Designing Bridges for Tsunami Hazard

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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 guide/spec document.
- Project is supported through a pooled fund with contributors from California, Oregon, Washington, Alaska, and Hawaii.
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- 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
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- 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
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1000 yr return period
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- Working Group 1: Tsunami Hazard and Mapping
  - Inundation Map Coverage
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- Working Group 1: Tsunami Hazard and Mapping
  - Inundation Map Coverage

CA OR WA HI

2019 PEER Annual Meeting – UCLA
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- 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)
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- **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 \(m = \frac{dz}{dx}\) is the local ground slope and \(S = \frac{dH}{dx}\) is the local friction slope

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

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

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

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. 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

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

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

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

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

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

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- Working Group 2: Tsunami Loading of Bridges

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

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

Adjustment factors for hydrostatic and hydrodynamic components

\[ F_{H0} = C_1 (0.5 \rho g (2h_0 - d_b)d_b) + C_2 (0.5 \rho C_d u^2) \]  \hspace{1cm} (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

\[ F_{U0} = C_{UP} (\rho g V + 0.5 \rho u^2 b_d) \]  \hspace{1cm} (6)

- \(C_1\) 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

\[ F_{U0} = C_1 (\rho g V) + C_2 (0.5 \rho u^2 b_d) \]  \hspace{1cm} (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
    \(C_1 = 1.0, C_2 = 0.2(h_0/(h_g - h))\)
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- **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

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

- **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

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

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))
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- Working Group 2: Tsunami Loading of Bridges

Modify nominal loads by factors for 3D orientation

(a) Superelevation

(b) Skew

(c) Slope

Horizontal load

\[ F_H = C_{\text{super}}C_{\text{skew}}C_{\text{slope}}F_{H0} \]

Similar expressions for \( F_U \) and \( F_D \)
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- 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 $C_{\text{debris}} = 1.06$ for small debris in only the horizontal load calculations
- Large debris assumed only for horizontal load

\[
F_H = C_{\text{skew}}C_{\text{slope}}C_{\text{debris}}F_{H0} + F_{\text{debris}} \tag{10}
\]
\[
F_U = C_{\text{skew}}C_{\text{slope}}F_{U0} \tag{11}
\]
\[
F_D = C_{\text{skew}}C_{\text{slope}}F_{D0} \tag{12}
\]

- 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

\[
F_{\text{debris}} = 1.3u\sqrt{km}
\]

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

Current Speeds (m/s)
Time = 65 min
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- Working Group 2: Tsunami Loading of Bridges – LARGE DEBRIS
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- 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 $C_{\text{debris}} = 1.06$ for small debris in only the horizontal direction
- Large debris (e.g., shipping containers)

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

Buckle & Istrati, Reno

![Graph showing load distribution across bearings](image)

\[ F_s = 1.3u\sqrt{km} \]

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