



**JAPAN LESSONS-LEARNED PROJECT DIRECTORATE**

**JLD-ISG-2012-06**

**Guidance for Performing a Tsunami, Surge, or  
Seiche Hazard Assessment**

**Interim Staff Guidance**  
*Revision 0*



# U.S. NRC

UNITED STATES NUCLEAR REGULATORY COMMISSION

*Protecting People and the Environment*

## JAPAN LESSONS-LEARNED PROJECT DIRECTORATE

### JLD-ISG-2012-06

## Guidance for Performing a Tsunami, Surge, or Seiche Hazard Assessment

### Interim Staff Guidance

*Revision 0*

ADAMS Accession No.: ML12314A412

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**INTERIM STAFF GUIDANCE  
JAPAN LESSONS-LEARNED PROJECT DIRECTORATE  
GUIDANCE FOR PERFORMING A TSUNAMI, SURGE, OR SEICHE HAZARD  
ASSESSMENT  
JLD-ISG-2012-06**

**PURPOSE**

This interim staff guidance (ISG) is being issued to describe to stakeholders methods acceptable to the staff of the U.S. Nuclear Regulatory Commission (NRC) for performing a tsunami, surge, or seiche hazard assessment for external flooding as described in NRC's March 12, 2012, request for information (Ref. 1) issued pursuant to Title 10 of the *Code of Federal Regulations* (10 CFR), Section 50.54, "Conditions of licenses," regarding Recommendation 2.1 of the enclosure to SECY-11-0093, "Recommendations for Enhancing Reactor Safety in the 21<sup>st</sup> Century, the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident" (Ref. 2). Among other actions, the letter dated March 12, 2012, requests that respondents reevaluate flood hazards at each site and compare the reevaluated hazard to the current design basis at the site for each flood mechanism. Addressees are requested to perform an integrated assessment if the current design-basis flood hazard does not bound the reevaluated flood hazard for all mechanisms. This ISG will assist operating power reactor respondents and holders of construction permits under 10 CFR Part 50 in performing tsunami, surge, and seiche hazard assessments. The guidance provided in this ISG describes methods that can be used as part of performing the flooding hazard reanalysis requested in Enclosure 2 of the letter dated March 12, 2012.

**BACKGROUND**

Following the events at the Fukushima Dai-ichi nuclear power plant, the NRC established a senior-level agency task force referred to as the Near-Term Task Force (NTTF). The NTTF conducted a systematic and methodical review of the NRC regulations and processes and determined if the agency should make additional improvements to these programs in light of the events at Fukushima Dai-ichi. As a result of this review, the NTTF developed a comprehensive set of recommendations, documented in the enclosure to SECY-11-0093 (Ref. 2). These recommendations were enhanced by the NRC staff following interactions with stakeholders. Documentation of the NRC staff's efforts is contained in SECY-11-0124, "Recommended Actions to be Taken Without Delay From the Near-Term Task Force Report," dated September 9, 2011 (Ref. 3), and SECY-11-0137, "Prioritization of Recommended Actions to be Taken in Response to Fukushima Lessons Learned," dated October 3, 2011 (Ref. 4).

As directed by the staff requirements memorandum in the enclosure to SECY-11-0093 (Ref. 5), the NRC staff reviewed the NTTF recommendations within the context of the NRC's existing regulatory framework and considered the various regulatory vehicles available to the NRC to implement the recommendations. SECY-11-0124 and SECY-11-0137 established the staff's prioritization of the recommendations based upon the potential safety enhancements.

As part of the staff requirements memorandum for SECY-11-0124, dated October 18, 2011 (Ref. 6), the Commission approved the staff's proposed actions, including the development of three information requests under 10 CFR 50.54(f). The information collected will be used to support the NRC staff's evaluation of whether further regulatory action should be pursued in the areas of seismic and flooding design and emergency preparedness. In addition to Commission direction, the Consolidated Appropriations Act, Public Law 112-074, which contains the Energy and Water Development Appropriations Act, 2012, was signed into law on December 23, 2011. Section 402 of the law requires a reevaluation of licensees' design basis for external hazards.

In response to the aforementioned Commission and Congressional direction, the NRC issued a request for information to all power reactor licensees and holders of construction permits under 10 CFR Part 50 on March 12, 2012 (50.54(f) letter)(Ref. 1). The March 12, 2012, 50.54(f) letter includes a request that respondents reevaluate flooding hazards at nuclear power plant sites using updated flooding hazard information and present-day regulatory guidance and methodologies. The letter also requests the comparison of the reevaluated hazard to the current design basis at the site for each potential flood mechanism. If the reevaluated flood hazard at a site is not bounded by the current design basis, respondents are requested to perform an integrated assessment. The integrated assessment will evaluate the total plant response to the flood hazard, considering multiple and diverse capabilities such as physical barriers, temporary protective measures, and operational procedures. The NRC staff will review the responses to this request for information and determine whether regulatory actions are necessary to provide additional protection against flooding. This ISG is specific to the assessment of tsunami, surge, or seiche hazards.

On October 26, 2012, the NRC staff issued a draft version of this ISG and published a notice of its availability for public comment in the *Federal Register* (77 FR 65417). The 30-day comment period ran October 26, 2012, through November 26, 2012, during which the staff received 38 public comments. Comments were received related to the following topical areas: (1) general comments; (2) comments specific to the storm surge evaluation; and (3) comments specific to the tsunami evaluation. In public meetings on October 24-25, 2012, and November 14, 2012, the NRC staff interacted with external stakeholders to discuss, understand, and resolve public comments. Modifications were made to text of the ISG in response to the public comments and the outcomes of the public meetings. Full detail of the comments, staff responses, and the staff's bases for changes to the ISG are contained in "NRC Response to Public Comments" to JLD-ISG-2012-06 (Docket ID NRC-2012-0261) (Ref. 7).

## **RATIONALE**

On March 12, 2012, the NRC issued a request for information to all power reactor licensees and holders of construction permits under 10 CFR Part 50. The request was issued in accordance with the provisions of Sections 161c, 103b, and 182a of the Atomic Energy Act of 1954, as amended (the Act), and NRC regulation in Title 10 of the *Code of Federal Regulations*, Part 50, Paragraph 50.54(f). Pursuant to these provisions of the Act and this regulation, respondents were required to provide information to enable the staff to determine whether a nuclear plant license should be modified, suspended, or revoked.

The information request directed respondents to submit a reevaluated flooding hazard for their sites using updated information and present-day regulatory guidance and methodologies. This ISG describes an approach for performing an tsunami, surge, or seiche hazard assessment.

## **APPLICABILITY**

This ISG shall be implemented on the day following its approval. It shall remain in effect until it has been superseded or withdrawn.

## **PROPOSED GUIDANCE**

This ISG is applicable to holders of operating power reactor licenses and construction permits under 10 CFR Part 50. For combined license holders under 10 CFR Part 52, the issues in NTTF Recommendations 2.1 and 2.3 regarding seismic and flooding reevaluations and walkdowns are resolved and thus, this ISG is not applicable.

## **IMPLEMENTATION**

Except in those cases in which a licensee or construction permit holder under 10 CFR Part 50 proposes an acceptable alternative method for tsunami, surge, or seiche hazard assessment, the NRC staff will use the methods described in this ISG to evaluate the results of the assessment.

## **BACKFITTING DISCUSSION**

This ISG does not constitute backfitting as defined in 10 CFR 50.109 (the Backfit Rule) and is not otherwise inconsistent with the issue finality provisions in Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," of 10 CFR. This ISG provides guidance on an acceptable method for responding to a portion of an information request issued pursuant to 10 CFR 50.54(f). Neither the information request nor the ISG require the modification or addition to systems, structures, or components, or design of a facility. Applicants and licensees may voluntarily use the guidance in JLD-ISG-2012-06 to comply with the request for information. The information received by this request may, at a later date, be used in the basis for imposing a backfit. The appropriate backfit review process would be followed at that time.

## **FINAL RESOLUTION**

The contents of this ISG, or a portion thereof, may subsequently be incorporated into other guidance documents, as appropriate.

## **ENCLOSURES**

1. Guidance for Performing a Surge or Seiche Hazard Assessment
2. Guidance for Performing a Tsunami Hazard Assessment
3. Glossary

## REFERENCES

1. U.S. Nuclear Regulatory Commission, "Request for Information Pursuant to Title 10 of the *Code of Federal Regulations* 50.54(f) Regarding Recommendations 2.1, 2.3, and 9.3, of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," March 12, 2012, Agencywide Documents Access and Management System (ADAMS) Accession No. ML12053A340.
2. U.S. Nuclear Regulatory Commission, "Recommendations for Enhancing Reactor Safety in the 21st Century, The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," Enclosure to SECY-11-0093, July 12, 2011, ADAMS Accession No. ML111861807.
3. U.S. Nuclear Regulatory Commission, "Recommended Actions to be Taken Without Delay From the Near Term Task Force Report," SECY-11-0124, September 9, 2011, ADAMS Accession No. ML11245A158.
4. U.S. Nuclear Regulatory Commission, "Prioritization of Recommended Actions to be Taken in Response to Fukushima Lessons Learned," SECY-11-0137, October 3, 2011, ADAMS Accession No. ML11272A111.
5. U.S. Nuclear Regulatory Commission, "Staff Requirements - SECY-11-0093 - Near-Term Report and Recommendations for Agency Actions Following the Events in Japan," August 19, 2011, ADAMS Accession No. ML112310021.
6. U.S. Nuclear Regulatory Commission, "Staff Requirements - SECY-11-0124 - Recommended Actions to be Taken Without Delay From the Near-Term Task Force Report," October 18, 2011, ADAMS Accession No. ML112911571.
7. U.S. Nuclear Regulatory Commission, "NRC Responses to Public Comments, Japan Lessons-Learned Project Directorate Interim Staff Guidance (JLD-ISG-2012-06): Guidance for Performing a Tsunami, Surge, or Seiche Hazard Assessment in Response to the March 2012 Request for Information Letter," January 4, 2013, ADAMS Accession No. ML12314A414.

## GUIDANCE FOR PERFORMING A SURGE OR SEICHE HAZARD ASSESSMENT

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## **1. Introduction**

The purpose of this interim staff guidance (ISG) is to provide the U.S. Nuclear Regulatory Commission (NRC) staff with a technical basis for reviewing storm surge or seiche hazard assessments per the March 12, 2012, letters issued to operating nuclear power plants and holders of construction permits in accordance with the provisions of Sections 161.c, 103.b, and 182.a of the Atomic Energy Act of 1954, as amended (the Act), and NRC regulations in 10 CFR 50.54(f).

All coastal nuclear power plant sites must consider the potential for flooding from hurricanes, windstorms, and squall lines, as well as storm surge, seiche, and windwaves as part of the hazard reevaluation.

### **1.1. Format of Guidance**

Section 1.2 (Historical Perspective) discusses the evolution in surge and seiche regulatory guidance during the time period between the licensing of the operating plants and the licensing activities for new reactors. Section 2 (Acceptance Criteria) continues with a discussion of existing regulatory guidance (Section 2.1) and guidance updates (Section 2.2) based on the ongoing new reactor safety reviews and current state of knowledge. Section 2 gives particular attention to terms and definitions, as well as current good practices.

Section 3 (Surge Hazard Assessment) closely follows the format provided in Section 2.4.6 of Regulatory Guide 1.206, "Combined License Applications for Nuclear Power Plants," and NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants (LWR [light-water reactor] Edition)" (SRP). Section 3.1 (Overview) describes the Hierarchical Hazard Assessment (HHA) approach and the role that deterministic and combined deterministic-probabilistic methods play in surge hazard assessments. Section 3.2 (Meteorological Parameters) describes deterministic and combined deterministic-probabilistic storm-generating methods for input into numerical surge models, which are discussed in Section 3.3. In Section 3.3 (Surge Parameters), pre-surge modeling steps are discussed, beginning with vertical datums (Section 3.3.1) followed by antecedent water levels (Section 3.3.2). Section 3.3.3 (Surge Water Levels) provides a discussion of two state-of-the-art surge models that the NRC and other Federal agencies use.

A discussion of seiche hazard assessment is provided in Section 4. Section 5 (Wave and Inundation Effects for Surge and Seiche), which discusses post-numerical modeling effects, follows it. Factors that should be considered in all surge and seiche hazard assessments include coincident wave heights, inundation, and wave runup and drawdown, which are described in Sections 5.1 through 5.4. Sections 5.5 through 5.7 discuss factors that should be considered for "wet" sites, including hydrostatic and hydrodynamic forces, debris and waterborne projectiles, and the effects of sediment erosion and deposition. References are provided in Section 7.

### **1.2. Historical Perspective**

In 1959, the U.S. Army Corps of Engineers (USACE) contracted the National Weather Service (NWS) to develop a hypothetical hurricane that could be used to design hurricane protection projects along the Gulf and Atlantic Coasts of the United States. The NWS, as part of its National Hurricane Research Project, set out to define "the most severe storm that is considered reasonably characteristic of a region." A storm with such characteristics was



termed the “Standard Project Hurricane” (SPH). The U.S. Weather Bureau Report No. 33 (Graham and Nunn, 1959) describes this effort.

NWS Technical Report 23 (Schwerdt et al., 1979) redefined the SPH as “a steady-state hurricane having a severe combination of values of meteorological parameters that will give high sustained wind speeds reasonably characteristic of a given region,” removing the idea from the definition of the SPH that the SPH pertained to the “most severe storm” for a particular area. The concept of a “probable maximum hurricane” (PMH) also was introduced as “a hypothetical steady-state hurricane having a combination of values of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location.” The PMH was intended to be an event much rarer than the SPH, but NWS Report 23 (NWS 23), “Meteorological Criteria for Standard Project Hurricane (SPH) and Probable Maximum Hurricane (PMH) Wind Fields, Gulf and East Coasts of the United States,” did not offer an objective definition. In 2007, the evaluation of the PMH characteristics was superseded by the adoption of the probable maximum storm surge (PMSS) hazard assessment.

Historically, design-basis surge and seiche hazard flood estimates for nuclear power plants (NPPs) have been developed using deterministic analysis approaches based on the “probable maximum” or “maximum credible” event concept (i.e., the event thought to have “virtually no risk of exceedance”). The level of analysis may range from very conservative, based on simplifying assumptions, to detailed analytical estimates of each facet of the flood-causing mechanism studied.

In response to Hurricane Katrina in 2005, the NRC formed a storm surge research program focused on developing modern, risk-informed, hazard assessment techniques and additional guidance through cooperation with the National Oceanic and Atmospheric Administration (NOAA) and USACE. This research program produced several technical reports. NOAA, U.S. Department of Energy (DOE) laboratories, USACE, and commercial contractors currently are assisting the NRC’s Office of New Reactors (NRO) in reviewing storm surge hazards and updating regulatory guidance.

In 2009, the NRC’s Office of Nuclear Regulatory Research (RES) tasked the USACE Engineer Research and Development Center/Coastal and Hydraulics Laboratory (ERDC CHL) to review NOAA Technical Report NWS 23 and NRC Regulatory Guide 1.59, “Design Basis Floods for Nuclear Power Plants.” ERDC CHL found that several assumptions in the PMH described in NWS 23 are not consistent with the current state of knowledge and recommended that the PMH concept be updated in accordance with new theoretical concepts and data (USACE, 2009).

The 2009 ERDC CHL report also states that the ocean model recommended in Regulatory Guide 1.59 (1977) is “extremely limited by restrictions and simplifications made in order to make the problem computationally tractable given the computer resources available in the early to mid-1970’s” (Resio et al., 2012; USACE, 2009). The review findings recommended adoption of a modern combined system of wind, wave, and coastal circulation models that properly define the physical system and include an appropriate nonlinear coupling of the relevant processes. Thus, the simplified methods provided in Appendix C, “Simplified Methods of Estimating Probable Maximum Surges,” of Regulatory Guide 1.59 (1977) are not considered acceptable or used for new reactor application storm surge hazard assessments. However, the approach provided in NWS 23 (1979) is still acceptable for licensing decisions.

## 2. Acceptance Criteria

### 2.1. Existing Regulatory Guidance

The applicable regulatory requirements for identifying surge and seiche hazards are as follows:

- 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities.” General Design Criterion 2 (GDC 2), “Design Bases for Protection against Natural Phenomena,” of Appendix A, “General Design Criteria for Nuclear Power Plants,” requires that structures, systems, and components important to safety be designed to withstand the effects of natural phenomena such as floods, tsunamis, and seiches without loss of capability to perform their safety functions. Criterion 2 also requires that design bases for these structures, systems, and components reflect (1) appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding region with sufficient margin for the limited accuracy and quantity of the historical data and the period when the data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, and (3) the importance of the safety functions to be performed.
- 10 CFR Part 100, “Reactor Site Criteria,” requires that physical characteristics of the site, including seismology, meteorology, geology, and hydrology, be taken into account when determining the acceptability of a site for a nuclear power reactor.

Other NRC guidance documents, such as NUREGs and regulatory guides, describe methods that the NRC staff considers acceptable to use in implementing specific parts of the agency’s regulations, to explain techniques the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants and licensees. Compliance with recommendations contained in the NRC guidance is not mandated. Thus, in addition to the applicable regulatory requirements, the NRC staff uses appropriate sections of the following guidance documents for the identified acceptance criteria:

- NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants (LWR Edition),” provides guidance to NRC staff in performing safety reviews under 10 CFR Part 50 and 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants.” Section 2.4.5 provides general guidance for estimating flooding due to storm surge and seiche.
- NUREG/CR-7046, “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America,” issued November 2011, provides present-day methodologies and technologies that can be used to estimate design-basis floods at nuclear power plants for a range of flooding mechanisms. Sections 3.5, 3.6, Appendix E, and Appendix F provide additional guidance and an illustrative case study for a probable maximum storm surge analysis (Prasad et al., 2011).
- Regulatory Guide 1.59, “Design Basis Floods for Nuclear Power Plants,” Revision 2, issued August 1977, as supplemented by best current practices (NRC, 1977).

- Regulatory Guide 1.27, “Ultimate Heat Sink for Nuclear Power Plants,” Revision 2 (NRC, 1976a).
- Regulatory Guide 1.102, “Flood Protection for Nuclear Power Plants,” Revision 1, provides guidance for the protection of nuclear power plants from flooding (NRC, 1976b).
- Regulatory Guide 1.206, “Combined License Applications for Nuclear Power Plants.” Section C.I.2.4.5 provides general guidance for estimating flooding due to storm surge and seiche (NRC, 2007).
- ANSI/ANS-2.8-1992, “American National Standard for Determining Design Basis Flooding at Nuclear Reactor Sites,” provides a methodology for estimating storm surges and seiches at estuaries and coastal areas on oceans and large lakes. Appendix C gives a simplified method of estimating surges on the Atlantic and Gulf Coasts (ANS, 1992).
- JLD-ISG-2012-05 provides guidance for performing the integrated assessment for flooding, when necessary (NRC, 2012b).

## **2.2. Updates to Guidance**

In the SRP 2007 update, the adoption of the PMSS superseded the evaluation of the PMH characteristics. The 2007 update also clarified the PMH. The SRP relates the PMSS and the PMH when it states that the “PMSS is the surge that results from a combination of meteorological parameters of a probable maximum hurricane (PMH)...and has virtually no probability of being exceeded in the region involved.” To avoid confusion with strictly probabilistic flood hazard assessments, the “probable maximum” terminology referenced in NUREG-0800, Regulatory Guide 1.59, Regulatory Guide 1.206, and ANSI/ANS-2.8-1992 is not used in this guidance. Instead, the terms “simulated” and “design basis” are used and the following terms are defined in the Appendix:

- simulated hurricane (SH)
- simulated wind storm (SWS)
- simulated storm surge (SSS)
- design-basis storm surge (DBSS)

No other Federal agencies, such as the USACE, NOAA, and the Federal Emergency Management Agency (FEMA), currently use the “probable maximum” or “standard project” terminology for storm surge. However, NRC guidance uses these terms. This document is the first attempt to make NRC guidance more consistent with the guidance of other Federal agencies.

NUREG-0800, Revision 3 (March 2007), recommends the DBSS that the PMH induces should be estimated as recommended by Regulatory Guide 1.59 and supplemented by current best practices. However, the determination of the storm surge from bathystrophic models (Bretschneider, 1966; Bodine, 1969; Pararas-Carayannis, 1975) used in Regulatory Guide 1.59, which is based on earlier wind field calculations, is not consistent with the

current state of knowledge. Therefore, the DBSS estimates using the simplified methods provided in Appendix C of Regulatory Guide 1.59 (1977) are not considered acceptable and are not used for new reactor application storm surge hazard assessments. However, the approach in NWS 23 (1979) is still acceptable for licensing decisions. The current practice in storm-surge modeling is based on the use of coupled hydrodynamic ocean circulation and wave models, both driven by a planetary boundary layer (PBL) model that provides atmospheric forcing (Figure 1). Storm surge models should be validated using historical information and data in the region of interest.

For seiche, analytical methods can be used for screening. However, if seiche cannot be eliminated from further consideration using analytical methods, numerical modeling will be necessary. Seiche models should be validated using historical information and data in the region of interest.

The NRC Web site (NRC, 2012) provides combined license (COL) and early site permit safety analysis reports and NRC requests for additional information (RAIs) addressing surge and windwave evaluations associated with recent new reactor reviews.

### **3. Surge Hazard Assessment**

All coastal nuclear power plant sites and nuclear power plant sites located adjacent to cooling ponds or reservoirs subject to potential hurricanes, windstorms, and squall lines must consider the potential for inundation from storm surge and windwaves. For example, a hurricane, extra-tropical storm, or squall line could cause a water-level change in an adjacent body of water. The resulting change in water levels, if not considered in the project design, could affect safety-related structures located at the plant site.

All water wave processes, including surge, consist of generation, propagation, and dissipation. Section 3 of this ISG (Surge Hazard Assessment) describes the HHA approach and the role that deterministic and combined deterministic-probabilistic methods play in surge hazard assessments. Section 3.2 (Meteorological Parameters) provides three surge generation approaches. For hurricanes, Section 3.2.1 (Hurricane Parameters) discusses a deterministic approach in Section 3.2.1.1 (Probable Maximum Hurricane) and a combined deterministic-probabilistic approach in Section 3.2.1.2 (Joint Probability Method). Similarly, for extra-tropical storms and squalls lines (Section 3.2.2), Section 3.2.2 (ANSI/ANS-2.8-1992) and Section 3.2.2.1 (Empirical Simulation Technique) provide deterministic and combined deterministic-probabilistic surge generation approaches.

Section 3.3 (Surge Parameters) addresses the propagation of surge phase beginning with a discussion of datums (Section 3.3.1). Starting a surge hazard assessment with bathymetric and topographic data using appropriate vertical datums is essential to correctly reference water levels with site elevations. For additional margin, Section 3.3.2 (Antecedent Water Levels) provides guidance on the determination of pre-surge model propagation stillwater levels using astronomical tides (Section 3.3.2.1), initial rise (Section 3.3.2.2), and sea-level rise (Section 3.3.2.3). Section 3 ends with the surge propagation phase described in Section 3.3.3 (Surge Water Levels). Section 3.3.3.1 (*ADvanced CIRCulation Surge Model* (ADCIRC)) and Section 3.3.3.2 (Sea, Lake, Overland Surge from Hurricanes (SLOSH)) provide a discussion of two state-of-the-art surge models that the NRC and other Federal agencies currently use.

### **3.1. Overview**

Site hazard assessments follow a progressive screening approach, consisting of a series of progressively refined methods that increasingly use more detailed site-specific data to demonstrate whether the site is protected from the adverse effects of severe floods. This approach (Figure 2) is formalized in the HHA approach described in NUREG/CR-7046 (Prasad et al., 2011). The HHA approach provides a roadmap for applying a hierarchy of conceptual and mathematical models for the efficient determination of design-basis flood mechanisms and levels.

Probabilistic-only and the deterministic-only approaches to the estimation of very low-probability storm surges have their strengths and deficiencies, depending on the safety hazard assessment objective. Previous site hazard assessments for storm surge have used a deterministic-only HHA approach. However, other Federal agencies recently begun to join the two approaches to provide some advantages over either approach implemented independently (Resio et al., 2012). This document is the first attempt to make NRC guidance more consistent with other Federal agency guidance.

The USACE has developed a probabilistic-deterministic methodology for storm surge hazard assessment that can be combined with the HHA approach to provide a DBSS with risk information. The methodology uses an integrative, interdisciplinary approach that incorporates state-of-the-art knowledge in hurricane science, hydrology, and probabilistic methods. This methodology involves the following steps:

- (1) Selection of a stochastic set of simulated storm tracks affecting the region of interest.
- (2) Hydrodynamic simulation of the region of interest using a high-resolution surge model and the simulated storm tracks to generate time histories of wind speeds and corresponding time histories of storm surge heights at sites within the affected region.
- (3) Use of wind speed and storm surge height information generated in Steps (1) and (2) to develop probabilistic information on the joint probability of wind speed and storm surge height events (Resio et al., 2012).

Regardless of the method used, an assessment of sensitivities and uncertainties should be provided for model parameters that may have significant influence on design-basis storm surge estimates.

### **3.2. Meteorological Parameters**

Storm surge can result from several different types of storms (e.g., tropical cyclones, extra-tropical cyclones, squall lines, and hybrid storms). For example, extra-tropical cyclones, also known as Northeasters, move along the Atlantic coast with winds from the northeast onto the shoreline, typically producing winds ranging from 30 to 40 mph (48 to 64 km/h) with gusts that can exceed 74 mph (119 km/h). Although below hurricane force, these winds can persist for several days to a week and generate large waves and storm surges. In comparison, wind speed and storm surge elevations are more severe in hurricanes. Their shoreline effects tend to be more localized, and they are generally confined to stretches of coastline of about 65 miles (105 km) or fewer.

For the storm surge hazard assessments, the historical record for each storm type appropriate to the region should be examined to determine estimates for extreme winds. This detailed analysis of historical storm events in the region should be augmented by synthetic storms parameterized to account for conditions more severe than those in the historical record, but considered to be reasonably possible on the basis of technical reasoning.

This guidance considers four techniques for synthetic storm generation:

- Probable Maximum Hurricane (PMH)
- Joint Probability Method (JPM)
- ANSI/ANS-2.8-1992
- Empirical Simulation Technique (EST)

PMH and JPM are used for generation of synthetic hurricanes (Figure 3). ANSI/ANS-2.8-1992 and EST are used to generate synthetic extra-tropical storms and squall lines.

### **3.2.1. Hurricane Parameters**

This section applies to all coastal sites, excluding the Great Lakes, as described in ANSI/ANS-2.8-1992.

#### *3.2.1.1. Probable Maximum Hurricane*

The NOAA NWS Technical Report 23 (Schwerdt et al., 1979) describes the PMH method in detail. PMH meteorological parameters, as described in NUREG-0800, Section 2.4.5, define the physical attributes of the PMH to derive wind fields that can serve as input into an atmospheric model. Storm surge model simulations are performed with numerous combinations of PMH parameters to obtain the highest design-basis storm surge (DBSS) at the site.

NOAA NWS Technical Report 23 (NWS 23) provides methods for estimating PMH wind fields. The PMH is defined as a hypothetical steady-state hurricane with a combination of values of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location (NOAA, 1979). The term steady-state is meant to indicate that there is no change in the value of hurricane wind-field parameters during, at least, the last several hours before the PMH makes landfall. The meteorological parameters that define the PMH wind field include the hurricane peripheral pressure, central pressure, radius of maximum winds, forward speed, and track direction. Note that the NWS 23 method provides no risk information (e.g., return period) and is only applicable to the deterministic storm surge analysis of hurricanes.

The PMH parameter values in NWS 23 were based on data from historical hurricanes from 1851 to 1977 and were presented for multiple locations along the Gulf of Mexico and Atlantic Ocean coastlines corresponding to their milepost distances from the U.S. to Mexico border. Comparisons of hurricane climatology during the period evaluated in NWS 23 with hurricanes making landfall after 1975 indicate that the NWS 23 parameters for the PMH are still applicable (NOAA, 2007; Ho et al., 1987; Knutson et al., 2010). However, consistent with NUREG-0800, Section 2.3, a detailed site- or region-specific hurricane climatology study should be provided to show that the PMH parameters are consistent with the current state of knowledge.

Surge elevation increases with increasing hurricane size. In addition, based on site-specific topography or bathymetry, the increase in storm surge with increasing hurricane size may reach an upper bound. Thus, this behavior should be further investigated by varying the PMH size (radius of maximum wind) beyond the upper bound specified in NWS 23 for a PMH approaching the site (Irish et al., 2008a; Resio and Westerink, 2008). ANSI/ANS-2.8-1992, Section 7, provides additional guidance on the critical combinations of PMH parameters.

Appendix E, "Flooding from Storm Surges: A Case Study," of NUREG/CR-7046 contains an example of how the PMH wind field is estimated using the NWS 23 procedure.

### 3.2.1.2. *Joint Probability Method*

The JPM (Myers, 1970) approach quantifies the return periods of storm surges. Statistical simulation methods such as JPM are needed for coastal flood frequency analysis primarily because of the unavailability of sufficient historical record from which to derive frequencies by more conventional means, such as gage analysis. Hurricanes, for example, are both sporadic and of limited spatial extent, contributing to a great deal of sample variation (sample error) in local tide gage records. As such, JPM is widely used in coastal flood studies that USACE and FEMA perform. For example, Federal agencies adopted the JPM for critical post-Katrina determinations of hurricane surge frequencies (IPET, 2007).

The JPM has been used for simulating hurricanes since the late 1960s. The original JPM application, while not called JPM, was developed for predicting wave loads on offshore structures in the Gulf of Mexico (Russell, 1968). The JPM approach that Russell used was a full Monte Carlo simulation in which model hurricanes were simulated using straight-line segments with wind and wave fields computed using hurricane wind and wave models. The methodology was first introduced because the number of historical events (hurricanes) at any one location is insufficient to enable standard statistical techniques (such as extreme value analyses) to estimate flood risk, wave height risk, wind speed risk, etc. The JPM method can be used as an alternative to PMH for deterministic storm surge analysis or used as an option in a combined deterministic-probabilistic analysis for risk information.

The JPM approach is a simulation methodology that relies on the development of statistical distributions of key hurricane input parameters (central pressure, radius of maximum winds, translation speed, and heading) and sampling from these distributions to develop model hurricanes. The simulation results in a family of modeled storms that preserve the relationships between the various input model parameters, but provides a way to model the effects and probabilities of storms that have not yet occurred. The method known as JPM-OS (Joint Probability Method–Optimum Sampling) also can be used, which reduces the number of JPM simulated storms needed (Toro et al., 2010).

Resio et al. (2007) first introduced long duration tracks that mimic the behavior of hurricanes while they are off shore (and generating a wave field). Vickery et al. (2000a) introduced modeling the full storm track from a wind-only point of view. The simulation methodologies that Resio et al. (2007) and Vickery et al. (2000b) used both attempt to properly model the correlations between storm intensity (central pressure) and radius to maximum winds (RMW). Vickery et al. (2000a) also modeled a relationship between RMW and the Holland B (Holland, 1980) parameter. Overall, the JPM approach has the conceptual advantage of considering all possible storms consistent with the local climatology, each

weighted by its appropriate rate of occurrence. Unlike the NWS 23 method, the key model hurricane parameters are developed through an analysis of continuously updated local climatology derived from NOAA's historical hurricane database (HURDAT; Landsea et al., 1996; Landsea et al., 2004; Blake et al., 2007; Blake and Gibney, 2011; and NOAA, 2012b). All parameter combinations analyzed (each defining a synthetic storm) should be simulated using a surge model constructed to accurately represent the site's bathymetry, topography, and ground cover.

For examples of detailed discussions and guidance on the application of the JPM to coastal issues see Ferro (2007), Niedorodu et al. (2010), Phan et al. (2007), Resio et al. (2007; 2012), Schmalz (1983), Scheffner et al. (1996), and Toro (2007). Divoky and Resio (2007) provides a comparison of JPM and EST methods.

The NRC and the American Society of Civil Engineers (ASCE) also used the JPM method for design-basis hurricane wind speeds for nuclear power plants (Vickery et al., 2011; NRC, 2011) and minimum design loads for buildings and other structures (ASCE, 2010).

### **3.2.2. Extra-tropical Storm and Squall Line Parameters**

A detailed site- or regional-specific meteorological study consistent with SRP Section 2.3 should be conducted to identify applicable mechanisms and to verify that the ANSI/ANS-2.8-1992 assumptions reflect the most severe meteorological parameters. This applies to all coastal sites, including the Great Lakes (ANSI/ANS-2.8-1992).

The ANSI/ANS-2.8-1992 standards provide detailed guidance on extra-tropical windstorms (Section 7.2 of ANSI/ANS-2.8-1992) and squall lines (Section 7.3 of ANSI/ANS-2.8-1992). For the Great Lakes, a set of fixed criteria of extra-tropical storm parameters is provided instead of a meteorological study (Sections 7.2.2.3.1 and 7.2.2.3.3 of ANSI/ANS-2.8-1992). In addition, Section 7.2.3.1 of ANSI/ANS-2.8-1992 states that "[a] moving squall line should be considered for the locations along Lake Michigan where significant surges have been observed because of such a meteorological event. The possible region of occurrence includes others of the Great Lakes."

#### **3.2.2.1. Empirical Simulation Technique**

The Empirical Simulation Technique (EST) (Scheffner et al., 1999) quantifies the return periods of storm surges. Statistical simulation methods, such as EST, are necessary for coastal flood frequency analysis primarily because there is an insufficient historical record from which frequencies could be derived by more conventional means, such as gage analysis. For this reason, USACE and FEMA widely use EST in coastal flood studies that they have performed.

The EST method is an option for a combined deterministic-probabilistic methodology. However, unlike tropical storms, a set of storm parameters does not easily represent extra-tropical storms. Thus, the EST frequency analysis is recommended to determine storm surge stillwater return periods for extra-tropical storms.

EST site estimates are based entirely on the historical storms and flood levels observed at that site. Alternate life cycles are simulated by assuming that storm occurrence follows a Poisson process and by implementing a bootstrap resampling from the set of observed events to construct synthetic records. Flood frequency and variability estimates are then



derived from this synthetic data. The only assumption is that future events will be statistically similar in magnitude and frequency to past events. The method begins with an analysis of historical events that have affected a specific location. The selected database of events is then parameterized to define the characteristics of the event and the impacts of that event. Parameters that define the storm are referred to as input vectors. Response vectors define storm-related impacts, such as surge elevation, inundation, and shoreline or dune erosion, etc. These input and response vectors are then used as a basis for generating life-cycle simulations of storm-event activity with corresponding impacts.

For detailed discussions and guidance on the application of the EST method to coastal issues, see, for example, Scheffner et al. (1996), Scheffner et al. (1999), Wilbury et al. (2007), Zimmer (2008), RENCI (2011), and FEMA (2011, 2012). The USACE Coastal Engineering Design and Analysis System (CEDAS) includes an EST model for the generation of storm profiles (USACE, 2012b). Divoky and Resio (2007) compare the JPM and EST methods.

### **3.3. Surge Parameters**

This section provides guidance on propagation of the surge phase and includes a discussion of datums and antecedent water levels (astronomical tides, initial rise, and sea-level rise). In addition, this section provides guidance on determining surge water levels.

#### **3.3.1. Datums**

There are two types of datums: tidal and fixed. For example, mean sea level pertains to the local mean sea level (MSL), which is a tidal datum based on astronomical tides. A tidal datum is determined over a 19-year National Tidal Datum Epoch. North American Vertical Datum of 1988 (NAVD88) and National Geodetic Vertical Datum of 1929 (NGVD29) are fixed geodetic datums whose elevation relationships to local MSL and other tidal datums may not be consistent from one location to another. NAVD88 replaced NGVD29 as the national standard geodetic reference for heights.

Licensees select the applicable datum to conform to site-specific requirements (e.g., local and state requirements) as well as best practices and engineering judgement. Once selected, the datum should be applied universally for all flood evaluations and documentation.

#### **3.3.2. Antecedent Water Levels**

Antecedent water levels should be included in storm surge DBSS estimation. Regulatory Guide 1.59 (NRC, 1977) and ANSI/ANS-2.8-1992 recommend that the 10 percent exceedance high tide be used to represent the antecedent water level. In addition, long term sea level changes should also be considered. For example, antecedent water level should be taken as the sum of the stillwater depth (i.e., mean sea or lake level), 10 percent exceedance high tide, and long-term sea-level rise. Because of the non-linear wave effects, the antecedent water level should be applied as the initial storm surge model stillwater level. Section 5 addresses post-modeling storm surge water level additions, such as wind waves and wave runup.

### 3.3.2.1. *Tides*

In computing the surge level, the 10% exceedance high tide should be considered to occur coincidentally with the storm surge. The 10% exceedance high tide is the high-tide level that is equaled or exceeded by 10% of the maximum monthly tides over the tidal epoch (a continuous 21-yr period in most locations). This tide can be determined from the recorded tide or from the predicted astronomical tide. If astronomical tides are used, sea level anomaly should be added. Sea level anomalies (also referred to as initial rise) are departures of the water surface elevation from astronomical tides due to various meteorological and oceanographic forcings. Historical and current tide observations, information on tidal datums, as well as predicted tide levels can be found on the NOAA Tides and Currents Web site (NOAA, 2012a). NOAA maintains a network of tide gage stations along the U.S. shoreline, including the Great Lakes.

### 3.3.2.2. *Initial Rise*

For locations where the 10 percent exceedance high spring tide is estimated from observed tide data, Regulatory Guide 1.59 and ANSI/ANS-2.8-1992 indicate that a separate estimate of the initial rise is not necessary. This approach for estimating 10 percent exceedance high tide, based on recorded tides, intrinsically includes the effects of initial rise.

### 3.3.2.3. *Long-Term Sea Level Rise*

Relative sea-level rise is the combined effect of water-level change and land subsidence. The NOAA National Ocean Service, the U.S. Global Change Research Program, and the Intergovernmental Panel on Climate Change (IPCC) monitor and report sea-level rise information, which also should be included in design-basis flood analysis for coastal sites (IPCC, 2007).

NOAA maintains tide gage stations along the U.S. shoreline (NOAA, 2012a) and has evaluated the trend of sea-level rise. Measurements at any given tide station include both global sea-level rise and vertical land motion, such as subsidence, glacial rebound, or large-scale tectonic motion. Thus, the long-term sea-level rise should be derived for the expected life of the nuclear power plant based on the trend in site or regional tide gage station data. As part of the HHA approach, regional or global sea-level rise trends can be added in initial storm surge simulations to the site or regional observed trend for additional margin.

### 3.3.3. Surge Water Levels

This section provides guidance on methods for computation of surge water levels. Storm surge models developed by Federal agencies, such as USACE or academic and research institutions, that are currently being used in standard engineering practice are adequate for storm surge hazard analysis. However, other models may be used with documentation of their site-specific application as outlined in Section 5.3 of NUREG/CR-7046. For examples of current state-of-the-art storm surge models, the following models developed by Federal agencies are described:

- *ADvanced CIRCulation Surge Model (ADCIRC)*
- *Sea, Lake, Overland Surge from Hurricanes (SLOSH)*

#### 3.3.3.1. *ADvanced CIRCulation Surge Model*

The development of the ADCIRC model occurred at the USACE Dredging Research Program as a family of two- and three-dimensional finite element-based models (Luettich, Westerink, and Scheffner, 1992; Westerink et al., 2008). An important feature of the model is its ability to simulate tidal circulation and storm-surge propagation over very large computational domains while simultaneously providing high resolution in areas of complex shoreline configuration and bathymetry.

The USACE hurricane modeling system used for the safety evaluation of new reactor COL applications (Resio, 2012) combined various wind models (TC96 PBL), the Wave Prediction Model (WAM) offshore and steady-state spectral wave (STWAVE) nearshore wave models, and the ADCIRC basin to channel scale unstructured grid circulation model (Figure 1).

For detailed discussions and guidance on the application of ADCIRC to coastal issues, see, for example, Dean et al. (2004), Luettich and Westerink (2004), Coastal Protection and Restoration Authority of Louisiana (2007), IPET (2007), Toro (2007), Blandon and Vickery (2008), Westerink et al. (2008), and Resio et al. (2007, 2012). Refer to Resio (2012) for application of the ADCIRC model to new reactors using the JPM-OS method.

#### 3.3.3.2. *Sea, Lake, Overland Surge from Hurricanes*

NOAA developed the SLOSH (Sea, Lake, Overland Surge from Hurricanes) computer model to forecast real-time hurricane storm surge levels on continental shelves, across inland bodies of water and along coastlines, including inland routing of water levels. SLOSH is a depth-averaged two-dimensional finite difference model on curvilinear polar, elliptical, or hyperbolic grid schemes. Modification of storm surges because of the overtopping of barriers (including levees, dunes, and spoil banks), the flow through channels and floodplains, and barrier cuts and breaches are included in the model. The effects of local bathymetry and hydrography also are included in the SLOSH simulation. SLOSH also incorporates an atmospheric model for tropical cyclones.

The SLOSH model inputs are hurricane pressure difference, hurricane track description including landfall location, forward speed, and size, given as the radius of maximum wind, which define the physical attributes of a hurricane in performing a storm surge simulation (Jelesnianski, 1992). NOAA provides two models: (1) SLOSH Display Program, and (2) SLOSH v3.95 FORTRAN code. The SLOSH Display Program is only valid for Category 1 through Category 5 hurricanes. Therefore, SLOSH Display Program results and methods

extrapolating these results beyond Category 5 hurricanes are not acceptable for licensing reviews. The SLOSH v3.95 FORTRAN code using NWS-23, JPM, and EST methods is one acceptable software package for performing storm surge hazard assessments. Details of SLOSH model formulation and application can be found in Jelesnianski (1992), NOAA (2006, 2009), and Glahn et al. (2009).

SLOSH model predictions have been validated against observed hurricane surge levels at several locations (Jelesnianski, 1992; Jarvinen, 1985). For example, as an emergency management tool, SLOSH is applied to the entire U.S. East Coast, Gulf of Mexico coastlines, Hawaii, Guam, Puerto Rico, and the U.S. Virgin Islands. The errors of the SLOSH model predictions, defined by subtracting the observed surge water levels from model predictions, were evaluated for 10 storms in 8 SLOSH model basins, 90 percent of which were in the Gulf of Mexico. Based on a comparison of the SLOSH simulated surge heights against observations, NOAA concludes that the model results generally stayed within  $\pm 20$  percent for significant surges (Jarvinen, 1985).

SLOSH does not include astronomical tides, wave run ups, or additional heights generated by wind-driven or breaking waves on top of the stillwater storm surge. In addition, the SLOSH v3.95 FORTRAN code that NWS provides contains a limitation in which grid cells with elevations greater than 10.7 meters (m) (35 feet (ft)) NAVD88 were removed from the flooding computation (i.e., these cells could never be flooded). NWS confirmed that the 10.7 m (35 ft) limit for surge in the SLOSH program is historical and does not pose any particular problems when it is relaxed. The SLOSH program code should be validated with and without the changes in the code to determine that the changes in the code are effective and accurate in allowing flooding at elevations greater than 10.7 m (35 ft). One method is to compare the same hurricane scenario for each code through validation against historical storm surge data.

NOAA has developed the Extra-Tropical Storm Surge Model (ET-Surge; NOAA, 2012d), which can use a separate planetary boundary wind model in conjunction with a modified SLOSH model to predict storm surge based on large extra-tropical storms as opposed to the tropical storms for which SLOSH was originally developed (Kim et al., 1996).

Appendix E of NUREG/CR-7046 contains an example of how the DBSS is estimated using SLOSH and the NWS 23 procedure.

#### **4. Seiche Hazard Assessment**

Seiche is an oscillatory wave generated in lakes, bays, or gulfs as a result of seismic or atmospheric disturbances and with a period ranging from a few minutes to a few hours. The oscillatory modes for the body of water in question should be calculated from a variety of potential sources. Sources to consider include (1) local or regional forcing phenomena, such as barometric pressure fluctuations, strong winds, rapid changes in wind direction, surge associated with passage of local storms; and (2) distant but large forcing mechanisms such as distant storms, tsunamis, or earthquake-generated seismic waves. For bodies of water with simple geometries, modes of oscillation can be predicted from the shape of the basin using analytical formulas. For example, the resonance within a makeup water reservoir may be approximated by a rectangular basin(s) using an approach provided in the USACE Coastal Engineering Manual (CEM) (USACE, 2008; Dean and Dalrymple, 1991).

Most natural bodies of water have variable bathymetry and irregular shorelines and may be driven by a combination of forcing mechanisms. For such bodies, seiche periods and water surface profiles should be determined through numerical long-wave modeling. The USACE SMS or CEDAS modeling systems, as well as documented models, such as the Princeton Ocean Model, should be used for complex seiche analyses. Appendix F of NUREG/CR-7046 (Prasad et al., 2011) provides a case study of seiche flooding using analytical formulas.

## **5. Wave and Inundation Effects Associated with Surge or Seiche**

This section relates to the wave dissipation phase in which surge and seiche wave action can directly affect the site. Wave action includes deep and shallow water-wave generation. Wind-generated wave activity that can occur independently of, or coincidentally with storm surge or seiche should be included in surge and seiche flood hazard analyses. Available records should be used to characterize the wave climate near the site using measures such as significant and maximum wave heights. Tides, wave setup, wave runup, splash, or overtopping, as appropriate, also should be considered in the analyses and surge and seiche flooding estimates.

Section 5.1 (Coincident Wave Heights) provides guidance on the calculation of wind waves that can occur coincidentally with the storm surge or seiche stillwater level. If the inundation (Section 5.2) reaches the site, other factors such as wave runup (Section 5.3), drawdown (Section 5.4), hydrostatic and hydrodynamic forces (Section 5.5), debris and water-borne projectiles (Section 5.6), and the effects of sediment erosion and deposition (Section 5.7) should be considered, as appropriate.

### **5.1. Coincident Wave Heights**

ANSI/ANS-2.8-1992 recommends using the USACE Shore Protection Manual (SPM) (USACE, 1984) for analyzing wave action. However, the USACE CEM (USACE, 2008) has superseded the SPM. The CEM recommends methods to apply to areas with simple bathymetry. Per the HHA approach, a numerical model may be needed, depending on the complexity of the bathymetry.

If needed, the current practice in storm-surge modeling is coupled hydrodynamic ocean circulation and wave models, both driven by a planetary boundary layer (PBL) model that provides the atmospheric forcing (Figure 1). Per USACE CEM guidance, off-coast wave activity is determined using either the WAM or WAVEWATCHIII models. For nearshore and surf zone wave processes, SWAN (Simulating Waves Nearshore) or STWAVE (STeady State spectral WAVE) are capable of computing the wave conditions. For detailed discussions and guidance on the application of these models, see Smith et al. (2001), Smith and Sherlock (2007), and USACE (2012).

### **5.2. Inundation**

Inundation effects should be evaluated and typically are available from standard surge models.

### **5.3. Wave Runup**

Wave runup can be calculated using the lesser of the maximum wave height (1.67 x the significant wave height) or the maximum breaker height, in accordance with ANSI/ANS-2.8-1992 and the USACE CEM (USACE, 2008). Wave runup models also can be used in addition to the calculation of overtopping rates when waves encounter a shoreline or embankment. The inputs include wave type, breaking criteria, wave height, wave period, structure slope, structure height, slope type, material used (e.g., rip-rap, rubble, tetrapods), and roughness coefficient. In calculating overtopping rates, the relative heights of the embankment to the still-water level are important. For state-of-the-art solutions to wave runup, the USACE Automated Coastal Engineering System (ACES) is available from the CEDAS interface (USACE, 2012b).

### **5.4. Drawdown (Low Water Level)**

Drawdown may be an issue when safety-related structures and equipment (e.g., UHS intakes) depend on water sources where storm surge or seiche may affect the availability of water (NRC, 1976a).

Numerical models, such as ADCIRC and SLOSH, provide a visual or quantitative estimation of low-water level conditions. Thus, storm surge and seiche model flooding elevation data should be retained and used for a detailed analysis of low-flow conditions.

### **5.5. Hydrostatic and Hydrodynamic Forces**

The hydrostatic and hydrodynamic forces should be determined when storm surge or seiche flood levels impinge on flood protection or safety-related structures, systems and components (SSCs). Thus, storm surge or seiche model current velocity and wave and wind data should be retained and used for a detailed analysis of hydrostatic and hydrodynamic forces.

The USACE CEM provides guidance on hydrostatic and hydrodynamic forces for coastal structures (USACE, 2008).

### **5.6. Debris and Water-Borne Projectiles**

The effect from debris and waterborne projectiles should be considered when storm surge or seiche flood levels impinge on flood protection or safety-related SSCs. Thus, storm surge or seiche model current velocity and wave and wind data should be retained and used for a detailed analysis of debris and waterborne projectiles.

### **5.7. Effects of Sediment Erosion or Deposition**

The impact of sediment erosion and deposition should be considered when storm surge or seiche flood levels impinge on flood protection, safety-related SSCs, and foundation materials. Thus, storm surge or seiche model current velocity plus wave and wind data should be retained and used for a detailed analysis of the effects of sediment erosion and deposition.

The USACE CEM provides guidance on the impacts of sediment erosion and deposition for coastal structures (USACE, 2008).

6. Figures

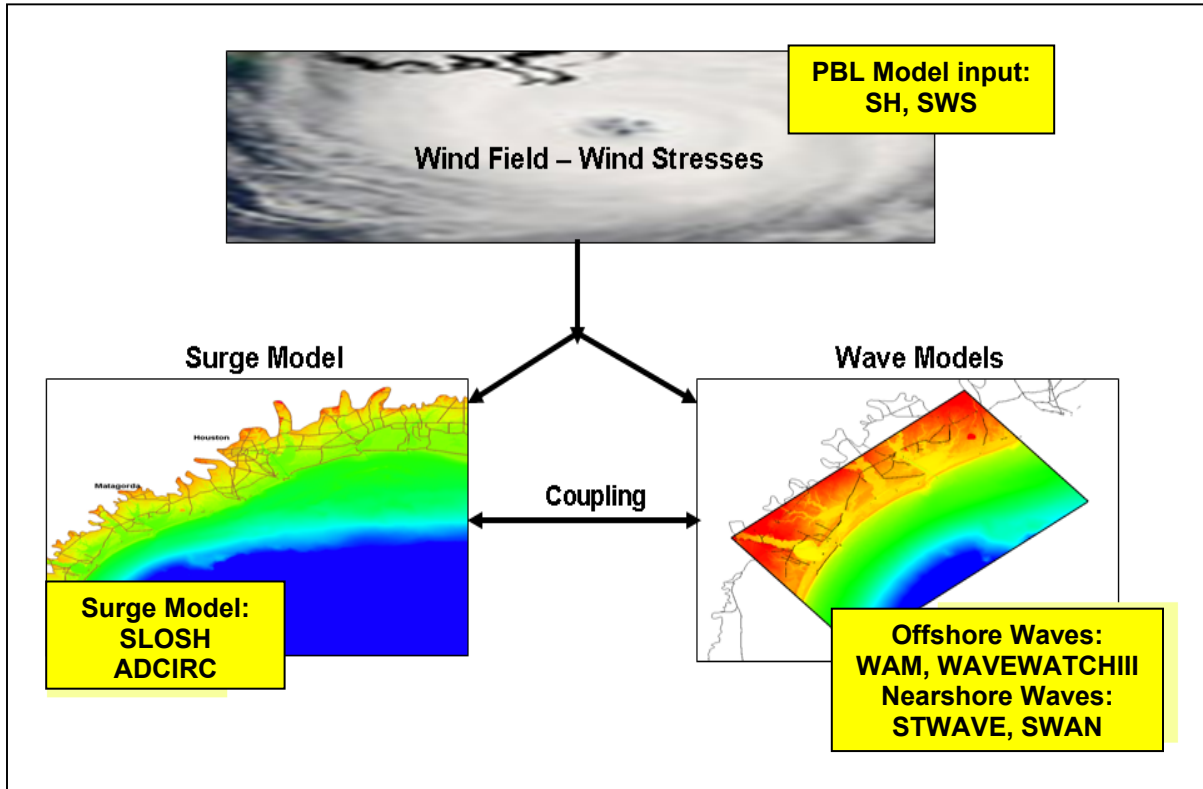
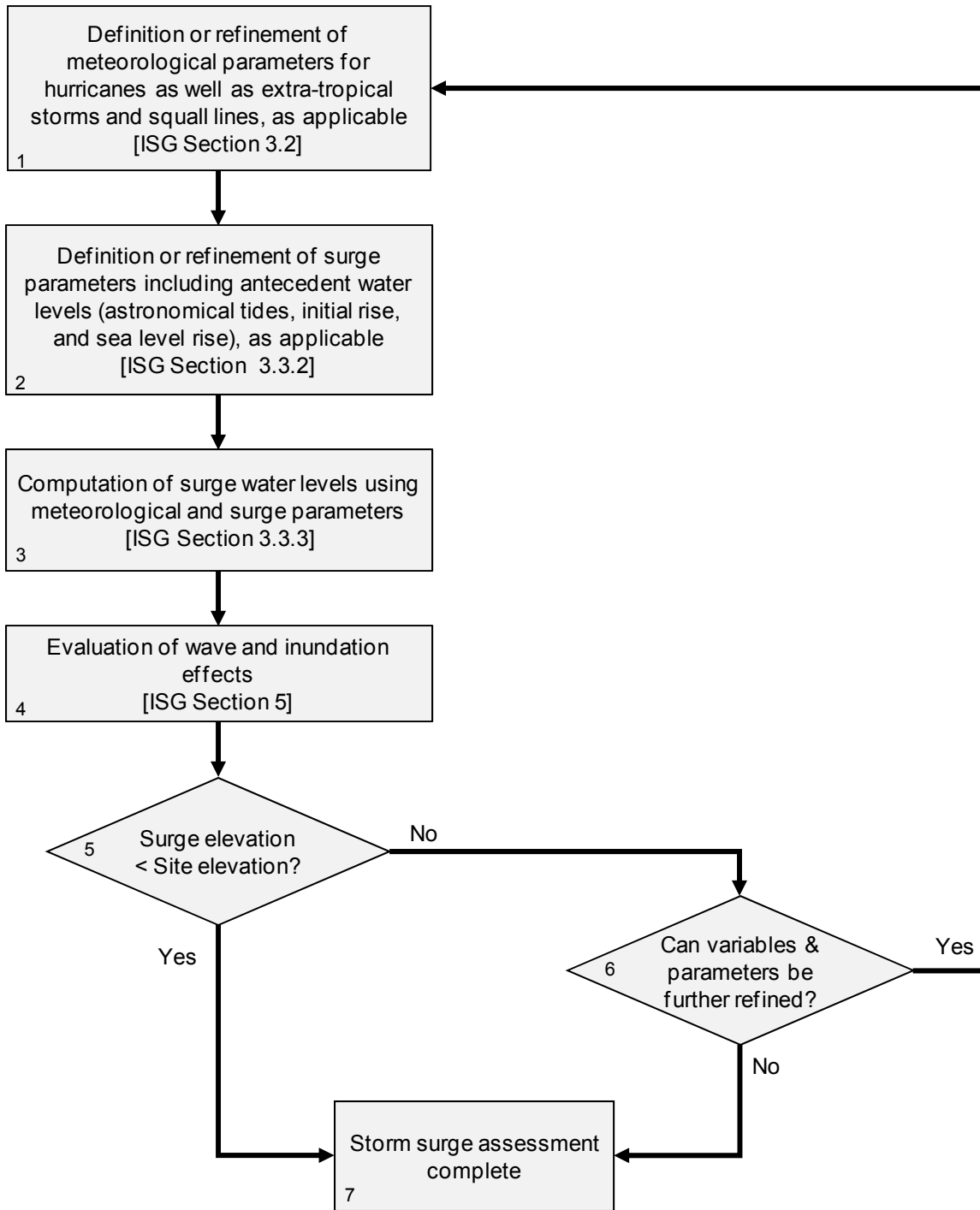


Figure 1. Storm Surge Modeling System (Resio et al., 2012)





**Figure 2. Storm Surge Hierarchical Hazard Assessment**

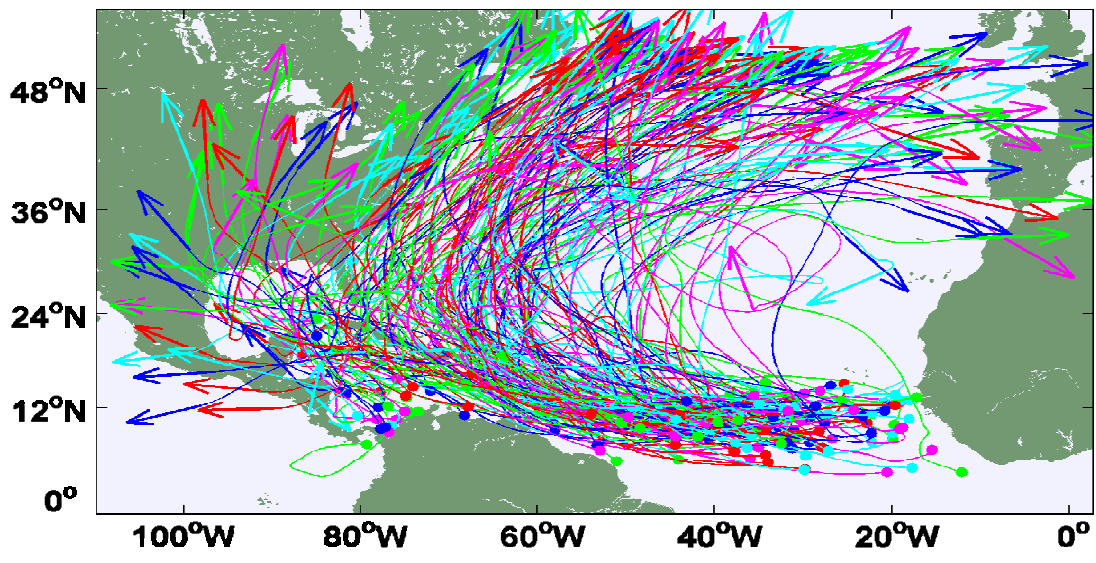


Figure 3. Illustration of 200 Synthetic Storm Tracks (Emanuel, 2012)

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## GUIDANCE FOR PERFORMING A TSUNAMI HAZARD ASSESSMENT

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## **1. Introduction**

The purpose of this interim staff guidance (ISG) is to provide the U.S. Nuclear Regulatory Commission (NRC) staff with a technical basis for reviewing tsunami hazard site characteristics per the March 12, 2012, letters issued to operating nuclear power plants in accordance with the provisions of Sections 161.c, 103.b, and 182.a of the Atomic Energy Act of 1954, as amended (the Act), and NRC regulations in 10 CFR 50.54(f).

### **1.1. Format of Guidance**

Section 1.2 (Historical Perspective) discusses the evolution in tsunami regulatory guidance during the time between the licensing of the operating plants and the licensing activities for new reactors. Section 2 (Acceptance Criteria) continues with a discussion of the existing regulatory guidance (Section 2.1) and guidance updates (Section 2.2) based on the ongoing new reactor safety reviews and current state of knowledge. Particular attention is given here to tsunami term definitions and current best practices.

Section 3.1 (Overview) describes the Hierarchical Hazard Assessment (HHA) approach and the role that deterministic and combined deterministic-probabilistic methods play in tsunami hazard assessments. The tsunami source generation is discussed in Section 3.2 (Historical Tsunami Data) and Section 3.3 (Source Generator Characteristics). Section 3.4 discusses tsunami model initial conditions. Section 3.5 (Tsunami Propagation Models) describes the state-of-the-art tsunami models that the NRC, industry, and other Federal agencies currently use.

Section 4 (Wave and Inundation Effects of Tsunami) consists of tsunami wave dissipation and where tsunami wave action can directly affect the site. Wave action includes deep and shallow water wave generation. Tides, wave setup, wave runup, splash, or overtopping, as appropriate, should be considered in the analyses and included in tsunami flooding estimates. Inundation (Section 4.1) looks at the horizontal distance that tsunami wave propagates inland before dissipation (wave breaking). If the inundation reaches the site, wave runup (Section 4.2), drawdown (Section 4.3), hydrostatic or hydrodynamic forces (Section 4.4), debris and waterborne projectiles (Section 4.5) and the effects of sediment erosion and deposition (Section 4.6) should be considered. References are provided in Section 5.

### **1.2. Historical Perspective**

In response to the 2004 Indian Ocean tsunami, the NRC coordinated a tsunami safety study in 2005 with the National Tsunami Safety initiative that the National Oceanic and Atmospheric Administration (NOAA) conducted. The Pacific Northwest National Laboratory (PNNL) and the Pacific Marine and Environmental Laboratory (PMEL), which is a part of NOAA, conducted the NRC tsunami hazard study. This effort resulted in the publication of two documents: NUREG-CR 6966 (Prasad, 2008), which was published in final form in March 2009, and NOAA Technical Memorandum OAR PMEL-136, "Scientific and Technical Issues in Tsunami Hazard Assessment of Nuclear Power Plant Sites," which was published in 2007.

In 2006, the NRC also initiated a long-term tsunami research program. This program, which includes cooperative work with the U.S. Geological Survey (USGS) and NOAA, was designed both to support activities associated with the licensing of new nuclear power plants

in the U.S. and to support development of new regulatory guidance. This research program has resulted in several publications and made important contributions to tsunami modeling approach and standards, as summarized in conference papers by Kammerer (2008).

The NRC research program includes assessment of both seismic- and landslide-based tsunamigenic sources in both the near and far fields. The inclusion of tsunamigenic landslides, an important category of sources that affect tsunami hazard levels for the Atlantic and Gulf Coasts, is a key difference between NRC's research program and most other tsunami hazard assessment programs that existed at the time. The initial phase of work undertaken by the USGS as part of the research program consisted of collection, interpretation, and analysis of available offshore data, with significant effort focused on characterizing offshore near-field landslides and analyzing their tsunamigenic potential and properties. This work is summarized in ten Brink et al. (2008). In addition, a compendium of eight papers was published in a special edition of *Marine Geology Special Issue: Tsunami Hazard along the U.S. Atlantic Coast*, Volume 264, Issues 1-2, (2009), which documents the results of the NRC research program.

More recently, as part of the NRC research program, the USGS has performed studies to fill in gaps in the original data set. The USGS and NRC have also investigated the potential for increased implementation of probabilistic hazard assessment methods. This effort included holding a workshop to investigate probabilistic hazard assessment of landslide-induced tsunami (Geist and ten Brink, 2012). The NRC may augment its guidance on tsunami hazard assessments after the completion of ongoing research.

## **2. Acceptance Criteria**

### **2.1. Regulatory Guidance**

The applicable regulatory requirements for identifying tsunami hazards are as follows:

- 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities." General Design Criterion 2 (GDC2), "Design Bases for Protection against Natural Phenomena," of Appendix A, "General Design Criteria for Nuclear Power Plants," requires that structures, systems, and components (SSCs) important to safety be designed to withstand the effects of natural phenomena such as floods, tsunami, and seiches without loss of capability to perform their safety functions. Criterion 2 also requires that design bases for these SSCs reflect (1) appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding region with sufficient margin for the limited accuracy and quantity of the historical data and the period of time in which the data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, and (3) the importance of the safety functions to be performed.
- 10 CFR Part 100, "Reactor Site Criteria," requires that physical characteristics of the site, including seismology, meteorology, geology, and hydrology, be taken into account when determining the acceptability of a site for a nuclear power reactor.

Other NRC guidance documents, such as NUREGs and regulatory guides (RGs) describe methods that the NRC staff considers acceptable to use in implementing specific parts of the agency's regulations, to explain techniques the staff uses in evaluating specific

problems or postulated accidents, and to provide guidance to applicants and licensees. Compliance with recommendations contained in the guidance is not mandated. Thus, in addition to the applicable regulatory requirements, the staff uses appropriate sections of the following regulatory guides for the identified acceptance criteria:

- NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants (LWR [light-water reactor] Edition)” provides guidance to NRC staff in performing safety reviews under 10 CFR Part 50 and 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants.” Section 2.4.5 provides general guidance for estimating flooding because of tsunami hazards.
- NUREG/CR-6966, “Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America,” provides present-day methodologies and technologies that can be used to estimate design-basis floods at nuclear power plants for tsunami hazards (Prasad, 2009).
- Regulatory Guide 1.27, “Ultimate Heat Sink for Nuclear Power Plants, Revision 2” (NRC, 1976a).
- Regulatory Guide 1.102, “Flood Protection for Nuclear Power Plants,” Revision 1 (NRC, 1976b) provides guidance for the protection of nuclear power plants from flooding.
- Regulatory Guide 1.206, “Combined License Applications for Nuclear Power Plants,” 2007. Section C.I.2.4.5 provides general guidance for estimating flooding due to tsunami hazards (NRC, 2007).
- JLD-ISG-2012-05 provides guidance for performing the integrated assessment for flooding, when necessary (NRC, 2012b).

## **2.2. Updates to Guidance**

Section 2.4.6 of NUREG-75/087 (1975) provided guidance on tsunami hazard safety reviews. However, this guidance included few details or quantitative techniques. To fill this information gap, the NRC funded a study of tsunami hazard on the Pacific, Atlantic, and Gulf Coasts of the United States, which was published as NUREG/CR-1106 (Brandsma et al., 1979). However, NUREG/CR-1106 only addresses distant seismic-generated tsunamis and does not consider the effects of locally generated tsunamis (e.g., submarine landslides).

RG 1.59 (1977) mentions tsunamis as a source of flooding but does not provide detailed guidance on tsunami hazards assessment. Regulatory Guide 1.59 is currently being updated and will include guidance on tsunami hazard assessments.

NOAA Technical Memorandum OAR PMEL-135 (“Standards, Criteria, and Procedures for NOAA Evaluation of Tsunami Numerical Models”) and NOAA Technical Memorandum OAR PMEL-136 (“Scientific and Technical Issues in Tsunami Hazard Assessment of Nuclear Power Plant Sites”) were produced in response to the 2004 Indian Ocean tsunami. These documents form the basis of the 2007 tsunami-related updates to NUREG-0800. Additional publications addressing tsunami hazards include NUREG/CR-6966 (Prasad, 2008), and the work of ten Brink et al. (2008).

No other Federal agencies, such as the U.S. Army Corps of Engineers (USACE), National Oceanic and Atmospheric Administration (NOAA), and Federal Emergency Management Agency (FEMA) currently use the “probable maximum” or “standard project” terminology. However, existing NRC guidance continues to use these terms. This document is the first attempt to make NRC guidance more consistent with the guidance of other Federal agencies. In this ISG, the term design-basis tsunami hazard (DBTH) replaces probable maximum tsunami (PMT).

For examples of new reactor tsunami hazard safety assessments, the NRC Web site (NRC, 2012a) provides combined license and early site permit safety analysis reports and related NRC requests for additional information (RAIs).

### **3. Tsunami Hazard Assessment**

All coastal nuclear power plant sites (including sites located adjacent to oceans, seas, lakes, rivers, and other inland bodies of water) must consider tsunami hazards. For example, a tsunami could cause a water-level change in an adjacent body of water. The resulting change in water levels, if not considered in the project design, could affect safety-related structures located at the plant site. If eliminated from consideration, detailed hydrological and geological reasoning should be provided and should be consistent with Sections 2.4 and 2.5 of the Standard Review Plan.

All water wave processes, including tsunamis, consist of generation, propagation, and dissipation. Section 3.1 (Overview) describes the Hierarchical Hazard Assessment (HHA) approach and the role that deterministic and combined deterministic-probabilistic methods play in tsunami hazard assessments. The tsunami source generation phase is discussed in Section 3.2 (Historical Tsunami Data) and Section 3.3 (Source Generator Characteristics).

Section 3.4 discusses tsunami model initial conditions, beginning with guidance on vertical datums (Section 3.4.1). Starting a tsunami hazard assessment with bathymetric and topographic data using appropriate vertical datums is essential to correctly reference water levels with site elevations. For additional margin, Section 3.4.2 (Antecedent Water Levels) provides guidance on the determination of pre-tsunami model propagation stillwater levels using astronomical tides (Section 3.4.2.1), initial rise (Section 3.4.2.2), and sea-level rise (Section 3.4.2.3). Section 3.5 (Tsunami Propagation Models) ends the tsunami propagation phase with descriptions of the state-of-the-art tsunami models that the NRC, industry, and other Federal agencies currently use.

#### **3.1. Overview**

Design-basis flood (DBF) estimation for power plant sites in tsunami hazard zones should consider the effects of tsunami or tsunami-like waves, including runup, flooding, erosion, hydrodynamic forces, debris loads, and rundown or return flow of water. The absence of tsunami events in the site or regional historical record, or upriver location from a coast, is not a sufficient basis to eliminate the need for a detailed tsunami hazard assessment.

If a regional or site-specific screening, as described in NUREG/CR-6966 (Prasad, 2008), determines a site is subject to tsunami hazards, a detailed assessment should be undertaken to ensure that the plant design bases account for these hazards adequately. This step should include identification of potential tsunami source mechanisms, estimation

of source characteristics, initiation of the tsunami wave, propagation toward the site, and estimation of tsunami hazards at the site. For deterministic and probabilistic approaches, a detailed description of the controlling tsunami generator (e.g., location, dimensions, orientation, and maximum displacement) should be provided. In addition, a detailed description of the analysis procedure and models used to estimate tsunami wave height and period at the site, as well as the development of input parameters, should be included.

For tsunami hazard safety evaluations, a deterministic screening approach consisting of a series of progressively more refined methods that increasingly use more detailed site-specific data is used to demonstrate whether the site is protected from the adverse effects of severe floods. This approach has been formalized in the HHA approach described in NUREG/CR-7046 (Prasad et al., 2011) and NUREG/CR-6966 (Prasad, 2008).

On the other hand, the use of probabilistic methods facilitates estimation of a range of tsunami and their associated probabilities rather than focusing on a single, large tsunami that is construed to represent an upper bound. Probabilistic tsunami hazard assessment (PTHA) combines the use of deterministic hydrodynamic ocean wave and source generation models and probabilistic methods. Although the NRC has not published guidance on frameworks and toolsets for PTHA, the NRC will accept PTHA and deterministic approaches for tsunami hazard reevaluations. Example applications of PTHA methodologies can be found in the technical literature (e.g., Uslu, 2008; Geist, E.L. and T. Parsons; Arcas and Uslu, 2010). The NRC continues to sponsor research in this area with USGS and NOAA (Gonzalez et al., 2009; Geist and Parsons, 2006; ten Brink et al., 2009).

Regardless of which approach is adopted, a tsunami hazard submittal should include an assessment of sensitivities and uncertainties that may have significant influence on DBTH estimates. The details for reporting of the tsunami hazard assessment can be found in RG 1.206 and NUREG-0800.

### **3.2. Historical Tsunami Data**

Reviews should be conducted of historical tsunami data, including regional records, eyewitness reports, and recently available tide gauge and real-time bottom pressure gauge data (NUREG-0800 and RG 1.206). UREG/CR-6966 (Prasad, 2008) provides further details and additional guidance.

### **3.3. Source Generator Characteristics**

A regional or site-specific survey and assessment of tsunamigenic sources should be performed to determine if a tsunami poses a hazard to the site. The survey and assessment should include all potential near-field and far-field sources and mechanisms that could generate a tsunami. Nuclear power plant sites located near the ocean should consider hazards from oceanic tsunamis. Inland sites should consider the possibility of tsunami-like waves generated in water bodies within the region (e.g., due to hill-slope failure or seismic sources). Any relevant paleo-tsunami evidence also should be assessed. The assessment can be accomplished through a review of existing information. NUREG/CR-6966 (Prasad, 2008) provides further details and additional guidance. The USGS technical report, "Evaluation of Tsunami Sources with the Potential to Impact the U.S. Atlantic and Gulf Coasts" (ten Brink et al., 2008), also provides additional information on the location and characteristics of potential tsunami sources for the Atlantic and Gulf coasts. Several studies have also characterized sources for the Pacific Ocean (e.g., Uslu, 2008; and Arcas and Uslu, 2012).

### **3.4. Tsunami Computational Model Initial Conditions**

#### **3.4.1. Datums**

Datums may be tidal or fixed. For example, mean sea level pertains to the local mean sea level (MSL), which is a tidal datum based on astronomical tides. A tidal datum is determined over a 19-year National Tidal Datum Epoch. North American Vertical Datum of 1988 (NAVD88) and National Geodetic Vertical Datum of 1929 (NGVD29) are fixed geodetic datums having elevation relationships to local MSL and other tidal datums may not be consistent from one location to another. NAVD88 replaced NGVD29 as the national standard geodetic reference for heights.

Licensees select the applicable datum to conform to site-specific requirements (e.g., local and state requirements) as well as best practices and engineering judgement. Once selected, the datum should be applied universally for all flood evaluations and documentation.

#### **3.4.2. Antecedent Water Levels**

Antecedent water levels should be included in storm surge DBTH estimation. Regulatory Guide 1.59 (NRC, 1977) and ANSI/ANS-2.8-1992 recommendations that the 10 percent exceedance high tide be used to represent the antecedent water level for storm surge can also be applied to DBTH estimates. In addition, long term sea level changes should also be considered. For example, antecedent water level should be taken as the sum of the stillwater depth (i.e., mean sea or lake level), 10 percent exceedance high tide, and long-term sea-level rise. Because of the non-linear wave effects, the antecedent water level should be applied as the initial tsunami model stillwater level. Section 4 addresses post-modeling tsunami water level additions, such as wind waves and wave runup.

##### **3.4.2.1. Tides**

In computing the surge level, the 10 percent exceedance high tide should be considered to occur coincidentally with the storm surge. The 10% exceedance high tide is the high-tide level that is equaled or exceeded by 10 percent of the maximum monthly tides over the tidal



epoch (a continuous 21-yr period in most locations). This tide can be determined from the recorded tide or from the predicted astronomical tide. If astronomical tides are used, sea level anomaly should be added. Sea level anomalies (also referred to as initial rise) are departures of the water surface elevation from astronomical tides due to various meteorological and oceanographic forcings. Historical and current tide observations, information on tidal datums, as well as predicted tide levels can be found on the NOAA Tides and Currents Web site (NOAA, 2012a). NOAA maintains a network of tide gage stations along the U.S. shoreline, including the Great Lakes.

#### 3.4.2.2. *Initial Rise*

For locations where the 10 percent exceedance high spring tide is estimated from observed tide data, RG 1.59 and ANSI/ANS-2.8-1992 indicate that a separate estimate of the initial rise is not necessary. This approach for estimating 10 percent exceedance high tide, based on recorded tides, intrinsically includes the effects of initial rise. For other locations, the initial rise must be estimated and used as an input to the tsunami inundation calculations or included in the tsunami inundation calculations themselves.

#### 3.4.2.3. *Long-Term Sea Level Rise*

Relative sea-level rise is the combined effect of water-level change and land subsidence. The NOAA National Ocean Service, the U.S. Global Change Research Program, and the Intergovernmental Panel on Climate Change (IPCC) monitor and report sea-level rise information, which also should be included in design-basis flood analysis for coastal sites (IPCC, 2007).

NOAA maintains tide gage stations along the U.S. shoreline (NOAA, 2012a) and has evaluated the trend of sea-level rise. Measurements at any given tide station include both global sea-level rise and vertical land motion, such as subsidence, glacial rebound, or large-scale tectonic motion. Thus, the long-term sea-level rise should be derived for the expected life of the nuclear power plant based on the trend in site or regional tide gage station data. As part of the HHA approach, regional or global sea-level rise trends can be added in initial storm surge simulations to the site or regional observed trend for additional margin.

### 3.5. **Tsunami Propagation Computational Modeling Tools**

This section describes the tsunami generation and propagation phase with a discussion of the state-of-the-art computational tsunami modeling tools that the NRC, industry, and other Federal agencies currently use.

The National Tsunami Hazard Mitigation Program, sponsored by NOAA, currently uses several complex tsunami computational modeling tools to produce tsunami inundation and evacuation maps for Alaska, California, Hawaii, Oregon, and Washington. The computational modeling packages include MOST, developed originally by University of Southern California researchers (1998); COMCOT (Cornell Multi-grid Coupled Tsunami Model), developed at Cornell University (1995); and TSUNAMI2, developed at Tohoku University in Japan (1996). All three packages solve the depth-integrated and 2D horizontal (2HD) nonlinear shallow-water equations with differing finite-difference algorithms. There are a number of additional computational modeling tools that can be used to solve shallow-water wave propagation problems, including the finite element model ADCIRC (ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters, 1994).

Computational modeling tools based on the shallow-water equation have been shown to be reasonably accurate throughout the evolution of a tsunami, and are widely used. However, these tools lack the capability to simulate dispersive waves, which could be the predominate features in landslide-generated tsunami, and for tsunami traveling a long distance. Several higher-order depth-integrated wave hydrodynamics models (Boussinesq models) are now available for simulating nonlinear and weakly dispersive waves, such as COULWAVE (Cornell University Long and Intermediate Wave Modeling Package, 2002) and FUNWAVE (Fully Nonlinear Boussinesq Wave Model, 2000). The major difference between the two is in their treatment of moving shoreline boundaries. During 2003, COULWAVE was applied to the 1998 Papua New Guinea tsunami with a landslide source; the results agreed reasonably well with field surveys and observed data. Recently, several finite element models also have been developed based on Boussinesq-type equations. NUREG/CR-6966 (Prasad, 2008) provides additional details and guidance.

See NOAA Technical Memorandum OAR PMEL-135 "Standards, Criteria, and Procedures for NOAA Evaluation of Tsunami Numerical Models" (Gonzalez et al., 2007) for additional guidance on validation, benchmarking, and quality control.

#### **4. Wave and Inundation Effects for Tsunami**

This section describes the wave dissipation phase, in which tsunami wave action can directly affect the site. Wave action includes deep and shallow water wave generation. Tides, wave setup, wave runup, splash, or overtopping, as appropriate, should be considered in the analyses and included in tsunami flooding estimates.

Section 4.1 (Inundation) looks at the horizontal distance that tsunami wave propagates inland before dissipation (wave breaking). If the inundation reaches the site, other factors such as wave runup (Section 4.2), drawdown (Section 4.3), hydrostatic or hydrodynamic forces (Section 4.4), debris and waterborne projectiles (Section 4.5), and the effects of sediment erosion and deposition (Section 4.6) should be considered, as appropriate.

##### **4.1. Inundation**

Inundation effects should be evaluated and are typically available from standard tsunami model outputs.

##### **4.2. Wave Runup**

Tsunami wave runup guidance is provided in NUREG/CR-6966. Wave runup can also be provided by tsunami models. For state-of-the-art solutions to tsunami wave runup, see Liu et al., 2008.

##### **4.3. Drawdown (Low Water Level)**

Drawdown is an issue when safety-related structures and equipment (e.g., UHS intakes) depend on water sources that a tsunami has the potential to affect (NRC, 1976a).

Tsunami numerical models such as MOST, FUNWAVE, COULWAVE, TSUNAMI and COMCOT can provide a visual and quantitative estimation of low water-level conditions. Thus, tsunami model flooding elevation data should be retained and used for a detailed

analysis of low-flow and low-water conditions. See NUREG/CR-6966 for additional details (Prasad, 2008).

#### **4.4. Hydrostatic and Hydrodynamic Forces**

The hydrostatic and hydrodynamic forces should be determined when tsunami flood levels impinge on flood protection or safety-related SSCs. Thus, tsunami model current velocity, wave, and wind data should be retained and used for a detailed analysis of hydrostatic and hydrodynamic forces.

The USACE CEM (USACE, 2008) and NUREG/CR-6966 (Prasad, 2008) provides guidance on hydrostatic and hydrodynamic forces for coastal structures.

#### **4.5. Debris and Waterborne Projectiles**

The effect from debris and waterborne projectiles should be considered when tsunami flood levels impinge on flood protection or safety-related SSCs. Thus, tsunami model current velocity, and wave data should be retained and used for a detailed analysis of debris and waterborne projectiles. See NUREG/CR-6966 for additional details (Prasad, 2008).

#### **4.6. Effect of Sediment Erosion and Deposition**

The impact of sediment erosion and deposition should be considered when tsunami flood levels impinge on flood protection, safety-related SSCs and foundation materials. Thus, tsunami model current velocity, wave, and wind data should be retained and used for a detailed analysis of the effects of sediment erosion and deposition.

The USACE CEM provides guidance on the impacts of sediment erosion and deposition for coastal structures (USACE, 2008).

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## **Appendix: GLOSSARY AND ACRONYMS**

ADCIRC – Advanced Circulation Model.

ASCE - American Society of Civil Engineers

ANS - American Nuclear Society

ANSI - American national Standards Institute

Bootstrap Sampling – Bootstrap sampling is the practice of estimating properties of an estimator (such as its variance) by measuring those properties when sampling from an approximating distribution. One standard choice for an approximating distribution is the empirical distribution of the observed data. In the case where a set of observations can be assumed to be from an independent and identically distributed population, this can be implemented by constructing a number of re-samples of the observed dataset (and of equal size to the observed dataset), each of which is obtained by random sampling with replacement from the original dataset.

CFR - *Code of Federal Regulations*

Coastal: Refers to the near-shore regions of any water body (e.g., ocean, bay, sea, sound, lake, or estuary) where wind wave or gravity wave phenomena may occur, not solely to regions adjacent to the open ocean.

Coastal Storm Modeling System (C-Storm) - The U.S. Army Corps of Engineer's Engineering Research and Development Center's Coastal Storm Modeling System (CSTORM-MS) is a physics-based modeling capability for simulating tropical and extra-tropical storm, wind, wave, water level and coastal response (erosion, breaching, and accretion).

COMCOT - Cornell Multi-grid Coupled Tsunami Model

COULWAVE - Cornell University Long and Intermediate Wave Modeling

Design Basis Storm Surge (DBSS) - The most adverse storm surge flooding at the nuclear power plant site caused by a Simulated Wind Storm (SWS) or Simulated Hurricane (SH) due to a combination of severe meteorological storm parameters, critical path, and rate of movement.

Design Basis Tsunami Hazard (DBTH) – Formerly probable maximum tsunami (PMT), DBTH is tsunami for which the impact at the site is derived from the use of best available scientific information to arrive at a set of scenarios reasonably expected to affect the nuclear power plant site taking into account: (a) appropriate consideration of the most severe of the natural phenomena that have been historically reported or determine from geological and physical data for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated; (b) appropriate combinations of the effects of normal and accident conditions with the



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effects of the natural phenomena; and (c) the importance of the safety functions to be performed.

Empirical Simulation Technique (EST) - Procedure for simulating multiple life-cycle sequences of non-deterministic multi-parameter systems. Based on a Bootstrap resampling-with-replacement, interpolation, and subsequent smoothing technique, EST employs random sampling of a finite length database to generate a larger database. The basic assumption is that future events are statistically similar in magnitude and frequency to past events.

Extra-tropical Cyclone - A storm that forms outside the tropics, sometimes as a tropical storm or hurricane.

FUNWAVE – Fully Nonlinear Boussinesq Model.

Grade Elevation - Topographical elevation of the site near facilities of the nuclear power plant usually used as a base reference to describe elevations of other SSCs.

Hierarchical Hazard Assessment (HHA) Approach – HHA approach is a progressively refined, stepwise estimation of site-specific hazards that evaluates the safety of SSCs with the most conservative plausible assumptions consistent with available data. The HHA process starts with the most conservative simplifying assumptions that maximize the hazards from the probable maximum event for each natural flood-causing phenomenon expected to occur in the vicinity of a proposed site.

HURDAT - The National Weather Service and the National Hurricane Center's official hurricane database for the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea, including those that have made landfall in the United States, is currently being updated, See Landsea et al. (2004).

Hurricane - A tropical cyclone with winds of 74 mph or more. Normally applied to such storms in the Atlantic Basin and the Pacific Ocean east of the International Date Line.

Hydrodynamic Loads - Hydrodynamic loads are loads that result from water flowing against and around a rigid structural element or system. The hydrodynamic loads can include the effects of broken and non-breaking waves striking structures, initial impact of a rapidly varying flood wave (e.g. dam break or tsunami flood wave), and drag forces on a structure (caused by the pressure differential between the upstream and downstream side of the structure).

Inundation - The distance that a storm surge penetrates onto the shore, measured horizontally from the mean sea level position of the water's edge. It is usually measured as the maximum distance for a particular segment of the coast.

Joint Probability Method (JPM) – JPM is a simulation methodology that relies on the development of statistical distributions of key tropical or extra-tropical wind storm parameters and sampling from these distributions. The simulation results in a group of modeled storms that preserves the relationships with the historical storms but provides a means to model the effects and probabilities of storms that have not yet occurred.

JPM-OS - JPM-Optimal Sampling

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Maximum Breaker Height - The maximum wave height that can be achieved during shoaling.

MOST - Method of Splitting Tsunami

NAVD88 - North American Vertical Datum of 1988

NGVD29 - National Geodetic Vertical Datum of 1929

NOAA - National Oceanic and Atmospheric Administration

NRC - U.S. Nuclear Regulatory Commission

NWS - National Weather Service

Planetary Boundary Layer (PBL) – The planetary boundary layer (PBL), also known as the atmospheric boundary layer (ABL), is the lowest part of the atmosphere and its behavior is directly influenced by its contact with a planetary surface.

Probable Maximum Events - Probable maximum events are thought to approach the physical limits of the phenomena, are deterministic in nature, and are thought to exceed historical occurrences of the phenomena at the time of the analysis.

Probable Maximum Hurricane (PMH) - The PMH is a hypothetical hurricane having a combination of characteristics that generate the most severe storm surge that can reasonably occur in the particular region.

Probable Maximum Wind Storm (PMWS) - A hypothetical extra-tropical cyclone that might result from the most severe combination of meteorological storm parameters that is considered reasonably possible in the region involved. The windstorm approaches the point under study along a critical path and at an optimum rate of movement, which will result in the most adverse flooding.

Probable Maximum Storm Surge (PMSS) - The PMSS is generated by the Probable Maximum Hurricane (PMH) or Probable Maximum Windstorm (PMWS).

RAI - Request for additional information

Seiche - An oscillation of the water surface in an enclosed or semi-enclosed water body that is initiated by an external cause (e.g., barometric pressure fluctuations, strong winds, rapid changes in wind direction, surge associated with passage of storms, tsunamis, or local landslides).

SER - Safety Evaluation Report

Significant Wave Height - In physical oceanography, the significant wave height (SWH or  $H_s$ ) is defined traditionally as the mean wave height (trough to crest) of the highest third of the waves ( $H_{1/3}$ ). Nowadays, it is usually defined as four times the standard deviation of the

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surface elevation – or equivalently as four times the square root of the zeroth-order moment (area) of the wave spectrum. The symbol  $H_{m0}$  is usually used for that latter definition. The significant wave height may thus refer to  $H_{m0}$  or  $H_{1/3}$ ; the difference in magnitude between the two definitions is only a few percent.

Simulated Hurricane (SH) - A hypothetical tropical cyclone (Hurricane) generated by the probable maximum hurricane (PMH) or synthetic storm methodology (JPM and EST) using a combination of meteorological storm parameters considered reasonably possible for the region involved. The simulated hurricane approaches the nuclear power plant site along multiple paths and rates of movement.

Simulated Tsunami (ST) – A hypothetical tsunami propagated by a tsunami numerical model using input from variable tsunami sources (e.g., earthquakes, submarine landslides) and source parameters (e.g., landslide volume, fault length, slip amount, etc).

Simulated Wind Storm (SWS) – A hypothetical extra-tropical cyclone generated through the synthetic storm methodology (JPM and EST) using a combination of meteorological storm parameters considered reasonably possible for the region involved. The SWS approaches the nuclear power plant site along multiple paths and rates of movement.

SLOSH - Sea, Lake, Overland Surge from Hurricanes

SMS – Surface Modeling System

SPH - Standard Project Hurricane

Still Water Level (SWL) – The water level in the absence of wave effects.

Storm Surge - Storm surge is the rise of offshore water elevation caused principally by the shear force of tropical or extra-tropical winds acting on the water surface and the associated pressure differential.

SWAN – Simulating Waves Nearshore.

STWAVE - STEady State spectral WAVE

Tropical Cyclone - low-pressure weather system in which the central core is warmer than the surrounding atmosphere. The term "tropical cyclone" is also used in the Indian Ocean and around the Coral Sea off northeastern Australia to describe storms called "hurricanes" and "typhoons" in other areas.

Tsunami - A series of water waves caused by the displacement of a large volume of a body of water, typically an ocean or a large lake. Earthquakes, landslides, submarine landslides, glacier calvings, meteorite impacts and other disturbances above or below water all have the potential to generate a tsunami.

UHS - ultimate heat sink

USACE - U.S. Army Corps of Engineers

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WAM - WAVE prediction *Model*

Wave Runup - Wave runup is the maximum vertical extent of wave uprush on a beach or structure above the still water level (SWL).

Wave Setup - Additional water level that is due to the transfer of wave-related momentum to the water column during the wave-breaking process.

Wind Waves - Waves generated by wind passing over the surface of an open body of water caused by wind shear forces along the water surface and air pressure differences across the wave crest.