Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division VII

Development of a Framework for Probabilistic Storm Surge Hazard Assessment for United States Nuclear Power Plants

Michelle Bensi[1] and Joseph Kanney[2]

[1] Civil Engineer, United States Nuclear Regulatory Commission, USA
[2] Hydrologist, United States Nuclear Regulatory Commission, USA

ABSTRACT

The United States Nuclear Regulatory Commission's risk-informed regulatory framework incorporates the use of risk tools consistent with the Commission's policy on the use of Probabilistic Risk Assessment (PRA). The NRC's PRA Policy Statement (Ref. [1]) formalized the Commission's commitment to risk-informed regulation through the expanded use of PRA. The policy states that the NRC will increase the use of PRA methods in nuclear regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approaches.

Experience with external flooding PRA for nuclear power plants is limited; well-established, broadly-accepted probabilistic flood hazard assessments methods for characterizing hazards at return periods of relevance for siting United States nuclear power plants (NPPs) are not available for most flood mechanisms. Probabilistic storm surge hazard assessment (PSSHA) provides the annual probability (or frequency) of exceeding some level of surge severity at a site. PSSHA has been employed to assess storm surge hazards for coastal applications other than NPPs and for return periods up to approximately 500 or 1000 years. However, rigorous PSSHA methods have not been developed to address the return periods of relevance to siting NPPs, which are typically several orders of magnitudes larger. Moreover, NRC has not issued staff or regulatory guidance associated with PSSHA. This paper describes initial development of a technically defensible framework for evaluating PSSHA for NPP sites and describes efforts currently underway at NRC to further expand applications in line with the agency's risk-informed regulation.

INTRODUCTION

The United States Nuclear Regulatory Commission (NRC) utilizes a risk-informed regulatory framework, which considers both the probability of an event and the event's possible consequences to understand the event's importance. Probabilistic risk assessment (PRA) facilitates this risk-informed framework. A PRA for external flooding involves three key elements: (1) external flood hazard analysis, (2) external flood fragility evaluation, and (3) external flood plant response modelling and quantification (Refs. [2] and [3]). This paper focuses on the first technical element related to external flood hazard analysis, with particular emphasis on the storm surge hazard.

Probabilistic flood hazard assessment (PFHA) is required for the external flood hazard analysis element of the external flooding PRA. PFHA is a systematic assessment of the likelihood that a specified parameter or set of parameters representing flood severity (e.g., flood elevation, flood event duration, and associated effects) will be exceeded at a site or in a region during a specified exposure time. The results of such an assessment are expressed as estimated probabilities per unit time (e.g., annual exceedance probability) or estimated frequencies and typically displayed as a set of hazard curves. A PFHA performed specifically for the storm surge hazard is referred to in this paper as probabilistic storm surge hazard assessment (PSSHA).

BACKGROUND

Storm Surge Hazard

Storm surge is a natural phenomenon characterized by an abnormal rise of water generated by a storm, over and above the predicted astronomical tides. It is a complex phenomenon involving the interactions of several processes including direct forcing from the storm wind and pressure fields, the effects of wind-driven waves, and effects of the earth's rotation. Storm surge is strongly influenced by topographic and bathymetric features near a site. In particular, the geometry of the basin and the continental shelf leading up to the coastal floodplain, as well as details of near-shore bathymetry, have significant influence on surge height, currents, and wave effects. Propagation of the surge over land is strongly influenced by topography and land cover. As storms make landfall, there may be significant interaction of the storm surge with the astronomical tides, and in some cases (e.g., estuary sites), riverine flooding caused by storm or antecedent rainfall. In addition, the effects of wind setup, wave runup and overtopping of flood protection features, such as levees, should be considered.

Existing Guidance for Flood Hazard Assessment for U.S. Commercial Nuclear Power Plants

The current state of practice in flood hazard assessment used for siting of commercial nuclear power plants in the United States is primarily deterministic, including the estimation for inundation from storm surge. Regulatory Guide 1.59 (RG 1.59), "Design-Basis Floods for Nuclear Power Plants" (Ref. [4]), describes the design basis floods that nuclear power plants should be designed to withstand. For example, RG 1.59 describes estimation of (deterministic) probable maximum storm surge (PMSS) determined by use of the (deterministic) probable maximum hurricane (PMH) wind field parameters applied to a one-dimensional bathytrophic surge model. RG 1.59 was last updated in 1977. Since that time, there have been significant advances in capability to perform storm surge hazard analyses. For example, computing capability now facilitates the use of two- and three-dimensional numerical models for evaluating storm surge, especially near a site. NRC staff is currently in the process of revising RG 1.59. To support the update, NRC issued NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America" in November 2011 (Ref. [5]).

As a result of the events at Fukushima, NRC requested that all operating reactors licensees (and holders of construction permits) re-evaluate flooding hazards at their sites using "present-day guidance and methods" used to site new nuclear reactors.[1] Present-day guidance and methods

---

[1] As part of the response to the events at Fukushima, NRC requested (Ref. [19]) that operating power plants perform a reevaluation of flooding hazards at their sites, considering all appropriate external flooding sources, using present-day regulatory guidance and methods. If the reevaluated hazard exceeds the plant's design basis, the plant is subsequently requested to perform an assessment of the plant's capability to respond to the reevaluated hazard. This assessment is known as an integrated assessment for external flooding. In 2012, the NRC published guidance to support the performance of the integrated assessments in JLD-ISG-2012-05, "Guidance for Performing the Integrated Assessment for External Flooding" (Ref. [20]).

refers to those described in NUREG/CR-7046 and supplemental interim staff guidance in JLD-ISG-2012-06, "Guidance for Performing a Tsunami, Surge, or Seiche Hazard Assessment" (Ref. [6]). JLD-ISG-2015-06 describes the use of the Joint Probability Method (JPM; additional details described in a subsequent section of this paper) as a means of selecting hurricane parameters using analysis of available meteorological data. This is provided as an alternative to selection of hurricane parameters based on NOAA NWS Technical Report 23, which has conventionally been used for defining PMH parameters. JLD-ISG-2012-06 references NUREG/CR-7134, "The Estimation of Very-Low Probability Hurricane Storm Surges for Design and Licensing of Nuclear Power Plants in Coastal Areas" (Ref. [7]) as describing the use of the ADCIRC model in conjunction with JPM for estimation of surge water levels. NUREG/CR-7134 recommends a hybrid probabilistic-deterministic approach for evaluating design basis storm surge elevations. While NUREG/CR-7134 describes many of the components required for a probabilistic evaluation, it discourages the use of a strictly probabilistic approach. Specifically, NUREG/CR-7134 does not provide guidance for development of a flood hazard curve but rather provides guidance for assessing the impacts of uncertainties on the estimated upper surge limit through the use of additive factors as part of a hybrid (combined) deterministic-probabilistic approach.

Existing Guidance related to External Flooding PRA for U.S. Commercial NPPs

In Regulatory Guide 1.200, "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities" (RG 1.200, [2]), NRC staff endorsed ASME/ANS RA-Sa-2009, "Addenda to ASME/ANS RA-Sa-2009 Standard for Level 1 / Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications" (the PRA Standard; Ref. [3]). Part 8 of the PRA Standard establishes technical requirements for a PRA of the external flood hazard group. The PRA Standard notes that the collective experience with external-flooding PRA analysis is limited and detailed guidance documents are unavailable. It goes on to state that the team performing a flood PRA may need to "improvise its approach to external-flooding analysis following the overall methodology requirements in [Part 8]." Because of this potential need for unique approaches, the PRA Standard stresses the importance of peer review. Consistent with the intent and overall structure of the PRA Standard, the PRA standard does not provide implementation guidance. Nonetheless, the requirements in the PRA Standard related to flooding may be contrasted with the more detailed requirements with respect to seismic PRA in the same standard. Because of the maturity of the field of probabilistic seismic hazard analysis, it was possible to develop these detailed requirements.

Other Applications

It is noted that probabilistic methods for assessment of storm surge hazards have been used fairly widely in the U.S. outside of nuclear power plant siting applications. For example, several U.S. federal agencies have performed probabilistic storm surge assessments as part of regional hazard assessments (e.g., inundation maps for flood insurance and emergency evacuation plans, design of shore protection structures) with typical return periods up to 500-years. For this reason, use of probabilistic methods for storm surge hazards are not considered novel. However, because the return periods of relevance for nuclear power plant sites are significantly longer than those of relevance for flood studies performed by many other federal agencies, it may be appropriate and necessary to deviate from the assumptions used in these other applications to account for issues that arise due to longer return periods of relevance, and other factors. It is expected that deviations will be generally consistent with a more comprehensive and systematic treatment of uncertainty and larger ranges of parameters than necessary for the studies focused on shorter return periods.

AVAILABLE APPROACHES

In order to assess the risk to a site from storm surge events, it is necessary to understand the frequency of exceeding some measure of storm surge severity (typically represented by surge height). If a sufficiently long period of record was available, it would be possible to develop technically-defensible estimates of this frequency based on data and statistical analysis. However, the period of record is not of sufficient length to support such estimates, particularly for low frequencies (long return periods).

Two general approaches have been typically considered by practioners for probabilistically-informed storm surge assessment for tropical cyclones: the empirical simulation technique (EST) and the joint probability method (JPM). The EST is a "statistical procedure for simulating nondeterministic multiparameter systems such that frequency-of-occurrence relationships for storm-related response parameters such as maximum surge level can be determined" (Ref. [8]). The EST is a bootstrapping, resampling-based method that assumes future events will be statistically similar in magnitude and frequency to past events. Specifically, the EST begins with an analysis of historical events impacting a site. Historical events are parameterized by characteristics of the storm (input vectors) and the impacts of that storm (response vectors). Input vectors describe the physical characteristics of the storm event and its location (e.g., central pressure, radius to maximum winds, distance between the storm and the site). Response vectors define storm-related impacts (e.g., surge elevation, inundation, shoreline/dune erosion). These input and response vectors are then used to develop multiple simulations of future responses. Frequency estimates are then developed based on the set of synthetic data generated after applying the EST (Refs. [8] and [9]).

The JPM was initially developed in the 1970s (Refs. [10] and [11]). The JPM, as commonly implemented in practice, utilizes a parametric representation of tropical cyclones and assigns a joint probability to each combination of storm parameters. However, the approach need not be constrained to consideration of only storm parameters and other factors (e.g., parameters and modelling decisions associated with numerical models) may be relevant. The joint probability is computed as a product of marginal or conditional distributions associated with each storm parameter, typically (but not exclusively) developed based on statistical analysis of historical data. The distributions are discretized into a set of representative values and each parameter combination is simulated using numerical meteorological and hydrodynamic models to compute (maximum) water elevations at locations of interest. Additional details regarding the JPM are provided in a subsequent section of this paper.

Ref. [12] provides a comparison of the performance of EST and JPM. While noting that both approaches have conceptual strengths, Ref. [12] ultimately concluded that JPM was "remarkably robust" and insensitive to choice of distribution forms and to parameter correlations. Conversely, EST was found to be "extremely sensitive to sample variation." However, the authors caution that their conclusions are illustrative and thus cannot be read as a final statistical evaluation of the

JPM versus EST. Moreover, the authors emphasize that their findings apply to hurricane surge but not to other applications for which "EST may perform well, and may be the tool of choice" (e.g., as described in Ref. [9]). It is noted that, in performing the comparison of methods, Ref. [12] focuses on return periods of 50-500 years, which are shorter that those typically of relevance for siting new NPPs. Consistent with Ref. [12], FEMA Operating Guidance (Ref. [13]) related to JPM notes that "[i]n recent years, it has been recognized that of the available methods, JPM is preferred for the tropical storm environment." Moreover, Ref. [7] notes that use of JPM in current practices (e.g., FEMA studies) are focused on providing estimates of surges for a range of return periods of approximately 50- to 1000-years. Ref. [7] further notes that, while it has been clearly established that estimates from the JPM are more stable than estimates based only on historical hurricanes, the confidence limits in estimated values using either of these methods is expected to become very large for surge values associated with longer return periods.

While the above discussion focuses on methods for evaluating the frequencies of surges from tropical cyclones, it is noted that treatment of the contribution to hazard from extratropical storms has commonly used extreme value analysis based on historical data.

JOINT PROBABILITY METHOD

Using the JPM (as commonly applied in practice), the rate of exceeding a given surge elevation (n) at a given site may be expressed using the Theorem of Total Probability (e.g., see Ref. [14]) as:

$$\lambda_{\eta_{max}>n} = \lambda \int P(\eta_{max}(\boldsymbol{x}) + \epsilon > n | \boldsymbol{x}, \epsilon) f_{\boldsymbol{X}}(\boldsymbol{x}) f_{\epsilon}(\epsilon) dx d\epsilon \tag{1}$$

Where:

- $\lambda =$ annual rate of storms of interest affecting the site
- $\boldsymbol{x} =$ vector representation of pertinent storm characteristics such as central pressure deficit (Δp), radius to maximum winds (R_{max}), storm translational forward speed (V_f), storm track direction (θ), and landfall location
- $\epsilon =$ error term, typically comprised of multiple components (e.g., $\epsilon_{total} = \epsilon_1 + \epsilon_2 + \epsilon_3 + \epsilon_4 + \cdots$) to capture variability associated with parameters not explicitly included in the above integral as well as lack of skill of the numerical models (e.g., hydrodynamic ocean circulation and wave models) and departures in the real behaviour of hurricane wind and pressure fields that are not represented by the planetary boundary layer or other meteorological model used to describe the storms (Ref. [13])
- $f_{\boldsymbol{X}}(\boldsymbol{x}) =$ joint probability of storm characteristics
- $\eta_{max}(\boldsymbol{x}) =$ peak inundation resulting from surge generated by a storm with characteristics $\boldsymbol{x}$ as computed by a numerical model
- $P(\eta_{max}(\boldsymbol{x}) + \epsilon > n | \boldsymbol{x}, \epsilon) =$ conditional probability that $\eta_{max}(\boldsymbol{x}) + \epsilon$ is greater than n given $\boldsymbol{x}$ and ϵ

The above integral is evaluated (in discrete form as a summation) by discretizing the storm parameter space to yield a set of storm parameter combinations (often referred to as synthetic storms), each associated with a probability mass. A numerical model is used to generate a surge height for each parameter combination. State-of-the-art numerical models are typically comprised of coupled high-resolution hydrodynamic ocean circulation and wave models driven by a planetary boundary layer model that provides the atmospheric forcing. Then, the discretized error is included in the discrete summation along with the rate term. It is noted that direct evaluation of the above integral (and the corresponding discrete form) through "brute-force" methods is computationally challenging, and it many cases, impractical. Use of this approach to estimate storm surge requires high-resolution bathymetric and topographic data, historical tidal information, meteorological data, and significant computational resources. While hindcasting studies have clearly demonstrated the value of the coupled high-resolution approach (especially in regions of complex bathymetry), it presents certain challenges with respect to fully characterizing and propagating uncertainties. Most significantly, the time and computational resources required to perform the simulations makes it challenging to run the large number of simulations required. To address this issue, multiple methods have been developed that seek to reduce the number of simulations required. These are known as "optimal sampling" approaches. Two commonly applied methods are response surface methods and quadrature methods. Discussion of these methods is outside the scope of this paper, but an overview of these methods, including additional reference material, can be found in Ref. [13].

TREATMENT OF UNCERTAINTIES

Understanding uncertainties is an important component of any deterministic or probabilistic hazard assessment. When using deterministic methods, uncertainties are typically addressed using conservative modelling decisions that are often subjective and typically do not include explicit quantification. Probabilistic methods attempt to address uncertainties comprehensively, and consistently, including explicit quantification. Typically, uncertainty is categorized in one of two ways:

- *Aleatory variability*: Aleatory variability is the inherent randomness in a process. In theory, aleatory variability cannot be reduced, because it is interpreted as representing an inherent quality of nature. Aleatory variability is represented by a probability distribution, which reflects our understanding that we do not know which value a parameter will take in any particular instance. The spatial, temporal and other relevant characteristics of future realizations of meteorological, climatological, oceanographic, hydraulic, or other parameters typically is associated with aleatory variability. Aleatory variability gives rise to a hazard curve.
- *Epistemic uncertainty*: Epistemic uncertainty arises because our analyses are conducted using models rather than directly on real systems. It also stems from our lack of knowledge concerning the validity of these models and the numerical values of their parameters. There are various options for addressing epistemic uncertainty. Epistemic uncertainty is expressed using multiple hazard curves from which a mean, median or other fractile hazard curve can be derived. Examples of epistemic uncertainty include: the selection of the probability distribution that is appropriate for capturing aleatory uncertainty in hurricane parameters, selection of a technique to parse available datasets for relevance to a particular site, the appropriate hydrodynamic or meteorological model to use, and the choice of various parameters needed to utilize existing models.

As illustrated by the discussion of EST and JPM, there is a range of legitimate technical views regarding appropriate approaches for performing a probabilistic assessment of the storm surge hazard. The variety of technically defensible approaches that have been used in performing various analyses arises from important epistemic uncertainties. For example, there are limited scientific research/experience, data, models, or methods related to the certain elements necessary to perform the assessment. The validity or necessity of including various data is also a source of considerable differences in technical opinion. These limitations and differences of interpretation translate into significant state-of-knowledge uncertainties, particularly when used for estimation of surges associated with long return periods.

NRC guidance related to probabilistic seismic hazard analysis (PSHA) provides a robust framework for identification and quantification of aleatory variability and epistemic uncertainties and for propagating these uncertainties through an analysis. For example, in PSHA it is common to treat epistemic uncertainty through logic trees.[2] In order to facilitate complete and accurate representations of the legitimate range of technically defensible interpretations of data, models and methods among the informed technical community (e.g., to determine weights needs for logic trees) when performing a PSHA, NRC guidance for PSHA utilizes the SSHAC process.[3] This is a process in which experts are used in a structured, transparent, and well-documented manner that allows peer reviewers and external reviewers to understand the basis for all technical decisions. Additional information regarding PSHA and the SSHAC is available in existing NRC references (e.g., Refs. [15] and [16]).

NRC is currently exploring the ways in which NRC's existing practice (including associated guidance) and past experience can or should be applied to develop a robust framework for performing PSSHA for siting of U.S. NPPs.

CURRENT ACTIVITIES AND NEXT STEPS

NRC has recently undertaken several activities related to development of a framework for performing PFHA (including PSSHA) for U.S. NPPs. In January 2013, the NRC, in cooperation with Federal agency partners (e.g., U.S. Department of Energy; Federal Energy Regulatory Commission; U.S. Army Corps of Engineers; U.S. Bureau of Reclamation; and U.S. Geological Survey), organized and conducted a "Workshop on Probabilistic Flood Hazard Assessment (PFHA)." The workshop provided a venue for the sharing of information on PFHA of extreme natural and human-related events among the Federal community. The proceedings from the workshop and record of the webcast are available on the NRC public website (Ref. [17]).

In April 2014, NRC partnered with the Federal Energy Regulatory Commission to hold a workshop to explore possibility and potential for adaptation of a SSHAC process for use in flooding applications. Proceedings from the workshop are currently in press.

---

[2] The concept of the logic tree is relatively straightforward: for each input (modelling decision), branches are set up for alternative models or alternative parameter values, and weights are assigned to each branch to reflect the relative confidence that the analyst(s) has in each model being the best representation of that component of the hazard input. The hazard calculations are then performed for every possible combination of branches. Each individual combination of branches results in an associated individual hazard estimate and an associated total probability that is determined by calculating the product of all the branch weights involved in that calculation. For any given value of the selected flood parameter (e.g., flood elevation), the final product is a suite of annual exceedance frequencies (hazard estimates) and their associated probabilities.

[3] The SSHAC process derives its name from the Senior Seismic Hazard Analysis Committee (SSHAC), which developed a structured, multi-level assessment process for utilizing expert assessments (the ”SSHAC process”).

Beginning in 2014, NRC's Office of Nuclear Regulatory Research, in coordination with other NRC offices, began implementing a Probabilistic Flood Hazard Assessment (PFHA) Research Plan. The Research Plan supports development of a risk-informed licensing framework for flood hazards and design standards at new facilities and significance determination tools for evaluating inspection findings related to flood protection at operating facilities. The PFHA research plan aims to build upon recent advances in deterministic, probabilistic, and statistical modelling to develop regulatory tools and guidance for NRC staff with regard to PFHA for nuclear facilities. The tools and guidance developed will support and enhance NRC's capacity to perform thorough and efficient reviews of license applications and license amendment requests. They will also support risk-informed significance determination of inspection findings, unusual events, and other oversight activities (Ref. [18]).

The Research Plan includes a project focused specifically on the storm surge hazard. The objective of the storm surge research project is to develop and demonstrate an approach to characterize uncertainties in site-specific storm surge flood hazard estimates for the full range of return periods of interest for NPPs. The focus areas of the research activities include:

1. A compilation and review of previous storm surge studies.
2. Investigation of epistemic uncertainties in site-specific storm occurrence rate models, including an assessment of the relative merits of relevant different data, models, and methods
3. Exploration of the range of technically defensible data, models, and methods for defining the joint probability of storm parameters, including investigation of approaches for characterizing and quantifying the site-specific joint probability of storm parameters. This includes identification of the center, body, and range of technically defensible data, models, and methods
4. Exploration of the center, body, and range of technically defensible models, and methods for generating synthetic storm sets, including topics associated with discretization of storm parameter space, trade-offs between model accuracy and computational demands (e.g., through use of less-sophisticated or approximate methods), and relative merits of different approaches currently utilized in practice (e.g.,. response surface versus quadrature approaches)
5. Investigation of approaches for characterizing errors arising from factors such as numerical surge simulation and exclusion of parameters from the JPM-OS integral to reduce dimensionality

The project will include a synthesis of the above items to support development of an overall approach to perform probabilistic storm surge assessment for use in nuclear power plant applications. NRC plans to complete the project related to the storm surge hazard in April 2017, although interim results should be available sooner.

CONCLUSION

To date, most storm surge calculations performed to assess the storm surge hazard for U.S. NPPs have been performed using deterministic methods. However, evaluations using probabilistic-deterministic hybrid approaches have been recently submitted to NRC. As a result, and in anticipation of future needs, NRC is currently working to develop tools and guidance to support PSSHA for U.S. NPPs. This paper describes some of the existing approaches used by practioners for PSSHA outside of NPP applications. This paper also describes efforts underway at NRC that build upon these existing tools related to PSSHA as well as NRC experience with probabilistic assessment of other hazards (e.g., seismic hazards) to develop and demonstrate an approach to characterize uncertainties in site-specific storm surge flood hazard estimates for the full range of return periods of interest to U.S. NPPs.

ACKNOWLEMENT

The authors acknowledge the helpful feedback provided on this paper provided by Dr. Christopher Cook.

DISCLAIMER

Any opinions, findings and conclusions expressed in this presentation are those of the authors and do not necessarily reflect the views of the United States Nuclear Regulatory Commission.

REFERENCES[4]

[1] U.S. Nuclear Regulatory Commission, 60 FR 42622, Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities: Final Policy Statement, 8/16/95.

[2] U.S. Nuclear Regulatory Commission, "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities," Regulatory Guide 1.200, Revision 2, ADAMS Accession No. ML090410014, March 2009.

[3] The American Society of Mechanical Engineers, Addenda to ASME/ANS RA-Sa-2009, Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications.

[4] U.S. Nuclear Regulatory Commission, Regulatory Guide 1.59, "Design-basis Flood for Nuclear Power Plants," ADAMS Accession No. ML003740388, 1977.

[5] U.S. Nuclear Regulatory Commission, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," NUREG/CR-7046, ADAMS Accession No. ML11321A195, November 2011.

[6] U.S. Nuclear Regulatory Commission, " Guidance for Performing a Tsunami, Surge, or Seiche Hazard Assessment," JLD-ISG-2012-06, ADAMS Accession No. ML12314A412, January 4, 2013.

[7] D. Resio, T. Wamsley and M. Cialone, “The Estimation of Very-Low Probability Hurricane Storm Surges for Design and Licensing of Nuclear Power Plants in Coastal Areas,” NUREG/CR-7134, ADAMS Accession No. ML12310A025, 2012.

[8] N. W. Scheffner, L. E. Borgman and D. J. Mark, “Empirical Simulation Technique Based Storm Surge Frequency Analyses,” Journal of Waterway, Port, Coastal, and Ocean Engineering, vol. 122, pp. 93-101, 1996.

[9] N. W. Scheffner, J. E. Clausner, A. Militello, L. E. Borgman, B. L. Edge and P. J. Grace, Technical Report CHL-99-21, "Use and Application of the Empirical Simulation Technique: User's Guide," US Army Corps of Engineers, Engineer Research and Development Center,

---

[4] Many of the references below include accession numbers for use in conjunction with the NRC’s Agencywide Documents Access and Management System (ADAMS).

1999.

[10] F. Ho and V. Myers, NOAA Technical Report WS 18, "Joint Probability Method of Tide Frequency Analysis applied to Apalachicola Bay and St. George Sound, Florida," 43pp, 1975.

[11] V. Myers, NOAA Technical Report NWS-16, “Storm Tide Frequencies on the South Carolina Coast,” 79pp, 1975.

[12] D. Divoky and D. T. Resio, “Performance of the JPM and EST Methods in Storm Surge Studies,” in 10th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium, North Shore, Oahu, Hawaii, November 11 – 16, 2007.

[13] Federal Emergency Management Agency (FEMA), Operating Guidance No. 8-12, "Joint Probability – Optimal Sampling Method for Tropical Storm Surge Frequency Analysis," March 2012.

[14] A.-S. Ang and W. Tang, "Probability Concepts in Engineering, Emphasis on Applications to Civil and Environmental Engineering," John Wiley & Sons, Inc., 2007.

[15] U.S. Nuclear Regulatory Commission, NUREG-2117, "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies," Rev. 1, ADAMS Accession No. ML12118A445, 2012.

[16] R. Budnitz, G. Apostolakis, D. Boore, L. Cluff, K. Coppersmith, C. Cornell and P. Morris, NUREG/CR-6372, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts (Main Report)," ADAMS Accession No. ML080090003, April 1997.

[17] U.S. Nuclear Regulatory Commission, “Workshop on Probabilistic Flood Hazard Assessment,” [Online]. Available: http://www.nrc.gov/public-involve/public-meetings/meeting-archives/research-wkshps.html. [Accessed 24 May 2015].

[18] U.S. Nuclear Regulatory Commission, Probabilistic Flood Hazard Assessment Research Plan, ADAMS Accession No. ML14296A442, 2014.

[19] U.S. Nuclear Regulatory Commission, “Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) Rregarding Recommendations 2.1, 2.3, and 9.3 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,” ADAMS Accession No. ML12053A340, March 12, 2012.

[20] U.S. Nuclear Regulatory Commission, "Guidance for Performing the Integrated Assessment for External Flooding," JLD-ISG-2012-05, ADAMS Accession No. ML12311A214, November 30, 2012.

Development of a Framework for Probabilistic Storm Surge Hazard Assessment for United States Nuclear Power Plants

Michelle T. Bensi, Ph.D.
Joseph Kanney, Ph.D.
U.S. Nuclear Regulatory Commission

SMiRT23
Manchester, England
August 10-14, 2015

Background: Flood PRA

- Significant benefits realized from probabilistic risk analysis (PRA)
- A PRA for external flooding involves three key technical elements:
  1. external flood hazard analysis
  2. external flood fragility evaluation
  3. external flood plant response modelling and quantification
- Challenges arise from limitations in current state of practice for flooding PRA for U.S. nuclear power plants

Background: Storm Surge

- Natural phenomenon characterized by an abnormal rise of water generated by a storm, over and above the predicted astronomical tides
  - Tropical cyclones
  - Extratropical events
- Involves several processes
  - direct forcing from the storm wind and pressure fields
  - effects of wind-driven waves
  - effects of the earth's rotation
- Strongly influenced by topographic and bathymetric features near a site

Background: Existing NRC guidance for storm surge

- Regulatory Guide (RG) 1.59
  - Deterministic - Estimation of probable maximum storm surge determined by use of the probable maximum hurricane wind field parameters applied to a one-dimensional bathytrophic surge model
  - Last updated 1977
  - Significant advances in capability to perform storm surge hazard analyses since 1977
  - Currently under revision
- ANSI/ANS 2.8-1992

Background: Existing NRC guidance for storm surge

- JLD-ISG-2012-06
  - – Describes the use of the Joint Probability Method (JPM) as a means of selecting hurricane parameters using analysis of available meteorological data (as alternative to NWS 23)
  - – Describes assessment of extratropical events
  - – Refers to NUREG-7134
    - Describes the use of the ADCIRC model in conjunction with JPM
    - Recommends a hybrid probabilistic-deterministic approach
    - Does not provide guidance for development of a hazard curve
    - Provides guidance for assessing the impacts of uncertainties (e.g., tides, climate, numerical models) on the estimated upper surge limit through the use of additive factors
- Regulatory Guide 1.200
  - – Guidance related to external hazard PRA

Background: Other U.S. Applications

- Probabilistic methods for assessment of storm surge hazards have been used in the U.S. outside of commercial nuclear power plant siting
- Return periods of relevance for nuclear power plant sites are significantly longer than for other applications
- Modifications to existing approaches may be necessary

Available probabilistic storm surge assessment approaches

Existing approaches:

- Empirical simulation technique (EST)
  - Bootstrapping, resampling-based method
  - Assumes future events will be statistically similar in magnitude and frequency to past events
  - Input and response vectors (based on historical events) used to develop multiple simulations of future responses (synthetic data)
  - Frequency estimates are developed based on synthetic data

Available probabilistic storm surge assessment approaches

Existing approaches:

- Joint probability method (JPM)
  - Utilizes a parametric representation of tropical cyclones characterizing intensity, size, track, direction, and speed
  - Assigns a joint probability to each combination of storm parameters
  - Joint probability is computed as a product of marginal or conditional distributions associated with storm parameters
  - Discretized parameter combinations simulated using numerical meteorological and hydrodynamic models to compute (maximum) water elevations at locations of interest

Joint Probability Method

$$\lambda_{\eta_{max}>n} = \lambda \int P(\eta_{max}(\boldsymbol{x}) + \epsilon > n | \boldsymbol{x}, \epsilon) f_{\boldsymbol{X}}(\boldsymbol{x}) f_{\epsilon}(\epsilon) dx d\epsilon$$

- $\lambda =$ annual rate of storms of interest affecting the site
- $\boldsymbol{x} =$ vector representation of pertinent storm parameters characterizing intensity, size, track, direction, and speed
- $\epsilon =$ error term
- $f_{\boldsymbol{X}}(\boldsymbol{x}) =$ joint probability of storm characteristics
- $\eta_{max}(\boldsymbol{x}) =$ peak inundation resulting from surge generated by a storm with characteristics $\boldsymbol{x}$ as computed by a numerical model

Treatment of Uncertainties

Typically uncertainty characterized in two ways:

- Aleatory variability:
  - Inherent randomness in a process
  - Represented by a probability distribution
  - Gives rise to a hazard curve
- Epistemic uncertainty:
  - Arises because analyses are conducted using models rather than directly on real systems
  - Stems from lack of knowledge concerning the validity of models and the numerical values of parameters
  - Expressed using multiple hazard curves from which a mean, median or other fractile hazard curve can be derived

Treatment of Uncertainties

- NRC guidance related to probabilistic seismic hazard analysis (PSHA) provides a robust framework for:
  - Identification and quantification of aleatory variability and epistemic uncertainties
  - Propagating uncertainties through an analysis
- Tools include:
  - Use of logic trees
  - SSHAC Process
- NRC is exploring the ways in which NRC's existing guidance and experience can or should be applied to assessment of storm surge hazard

Ongoing Activities

- Recent NRC activities related to probabilistic flood hazard assessment (PFHA)
  - Workshop on Probabilistic Flood Hazard Assessment (2013)
  - Workshop to explore adaptation of SSHAC process to flooding (2014)
  - Initiation of PFHA Research Plan (Fall 2014)

Ongoing Activities: Research Plan

- Research Plan includes a project focused specifically on the storm surge hazard
- Working with U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory
- Activities include:
  - Compilation/review of previous storm surge studies.
  - Investigation of epistemic uncertainties in storm occurrence rate models
  - Exploration of the range of technically defensible data, models, and methods for:
    - defining the joint probability of storm parameters
    - models and methods for generating synthetic storm sets
  - Investigation of approaches for characterizing errors

Disclaimer

Any opinions, findings and conclusions expressed in this presentation are those of the authors and do not necessarily reflect the views of the United States Nuclear Regulatory Commission