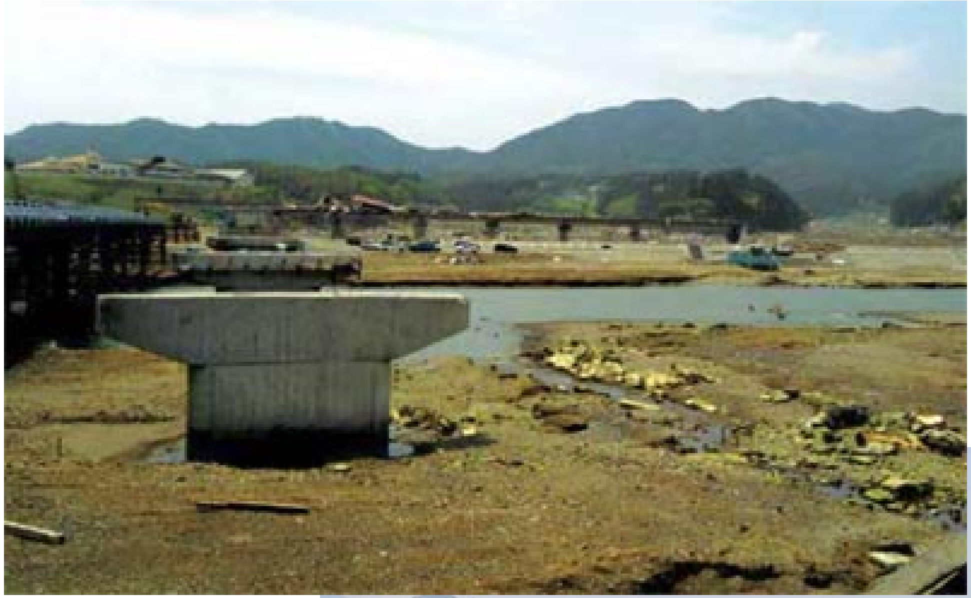
Designing Bridges for Tsunami Hazard

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)

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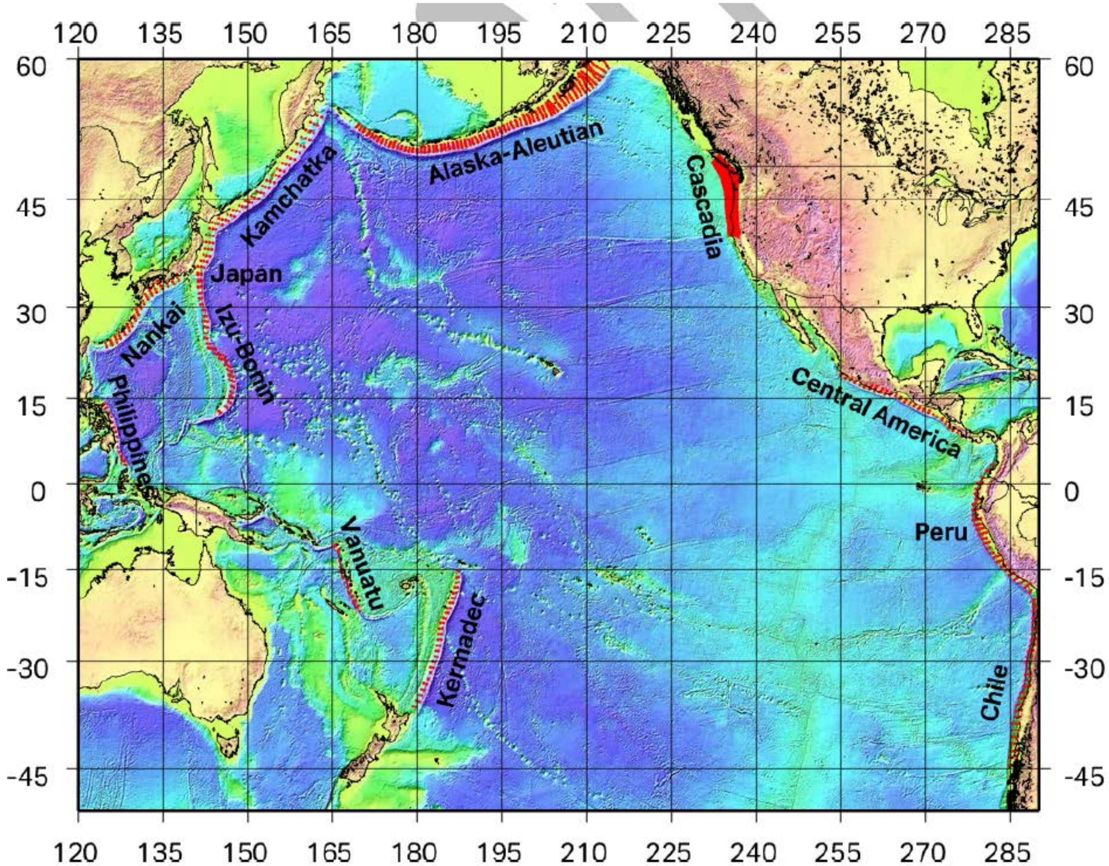
- Working Group 1: Tsunami Hazard and Mapping
  - PTHA



Tsunami Design Guidelines for Coastal Bridges

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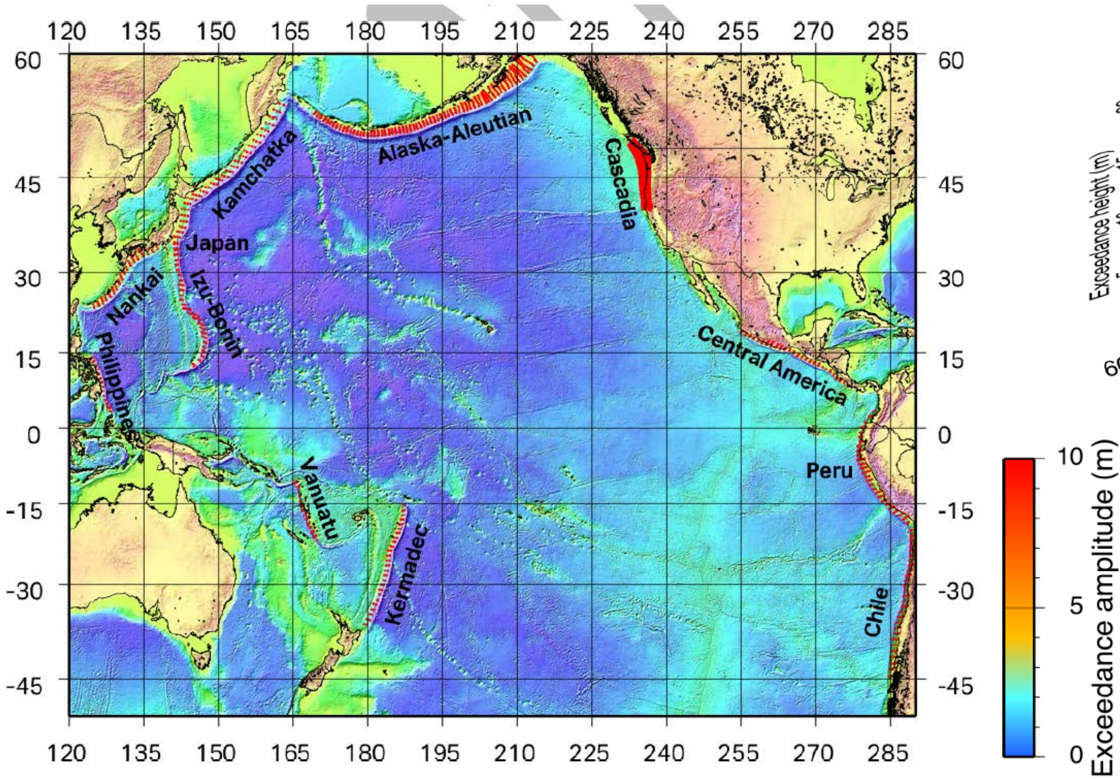
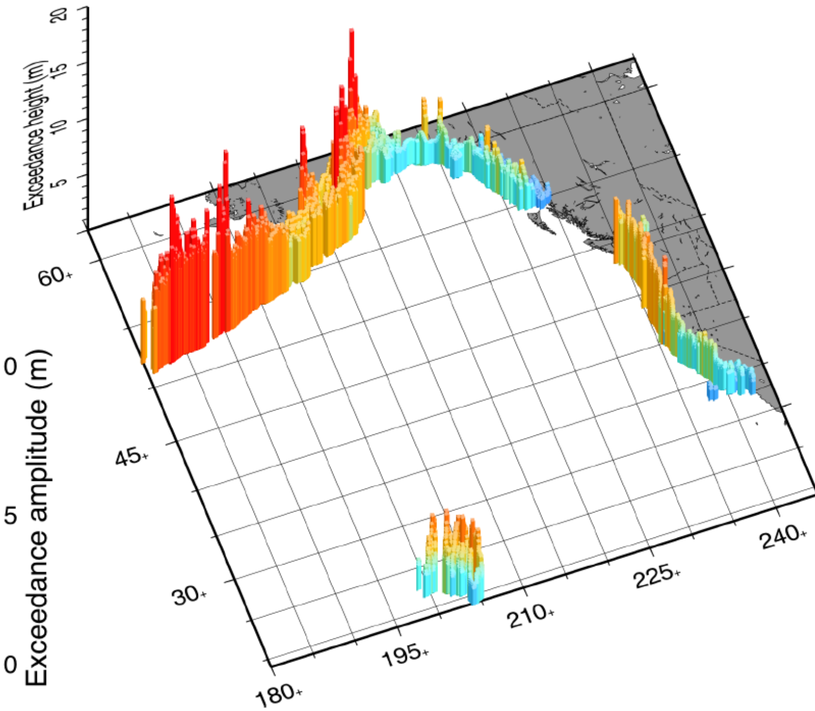
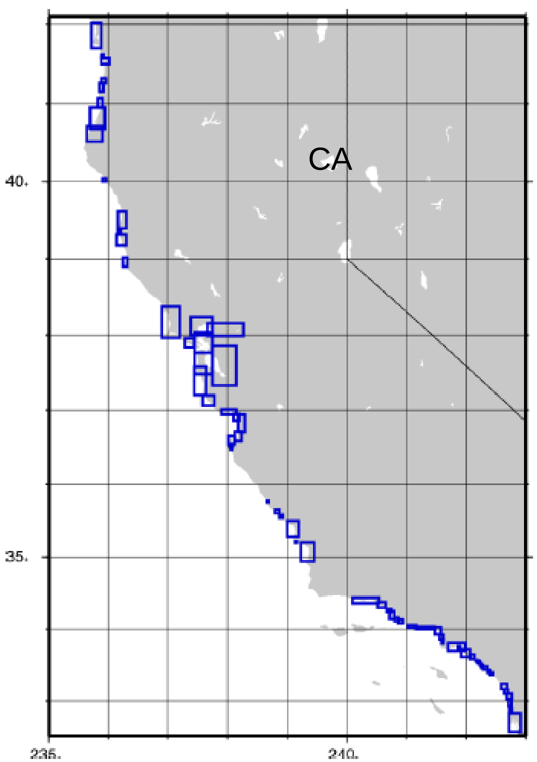


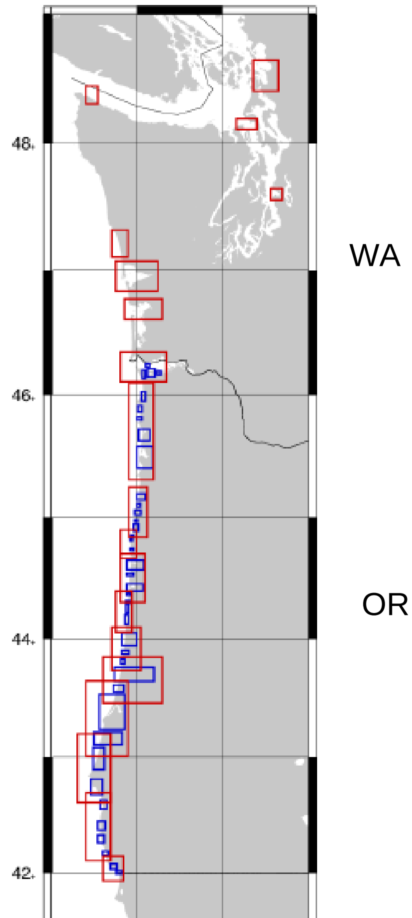
1000 yr return period

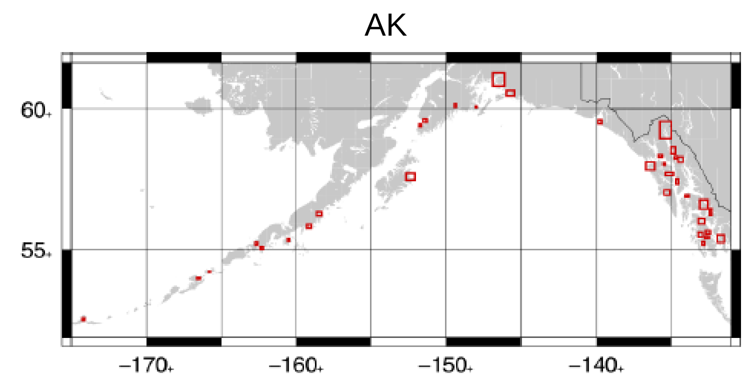


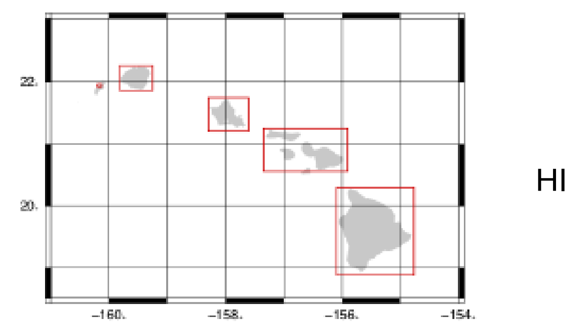
Tsunami Design Guidelines for Coastal Bridges

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









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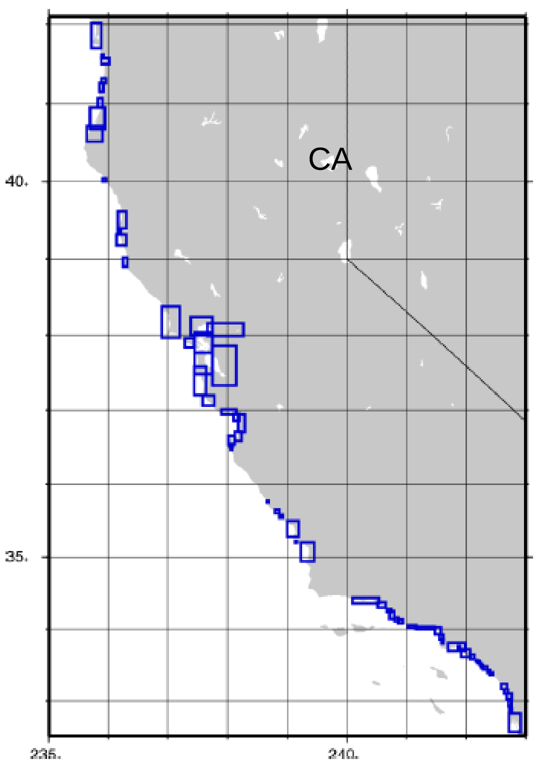

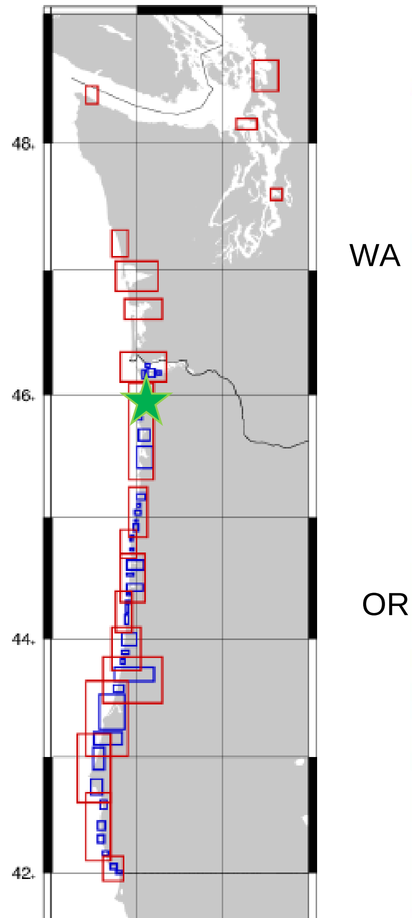

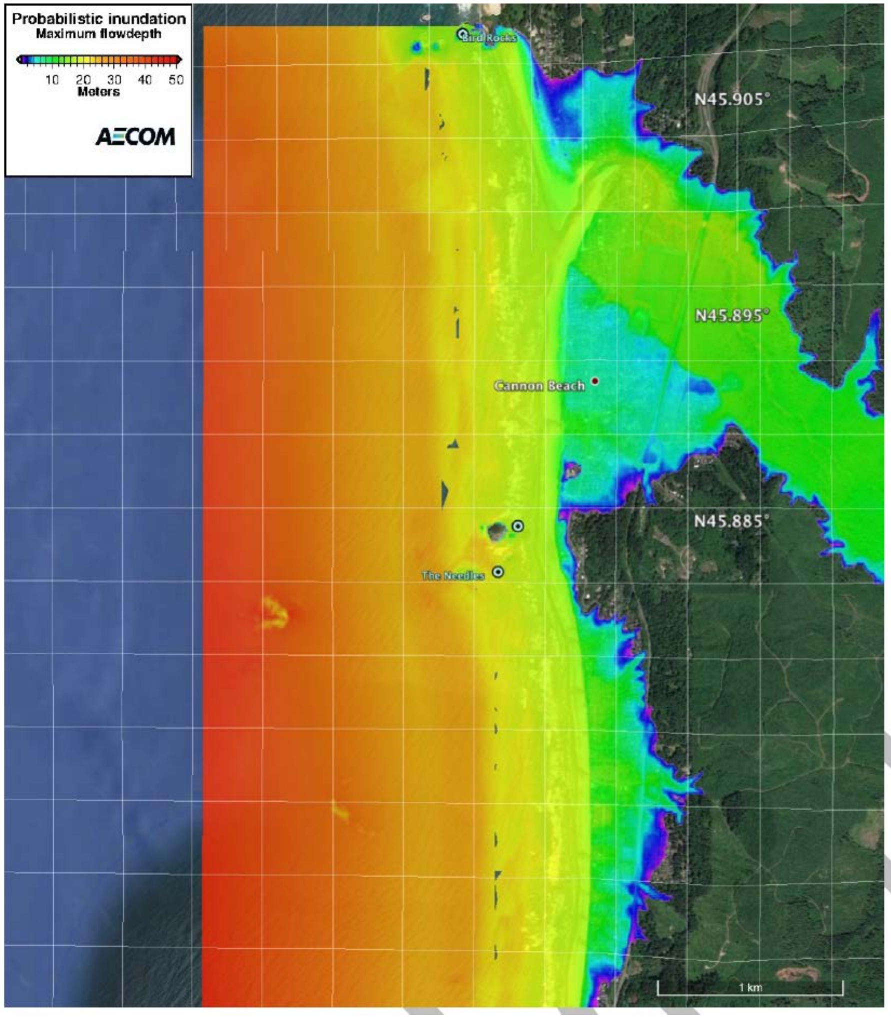

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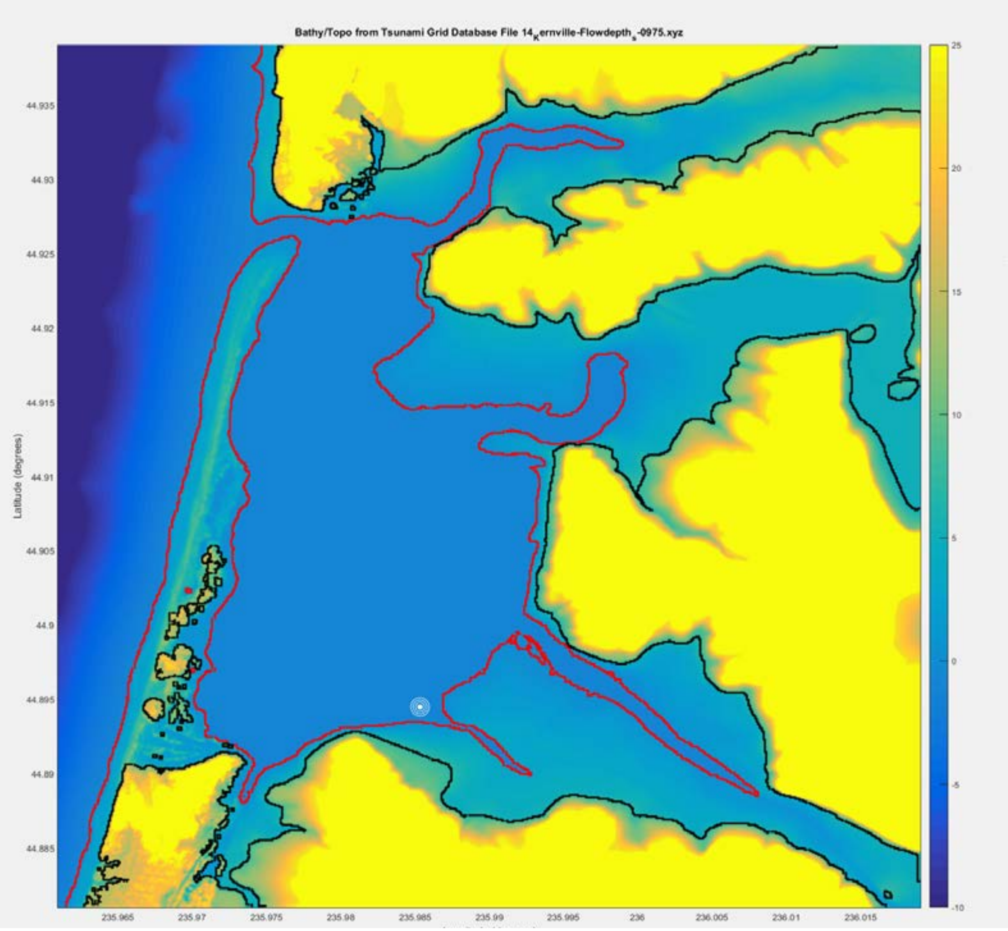


Red line – shoreline at high tide
Black line – inundation limit of 1000-year tsunami

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

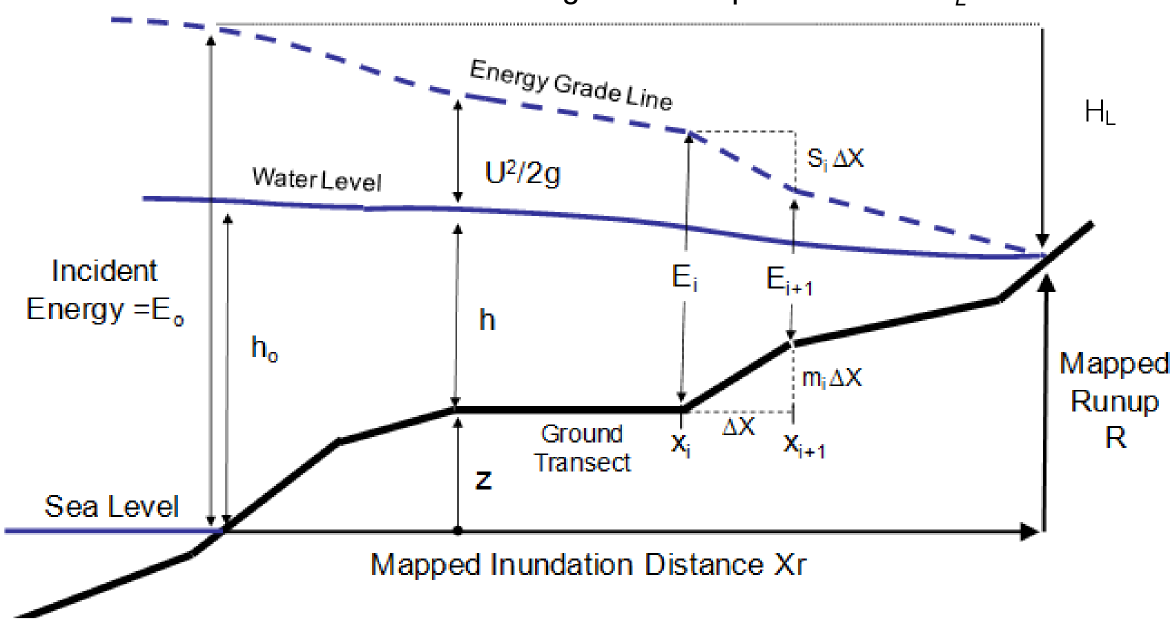
For numerical grids in database with resolution of 10-m, database results can be used directly for site-specific hazard (LEVEL 2)

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



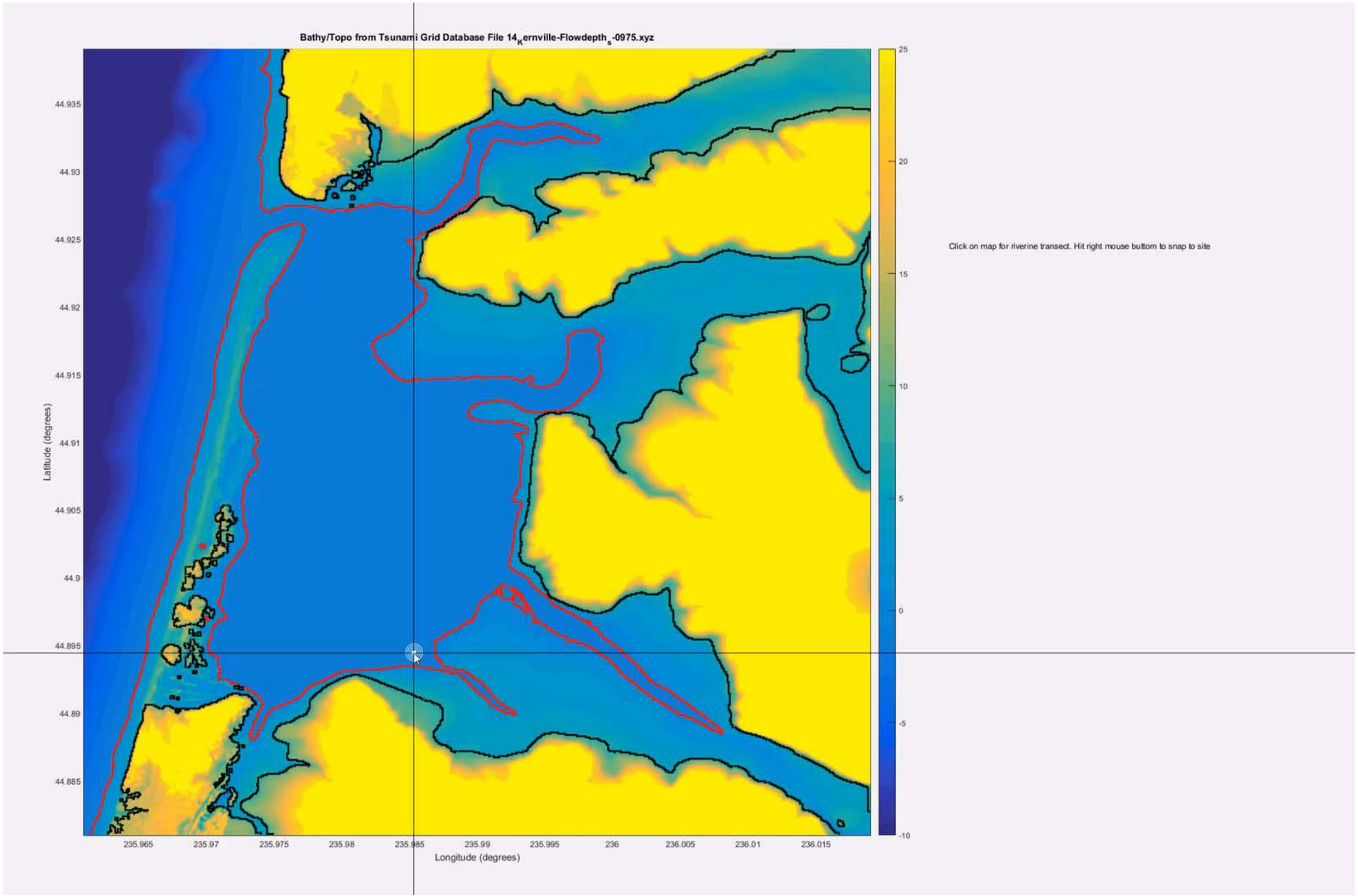
INPUTS:
1. **Transect Data [x,z] starting from shoreline**
2. **Runup location on transect**
3. **Bottom roughness coefficient**

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

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



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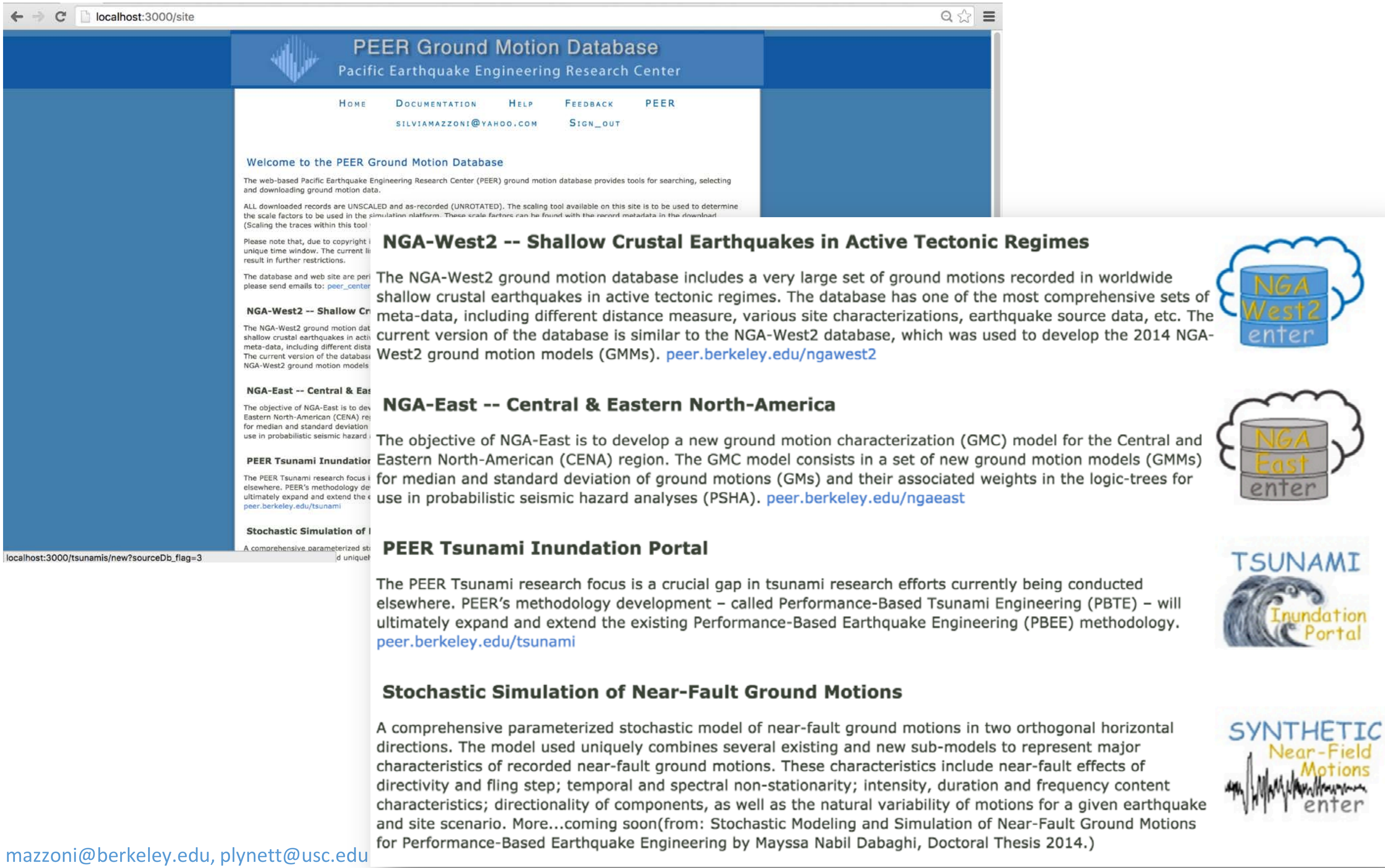
- Working Group 1: Tsunami Hazard and Mapping
  - PEER web portal



PEER Tsunami Inundation Portal

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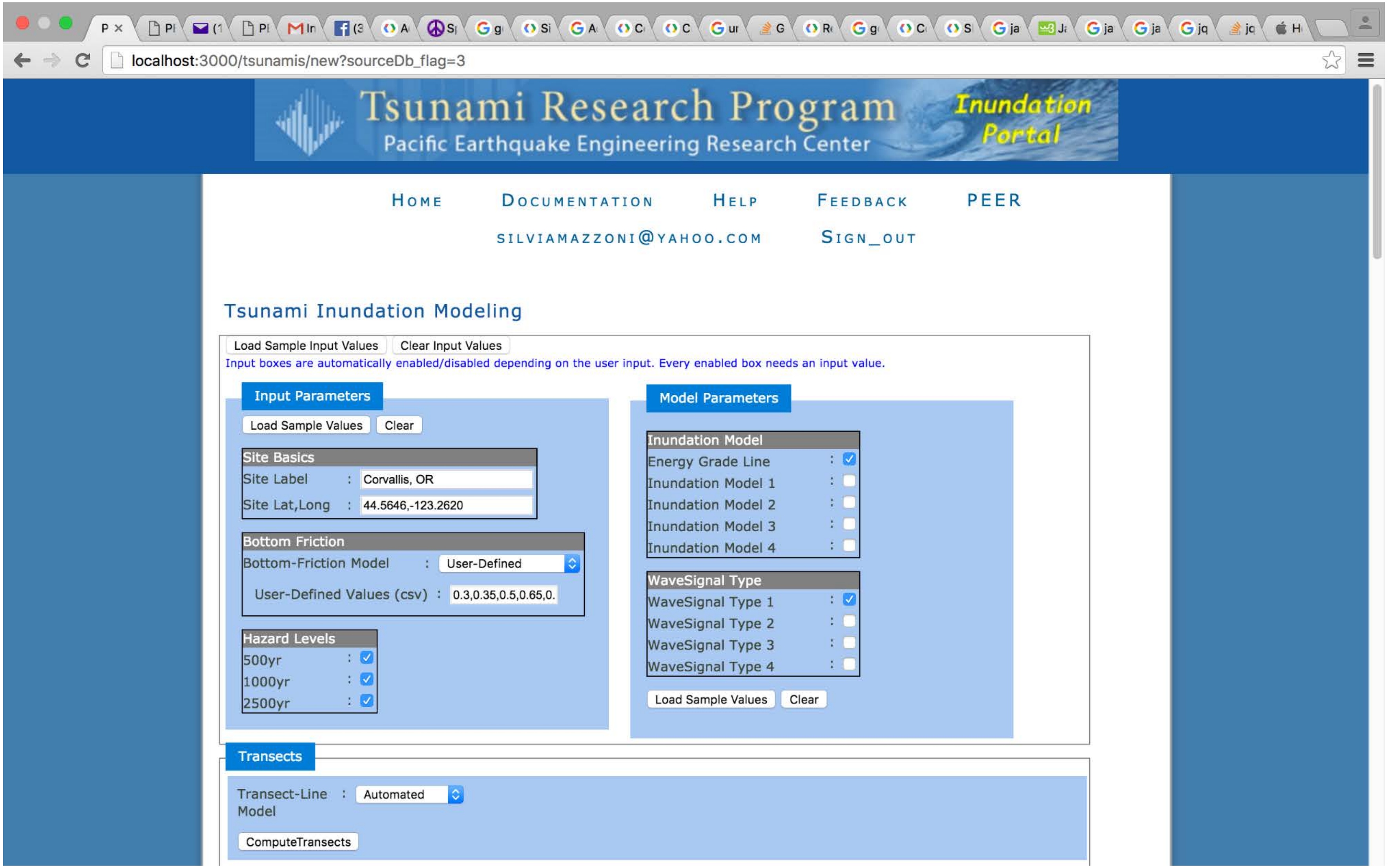
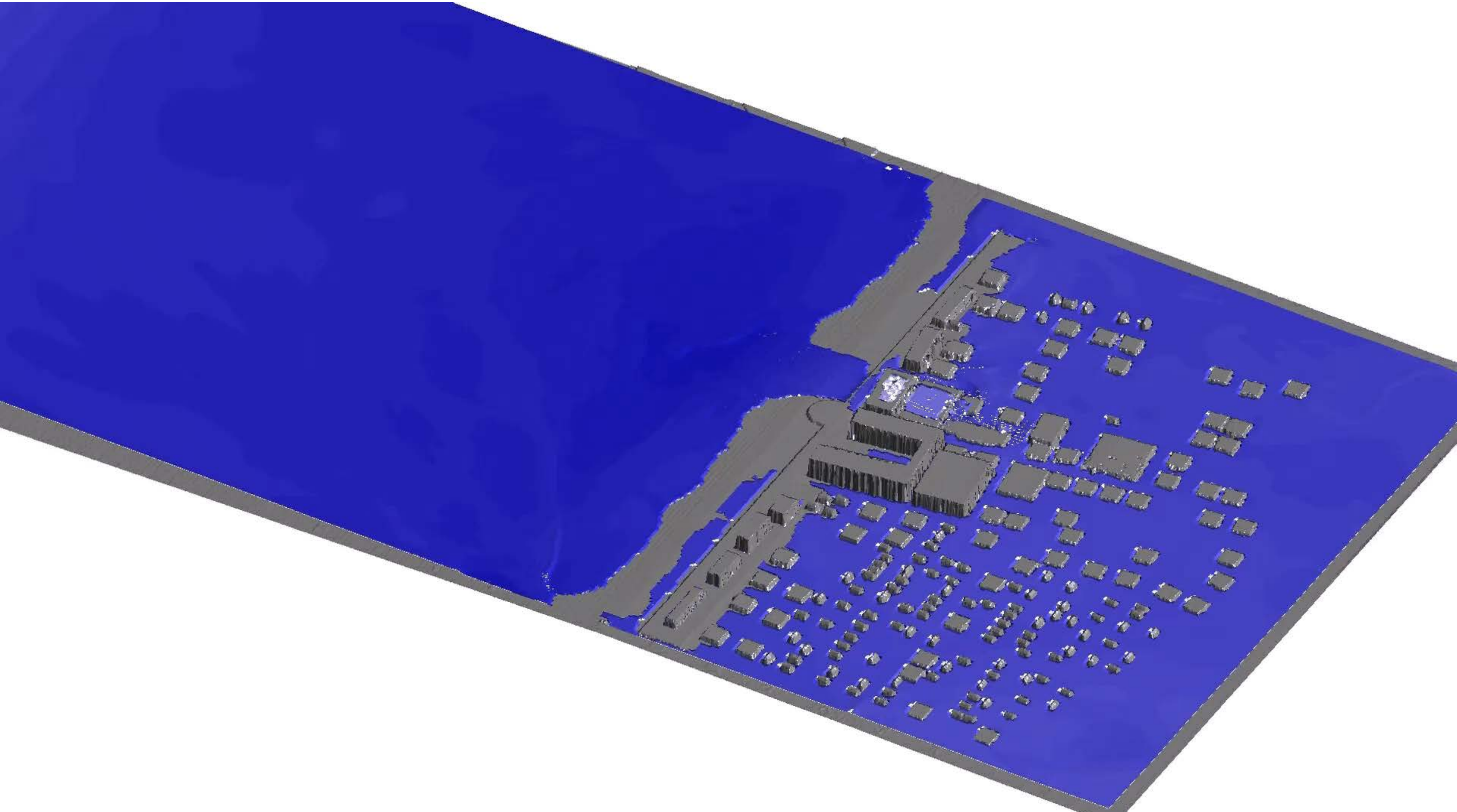


PEER Tsunami Inundation Portal

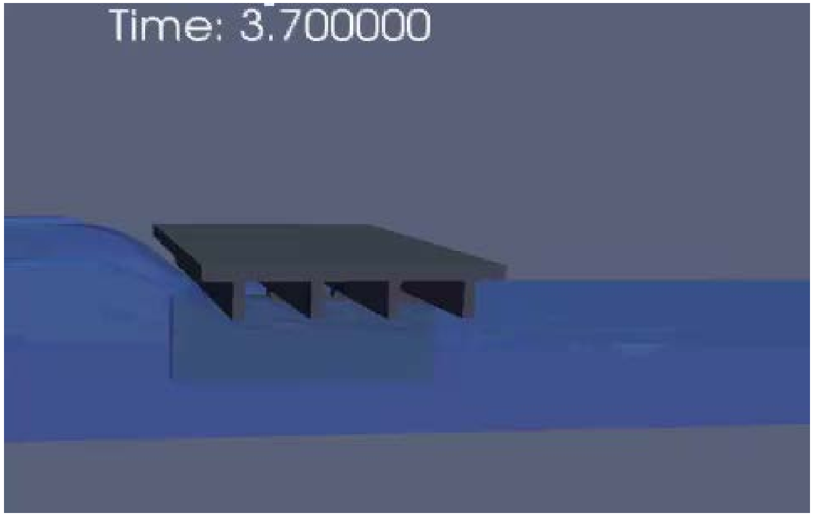
Tsunami Design Guidelines for Coastal Bridges

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



Tsunami Design Guidelines for Coastal Bridges

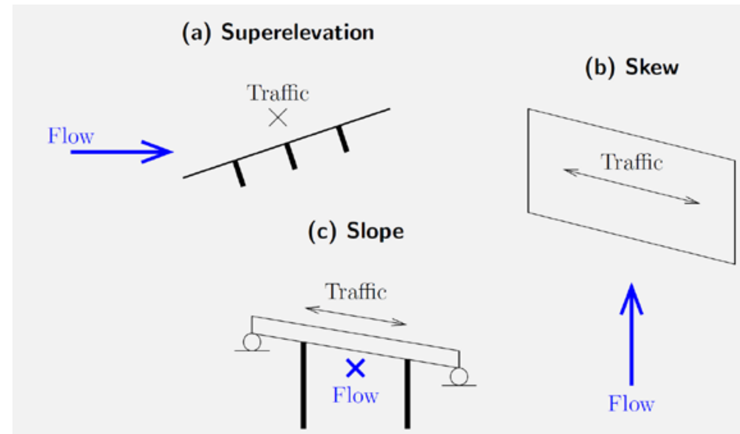
- Once we have the site-specific hydrodynamic hazard, on to:
- Working Group 2: Tsunami Loading of Bridges
- Literature review of existing and ongoing methods to estimate loads on bridges / tsunami loads on general structures
  - Determine whether existing methods can be extended tsunami loads on bridges
  - 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

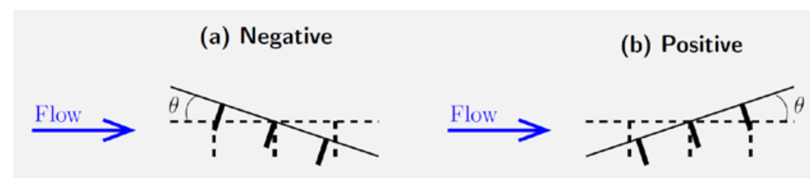


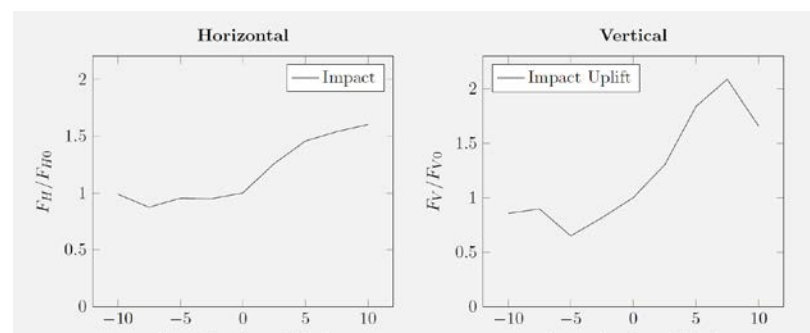
- Determination of loading calculation approach
  - Presentation of example loading calculations, from source (or hazard level) specification, to loadings

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)

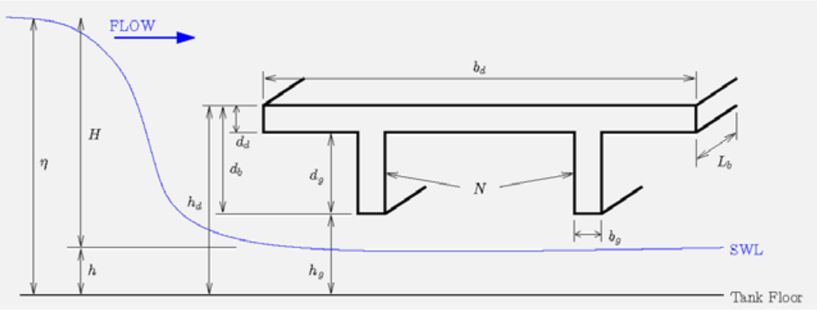
$$F_H = ((1 + C_r(N-1))C_{h,va})(\rho g)(\eta - h_g)A_h$$

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)

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



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

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

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)

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

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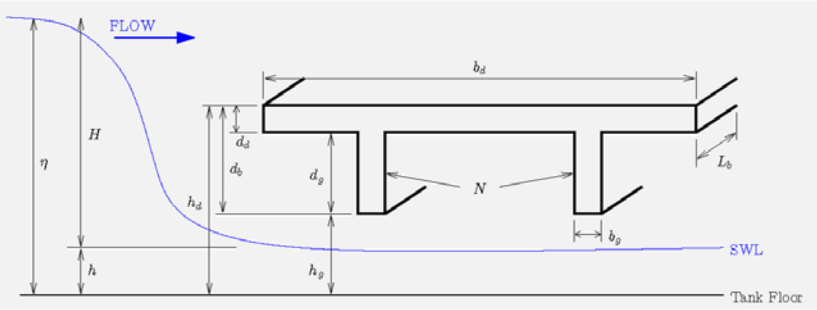

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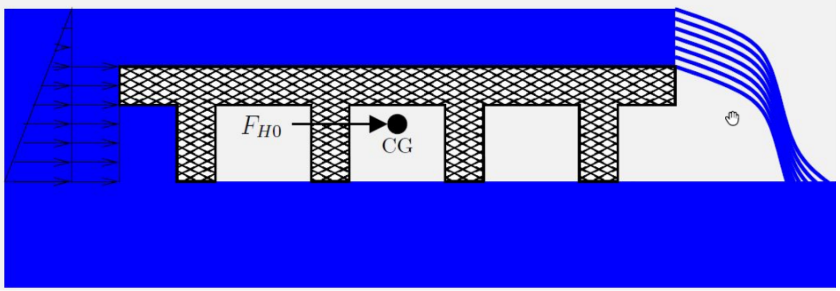
Tsunami Design Guidelines for Coastal Bridges

- 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

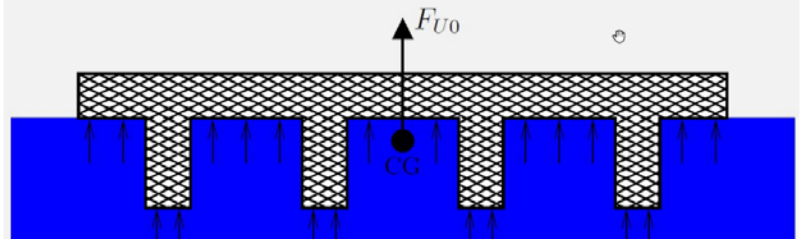
$$F_{H0} = C_1(0.5\rho g(2h_0 - d_b)d_b) + C_2(0.5\rho C_d d_b u^2) \qquad (5)$$

- 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

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

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

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

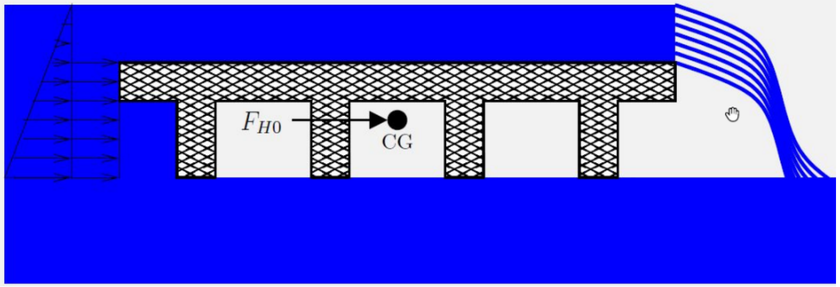
- C_1 and C_2 based on correlation with simulations for horizontal impact and steady state loads
- Simulations also showed dependence on clearance
- Box girder
  $C_1 = 1.0,\ C_2 = 0.6(h_0/(h_g - h))$
- Open girder
  $C_1 = 1.0,\ C_2 = 0.2(h_0/(h_g - h))$

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

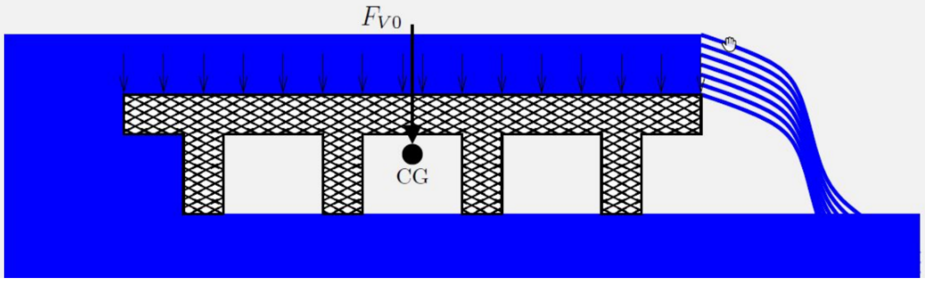
$$F_{H0} = C_1(0.5\rho g(2h_0 - d_b)d_b) + C_2(0.5\rho C_d d_b u^2) \quad (5)$$

- 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

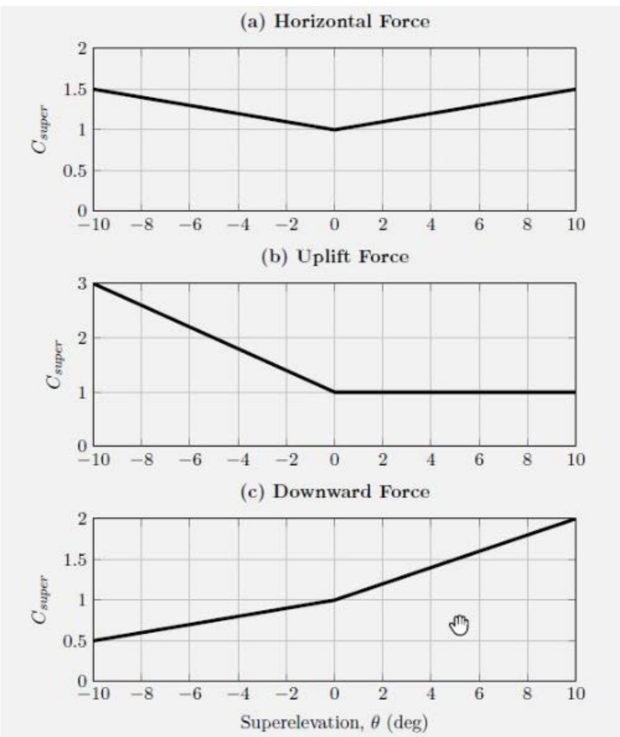
$$F_{D0} = C_{DV}(\rho g(h_0 - d_b)b_d + \text{slamming}) \quad (8)$$

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))

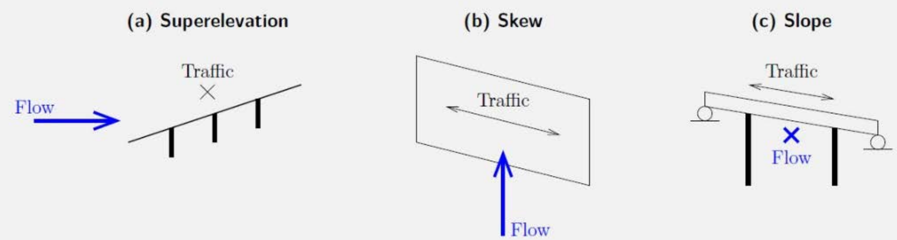


Tsunami Design Guidelines for Coastal Bridges

- Working Group 2: Tsunami Loading of Bridges



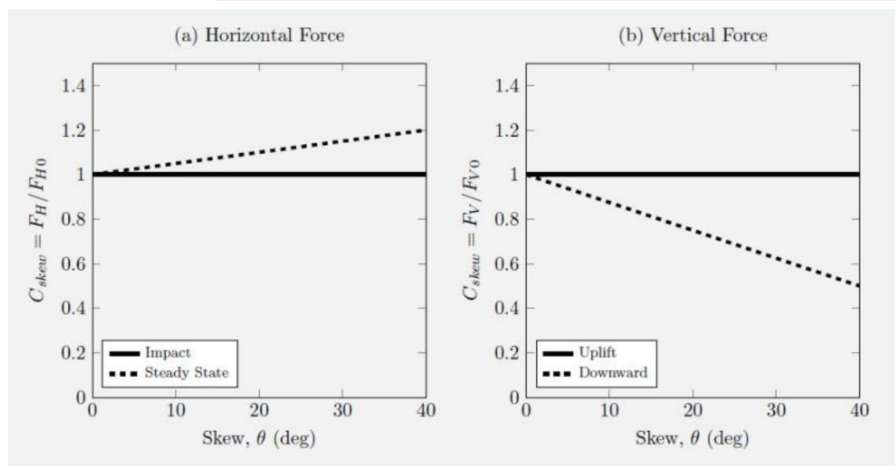
Modify nominal loads by factors for 3D orientation



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 $\rho = 1040$ 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

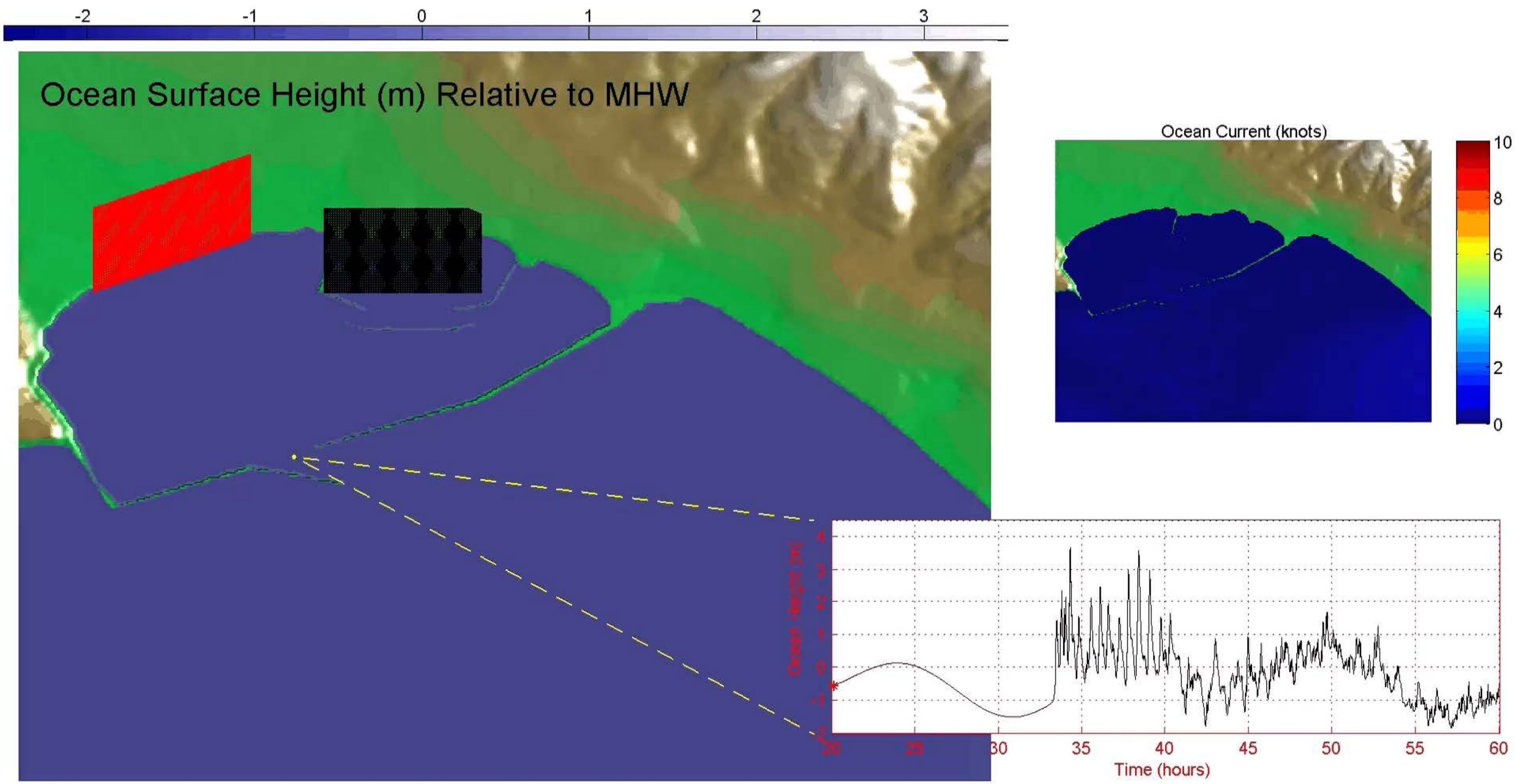
$$F_{debris} = 1.3u\sqrt{km}$$

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

- Elastic impact – full shipping container 1440 kip at u=4 m/s

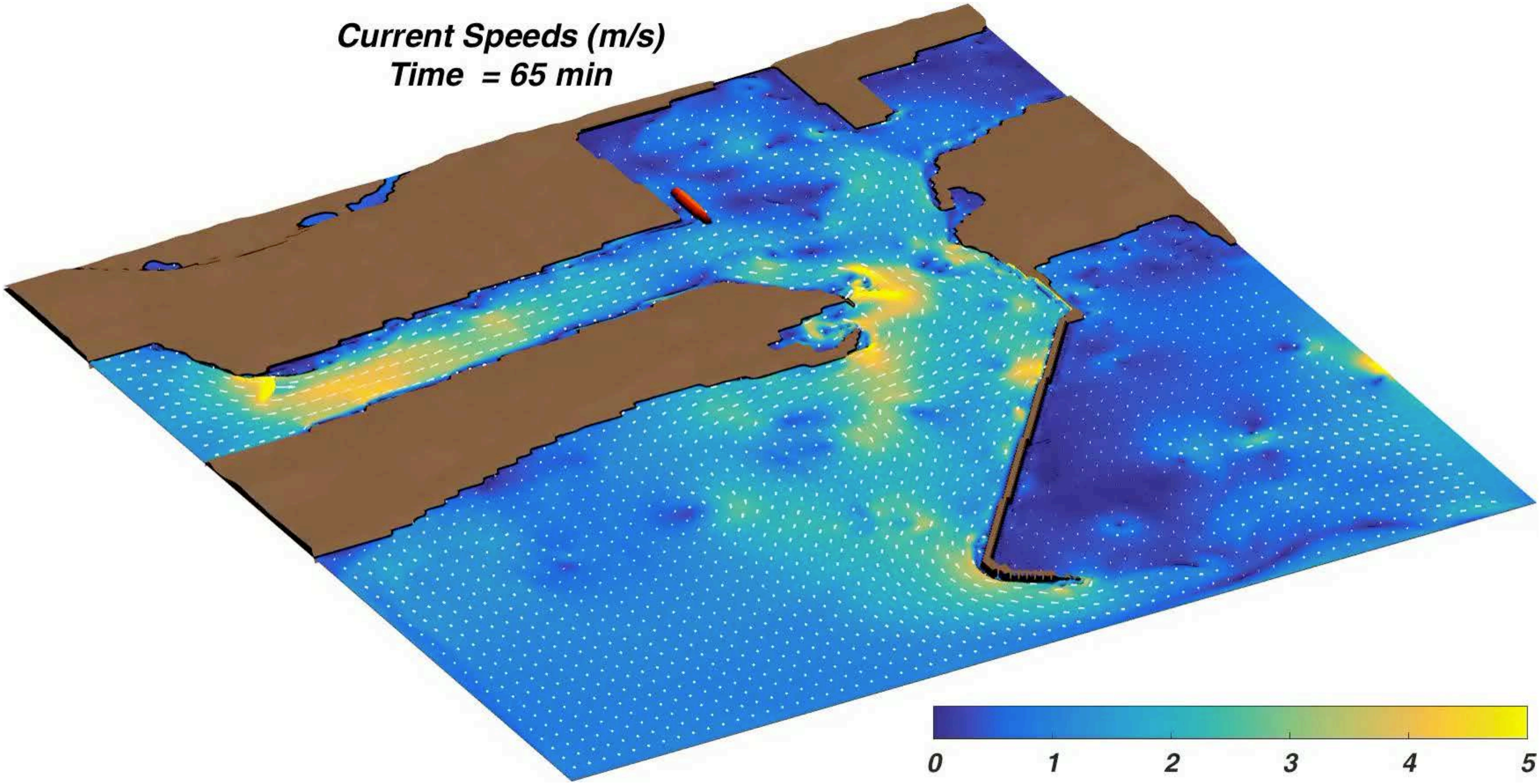
Tsunami Design Guidelines for Coastal Bridges

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



Tsunami Design Guidelines for Coastal Bridges

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



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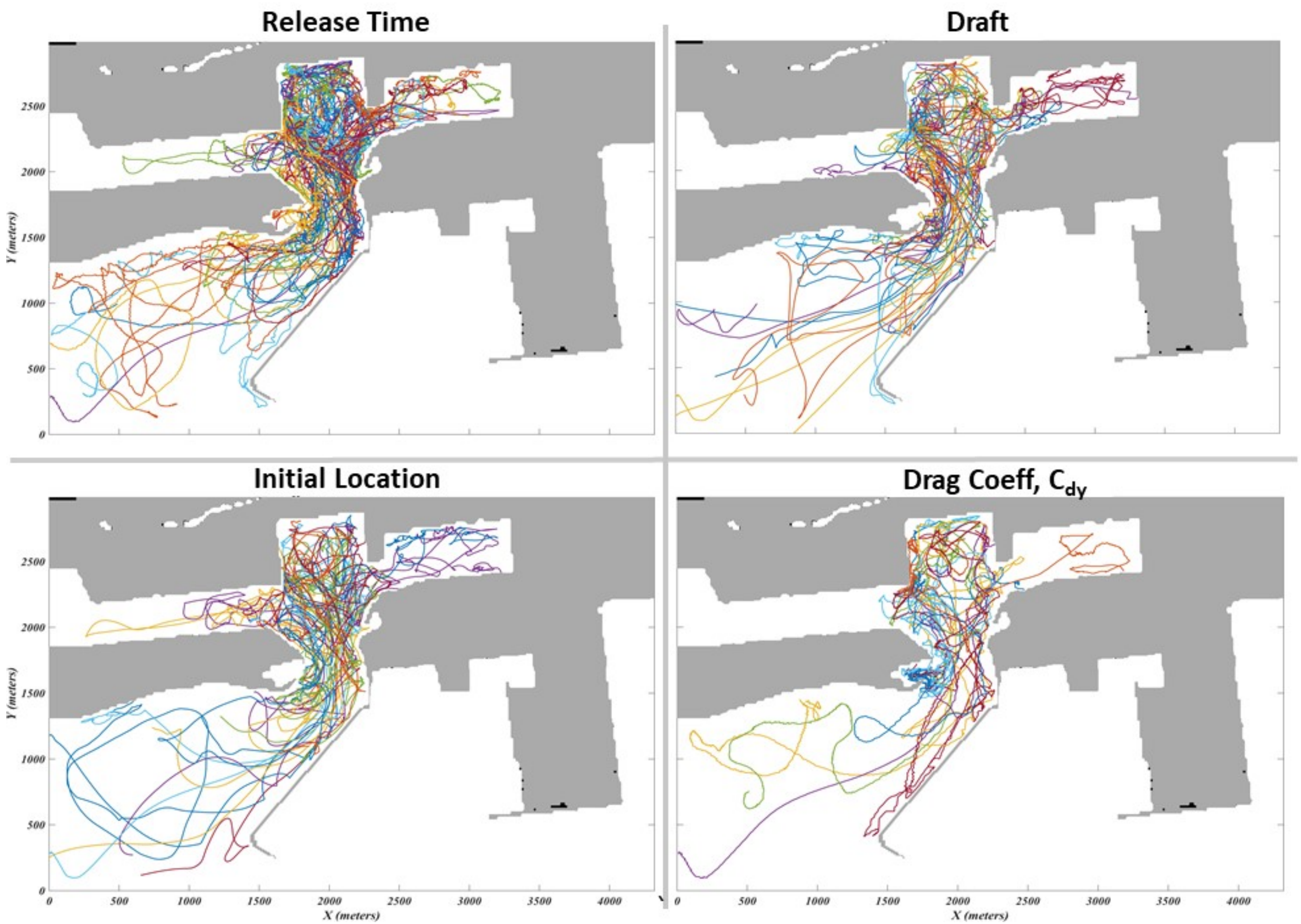

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- Large debris

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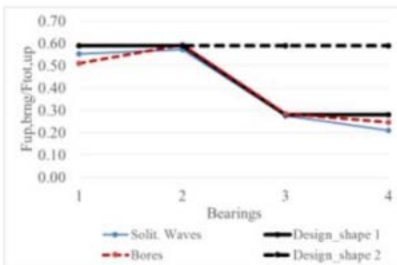
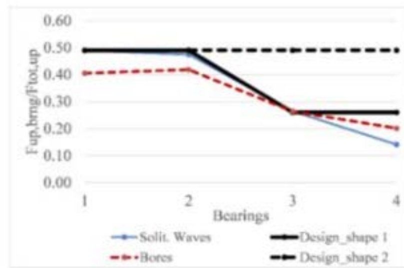
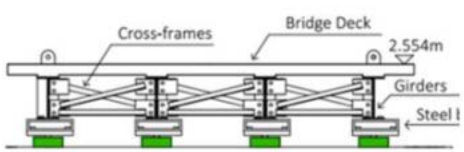
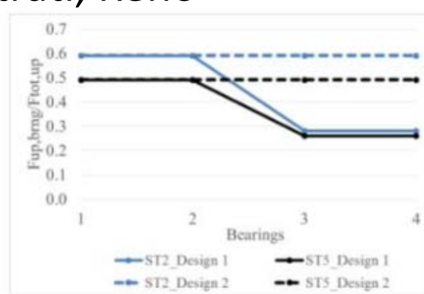
Open girder bridge with elastomeric bearings: Cross-frames vs diaphragms





Buckle & Istrati, Reno





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

or shipping containers

ck

ng 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 m/s

Tsunami Design Guidelines for Coastal Bridges

- 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