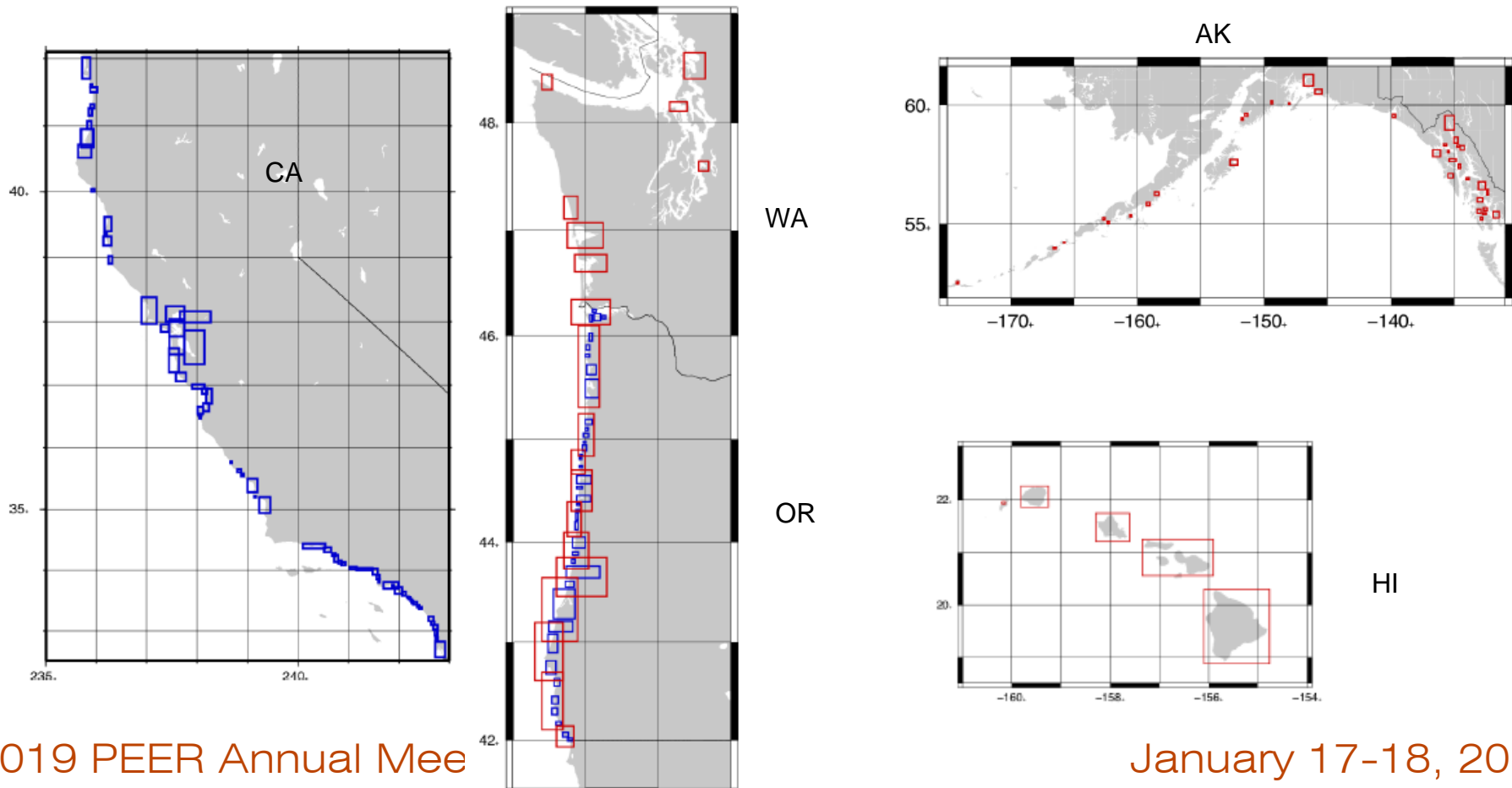
1000 yr return period





# Tsunami Design Guidelines for Coastal Bridges

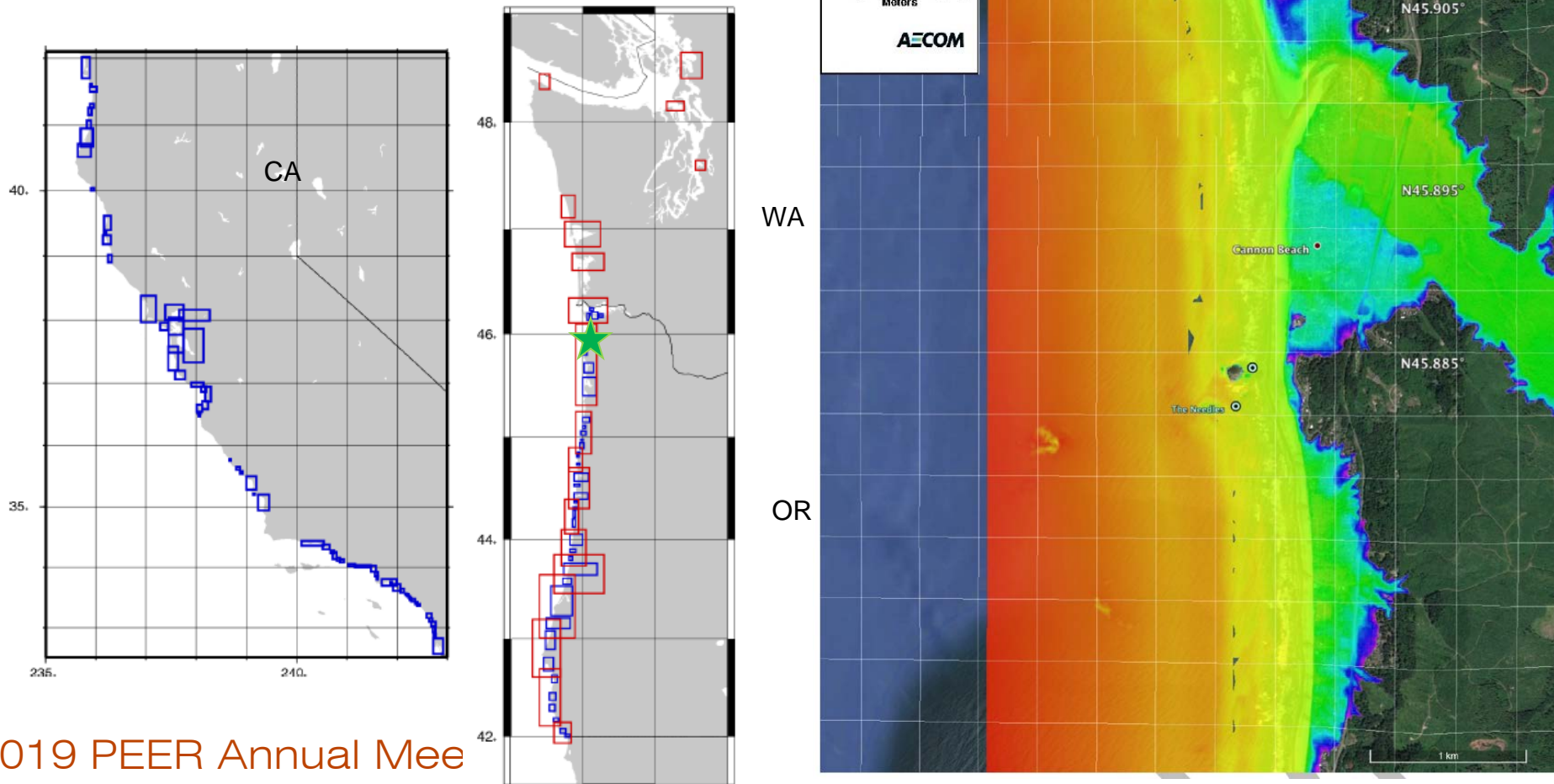
- Working Group 1: Tsunami Hazard and Mapping
  - Inundation Map Coverage





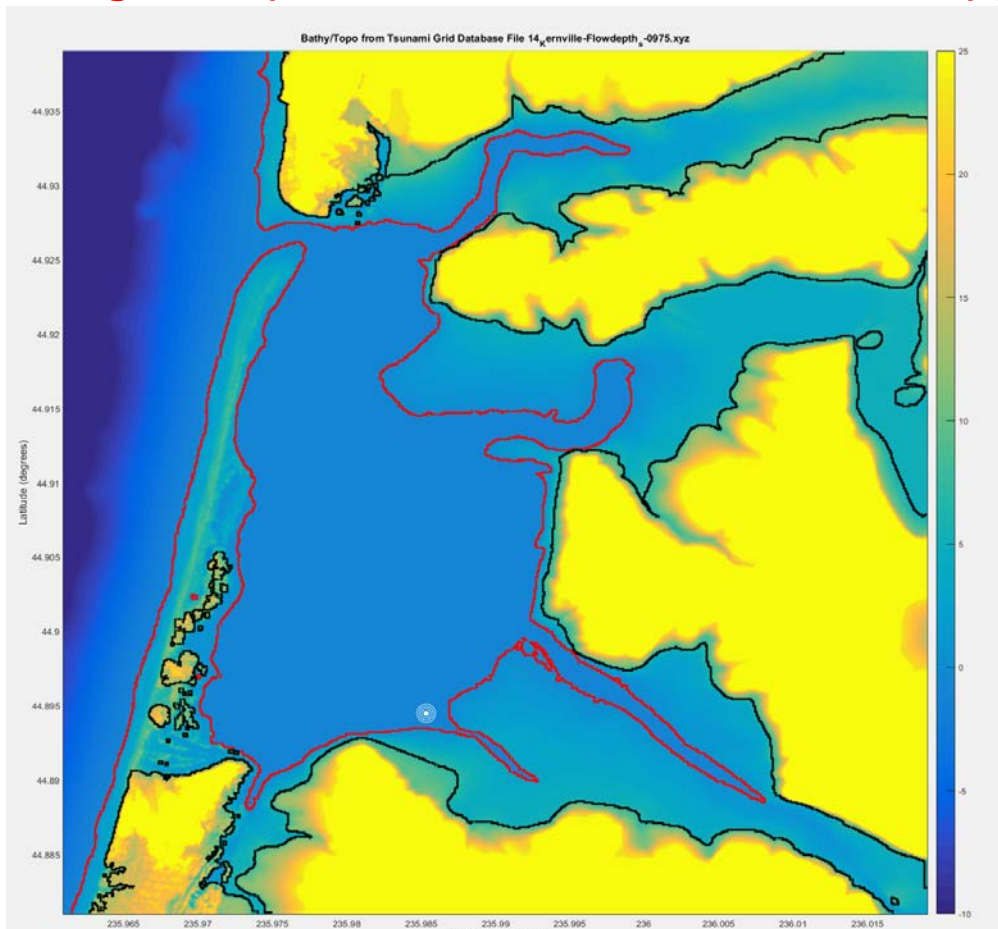
# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping
  - Inundation Map Coverage



# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping



Red line – shoreline at high tide  
Black line – inundation limit of  
1000-year tsunami

Modeling database contains  
maximum flow elevation, flow  
speed, flow direction, and  
momentum flux at all inundated  
grid points

For numerical grids in database  
with resolution of 10-m, database  
results can be used directly for  
site-specific hazard (LEVEL 2)

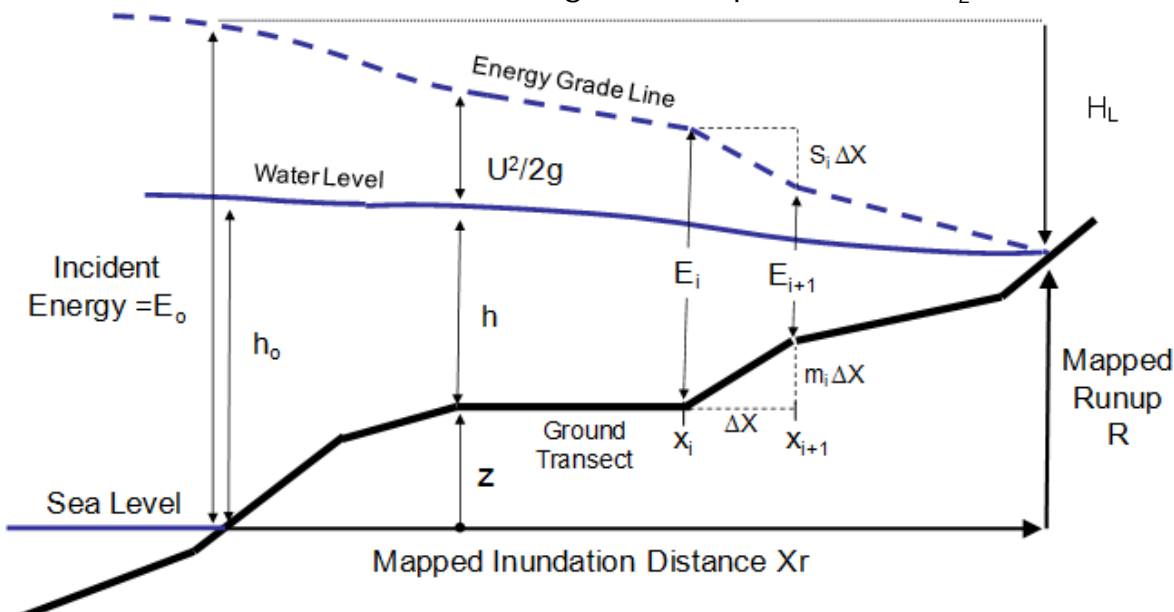
# Tsunami Design Guidelines for Coastal Bridges

## Working Group 1: Tsunami Hazard and Mapping

- Approaches to determine local hazard: LEVEL 1: EGL/transect approach (for areas where mapping uses resolution of >30m)
  - Details in Kriebel et al. (2017)
  - Based on tracking the total energy (potential and kinetic) over changing ground elevation with energy dissipation due to friction
    - Conceptually tracking the crest of a long wave as it moves inland

$$\frac{dE}{dx} = -(m + S)$$

where  $m = dz/dx$  is the local ground slope and  $S = dH_L/dx$  is the local friction slope



### INPUTS:

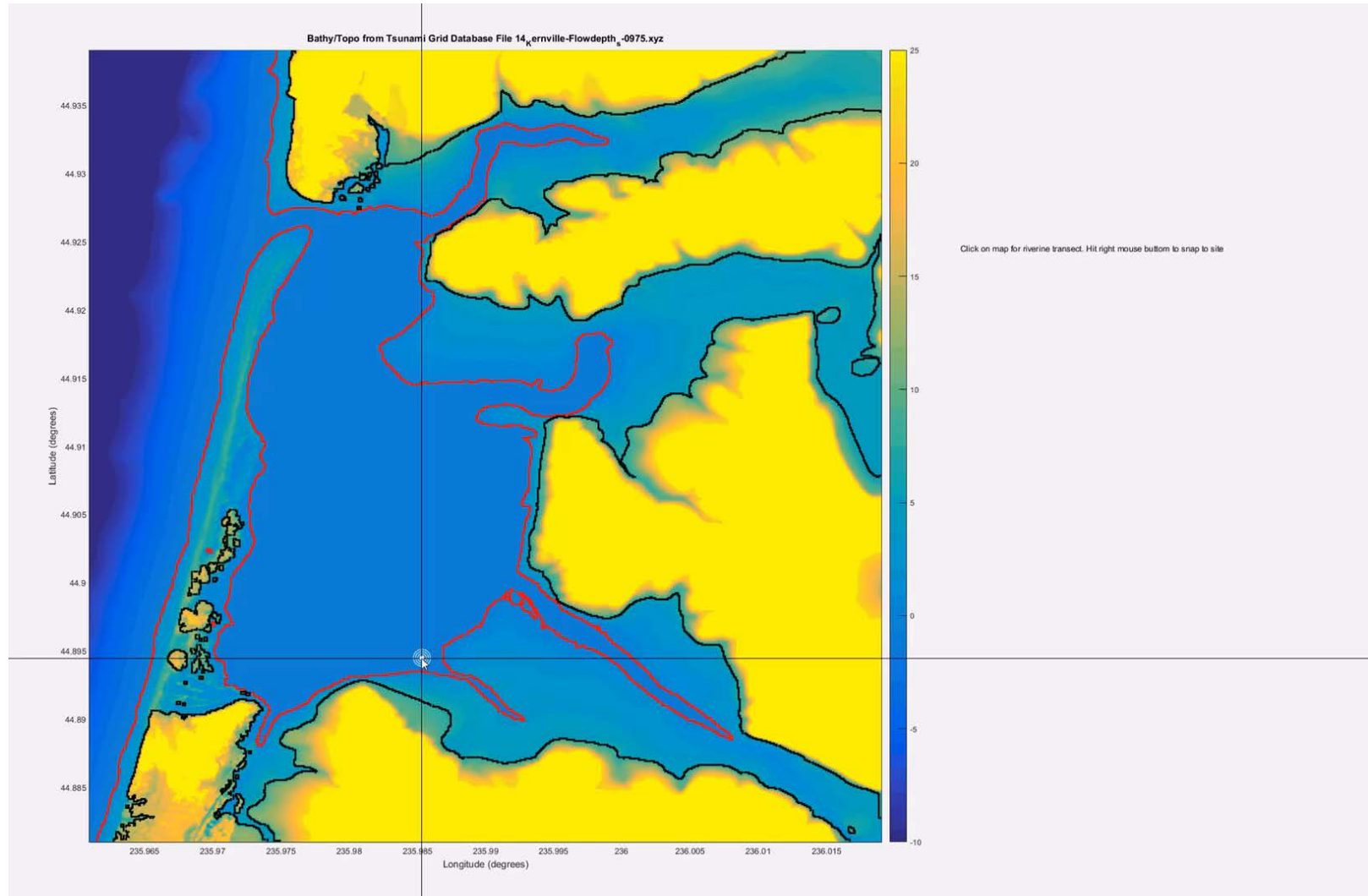
1. Transect Data  $[x, z]$  starting from shoreline
2. Runup location on transect
3. Bottom roughness coefficient

$$F_r = F_{ro} \left(1 - \frac{x}{x_R}\right)^{1/2}$$

Start with the runup location, as given by a hazard map, and solve the gradient equation backwards until reaching the shoreline

# Tsunami Design Guidelines for Coastal Bridges

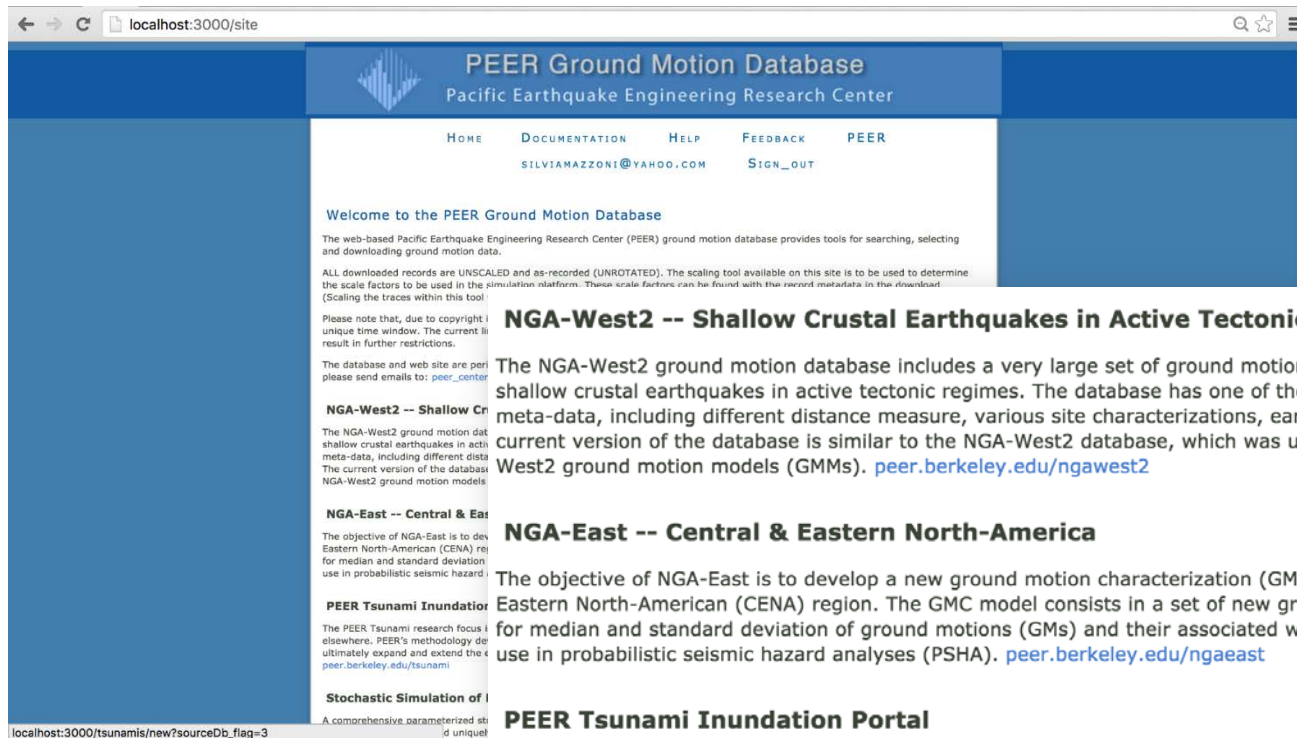
- Working Group 1: Tsunami Hazard and Mapping
  - Application of EGL / animation





# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping
  - PEER web portal



## NGA-West2 -- Shallow Crustal Earthquakes in Active Tectonic Regimes

The NGA-West2 ground motion database includes a very large set of ground motions recorded in worldwide shallow crustal earthquakes in active tectonic regimes. The database has one of the most comprehensive sets of meta-data, including different distance measure, various site characterizations, earthquake source data, etc. The current version of the database is similar to the NGA-West2 database, which was used to develop the 2014 NGA-West2 ground motion models (GMMs). [peer.berkeley.edu/ngawest2](http://peer.berkeley.edu/ngawest2)



## NGA-East -- Central & Eastern North-America

The objective of NGA-East is to develop a new ground motion characterization (GMC) model for the Central and Eastern North-American (CENA) region. The GMC model consists in a set of new ground motion models (GMMs) for median and standard deviation of ground motions (GMs) and their associated weights in the logic-trees for use in probabilistic seismic hazard analyses (PSHA). [peer.berkeley.edu/ngaeast](http://peer.berkeley.edu/ngaeast)



## PEER Tsunami Inundation Portal

The PEER Tsunami research focus is a crucial gap in tsunami research efforts currently being conducted elsewhere. PEER's methodology development – called Performance-Based Tsunami Engineering (PBTE) – will ultimately expand and extend the existing Performance-Based Earthquake Engineering (PBEE) methodology. [peer.berkeley.edu/tsunami](http://peer.berkeley.edu/tsunami)



## Stochastic Simulation of Near-Fault Ground Motions

A comprehensive parameterized stochastic model of near-fault ground motions in two orthogonal horizontal directions. The model used uniquely combines several existing and new sub-models to represent major characteristics of recorded near-fault ground motions. These characteristics include near-fault effects of directivity and fling step; temporal and spectral non-stationarity; intensity, duration and frequency content characteristics; directionality of components, as well as the natural variability of motions for a given earthquake and site scenario. More...coming soon(from: Stochastic Modeling and Simulation of Near-Fault Ground Motions for Performance-Based Earthquake Engineering by Mayssa Nabil Dabaghi, Doctoral Thesis 2014.)



# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping
  - PEER web portal

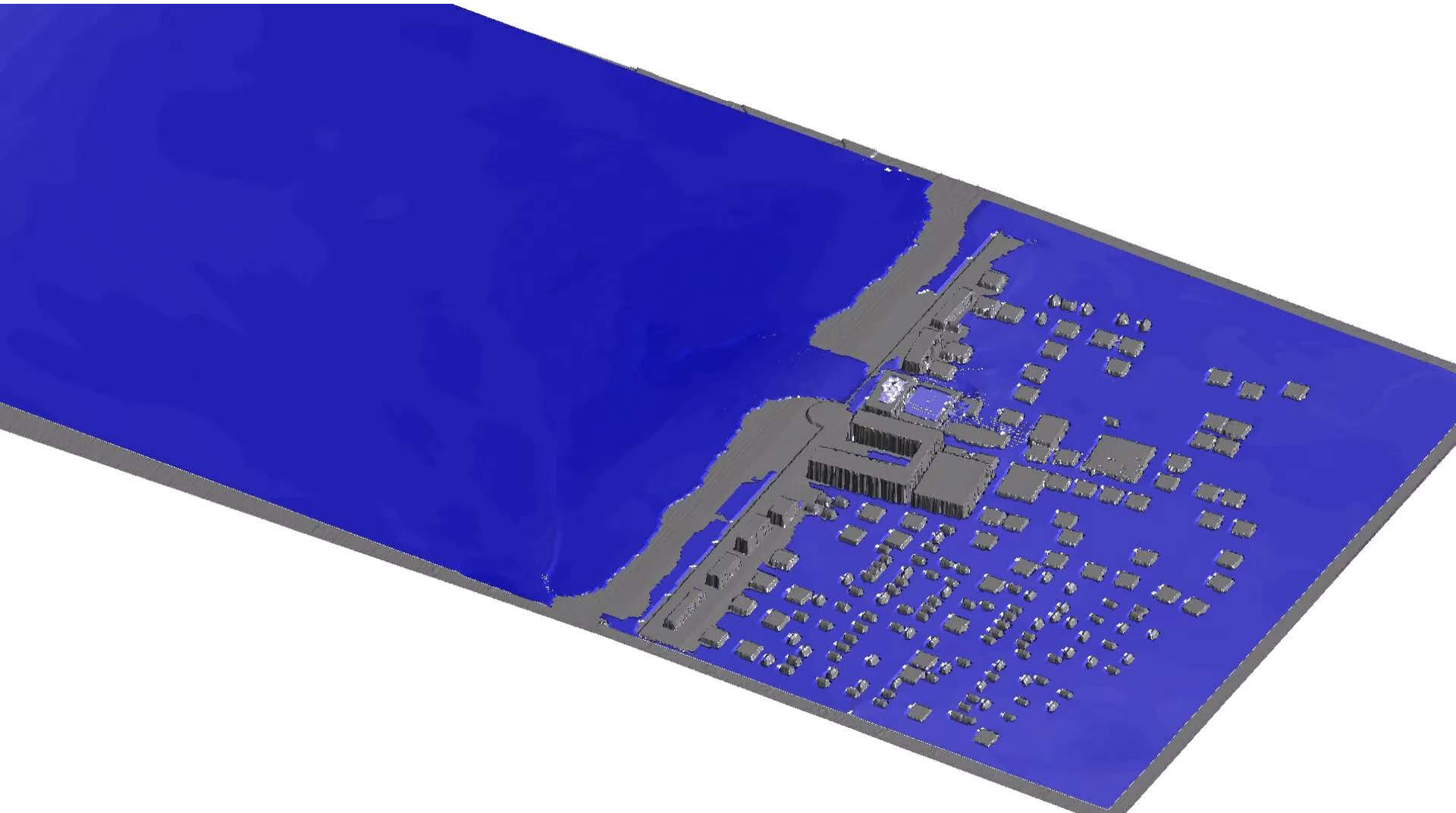
The screenshot shows a web browser window with the URL `localhost:3000/tsunamis/new?sourceDb_flag=3`. The page header features the "Tsunami Research Program" logo and the text "Pacific Earthquake Engineering Research Center" and "Inundation Portal". The navigation menu includes links for HOME, DOCUMENTATION, HELP, FEEDBACK, PEER, and a contact email `SILVIAMAZZONI@YAHOO.COM`, along with a SIGN\_OUT button.

The main content area is titled "Tsunami Inundation Modeling" and contains several input sections:

- Input Parameters**: Includes buttons for "Load Sample Input Values" and "Clear Input Values". A note states: "Input boxes are automatically enabled/disabled depending on the user input. Every enabled box needs an input value." This section contains three sub-forms:
  - Site Basics**: Fields for "Site Label" (filled with "Corvallis, OR") and "Site Lat,Long" (filled with "44.5646,-123.2620").
  - Bottom Friction**: A dropdown for "Bottom-Friction Model" set to "User-Defined" and a text input for "User-Defined Values (csv)" containing "0.3,0.35,0.5,0.65,0".
  - Hazard Levels**: Three checkboxes for "500yr", "1000yr", and "2500yr", all of which are checked.
- Model Parameters**: Contains two sub-forms:
  - Inundation Model**: A list of four models. "Energy Grade Line" is checked, while "Inundation Model 1", "Inundation Model 2", "Inundation Model 3", and "Inundation Model 4" are unchecked.
  - WaveSignal Type**: A list of four types. "WaveSignal Type 1" is checked, while "WaveSignal Type 2", "WaveSignal Type 3", and "WaveSignal Type 4" are unchecked.
- Transects**: A dropdown for "Transect-Line" set to "Automated" and a "ComputeTransects" button.

# Tsunami Design Guidelines for Coastal Bridges

- Working Group 1: Tsunami Hazard and Mapping
  - Example of detailed 2D/3D modeling (LEVEL 2 Analysis)



# Tsunami Design Guidelines for Coastal Bridges

- Once we have the site-specific hydrodynamic hazard, on to:
- Working Group 2: Tsunami Loading of Bridges
- Literature review of existing and ongoing methods to estimate loads on bridges / tsunami loads on general structures
  - Determine whether existing methods can be extended tsunami loads on bridges
  - If additional information or testing is needed, develop a plan to obtain
- Testing and modeling to fill in knowledge gaps
  - Based on gaps determined, perform physical or numerical tests
  - Focus on numerical simulation

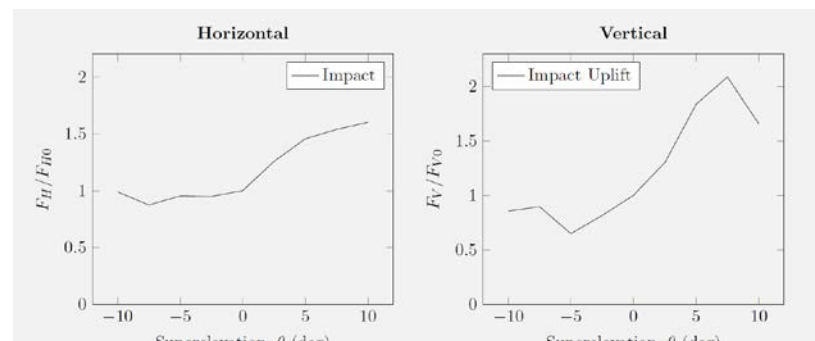
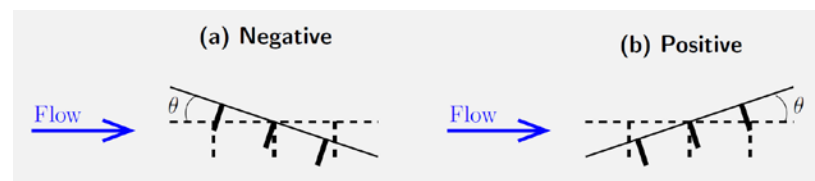
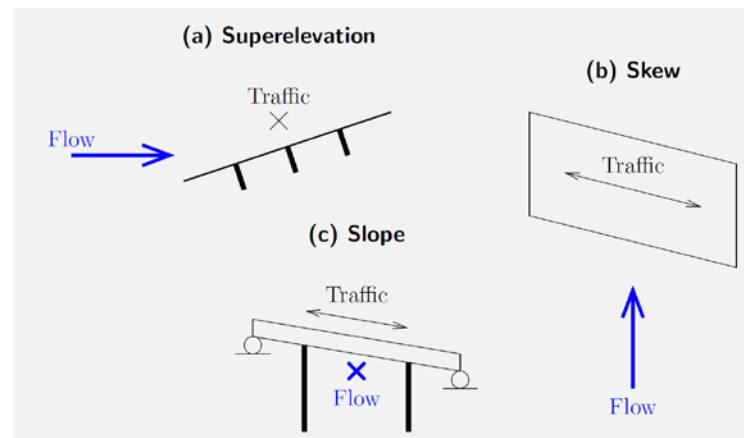


- ▶ Determination of loading calculation approach
  - Presentation of example loading calculations, from source (or hazard level) specification, to loadings



# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges
- Numerical “gap” studies will provide loading coefficient / modification factors to account for:
  - Wave Form – characteristics of the leading (or maximum) wave
  - Bridge Geometry
    - Cross-section (for typical/ordinary bridges on Pacific Coast)
    - Global Orientation of deck
    - Mass and stiffness (connection to piers, abutments); dynamic response
    - Data and studies from Buckle, Motley
  - Debris – multiplier for different zones around bridge
    - Industrial, Residential, Natural
  - Tsunami Protection
    - Fairing, fuse, sacrificial bridge
- Other considerations
  - Load cases
    - 2-3 different load cases (e.g. max speed at X% max flow height, max flow height at X% max speed)
  - Load distribution



# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges
- Examples of loading equations

Douglass (2006)

$$F_H = ((1 + C_r(N - 1))C_{h,va})(\rho g)(\eta - h_g)A_h$$

Azadbakht and Yim (2014)

$$F_H = \left( \frac{1}{2} \rho g (2h_0 - d_b) d_b + \frac{1}{2} \rho C_d d_b u_{max}^2 \right) L_b$$

Xiang (2016)

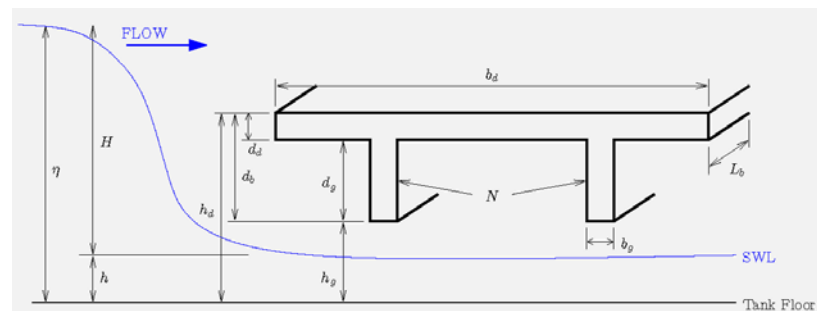
$$F_H = (C_H + C_{H,SL}) \left( \frac{1}{2} \rho g (2h_0 - d_b) d_b + \frac{1}{2} \rho C_d d_b u_{max}^2 \right) L_b$$

FEMA P-646

$$F_H = \frac{1}{2} \rho C_d d_b L_b u_{max}^2$$

McPherson (2008)

$$F_H = \frac{1}{2} ((\eta - h_g) + (\eta - (h_d - d_d))) d_g L_b (\rho g)$$



Many different choices...

Choose one based on comparison with data and applicability with tsunami -> A&Y

# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges
- Examples of loading equations

Douglass (2006)

$$F_H = ((1 + C_r(N - 1))C_{h,va})(\rho g)(\eta - h_g)A_h$$

McPherson (2008)

$$F_H = \frac{1}{2}((\eta - h_g) + (\eta - (h_d - d_d)))d_g L_b(\rho g)$$

Azadbakht and Yim (2014)

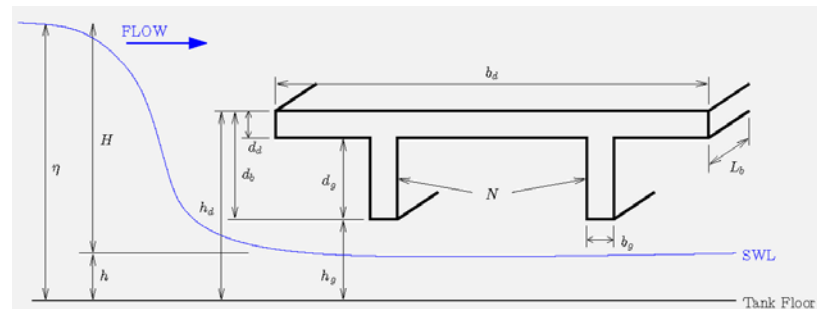
$$F_H = \left( \frac{1}{2}\rho g(2h_0 - d_b)d_b + \frac{1}{2}\rho C_d d_b u_{max}^2 \right) L_b$$

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FEMA P-646

$$F_H = \frac{1}{2}\rho C_d d_b L_b u_{max}^2$$



Many different choices...

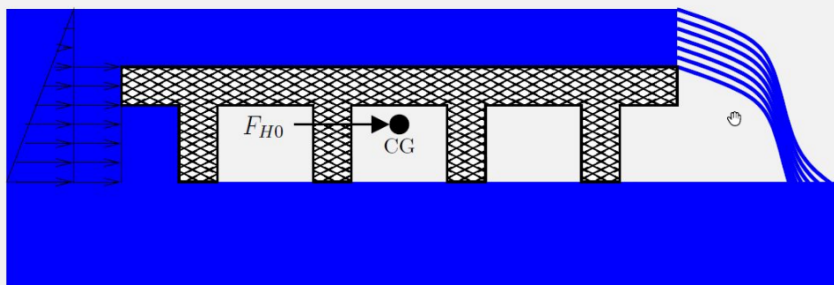
Choose one based on comparison with data and applicability with tsunami -> A&Y

# Tsunami Design Guidelines for Coastal Bridges

## Working Group 2: Tsunami Loading of Bridges

Estimate of maximum horizontal load from Azadbakht and Yim (2014) – hydrostatic and hydrodynamic components

$$F_{H0} = 0.5\rho g(2h_0 - d_b)d_b + 0.5\rho C_d d_b u^2$$



Adjustment factors for hydrostatic and hydrodynamic components

$$F_{H0} = C_1(0.5\rho g(2h_0 - d_b)d_b) + C_2(0.5\rho C_d d_b u^2) \quad (5)$$

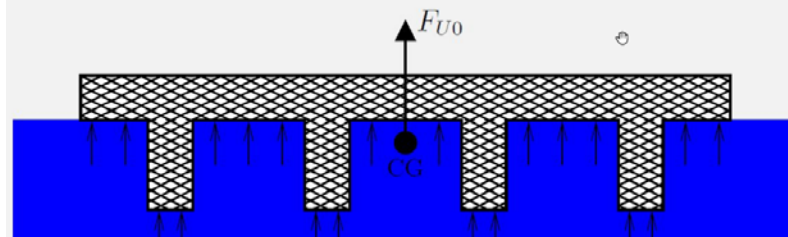
- $C_1$  and  $C_2$  based on correlation with simulations for horizontal impact and steady state loads
- Box girder  
Impact:  $C_1 = 2.0$ ,  $C_2 = 1.1$   
Steady State:  $C_1 = 0.8$ ,  $C_2 = 0.5$
- Open girder  
Impact:  $C_1 = 1.5$ ,  $C_2 = 1.2$   
Steady State:  $C_1 = 0.8$ ,  $C_2 = 0.4$

Estimate of maximum upward load from Azadbakht and Yim (2014) – hydrostatic and vertical lift components

$$F_{U0} = C_{UP}(\rho g V + 0.5C_l \rho u^2 b_d) \quad (6)$$

$C_l$  is lift coefficient (taken as 1.0)

$C_{UP}$  is an empirical coefficient to correlate numerical results with uplift load equation ( $C_{UP} = 0.77$  from A&Y (2014))



Adjustment factors for hydrostatic and lift components

$$F_{U0} = C_1(\rho g V) + C_2(0.5\rho b_d u^2) \quad (7)$$

- $C_1$  and  $C_2$  based on correlation with simulations for horizontal impact and steady state loads
- Simulations also showed dependence on clearance
- Box girder  
 $C_1 = 1.0$ ,  $C_2 = 0.6(h_0/(h_g - h))$
- Open girder  
 $C_1 = 1.0$ ,  $C_2 = 0.2(h_0/(h_g - h))$

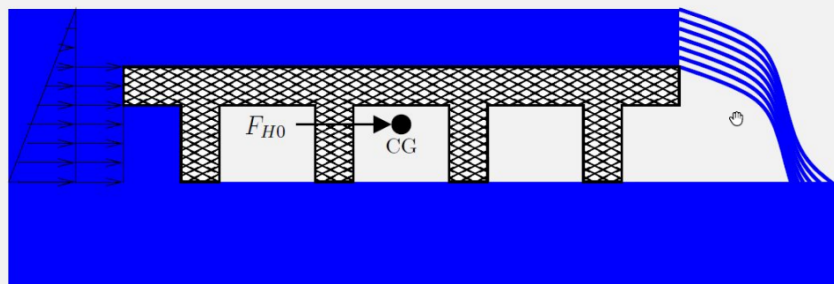


# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges

Estimate of maximum horizontal load from Azadbakht and Yim (2014) – hydrostatic and hydrodynamic components

$$F_{H0} = 0.5\rho g(2h_0 - d_b)d_b + 0.5\rho C_d d_b u^2$$



Adjustment factors for hydrostatic and hydrodynamic components

$$F_{H0} = C_1(0.5\rho g(2h_0 - d_b)d_b) + C_2(0.5\rho C_d d_b u^2) \quad (5)$$

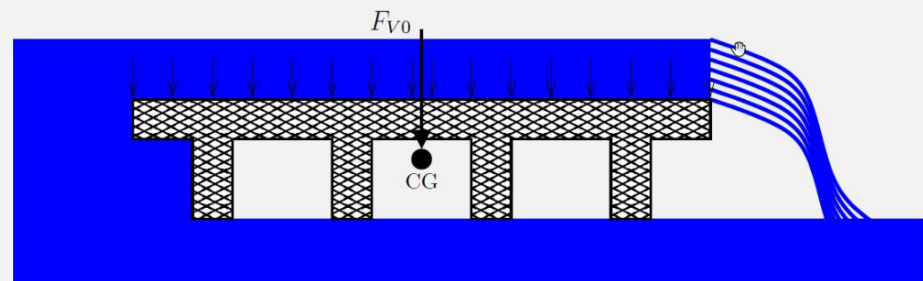
- $C_1$  and  $C_2$  based on correlation with simulations for horizontal impact and steady state loads
- Box girder  
Impact:  $C_1 = 2.0$ ,  $C_2 = 1.1$   
Steady State:  $C_1 = 0.8$ ,  $C_2 = 0.5$
- Open girder  
Impact:  $C_1 = 1.5$ ,  $C_2 = 1.2$   
Steady State:  $C_1 = 0.8$ ,  $C_2 = 0.4$

Estimate of maximum downward load from Azadbakht and Yim (2014) – hydrostatic and vertical slamming components

$$F_{D0} = C_{DV}(\rho g(h_0 - d_b)d_d + \text{slamming}) \quad (8)$$

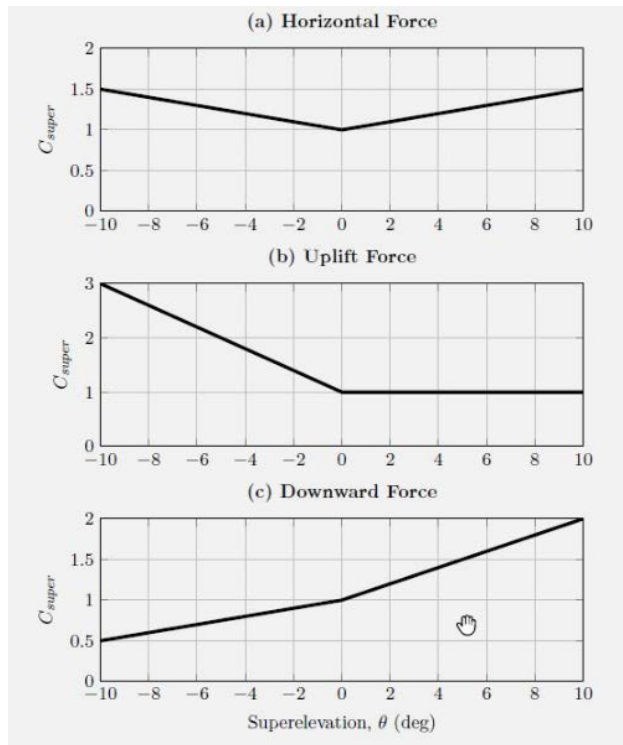
Slamming component only if barriers present

$C_{DV}$  is an empirical coefficient to correlate numerical results with downward load equation ( $C_{DV} = 0.53$  from A&Y (2014))

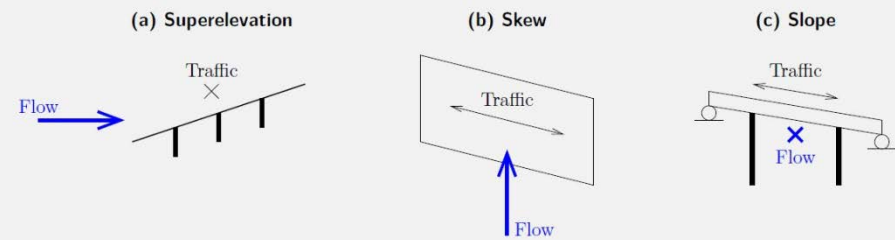


# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges



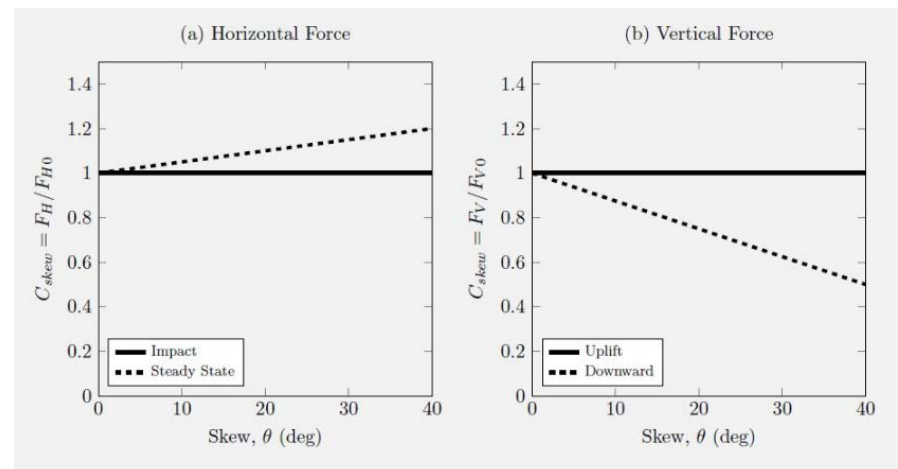
Modify nominal loads by factors for 3D orientation



Horizontal load

$$F_H = C_{super} C_{skew} C_{slope} F_{H0}$$

Similar expressions for  $F_U$  and  $F_D$



# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges

- Use  $\rho = 1040 \text{ kg/m}^3$  in all reference load calculations to account for sediments
- Use an additional factor of  $C_{debris} = 1.06$  for small debris in only the horizontal load calculations
- Large debris assumed only for horizontal load

$$F_H = C_{skew}C_{super}C_{slope}C_{debris}F_{H0} + F_{debris} \quad (10)$$

$$F_U = C_{skew}C_{super}C_{slope}F_{U0} \quad (11)$$

$$F_D = C_{skew}C_{super}C_{slope}F_{D0} \quad (12)$$

- Large objects, e.g., vehicles or shipping containers
- Impact loading on bridge deck
- Difficult to determine stopping distance and impact time
- FEMA (2012) approximation of impact force

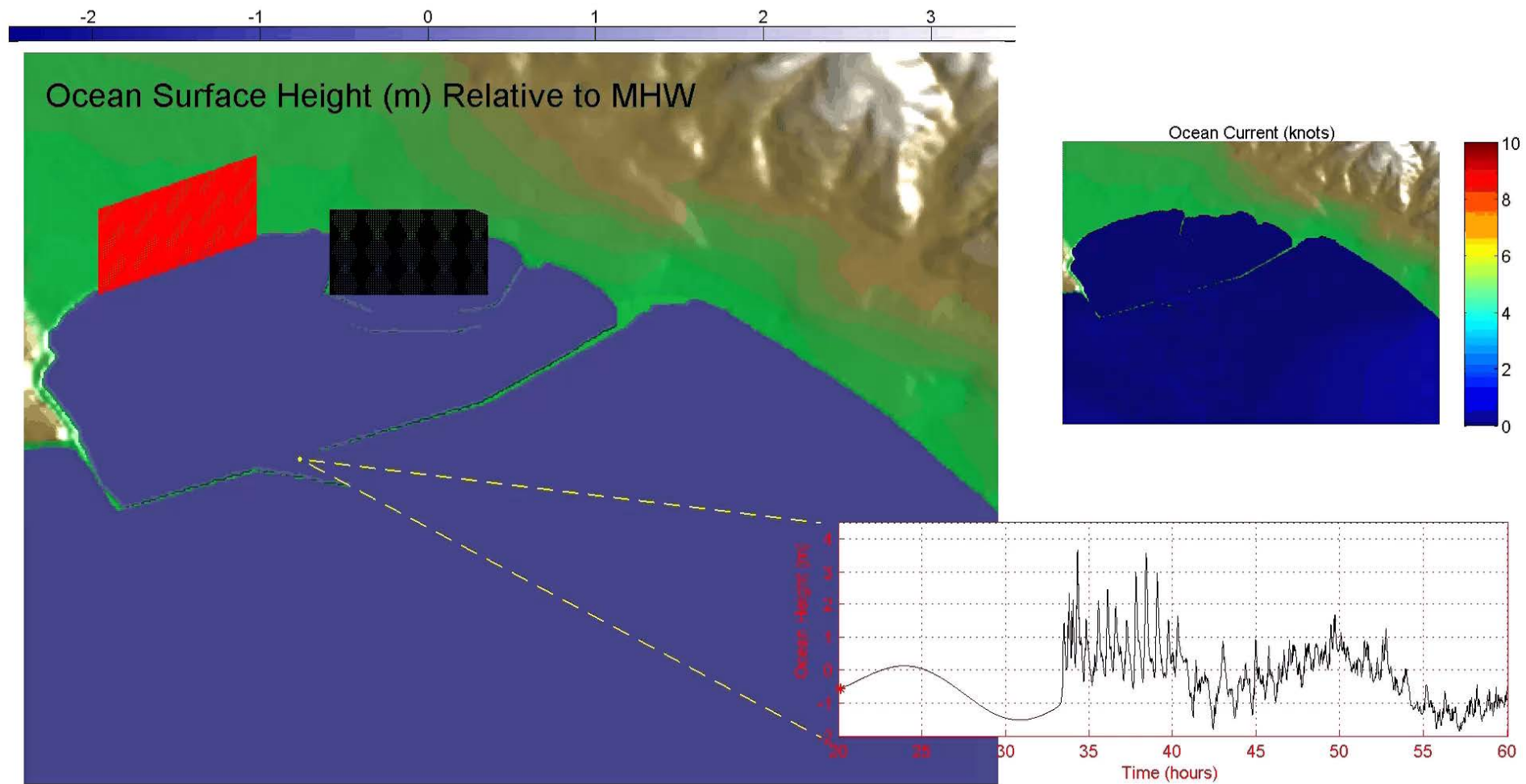
$$F_{debris} = 1.3u\sqrt{km}$$

1.3=importance factor,  $u$ =flow speed,  $k$ =debris stiffness,  $m$ =debris mass

- Elastic impact – full shipping container 1440 kip at  $u=4 \text{ m/s}$

# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges – SMALL DEBRIS

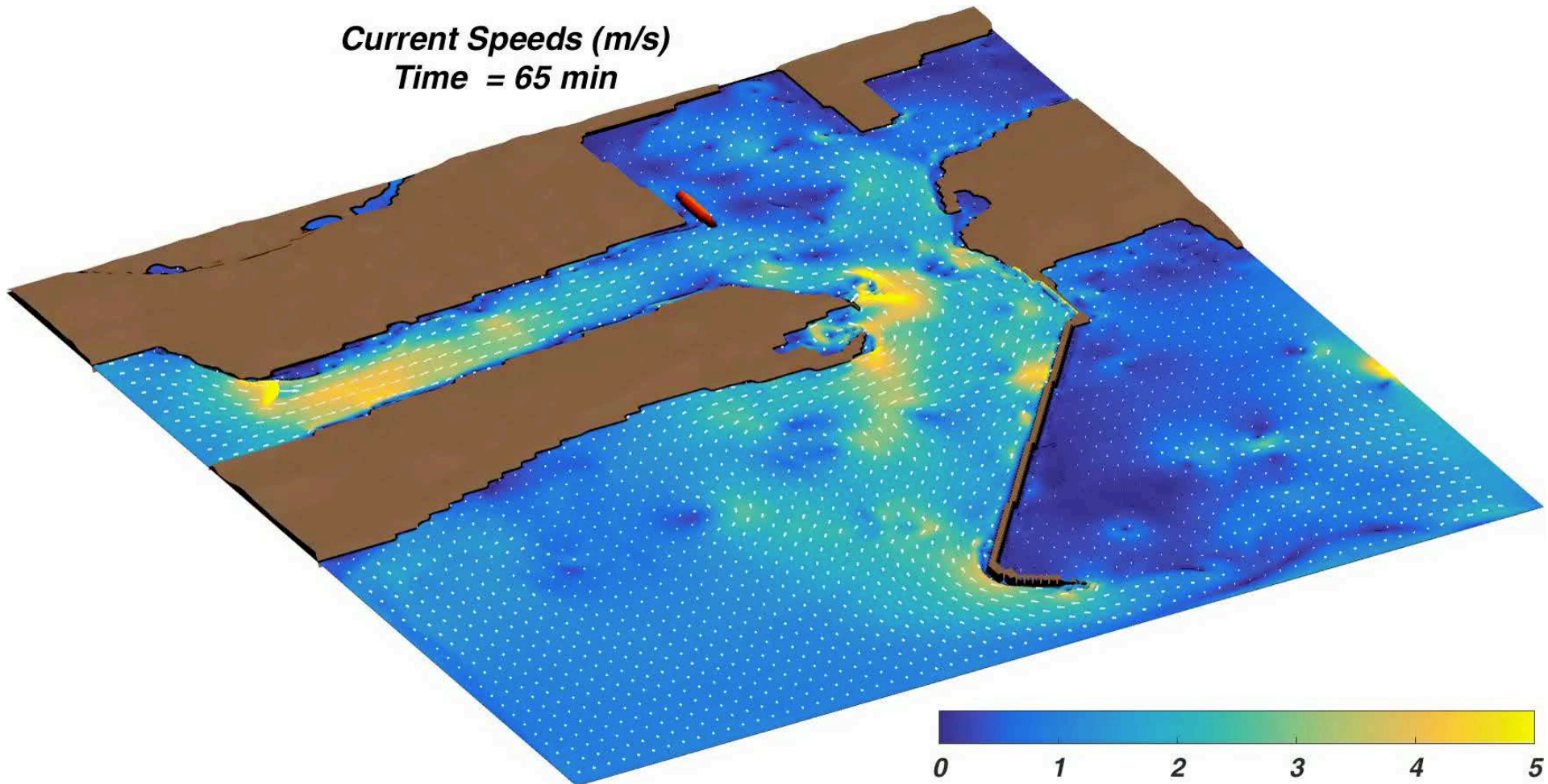




# Tsunami Design Guidelines for Coastal Bridges

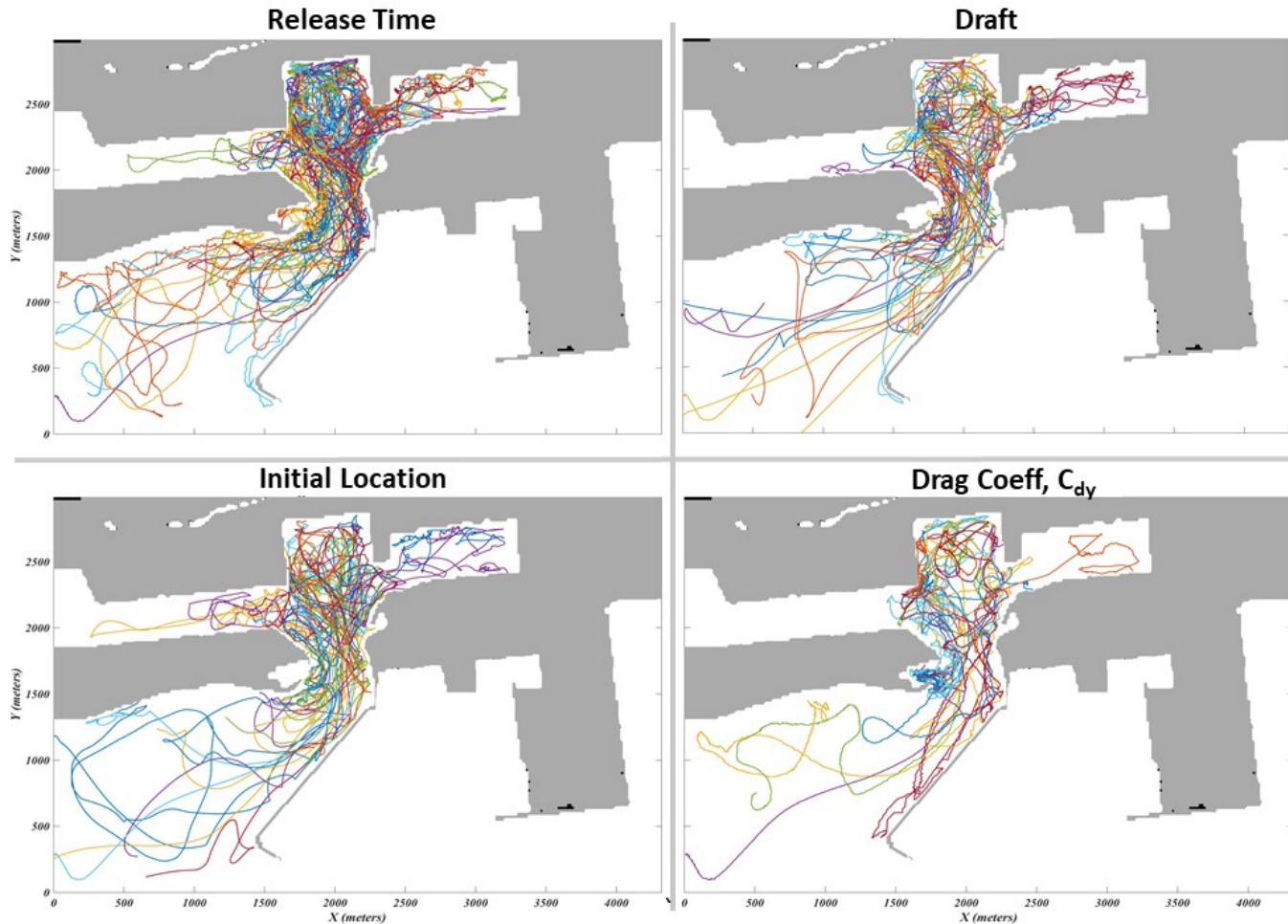
- Working Group 2: Tsunami Loading of Bridges – LARGE DEBRIS

*Current Speeds (m/s)*  
*Time = 65 min*



# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges – LARGE DEBRIS



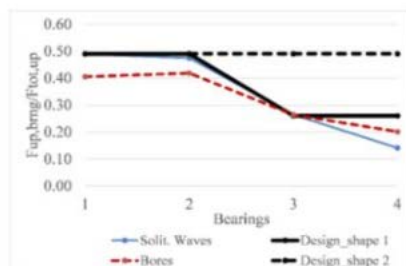
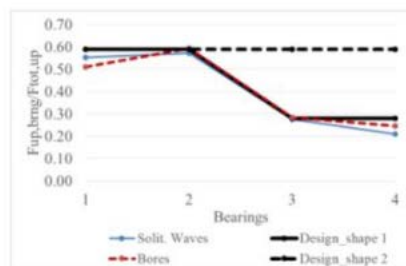
# Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges

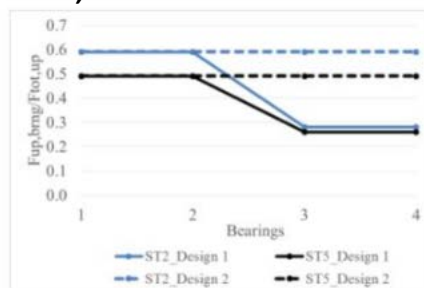
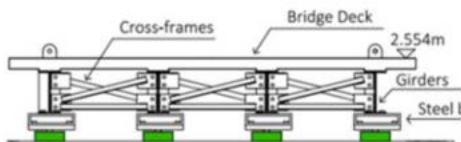
- Use  $\rho = 1040 \text{ kg/m}^3$  in all reference load calculations to account for sediments
- Use an additional factor of  $C_{debris} = 1.06$  for small debris in only the horizontal direction
- Large debris

OK.. Now how is this load distributed across the bearings???

Open girder bridge with elastomeric bearings: Cross-frames vs diaphragms



Buckle & Istrati, Reno



or shipping containers

ck

ing distance and impact time  
n of impact force

$$s = 1.3u\sqrt{km}$$

1.3=importance factor,  $u$ =flow speed,  $k$ =debris stiffness,  $m$ =debris mass

- Elastic impact – full shipping container 1440 kip at  $u=4 \text{ m/s}$

- Working Group 5: Guide Specifications for Bridge Design for Tsunami Hazard
  - Draft Guidespecs and commentary
    - Construct outline and partially filled guidespec / commentary, based on Working Group 2 results
  - Review of Draft and Final Guidespec
  - Will include performance objectives
- Draft guidespec delivered to sponsor soon

