Resilience under Non-Stationary Extreme Design Loads due to Climate Change for Coastal Concrete Structures

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ACI Concrete Convention in San Francisco, California
April 3rd, 2023

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Motivations

- **ACI 348 Structural Reliability and Safety** committee will focus on the effects of **climate change** on structural safety and resilience of structures and infrastructure systems, where non-stationary design loads caused by extreme climate and weather events shall be developed and the corresponding vulnerabilities and risks shall be considered in the initial planning phase of infrastructure systems.

- **ASCE** has entered into an agreement with the National Oceanic and Atmospheric Administration (NOAA) in February, 2023 to work toward climate-ready infrastructure, where NOAA will provide key science and product data that will be applied to building and civil engineering codes, standards, and best practice manuals developed by ASCE (e.g. ASCE 7)

- There is an academic, commercial (*e.g.* insurance) and public interest in developing a general methodology and framework for structural safety and infrastructure resilience planning with consideration of climate change.

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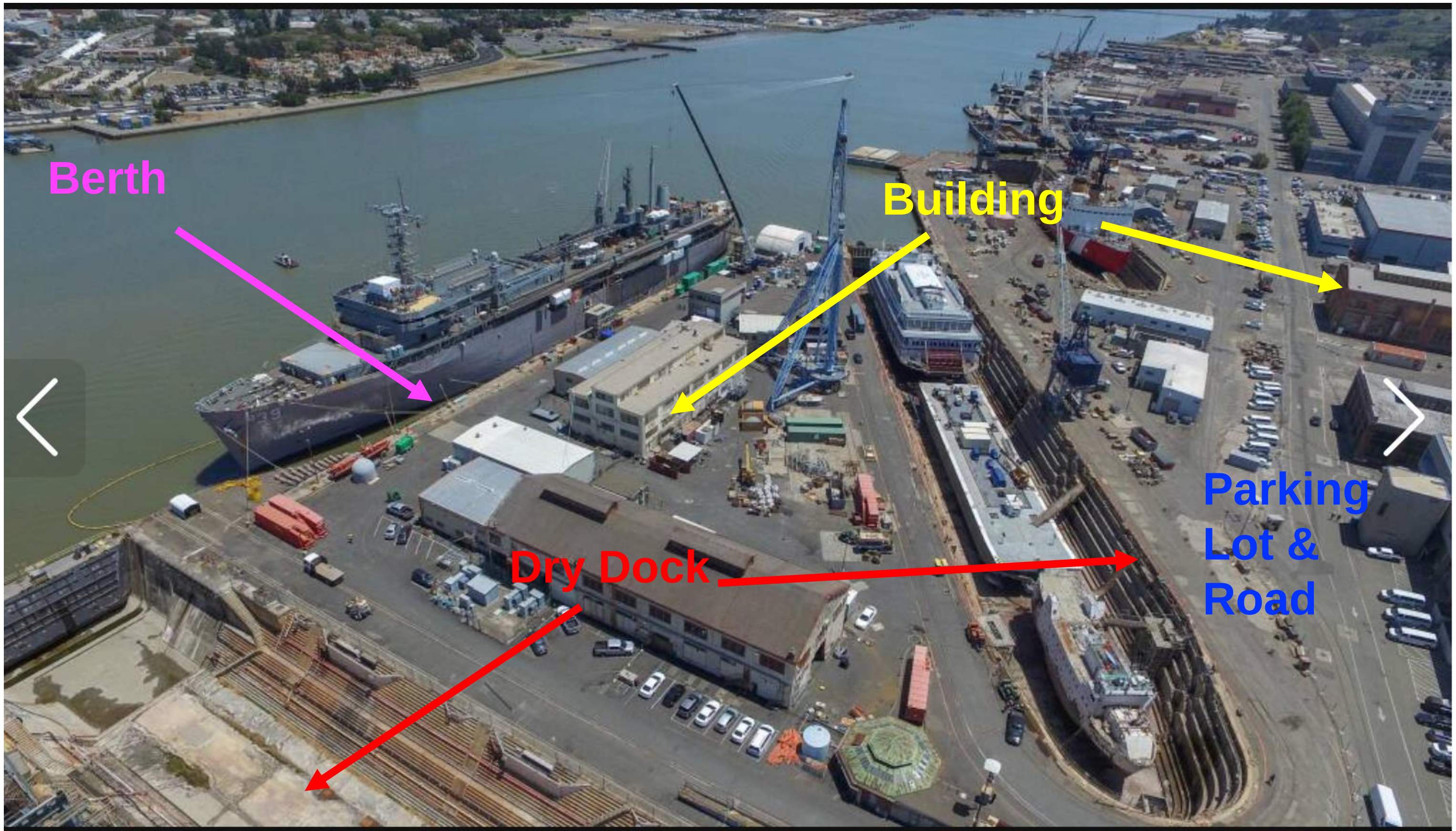
Coastal Concrete Structures and Infrastructure Systems



https://www.northbaybusinessjournal.com/article/article/mare-island-dry-dock-wins-1m-federal-shipyard-grant-to-buy-crane-for-expan/?artslide=0 (June, 27, 2021)

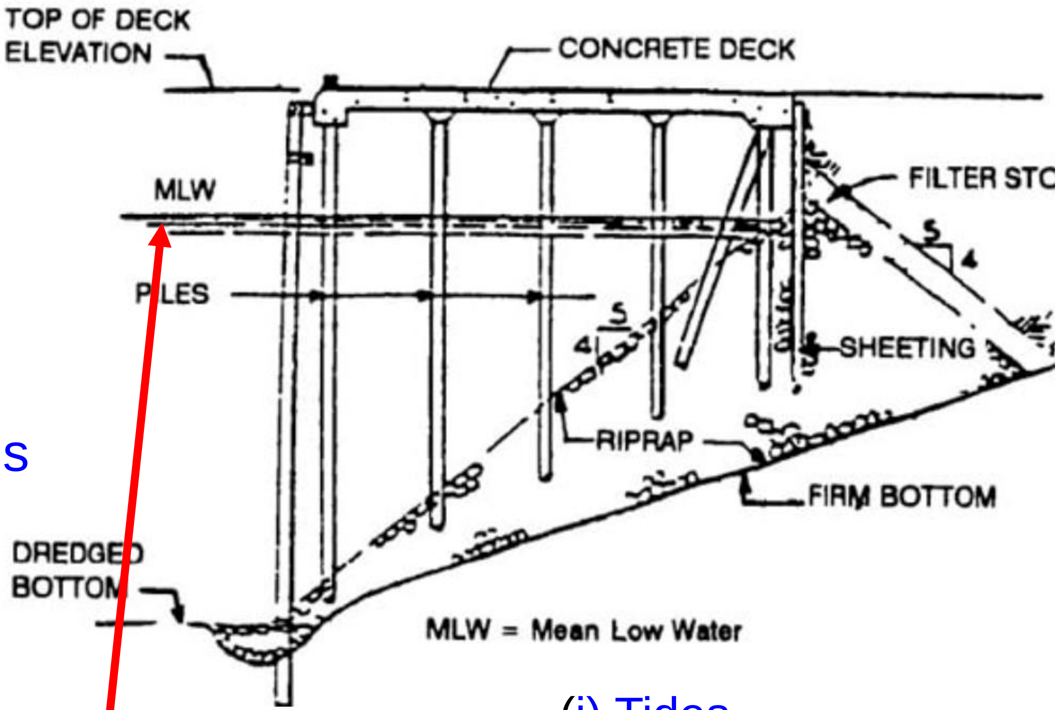
SLIDE 2 OF 2

Mare Island Dry Dock's two docks and shoreline berth in Vallejo are seen here in this June 18, 2018, photo full of Navy, Coast Guard and other vessels. (courtesy photo)

Structural Type

(https://theconstructor.org/structures/types-marine-structures-construction-uses/16854/)

(i) Most of berths, piers, and wharves are the pile-supported structures.



(ii) Dry docks are similar to dams and retaining walls.

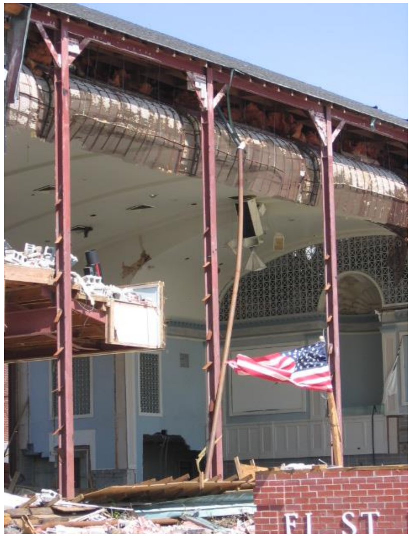
(https://www.loc.gov/resource/hhh.wa0565.photos/)

Extreme Water Level (EWL)

(i) Tides
(ii) Storm Surge
(iii) SLR

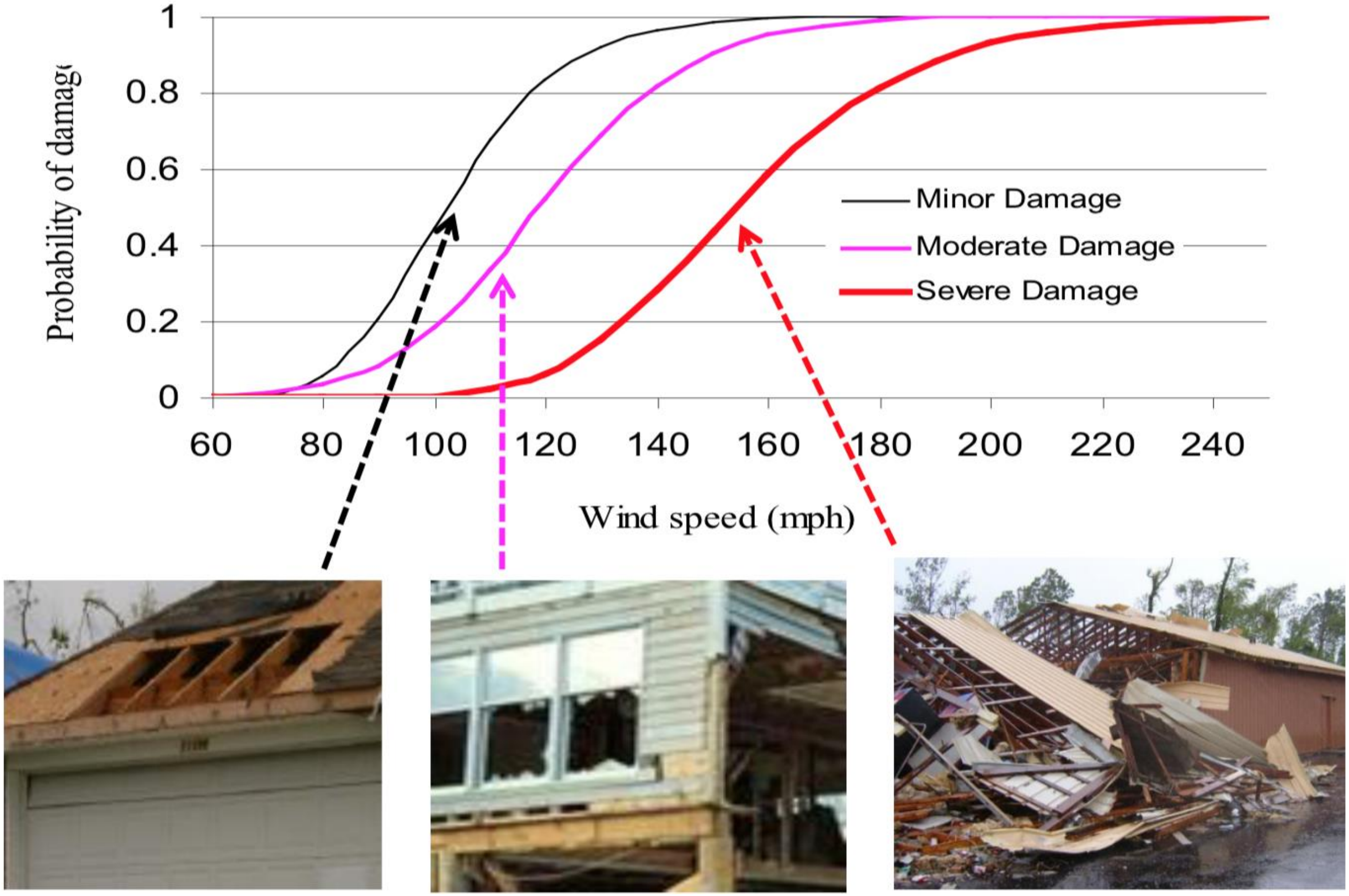
Damages to Concrete Structures by Extreme Weather

2005 Alabama, Mississippi, Louisiana, and Texas, Hurricanes Katrina and Rita



2017 Puerto Rico and
Virgin Islands,
Hurricanes Maria and Irma

Probability of Hurricane Damage



Effects of Climate Change on Structural Performance

(i) Temperature effects

Extreme high or low temperature affects structural performance. Current climate change models indicate that climatological variables associated with extreme temperature can be analyzed with reasonable confidence.

(ii) Wind effects – extratropical, hurricane / storm surge

Current climate change models predict hurricanes with little confidence.

(iii) Precipitation and pluvial flooding due to extreme rainfalls

Extreme rainfalls in urban areas may be predicted with limited confidence.

(iv) Riverine (fluvial) flooding

Hydrostatic flood load is a function of the depth and density of water.
Hydrodynamic load has an additional term of the flow velocity.

(v) Coastal inundation due to sea level rise (SLR)

(vi) Snow loads on roofs

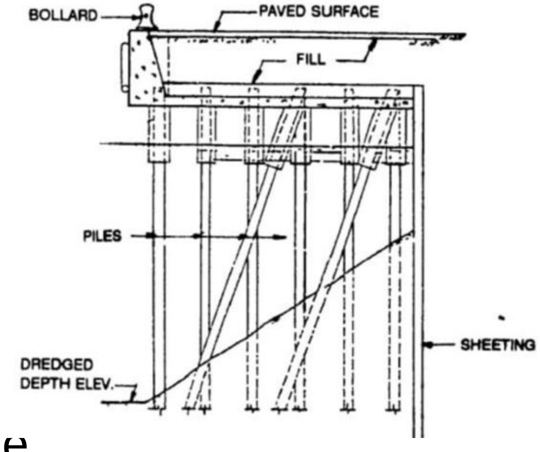
Impacts of Climate Change on Coastal Concrete Structures

(1) Design loads for piers

(i) SLR will change the mooring cable orientation and the loading conditions on the pile supporting system.

(ii) Increase on wind and wave loads.

(iii) Are storm surge loads comparable with tsunami loads (ASCE 7, Chapter 6)?



(2) Load effects due to longer piles

Since the water depth is a typical of 30 ~ 45 ft, if SLR = 5 ~ 10 ft, the increase of the pile length will be 10% to 33% and the load effects may be double.

(3) Accelerated structural deterioration due to climate change

Increases in atmospheric CO_2 concentration, climate change on environmental temperature, relative humidity, rainfall, etc. can lead to reduced time to corrosion initiation and accelerated corrosion propagation.

Design Wind Load in ASCE/SEI 7-16

The wind pressure is determined from

$$W = q_h[(GC_p) - (GC_{pi})]$$

- q_h: Velocity pressure
- G: Gust factor
- C_p/C_{pi}: External/Internal pressure coefficient

Velocity pressure q_h

$$q_h = 0.00256\ K_z\ V^2\ I$$

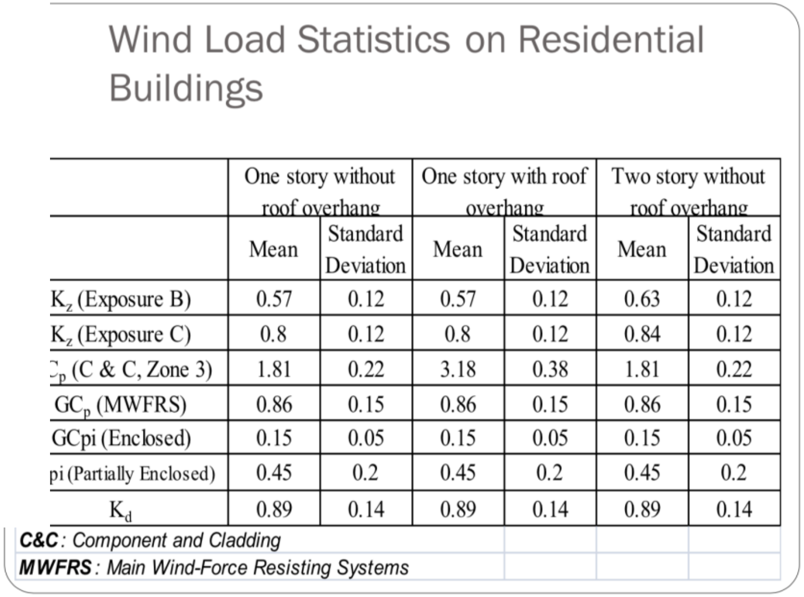
- K_z: Exposure coefficients
- V: Wind speed (3 sec gust)
- I: Importance factor

Extreme Value Type I Distribution

Maximum 50-year load:

Mean to nominal ratio: 0.97

Coefficient of variation (CoV): 24%



Wind Load Statistics on Residential Buildings

	One story without roof overhang		One story with roof overhang		Two story without roof overhang	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
K_z (Exposure B)	0.57	0.12	0.57	0.12	0.63	0.12
K_z (Exposure C)	0.8	0.12	0.8	0.12	0.84	0.12
C_p (C & C, Zone 3)	1.81	0.22	3.18	0.38	1.81	0.22
GC_p (MWFRS)	0.86	0.15	0.86	0.15	0.86	0.15
GCpi (Enclosed)	0.15	0.05	0.15	0.05	0.15	0.05
pi (Partially Enclosed)	0.45	0.2	0.45	0.2	0.45	0.2
K_d	0.89	0.14	0.89	0.14	0.89	0.14

C&C: *Component and Cladding*

MWFRS: *Main Wind-Force Resisting Systems*

Design Wind Load (velocity pressure)

- $q_h = (0.00256).(K_z).(K_{zl}).\quad(K_e).\quad(K_d).\quad(\text{nominal } V^2)$

(0.57 ~ 1.43 when z < 100 ft.) (0.8 ~ 1.0) (0.85 ~ 1.0) (Section 26.5 of **ASCE/SEI 7-16**)

(shape factor) (exposure factor) (directional factor)

Random Variable	Bias coef.	COV	Probability Distribution
(K_z) (K_{zl})	1.0	0.2* 0.10 ~ 0.30**	Log-normal*, ** except for V ~ Gumbel**
(K_e) (K_d)	1.0	0.15* 0.10 ~ 0.20**	
(V)	0.14 ~ 0.41* 10 min. mean**	0.49 ~ 0.72* 0.20 ~ 0.30**	
maximum wind	0.78***	0.37***	

* Refer to “Structural Reliability Handbook” (2015, Australian Building Codes Board)

** Refer to “Risk and Safety in Civil, Surveying and Environmental Engineering”
(by Prof. Michael Faber, Swiss Federal Institute of Technology, ETH Zurich)

*** Refer to “Calibration of Design Code for Buildings (ACI318): Part 2” (2003)
(by Prof. Andrzej Nowak, University of Michigan, currently, Auburn University)

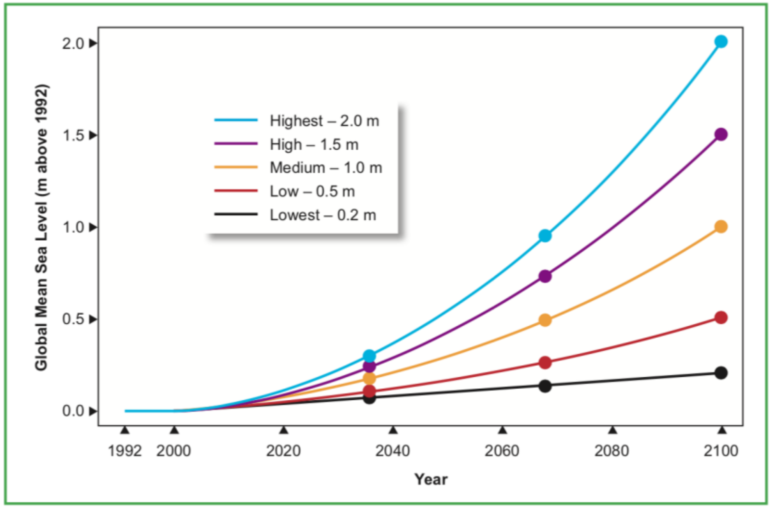
Extreme Water Level (EWL)

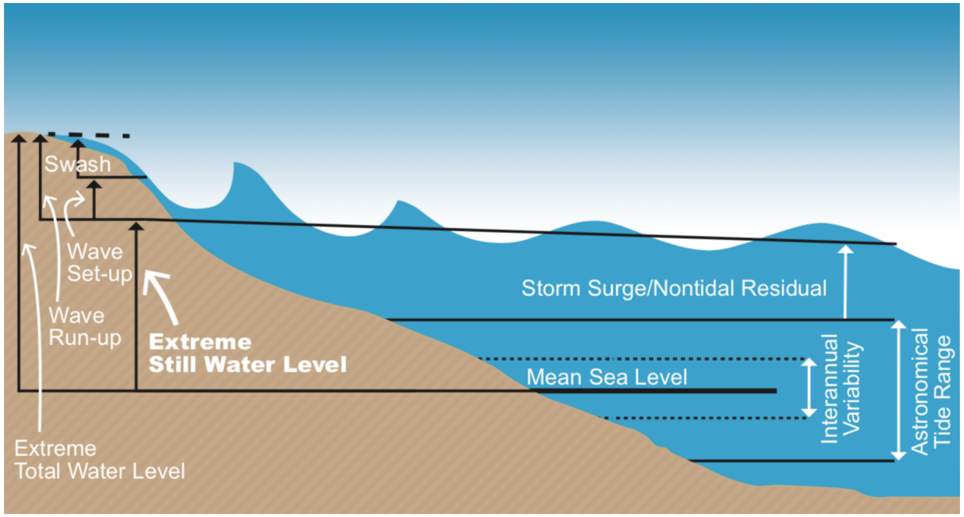
(1) Tides: the average of all hourly tides is the mean sea level (MSL). The North American Vertical Datum of 1988 (NAVD88) or the National Geodetic Vertical Datum of 1929 (NGVD29) are the standard vertical datum for the FEMA Flood Insurance Studies. (NOAA Website, http://tidesandcurrents.noaa.gov/).

(2) Storm Surge: the rise of the ocean surface that occurs in response to barometric pressure variations and to the stress of the wind acting over the water surface. This can be caused by tropical cyclones/hurricanes or extratropical cyclones. Tides and storm surge interact each other.

(3) SLR: the five global SLR scenarios adopted by the the Intergovernmental Panel on Climate Change (IPCC) resulted in the global SLR ranging from 0.2 to 2.0 m. by 2100 when starting from 1992. This range should be further adjusted by the considerations of (i) vertical land movement (VLM), (ii) dynamical sea level (DSL) and (iii) ice melt for regional SLR.

Global SLR and EWL





Global Scenario	Range of Sea-Level Change Adjustments by Scenario and Time Horizon (meters)			Range of Annual Chance Event Values (ACE) (meters)			
	2035	2065	2100	20% ACE	5% ACE	2% ACE	1% ACE
2.0 meters		-1.6 to 0.9	-2.2 to 1.5	0.2 to 3.0	0.3 to 3.6	0.3 to 4.0	0.3 to 4.3

USACE Tool: https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html

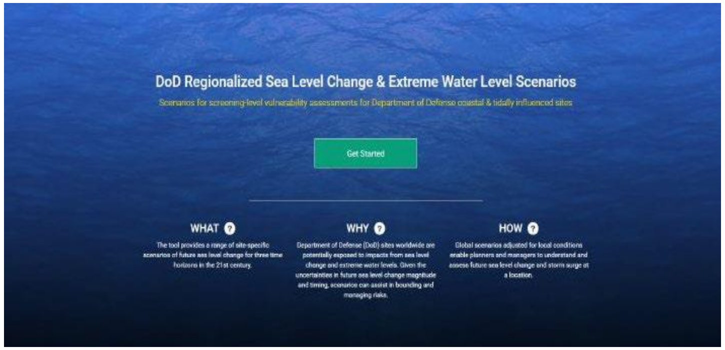
Regional SLR and EWL in UFC

ASCE Flood Design Class	Freeboard Approach [1]	DRSL Approach [2,3,4]
1 (minimal risk; non-essential facilities)	BFE	Lowest 2065
2 (moderate risk; non-essential facilities)	BFE + 2 ft (600 mm)	Low 2065
3 Subcategory 3a (high risk; non-essential facilities)	BFE + 2 ft (600 mm)	Medium 2065
3 Subcategory 3b[5] (high risk; essential facilities)	BFE + 3 ft (900 mm)	High 2065
4[6] (high risk; essential facilities)	BFE + 3 ft (900 mm)	Highest 2065

1. The freeboard approach complies with PL 115-232, Section 2805(a)(4)(A) and (B).
2. The default sea level rise scenario complies with USD (A&S) memorandum, "Improving Defense Installation Resilience to Rising Sea Levels," dated February 24, 2020.
3. Use the site-specific value from the DoD Regional Sea Level (DRSL) database corresponding to the designated scenario (lowest/low/medium/high/highest) for the year 2065. The DRSL database is available at https://sealevelscenarios.serdp-estcp.org.
4. These are default values in the absence of a Basis for Flood Risk Design. When provided, use the component's Basis for Flood Risk Design in lieu of the value provided in this column.
5. Essential facilities that would not need to remain operational during the design flood event but would need to fully operational immediately following a storm event.
6. Essential facilities that would need to remain operational during the design flood event.

DRSL

(USACE on-line tool)



DoD Regionalized Sea Level Change & Extreme Water Level Scenarios

Scenarios for screening-level vulnerability assessments for Department of Defense coastal & tidally influenced sites

WHAT ?

The tool provides a range of site-specific scenarios of future sea level change for three time horizons in the 21st century.

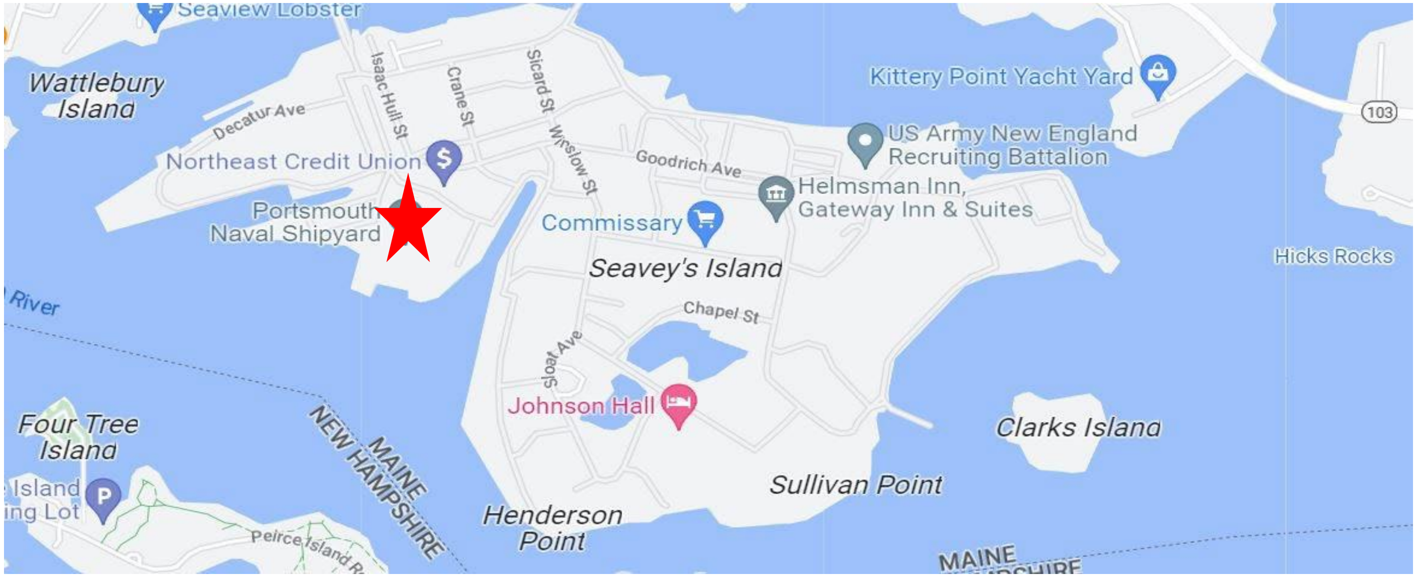
WHY ?

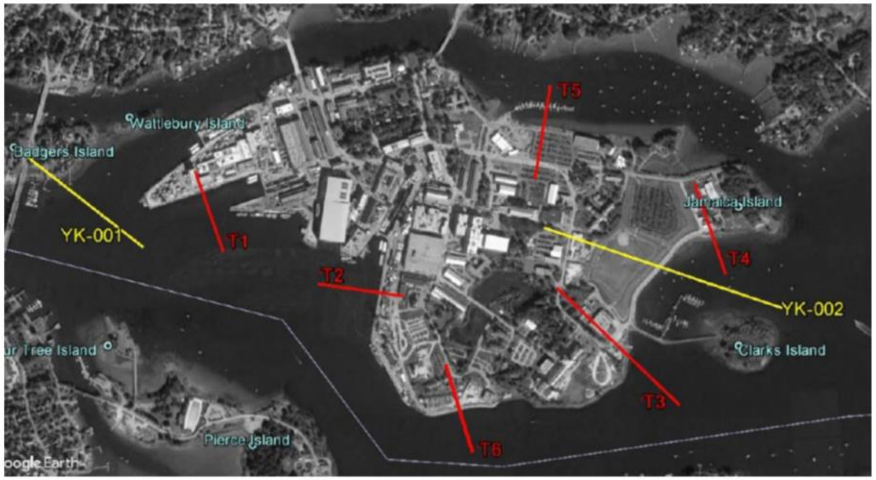
Department of Defense (DoD) sites worldwide are potentially exposed to impacts from sea level change and extreme water levels. Given the uncertainties in future sea level change magnitude and timing, scenarios can assist in bounding and managing risks.

HOW ?

Global scenarios adjusted for local conditions enable planners and managers to understand and assess future sea level change and storm surge at a location.

Example: Regional SLR and EWL





FEMA Flood Insurance Rate Map:

YK-001

YK-002

Regional SLR Study:

T1 to T6

Appeal of the 2017 FEMA Preliminary Flood Insurance Rate Map (yellow lines) for Seavey's island

Principles in Load Combinations

- **Turkstra's** load combination rule **(1980)**

  The maximum value of the combined loads occurs when one of the loads reaches its maximum value (primary load), while other loads have their instantaneous or arbitrary-point-in-time values (companion load).

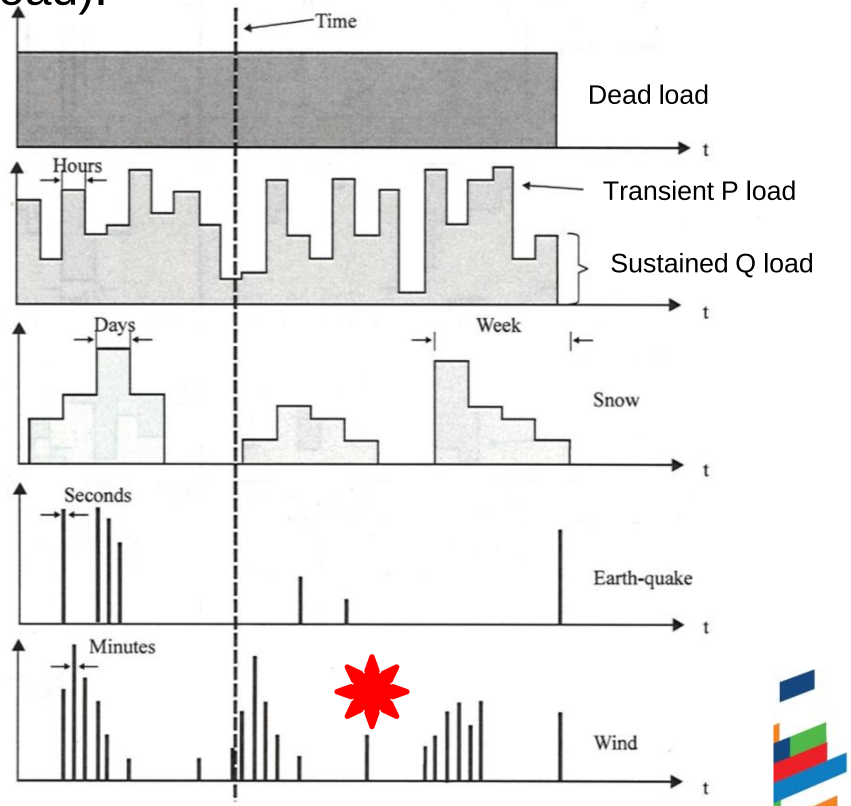
$$Z_1 = \max_T\{X_1(t)\} + X_2(t^*) + X_3(t^*) + \ldots + X_n(t^*)$$

$$Z_2 = X_1(t^*) + \max_T\{X_2(t)\} + X_3(t^*) + \ldots + X_n(t^*)$$

$$\vdots$$

$$Z_n = X_1(t^*) + X_2(t^*) + X_3(t^*) + \ldots + \max_T\{X_n(t)\}$$

$$X_{max}(T) \approx \max_i\{Z_i\}$$



(i) L = Q $_{max.}$ + P at occurrence of Q $_{max.}$
(ii) L = P $_{max.}$ + Q at occurrence of P $_{max.}$

Effects of Climate Change on Storm Surge (non-stationary)

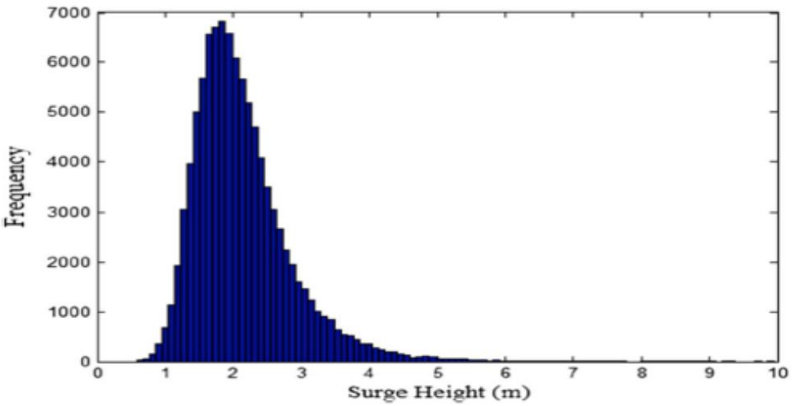
$$\widehat{\Delta p(t)} = \frac{\Delta p(t)}{p_{\mathrm{atm}}}$$

$$\widehat{R_{\max}(t)} = \frac{R_{\max}(t) \times g}{V_{\max}(t)^2}$$

$$\sqrt{\widehat{\zeta(t)}} = \left[\sqrt{R_{\max}(t)}\ 1\right] \left\{ \begin{matrix} - \\ C(S_0) \\ - \end{matrix} \begin{bmatrix} \widehat{\Delta p(t)}^2 \\ \widehat{\Delta p(t)} \\ 1 \end{bmatrix} \right\}$$

$$\widehat{\zeta(t)} = \frac{\zeta(t) \times g}{V_{\max}(t)^2}$$

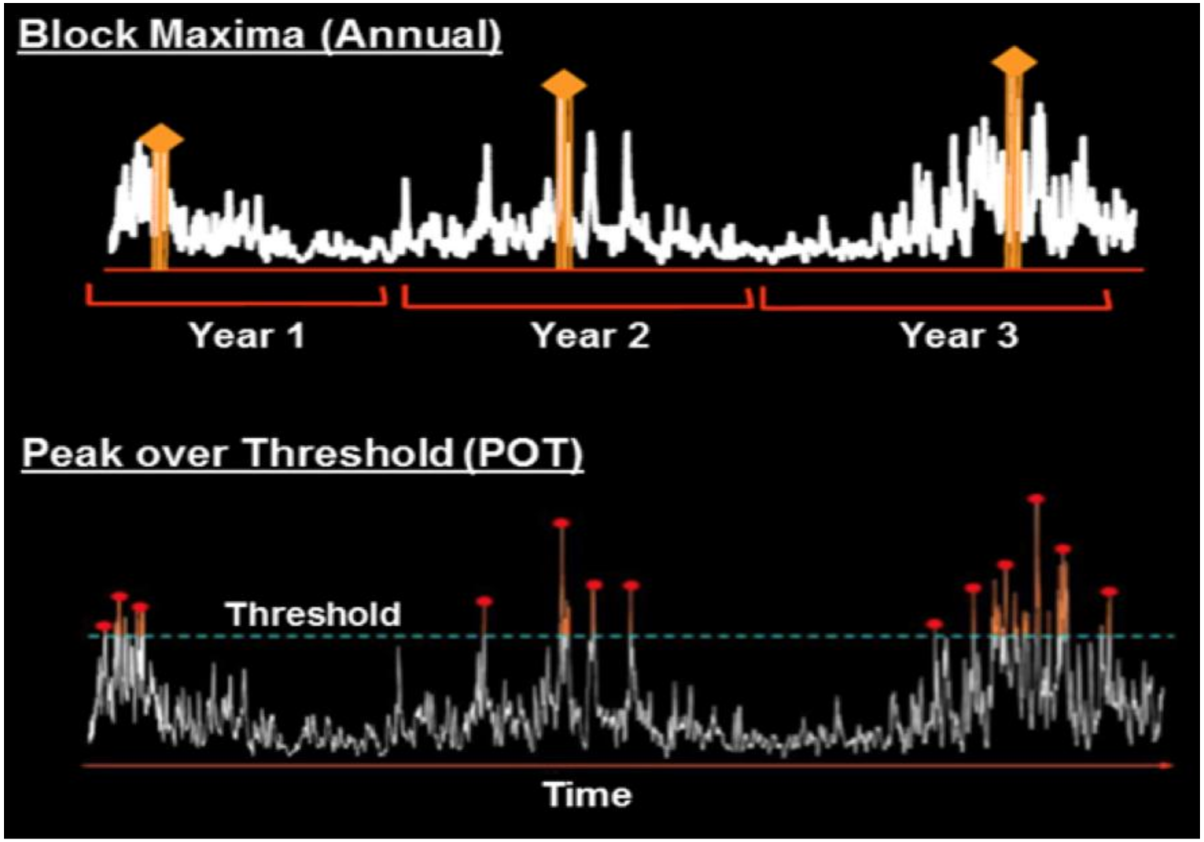
Δp: central pressure deficit at year t
Ω: surge height (m) at year t,
Rmax: the radius to maximum wind speed (km) at year t,
Vmax: peak 1-minute wind at 10m
C(S0) is the 2x3 curve fitting coefficient matrix for the ocean slope
Patm: atmospheric pressure



(i) the maximum storm intensities are increasing over the warming Sea Surface Temperature (SST).
(ii) The spatial variations in terms of storm frequency and intensity are considerable large.

Extreme Value Analysis (EVA) for Non-Stationary Scenario

- **Maximum daily, monthly or annual values vs. Peak-Over-Threshold (POT)**



(from 2015 SERDP Project RC-2335)

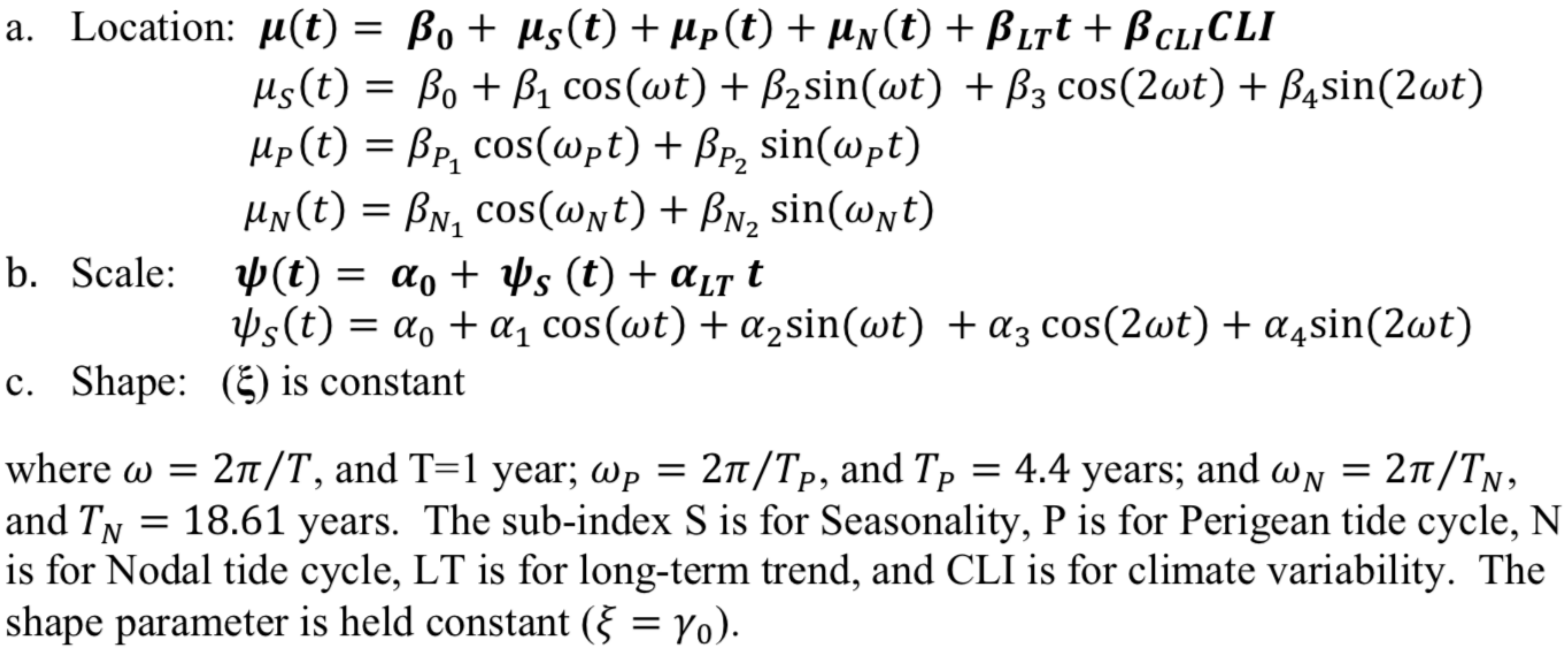
Generalized Extreme Value (GEV) with Annual Maxima

$$G(z,\theta) = \left\{ \exp\left\{ -\left[1 + \xi\left(\frac{z - \mu(t)}{\psi(t)} \right) \right]^{-1/\xi} \right\} \right. \qquad \psi(t) > 0$$

$$\theta = (\mu(t), \psi(t), \xi)$$

- **µ (location parameter)** that specifies where the distribution is centered.
- **Ψ (scale parameter)** that represents the dispersion.
- **ξ (shape parameter)** that determines the shape of the upper tail of the distribution.
- When $\xi > 0$ (Frechet), **$\xi < 0$ Weibull and $\xi = 0$ (Gumbel)**

GEV for non-stationary SLR (2015 SERDP project RC-2335)



a. Location: $\boldsymbol{\mu(t) = \beta_0 + \mu_S(t) + \mu_P(t) + \mu_N(t) + \beta_{LT} t + \beta_{CLI} CLI}$

$$\mu_S(t) = \beta_0 + \beta_1 \cos(\omega t) + \beta_2 \sin(\omega t) + \beta_3 \cos(2\omega t) + \beta_4 \sin(2\omega t)$$

$$\mu_P(t) = \beta_{P_1} \cos(\omega_P t) + \beta_{P_2} \sin(\omega_P t)$$

$$\mu_N(t) = \beta_{N_1} \cos(\omega_N t) + \beta_{N_2} \sin(\omega_N t)$$

b. Scale: $\boldsymbol{\psi(t) = \alpha_0 + \psi_S\,(t) + \alpha_{LT}\, t}$

$$\psi_S(t) = \alpha_0 + \alpha_1 \cos(\omega t) + \alpha_2 \sin(\omega t) + \alpha_3 \cos(2\omega t) + \alpha_4 \sin(2\omega t)$$

c. Shape: (ξ) is constant

where $\omega = 2\pi/T$, and T=1 year; $\omega_P = 2\pi/T_P$, and $T_P = 4.4$ years; and $\omega_N = 2\pi/T_N$, and $T_N = 18.61$ years. The sub-index S is for Seasonality, P is for Perigean tide cycle, N is for Nodal tide cycle, LT is for long-term trend, and CLI is for climate variability. The shape parameter is held constant ($\xi = \gamma_0$).

(i) Seasonality, tide cycles, long-term trend and climate variability are considered.

(ii) **ξ** (shape parameter) = constant < 0 (Weibull distribution).

(iii) **μ (location parameter) and *Ψ* (scale parameter) are time variant to account for non-stationary SLR.**

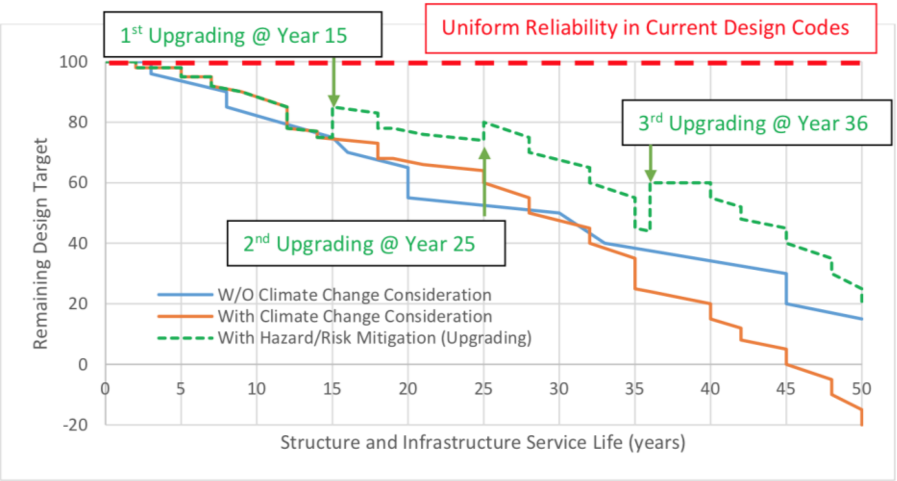
(iv) Sea Surface Temperature (SST) may be included in **μ** and *Ψ*.

Resilience and Risk Mitigation

(1) Resilience and risk mitigation include but are not limited to

Existing Pier/Wharf: Permanent or Temporary Relocation
Increased Pier Deck and Access Road Elevations
Pile Cap – Deck Connection
Uplift Forces from Wave Reflection Included

(2) Life-cycle cost-benefit analysis and optimization



(c) Effects of Climate Change and Hazard/Risk Mitigation (Upgrading) on Remaining Design Target

(3) ***The decision-making paradigm must shift from a predict-then-act approach to a scenario- based approach.***

Example: Resilience and Risk Mitigation

(1) Increased Deck and Access Road Elevations (millions $$$)

(2) Pile Cap – Beam - Deck Connections

(a) (b)

Figure 1: Damage in superstructure (a) uplift damage to pier slabs (b) destroyed bridge deck*

*TR-NAVFAC-EXWC-CI-1705 (2016). "Tsunami Loads and Effects on Navy Waterfront Facilities"

(3) Uplift Forces from Wave Reflection Included
(note: SLR may reduce the forces)

Summary

- Extreme Value Analysis (EVA) is a powerful tool to deal with non-stationary scenarios.

- The two of the three parameters in the GEV distribution are time variant time and may include SST to quantify non-stationary scenarios.

- **Regional / local effects and spatial variation must be considered.**

- ASCE/SEI 7 climate change team led by Don Scott, Director of SEI/ASCE, is working on the selection of the general methodology on effects of climate change on loads and load combination to update the versions in 2025 or 2028.

- Infrastructure resilience planning should based on life cycle cost-benefit analysis and optimization, but is difficult to codify the planning process.

Future Research Needs on Extreme Load Effects

- Novel rules and methods in load combinations (e.g. Monte Carlo simulation)

(i) Ferry Borges-Castanheta's model (1980, 1982)

The loads x_1 (Dead) and x_2 (Live) have the time duration of t_1 and t_2, respectively. During the design life *T* years, the occurrence of x_1 (*i.e.* change of the Dead) will be $n_1 = T/t_1$. During the duration of t_1, the occurrence of x_2 (*i.e.* change of the Live) will be $n_2 = t_1/t_2$ ($t_1 > t_2$). The maximum value of x_2 during $n_2 = max_{n_2}[x_2]$ Thus, the maximum value of the combined load $Y = x_1 + x_2 = max_{n_1}\left[x_1 + \ max_{n_2}(x_2)\right]$

(ii)Wen's load coincidence method (1978, 1981)

$$P(E,T) \approx 1\ -\ \left\{exp\{-[\textstyle\sum_{i=1}^{n} \lambda_i p_i + \sum_{i-1}^{n-1} \sum_{j=i+1}^{n} \lambda_{ij} p_{ij} + \cdots]T\}\right\}$$

- Collection of extreme loads and load effects (e.g. damages) using Structural Health Monitoring (SHM) and routine inspection data.

Thank you

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