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Extreme Load Combinations: A Survey of State Bridge Engineers

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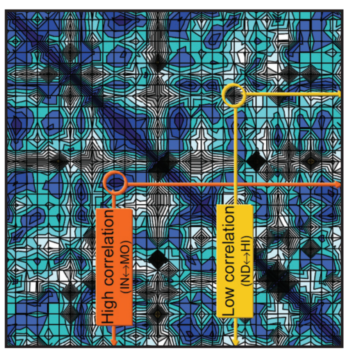

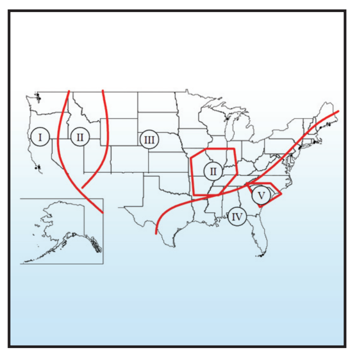

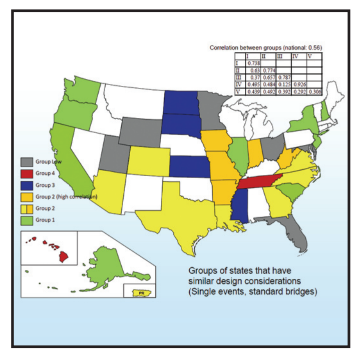

Technical Report MCEER-11-0007

October 14, 2011

This research was conducted at the University at Buffalo, State University of New York and was supported by the Federal Highway Administration under Contract Number DTFH61-08-C-00012.

Extreme Load Combinations:
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George C. Lee,[1] Zach Liang,[2] J. Jerry Shen[3] and Jerome S. O'Connor[4]

Workshop Steering Committee

Harry A. Capers, Jr., Arora and. Associates
John Kulicki, Modjeski and Masters
George C. Lee, University at Buffalo
Thomas Murphy, Modjeski and Masters
W. Phillip Yen, Federal Highway Administration

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1 Samuel P. Capen Professor of Engineering, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York
2 Research Associate Professor, Department of Mechanical and Aerospace Engineering, University at Buffalo, State University of New York
3 Research Specialist, Transportation Infrastructure Security Consultants (TISC), North Potomac, Maryland
4 Manager, Bridge Engineering Program, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, State University of New York

MCEER
University at Buffalo, State University of New York
Red Jacket Quadrangle, Buffalo, NY 14261
Phone: (716) 645-3391; Fax (716) 645-3399
E-mail: *mceer@buffalo.edu*; WWW Site: *http://mceer.buffalo.edu*

Preface

MCEER is a national center of excellence dedicated to the discovery and development of new knowledge, tools and technologies that equip communities to become more disaster resilient in the face of earthquakes and other extreme events. MCEER accomplishes this through a system of multidisciplinary, multi-hazard research, in tandem with complimentary education and outreach initiatives.

Headquartered at the University at Buffalo, The State University of New York, MCEER was originally established by the National Science Foundation in 1986, as the first National Center for Earthquake Engineering Research (NCEER). In 1998, it became known as the Multidisciplinary Center for Earthquake Engineering Research (MCEER), from which the current name, MCEER, evolved.

Comprising a consortium of researchers and industry partners from numerous disciplines and institutions throughout the United States, MCEER's mission has expanded from its original focus on earthquake engineering to one which addresses the technical and socio-economic impacts of a variety of hazards, both natural and man-made, on critical infrastructure, facilities, and society.

The Center derives support from several Federal agencies, including the National Science Foundation, Federal Highway Administration, National Institute of Standards and Technology, Department of Homeland Security/Federal Emergency Management Agency, and the State of New York, other state governments, academic institutions, foreign governments and private industry.

The Federal Highway Administration (FHWA) is supporting a study entitled "Principles of Multiple-Hazard Design for Highway Bridges." The project objectives are to establish a number of fundamental design principles and a framework to systematically expand the current AASHTO Load and Resistance Factor Design (LRFD) bridge design specification into a multi-hazard (MH)-LRFD. This is carried out by working closely with Federal Highway Administration experts, the AASHTO Subcommittee on Bridges and Structures (SCOBS) Technical Committee on Loads and Load Combinations (T-5), and with selected individuals who were largely responsible for the development of the current AASHTO LRFD. Several innovative technology developments for the mitigation of and response to extreme events are also part of this project. These include the development of software for a bridge damage database, development of a comprehensive framework for MH-LRFD, extreme hazard load effect calibration, multi-hazard design examples and case studies, traffic optimization software for multiple hazards, freight movement under multi-hazard conditions, development of a curvature sensor for bridge health monitoring, and education materials related to multi-hazard resilient bridges and highway infrastructure.

This report presents the findings of a survey whose purpose was to identify important extreme load combinations resulting from multiple hazards for which practical design limit state equations *for highway bridges can be established. The survey was conducted to obtain the opinions of State Bridge Engineers on the importance of potential extreme hazard loads and their combinations. A Multi-Hazard Design Workshop, held on April 26, 2010, was organized to review, interpret and disseminate the survey results to the participants, and to further discuss potential issues in the development of a MH-LRFD framework. The workshop participants identified five possible load cases for further study, which are being pursued by the research team.*

Executive Summary

This report briefly describes the recent progress of the current research program at MCEER sponsored by the Federal Highway Administration (FHWA) on the establishment of multiple hazard design principles for highway bridges followed by a more detailed discussion on one specific aspect of the study with respect to establishing a limited number of extreme load combinations for detailed study. One of the primary research tasks of the MCEER research program is to establish limit-state equations involving multiple hazard load effects within the context of the Load and Resistance Factor Design (LRFD) Specifications (AASHTO 2010), published by the American Association of State Highway and Transportation Officials (AASHTO) (Lee et al, 2008). This task compares the importance and design emphasis of the extreme loads as well as extreme load combinations by investigating the current practice and issues in design. A survey was conducted among the state bridge engineers that constitute AASHTO's Subcommittee on Bridges and Structures (SCOBS) to obtain their professional opinion on design considerations that are appropriate for their region. The result is an important reference for the establishment and simplification of extreme limit states.

The development of a framework for LRFD formulation requires three major research steps: 1) load specifications/resistance modeling, 2) reliability evaluation, and 3) establishment of limit state equations for design. The proposed Multi-Hazard LRFD (MH-LRFD) framework share the same underlying philosophy with the non-extreme LRFD bridge design specification, but the addition of extreme loads inflicts a number of technical difficulties. Additional guiding principles are required to develop simple and rational probability-based design specifications. The fundamental principles and guidelines that are being developed for the establishment of MH-LRFD equations are:

1. Consistent (not necessarily uniform) reliability principle: The attained reliability index from the MH-LRFD should reflect the bridge owners' needs, general public expectations about safety, and bridge life cycle cost. To this end, guidelines are needed to address the issues below.

    a. *Temporal distribution of extreme loads*

    b. *Non-Gaussian probability distribution*

2. Limit state convention: The results of many probabilistic studies are represented by a relatively small set of limit state equations (with factors) in design. This avoids the need for designers/owners to go through the complex probability computation in the design process. Thus, the following are necessary:

    a. *Practical set of limit state equations*

    b. *Determination of factors*

Creating a set of limit state equations for bridge design requires a delicate balance of sound theoretical background, accurate risk assessment, and a simple and practical format. In order to develop a mathematical basis for multi-hazard limit state equations in the United States that is practical, the research study requires active participation of AASHTO bridge engineers, design professionals, and researchers. A survey was conducted and the results were analyzed then further discussed in a Multi-Hazard Design Workshop.

The workshop discussions and survey will assist in establishment of limit state equation sets, but they also indicate that there are a few critical load combinations for which limit state equations should be a priority. This will be used as a reference for the selection of demonstration cases for the framework. These limit states are under the load combination of:

- Earthquake and live load
- Scour and earthquake
- Scour and vessel collision
- Earthquake and wind
- Vehicular collision followed by fire

Primary tasks that have been undertaken include:

1. Investigating various design guidelines to obtain potential useful information for the establishment of limit state equations and practical range of load factors.
    a. Existing limit states in practice.
    b. Range of load factors in use.
2. Surveying for significant issues and needs in practice: important limit states were sought to establish design equations and associated factors.
    a. Urgent needs in practice related to bridge reliability against extreme loads.
    b. Classification of bridge sites and simplification of design requirements.
    c. Establishing limit state lists for various bridge sites.
    d. Experience in extreme load intensity and load factors.

Acknowledgement

Technical guidance from the Workshop Steering Committee members, Harry Capers, Jr., John Kulicki, George Lee, Thomas Murphy and W. Phillip Yen, was critical to a successful and fruitful workshop. The participation of state bridge engineers in the workshop and survey was essential to identifying the practical needs and experience from the stakeholders. The authors express their sincere appreciation to the above individuals. Furthermore, they acknowledge the support of the Federal Highway Administration (FHWA) (through contract no. DTFH61-08-C-00012), led by Contract Officer's Technical Representative (COTR) W. Phillip Yen, Ph.D., P.E. HRDI-7, Senior Research Structural Engineer/Seismic Research Program Manager, FHWA.

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Section 1
Description of MCEER Multiple Hazard Project

1.1 Background

In recent years, engineers throughout the world have witnessed many bridge failures due to natural and manmade hazards. The most significant of these are the devastating collapses of bridges due to hurricanes, floods (include hydrodynamic force, debris flows and scour effect) and ocean waves. In addition, bridges fail due to vessel collision and vehicular impact. Many regions of the world have also experienced serious damage to bridges due to rainfall-induced landslides. Since September 11, 2001, terrorist attacks to critical infrastructure systems have been a major concern within the context of "homeland security." Statistics show that extreme events (including flood, scour, collisions, overloads, corrosion, wind, earthquakes, etc.) are the primary causes of bridge collapse and among the top reasons for bridge distress (Lwin, 2010). This phenomenon suggests that the risk of failure due to the extreme events is not very well controlled for the U.S. bridge population. While recent developments in bridge design specifications help guard against various types of extreme events and have greatly increased bridge resilience against individual hazard types, they have not been integrated under a consistent set of principles. Consequently, they do not provide adequate support for project evaluation and policy setting to bridge owners within the context of public safety and sensible spending considerations. There is a strong motivation to develop a multi-hazard or all-hazard approach to engineering design and construction, compatible to the AASHTO Load and Resistance Factor Design (LRFD).

The approach and associated data used in the calibration of current AASHTO LRFD may not be sufficient for the calibration of LRFD methods that include multiple extreme loads in addition to dead load and live load. While much research has been carried out related to probability-based bridge design against individual extreme loads, such as earthquake, hurricane/surge, vessel collision, and scour, one of the most significant efforts to summarize the development of multi-hazard design of bridges and to provide rational calibration of load factors is the NCHRP 12-48 project. The project report, NCHRP 489, recommends four additional scour-related Extreme Limit States be added to the AASHTO LRFD, and provides load factors obtained from analytical studies. The report also presents the first major attempt to systematically consider multiple extreme load effects of an extremely complex research domain to establish multiple hazard design principles and guidelines for bridges.

The establishment of Multi-Hazard Load and Resistance Factor Design (MH-LRFD) criteria includes works that can be broken down into three important steps:

1. Developing/identifying load (demand) and resistance (capacity) specifications
2. Computation of reliability of structures under the load effects
3. Establishing design limit state equations and load and resistance factors

The workshop carried out on April 26, 2010 was to develop information for both steps 1 and 3. The experience and practice from the state bridge officials represent an overall acceptance measure or public perception of acceptable risk. Such information is important in providing a basis for understanding the rationale of load intensity specification and the establishment of design equations.

1.1.1 Challenges and Needs

Limit states are the critical performance criteria used in LRFD. They are used to derive the formulas for the failure probability of a bridge meeting specified performance criteria. Current AASHTO LRFD (AASHTO, 2010) uses 13 limit states for three different performance criteria and a number of load conditions for each criterion. Extreme Limit States are fundamentally associated with strength performance requirements. An important goal of the MH-LRFD development is to create a system that better characterizes the probabilistic nature of the extreme and non-extreme loads without too much complexity in design procedures. It is conceivable that with the addition of potential combined effect of loads, it is necessary to set aside an adequate effort to study the best methods for simplifying the limit states to be checked in design.

The effort of completely calibrating the MH-LRFD will to be enormous. It is not the most beneficial strategy to plan for all load conditions being calibrated before partial implementation. Some results from the study can be provided to bridge engineers to help produce more rational and economical designs immediately. Most urgently needed subjects should be selected and guidelines provided for those.

Part of the reduction of complexity and the identification of significant urgent subjects can be done by studying all involved factors analytically. However, a very important and reliable source of such information is the experience of field engineers and bridge owners. Such data does not only include a combined effect from known and unknown factors, but also includes certain measures of consequence severity and public expectation of bridge performance, which may not be very well identified in analytical studies.

Acceptance of new probability-based design criteria by the bridge engineering community is expected to take time and effort. During the development, it is important to keep the practitioners’ and bridge owners’ perspectives in consideration when directing the study and shaping the product.

1.1.2 Objectives/Approach

The MCEER research project includes a task for reducing the complexity of design procedures. By properly classifying the bridge site and function, increase in design effort for including more extreme loads is minimized. The future specifications based on this framework will be calibrated using current bridge design practice, which should make the cost comparable with current design. In fact, since more extreme loads are included in the design procedure, it potentially reduces the design effort for checking each extreme hazard with individual guidelines. Having a better reliability measure also potentially reduces unnecessary conservatism, and subsequently reduces waste in construction cost. The MCEER study is expected to create a number of considerable benefits, including:

(a) Quantifiable bridge reliability/greater assurance for bridge safety

(b) No significant increase in cost (could reduce cost for specific subject areas, such as scour)

(c) Providing a research landscape for studies related to various extreme hazard combinations and cascading effects based on more consistent reliability principles and approaches.

The framework established in the MCEER study is intended for formulation and calibration of bridge LRFD guidelines in a general form that is capable of including all conceivable extreme loads. It requires the computation of bridge reliability to be combined with formulation of practical design equations (the limit state equations). The framework must be able to provide a platform for developing criteria that maintain a specified level of bridge reliability under the action of considered extreme and non-extreme loads. To establish limit state equations, both mathematical derivation and practicality are simultaneously considerations. With the suggestion of the Workshop Steering Committee, a survey was sent to the state bridge engineers throughout the country to assess the significance of individual extreme hazards and their combinations. This survey was followed by a workshop and webconferences to obtain further clarification and supplement on the survey data. A literature survey on currently available probability-based design criteria was also carried out. Results from this process are presented in Sections 2 – 6 of this report and are used in the development of establishing the MH-LRFD framework.

1.2 Deterministic-Based and Reliability-Based Design

In allowable stress design (ASD), the principle is to make sure the capacity, denoted by C, is, by an acceptable margin, greater than the load (demand), denoted by D. That is

$$C > D \cdots \tag{1.1}$$

To create an adequate margin of safety, a safety factor is used such that

$$C/FS \geqslant D \cdots \tag{1.2}$$

where FS is a factor of safety that makes only a part of the capacity, C, allowed to be utilized. Intuitively, this makes it "unlikely" that the capacity would be exceeded. This does not quantify the remaining probability of failure, however low it is. The bridge can easily be much over-designed, i.e., too expensive, or much under-designed, i.e., unsafe, without the owners' awareness.

The combination of different types of loads for ASD is mostly a simple addition of the maximum values (see Table 1-1). For example, the Load Group I combination is:

$$Load_{Group\ I}=D+(L+1)n+CF+\beta_E E+B+SF \cdots \tag{1.3}$$

It is very difficult to justify why the maximum value of one load occurs simultaneously with the maximum value of the other. Due to this lack of adequate consideration of uncertainties, a very small portion of the strength of material is used for the design computation (normally in the range of 40% to 50%).

Table 1-1 Load combinations for ASD and LFD

		1	2	3	3A	4	5	6	7	8	9	10	11	12	13	14
		β factors														
Group		γ	D	$(L+I)_n$	$(L+I)_p$	CF	E	B	SF	W	WL	LF	R+S+T	EQ	ICE	%
Service load	I	1.0	1	1	0	1	β_E	1	1	0	0	0	0	0	0	100
	IA	1.0	1	2	0	0	0	0	0	0	0	0	0	0	0	150
	IB	1.0	1	0	1	1	β_E	1	1	0	0	0	0	0	0	**
	II	1.0	1	0	0	0	1	1	1	1	0	0	0	0	0	125
	III	1.0	1	1	0	1	β_E	1	1	0.3	1	1	0	0	0	125
	IV	1.0	1	1	0	1	β_E	1	1	0	0	0	1	0	0	125
	V	1.0	1	0	0	0	1	1	1	1	0	0	1	0	0	140
	VI	1.0	1	1	0	1	β_E	1	1	0.3	1	1	1	0	0	140
	VII	1.0	1	0	0	0	1	1	1	0	0	0	0	1	0	133
	VIII	1.0	1	1	0	1	1	1	1	0	0	0	0	0	1	140
	IX	1.0	1	0	0	0	1	1	1	1	0	0	0	0	1	150
	X	1.0	1	1	0	0	β_E	0	0	0	0	0	0	0	0	100
Load factor design	I	1.3	β_D	1.67	0	1.0	β_E	1	1	0	0	0	0	0	0	Not Applicable
	IA	1.3	β_D	2.20	0	0	0	0	0	0	0	0	0	0	0	
	IB	1.3	β_D	0	1	1.0	β_E	1	1	0	0	0	0	0	0	
	II	1.3	β_D	0	0	0	β_E	1	1	1	0	0	0	0	0	
	III	1.3	β_D	1	0	1	β_E	1	1	0.3	1	1	0	0	0	
	IV	1.3	β_D	1	0	1	β_E	1	1	0	0	0	0	0	0	
	V	1.25	β_D	0	0	0	β_E	1	1	1	0	0	1	0	0	
	VI	1.25	β_D	1	0	1	β_E	1	1	0.3	1	1	1	0	0	
	VII	1.3	β_D	0	0	0	β_E	1	1	0	0	0	1	1	0	
	VIII	1.3	β_D	1	0	1	β_E	1	1	0	0	0	0	0	1	
	IX	1.2	β_D	0	0	0	β_E	1	1	1	0	0	0	0	1	
	X	1.3	1	1.67	0	0	β_E	0	0	0	0	0	0	0	0	

Load Factor Design (LFD) takes a step further and assigns various load factors to different loads to address the different uncertainties associated with individual loads (see Table 1-1). The Group I load combination becomes:

$$Load_{Group\ I}=1.3*(\beta_D D+1.67(L+1)n+CF+\beta_E E+B+SF) \qquad (1.4)$$

While this equation gives more leverage in individually tuning the factors to better estimate the safety margin, it still does not quantitatively provide a measurement of reliability; that is, the probability of failure is unknown.

In order to provide better risk management to the highway transportation system, AASHTO published the LRFD Specifications in 1994 and stopped maintaining the Standard Specifications in 1999. The basic design equation is

$$\sum \eta_i \gamma_i Q_i \le \phi R_n = R_r \qquad (1.5)$$

Load factors are organized by strength, serviceability, extreme event, and fatigue limit states (Table 1-2). Resistance factors vary with the concerned components. Although this formulation has a fairly similar format as that used in LFD, the factors are calibrated with a quantifiable probability and provide a more explicit measure of risk. Figure 1-1 shows the range of reliability attained by LFD and LRFD. While ASD/LFD will become history in bridge engineering, its remnants can easily be found in many parts of the practice. Current LRFD is calibrated to mimic the level of reliability that was provided by using ASD/LFD, but with a narrower range of variation in reliability. This is not expected to change any time soon. The calibration work following the establishment of the MH-LRFD framework will provide bridge designs that have a reliability similar to that obtained from AASHTO's standard and LRFD specifications.

Table 1-2 Load factors from AASHTO LRFD

Load Combination Limit State	*DC DD DW EH EV ES EL PS CR SH*	*LL IM CE BR PL LS*	*WA*	*WS*	*WL*	*FR*	*TU*	*TG*	*SE*	Use One of These at a Time *EQ*	*IC*	*CT*	*CV*
Strength I (unless noted)	γp	1.75	1.00	—	—	1.00	0.50/1.20	γTG	γSE	—	—	—	—
Strength II	γp	1.35	1.00	—	—	1.00	0.50/1.20	γTG	γSE	—	—	—	—
Strength III	γp	—	1.00	1.40	—	1.00	0.50/1.20	γTG	γSE	—	—	—	—
Strength IV	γp	—	1.00	—	—	1.00	0.50/1.20	—	—	—	—	—	—
Strength V	γp	1.35	1.00	0.40	1.0	1.00	0.50/1.20	γTG	γSE	—	—	—	—
Extreme Event I	γp	γEQ	1.00	—	—	1.00	—	—	—	1.00	—	—	—
Extreme Event II	γp	0.50	1.00	—	—	1.00	—	—	—	—	1.00	1.00	1.00
Service I	1.00	1.00	1.00	0.30	1.0	1.00	1.00/1.20	γTG	γSE	—	—	—	—
Service II	1.00	1.30	1.00	—	—	1.00	1.00/1.20	—	—	—	—	—	—
Service III	1.00	0.80	1.00	—	—	1.00	1.00/1.20	γTG	γSE	—	—	—	—
Service IV	1.00	—	1.00	0.70	—	1.00	1.00/1.20	—	1.0	—	—	—	—
Fatigue I—*LL*, *IM* & *CE* only	—	1.50	—	—	—	—	—	—	—	—	—	—	—
Fatigue I II— *LL*, *IM* & *CE* only	—	0.75	—	—	—	—	—	—	—	—	—	—	—

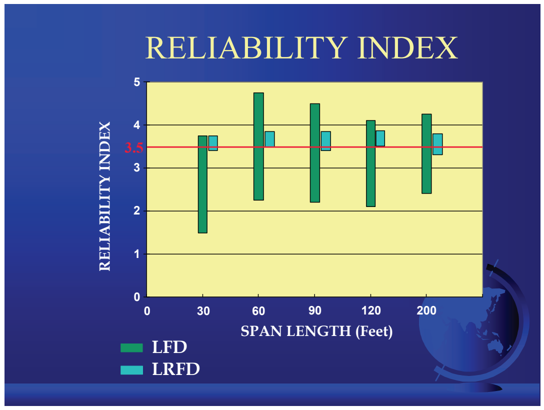


Figure 1-1 Range of reliability from LFD and LRFD

1.3 General Concept of Reliability-Based Design

To represent the uncertainty of the loads and strength of materials, it is necessary to treat both demand and capacity (load, Q, and resistance, R, in LRFD terminology) as random variables. With the probability distribution function (PDF) shown in Figure 1-2, the probability of failure is written as:

$$P(Q \geqslant R) = \int_{-\infty}^{\infty} f_L(q) \int_{-\infty}^{q} f_R(r)\,dr\,dq \quad \cdots\cdots (1.6)$$

The nominal load, mean load, and the design load are only reference values representing probability distribution of the load.

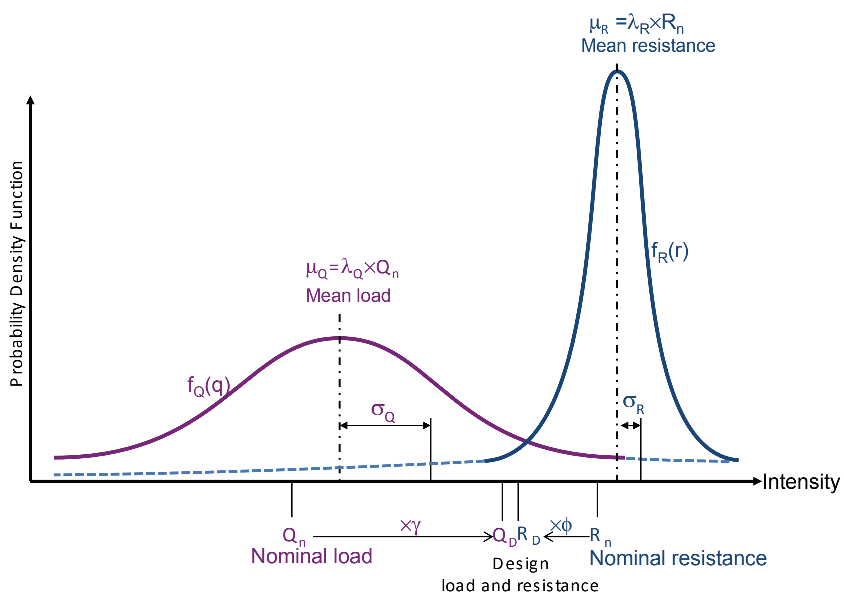


Figure 1-2 Probability distribution of load and resistance

Equation (1.6) does not always have a simple closed form expression. It is often assumed (sometimes with the help of the Central Limit Theorem) that both R and Q are normally distributed random variables in order to keep the computation relatively simple.

1.4 Limit State

A limit state is an important tool in relating the quantitative risk level to a "yes-or-no" decision criterion. The accurate definition depends on the context. In this case, it separates potential safety and failure events for a bridge. In the design specifications, it is used to separate the acceptable and unacceptable strength or other relevant bridge properties. For a simple failure controlled by ultimate strength, a limit state may be defined as

$$R=Q \qquad (1.7)$$

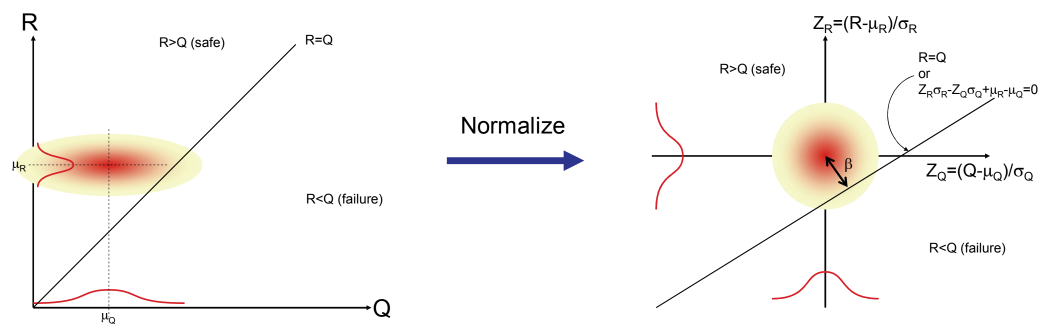


Figure 1-3 Limit state and reliability index β

Figure 1-3 shows the probability distribution of resistance and load with respect to the limit state. The resistance is intentionally positioned well above the limit state line with the given load condition to avoid failure. While the area with high joint probability of R and Q (dark-red color) is located on the upper-left (safe) side of the limit state, there is a slight possibility of failure, defined as when the random combination of R and Q falls in the lower-right area in Figure 1-3.

1.5 Reliability and Limit State Equations

The limit state expressed in the form of random variables (i.e., Q and R) needs to be mapped into one or more limit state equations expressed in terms of nominal loads and resistance to be used for design (i.e., Q_n and R_n). This mapping does not always have a closed-form representation. In current bridge design, this is done by introducing the Reliability Index, β (see Figure 1-3 "Normalize"). When the limit state in the random variable domain is a linear combination of one load and resistance, the limit state represented by nominal loads and resistance is in a very simple form. For the specific case shown in Figure 1-3, the limit state equation represented by nominal loads and resistance is given by

$$R_n = \frac{1+\sqrt{1-(1-\beta^2 V_Q^2)(1-\beta^2 V_R^2)}}{\lambda_R(1-\beta^2 V_R^2)}\lambda_Q Q_n \quad \text{(1.8)}$$

or

$$\phi R_n = \gamma Q_n$$

where

$$\frac{\gamma}{\phi} = \frac{1+\sqrt{1-(1-\beta^2 V_Q^2)(1-\beta^2 V_R^2)}}{\lambda_R(1-\beta^2 V_R^2)}\lambda_Q$$

This leads to the basis for the choice of load and resistance factors.

For a number of reasons, this simple form does not extend to the limit state equations involving multiple extreme loads. It may be required to use multiple limit state equations to represent a single set of load combinations. The governing factors on this phenomenon include:

1. Number of loads

   --earthquake, wind, flood, etc.

2. Coefficient of variation

   --greater uncertainties than those from dead load (DL) and live load (LL)

3. Physical formulation of the limit state

   --variation in properties of loads and bridge components

4. Likelihood of simultaneous occurrence

   --some dominated by single event, others by joint events

Figure 1-4 shows an example of curved limit state surface in the nominal load/resistance domain mapped from a linear limit state in random variable domain.

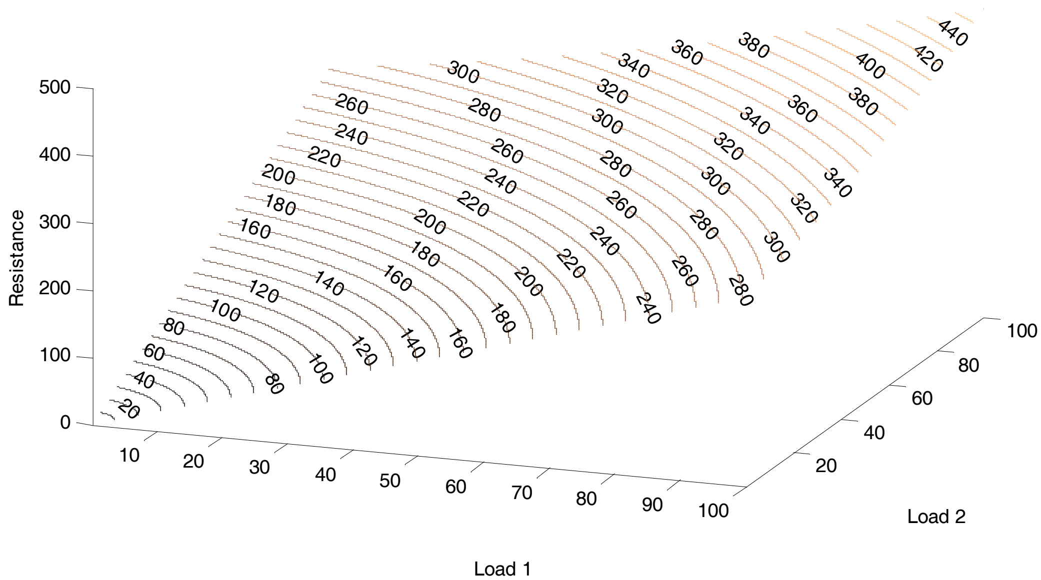


Figure 1-4 Curved limit state in nominal load/resistance domain that may require multiple limit state equations

While these factors are not critical concerns in the current AASHTO LRFD (in comparison with the potential situations in MH-LRFD), the effect may have already become apparent with the addition of the Strength Limit State IV. It is a modification from Strength Limit State I when the dead load to live load ratio exceeds 7.0, a case that normally applies only to long-span bridges. Figure 1-5 shows the usage of multiple limit states to better characterize the safety of structures.

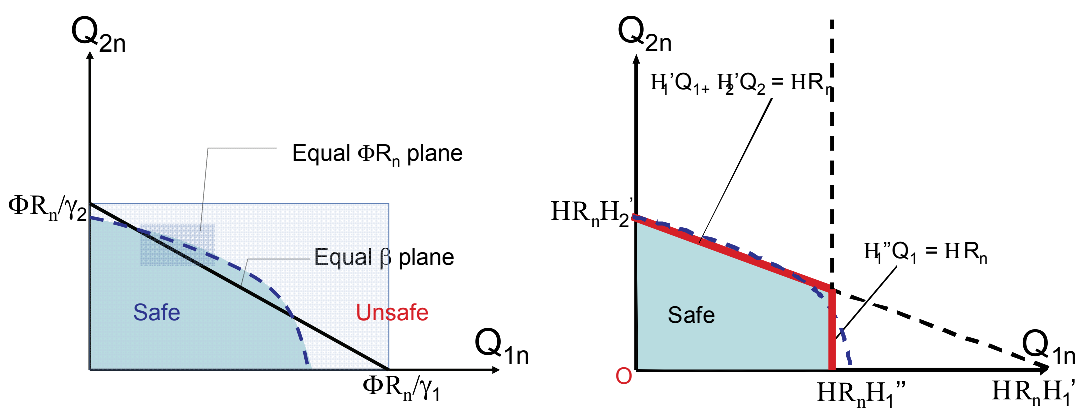


Figure 1-5 Graphical depiction of limit state equation(s)

1.6 Design Against Extreme Loads

Much effort has been spent on bridge design against other environmental loads and accidental (manmade) loads since the implementation of LRFD. The results are mostly brought back to the general design with AASHTO LRFD specifications for combination and limit state verification. This approach makes it very difficult to have a consistent measure of bridge reliability. For example, the vessel collision load is governed by the AASHTO Guide Specification (AASHTO, 2009a) in a format consistent with the probability principles of AASHTO LRFD. It results in an annual probability of failure of 1/10,000 for critical bridges, which may be translated to a reliability index for bridge life span (75-year) of approximately 2.4. However, the result is combined with dead load and live load in the same context of other extreme loads (Extreme Limit State II). The final reliability of the combination may not be clear. The status of considered extreme loads in current practice is listed in Table 1-3.

Table 1-3 Current (2010) status of the considered extreme loads in bridge design

	Status in AASHTO LRFD
Dead Load	Calibrated
Live Load	Calibrated
Earthquake	Included (Guide Specifications), but not completely calibrated
Scour	Not in LRFD framework
Wind	Integrated in AASHTO LRFD strength limit state, not completely calibrated
Fire	New guidance information available from NCHRP study
Vessel Collision	Structurally consistent with LRFD, but not calibrated consistently
Vehicular Collision	Rough estimate based on limited data
Storm Surge	New Guide Specification provides design details
Debris Flow	Provisions on debris raft (part of WA)

1.7 Load Combinations

Part of the primary advancements of the MH-LRFD framework is to provide a method to calibrate AASHTO LRFD for (1) a large number of loads (more than two), and (2) loads with various time-dependent characteristics so that it can handle the extreme loads. Current LRFD has accomplished these to the extent that is necessary for calibrating with dead load and live load. Four types of dead loads are considered and combined: weight of steel and precast concrete, weight of cast-in-place concrete, weight of wearing surface, and weight of railing and luminaires. Live load is from time-varying truck loads. It combines with dead loads and to other live loads, such as simultaneous truck passage on two or more lanes, and one truck followed by another. While earthquake and wind are included in the results of the current AASHTO LRFD calibration, the discussion is kept to a minimal level.

The formulation of combining time-varying load is a significant part of the development of a MH-LRFD framework. It requires sophisticated and flexible mathematical procedures to accommodate diverse forms of extreme events. Such development is ongoing and will be reported in future MCEER documents. In this workshop report, a practical aspect is used to investigate the load combination from the end-users' point of view. The approaches used in current bridge design and the urgent needs in the improvement of extreme event design methods are studied. The result can potentially help in establishing the proper format of the final design equations/procedures, and hopefully allow the research product to provide quick relief to the relevant engineering issues.

1.8 Variation of Loads

Extreme loads can have very different properties in different regions of the country and its effect can also vary on bridges of different functionality. This variation is currently handled very inconsistently in the specification of all loads. The live load model used for calibration of AASHTO LRFD assumes the fleet of traffic has similar physical properties and driving patterns throughout the country. The primary variation comes from ADTT. The conversion of ADTT is also based on the assumption of invariant statistical properties. The wind load model is pivoted at one velocity measure: maximum fastest-mile wind velocity in 50 years. This value is available on the wind design map. Statistical properties are invariant because the conversion for various exposure periods (associated with design of highway facility with different levels of importance) is uniform (see figure 1-6). Earthquake load specifications use two mapped intensity measures—S_s and S_1—and an independently mapped soil property to assemble the design spectrum (AASHTO, 2009b). This practice produces a significant geographical variation in the characteristics of the load. On the other hand, the return period for the design earthquake is uniformly chosen at 1,000 years. To have a uniform reliability in combination with other loads, an implicit assumption must have been embedded that the change in intensity with respect to return period is the same throughout the country (it can also be interpreted as the probability distributions having the same shape), which is quite far from the truth. The scour design requirement uses two different return periods for design flood and check flood. This approach would include the geographical variation of probability distribution in the design.

Adding all potential variations together, the number of limit state equations may drastically increase from the current 13 limit states. It would be a great burden to bridge owners and may become impractical for the design process. Reduction of limit states and simplification of the design checking process is an important step before implementation.

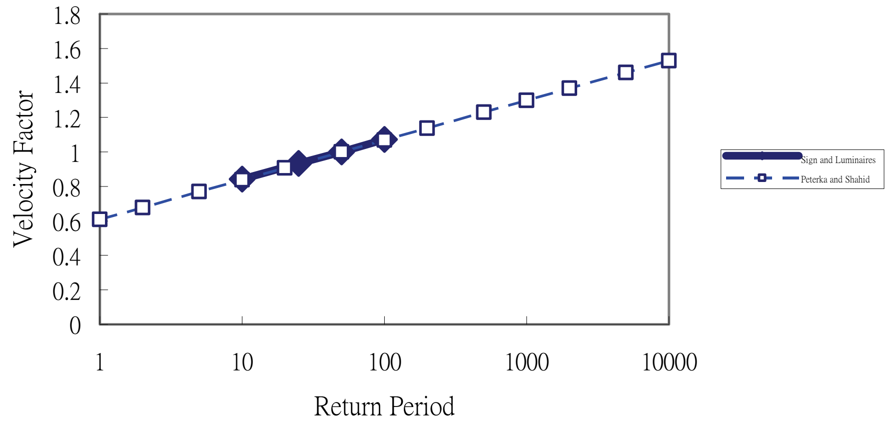


Figure 1-6 Exposure period conversion adopted by AASHTO Sign and Luminaire Design (AASHTO 2009c; Peterka et al., 1998)

It is commonly understood that some extreme events or combinations of extreme events never controls the design in certain area. It is also apparent that the rule of selection for controlling limit state equations varies with a number of factors, including importance, functionality (e.g., water-crossing, traffic pattern, …), structural system, bridge location (seismic zone, hurricane zone, …), seriousness of consequences, etc. Experienced bridge engineers know very well the important ones among the current 13 limit states. Better organized rules of selection are needed in this study to make the design procedure based on a sophisticated design philosophy that is friendly to practitioners.

The final format of the simplification process can be in a form of tables or flow charts that leads the user to a relatively short set of limit state equations. Computer software may also be produced to accelerate the process. In the next chapter, a first attempt in classifying bridge sites and functionalities is presented for this purpose.

1.9 Establishment of Limit State Equations for MH-LRFD

All theoretical studies and computations in the development of MH-LRFD are purported to provide rational bases and adequate data for the establishment of design formulas. These formulas take shape in the limit state equations in bridge design specifications. Three fundamental approaches are considered in the MCEER study to accomplish this as follows.

1. Analytical approach: With known load and resistance models, computations can be made to establish basic requirements on the limit state equations. This approach does not tend to lead to unique solutions for the format or detailed factors for the formulas. However, it provides the best physical or mathematical background for best practice. It is valuable in making design formulas more generally applicable to various conditions and providing guidance in proposals for improvement of practice.

2. Empirical approach: Current practice in the U.S. is an important indication of the demand from engineering society and socio-economical/environment conditions of this country.

Opinions from the bridge owners represent a certain consensus of acceptable practice from engineers, political entities, funding agencies, and general public. In this study, state bridge engineers were surveyed to gather and analyze the experience throughout the United States.

3. State-of-the-practice approach: Probability-based or non-probability based design equations from bridge-related guidelines and specifications from different geographical areas or countries may have different origins and may provide useful ideas and even justification for a specific practice. Sifting through these provisions may help produce a more complete pool of potential formulations for consideration. Design details and factors in the equations should be properly modified as needed to be suitable for usage in the U.S. or part of the U.S.

The first approach relies on the development of theoretical framework in other tasks of this study. While the analytical results can provide critical information for the proper form of the final design equations, it is understood that the findings from the state-of-the-practice and feedback from stakeholders can also provide much needed guidance to the analytical work to ensure that the product meets the expectations from the engineering profession as well as the general public. The three parts of this work are therefore put into action in parallel. The remainder of this report will present the findings from the study using the second approach.

Section 2

Survey of State Bridge Engineers

2.1 Background

Several questions were raised among the research team and identified as key issues for the development of a multi-hazard design framework (Project research team meeting, October 1, 2009). Some of these questions were found difficult to answer without extensive input from stakeholders, such as bridge owners. The following points represent a brief summary of opinions from the research team members:

a. LRFD is a rational and adaptable platform for the implementation of the multi-hazard framework developed in this study.

b. Compared to the current LRFD, which is calibrated for dead load and live load, the multi-hazard design procedure can potentially be complex and difficult to use.

c. Past performance data used in research represent various practices in different periods in the history of bridge engineering. The benefit of using such data in the validation and calibration of the developed framework may be limited.

d. The calibration of current LRFD assesses structural reliability from given load and resistance factors. It does not provide sufficient equations to determine relative values of all individual factors. Experiences in practice are needed to provide additional guidance in determining these factors.

e. State bridge engineers from key AASHTO committees need to be involved as the research moves forward with the new multi-year roadmap.

f. Practical questions need to be organized for use in discussion with selected AASHTO members. This should be combined with phone calls and one or a number of workshop(s) to discuss with the focus group and disseminate the results.

The LRFD relies on checking and ensuring design equations satisfied for all "limit states." The identification of significant limit states and establishment of proper limit state equations are among a few major issues to be resolved before the accomplishment of a MH-LRFD specification. To obtain a rational and practical set of limit state equations, the analytical development work needs to be accompanied by engineering experience from field experts. This chapter reports the research work on incorporating field experience and combining environmental factors to establish limit state equations.

The initial idea of the MH-LRFD survey is a result of further contemplation on the conclusions from this meeting. Further definition on the type of questions and focus group composition were brainstormed in the subsequent discussions (Research team meeting, January 12, 2010). The potential members of the focus group are the stakeholders, which includes primarily bridge owners. Leading experts in bridge design and extreme events should also be considered.

Input from stakeholders and/or experts was needed on:

a. Load combinations: The significant combinations with respect to regions and type of bridges need to be identified. To begin with, a matrix of combinations needs to be produced. Comparison of significance among loads may be used to reduce the number of combinations to be used in the design of any individual bridge.

b. Load intensity assessment in practice: The load intensity is related to the type of hazard, location of the bridge site, and exposure period. Although the scientific data are available from specialized agencies or institutes, the perception from practicing engineers is an important indication of the combined effect of these factors.

c. Acceptable risk: Required bridge reliability (acceptable failure probability) for individual hazards, combinations of hazards and cascading load effects needs to be identified. Criteria are needed to identify important combinations that need to be included in design.

The complexity of the MH-LRFD is attributable to the potential large number of limit states that needs to be considered in design. It is both an issue for a designer and for a developer of a design procedure. For the designer, it would appear that much time is spent on checking the limit states that may not be significant for a given bridge. For the developer, producing and calibrating the load and resistance factors for all limit states is time consuming and would prevent MH-LRFD from being implemented for a prolonged period. It is preferred that the most critical limit states that affect the majority of bridges are identified and calibrated first. In this way, the new design framework can be demonstrated and can start to benefit the industry in a relatively short time.

2.2 Potential Limit States

The research team has identified eight specific extreme loads as relatively significant and worth exploring for their impact on bridge design at present. These extreme loads include (in no particular order):

1. Earthquake
2. Scour
3. Wind
4. Storm surge
5. Vessel collision
6. Vehicular collision
7. Fire
8. Landslide/debris flow

Randomly combining amongst these extreme loads and their combinations with non-extreme loads can give a very large list that includes both significant and insignificant combinations. In order to produce a survey questionnaire that is reasonable in size and takes a manageable amount of time from the participants, certain reduction on the size of the list is in order. For this purpose, a review on limit states and load combinations in existing provisions was conducted (AASHTO, 2010, Highway Agency, 2001, BSI, 2006, Richardson and Davis, 2001, Transit New Zealand, 2003). Some research documents were also included in the review to incorporate the combinations that have been identified as significant but have not been fully comprehended (Ghosn et al, 2003, Buckle et al, 2006). The following list was created based on the results from this review. A few load combinations beyond the results from the review were also deemed beneficial to include and were therefore added after discussion within the research team. Such load combinations are conceivably worth further study but are not yet well defined (e.g., fire, wind + vehicular collision). The list of potential limit states is shown below. Note that load factors are omitted in this list because only the format of the limit state equations is of interest.

<u>Strength:</u>

DL+WA+LL	Non-extreme (AASHTO LRFD Strength I)
DL+WA+WS	Wind (AASHTO LRFD Strength III)
DL+WA+LL+WS+WL	Wind (AASHTO LRFD/NCHRP 489 Strength V)
<u>Extreme/Ultimate</u>	
DL+WA+LL@SC_{design}	Scour (NCHRP 489)
DL@2.0SC_{design}	Scour (NCHRP 489)
DL+WA@SC_{check}	Scour (HEC-18 superflood overtopping)
DL+LL+0.5SC_{LD}	(SC_{LD}: Long-term degradation)
DL+WS_{100}	Wind (Aerodynamic evaluation)
DL+$WS_{10,000}$	Wind (flutter for cable-supported bridges)
DL+LL+CT	Vehicular collision (AASHTO LRFD Extreme II)
DL+WA+LL+EQ_{500}	Earthquake (corresponding to approx. mean truck load)
DL+LL+EQ_{2500}	Earthquake (NCHRP 489 Extreme I)
DL+LL+CV	Vessel collision (AASHTO LRFD Extreme II)
DL+LL+DF	Debris flow
DL+WA+WS@SC_{100}	Scour+Wind (NCHRP 489)
DL+CV@SC_{design}	Scour+Vessel collision (NCHRP 489)

$DL+EQ_{2500}@SC_{100}$	Scour+Earthquake (NCHRP 489)
DL+LL+IC	Ice (debris flow) (AASHTO LRFD Extreme II)
$DL+LL+TG_{Fire}@Fire$	Fire (starting of fire, low temperature)
$DL+LL+TG_{Fire}@Fire$	Fire (early stage, low temperature)
DL@Fire	Fire (late stage, high temperature)
$DL+WA_{1000}+WS_{1000}$	Extreme wind+Surge (Transit NZ)
$DL+LL+CT+WS_{50}$	Wind+Vehicular collision
$DL+WA+LL+CV+WS_{50}$	Wind+Vessel collision
$DL+WA_{100}+LL+WS_{50}\ @SC_{100}$	Scour+Storm surge+Wind
$DL+WA+LL+CV+WS_{50}\ @SC_{100}$	Scour+Vessel collision+Wind
$DL+LL+EQ_{100}$	Earthquake ("expected earthquake" approx. 0.25g PGA at LA)
DL+WA+LL+BL	Blast
<u>Extreme/service</u>	
$DL+WA+LL@SC_{10}$	Scour (frequent flood)
DL+WA+WS	Wind (AASHTO LRFD Service IV)
$DL+LL+EQ_{10}$	Earthquake (very frequent small earthquake, approx. 0.08g PGA at LA)

An ideal MH-LRFD framework would be capable of accommodating these limit states, and potentially more identified during the study. It would be apparently impractical to simply check all these conditions in design regardless of the individual bridge location and functionality. Additional guidance is needed in identifying important limit states for a specific bridge. This is an element that does not explicitly exist in current design provisions. The survey to the state bridge engineers included two pieces of critical information to address the current needs of the research project:

1. Bridge classification and simplification of design procedure: The raw form of a comprehensive multi-hazard design procedure is expected to be complex. Although it is not a fundamental issue, the difficulty in practice will likely prevent its implementation. Similarities in design considerations among certain bridges can be identified and recommendations on significant limit states can be made accordingly.

2. Choice for case study: A few specific load combinations will be selected to showcase the MH-LRFD framework. It is sensible to select the combinations that provide immediate help to the current bridge engineering practice.

2.3 Multi-Hazard Design Questionnaire

A questionnaire was designed to obtain opinions from the state bridge engineers regarding the significance of certain loads and load combinations in bridge design based on their experience. A distinction was made between *standard* bridges (say less than 500' long) and *special* or long span bridges. With the suggestions and advice from the workshop steering committee, the survey was divided into three parts. The first part considers a single extreme event and concurrence of two or more events. This includes:

1. Single events

    1.1 Scour

    1.2 Vessel Collision

    1.3 Vehicular Collision

    1.4 Fire

    1.5 Earthquake

    1.6 Storm Surge

    1.7 Wind

    1.8 Debris Flow

    1.9 Other

2. Possibility of Two Concurrent Extreme Events

    2.1 Scour + Vessel Collision

    2.2 Scour + Earthquake

    2.3 Scour + Storm Surge

    2.4 Scour + Wind

    2.5 Scour + Debris Flow

    2.6 Vessel Collision + Storm Surge

    2.7 Vessel Collision +Wind

    2.8 Vessel Collision + Debris Flow

    2.9 Vehicular Collision + Wind

2.10 Fire + Wind

2.11 Earthquake + Wind

2.12 Storm Surge + Wind

2.13 Wind + Debris Flow

2.14 Other possible combinations

3. Three Concurrent Extreme Events

3.1 Scour +Vessel Collision + Storm Surge

3.2 Scour + Vessel Collision + Wind

3.3 Scour + Earthquake + Wind

3.4 Scour+ Storm Surge + Wind

3.5 Vessel Collision + Storm Surge + Wind

3.6 Vehicular Collision + Fire + Wind

3.7 Other

The second part deals with cascading events. Cascading events include two categories: (1) one or more concurrent events leading to another, and (2) a sequence of events occurring before the next bridge inspection or repair from a previous event. The first type may have a time gap of minutes, hours or possibly days. The second type may have a time gap of weeks or months. From the perspective of formulating MH-LRFD, they may be grouped together. Minor cascading effects can last through the remaining service life. Major cascading effect can last through an inspection or maintenance cycle. In all cases, the first occurrence will introduce damage or produce inelastic responses to the bridge. This includes:

1. Single events leading to (or followed by) another

1.1 Vessel Collision Earthquake

1.2 Vessel Collision Storm Surge

1.3 Vessel Collision Vessel Collision

1.4 Vehicular Collision Fire

1.5 Vehicular Collision Earthquake

1.6 Vehicular Collision Vehicular Collision

1.7 Earthquake Wind

1.8 Earthquake Fire

1.9 Earthquake Debris Flow

1.10 Earthquake Earthquake

1.11 Wind Vehicular Collision

1.12 Fire Wind

1.13 Storm Surge Storm Surge

1.14 Other

2. Cascading of Concurrent Events (due to the complexity of this group, only a few examples were given to lead the participants to provide further possibilities.)

Initial event(s) Subsequent event(s)

Vehicular Collision + Wind	→	Fire
Wind	→	Storm Surge + Vessel Collision
Earthquake + Vehicular Collision	→	Wind + Fire
Scour + Earthquake	→	Vessel Collision + Wind + Debris Flow
Earthquake	→	Vehicular Collision + Fire

The third part asked the participants to provide additional comments regarding their answers or any extreme conditions that need attention but were not in the questionnaire.

Responses from 35 states (including Puerto Rico) were received. The participants included: AK, AR, AZ, CA, CO, DE, FL, GA, HI, IA, IL, IN, KS, LA, MD, MN, MO, MS, NC, ND, NH, NJ, NY, OH, OR, PR, SC, SD, TN, TX, UT, VA, WA, WV, and WY (see Figure 2-1). The results show fairly good coverage of the entire country. The results from standard bridges and special bridges show the difference in load specifications for bridge projects of various scales. Additional load effects expressed by the participating states and territory are also plotted on the map.

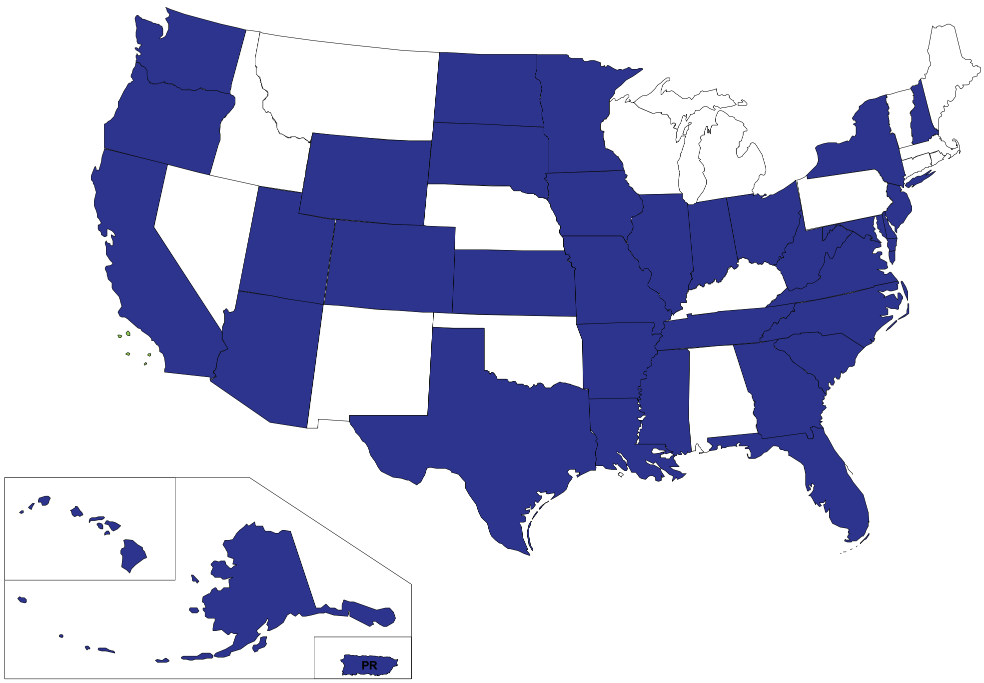


Figure 2-1 Responses received from states shown in blue

Section 3

Survey Results and Analysis

In order to provide a clear statistical presentation to aid further analysis, a score is given to each answer: 100 points are given to the answer “3” (always design for), 50 points are given to the answer “2” (considered), and 0 points are given to the answer “not necessary.” This put all the statistical parameters into a 0-to-100 scale for easy comparison. With a simple average, a ranking on the significance of each extreme load or combinations is made. In Figure 3-1, the average scores are shown in an order from high to low. Scour, wind, and collision loads are consistently high in rank. Earthquake, debris flow, and storm surge are the runner-ups. For concurrent extreme load effects or design conditions, the combination of scour with a few other extreme loads, such as wind, vessel collision and debris flow, are among the most considered. While fire is one of the major causes of bridge collapse, it is not common to design bridges to resist this hazard.

Figure 3-2 shows the ranking using the same averaging technique for special bridges. The overall trend remains similar, while minor changes in order can be observed. For example, earthquake is considered to be a greater concern for standard bridges than it is for special bridges in comparison to vessel collision.

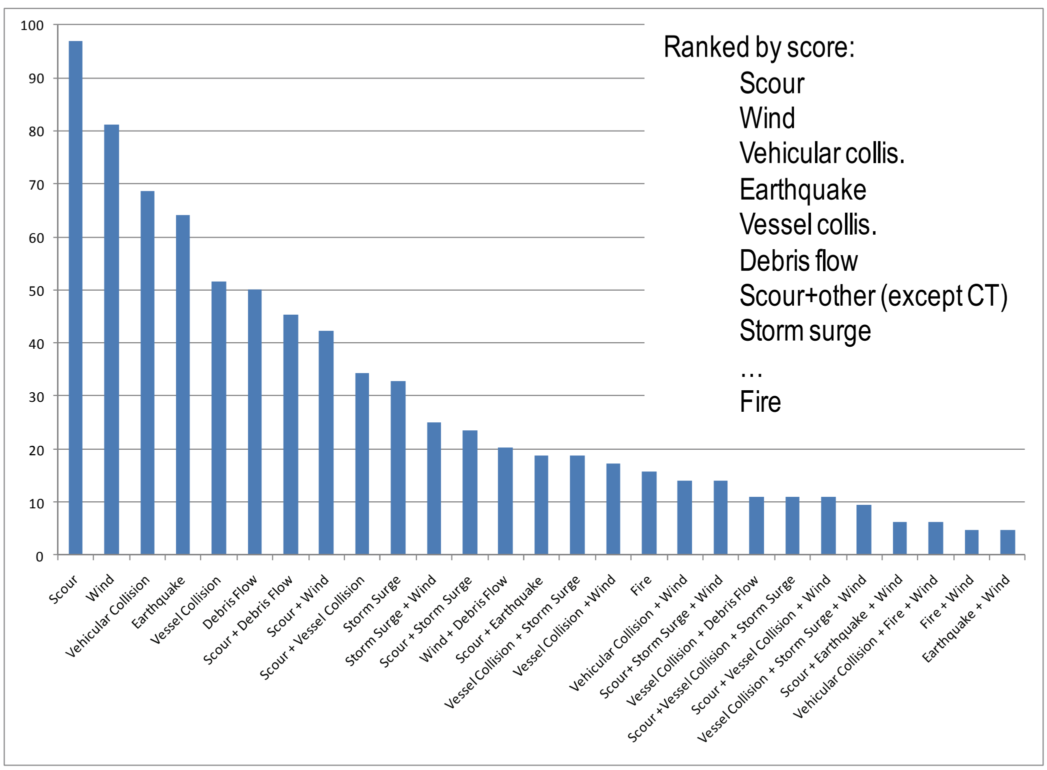


Figure 3-1 Rankings for extreme loads (standard bridges)

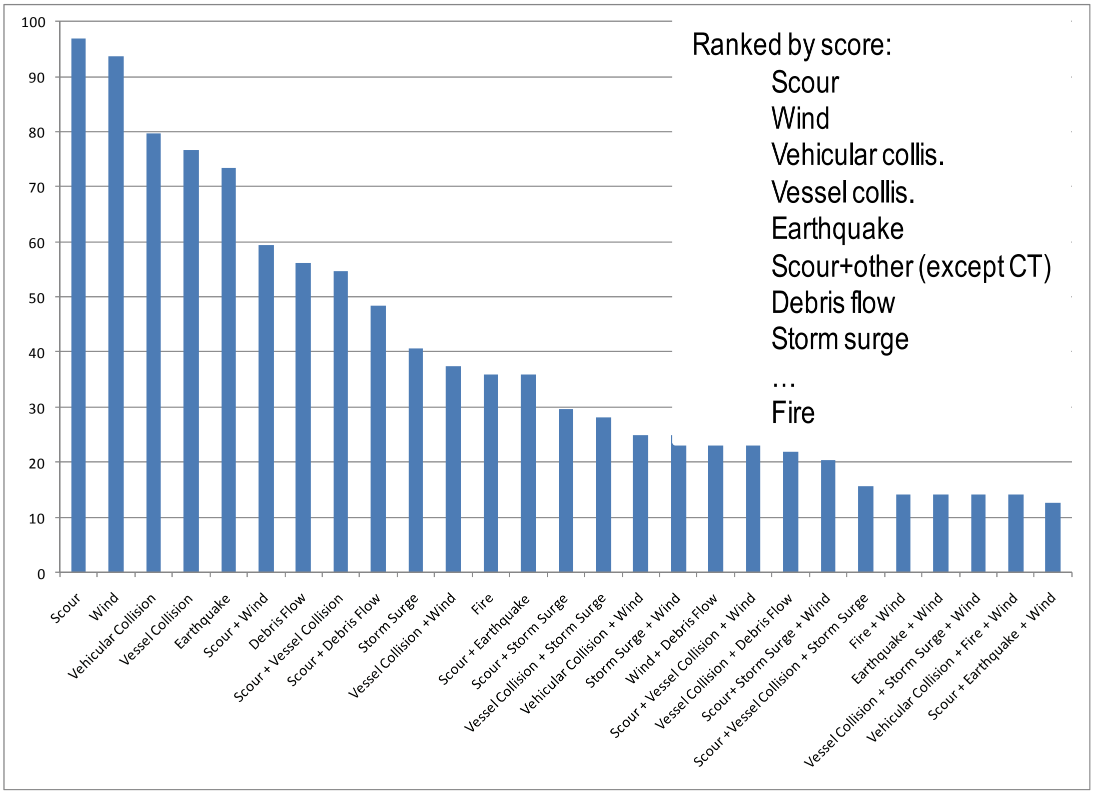


Figure 3-2 Rankings for extreme loads (special bridges)

Additional comments from participants also provide significant guidance perception on what may be missing in the original questionnaire or what may need further clarifications. A very brief summary is shown below:

Extreme loads related to bridge type/function

- Logical relation among the concurrent or cascading events is important.
- Only long span bridges are subject to vessel collision.
- Assume greater wind load than normal design (extreme vs 1.4WS50).
- Typical 2-span bridges CANNOT be over navigable waterway. They are therefore in a different group than longer bridges in vessel collision consideration.

Concerns of design complexity and cost

- Avoid designing for very rare concurrent events.
- Design guidance for scoured bridge is needed. Current design is not probabilistic and lack of basis in combination with other loads.

- Normally, bridges only need to be designed for controlling event in the concurrent or cascading sets. One load often dominates design for concurrent loads.

- Complexity in design specifications is undesirable.

- Current scour design is too conservative. NCHRP 489 is helpful in reducing this effect.

- In practice, multi-hazard design is sometimes only used for special bridges.

- Concurrent or cascading events should be considered for high-priced projects.

<u>Classification/definition</u>

- Short-span and medium-span bridges may have different concerns. Using a single category of short-medium span may not be sufficient.

- Regional boundaries may be different from state boundaries.

- Cascading is described as initial event(s) weakens the bridge.

- Another potential definition for cascading is that the occurrence of one load increases the likelihood of another.

- Scour is considered both a part of concurrent events and a leading event of cascading events in some responses. One may consider the initial weakening of a bridge foundation due to storm surge or scour, which then makes the bridge more vulnerable to a vessel collision happening some time later before repairs to the damage caused by storm surge can be made.

- Debris Flow is interpreted as (1) loads from debris raft or as (2) gravel/mud movement that impacts bridge pier or abutment.

- Structure type, ADT, detour length are factors in design against one or more extreme loads.

- Special bridges are those having expected life >75 yr.

- Wind, surge, tsunami, hurricane may not be clearly distinguished in definition.

<u>Mitigation methods that are not in design</u>

- Bridges are often closed, shored, or repaired between cascading events.

- Some of the answers “2” mean the problem is eliminated by design or avoidance

- CT+Fire is a likely case but design target and mitigation approaches against fire are usually not addressed in design. Potential mitigation includes:

- Providing adequate redundancy to the structural system to avoid collapse in case a member is lost due to fire.
- Providing adequate standoff of traffic from vulnerable members.
- Considering bridge location and emergency crew response time vs. member exposure time to fire.
- Fire resistant coatings.
- Fire suppression system.

<u>Recommended actions</u>

- A survey of actual multiple events should be undertaken.
- Redundancy is an important factor in LRFD calibration.
- Light rail on special bridges and train collision may be considered.
- Blast is an important concern for several states.
- More parameters need to be provided to vehicular collision.
- Consider adjusting or reducing reliability index (beta) for concurrent/cascading events

<u>Additional comments for scour design</u>

- Case study based on results from investigation.
- Extreme scour (500-year event) is used with extreme limit state; design scour (100-year event) is used with strength and serviceability limit states.
- Foundation geometry is checked by HEC-18 provisions.
- Effect of ice or debris raft on scour may need consideration. Example for combining with CV:

  a. 75 percent of the short-term scour computed for the 100-year event and 75 percent of the long-term scour, using a fully loaded, 15-barge flotilla and tugboat.

  b. 100 percent of the short-term scour computed for the 100-year event and 100 percent of the long-term scour using a drifting, empty, single barge.

  Example for combining with ice:

  a. 75 percent of the short-term scour computed for the 100-year event

  b. 100 percent of the long-term scour.

- A scour critical elevation is shown on the plans for use by bridge maintenance and inspection personnel in monitoring of the bridge foundation for possible future mitigation.

- The scour depth used for all cases is the sum of the channel scour plus the local contraction scour.

- Scour is normally not required to be combined with earthquake load (Extreme Event I). When it is considered, following methods have been used:

  a. For the functional evaluation earthquake design event, the full scour from the design flood (100-year event) is used. For the safety evaluation earthquake design event, half of the scour obtained from the design flood (100-year event) is used.

  b. When scour is considered with the Extreme Event I limit state, the soil resistance up to a maximum of 25% of the scour depth for the design flood event (100 year) is deducted from the lateral analysis of the pile or shaft. The loss of skin resistance for the full scour depth for the design flood is considered when checking axial capacity of the shaft for all strength and service limit states. The loss of skin resistance for the full scour depth of the check flood (500 year event) is considered when checking the axial capacity of the shaft for Extreme Event II limit states.

- Many practices are under the condition of "where economical."

- Criteria for existing bridge may be lower than those for new bridges.

- Piles may be designed for scour condition if necessary.

- Abutment may be protected by countermeasures.

3.1 General Observations

In Figure 3-3, the answers for standard bridges are tallied and plotted in pie-chart format for each extreme load. These charts display very similar information in a different format than that shown in the first part of Figure 3-1. However, they show the differences in the composition of the answers. For example, the Earthquake load and Vehicular Collision receive similar average scores, but the Earthquake load receives more "Always" (3) and "Not Necessary" (1), which evens out to make the average scores similar to that of Vehicular Collision with a majority of answers being "Considered" (2). This specific difference may be a result of some extreme loads being more localized than another, as suggested by some participants during the workshop after the survey. In the discussion, Debris Flow was raised as an example for which the answer of "Considered" (2) may represent some bridges within one state that definitely need to consider Debris Flow in design while others in the same state do not need to consider it at all. This is because the susceptibility to Debris Flow is strongly influenced by the bridge site condition and is often either very important or very unlikely. This is different from the case for which one extreme load is "somewhat important" to all bridges in one state.

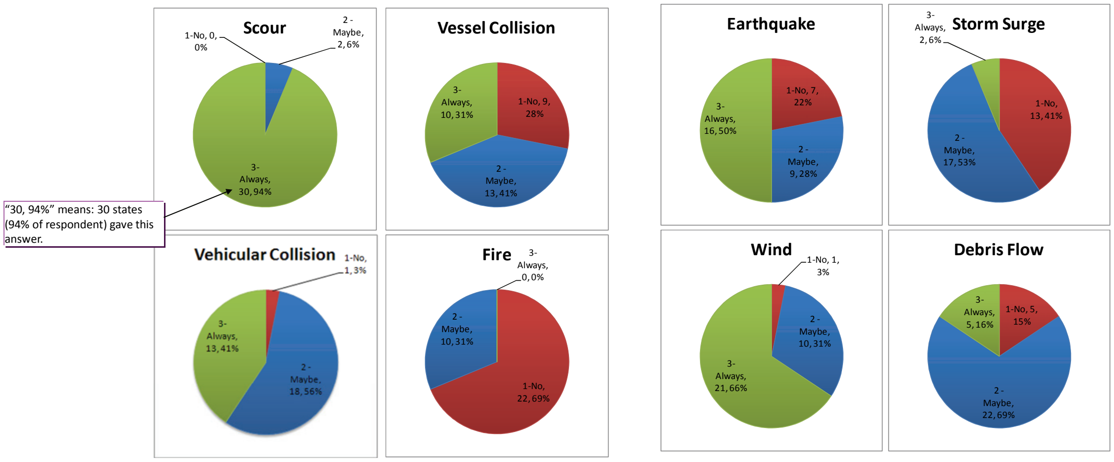


Figure 3-3 Ballot counting for standard bridges

The rankings shown in Figure 3-1 and Figure 3-2 provide a general sense of urgency relevant to each individual or combination of extreme loads. A few phenomena are noticed:

1. Scour is persistently the top hazard for bridges.

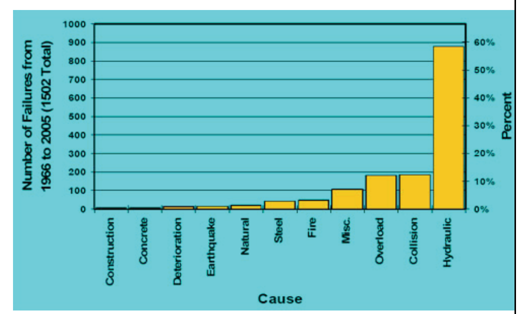
2. Combination of scour and another extreme load is often important.

3. Fire has low scores although it can be a major cause of bridge collapse.

The rankings are compared with bridge failure data from two bridge failure databases in Table 3-1. These bridge failure databases are composed to cover nationwide events with emphases on specific states. The database by Harik (Harik et al, 1990) focuses on Kentucky, while the NYS database focuses on New York State. In this comparison, fire/tanker explosion stands out to have the greatest difference between the design consideration and the level of threat. In the survey results, fire is less a design consideration than any individual hazard. However, in both databases, fire is one of the top causes of bridge failure by extreme events, next to scour and collision. It can also be found that overload has an effect comparable to extreme events. However, it is not even considered in this survey questionnaire, and no objection has been raised because of that. In the statistical sense, extreme overweight truck events are just the rare events in the high intensity tail of the probability distribution of trucks. It is a part of the regular live load and therefore not considered part of the extreme load survey. It shows that the extreme effect from all time-varying loads may need to be considered in the same context for MH-LRFD. A relevant observation is that the live load is part of the significant load combinations that require immediate attention as noted by the workshop participants. The combination of live load with other extreme events requires the study of both regular intensity and extreme overweight situations.

The workshop participants urged that care be taken on the time scale when a failure database is used. The year the collapsed bridge was built and the specifications it used are factors that contribute to the cause of collapse. Certain failure modes may not be applicable anymore after specific revisions in the design specifications.

Table 3-1 Comparison between survey results with bridge failure

This survey--Standard	This survey--Special	79 bridge failures during 1951-88 (Harik et al, 1990)	New York State Collapse Database
Scour	Scour	19 by ship collision	**NYS**
Wind	Wind	11 by truck collision	Hydraulic: 82
Vehicular Collision	Vehicular Collision	8 by flood	Collision: 37
Earthquake	Vessel Collision	6 by scour/erosion	Overload: 33
Vessel Collision	Earthquake	6 by train collision	Misc: 11
Debris Flow	Scour + Storm Surge	6 by age	Misc. Deterioration: 9
Scour + Debris Flow	Debris Flow	4 by fuel-tanker trucks exploding or burning next to bridges	Steel/Deterioration: 7
Scour + Wind	Scour + Wind	4 by soil and debris	Concrete/Deterioration: 4
Scour + Vessel Collision	Storm Surge	3 by wind	Construction: 4
Storm Surge	Vessel Collision + Storm Surge	2 by freeze	Nature: 4
Storm Surge + Wind	Fire	2 by multiple natural hazard	Fire: 3
Scour + Storm Surge	Scour + Vessel Collision	2 by overweight	
Wind + Debris Flow	Scour + Earthquake	1 by blasting	**Nationwide**
Scour + Earthquake	Scour + Debris Flow	1 by earthquake	
Vessel Collision + Storm Surge	Vessel Collision + Debris Flow	4 by other	
Vessel Collision +Wind	Scour + Vessel Collision + Wind		
Fire	Storm Surge + Wind		
Vehicular Collision + Wind	Earthquake + Wind	**Short-span bridge failure not reported nationally**:	
Scour+ Storm Surge + Wind	Vessel Collision +Wind	21/33 by overweight	
Vessel Collision + Debris Flow	Scour+ Storm Surge + Wind	5/33 vehicular collision	
Scour +Vessel Collision + Storm Surge	Fire + Wind		
Scour + Vessel Collision + Wind	Scour +Vessel Collision + Storm Surge		
Vessel Collision + Storm Surge + Wind	Scour + Earthquake + Wind		
Scour + Earthquake + Wind	Vehicular Collision + Fire + Wind		
Vehicular Collision + Fire + Wind	Vehicular Collision + Wind		
Fire + Wind	Vessel Collision + Storm Surge + Wind		
Earthquake + Wind	Wind + Debris Flow		

Similar rankings are given for cascading events in Figures 3-4 and 3-5. There is some difference in ranking between the standard bridges and special bridges. But the most significant feature is that those cascading events with higher scores include leading event(s) and subsequent event(s) that have clear correlation with each other. For example, vehicular collision often leads to fire (Ranking#1), an earthquake is normally followed by aftershocks. While a vehicular collision does not lead to another vehicular collision, the location where it occurs once is likely to have certain roadway geometry or bridge clearance that is prone to attract traffic incidents.

There is currently no clear provision on how to manage cascading effect. The significance of the cascading effect and a potential research approach need to be further studied. From one perspective, scour combined with another hazard may be considered as cascading events. However, they would be considered concurrent if the definition here is used. Figure 3-6 shows two examples for the events that can be considered cascading under this definition.

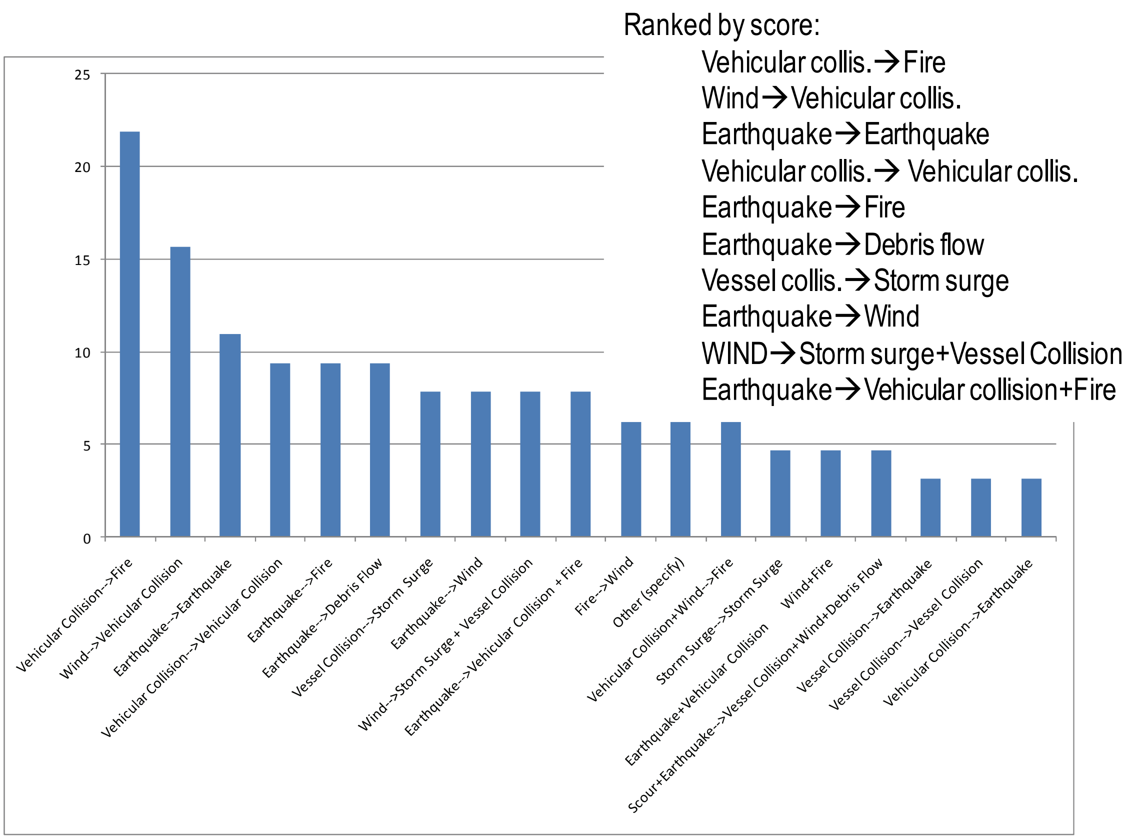


Figure 3-4 Average scores for cascading events (standard bridge)

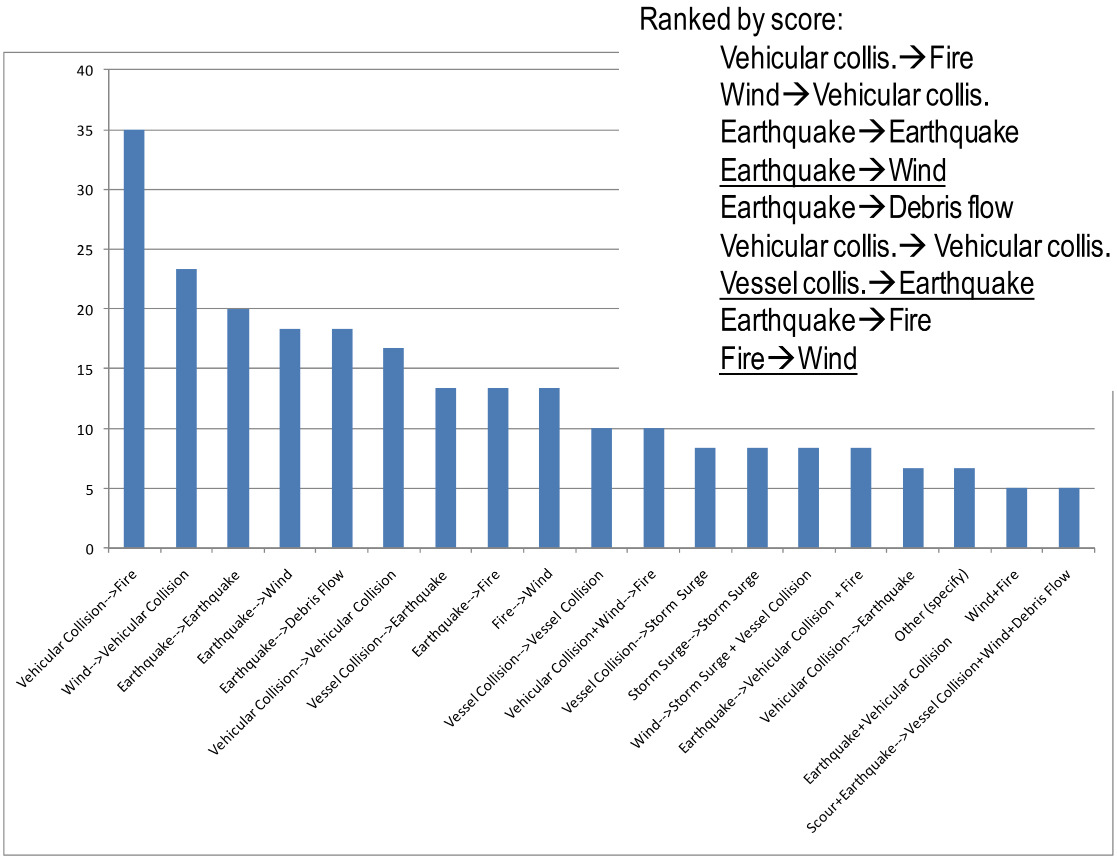


Figure 3-5 Average scores for cascading events (special bridge)

Bridge performance or environment during an extreme event is affected by a previous event.

Changing stream condition after earthquake that affect scour

Reduced column capacity after debris flow

Figure 3-6 Events meeting the definition of cascading events

3.2 Correlation to Bridge Site Characteristics

Survey results are clearly linked to geographic features. Coastline and inland waterways are related to storm surge and vessel collision. An exception is found for the two states enclosed in the yellow dashed line (Figure 3-7), where there is no coastline or significant navigable waterways. The authors followed up to verify the intent of this seemingly illogical response. Based on the follow-up communication (Thompson, 2011), these states do indeed consider these loads, though they are not expected to control the design. Article 3.4.1 of the LRFD bridge specification states that all relevant load combinations shall be applied, so the states in question were just stating that they routinely apply that provision of the specification. Engineers in all states employ their best judgment in the application of the specification when considering potential load cases.

The “Scour+Debris Flow” concurrent events are considered a significant design issue in the Rocky Mountain and Great Plains states. They are roughly along the paths of the Kansas River and Mississippi River (Figure 3-8). The occurrence of certain combinations is dominated by the occurrence of a relatively rare event with the other frequent and/or long-duration event “waiting” there. An example is scour and vessel collision. While nearly all states consider scour as an important extreme load/condition, those who consider vessel collision as somewhat or very important generally believe the combination of the two needs consideration (Figure 3-9). “Vessel Collision+Storm Surge” is considered in coastal states and areas with considerable ship traffic (Figure 3-10).

Some states with no clear geographical or environmental similarity gave similar answers. This phenomenon can be found in the survey response for vehicular collision and earthquake (see Figure 3-11a). Truck traffic goes through all states regardless of the seismic hazard intensity and frequency. It is also not very likely that seismic activity would significantly increase the frequency of vehicular collision. The pattern of significant seismic concern on the map shows much resemblance with that of the significant vehicular collision consideration. Earthquake is of no surprise critical to the west coast and New Madrid area. But the mid-Atlantic and northeast states also treat it as a significant threat, although seismicity is very low in this area. It can be found that these are the states with very high population density and traffic volume. The elevated seismic consideration may be because the stakes are very high (due to the high population/ADTT) in this area for any loss caused by earthquakes. The lower right figure shows the average score on all single extreme events for typical bridges. Some states simply have significant threats (e.g., CA, OR, SC, MS), while some are being more cautious due to low tolerance (e.g., northeastern states). Figure 3-11b shows the truck traffic volume on interstate highways. It can be compared with Figure 3-11a to show that the design consideration is a combined decision of extreme hazard intensity/frequency and consequence measurement.

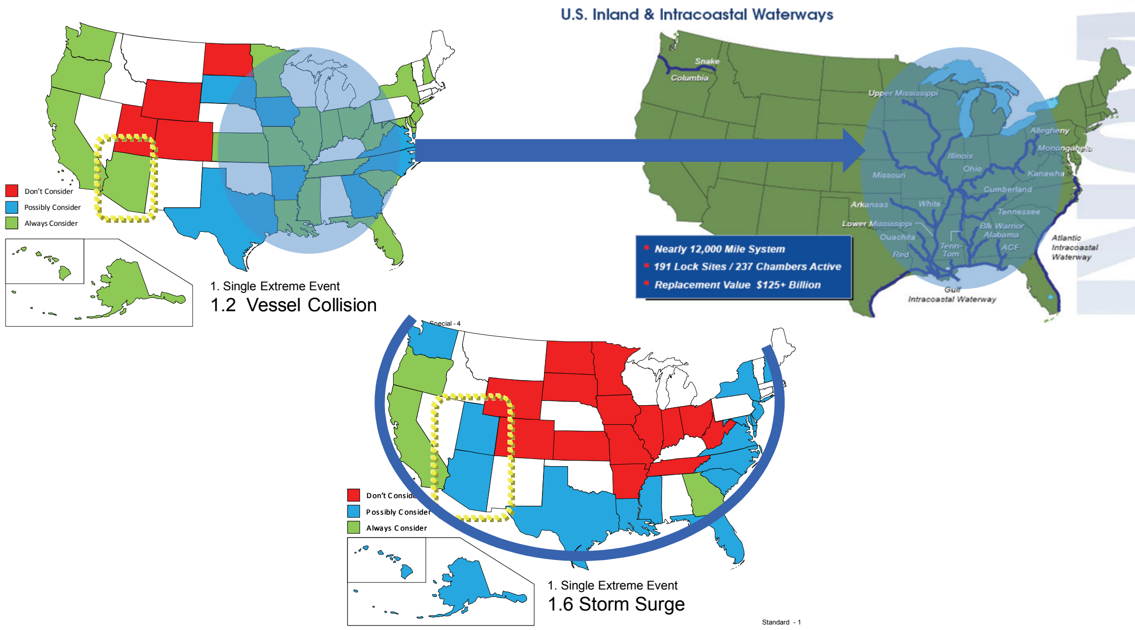


Figure 3-7 Regional character: navigable waterways and coastlines

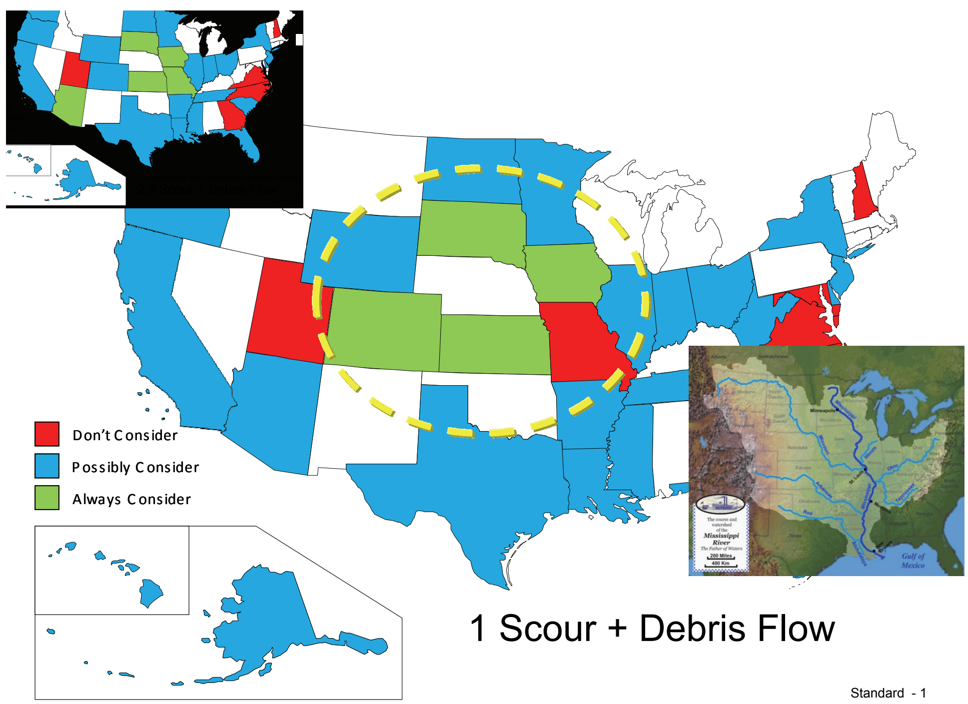


Figure 3-8 Combination of scour and debris flow

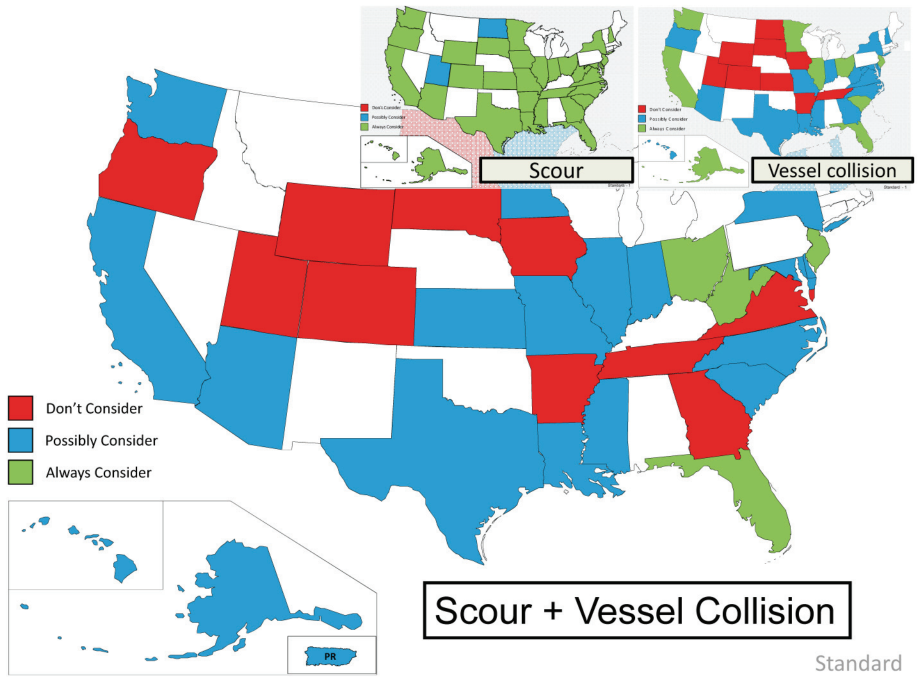


Figure 3-9 Comparison between scour, vessel collision, and scour+vessel collision

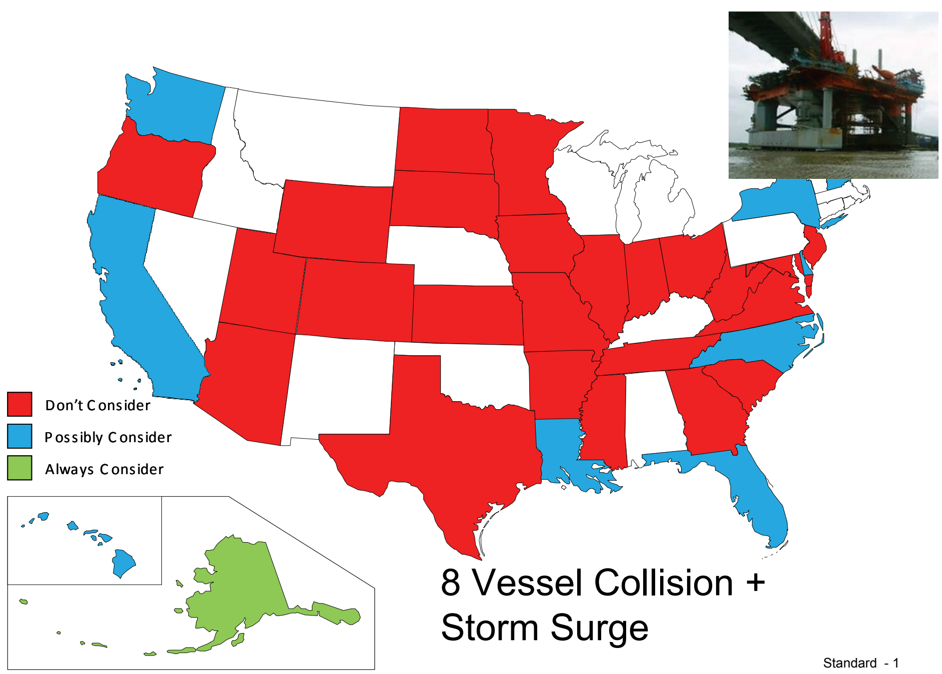
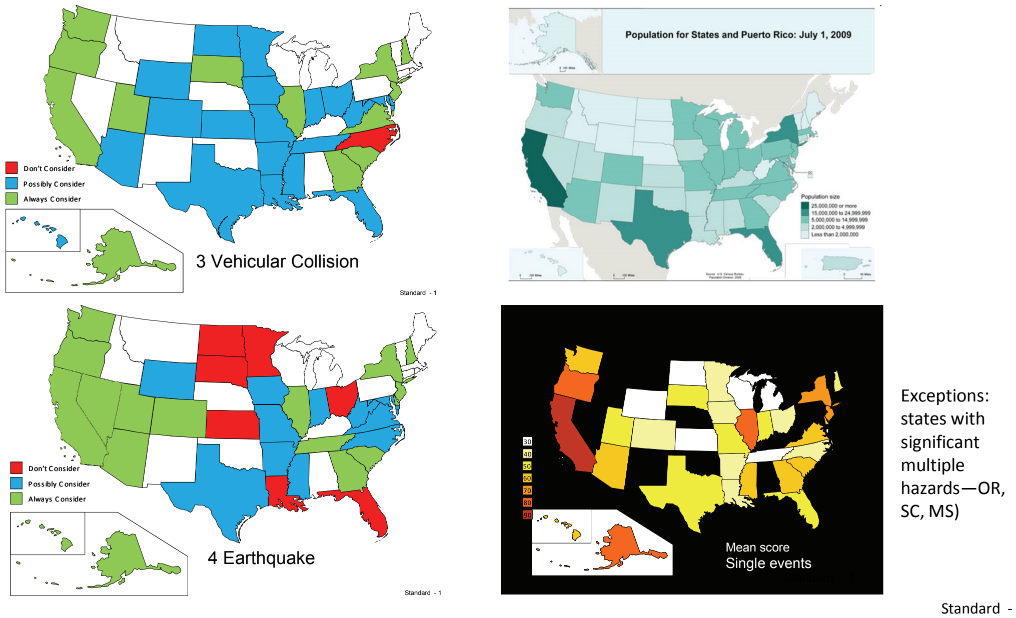
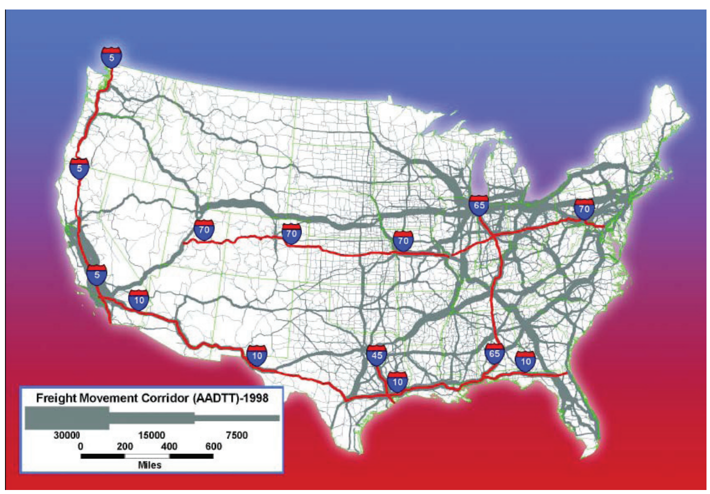


Figure 3-10 Maritime transportation volume and coastal storms



(a)



(b)

Figure 3-11 Non-natural environment factors (Mallett et al., 2006)

In order to provide more profound information to the development and simplification of the MH-LRFD, additional statistical parameters were studied. The correlation between responses from different states provides a basis that supports the classification of bridges. In Figure 3-12, the values of the correlation are plotted in color code. It helps to illustrate the similarity among different areas that may not be obvious from the raw data. The value of correlation can be from -1, which means the serious concerns in one state is never a concern of the other, to 1, which means the two states have exactly the same design considerations. In the figure, darker blue indicates a value close to unity, while gray to black are lower values. Yellow to orange colors are negative values as shown in the legend. In general, most areas of this plot exhibit positive values, indicating a basic similarity in bridge design considerations in the entire country. The diagonal line from the upper left corner to the lower right corner represents correlations of each state to itself, which is always one. The plot is symmetrical on two sides of this line. The upper-right half is a mirrored image of the lower-left half.

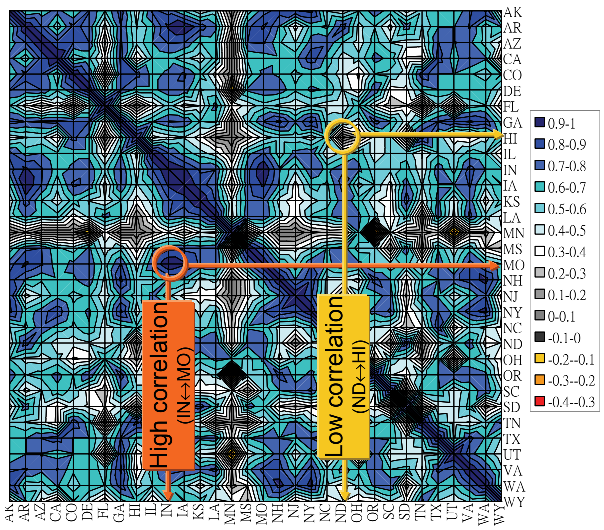


Figure 3-12 Correlation between states (single events)

The order of states can be rearranged to group states with high correlation values. Figure 3-13 shows such a process for single events. The target is to move the high values (blue) to areas near the diagonal line (axis of symmetry) and low values away from the line. In this illustration, this was done manually and the result may not have been optimized. If further study along these lines is deemed necessary, an automated process could be developed. The manual process resulted in a grouping shown on the right of Figure 3-13. When it becomes difficult to further compact high-correlation states, a few groups become visible in the graph. These groups are shown with color code in Figure 3-14. The table in Figure 3-14 shows the average correlation among groups. The diagonal cells from the upper left corner to the lower right corner presents the average value of correlations among states in each group. The off-diagonal terms are correlations between different groups. Good quality of the grouping can be seen from high values in diagonal cells and low values in off-diagonal terms. The results may be different if concurrent events, cascading events, or all events are used. Further study may be conducted if deemed desirable.

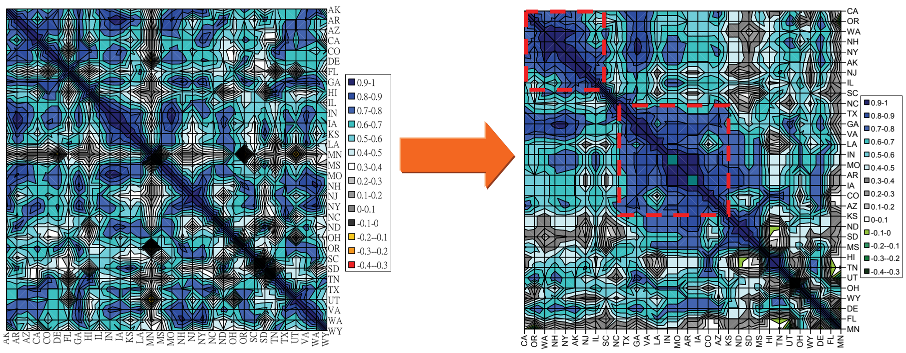
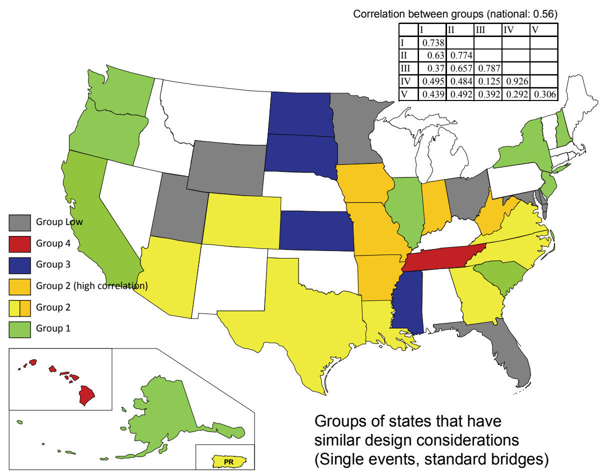
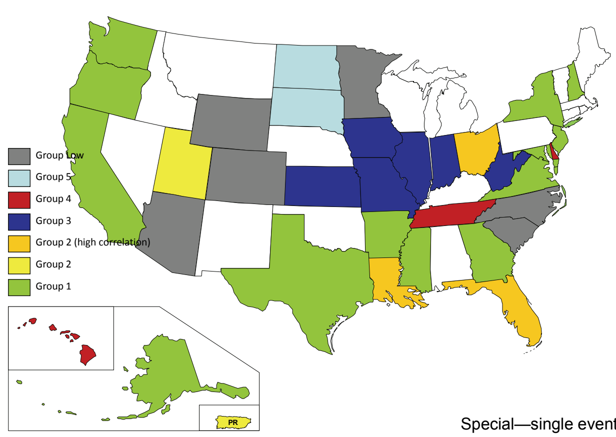


Figure 3-13 Regrouping states based on correlation (single events)



	I	II	III	IV	V
I	0.738				
II	0.63	0.774			
III	0.37	0.657	0.787		
IV	0.495	0.484	0.125	0.926	
V	0.439	0.492	0.392	0.292	0.306

(a) Standard bridges, single event



(b) Special bridges, single event

Figure 3-14 Grouping of states by survey results

The analysis of the survey response represents a combined effect from many factors. In addition to the natural environment, geographic features, and geological conditions of each state, it also involves experience in practice, engineering judgment, economical concern, past catastrophe, local public opinion, and potentially other engineering/non-engineering issues. The intention of developing any definitive conclusion for the complex results with such limited data would prove futile. However, the results can be a significant aid in developing a practical formulation of a probability-based design methodology from analytical development. It is apparent that the statistics provided above are the results of interwoven site characters and do not explicitly illustrate the rationale of a potential design strategy. They need to be combined with knowledge of various technical and non-technical factors to extract consistent guiding principles in comparison and mitigation of extreme loads in the scope of this study. The relevant geographical, geological, and meteorological settings are discussed in the next section for cross-referencing with survey results.

Section 4

Interpretation with Respect to Physical Environment

The natural environment including terrain, waterway character, weather, and seismicity are considered to cross-examine the results of the survey and to even out any potential bias from the survey data. Economic characteristics, local policies, and human habitat styles can be significant factors as well. For the purpose of establishing the design framework, a natural setting is first considered. Non-natural factors are not less influential to highway bridge design. Traffic specifications, socio-economical considerations, political environment, aesthetic requirements, and historical conventions can be an important part of determining design requirements. While these factors are embedded in the results of this survey, thorough discussion will not be included to avoid distraction from potentially unresolvable issues.

4.1 Earthquake Load

In earlier seismic design (e.g., Division I-A), the seismic load is measured primarily on the peak ground acceleration of a fixed (approximately 500-year) return period. Recent design and retrofitting guidelines started using multiple return periods and short/long-period response spectra values to better capture the seismic activities in different regions. Comparing the design by AASHTO Seismic Guide Specifications (lower left map in Figure 4-1, 1000-year return period) and that by the NCHRP 12-49 recommendation (lower right, 2500-year return period), some inland areas of the western U.S., the New Madrid zone in the midwest, and South Carolina are found to have high long-term seismic risk comparable to California, while short-term high seismic activity is only found on the western seashore. With such variation in seismicity, the bridge design strategy may be different. The classification shown in Figure 4-2 may be used as a simple characterization of seismic load effect of the bridge site. The central and eastern U.S. has a distinct seismic activity pattern when compared to the western U.S. Some areas in both regions have very high long-term seismic risk (labeled “2” on the maps) and therefore stand out from the rest of the areas.

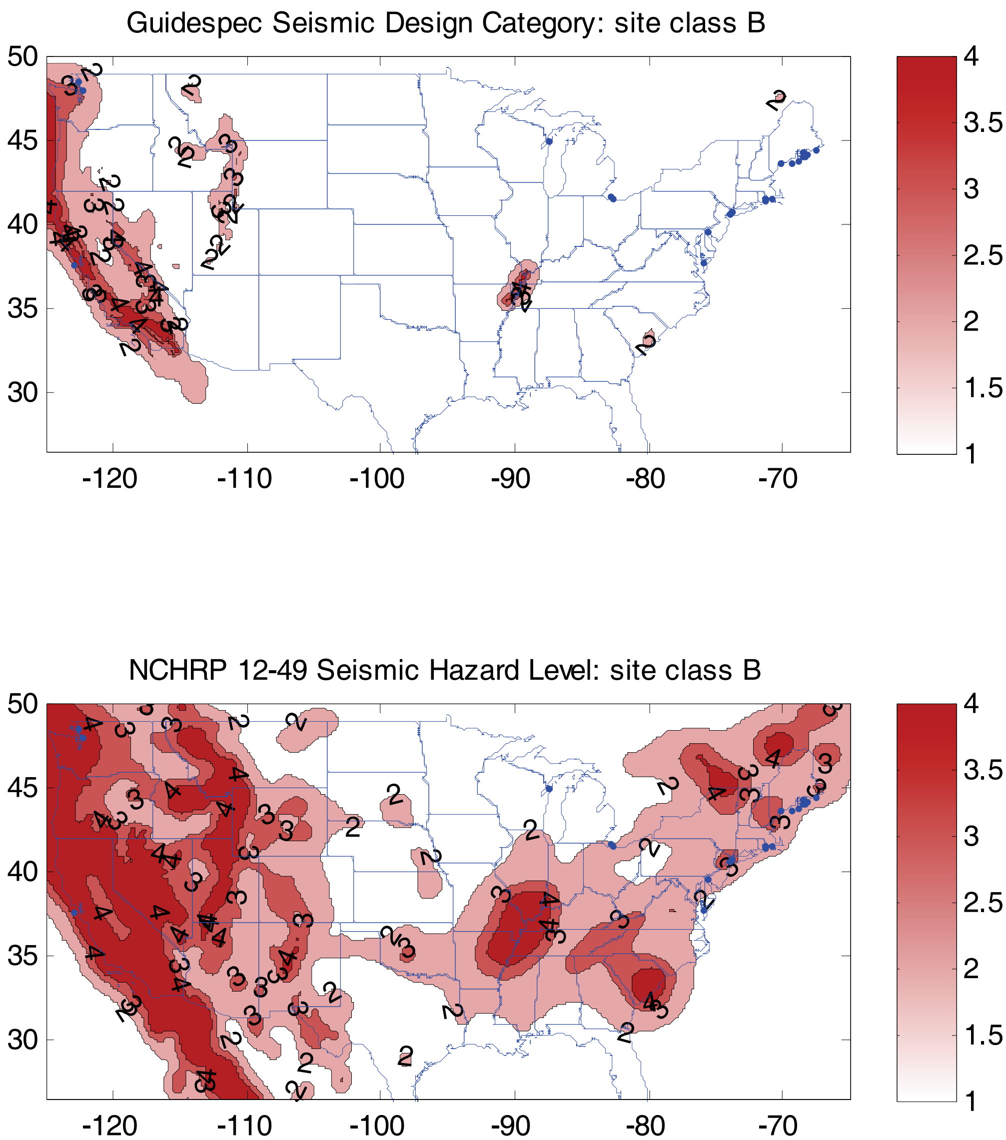


Figure 4-1 Short-term and long-term seismicity

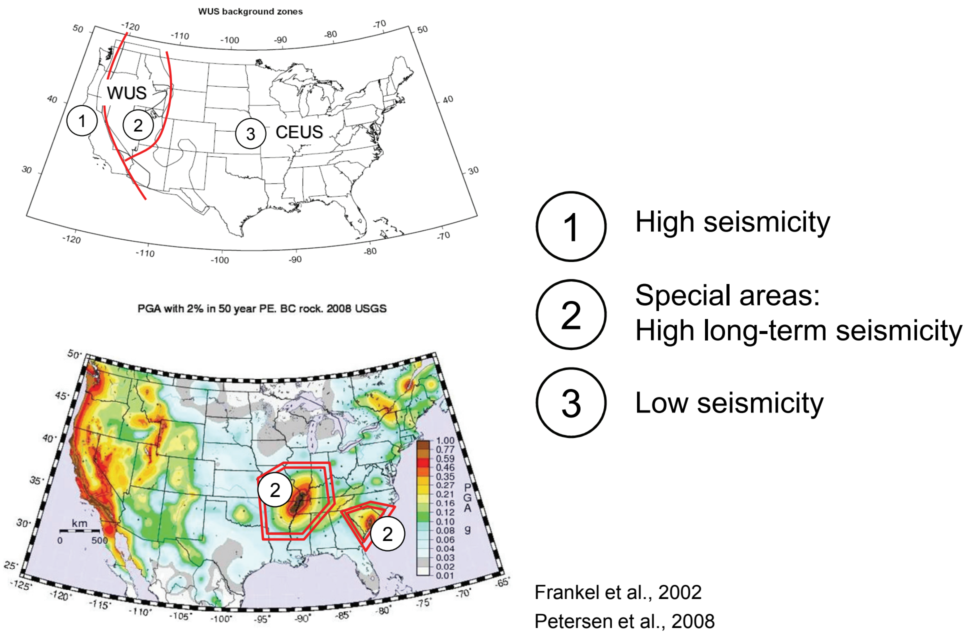


Figure 4-2 Potential classification by seismicity

4.2 Wind Load

Bridge design against non-hurricane wind load is governed by the map adopted by ASCE 7-88 (ASCE, 1988). Recent design procedures tend to use updated 3-sec gust map, but such conversion has not been made in AASHTO formulas. Either map includes a lower wind velocity zone in the Pacific seashore and a large uniform wind velocity area in the inland region. The east coast has a variety of high wind velocity specified by the map (Figure 4-3).

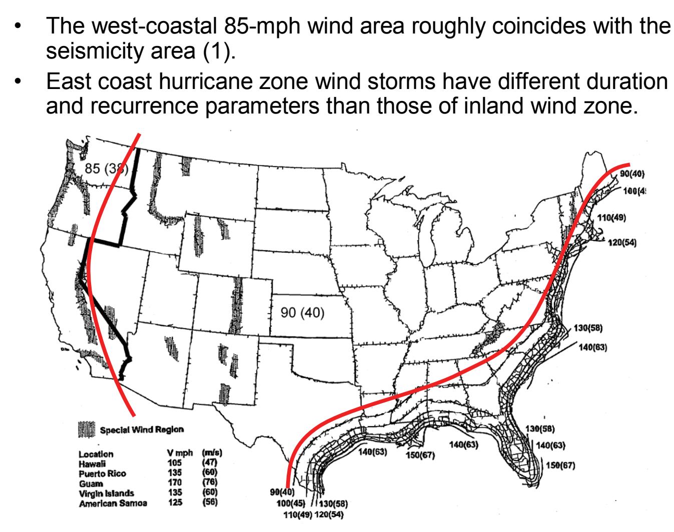
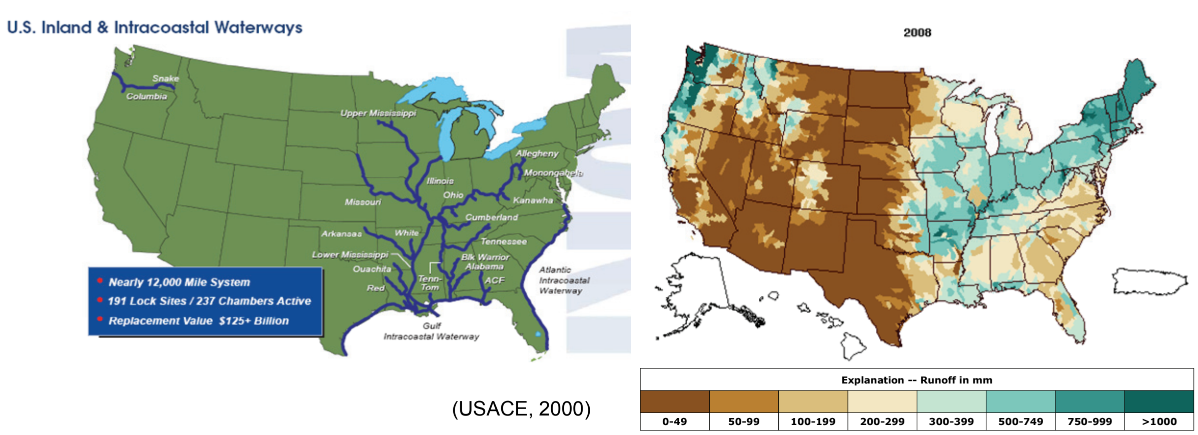


Figure 4-3 Wind load regions

4.3 Scour and Vessel Collision

Ship and barge traffic is critical to the calculation of vessel collision loads. The effect is more localized to the specific navigable waterways under a given bridge. Standard bridges with a small number of relatively short spans do not normally need any consideration for vessel collision. Only a limited number of bridges, mostly in the category of special bridges, would need to be designed for vessel collision. The AASHTO vessel collision design considers the number of vessel traffic, size/weight of vessels, channel geometry, vessel geometry, and current of the water. Such data can vary significantly for different navigation channels, and even different sections on the same water body. For research purposes, the part of the U.S. that utilizes considerable aquatic transportation can be identified by the passage of major navigable inland water bodies or adjacency to shorelines. Figure 4-4a shows the major navigable water in the U.S. A clear distinction between the different terrain of Rocky Mountains and the Great Plains keeps all major aquatic transportation in the Midwest area.

Bridge hydraulics is also specific to the site and does not fit any regional boundary. While rivers in the mountain area have greater potential energy that speeds up erosion, the higher precipitation in the eastern U.S. also contribute to significant scour potential (Figure 4-4b). This is consistent with the survey finding that scour hazard is uniformly high across the country.



(a) (b)

Figure 4-4 Inland waterway and hydraulics

4.4 Classification

Extreme and non-extreme loads are specified with various levels of variation for different bridge sites. Current AASHTO LRFD uses the following variation:

- Traffic load: uniform geographically), only varies with structural system (HL-93).
- Wind load: one parameter mapped.
- Earthquake load: two mapped spectral values (Guide Specifications).

- Vessel collision: customized for individual bridge site.
- Scour: governed by local hydrological study and 2 return period.
- Vehicular collision: a constant force for all conditions, based on very limited data.

Much of such variation is a result of experience and studies in recent years. Seismic load was changed from basing on one mapped value (PGA) given by Division I-A to two mapped spectral values given by the guide specification. The *Guide Specification for Vessel Collision Design* (AASHTO 2009a) adopted a probabilistic approach since 1991 to select boat size and collision force. Among these specifications, traffic load (HL-93) and vehicular collision (400 kip) are the ones having least variation. This does not necessarily indicate that these loads do not vary as much as others. An ongoing AASHTO survey from the Highways Subcommittee on Bridges and Structures (SCOBS) (BR-10-01 2010) revealed that 38% of the states chose to require compliance with the 400-kip vehicular collision load. The same survey also showed that 33% of states required Strength II check for a live load based on the states' own design permit truck. The detailed discussion on the rationale of such variation is beyond the scope of this study. However, it is clear that having one or more bridge site-specific parameters in the specification of extreme loads is a clear trend in the future. For this study, the classification can provide significant help in establishing a reasonably-sized set of limit states, which may greatly simplify the design procedure of MH-LRFD.

Combining natural environment and survey results, a preliminary regional boundary is presented. It can be used as a basis for establishing and simplifying limit state equations among each group of states (Figure 4-5). The regional characteristics are described below:

I: High seismicity, non-hurricane coastal wind

II: Long-term high seismicity, inland wind

III: Inland wind

IV: Hurricane zone

V: Long-term high seismicity, hurricane zone

Two phenomena observed in the survey were that: (1) two states in the north central area suggested ice load to be included, and (2) the northeastern states have similar answers with the west-most states. A line separating cold and mild temperature in the winter may be a potential addition. A special region may be needed to include highly populated states that treat all hazards cautiously due to the seriousness of consequences (Figure 4-6).

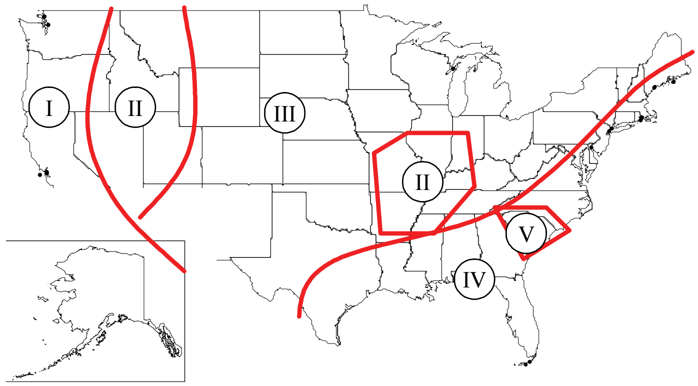


Figure 4-5 Tentative bridge site classification

Comparing the boundaries in Figure 4-5 with those in Figure 3-14(a), it can be observed that some boundaries roughly agree. The most pronounced difference is the northeastern states being in the same group with high-seismicity states. As explained earlier, this is very likely the result of high traffic volume and greater consequence from bridge failure. A special group is defined as shown in Figure 4-6 to include this phenomenon. This area not only has high traffic volume, but also exhibits great economic and political influence in the country. Based on the survey results, highway officials treat all potential hazard to bridges with extreme care and are willing to invest more capital in preventing rare catastrophic events.

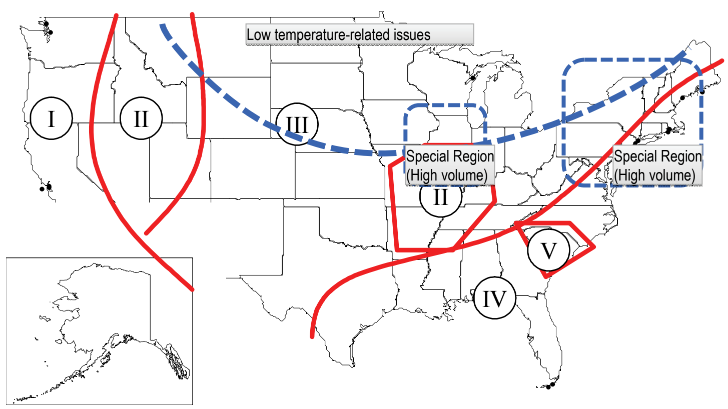


Figure 4-6 Additional boundaries from the survey results

In Figure 4-7, the average scores for single events of each region show different focus in each region. Scour is uniformly high. Regions II and III are low on vessel collision (Region II is somewhat higher for special bridges. Note that Region II includes a number of states along the Mississippi River and the Great Lakes.). Regions II and III are very low in storm surge (inland states), but high in wind. Region II is also fairly high in earthquake. Region I and the Special Region are above national average in most categories. Fire for typical bridges has very low scores. It may be caused by a lack of criteria for these apparently random occurrences and the choice of dealing with fire events by emergency response and repair.

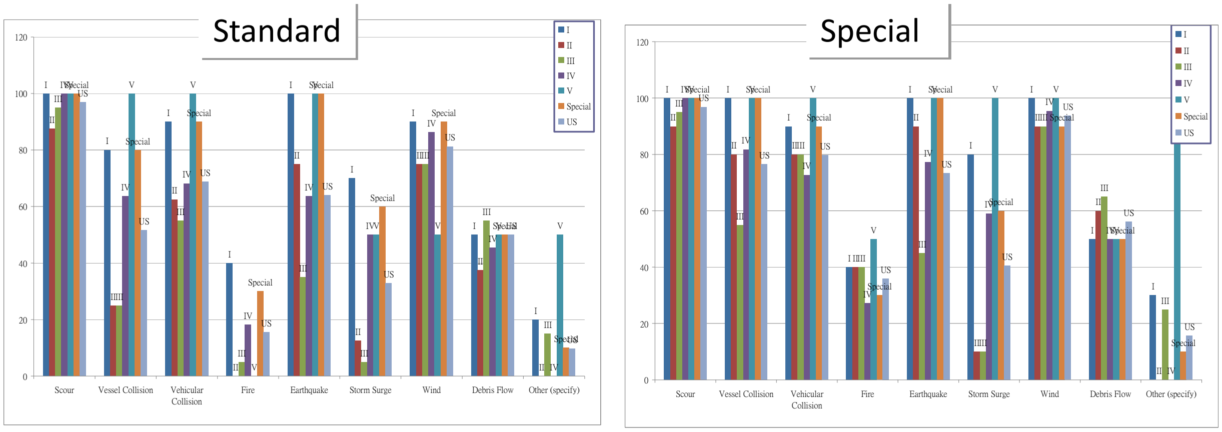
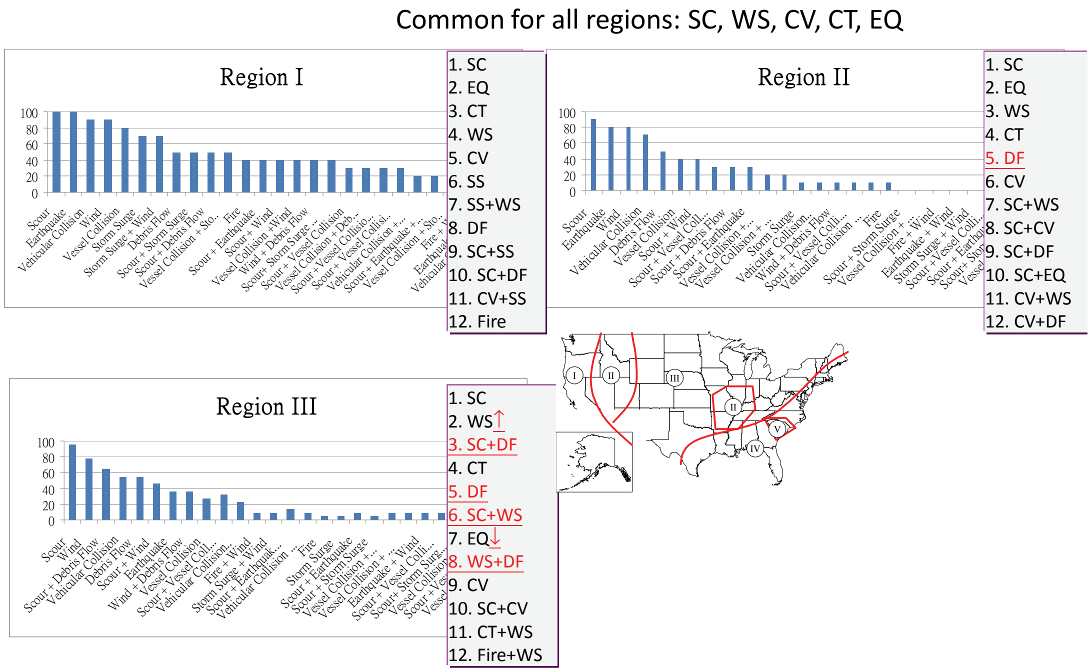


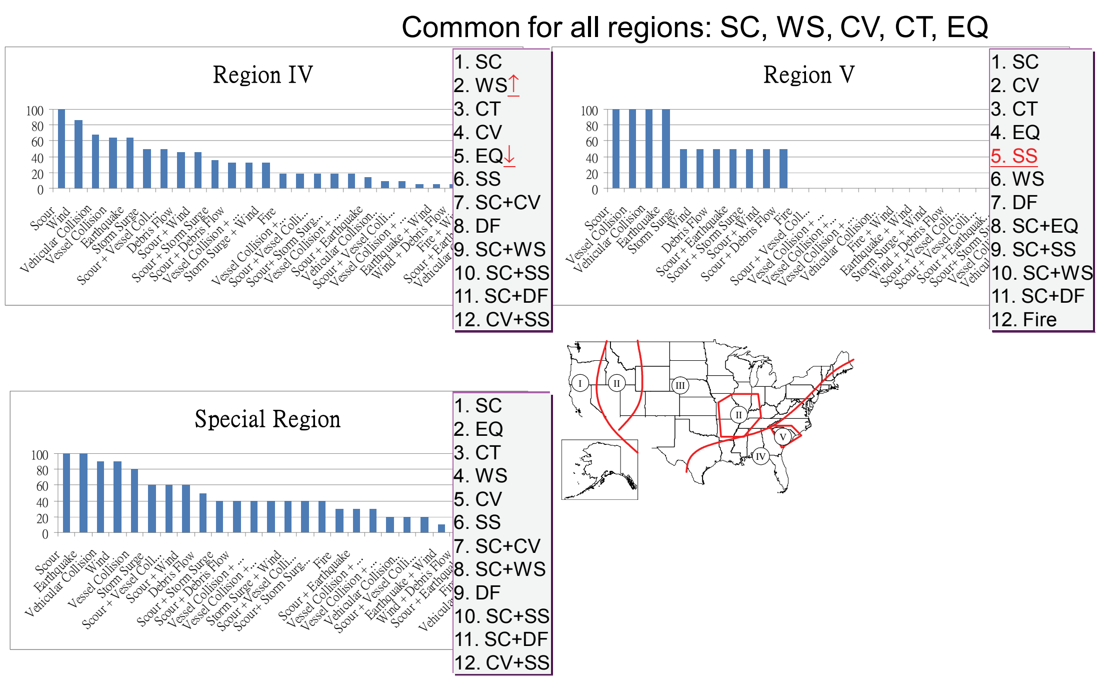
Figure 4-7 Variation among groups of states

Figures 4-8a and 4-8b show the rankings of design considerations within each region. Among the highest in all regions are SC, WS, CV, CT, EQ. Other events that stand out (reference to Region I) in each region are underlined. Debris Flow is a greater concern in Regions II and III. Wind is high wild earthquake is low in Region III. The combination of Scour+Debris Flow is the top concern for concurrent events (Region III). The Special Region has relatively low threat from natural hazards, but the result shows striking resemblance to Region I, which has many specific threats.

Figure 4-9 shows sample comparisons between typical and special bridges. Vessel Collision and its combination with others have higher scores for special bridges. As stated in comments, only special bridges can be over a navigation channel. Rare and non-related combinations such as Earthquake+Wind also move up in the special bridge category.



(a) Rankings within Region I~III (Standard bridges)



(b) Rankings within Region IV, V, and the special region (Standard bridges)

Figure 4-8 Regional Rankings

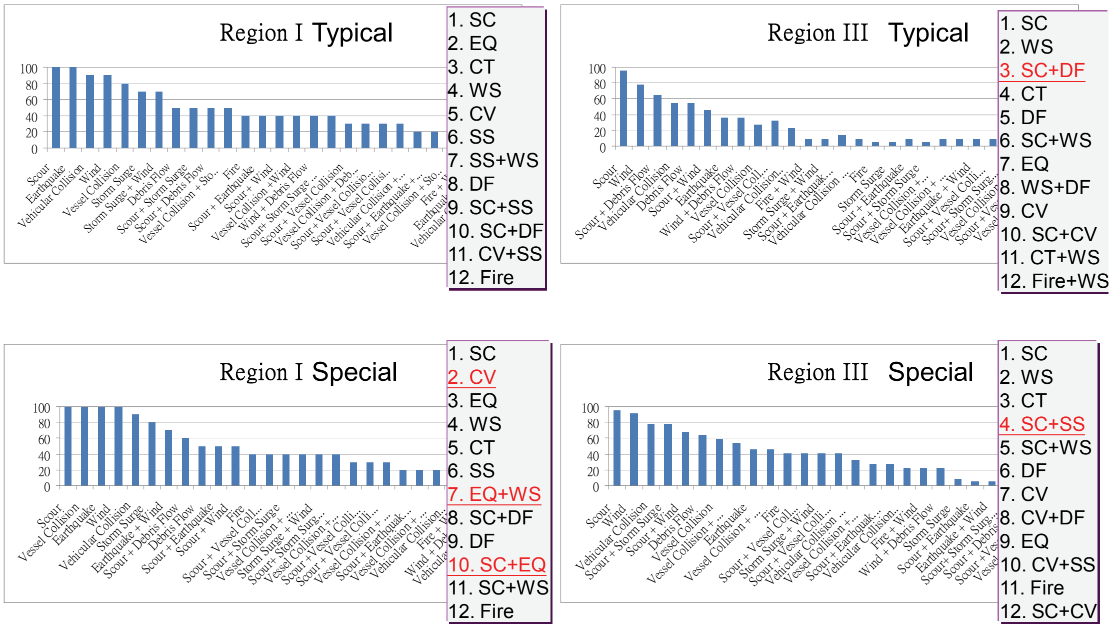


Figure 4-9 Comparison between standard and special bridges (Regions I and III)

Section 5

The Multi-Hazard Design Workshop

A workshop was organized after most responses were received and the preliminary analysis was finished. The results were presented to the invited group and further discussions were conducted on specific issues of interest to both the participants and the research team (April 26, 2010). Some concepts in the questionnaire that may not be clear to the participants were pointed out. While it was desirable to clarify some definitions, there may not always be a clear answer to these questions at this point.

5.1 Summary of Comments from the Participants

a. Some extreme loads in the survey were not very clearly or consistently defined. Examples:

    1- What is extreme wind? Is it referring to hurricane wind?

    2- Debris flow is a local phenomenon. Its condition varies throughout one state. This may impact the answers to survey.

b. In addition to design criteria, guidance on detailing against extreme loads is desirable.

c. The result of the study may be a guidance of mitigation strategy if not specifications.

d. Considering multiple extreme loads may not add to the cost because the design for one extreme load often increase resilience to another (although it can be the opposite sometimes).

e. ADTT is one of the factors that determines significant limit states.

f. Scour can have either no effect or full effect—scour line above or below bottom of footing.

g. In current practice, owners have certain freedom of choice for extreme loads (e.g., choice of return period for extreme wind).

h. Societal acceptance is important in determining performance criteria. The bar keeps rising.

i. An extreme load that can be predicted has different impact than that cannot be predicted (wind vs. earthquake).

j. AASHTO committees that have adopted new design guidelines may not easily make changes in a short time. The research team needs to move fast to catch the update schedule on design of individual extreme loads.

k. A second (refined) survey might be carried out after a phase 1 report is completed.

l. Defining loads is not in the scope, but gaps will be pointed out.

5.2 Future Research Needs

At the workshop and follow-up conference-call discussions, as well as further considerations by the Workshop Steering Committee, the following research activities are to be carried out in the next two years:

a. A framework for implementing extreme event limit states will be established. A few most needed and better understood limit states will be produced to demonstrate the methodologies and principles developed in the framework.

b. Chosen limit states for demonstration of the framework:

   - Earthquake and live load
   - Scour and earthquake
   - Scour and vessel collision
   - Earthquake and Wind
   - One cascading: Vehicular collision followed by fire

   More emphasis should be given to the first three combinations.

c. The first two combinations will be fully pursued by the research team for standard bridges. The third and fourth combinations, more important for special bridges, will be studied to the extent possible within the time and funding limit of the research project. The literature and available information of the fifth combination will be pursued. Important issues will be identified.

Section 6

Summary

A survey on multi-hazard bridge design was sent to state bridge engineers to obtain their opinions on the importance of potential extreme hazard loads and their combinations, including cascading events. The objective of this survey was to receive AASHTO input for the development of a method that can greatly reduce the complexity of future MH-LRFD procedures. The results showed regional correlation for some extreme events. Additional similarities and variations among different groups of bridges were also evident.

A Multi-Hazard Design Workshop was organized to review, interpret and disseminate the survey results to the participants, and to further discuss potential issues in the development of a MH-LRFD framework. Consensus was reached on some of the extreme events and combinations for which more research and practical guidance were most needed. Such prioritization was critical in guiding the long-term research planning as well as in accomplishing short-term research goals, which would serve to demonstrate the MH-LRFD framework and provide preliminary guidelines for the design against selected extreme events.

In accordance with the results from both the survey and the workshop, the goal of the MCEER project is to establish a MH-LRFD framework, together with the development of several selected design limit state equations to illustrate the principles and methodologies of the framework. The workshop participants identified five possible load cases for further study. These are: (1) earthquake and live load; (2) scour and earthquake; (3) scour and vessel collision; (4) earthquake and wind; and (5) vehicular collision followed by fire. They will be pursued by the research team, with more emphasis on the first three combinations. These cases are considered to be the most important, based on the collective opinion of the state bridge engineers. Results can be used by bridge designers until a comprehensive MH-LRFD is fully established in the future.

In general, the findings support the assertion that certain variation of extreme load specifications under different geographical, political, functional, or site-specific conditions may be necessary. This has already been embedded at various levels in current practice, and is identified as a potentially viable way to reduce the complexity of future MH-LRFD procedures.

Section 7

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Appendix A
Multi-Hazard Questionnaire

MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS

MCEER
University at Buffalo
The State University of New York
Red Jacket Quadrangle
Buffalo, New York 14261-0052

Phone: 716-645-3391
Fax: 716-645-3399
Email: mceer@buffalo.edu
Web: http://mceer.buffalo.edu

February 10, 2010

Dear Recipient:

This poll is being sent to you as part of a FHWA funded research project being conducted by MCEER. A principal objective of this project is to develop multiple hazard design principles for bridges. In support of this goal, a special workshop on extreme load effects is being organized and we are asking for your input to the following questions to facilitate discussion. Please respond within by February 22 if possible.

Thank you very much in advance.

The Workshop Steering Committee
Harry Capers, John Kulicki, George Lee, Tom Murphy and Phillip W. H. Yen

- -

QUESTIONNAIRE

Name: ____________________ State: _____ Tel#_____________ E-mail __________________

Note: The researchers who designed this survey are not interested in official state or AASHTO policy or practice, but rather the professional opinion of experienced bridge engineers who can help shape future guidance on the design of bridges for multiple hazards. Your response should be relevant to your region of the country, rather than to the US as a whole.

The probability-based approach used in the LRFD Bridge Design Specification was developed to provide a fairly consistent level of reliability. This approach is desirable for extreme load combinations as well as for the conventional design loads found in AASHTO. As part of the project, we plan to evaluate the level of acceptable failure probability when a bridge is subjected to a single or combination of extreme loads, recognizing that each hazard may have a different return period.

Because a bridge's exposure to hazards varies somewhat according to which part of the country it is in, the researchers are seeking input from bridge owners (the stakeholders) on the relative importance of different extreme loads and their possible combinations. This input may eventually lead to the development of multi-hazard (MH) LRFD design guidelines. With this in mind, please mark the following extreme load or load combination that, in your opinion, should be considered in your region. Please assume that the intensity of the hazard is sufficiently large that the design of bridge with design life of 75 – 100 years should consider it. Use the following scale:

1 to denote "I do <u>not</u> believe it is necessary to design for this,"
2 to denote "It should be investigated further and <u>considered</u>,"
3 to denote ""I believe that we should <u>always</u> design for this."

Part I Single and Concurrent Events

1. Single Extreme Event

		Standard, Short/Medium Span Bridges (Say <500')	Special or Long-Span Bridges
		1.No 2.Consider 3.Always	1.No 2.Consider 3.Always
1.1	Scour		
1.2	Vessel Collision		
1.3	Vehicular Collision		
1.4	Fire		
1.5	Earthquake		
1.6	Storm Surge		
1.7	Wind		
1.7	Debris Flow		
1.9	Other (specify)		

2. Possibility of Two Concurrent Extreme Events

		Standard, Short/Medium Span Bridges (Say <500')	Special or Long-Span Bridges
		1.No 2.Consider 3.Always	1.No 2.Consider 3.Always
2.1	Scour + Vessel Collision		
2.2	Scour + Earthquake		
2.3	Scour + Storm Surge		
2.4	Scour + Wind		
2.5	Scour + Debris Flow		
2.6	Vessel Collision + Storm Surge		
2.7	Vessel Collision +Wind		
2.8	Vessel Collision + Debris Flow		
2.9	Vehicular Collision + Wind		
2.10	Fire + Wind		
2.11	Earthquake + Wind		
2.12	Storm Surge + Wind		
2.13	Wind + Debris Flow		
2.14	Other possible combinations (specify)		

3. Three Concurrent Extreme Events

		Standard, Short/Medium Span Bridges (Say <500’)	**Special or Long-Span Bridges**
		1.No 2.Consider 3.Always	1.No 2.Consider 3.Always
3.1	Scour +Vessel Collision + Storm Surge		
3.2	Scour + Vessel Collision + Wind		
3.3	Scour + Earthquake + Wind		
3.4	Scour+ Storm Surge + Wind		
3.5	Vessel Collision + Storm Surge + Wind		
3.6	Vehicular Collision + Fire + Wind		
3.7	Other (specify)		

4. More than Three Events

Do you think more than 3 concurrent extreme events may need considerations (for example, scour+surge+vessel collision+high wind)? If so, please specify.

Part II Cascading Events

Cascading events include two categories: (1) one or more than one concurrent events leading to another and (2) a sequence of events occurring before the next bridge inspection or repair from previous event. The first type may have a time gap of minutes, hours or possibly days. The second type may have a time gap of weeks or months. From the perspective of formulating MH-LRFD, they may be grouped together. In all cases, the first occurrence will introduce damage or inelastic responses to the bridge.

Current FHWA funded research to establish a framework for MH-LRFD will not attempt to cover all possible combinations of cascading events. However, this study will attempt to address a few selected cases that are considered to be important. This question is intended to identify the important cascading events that need to be addressed.

1. Single Events Leading to (or Followed by) Another

Please use the scale described above.

	Initial Event	Subsequent Event	Standard, Short/Medium Span Bridges (Say <500')	Special or Long-Span Bridges
			1.No 2.Consider 3.Always	1.No 2.Consider 3.Always
1.1	Vessel Collision	Earthquake		
1.2	Vessel Collision	Storm Surge		
1.3	Vessel Collision	Vessel Collision		
1.4	Vehicular Collision	Fire		
1.5	Vehicular Collision	Earthquake		
1.6	Vehicular Collision	Vehicular Collision		
1.7	Earthquake	Wind		
1.8	Earthquake	Fire		
1.9	Earthquake	Debris Flow		
1.10	Earthquake	Earthquake		
1.11	Wind	Vehicular Collision		
1.12	Fire	Wind		
1.13	Storm Surge	Storm Surge		
1.14	Other (specify)			

2. Cascading of Concurrent Events

Do you think cascading of concurrent extreme events should be considered (see examples below)? If so, please specify. This means one or both of the cascaded events involve multiple concurrent events.

Examples of cascading of concurrent events

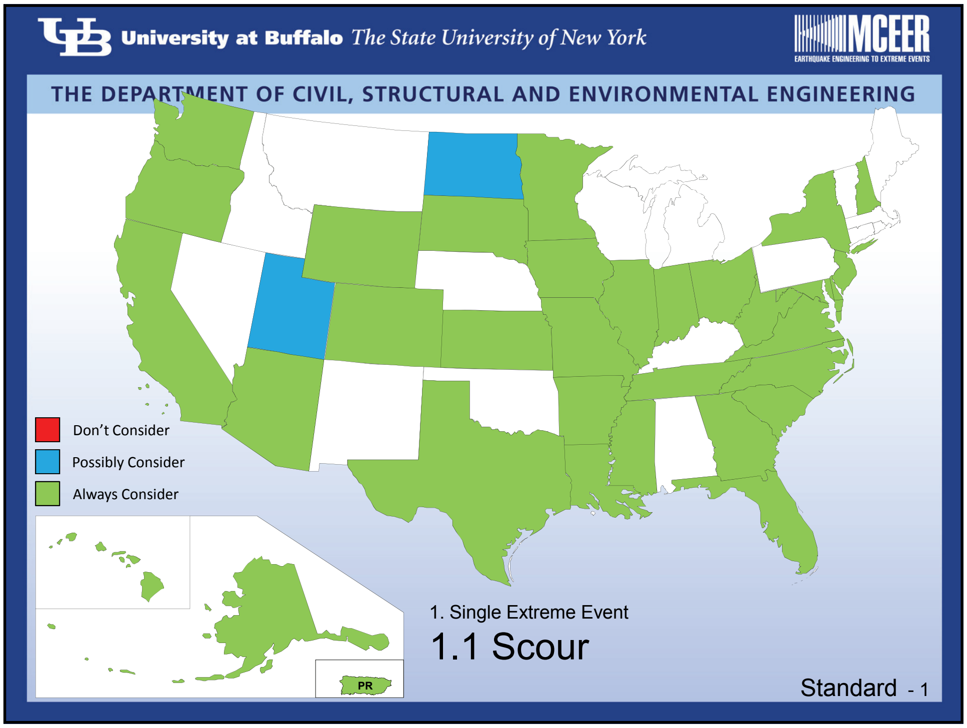
Initial event(s)	Subsequent event(s)
Vehicular Collision + Wind	Fire
Wind	Storm Surge + Vessel Collision
Earthquake + Vehicular Collision	Wind + Fire
Scour + Earthquake	Vessel Collision+Wind+Debris Flow
Earthquake	Vehicular Collision + Fire

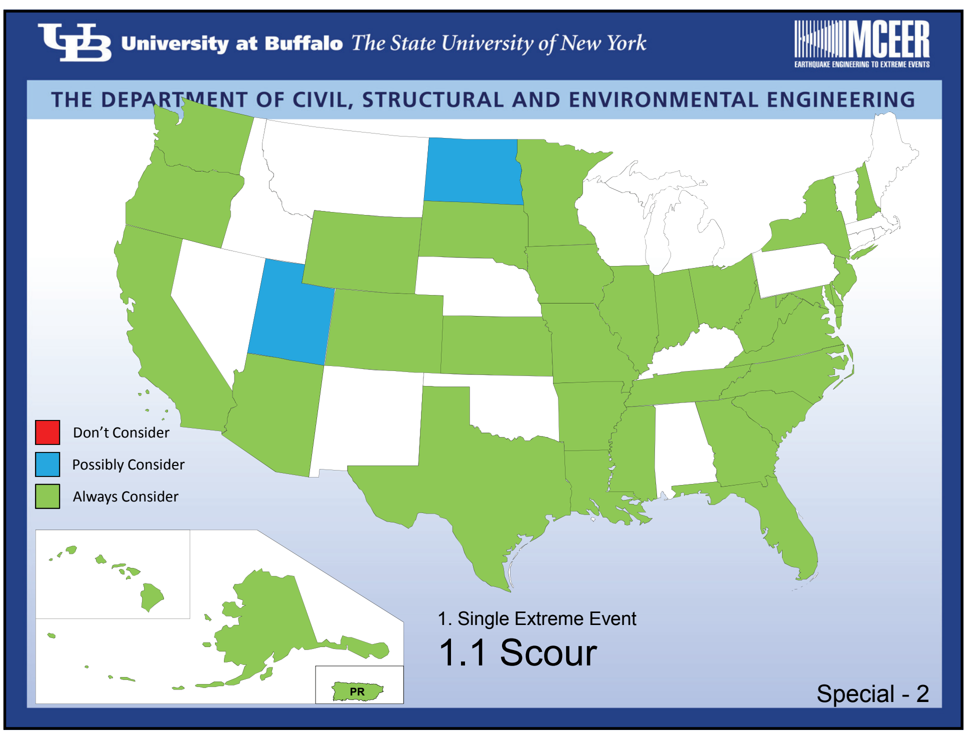
Part III Additional Comments

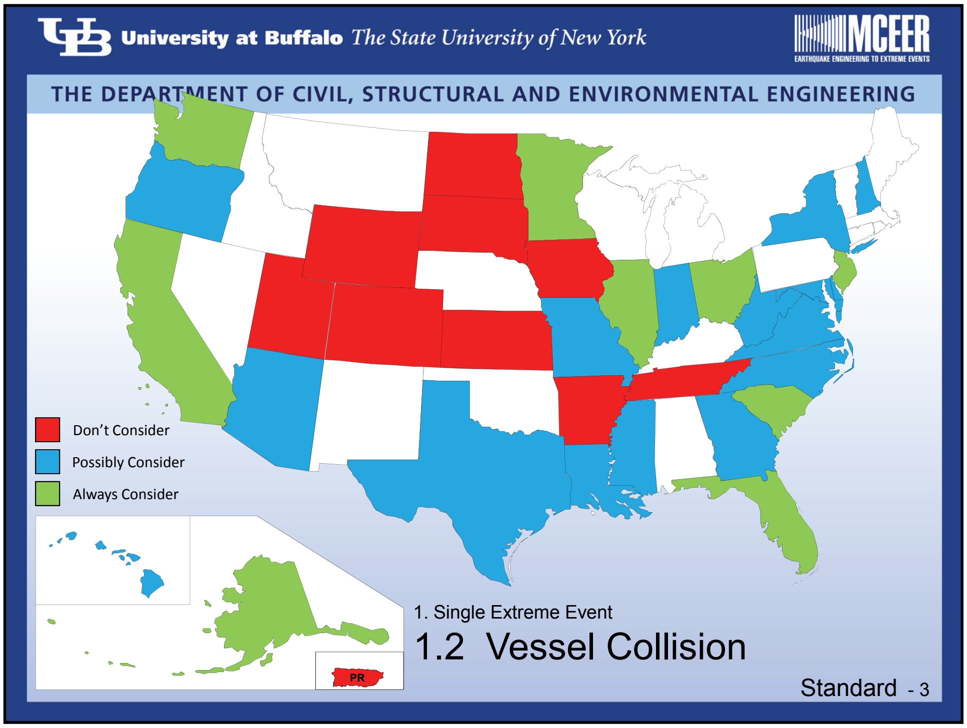
1. Please also provide information/explanation/qualifications on the answers you provided, if any.

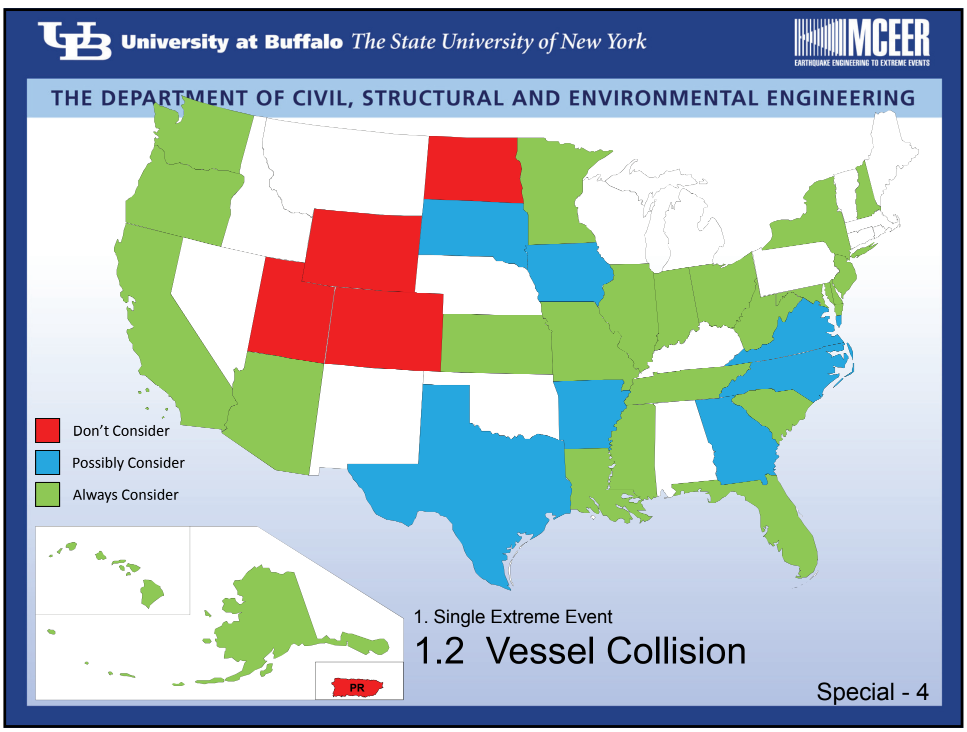
2. What other questions important to bridge design against extreme load and their combinations should be asked that were not included?

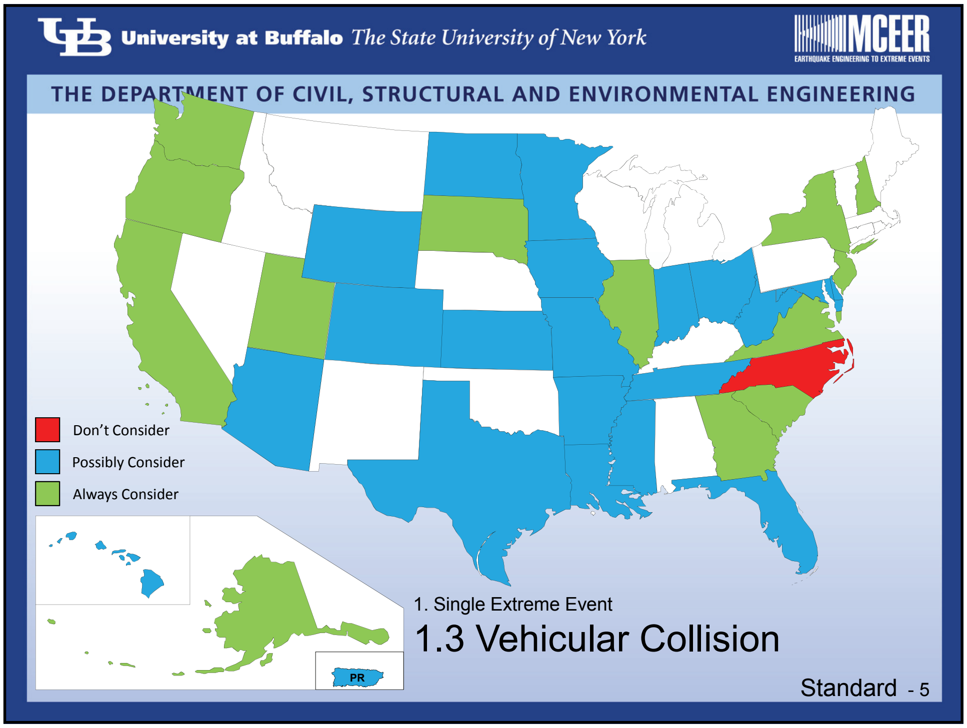
Appendix B
Questionnaire Responses

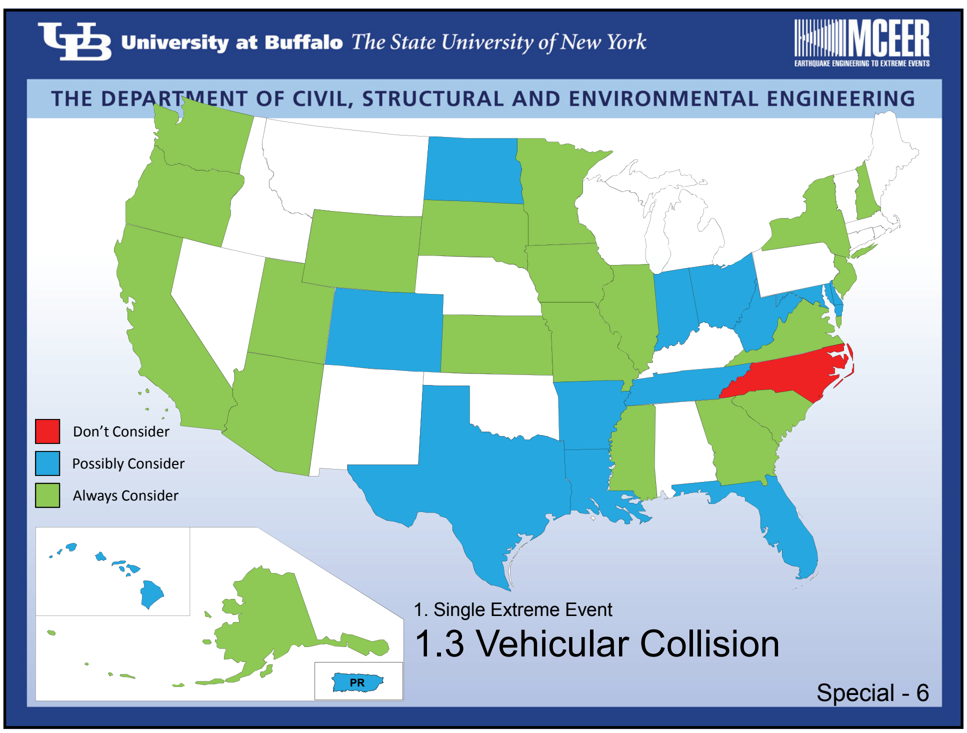


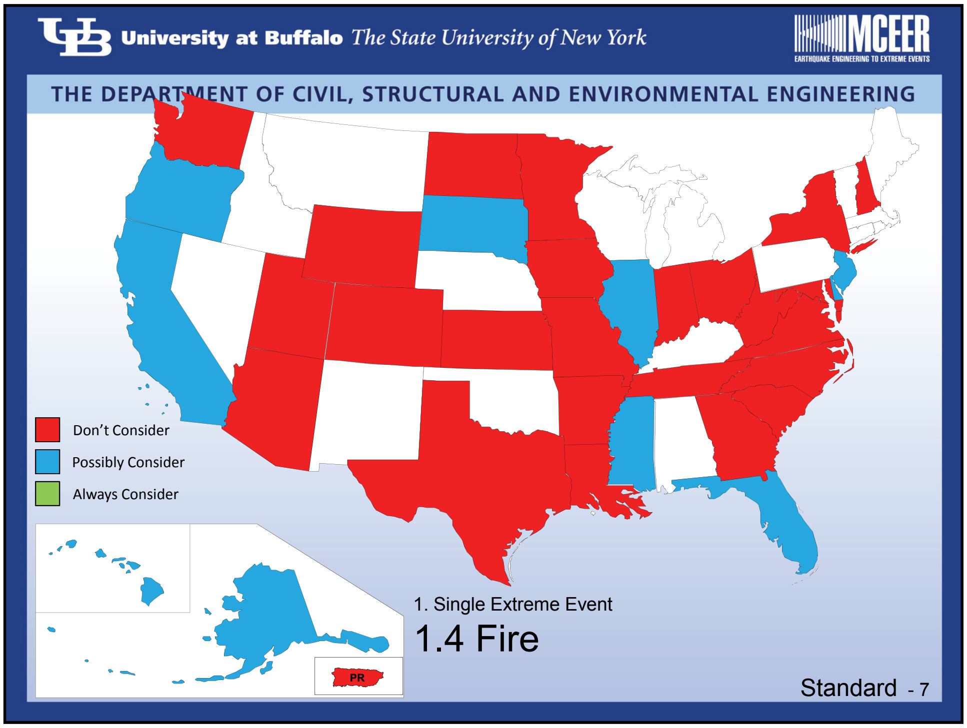


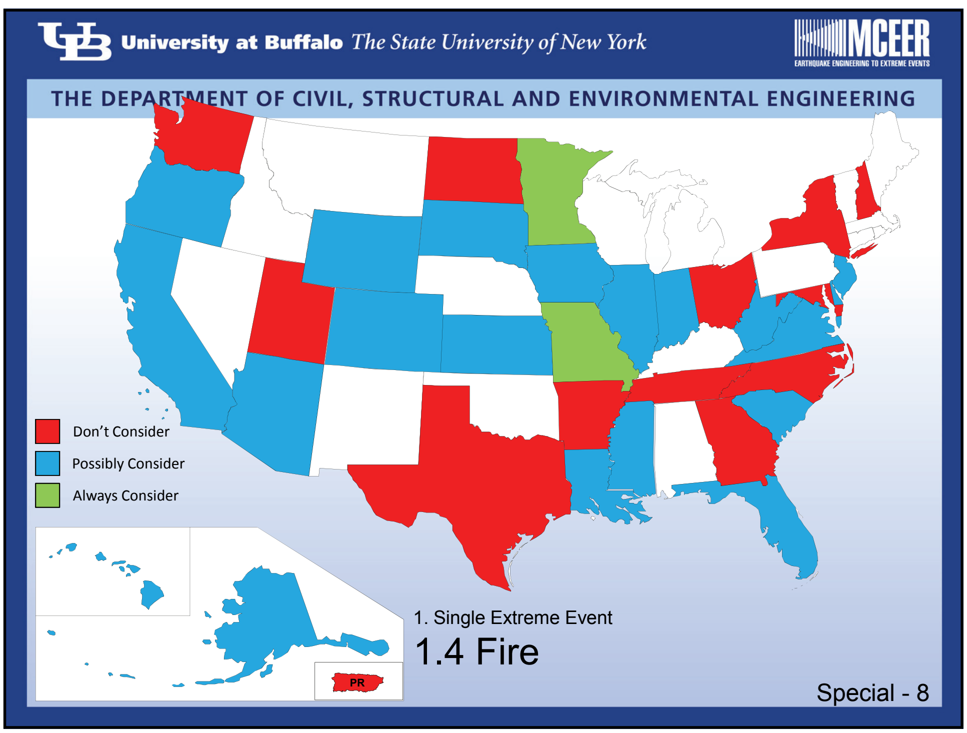

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.2 Vessel Collision
Standard - 3

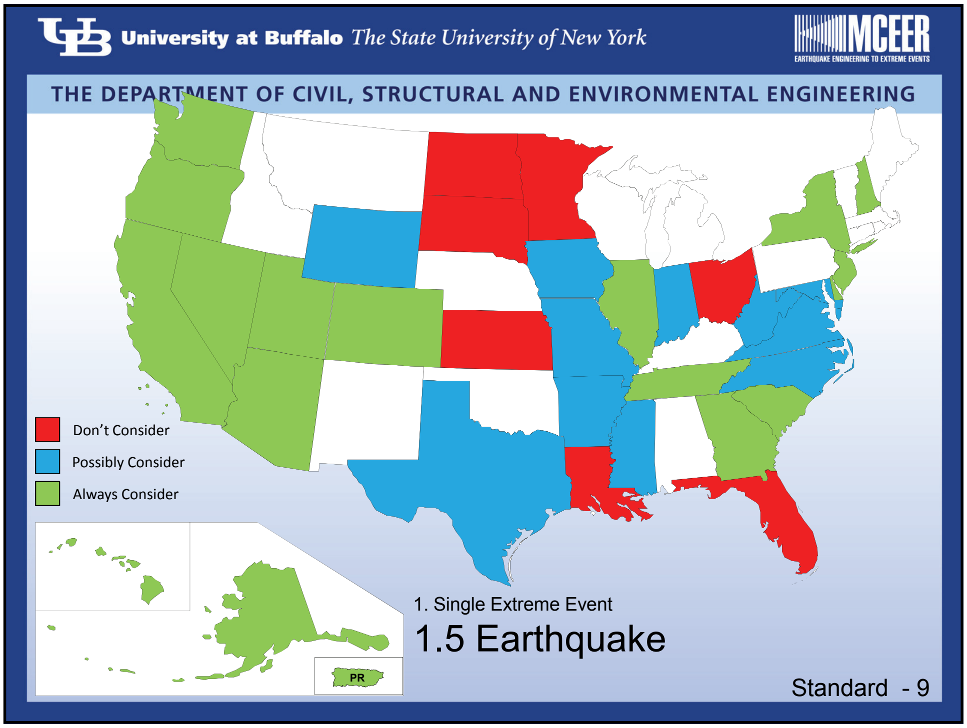

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.2 Vessel Collision
Special - 4

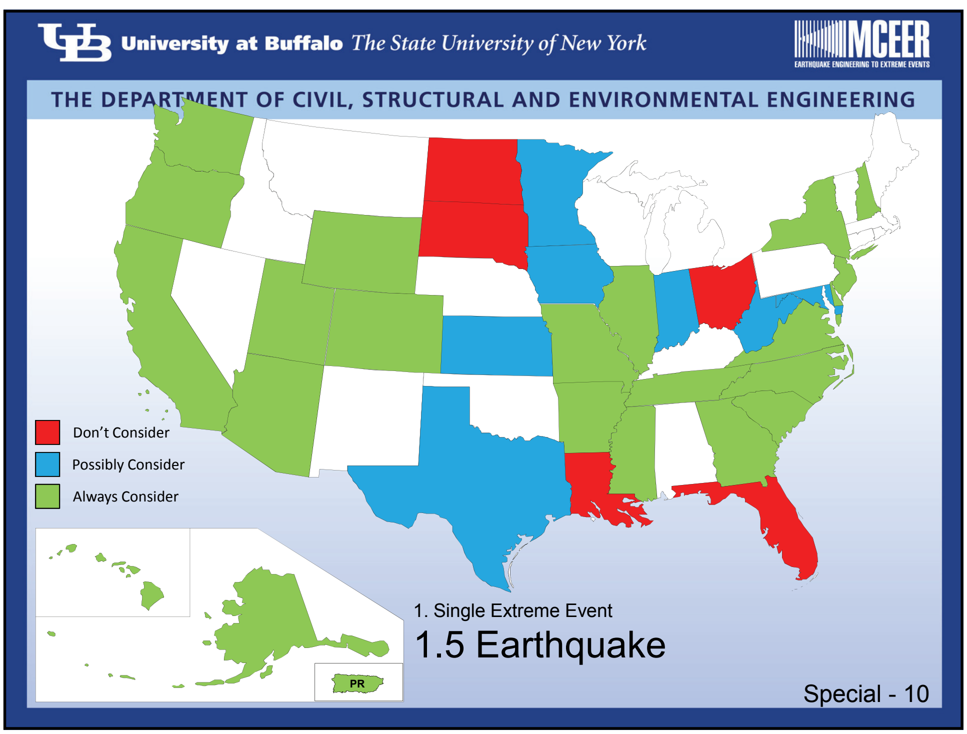

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.3 Vehicular Collision
Standard - 5

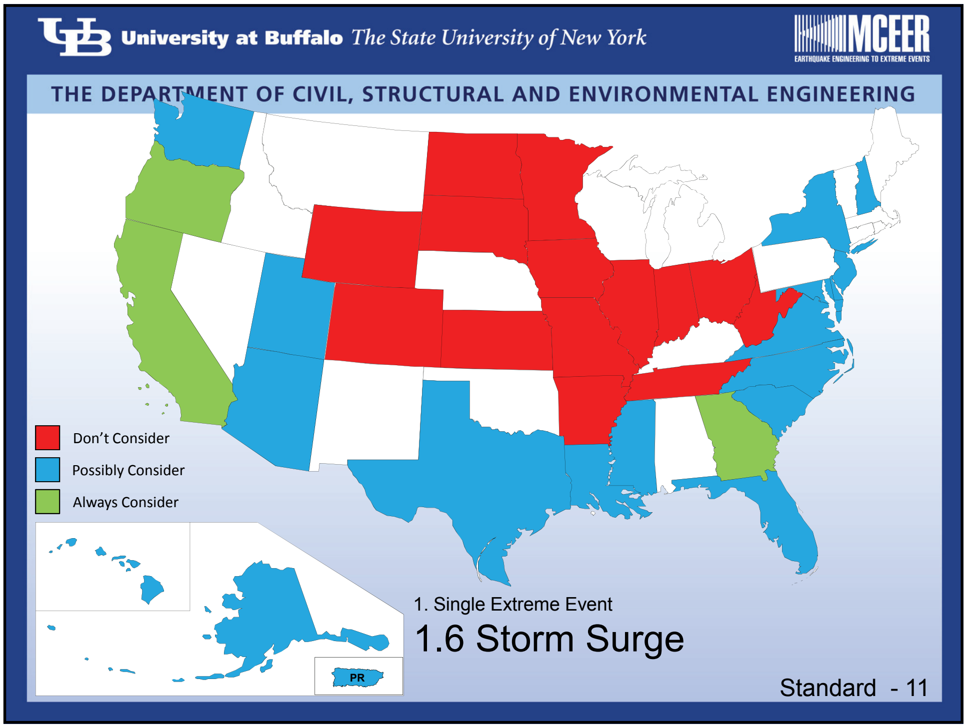

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.3 Vehicular Collision
Special - 6

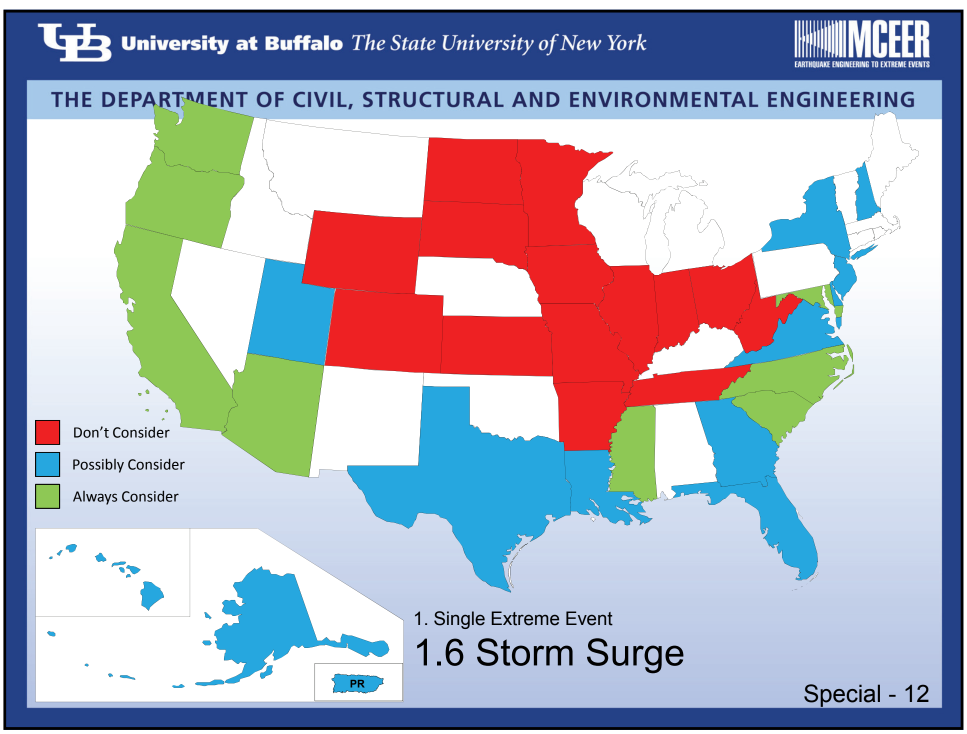

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.4 Fire
Standard - 7


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.4 Fire
Special - 8


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.5 Earthquake
Standard - 9


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.5 Earthquake
Special - 10


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.6 Storm Surge
Standard - 11


University at Buffalo The State University of New York
MCEER
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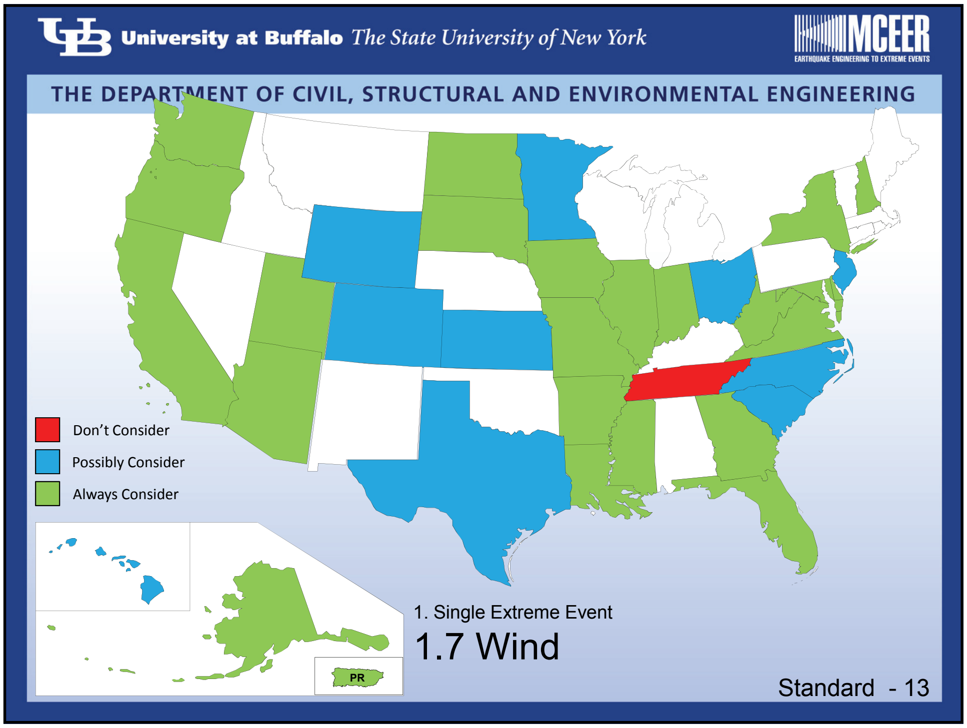
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.6 Storm Surge
Special - 12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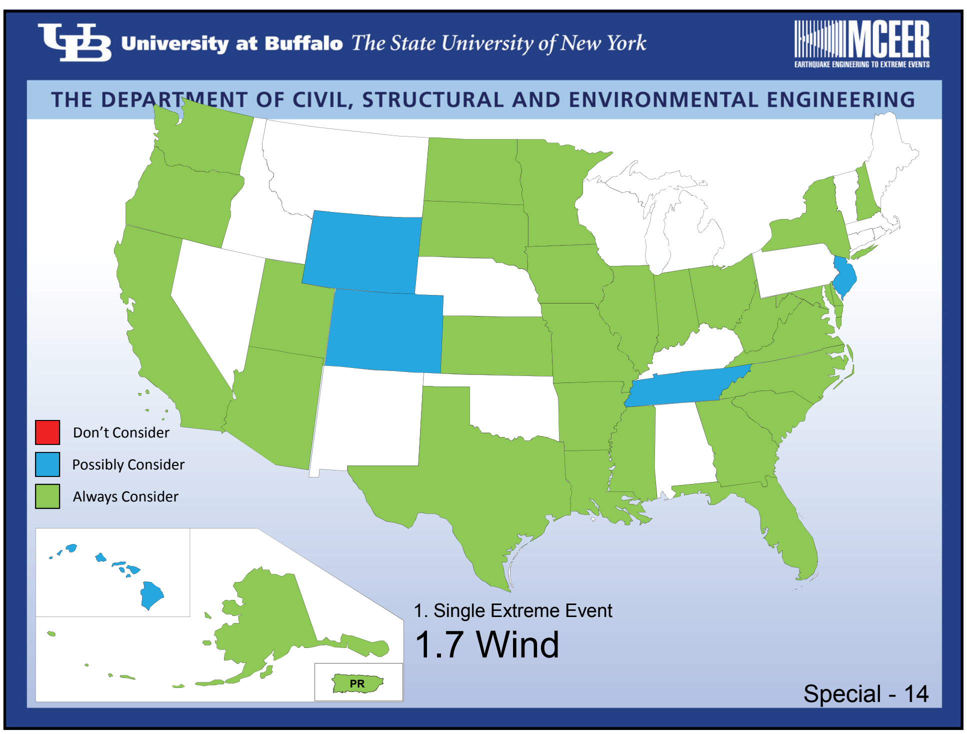
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.7 Wind
Standard - 13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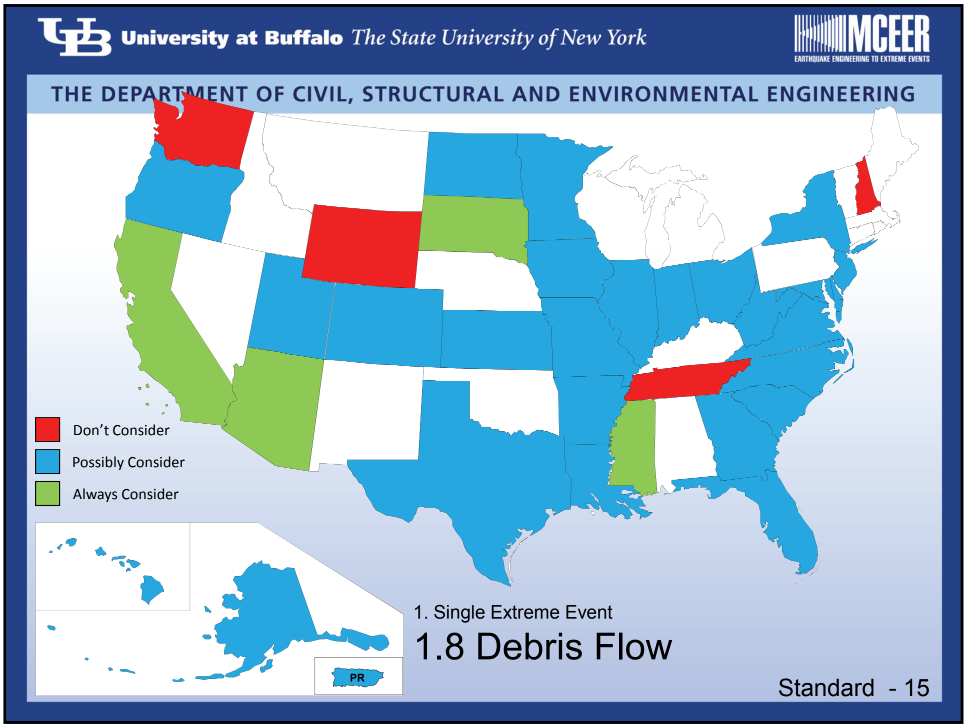
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.7 Wind
Special - 14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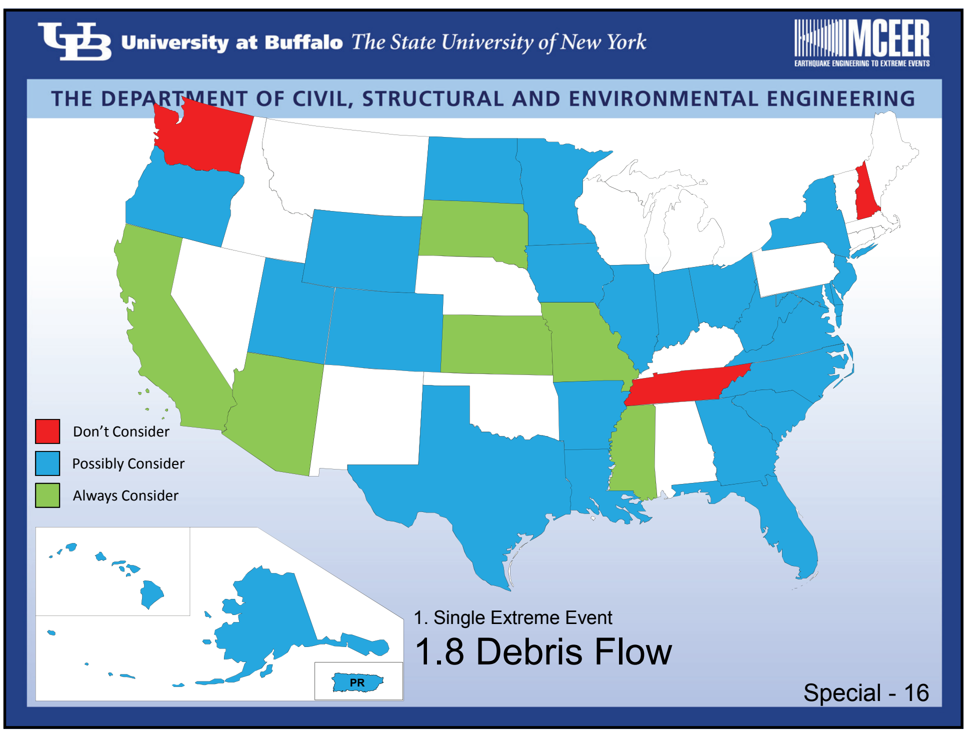
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.8 Debris Flow
Standard - 15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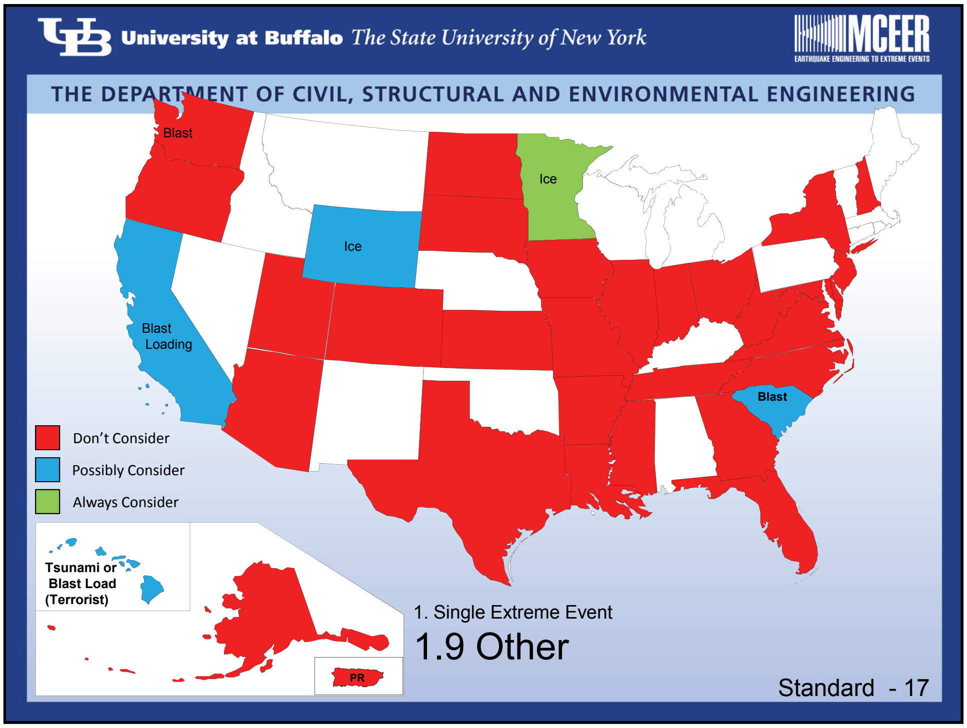
Don't Consider
Possibly Consider
Always Consider
PR
1. Single Extreme Event
1.8 Debris Flow
Special - 16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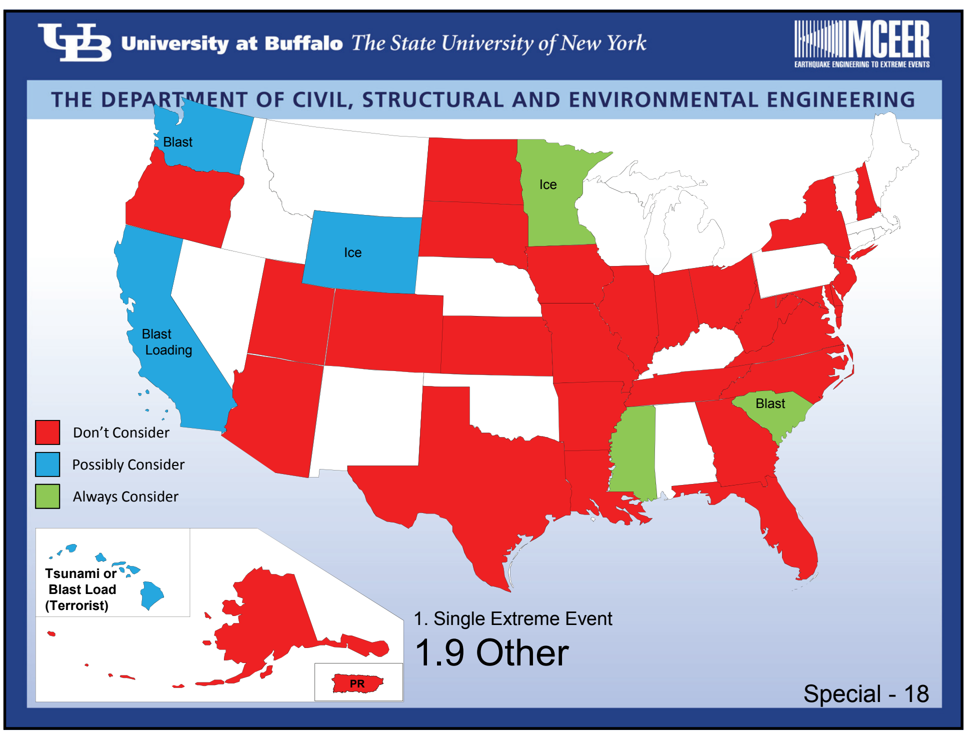
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Blast
Ice
Ice
Blast
Loading
Blast
Don't Consider
Possibly Consider
Always Consider
Tsunami or
Blast Load
(Terrorist)
PR
1. Single Extreme Event
1.9 Other
Standard - 17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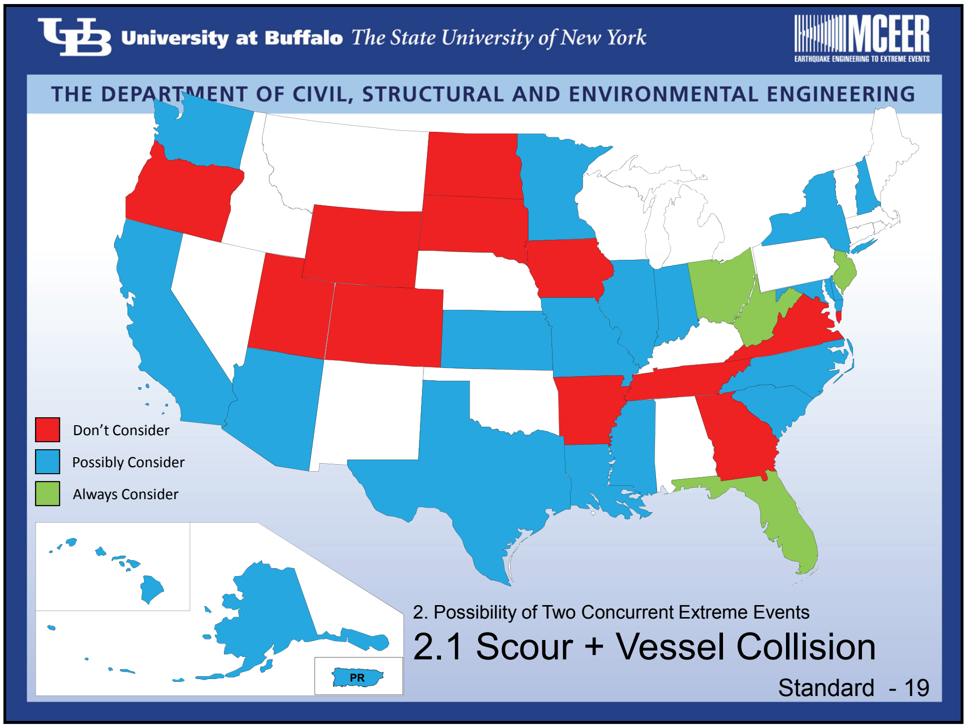
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Blast
Ice
Ice
Blast
Loading
Blast
Don't Consider
Possibly Consider
Always Consider
Tsunami or
Blast Load
(Terrorist)
PR
1. Single Extreme Event
1.9 Other
Special - 18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MCEER
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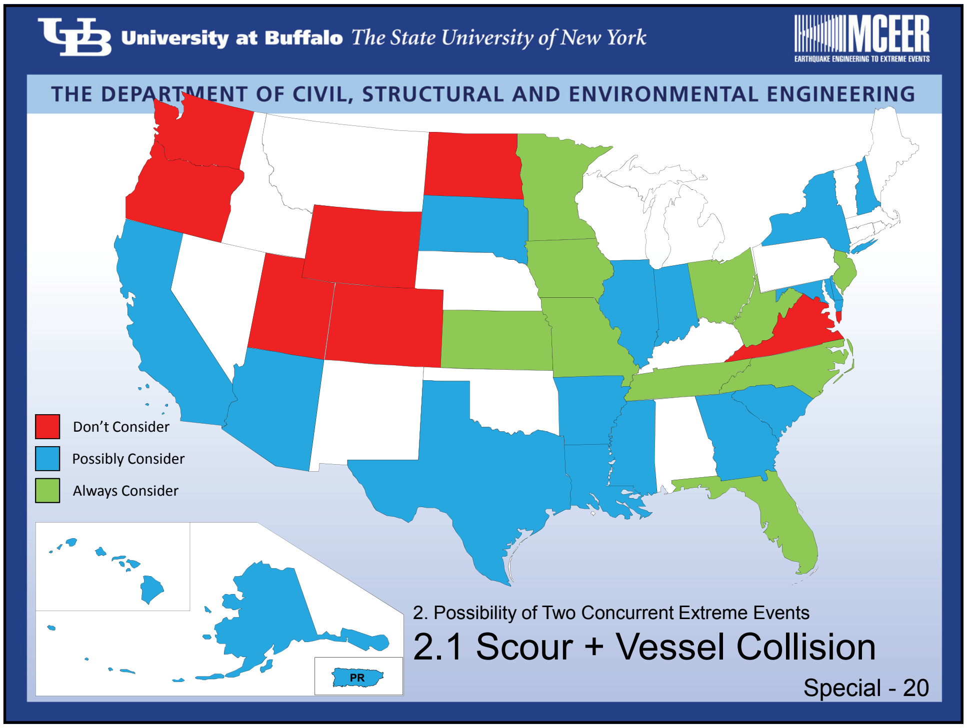
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.1 Scour + Vessel Collision
Standard - 19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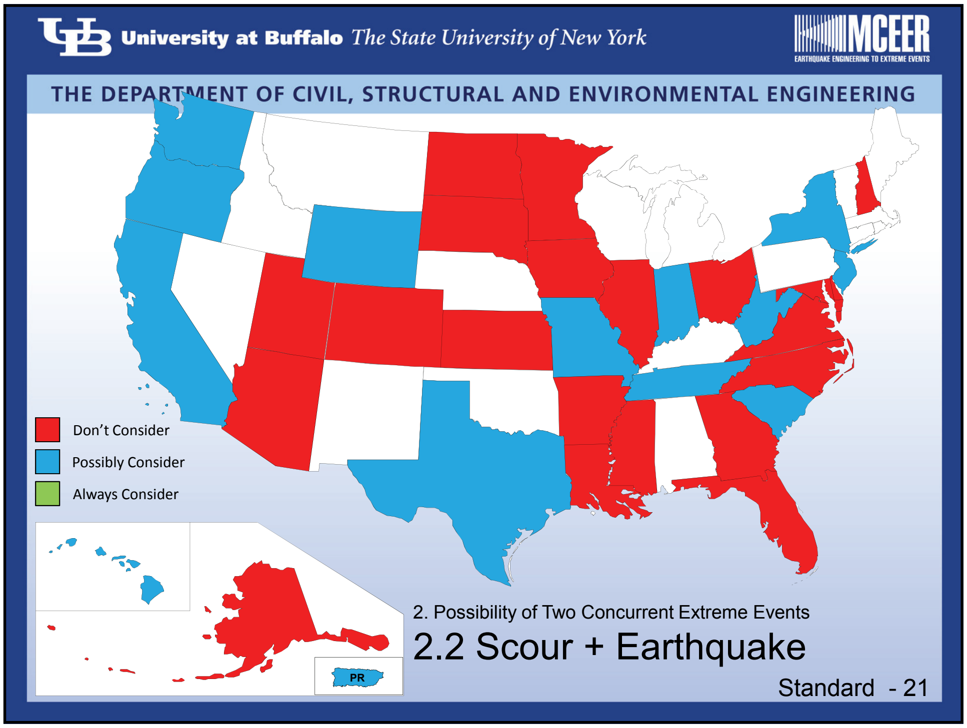
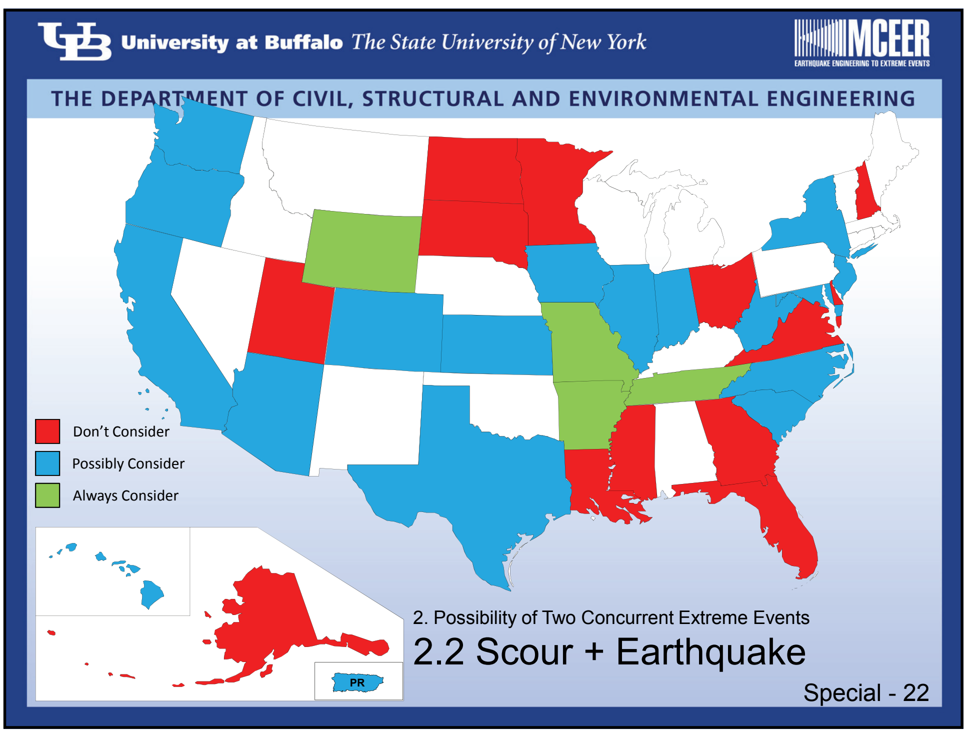
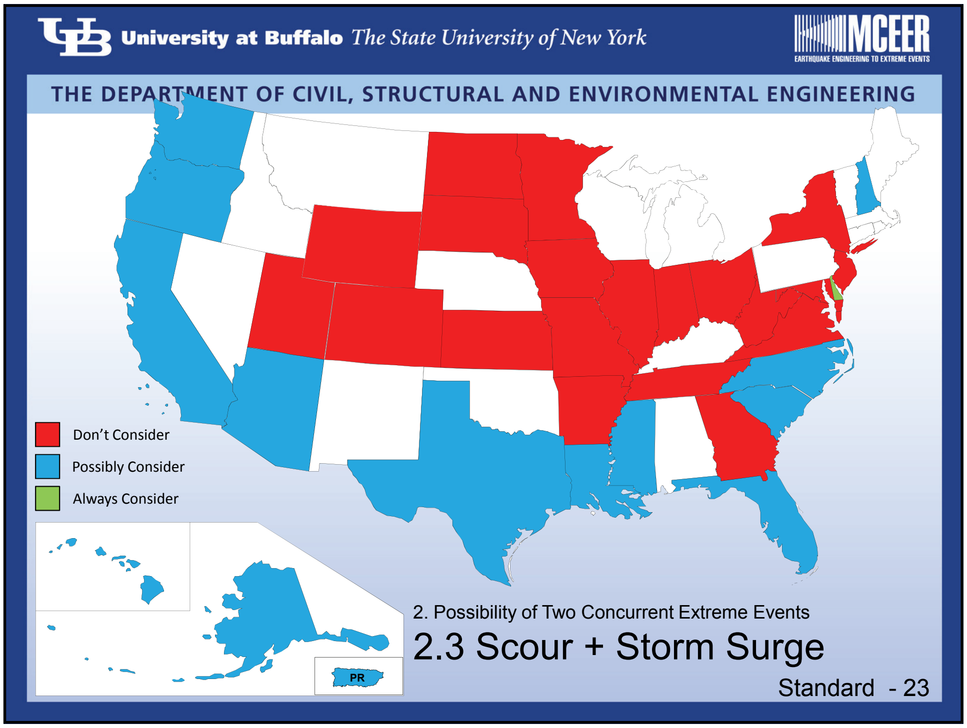
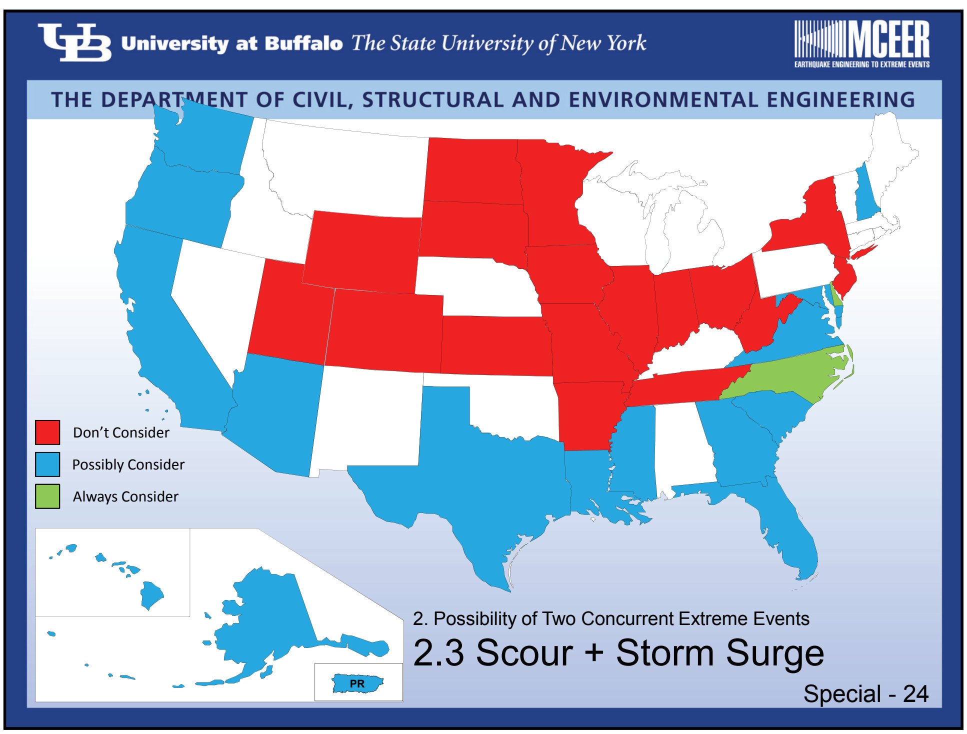
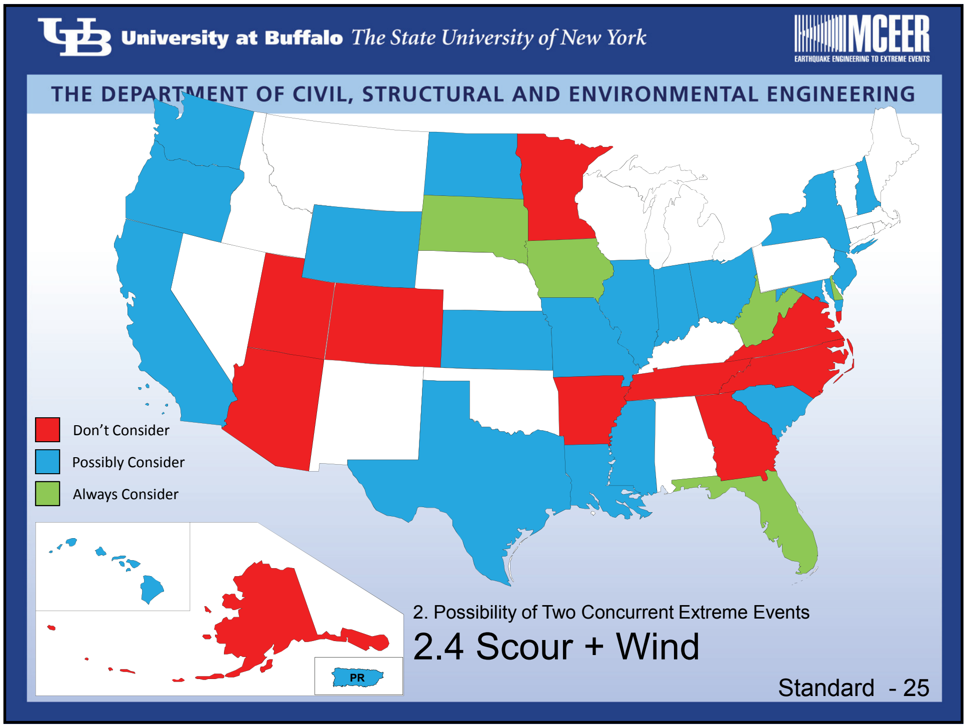
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.1 Scour + Vessel Collision
Special - 20

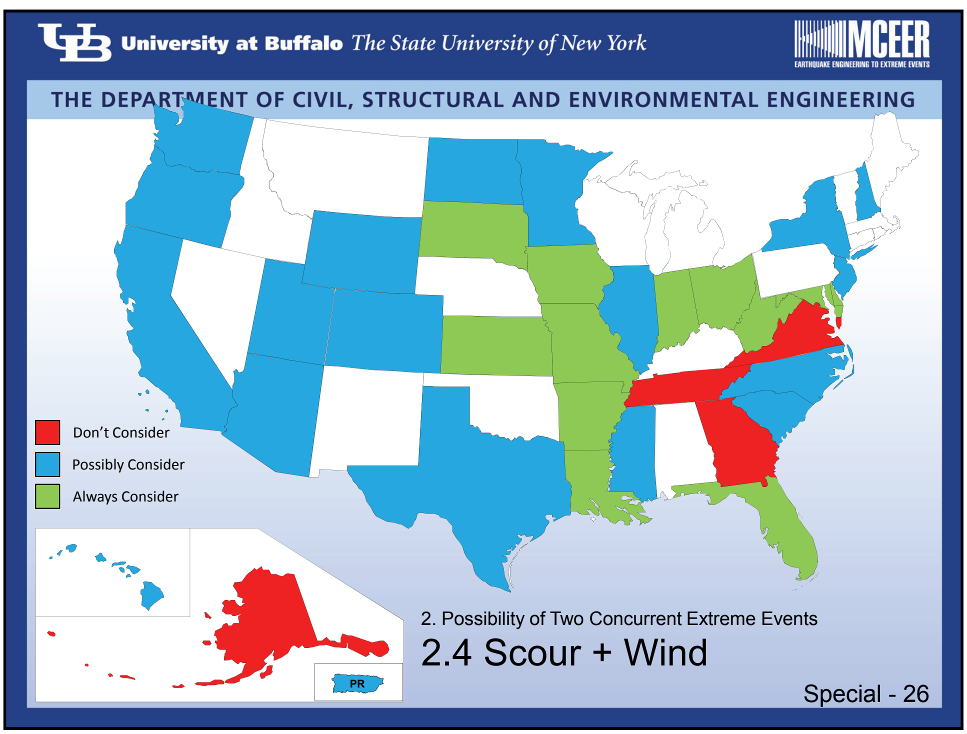

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.2 Scour + Earthquake
Standard - 21

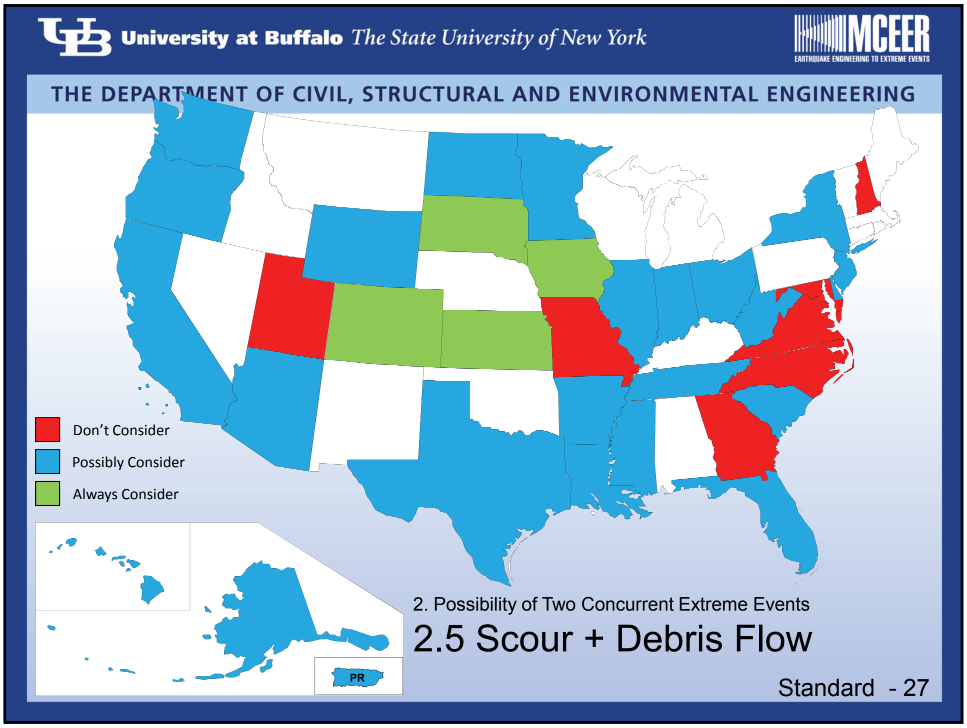

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.2 Scour + Earthquake
Special - 22

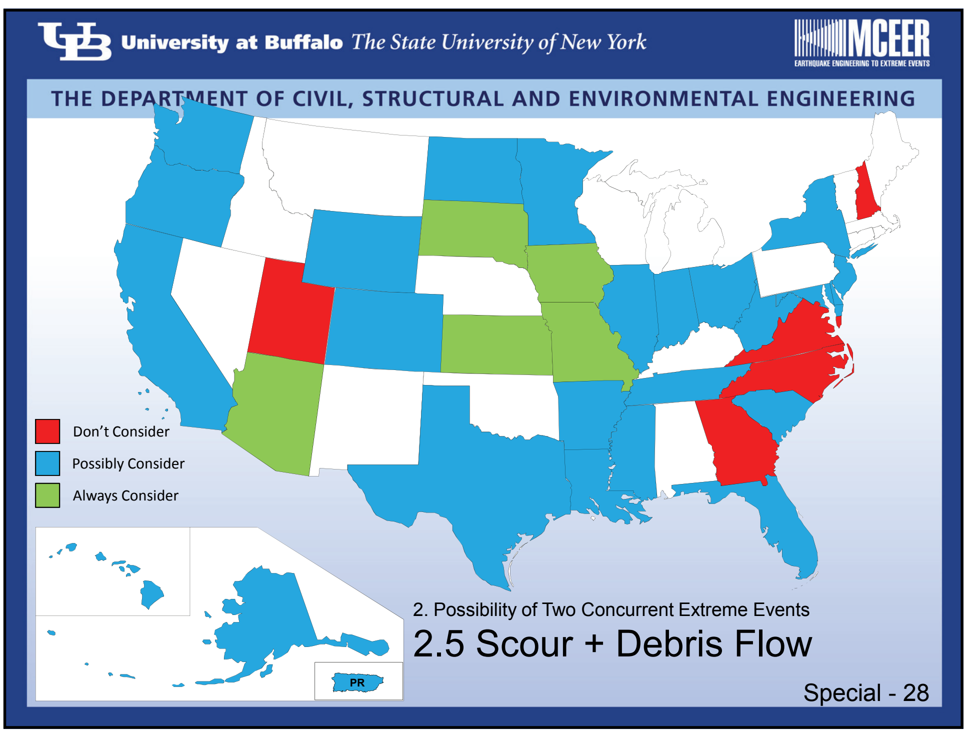

University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.3 Scour + Storm Surge
Standard - 23


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.3 Scour + Storm Surge
Special - 24


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.4 Scour + Wind
Standard - 25


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.4 Scour + Wind
Special - 26


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.5 Scour + Debris Flow
Standard - 27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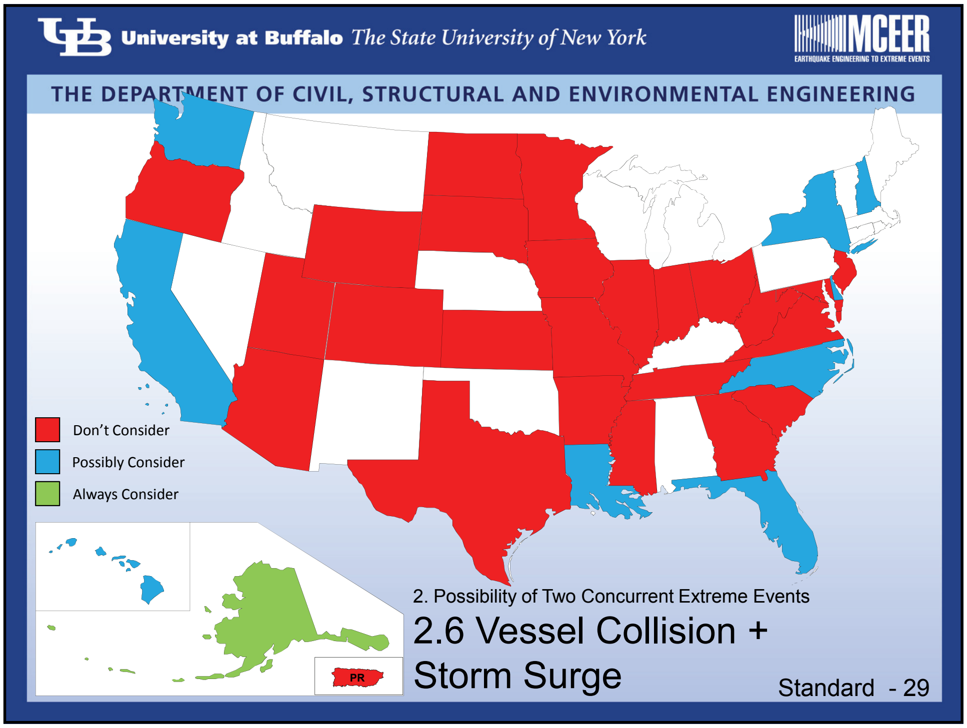
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.5 Scour + Debris Flow
Special - 28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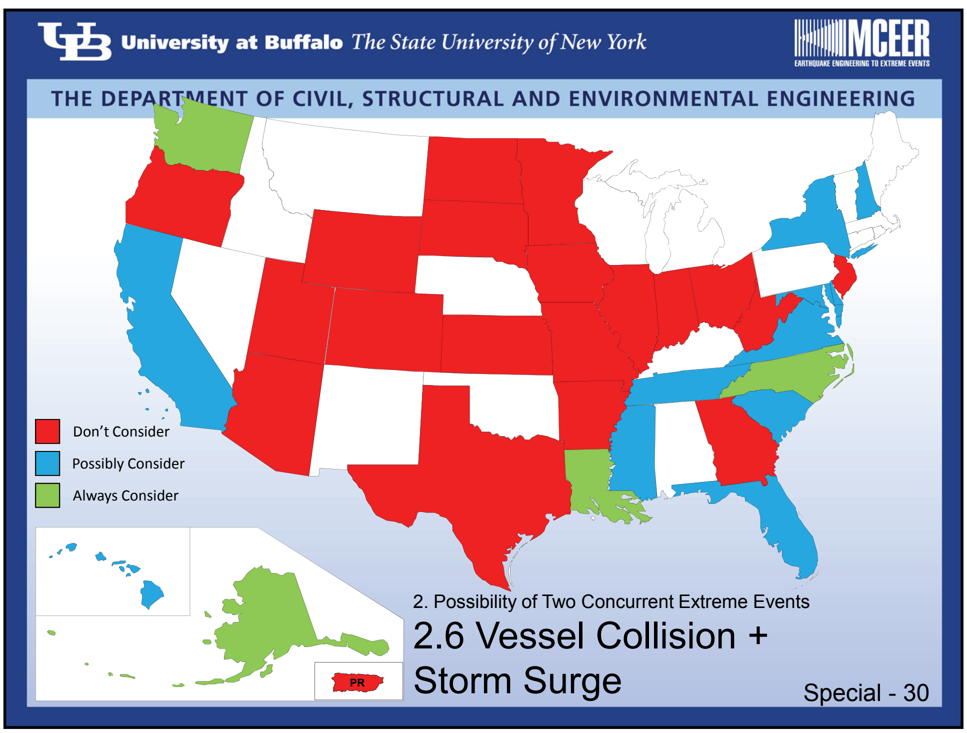
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.6 Vessel Collision + Storm Surge
Standard - 29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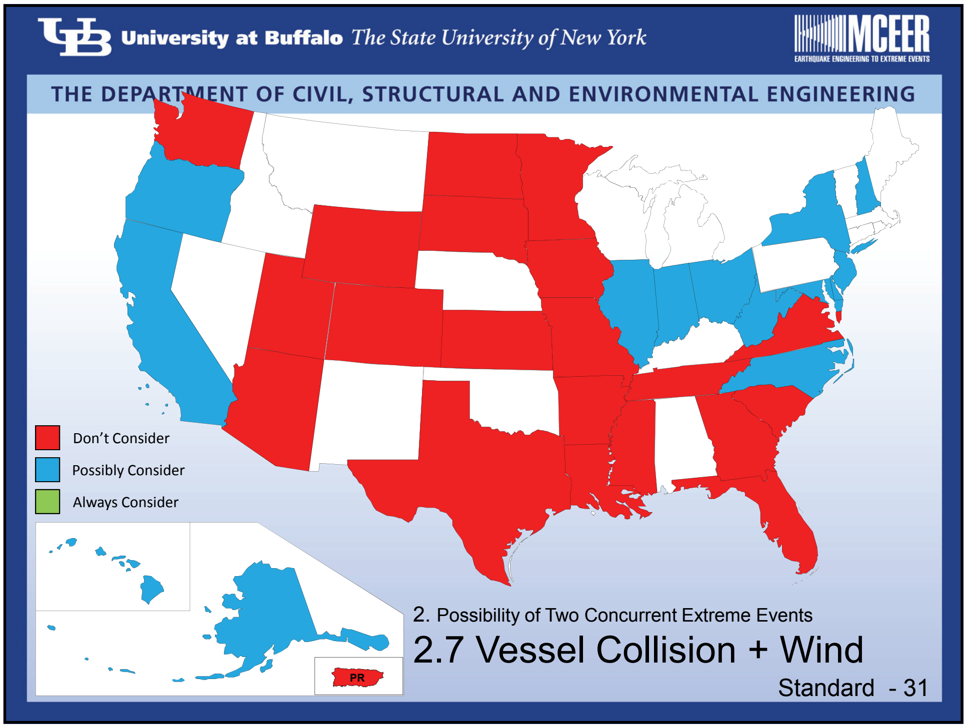
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.6 Vessel Collision + Storm Surge
Special - 30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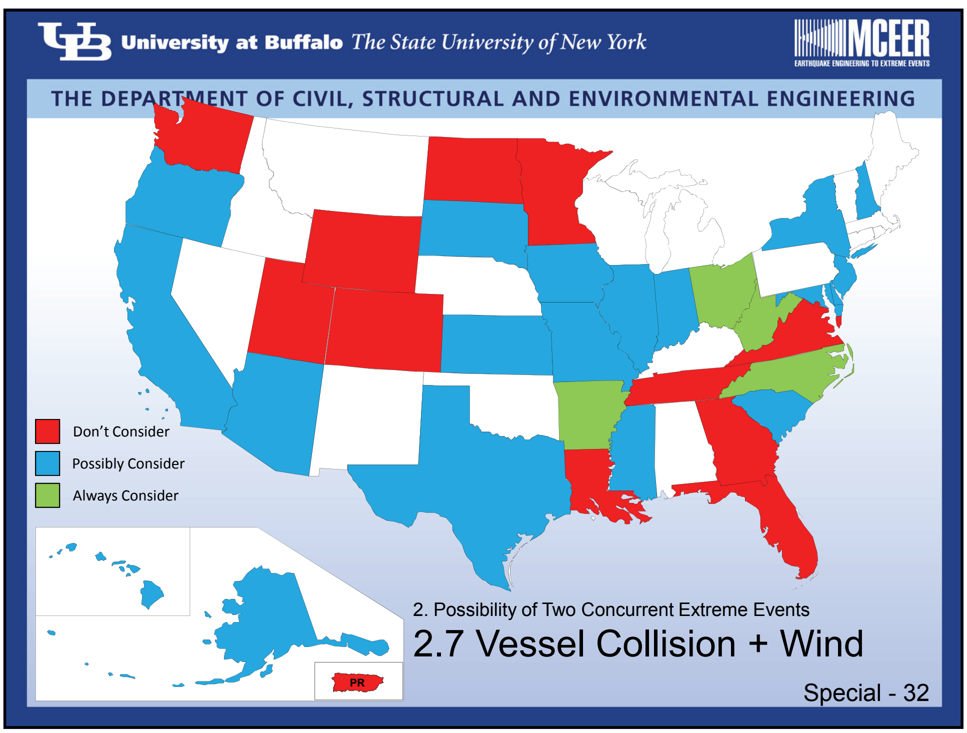
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.7 Vessel Collision + Wind
Standard - 31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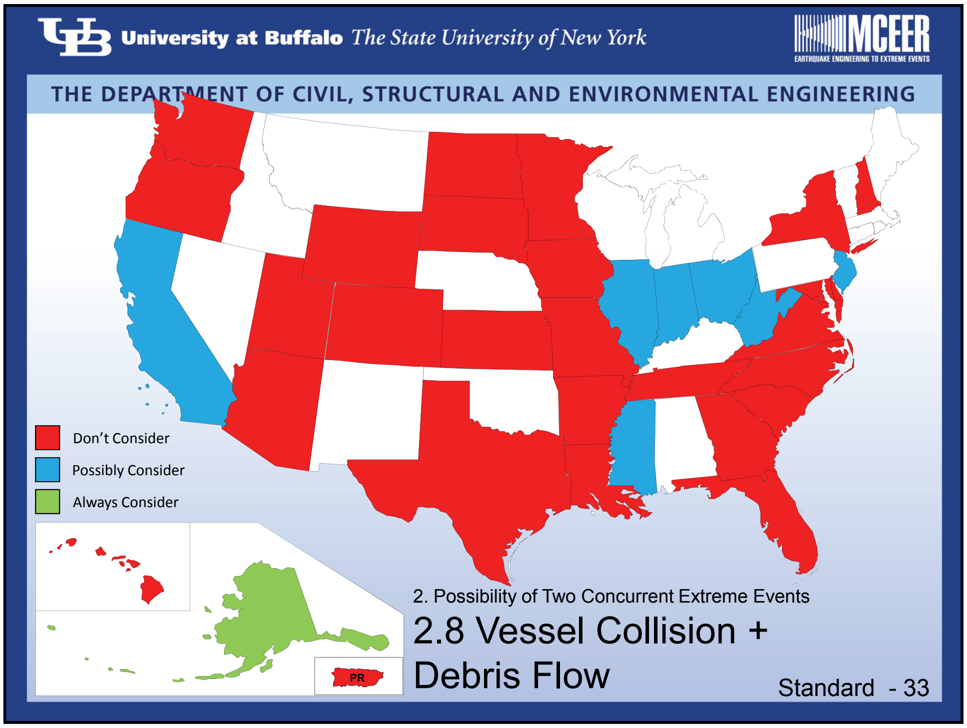
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.7 Vessel Collision + Wind
Special - 32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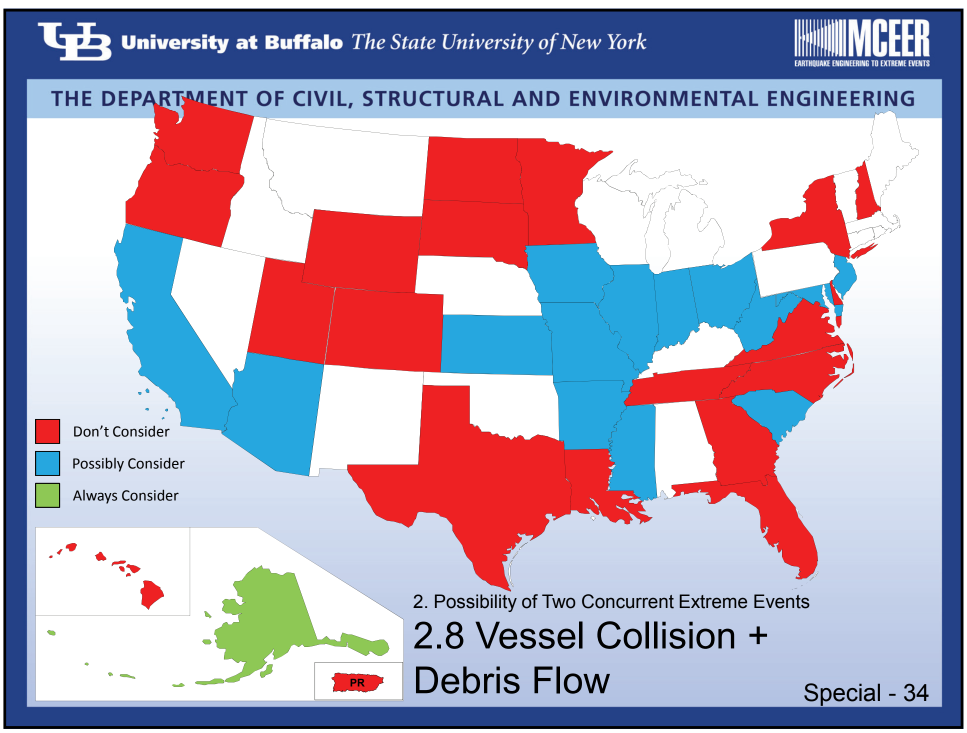
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.8 Vessel Collision + Debris Flow
Standard - 33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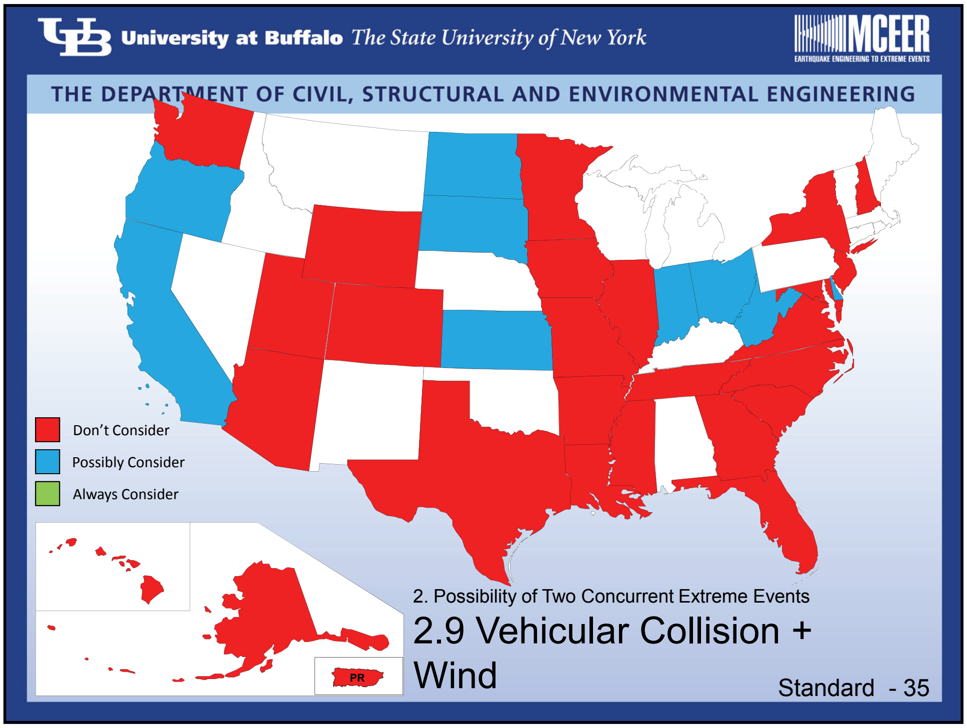
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.8 Vessel Collision + Debris Flow
Special - 34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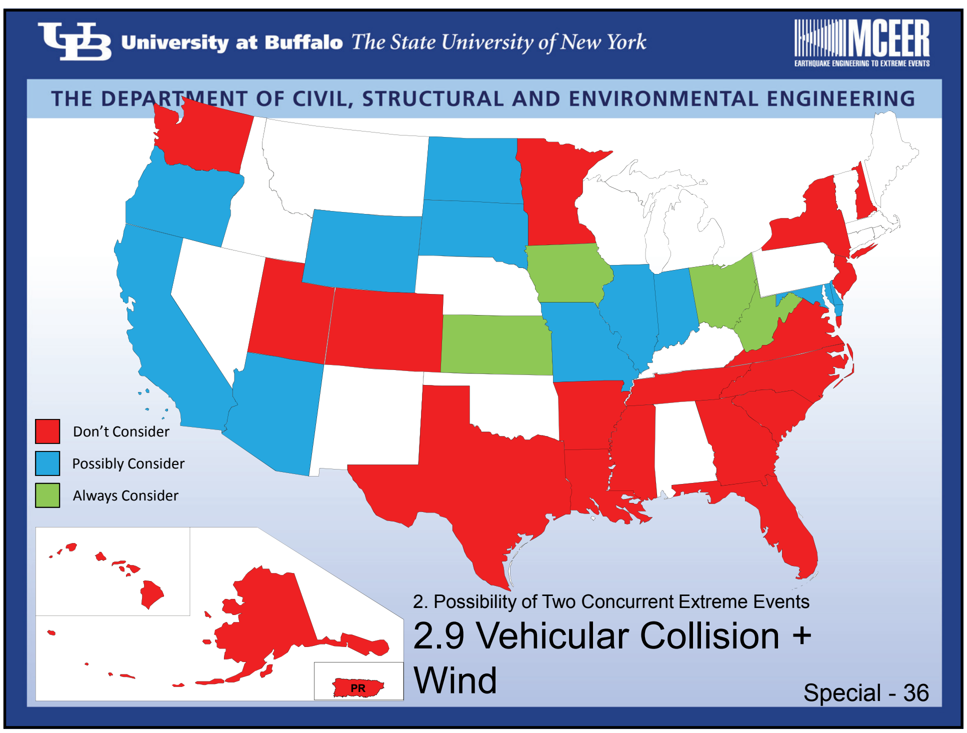
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.9 Vehicular Collision + Wind
Standard - 35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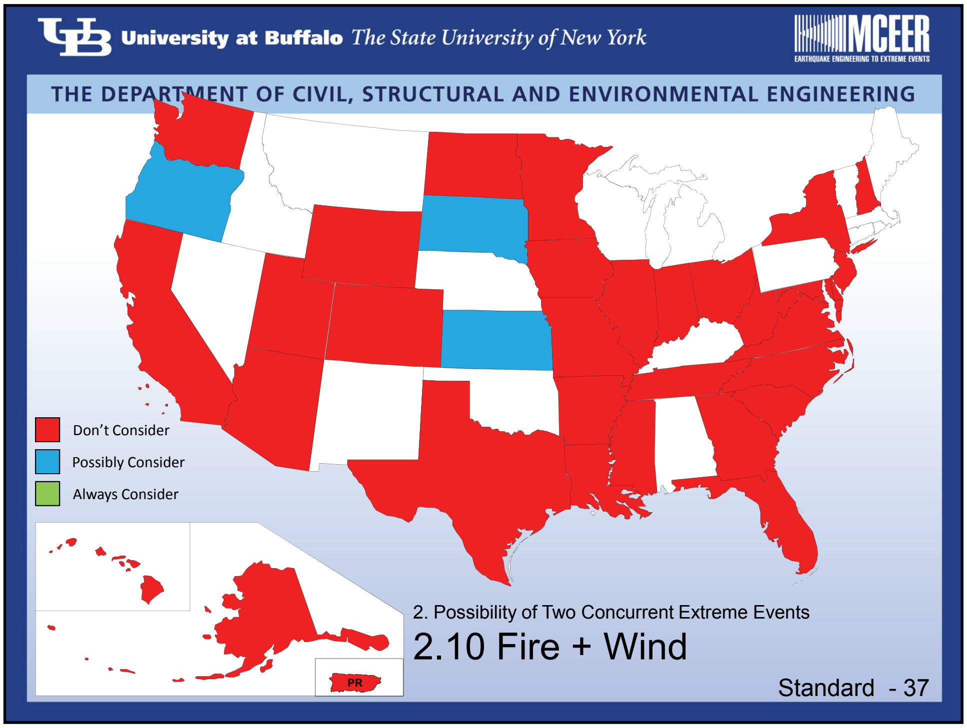
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.9 Vehicular Collision + Wind
Special - 36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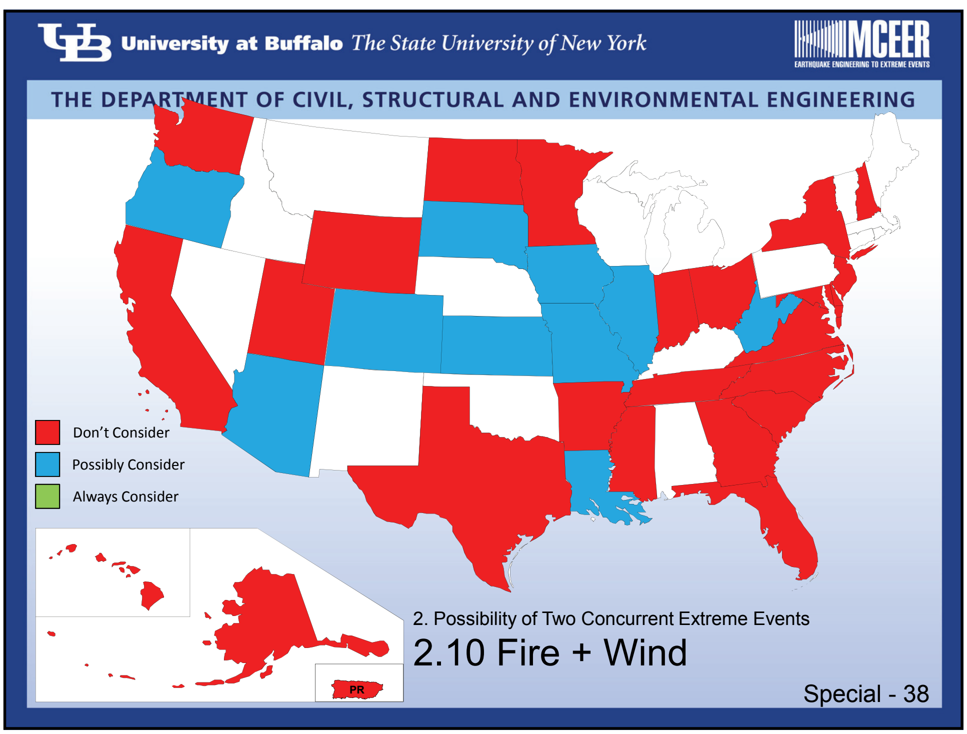
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.10 Fire + Wind
Standard - 37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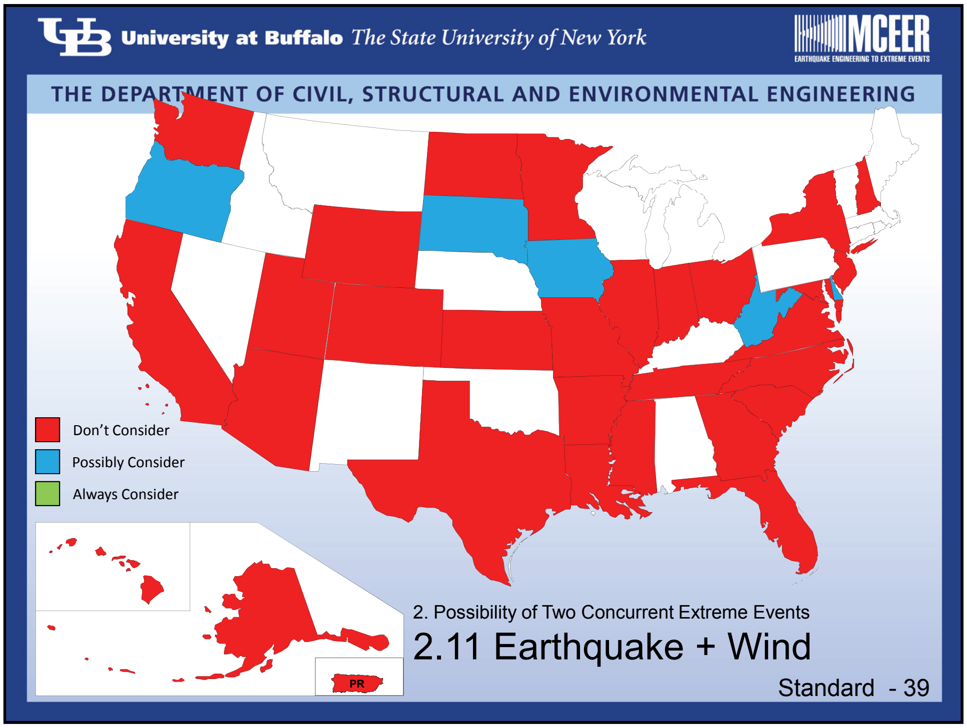
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.10 Fire + Wind
Special - 38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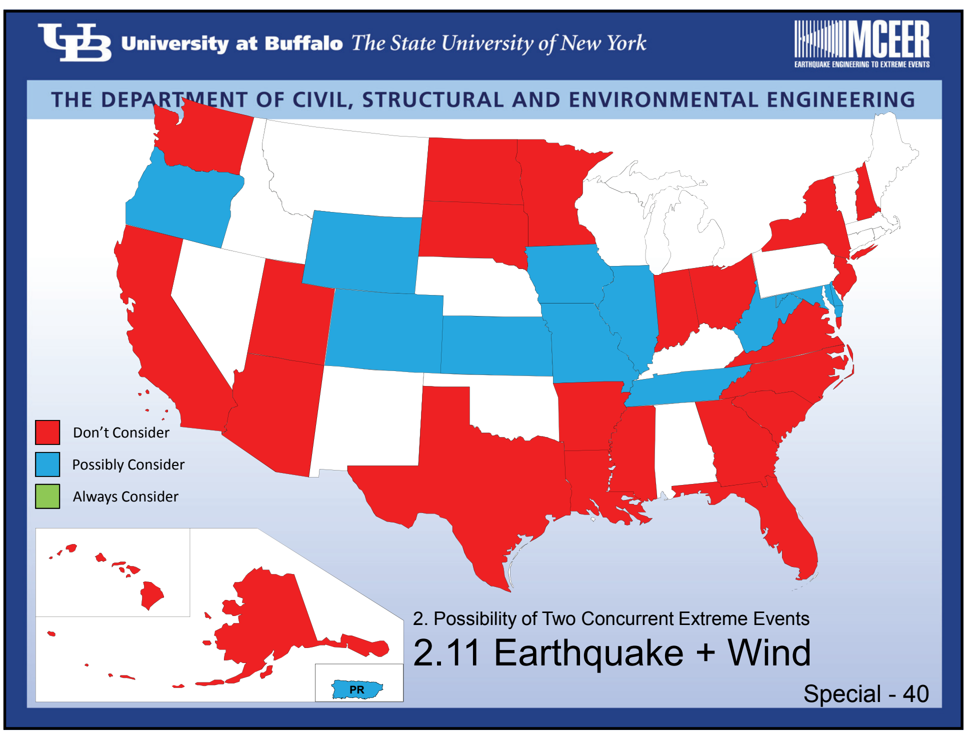
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.11 Earthquake + Wind
Standard - 39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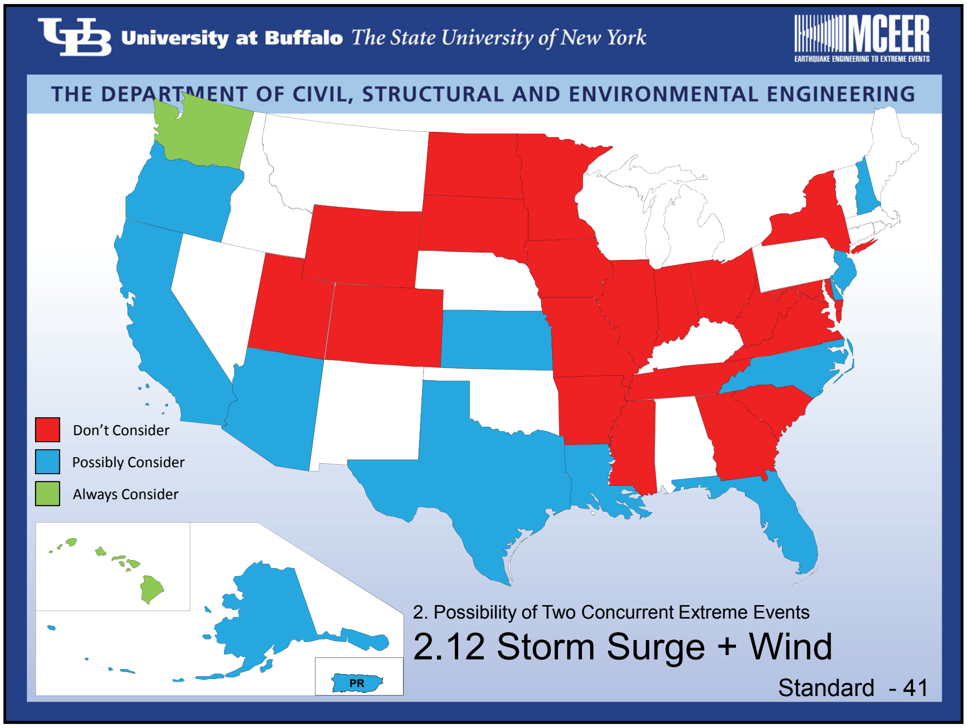
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.11 Earthquake + Wind
Special - 40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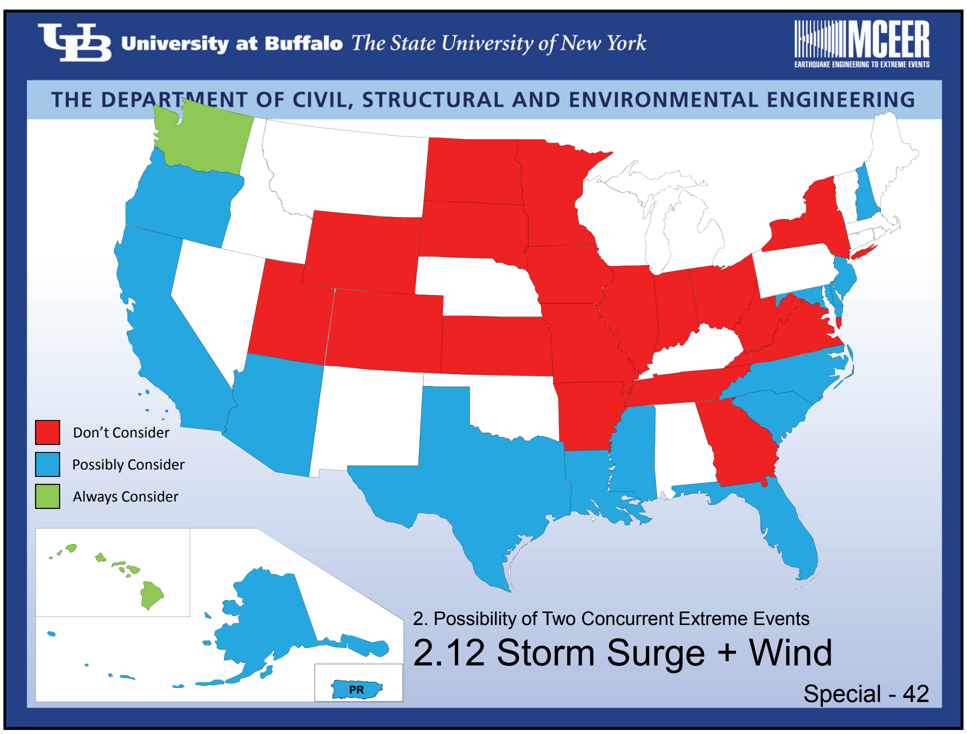
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.12 Storm Surge + Wind
Standard - 41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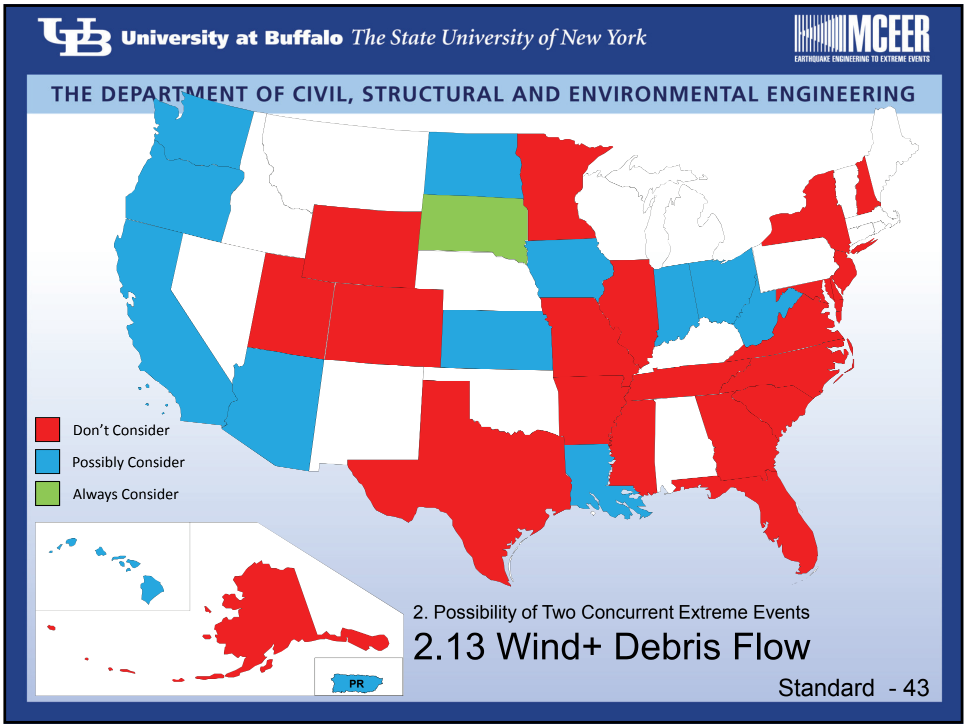
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.12 Storm Surge + Wind
Special - 42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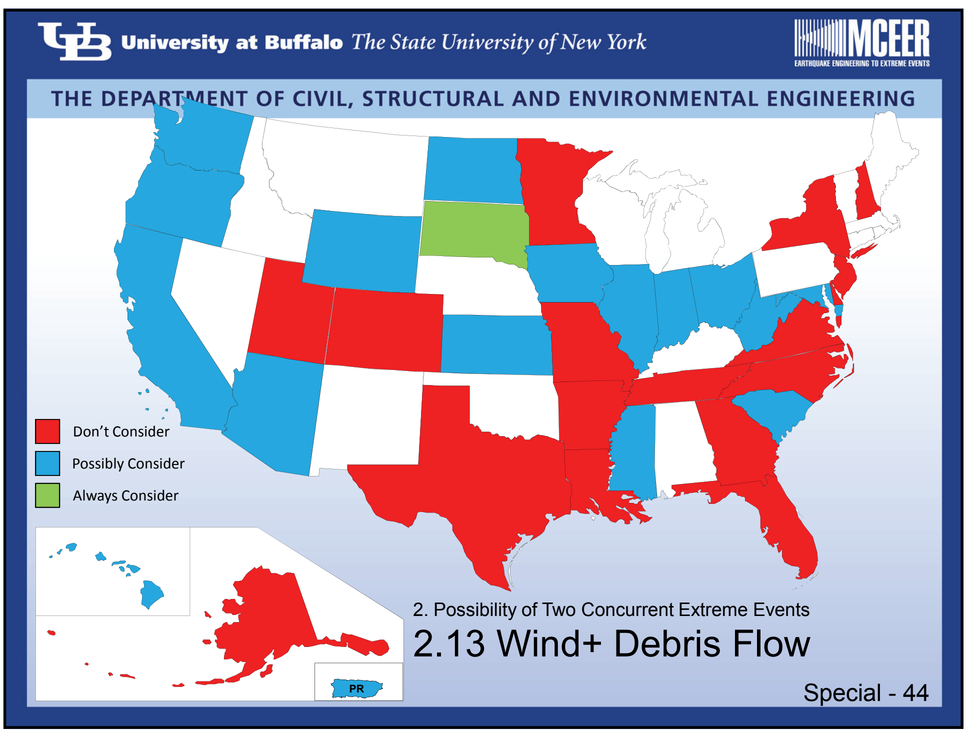
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.13 Wind+ Debris Flow
Standard - 43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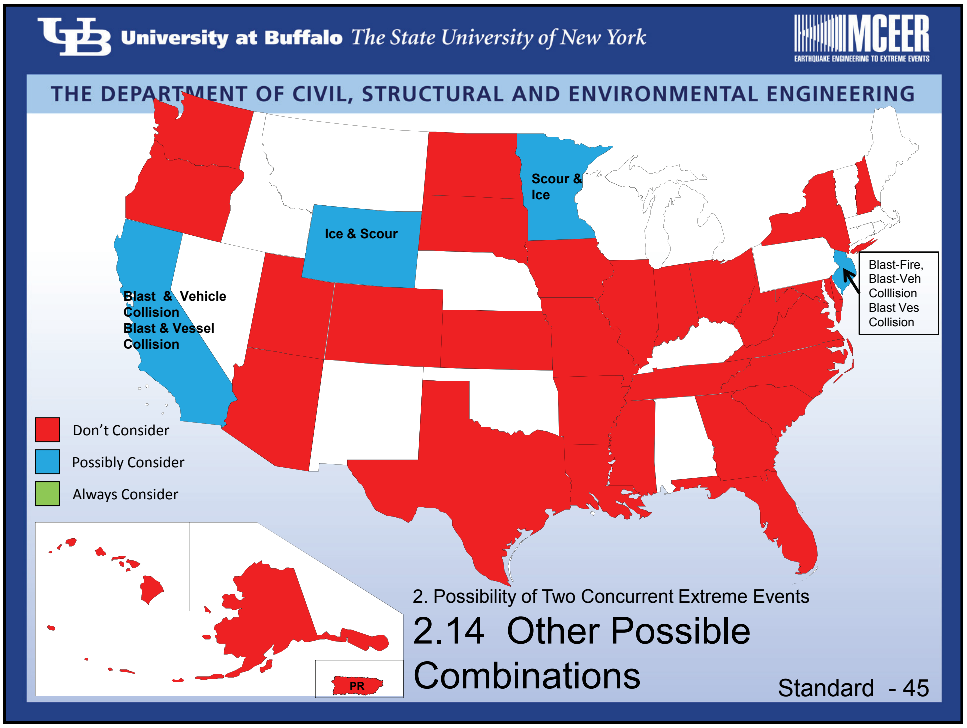
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.13 Wind+ Debris Flow
Special - 44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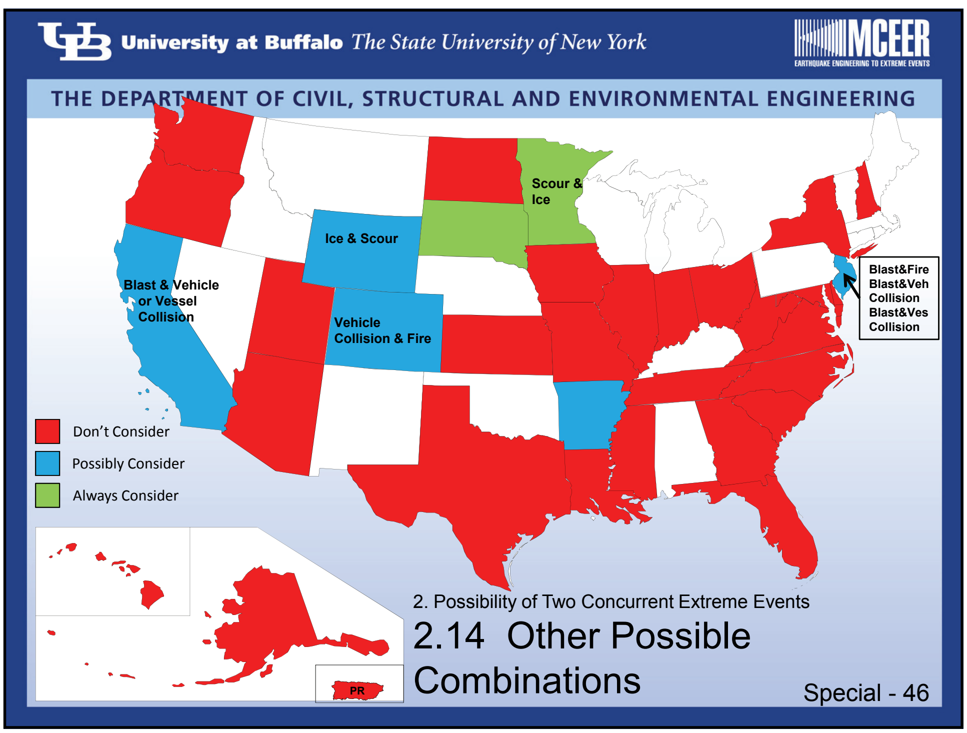
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Scour & Ice
Ice & Scour
Blast & Vehicle Collision
Blast & Vessel Collision
Blast-Fire, Blast-Veh Colllision Blast Ves Collision
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.14 Other Possible Combinations
Standard - 45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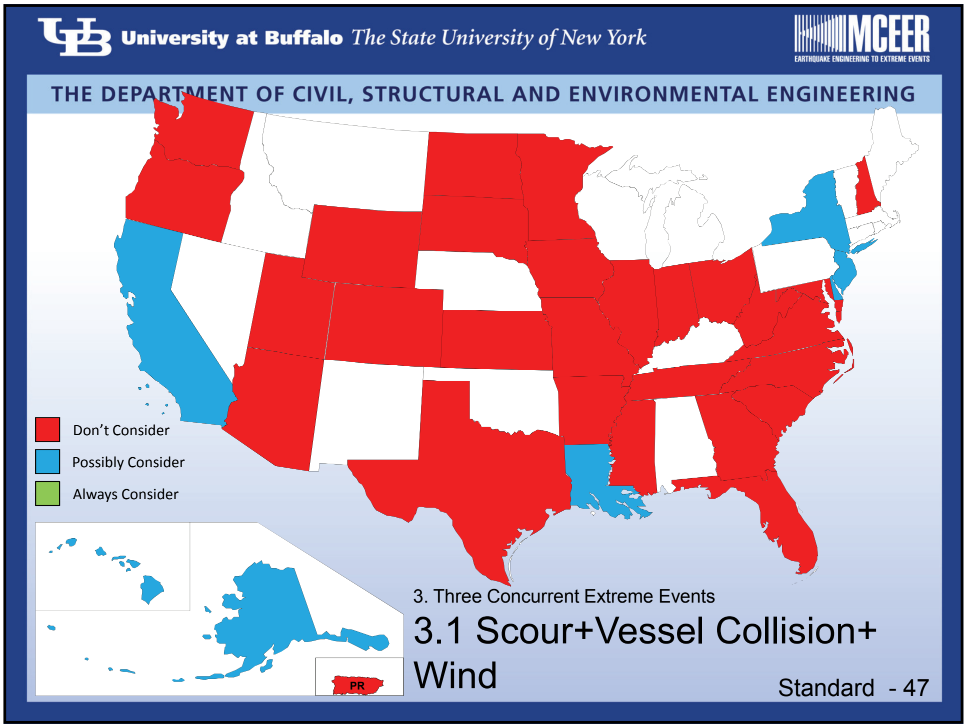
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Scour & Ice
Ice & Scour
Blast & Vehicle or Vessel Collision
Vehicle Collision & Fire
Blast&Fire Blast&Veh Collision Blast&Ves Collision
Don't Consider
Possibly Consider
Always Consider
PR
2. Possibility of Two Concurrent Extreme Events
2.14 Other Possible Combinations
Special - 46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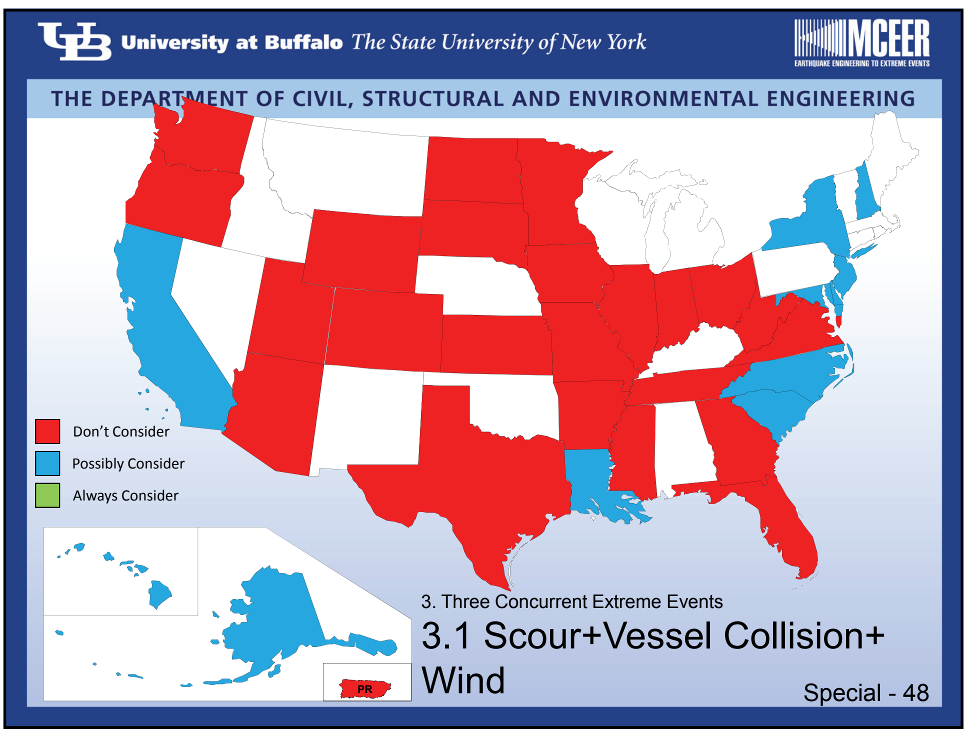
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.1 Scour+Vessel Collision+ Wind
Standard - 47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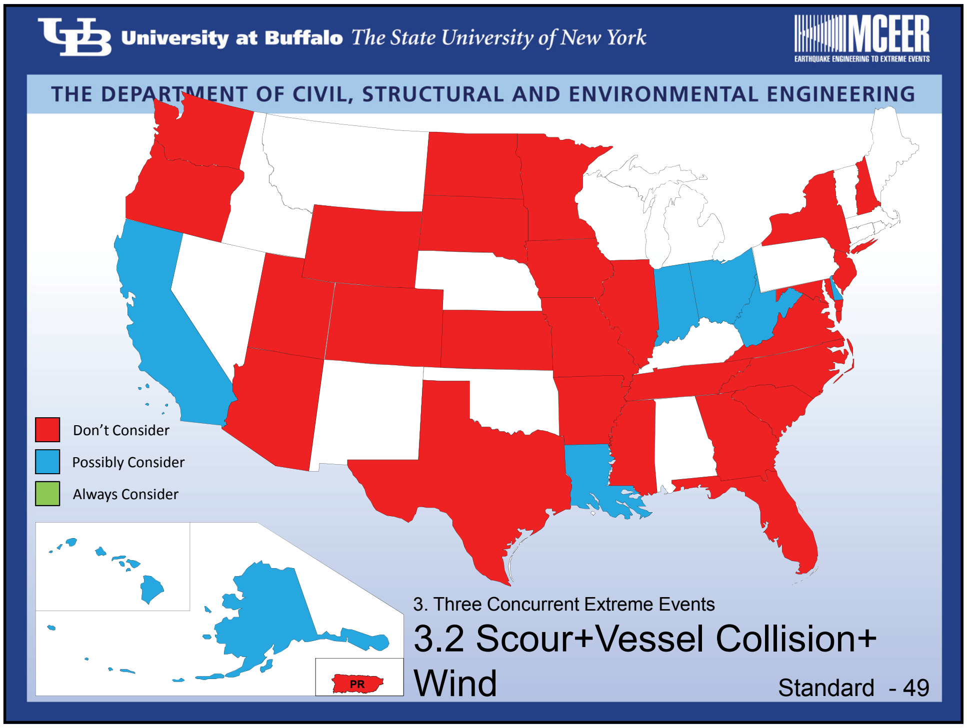
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.1 Scour+Vessel Collision+ Wind
Special - 48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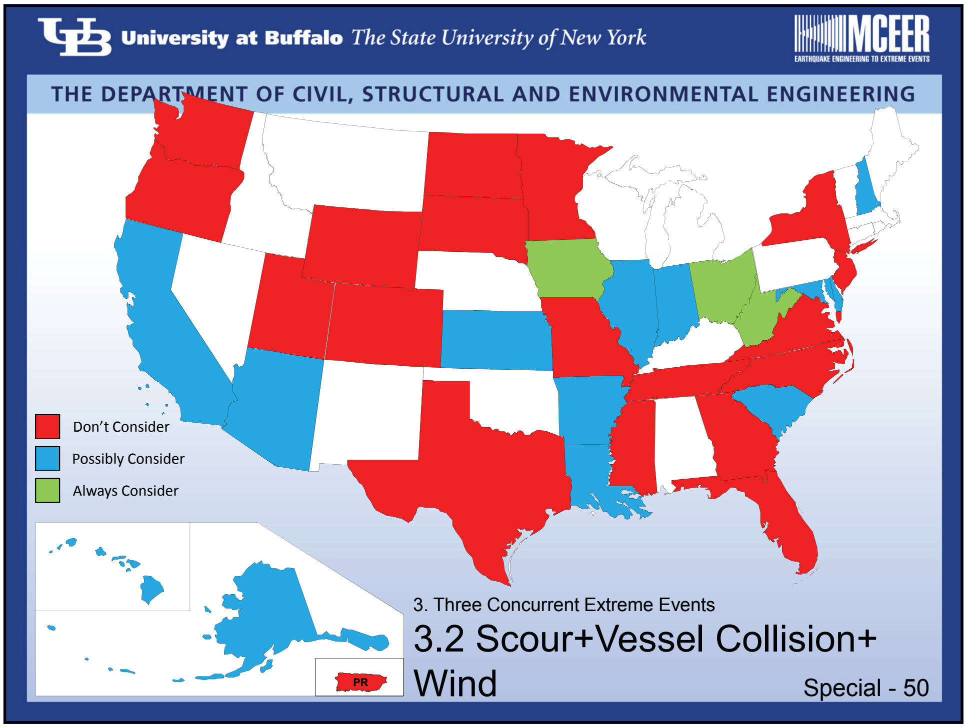
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.2 Scour+Vessel Collision+ Wind
Standard - 49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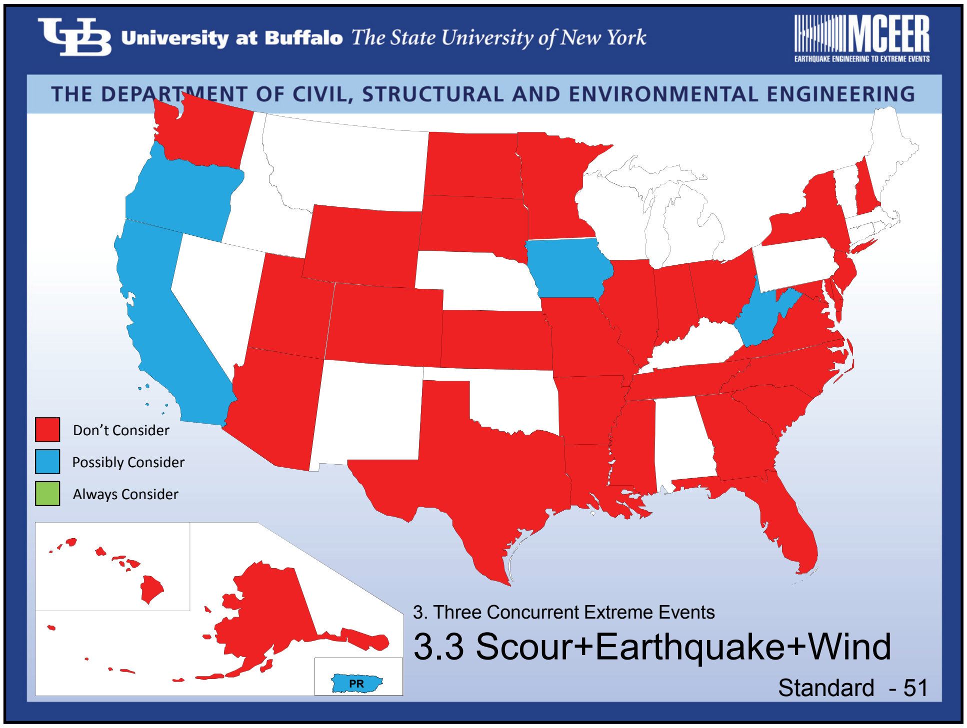
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.2 Scour+Vessel Collision+ Wind
Special - 50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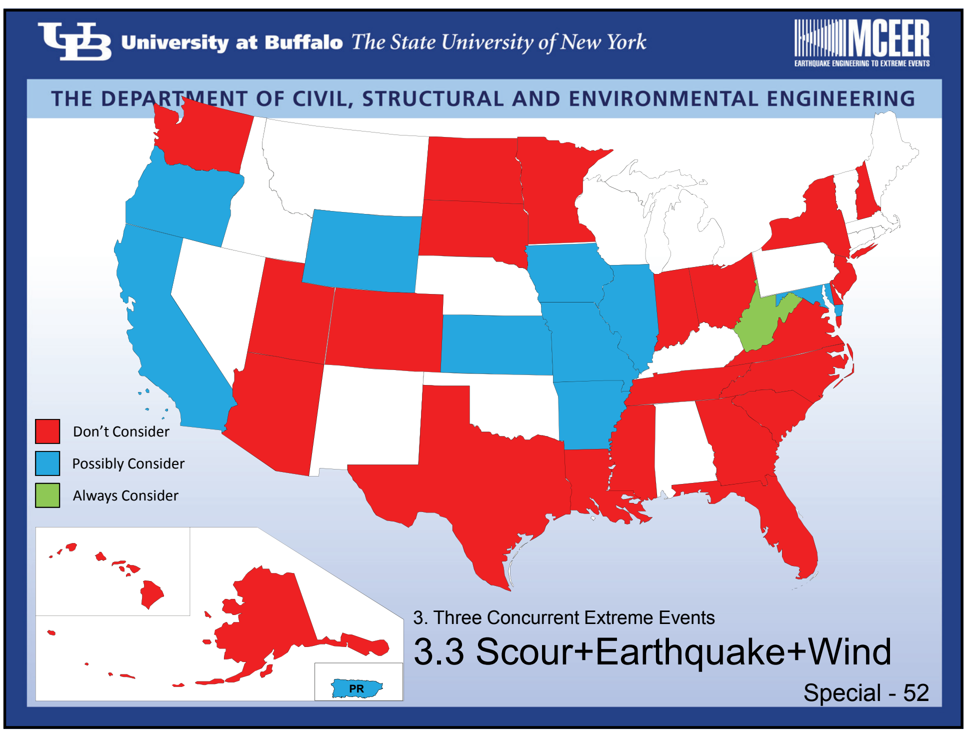
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.3 Scour+Earthquake+Wind
Standard - 51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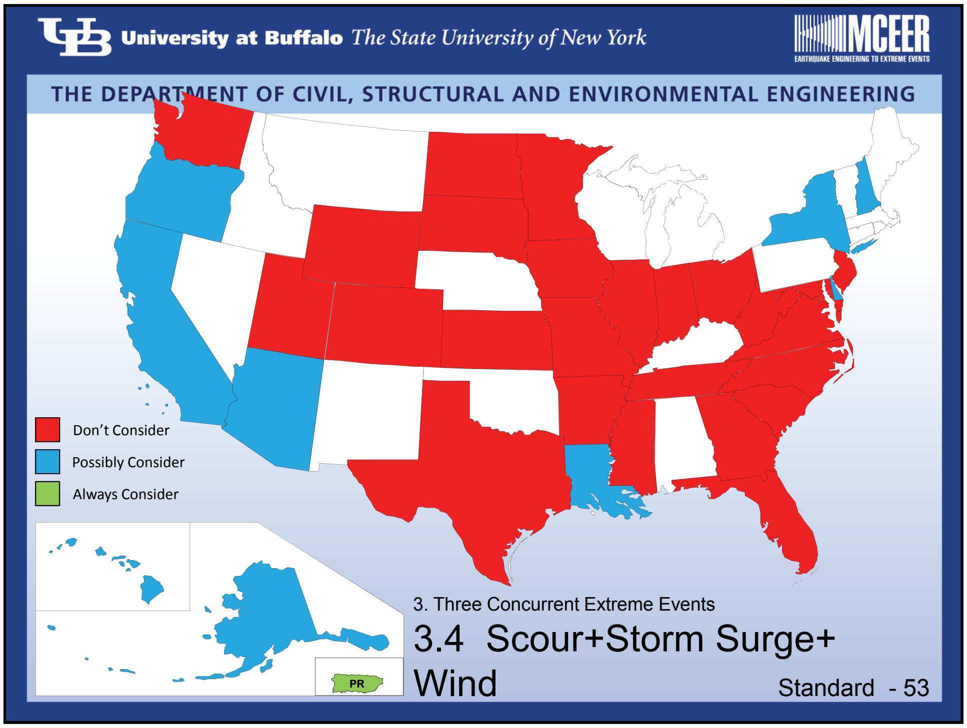
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.3 Scour+Earthquake+Wind
Special - 52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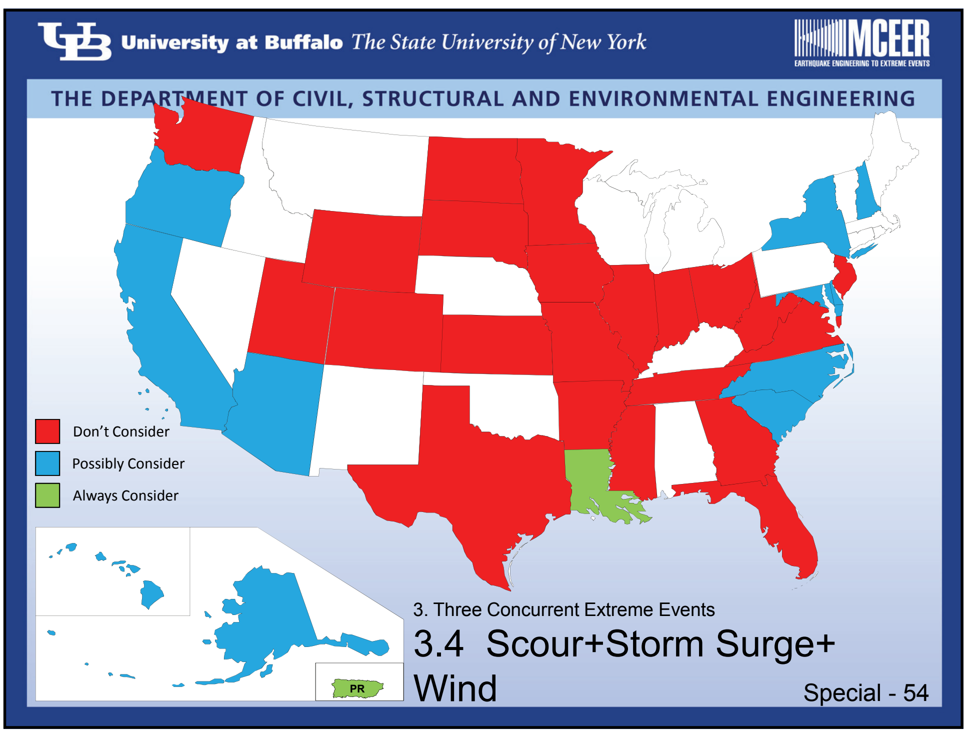
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.4 Scour+Storm Surge+ Wind
Standard - 53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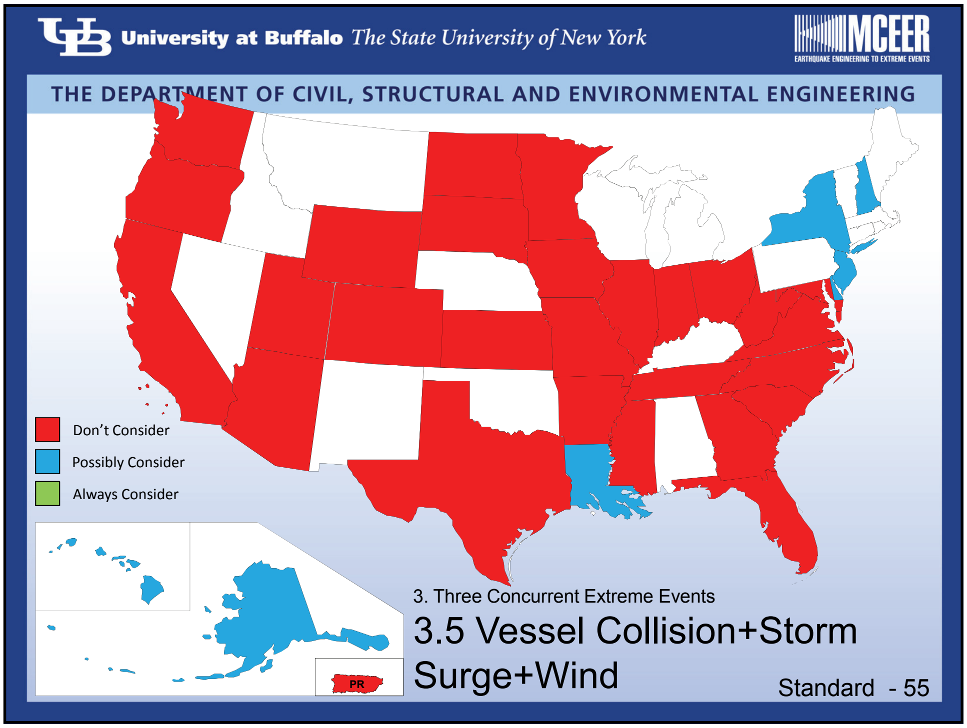
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.4 Scour+Storm Surge+ Wind
Special - 54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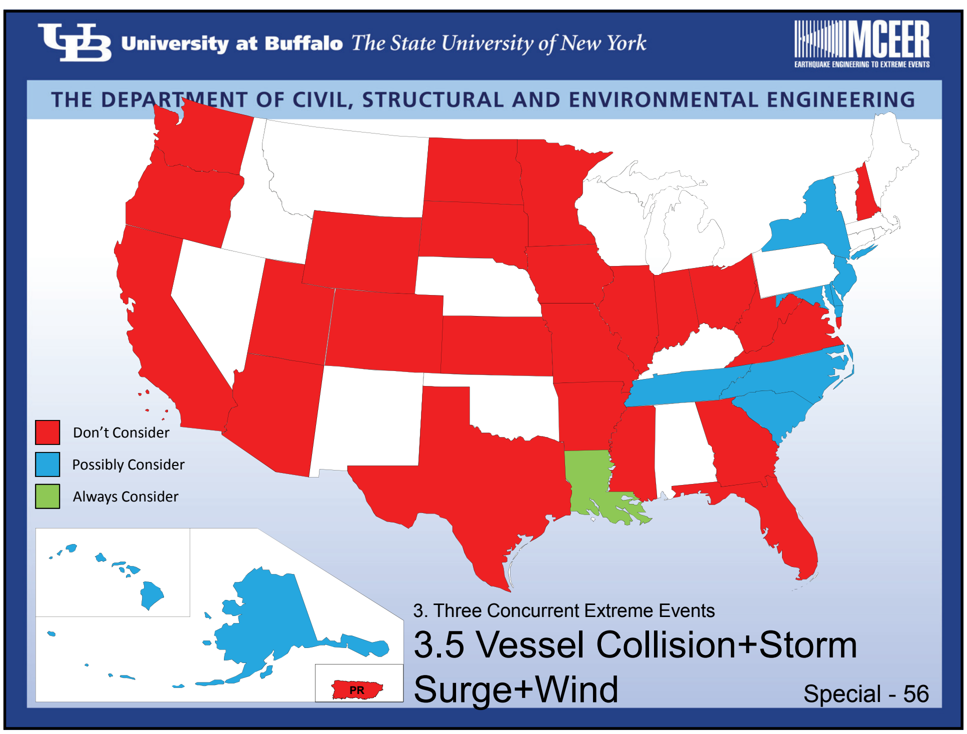
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.5 Vessel Collision+Storm Surge+Wind
Standard - 55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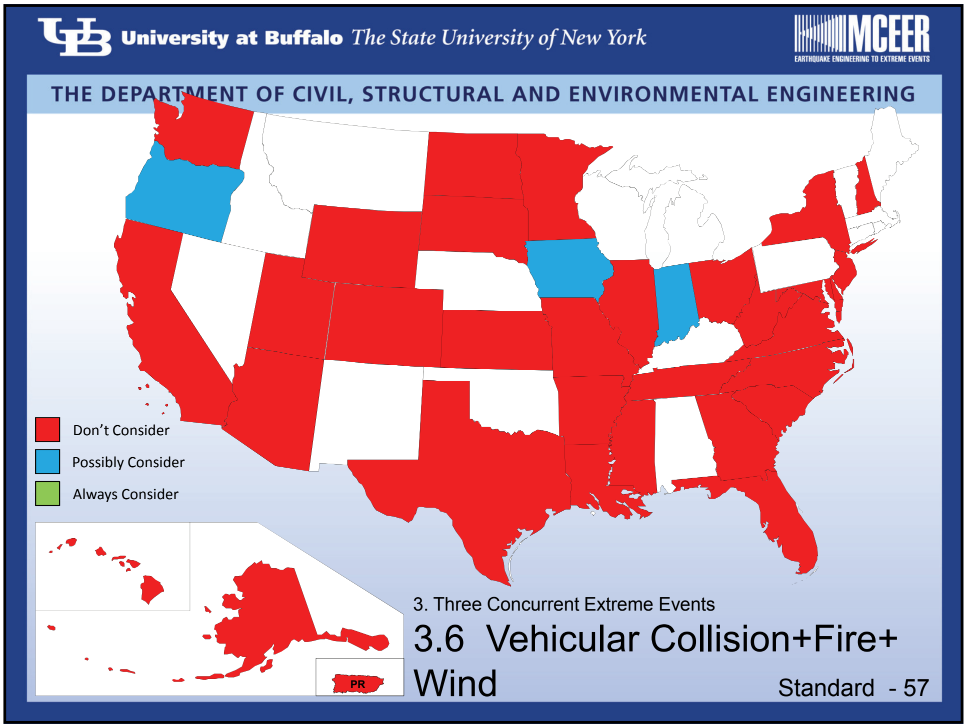
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.5 Vessel Collision+Storm Surge+Wind
Special - 56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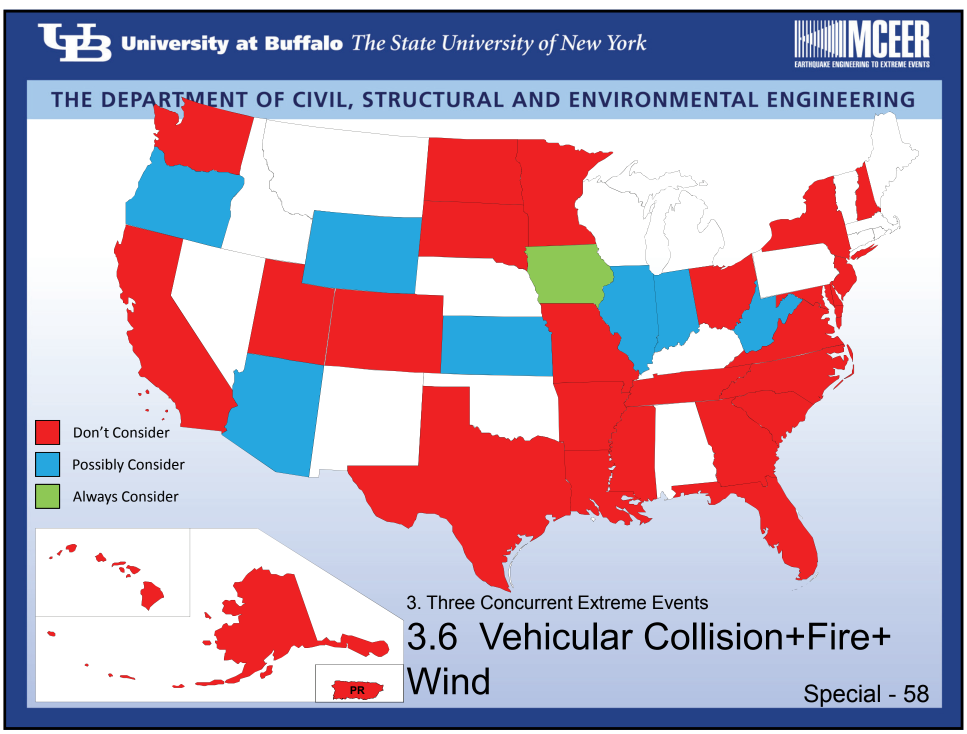
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.6 Vehicular Collision+Fire+ Wind
Standard - 57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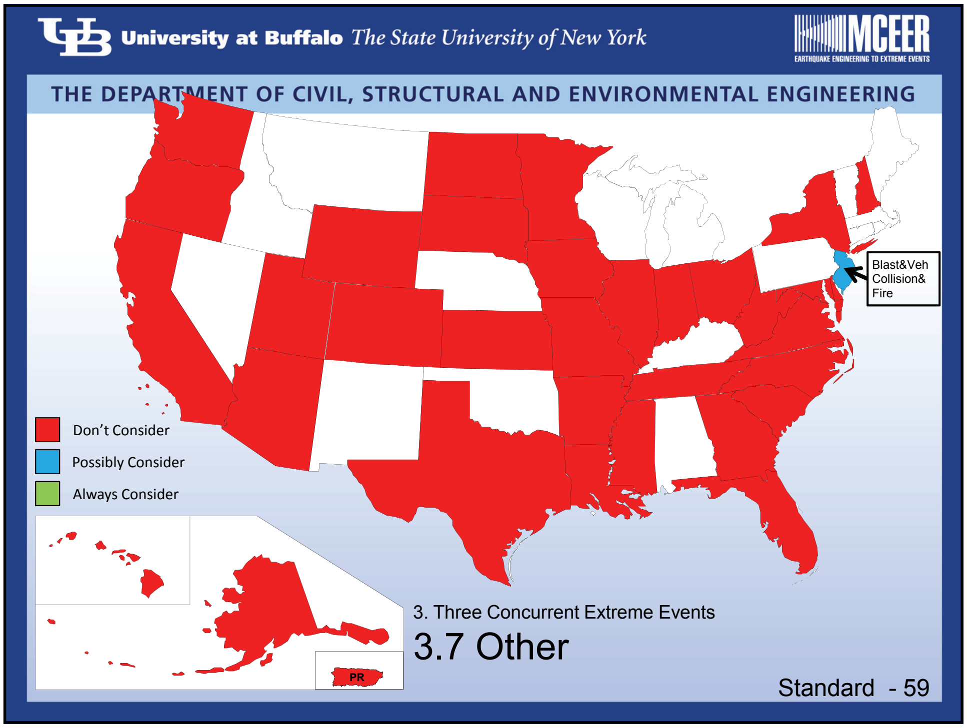
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.6 Vehicular Collision+Fire+ Wind
Special - 58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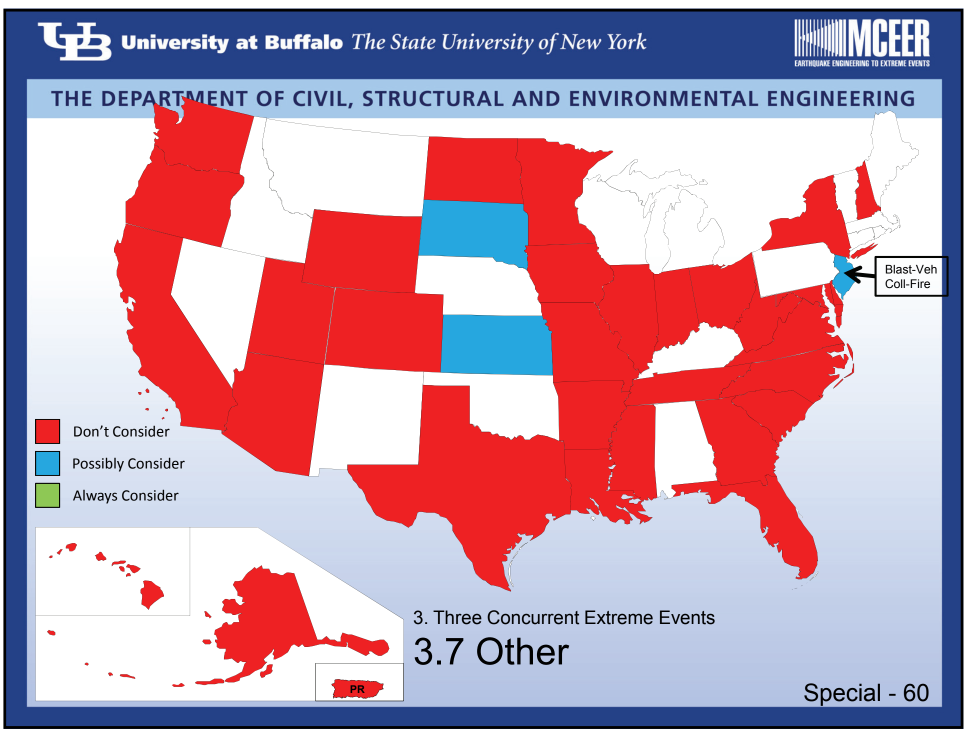
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Blast&Veh Collision& Fire
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.7 Other
Standard - 59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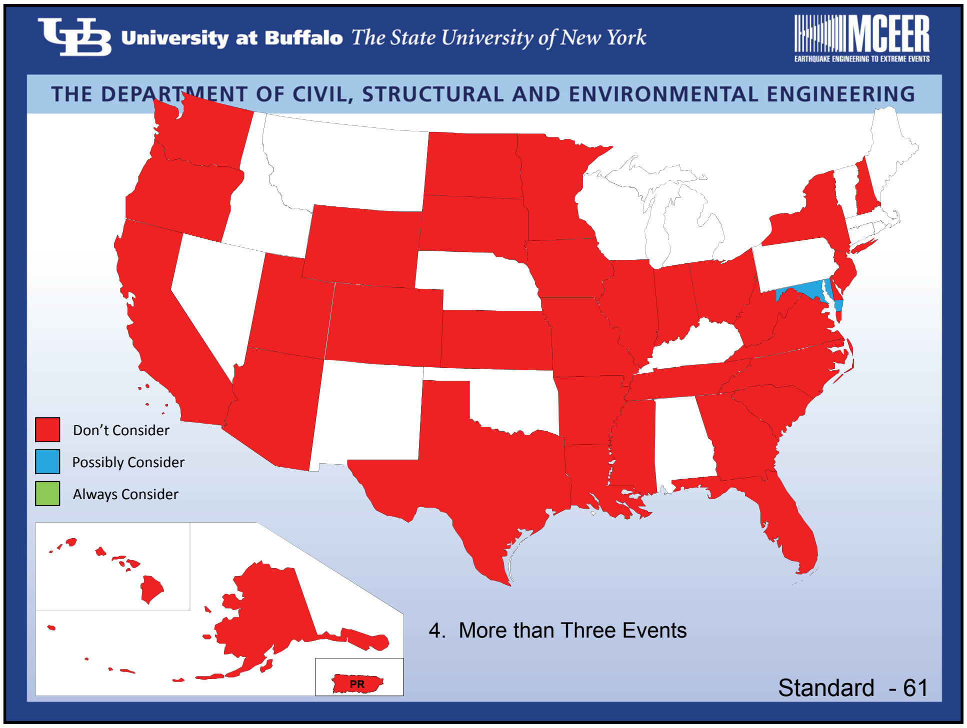
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Blast-Veh Coll-Fire
Don't Consider
Possibly Consider
Always Consider
PR
3. Three Concurrent Extreme Events
3.7 Other
Special - 60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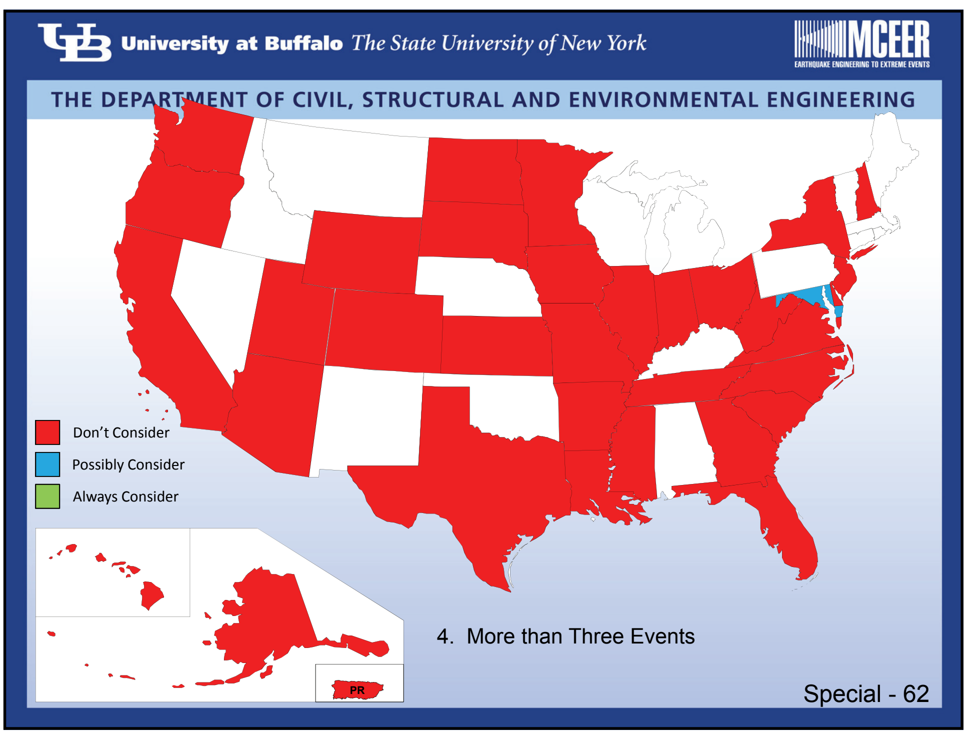
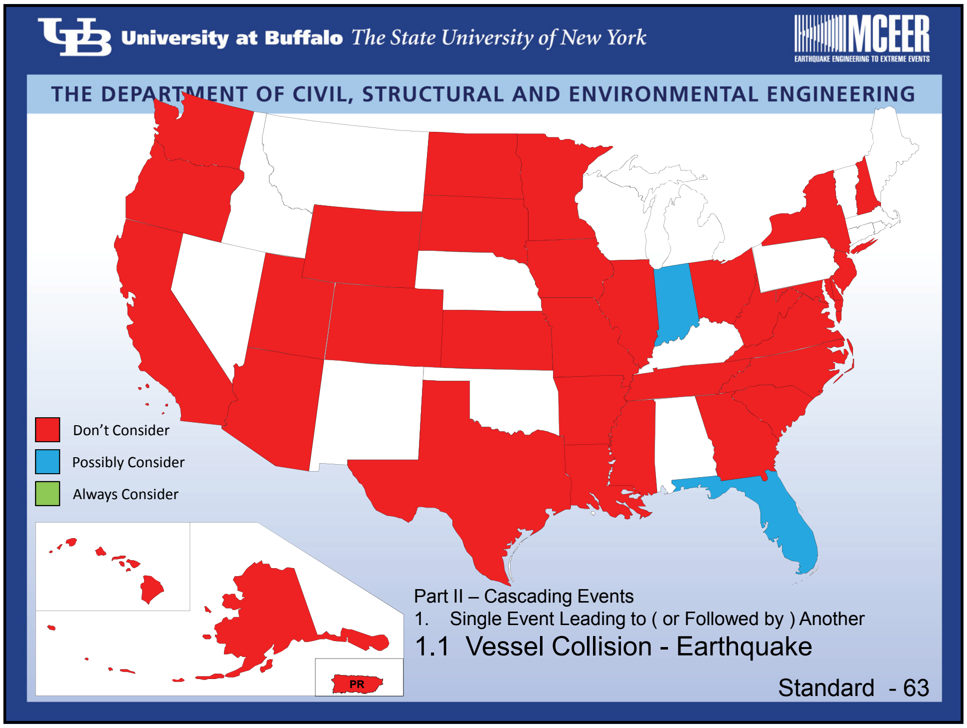
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
4. More than Three Events
Standard - 61


University at Buffalo The State University of New York
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
4. More than Three Events
Special - 62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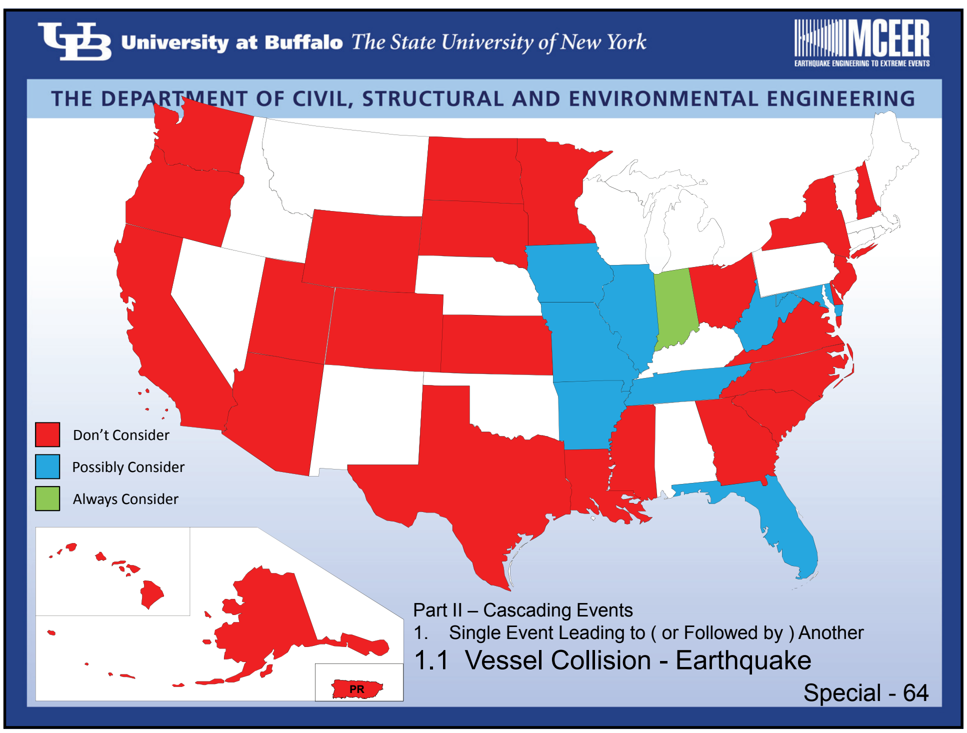
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.1 Vessel Collision - Earthquake
Standard - 63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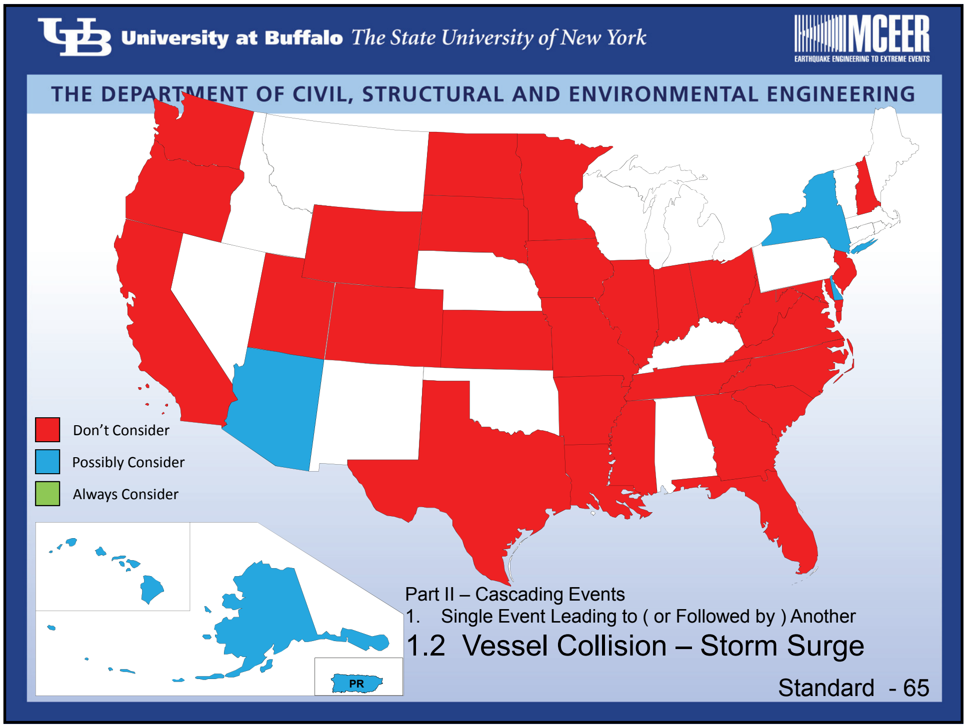
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.1 Vessel Collision - Earthquake
Special - 64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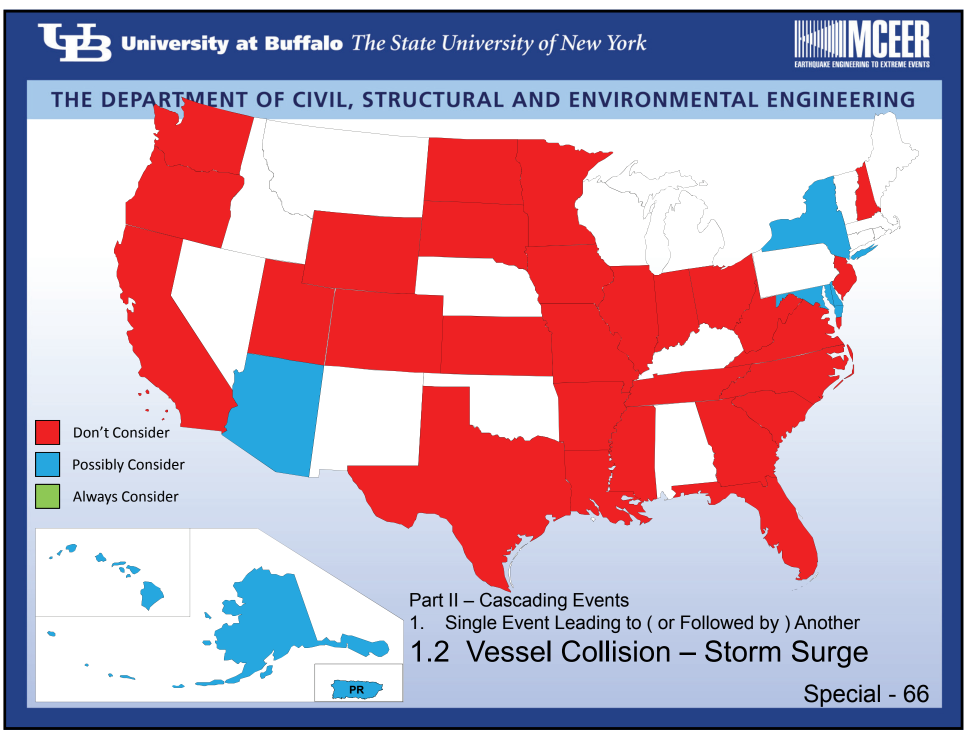
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.2 Vessel Collision – Storm Surge
Standard - 65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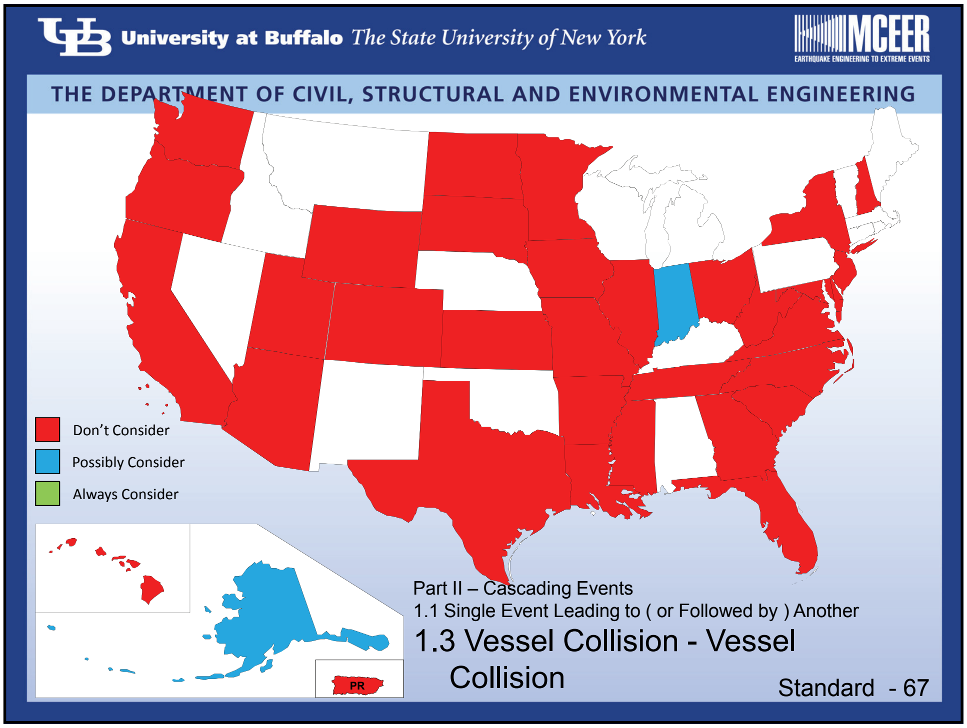
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.2 Vessel Collision – Storm Surge
Special - 66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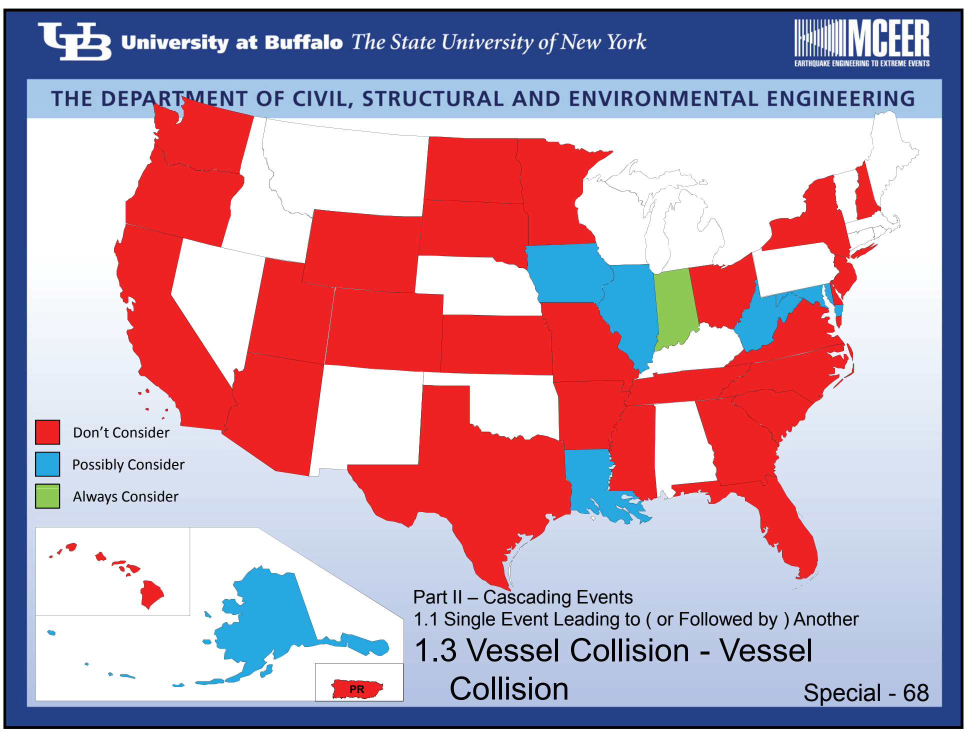
Part II – Cascading Events
1.1 Single Event Leading to (or Followed by) Another
1.3 Vessel Collision - Vessel Collision
Standard - 67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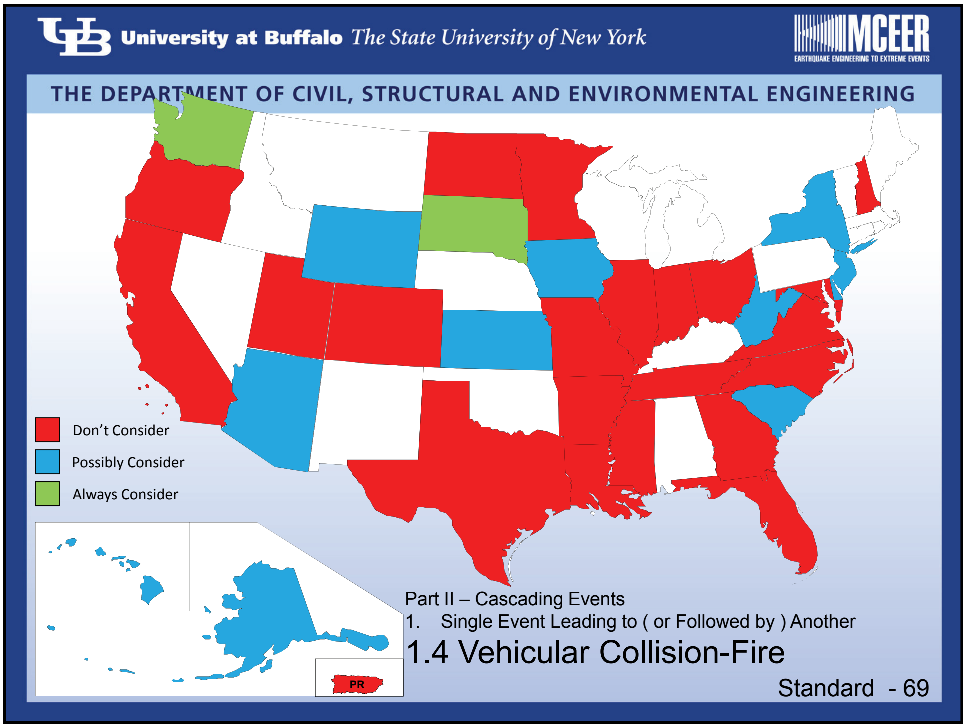
Part II – Cascading Events
1.1 Single Event Leading to (or Followed by) Another
1.3 Vessel Collision - Vessel Collision
Special - 68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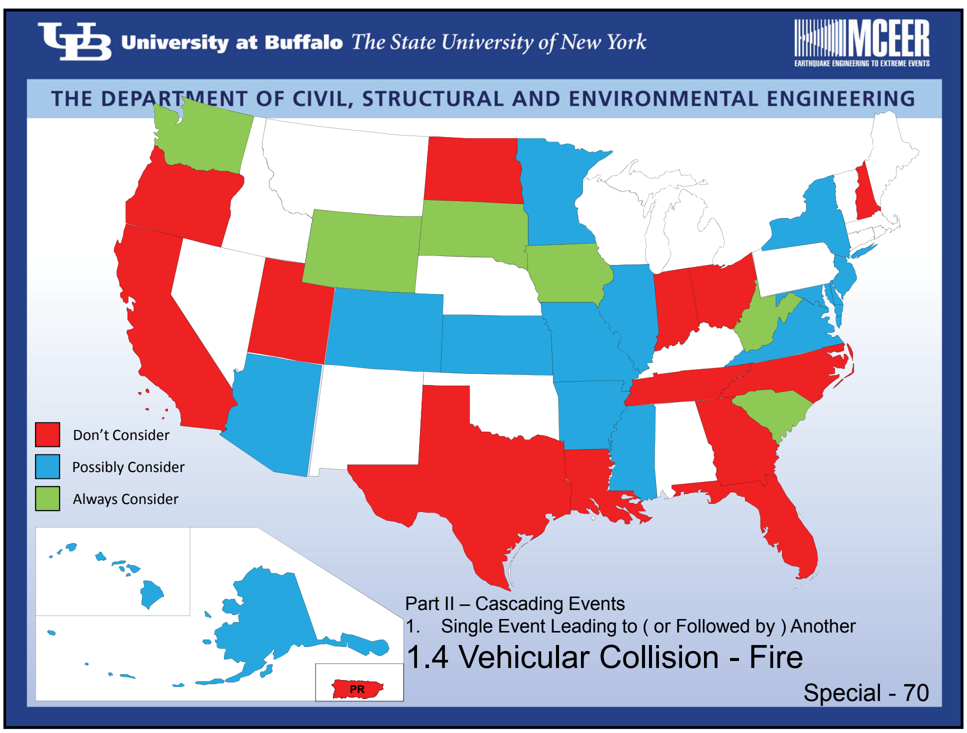
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.4 Vehicular Collision-Fire
Standard - 69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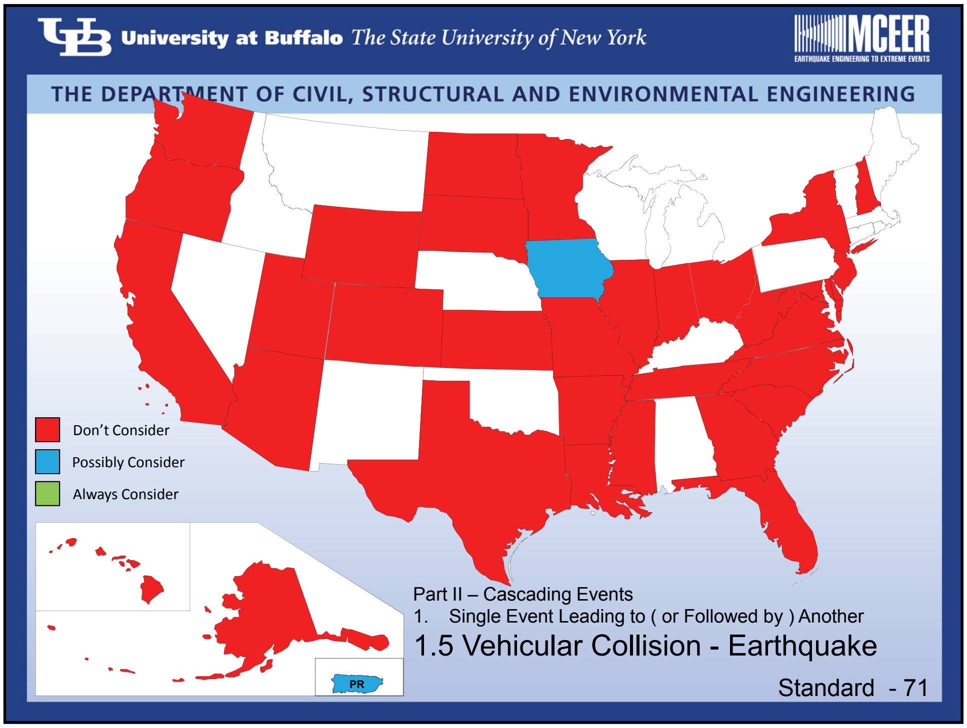
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.4 Vehicular Collision - Fire
Special - 70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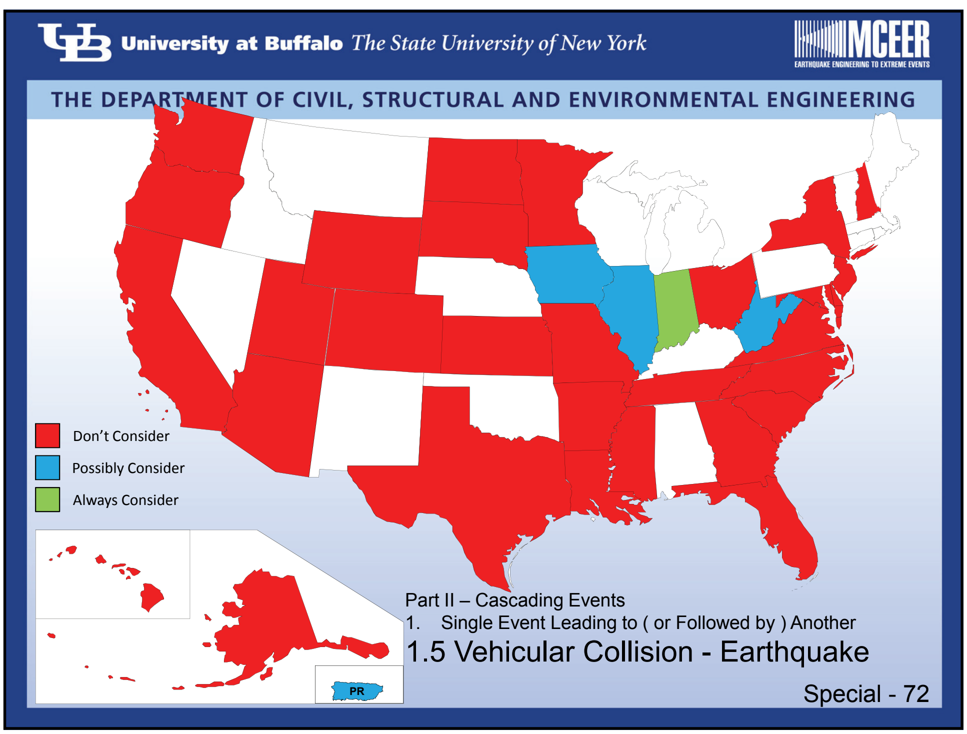
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.5 Vehicular Collision - Earthquake
Standard - 71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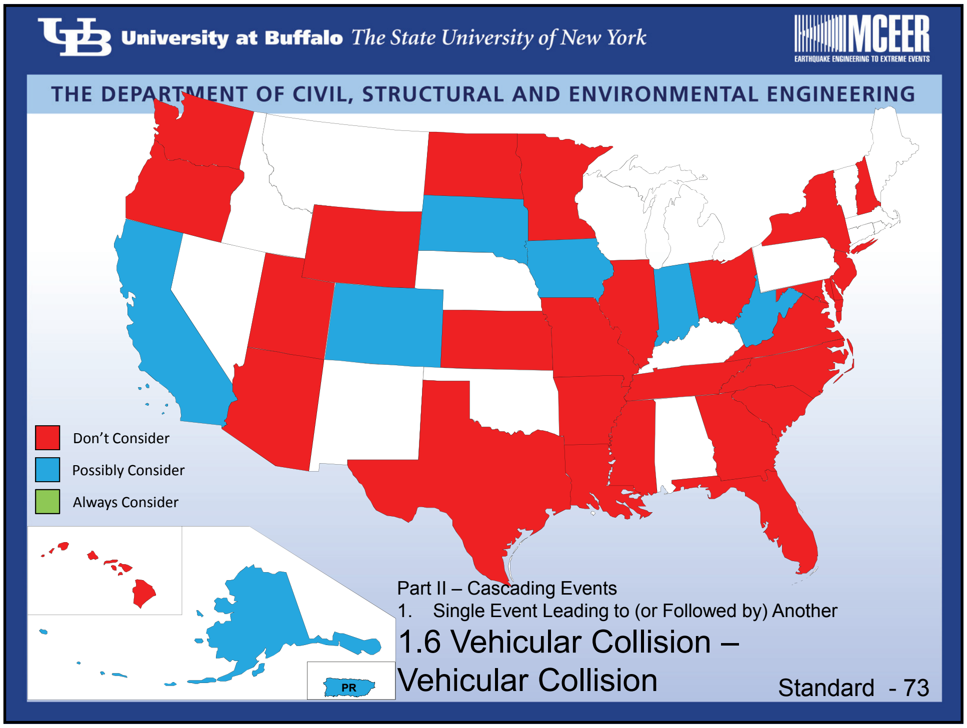
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.5 Vehicular Collision - Earthquake
Special - 72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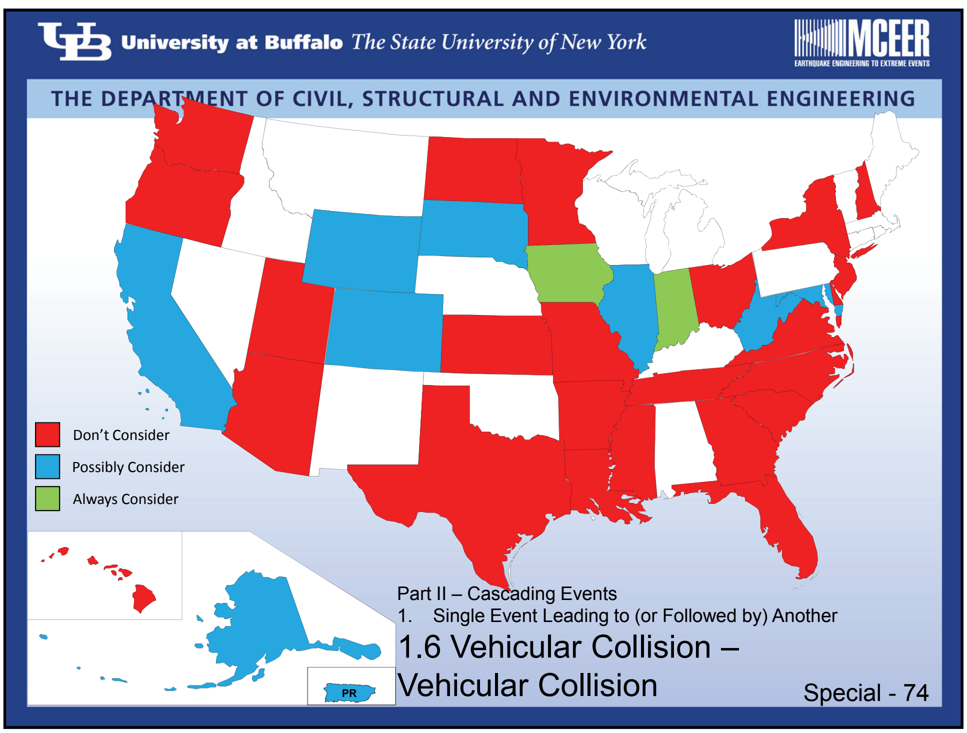
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.6 Vehicular Collision – Vehicular Collision
Standard - 73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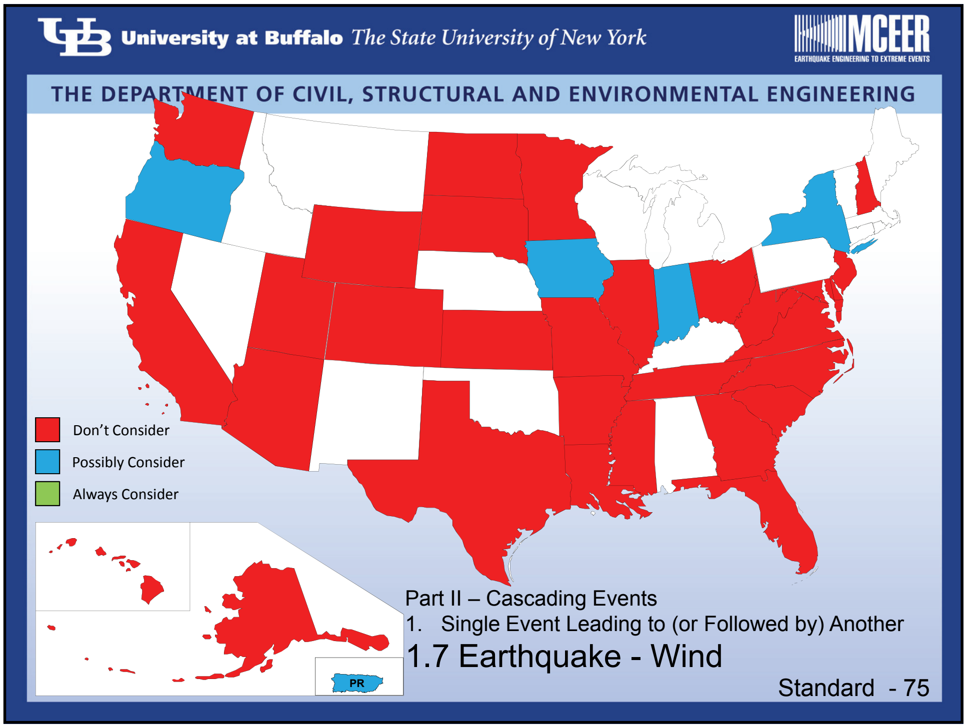
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.6 Vehicular Collision – Vehicular Collision
Special - 74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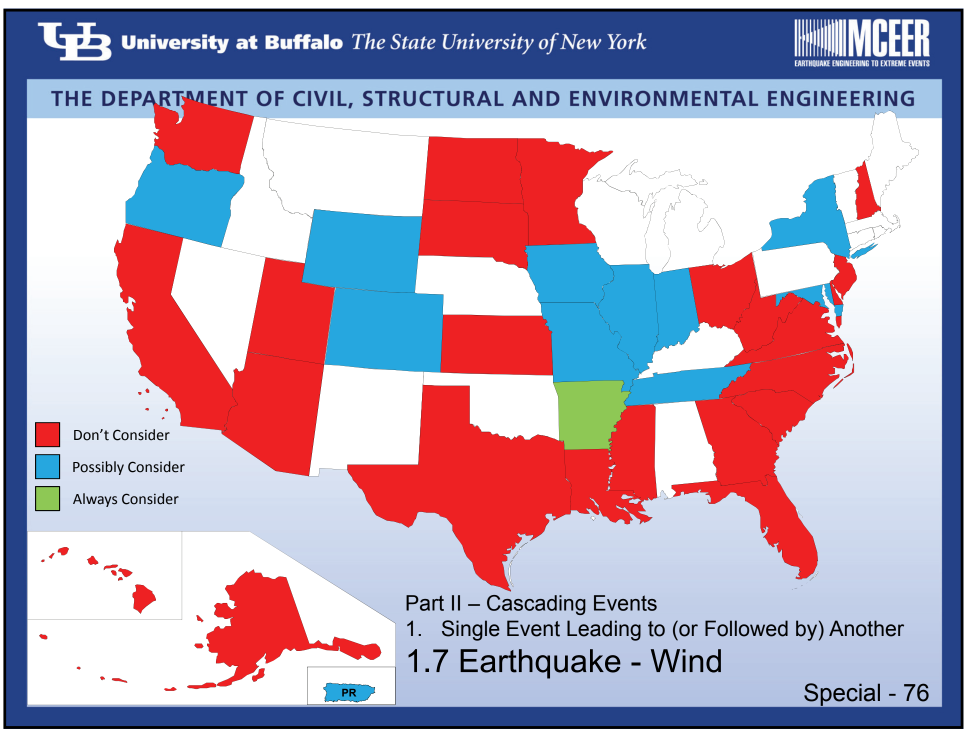
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.7 Earthquake - Wind
Standard - 75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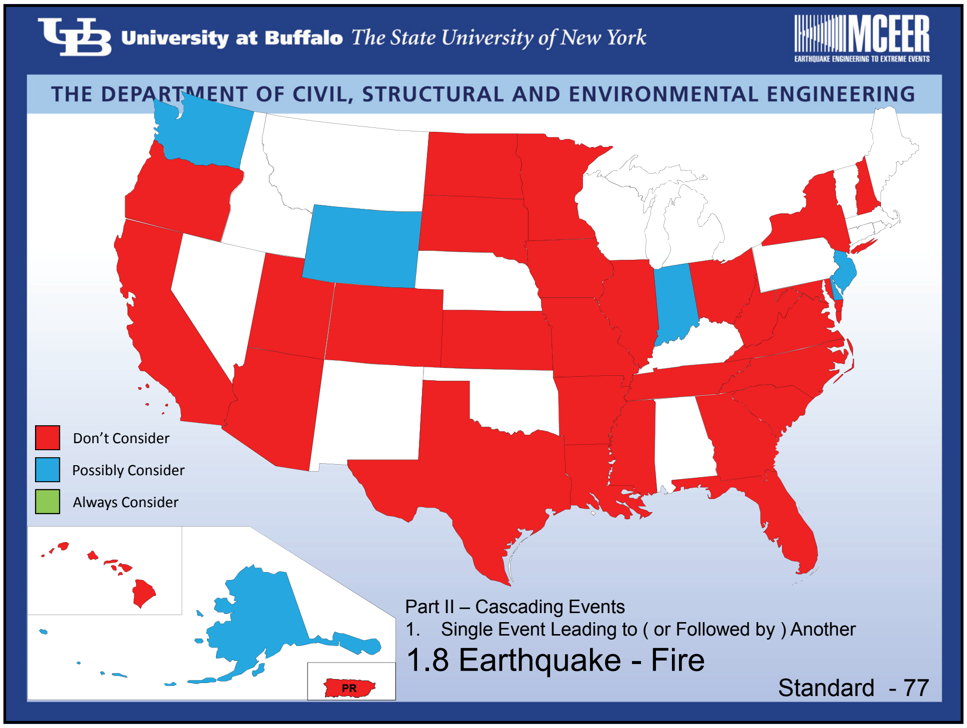
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.7 Earthquake - Wind
Special - 76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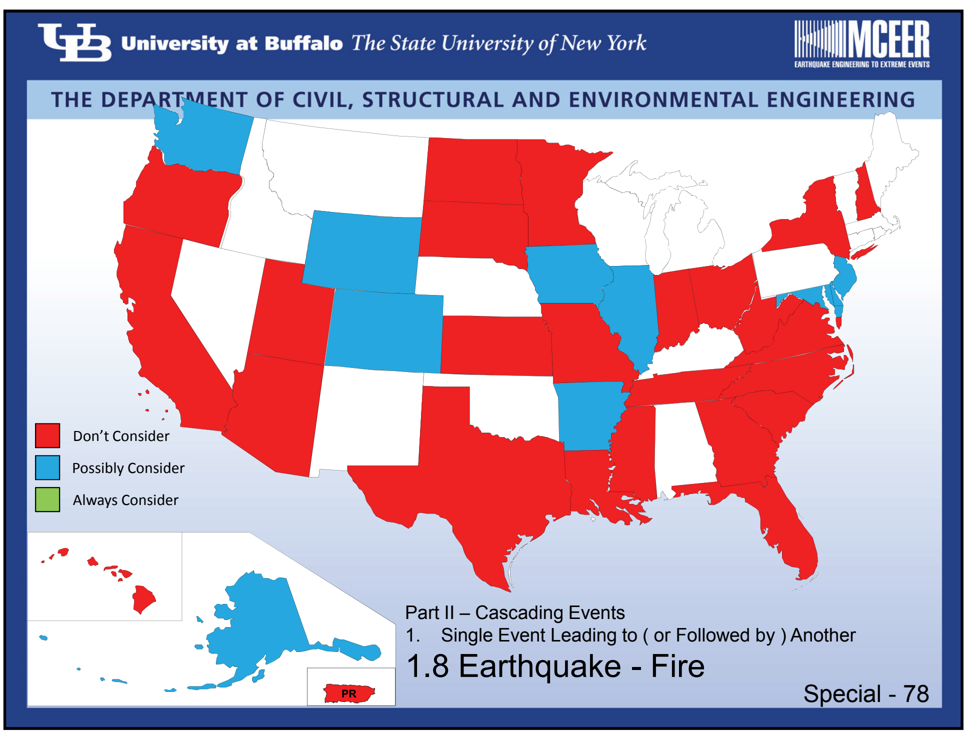
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.8 Earthquake - Fire
Standard - 77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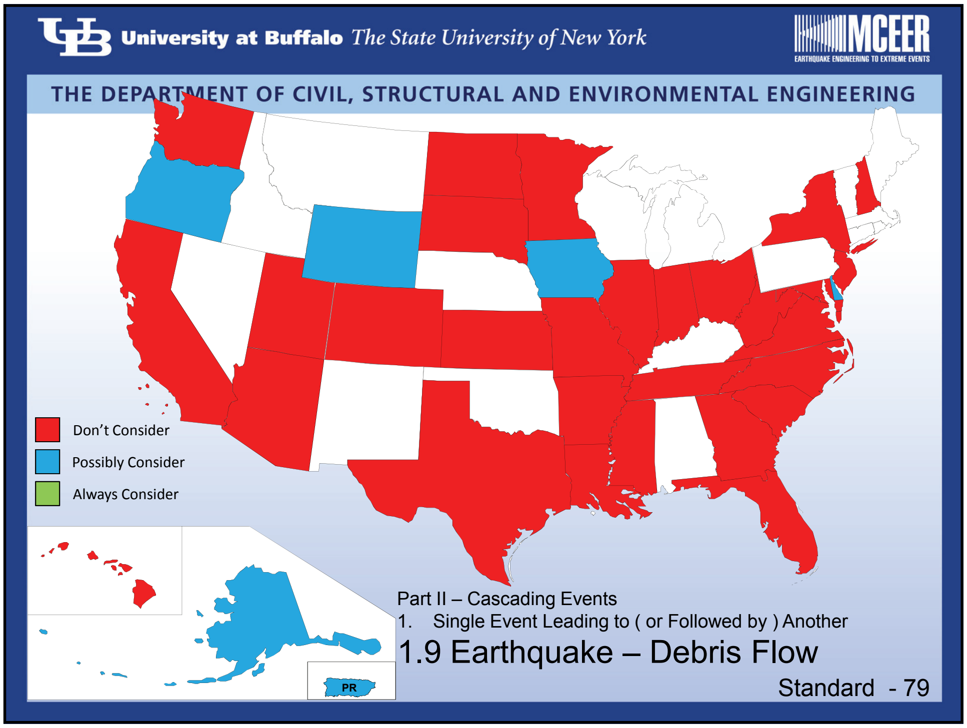
1. Single Event Leading to (or Followed by) Another
1.8 Earthquake - Fire
Special - 78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Always Consider
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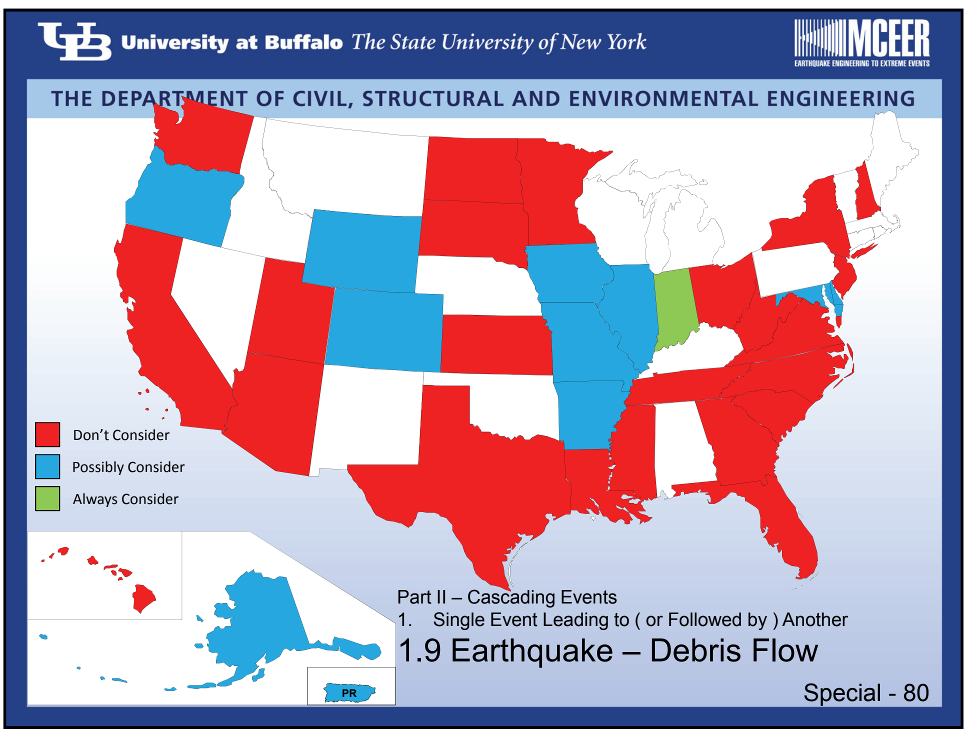
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.9 Earthquake – Debris Flow
Standard - 79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Don't Consider
Possibly Consider
Always Consider
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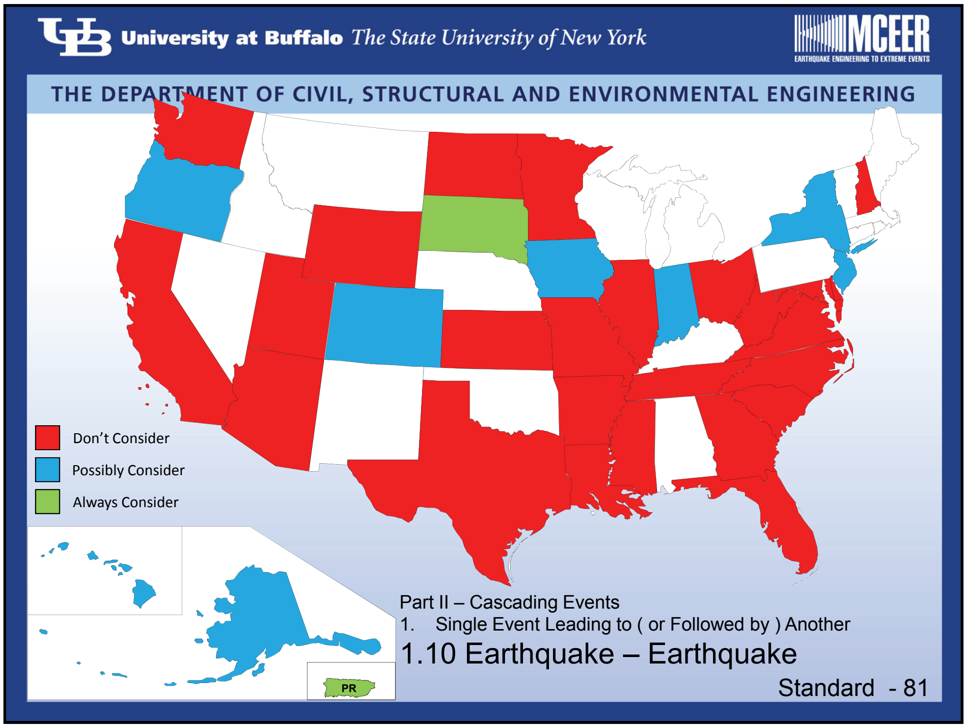
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.9 Earthquake – Debris Flow
Special - 80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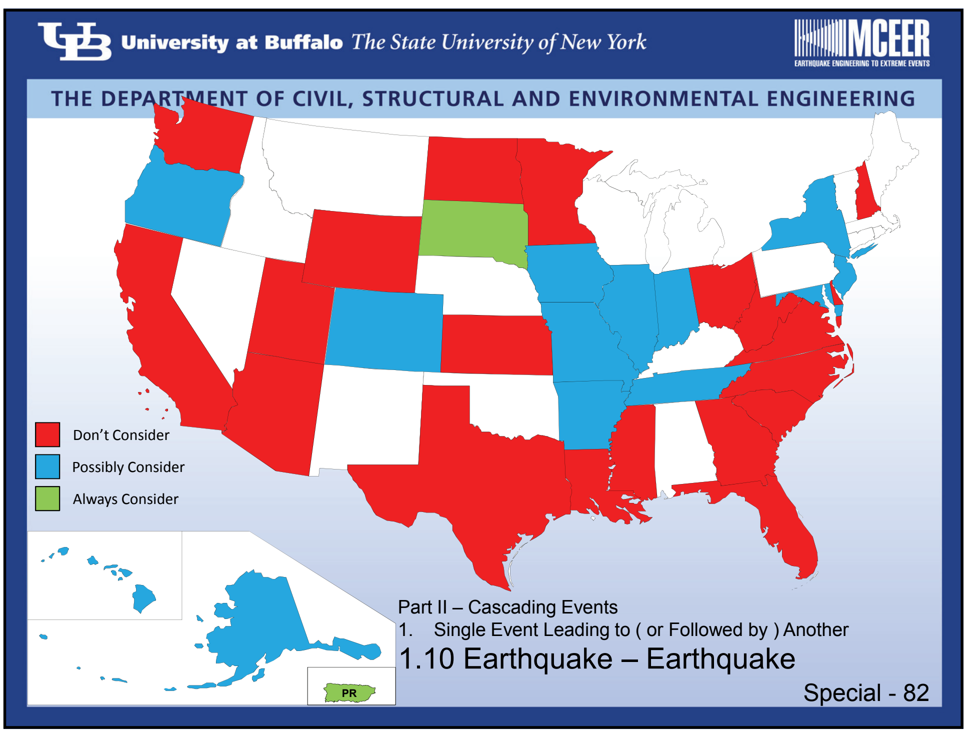
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.10 Earthquake – Earthquake
Standard - 81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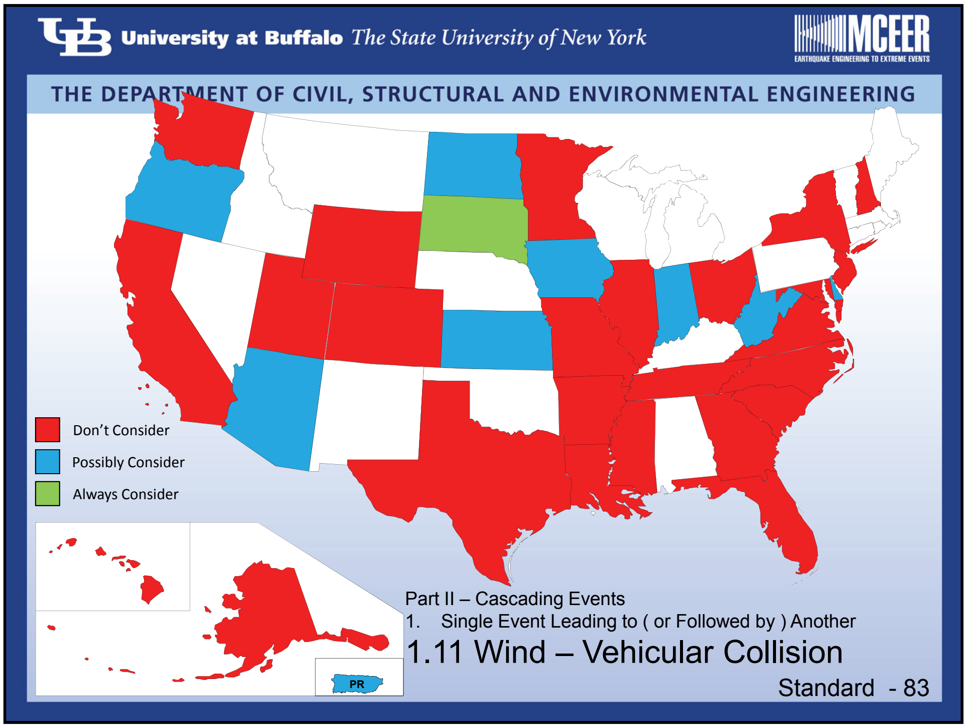
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.10 Earthquake – Earthquake
Special - 82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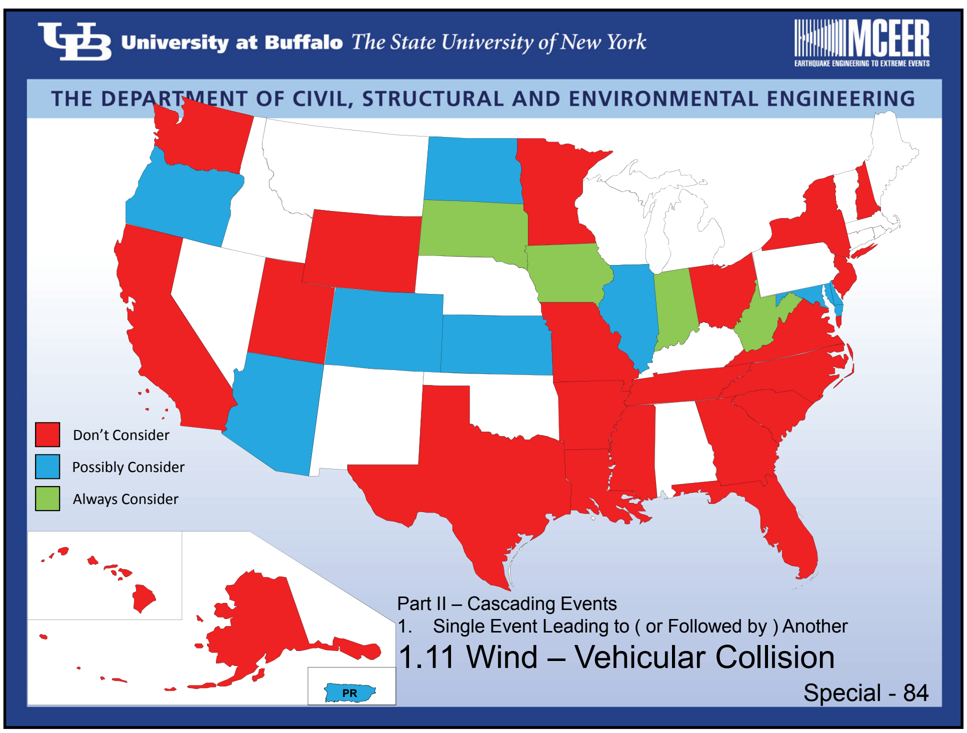
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.11 Wind – Vehicular Collision
Standard - 83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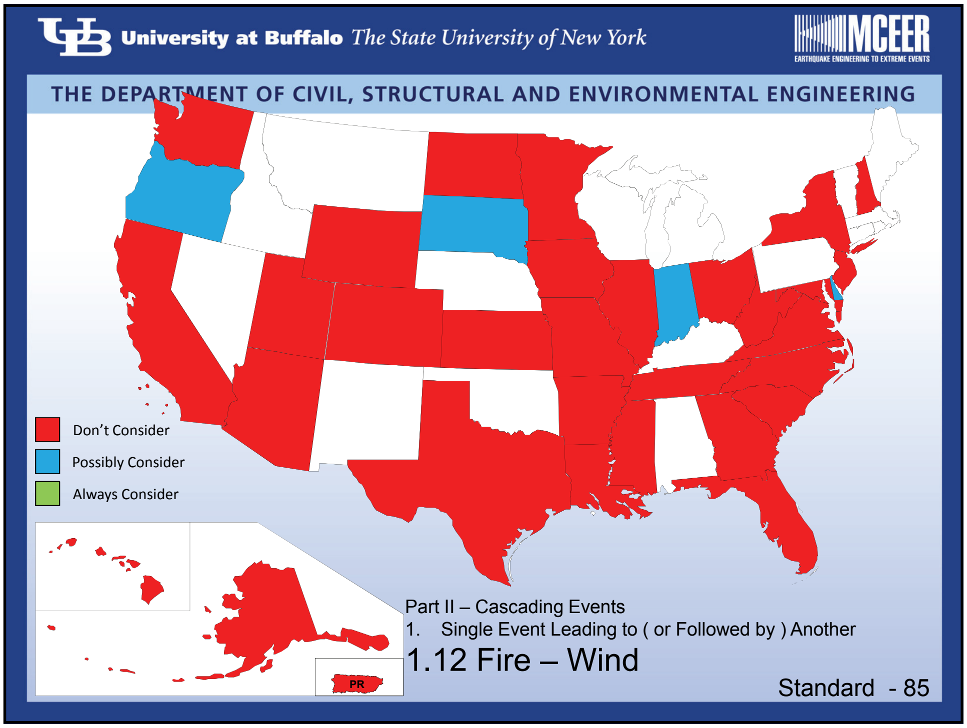
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.11 Wind – Vehicular Collision
Special - 84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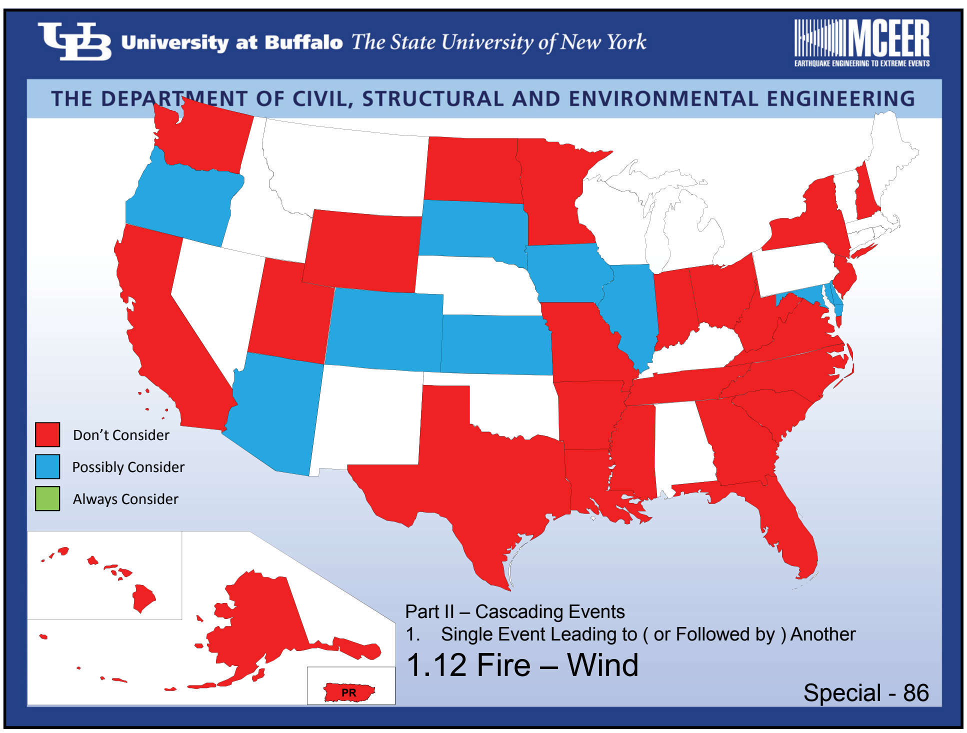
THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.12 Fire – Wind
Standard - 85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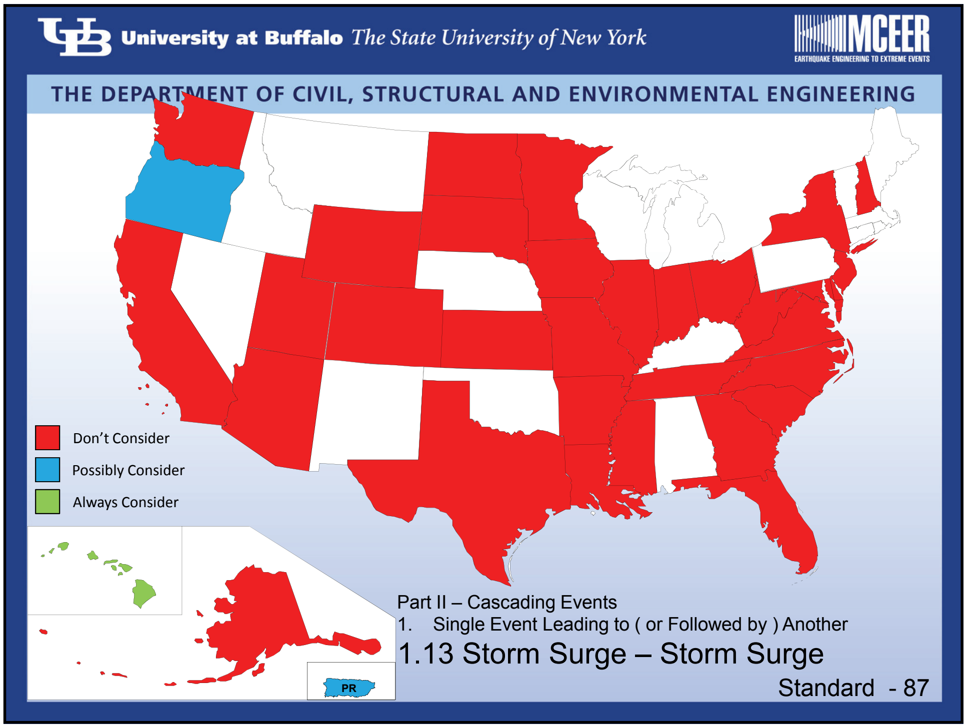
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.12 Fire – Wind
Special - 86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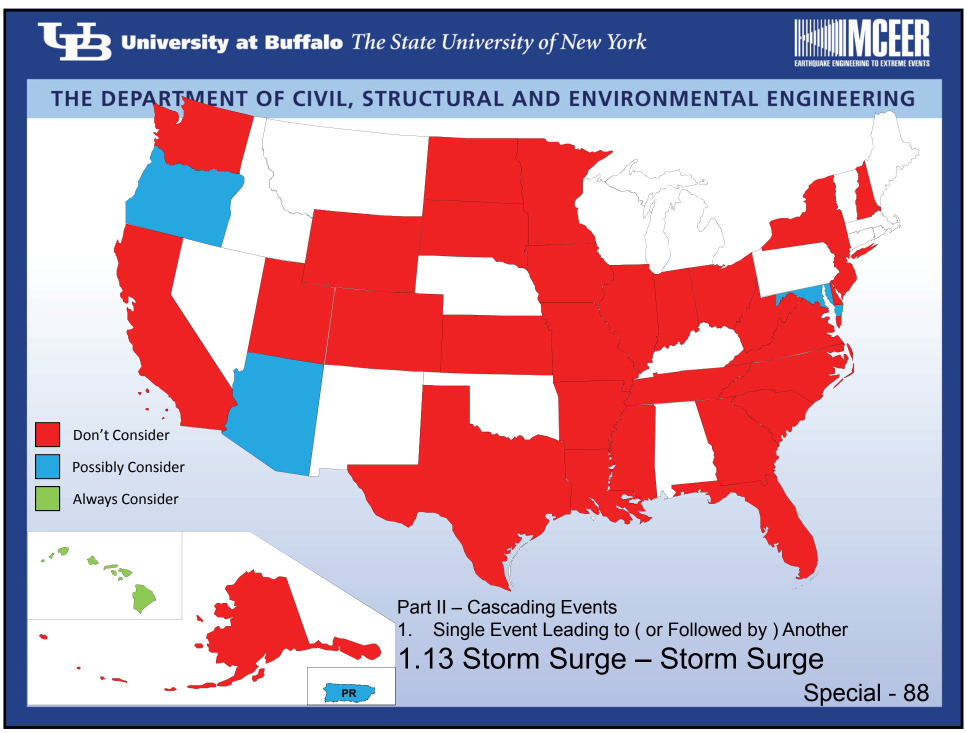
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.13 Storm Surge – Storm Surge
Standard - 87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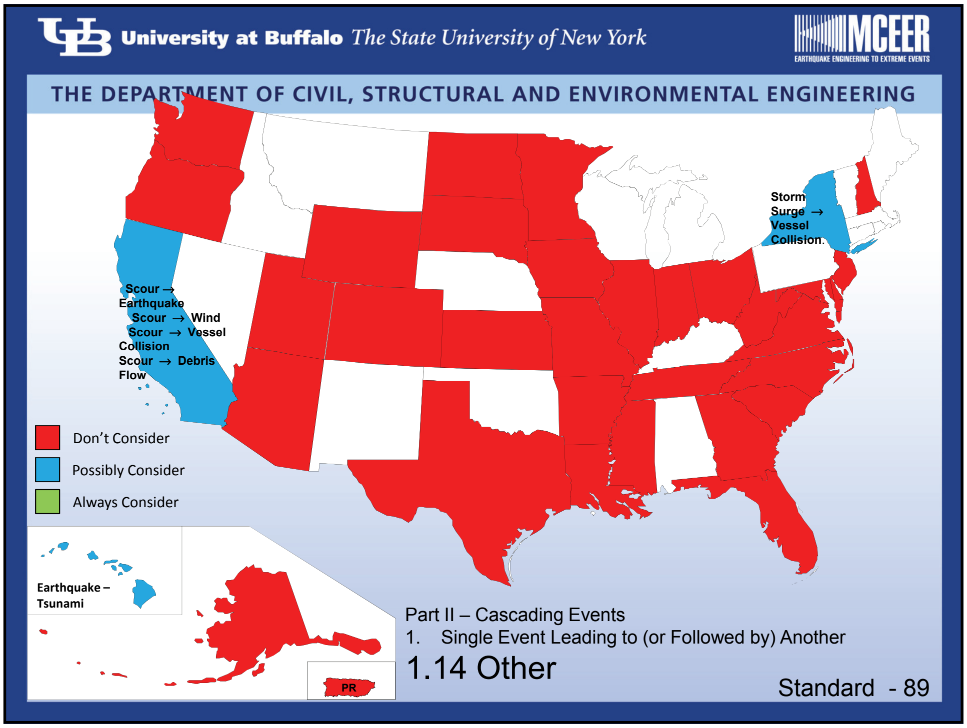
Don't Consider
Possibly Consider
Always Consider
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.13 Storm Surge – Storm Surge
Special - 88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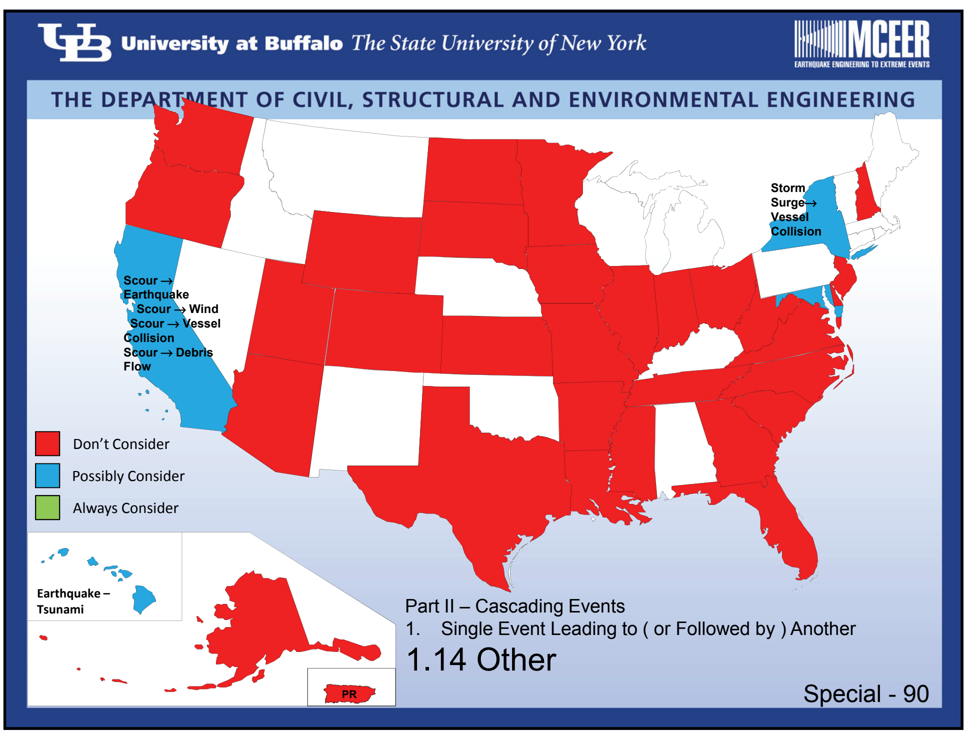
Storm Surge → Vessel Collision
Scour → Earthquake
Scour → Wind
Scour → Vessel Collision
Scour → Debris Flow
Don't Consider
Possibly Consider
Always Consider
Earthquake – Tsunami
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.14 Other
Standard - 89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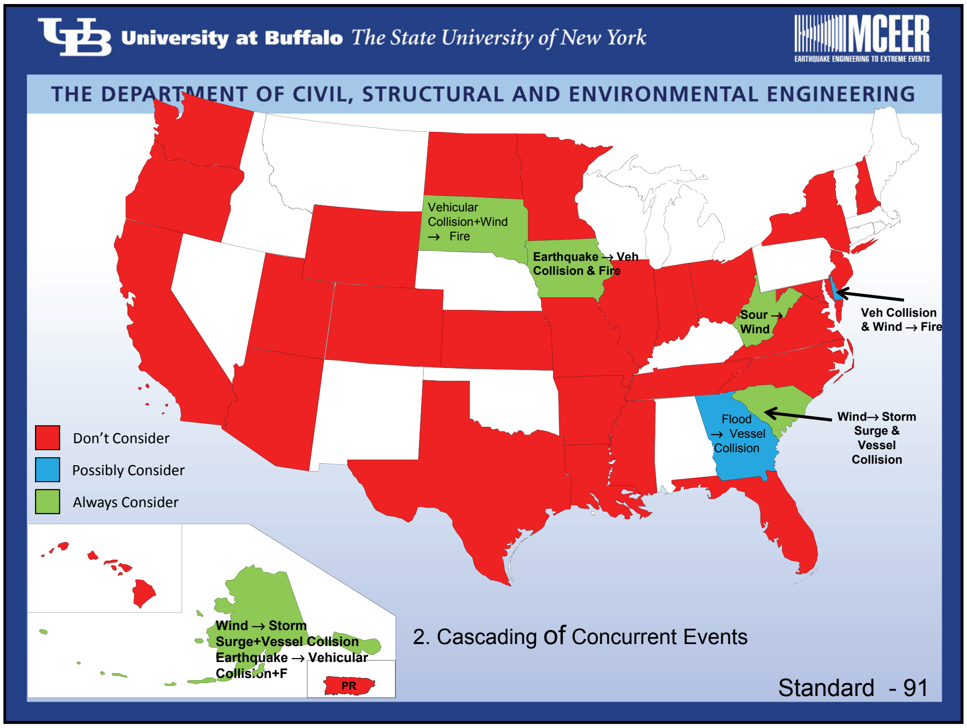
Storm Surge→ Vessel Collision
Scour → Earthquake
Scour → Wind
Scour → Vessel Collision
Scour → Debris Flow
Don't Consider
Possibly Consider
Always Consider
Earthquake – Tsunami
PR
Part II – Cascading Events
1. Single Event Leading to (or Followed by) Another
1.14 Other
Special - 90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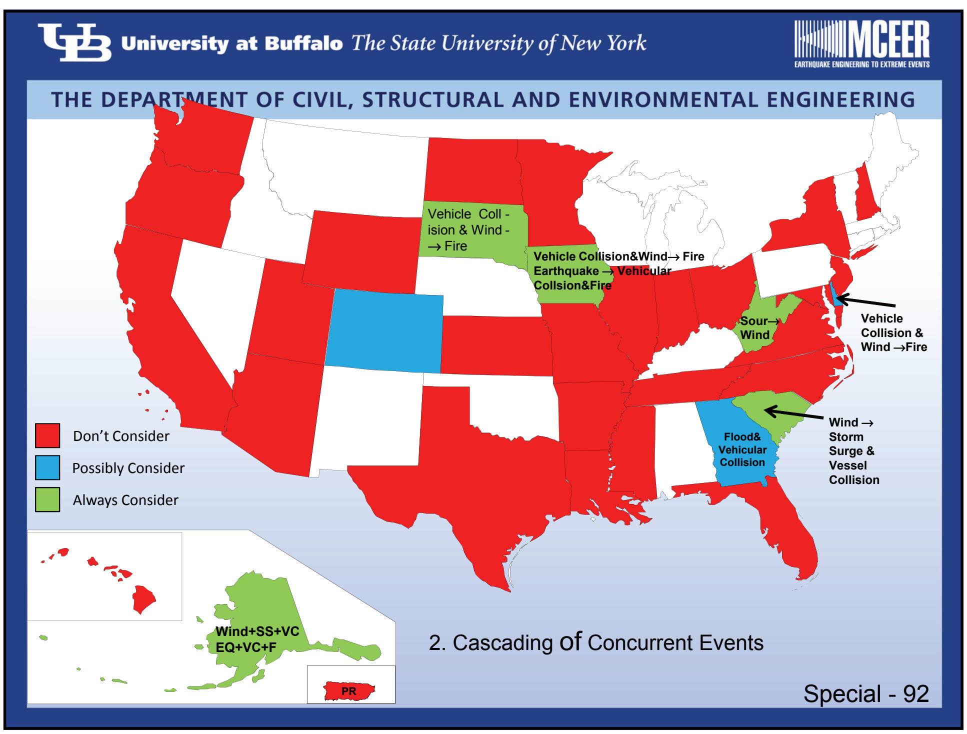
Vehicular Collision+Wind → Fire
Earthquake → Veh Collision & Fire
Sour → Wind
Veh Collision & Wind → Fire
Flood → Vessel Collision
Wind→ Storm Surge & Vessel Collision
Don't Consider
Possibly Consider
Always Consider
Wind → Storm Surge+Vessel Collision Earthquake → Vehicular Collision+F
PR
2. Cascading of Concurrent Events
Standard - 91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Vehicle Collision & Wind → Fire
Vehicle Collision&Wind→ Fire Earthquake → Vehicular Collsion&Fire
Sour→ Wind
Vehicle Collision & Wind →Fire
Flood& Vehicular Collision
Wind → Storm Surge & Vessel Collision
Don't Consider
Possibly Consider
Always Consider
Wind+SS+VC EQ+VC+F
PR
2. Cascading of Concurrent Events
Special - 92

Questionnaire Section III Free Form Comments

Extreme loads related to bridge type/function

- Logical relation among the concurrent or cascading events is important.
- Only long span bridges are subject to vessel collision.
- Assume greater wind load than normal design (extreme vs 1.4WS50).
- Typical 2-span bridges CANNOT be over navigable waterway. They are therefore in a different group than longer bridges in vessel collision consideration.

Concerns of design complexity and cost

- Avoid designing for very rare concurrent events.
- Design guidance for scoured bridge is needed. Current design is not probabilistic and lack of basis in combination with other loads.
- Normally, bridges only need to be designed for controlling event in the concurrent or cascading sets. One load often dominates design for concurrent loads.
- Complexity in design specifications is undesirable.
- Current scour design is too conservative. NCHRP 489 is helpful in reducing this effect.
- In practice, multi-hazard design is sometimes only used for special bridges.
- Concurrent or cascading events should be considered for high-priced projects.

Classification/definition

- Short-span and medium-span bridges may have different concerns. Using a single category of short-medium span may not be sufficient.
- Regional boundaries may be different from state boundaries.
- Cascading is described as initial event(s) weakens the bridge.

- Another potential definition for cascading is that the occurrence of one load increases the likelihood of another.

- Scour is considered both a part of concurrent events and a leading event of cascading events in some responses. One may consider the initial weakening of a bridge foundation due to storm surge or scour, which then makes the bridge more vulnerable to a vessel collision happening some time later before repairs to the damage caused by storm surge can be made.

- Debris Flow is interpreted as (1) loads from debris raft or as (2) gravel/mud movement that impacts bridge pier or abutment.

- Structure type, ADT, detour length are factors in design against one or more extreme loads.

- Special bridges are those having expected life>75 yr.

- Wind, surge, tsunami, hurricane may not be clearly distinguished in definition.

<u>Mitigation methods that are not in design</u>

- Bridges are often closed, shored, or repaired between cascading events.

- Some of the answers “2” mean the problem is eliminated by design or avoidance

- CT+Fire is a likely case but design target and mitigation approaches against fire are usually not addressed in design. Potential mitigation includes:

    - Providing adequate redundancy to the structural system to avoid collapse in case a member is lost due to fire.

    - Providing adequate standoff of traffic from vulnerable members.

    - Considering bridge location and emergency crew response time vs. member exposure time to fire.

    - Fire resistant coatings.

    - Fire suppression system.

<u>Recommended actions</u>

- A survey of actual multiple events should be undertaken.
- Redundancy is an important factor in LRFD calibration.
- Light rail on special bridges and train collision may be considered.
- Blast is an important concern for several states.
- More parameters need to be provided to vehicular collision.
- Consider adjusting or reducing reliability index (beta) for concurrent/cascading events

<u>Additional comments for scour design</u>

- Case study based on results from investigation.
- Extreme scour (500-year event) is used with extreme limit state; design scour (100-year event) is used with strength and serviceability limit states.
- Foundation geometry is checked by HEC-18 provisions.
- Effect of ice or debris raft on scour may need consideration. Example for combining with CV:

  c. 75 percent of the short-term scour computed for the 100-year event and 75 percent of the long-term scour, using a fully loaded, 15-barge flotilla and tugboat.

  d. 100 percent of the short-term scour computed for the 100-year event and 100 percent of the long-term scour using a drifting, empty, single barge.

  Example for combining with ice:

  c. 75 percent of the short-term scour computed for the 100-year event

  d. 100 percent of the long-term scour.

- A scour critical elevation is shown on the plans for use by bridge maintenance and inspection personnel in monitoring of the bridge foundation for possible future mitigation.
- The scour depth used for all cases is the sum of the channel scour plus the local contraction scour.

- Scour is normally not required to be combined with earthquake load (Extreme Event I). When it is considered, following methods have been used:

    c. For the functional evaluation earthquake design event, the full scour from the design flood (100-year event) is used. For the safety evaluation earthquake design event, half of the scour obtained from the design flood (100-year event) is used.

    d. When scour is considered with the Extreme Event I limit state, the soil resistance up to a maximum of 25% of the scour depth for the design flood event (100 year) is deducted from the lateral analysis of the pile or shaft. The loss of skin resistance for the full scour depth for the design flood is considered when checking axial capacity of the shaft for all strength and service limit states. The loss of skin resistance for the full scour depth of the check flood (500 year event) is considered when checking the axial capacity of the shaft for Extreme Event II limit states.

- Many practices are under the condition of "where economical."
- Criteria for existing bridge may be lower than those for new bridges.
- Piles may be designed for scour condition if necessary.
- Abutment may be protected by countermeasures.

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NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259, A03, MF-A01). This report is available only through NTIS (see address given above).

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University at Buffalo, The State University of New York
Red Jacket Quadrangle ▪ Buffalo, New York 14261
Phone: (716) 645-3391 ▪ Fax: (716) 645-3399
E-mail: *mceer@buffalo.edu* ▪ WWW Site *http://mceer.buffalo.edu*
University at Buffalo *The State University of New York*

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