standard is ASCE 24-14 (ASCE 2014). However, depending on the applicable building code refresh period, an earlier publication (e.g., ASCE 24-05) may still be in effect (ASCE 2005). The ASCE standard classifies infrastructure by importance, or an *occupancy/risk category*. The more important the asset, as indicated by the assigned category, the higher the level of protection. ASCE 24-14 will specify the required freeboard (additional depth to account for uncertainties added as a factor of safety) based on the classification of the structure. ASCE 24 DFEs are not explicit in intent to include or not include the effects of SLR.

5.2.2 Federal Executive Order 13690

On January 30, 2015, the US president signed EO 13690, establishing a federal flood risk management standard (FFRMS) (FEMA 2015). Although this EO has since been revoked, EO 13690 was the result of collaboration among various federal agencies and the president's Hurricane Sandy Rebuilding Task Force. The EO set minimum flood protection requirements for federally funded buildings and infrastructure to levels that are similar to the standards specified in ASCE 24. EO 13690 gave flexibility to select one of three approaches for establishing a DFE and, following issuance of EO 13690, the federal Water Resources Council approved revised guidance on implementing the FFRMS. As described in the guidance document, the approaches are as follows:

1. Climate-informed Science Approach (CISA)—use best available, actionable hydrologic and hydraulic data and methods that integrate current and future changes in flooding based on climate science and other factors or changes affecting flood risk to determine the vertical flood elevation and corresponding horizontal floodplain in a manner appropriate to policies, practices, criticality, and consequences.

2. Freeboard Value Approach (FVA)—use the BFE (or 1-percent-annual-chance flood determined using best available data) and an additional height to calculate the freeboard value. The additional height will depend on whether or not the action is a critical action.

3. The 0.2-percent-annual-chance Flood Approach (0.2PFA)—use the 0.2-percent-annual-chance flood elevation (also known as the 500-year flood elevation).

This term *critical action* is defined in the EO as ". . . any activity for which even a slight chance of flooding would be too great . . ." The FFRMS guidance states that the CISA, which provides agency to the designer for DFE criteria development, is preferred:

> The CISA is preferred. Agencies should use this approach when data to support such an analysis are available. . . . [T]he CISA uses existing, sound science and engineering methods (e.g., hydrologic and hydraulic analysis and methods used to establish current flood elevations and floodplain maps), supplemented with best available and actionable climate science and consideration of impacts from projected land cover/land use changes, long-term erosion, and other processes that may alter flood hazards over the lifecycle of the Federal investment. In cases where relevant data are not available, the other two approaches (Freeboard and 0.2-percent-annual-chance) are acceptable methods to determine the FFRMS floodplain, because each of these approaches can improve resilience to current and future flood risk.

Federal EO 13690 was revoked by the president in August 2017.

5.2.3 National Environmental Policy Act

The federal CEQ has released guidance requiring direct coordination between environmental planners and designers with respect to the effects of climate change for new proposed actions (CEQ 2016). The guidance states that agencies should "use the information developed during the National Environmental Policy Act (NEPA) review to consider alternatives that are more resilient to the effects of a changing climate" and that the analysis should also "consider an action in the context of the future state of the environment." Following this guidance, the NEPA analysis should review the build alternative(s) in the context of the impact of climate change and the implications of future climate conditions.

5.3 CLIMATE CHANGE–INFORMED DESIGN FLOOD ELEVATION

DFE criteria are often developed during conceptual or pre-design phases for a project and are subject to cost-benefit and sensitivity testing. The DFE should, at a minimum, conform to stakeholder requirements, industry standards (e.g., ASCE), model codes, and other regulatory requirements. The DFE criteria should be based on the estimated useful life and criticality of the project.

For projects that are anticipated to have a long useful life, it is not always feasible or cost effective to fully account for projected climate risks. As discussed in Chapter 3, adaptable design techniques (e.g., the OM) may be appropriate given the spreads between low- and high-end SLR projections, which increase exponentially over time. In addition, it is customary on many civil works projects to assume an initial economic service life that allows for extension of the service through major rehabilitation. Therefore, an interval that is less than the asset's anticipated useful life, between substantial completion and a planned intervention point, may be warranted to re-evaluate a project DFE based on the latest CISA at that time.

There are varying definitions of criticality, and methods for determining importance based on the consequence of an undesirable event. Chapter 7 provides several methods for quantifying uncertainty and risk. For the methods described in this chapter, Table 1.5-1 in *Minimum Design Loads for Buildings and Other Structures* (ASCE 2010), titled "Risk Category of Buildings and Other Structures for Flood, Wind, Snow, Earthquake, and Ice Loads" is one tool that can be used to determine criticality (i.e., risk category III and IV buildings and structures can be considered *critical* for the purposes of developing a DFE). Designers should also differentiate between noncritical and critical components within a larger facility or campus (e.g., an airport or maintenance yard). These components include but are not limited to electrical distribution and switch gear areas, motor-control centers, chemical feed equipment, boilers, communications systems, monitoring and safety equipment, HVAC units, fire alarms and suppression systems, furnaces, emergency fuel supplies, emergency generators, and hazardous material storage.

The following sections provide a DFE criteria model that can be used for a wide range of coastal projects. The model consists of a design flood event based on a given AEP, the addition of freeboard as a factor of safety, and an SLR adjustment to obtain the future equivalent flood level. Under all circumstances, designers must meet the minimum of all code- or regulation-mandated requirements.

In addition to flooding that occurs overland, it is important to consider what is happening underground as well. Many structures that are susceptible to storm surge flooding are in close proximity to the waterfront where the soil can be very permeable or consist of heterogeneous fill material with preferential pathways for water. In such cases, it is important to account for a rising groundwater table caused by seepage flows from a rising sea level and/or rainwater infiltration that can result in flood loads extending underground, ponding, and/or uplift on slabs.

5.3.1 1-percent Annual Chance BFE

Designers should evaluate a flood-level condition (e.g., permanent inundation, tidal flooding, or coastal storm surge) most appropriate for the facility in question. The design event specified by policy and engineering judgment (when policy allows design criteria to range over an interval) should be considered as a target point for specific performance parameters (Kilgore et al. 2016). A level of risk tolerance (e.g., 10%, 2%, 1%, 0.2% AEPs) can be obtained from tidal gauge data over the National Tidal Datum Epoch (or modified thereof) and/or analytical flood event data. In addition, the AEP of a known coastal flood elevation can be calculated directly using historical flood elevation data (e.g., records and reports, high water marks, debris lines, photographs, tidal gauge data, etc.) or indirectly based on modeling output. Engineering judgment should be used for indirect calculations and transformations to evaluate the applicability and statistical significance of the input data to the location of interest.

FEMA publishes flood event data via FIRMs and FISs for most locations. In some cases, designers will be required to perform site-specific hydrologic and hydraulic modeling to simulate design flood events. This may be to assess multiple flood event conditions (e.g., flood return intervals or SLR assumptions) and/or to evaluate proposed conditions (e.g., flooding with and without a new seawall or levee). This is particularly important for locations that may be subject to breaking waves under present or future conditions. Breaking wave heights may increase, and areas subjected to breaking wave forces will likely move farther inland than the areas presently depicted on FIRMs (see Chapter 6 for discussion of breaking wave loads). Site-specific modeling may also be required to evaluate potential *backdoor flooding* under varying design conditions, future conditions, or flooding resulting from combined precipitation and coastal storm events. For example, FEMA NFIP-compliant modeling (e.g., ADCIRC and MIKE 21) is required to meet FEMA's levee certification standards for modification to an effective FIRM or SFHA boundary (via a Letter of Map Revision).

Many FIS reports and FIRMs published in coastal regions are developed using ADCIRC coupled with the SWAN model. ADCIRC is a two-dimensional (2D) coastal circulation and storm surge model developed by a consortium of academia, the USACE, and private companies. SWAN is a spectral model that computes wind-generated waves for the coastal zone that was developed at the Delft University of Technology. The NFIP-compliant ADCIRC+SWAN package can be obtained for free online or for a fee on several graphical platforms. The modeling can be validated by tidal/non-tidal sea-level calibration and by using historical extra-tropical and/or tropical storms to determine SWEL AEPs. FEMA's WHAFIS can be used to simulate inland wave propagation using the calculated SWELs applied to each cross-shore transect in the study area and interpolated using topographic maps, land-use data, and land-cover data (as well as engineering judgment) to determine the extent of coastal flood zones. MIKE 21 is another widely used NFIP-compliant 2D coastal modeling platform developed by DHI. The MIKE 21 platform is broken up into in separate modules for a variety of engineering applications. In addition to storm surge modeling, MIKE 21 modules relevant to climate change impacts include numerical simulation tools respective to coastal erosion, dike/dune breaching, and water quality/ecology.

The SLOSH model, developed by NOAA, is primarily used to establish coastal evacuation zones and for storm surge forecasting. The SLOSH model estimates storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data. The SLOSH model produces a lower-resolution output as compared to the models noted above. SLOSH simulations create two composite products: MEOWs and MOMs. Because the output produced by SLOSH modeling is not representative of a single storm but rather of *worst cases* for all locations within a region from a composite of storms, the storm surge water surface elevations produced by SLOSH are very likely to exceed the actual flooding for a given storm event (Glahn et al. 2009). Because SLOSH projections are not referenced to a specific AEP and do not include wave heights, the model is not recommended for engineering use or as input for load factor calculations. Refer to Figure 5-4 for a comparison of SLOSH output for a Category 2 hurricane at varying forward speeds and FEMA BFEs that are calculated by coupled ADCIRC/SWAN modeling.

Site-specific modeling is not warranted for most noncritical projects because such studies have usually already been performed by FEMA's mapping partners and published in FIS reports and FIRMs for many locations. Published BFEs are required to be used, as a minimum, by most codes, and they are considered to be the best available flood hazard data by FEMA. Therefore, in the absence of more refined site-specific hydrologic and hydraulic modeling, the FEMA BFEs should be utilized as the basis for noncritical project DFEs.

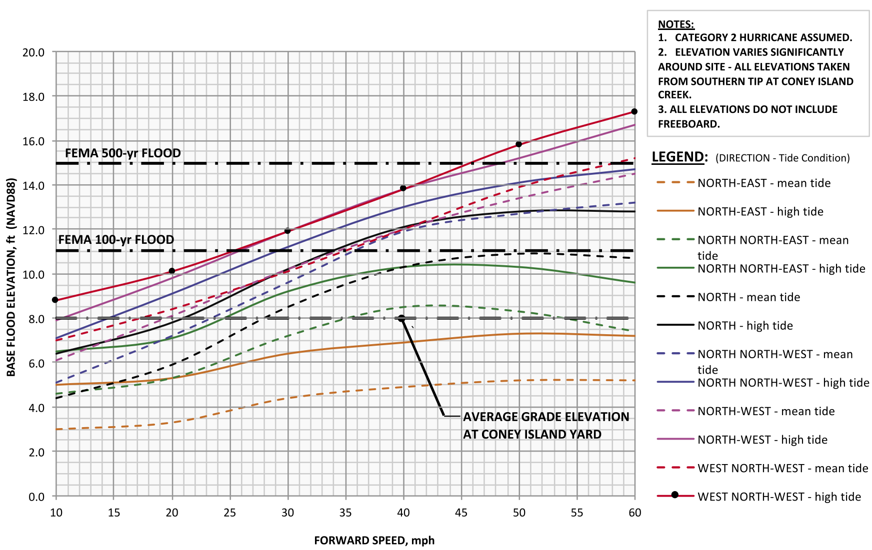

Figure 5-4. SLOSH Category 2 flood elevation versus forward speed with comparison to FEMA BFEs for a location near Coney Island, Brooklyn, NY.

For many locations, the 1% annual chance BFE and the 0.2% annual chance SWEL are provided by FEMA. For coastal locations, the SWEL should not be used as the basis for a project DFE because the full effects of wave action are not included. If the 500-year RP is desired for a project in such a case, a provision for wave action should be added to the SWEL using analytical methods (e.g., USACE's *Coastal Engineering Manual* or FEMA's WHAFIS model) and the data from the applicable FIS transect.

5.3.2 Freeboard as a Factor of Safety

The DFEs are determined by applying freeboard to the BFE. Per FEMA and ASCE, freeboard is a factor of safety, expressed in feet above a flood level. This component is not intended as an estimate for future SLR. Freeboard compensates for potential model and mapping inaccuracies or granularity and the many uncertainties that could contribute to flood heights, such as wave action, constricting or *funneling* obstructions, and other hydrological effects. These uncertainties are likely to be greater in magnitude for urbanized watersheds. In addition, locations in close proximity to the waterfront have additional flood height uncertainty owing to unknowns relating to the generation, propagation, and transformation of incoming waves. Most states and communities have adopted freeboard requirements. The NFIP requires the lowest floor of structures built in flood zones to be at or above the BFE plus 1 ft of freeboard, which should be considered the minimum for all projects within an SFHA. Although 1 to 3 ft of freeboard above a flood level is commonly used for engineering works, Table 5-2 provides proposed recommendations to selecting a freeboard value for projects in coastal floodplains.

5.3.3 SLR Adjustment

Flood elevations published by FEMA do not presently include the effects of SLR. The freeboard specified by ASCE 24 (ASCE 2014) is not explicit about whether it is intended to account for SLR. The EO 13690 criteria is intended to account for uncertainties in future conditions, including "anticipated

Table 5-2. Freeboard as a Factor of Safety Based on Project Type and Location.

	Non-coastal A or V zone	Coastal A or V zone
Noncritical project	1 ft	1–2 ft
Critical project	1–2 ft	2–3 ft

impacts of climate change," but it does not indicate the relative magnitude of SLR versus a safety factor accommodated for in the freeboard. The observed historical SLR at the tidal gauge located in Battery, New York, has been relatively constant at about 1.2 ft per 100 years (NOAA 2017a). As discussed in Chapter 2, observational data and global climate models suggest that, although the upward trend is continuing, more rapid or accelerating future rates of SLR are predicted. These predictions range from approximately 1 ft to over 8 ft by the year 2100, depending primarily upon assumptions made with regard to emissions scenarios, thermal expansion, and rate of ice melting. SLR will also vary locally owing to geologic changes, causing land to subside at varying rates along the seaboard owing to glacial isostatic adjustment, sediment compaction, groundwater and fossil fuel withdrawals, and other nonclimatic factors, oceanographic factors such as circulation patterns, changes in the Earth's gravitational field and rotation, and flexure of the crust and upper mantle owing to melting of land-based ice (NOAA 2017b).

The IPCC has developed five assessment reports since it formed in 1988. It released its fifth assessment report, AR5, between September 2013 and November 2014 (IPCC 2014). Kopp et al. (2016) recommends that practitioners, in conjunction with a similarly constituted set of scientific advisors, review relevant SLR and coastal storm data and projections shortly after future IPCC assessment reports, or every five years at a maximum. Similarly, practitioners and a set of scientific advisors should monitor the publication of federal climate projections and research, such as the projections set forth in the *National Climate Assessment*, for any major changes in assumptions or projections related to SLR and coastal storms. Such reassessment of data can assist engineers in their efforts to apply advances in scientific information into practice.

Climate models producing output on a global scale do not generally provide sufficient detail to be appropriate for the design of engineering works. However, downscaling approaches have been developed to provide regional projections that are sufficiently granular to be relevant for engineering and planning use. In January 2017, NOAA released a transparent and peer-reviewed assessment, titled *Global and Regional Sea Level Rise Scenarios for the United States*. The report was developed using CMIP5 projections, along with additional recent scientific literature, and it provides local SLR projections on 1° grid covering the US mainland coastline, Alaska, Hawaii, the Caribbean, and the Pacific Island territories for six representative scenarios: low, intermediate-low, intermediate, intermediate-high, high, and extreme. At this time, this set of projections are recommended for use for engineering works owing to the credibility of the peer review process afforded in the report, the transparency of the framework used assessing the scientific literature, the granularity of the local projections, and the breadth of coverage.

The New York City Panel on Climate Change report (NPCC 2015) is another example of a transparent and peer-reviewed assessment publication. The assessment utilized observed data, CMIP5 projections, and IPCC AR5 methodologies. The report included local estimates of the effects of climate change that were generally applicable to a 100-mile radius around the New York City metropolitan region, accounting for subsidence, changes in glacial and ice sheet *fingerprinting*, local water mass density, oceanographic processes, and land water storage. The NPCC has estimated the probabilistic rise at the 10th, 25th, 75th, and 90th percentile confidence levels. These projections are provided for the 2020s, 2050s, and 2080s time periods and for 2100. The range of differences in projected SLR between the different models increases as the century progresses. Table 5-3 depicts the latest SLR projections from NPCC, as well as additional *projections* derived by interpolating between the 2050 and 2080 estimates for the year 2070.

As an example, a critical project located in New York City with a useful life of 50 years and an anticipated substantial completion date of construction in the year 2020 should consider including an SLR adjustment up to 43 inches to obtain a future BFE (FBFE). The FBFE would be used for calculating flood loads (i.e., hydrostatic pressure, hydrodynamic pressure, and, depending upon the location of the structure in question, debris impact and/or breaking wave forces). The addition of freeboard as a factor of safety should be added on top of the FBFE to obtain the project DFE.

In addition to increasing the elevation of a flood event, SLR will also widen the boundaries of flood zones. Therefore, consideration of how an anticipated SLR relates to local topography must be given to structures outside of but in the vicinity of higher-level flood zones. For example, if the structure of interest is close to the LiMWA under present conditions, a wave height analysis that simulates inland wave transformation may be warranted to determine whether breaking wave loads should be addressed owing to the projected effects of SLR (refer to Chapter 6 for discussion).

Table 5-3. SLR Projections for New York City.

SLR baseline (2000–2004)	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2020's	+ 2 in	+ 4 to 8 in	+ 10 in
2050's	+ 8 in	+ 11 to 21 in	+ 30 in
2070	+ 11 in	+ 14 to 29 in	+ 43 in
2080's	+ 13 in	+ 18 to 39 in	+ 58 in
2100	+ 15 in	+ 22 to 50 in	+ 75 in

Source: *NPCC (2015)*.

Engineering designs should consider alternatives that are developed and assessed for the entire range of possible future rates of sea-level change. The alternatives should be evaluated using varying estimates (low, middle, and high, at a minimum) of future SLR for both with and without project conditions (USACE 2013). It is recommended that long-term structures include an accommodation for SLR based on a benefit-cost and/or feasibility assessment considering the sensitivity of project financial costs and externalities (e.g., asset functionality, environmental, community impacts, etc.) to varying SLR projections (e.g., low, middle, and high). Based on these factors, it may be appropriate for critical or noncritical projects to include a middle-range SLR estimate. When project elements can be designed without substantial implications to a higher level (up to a scientifically plausible upper-bound SLR projection), they should be; otherwise, they should be designed so that additional protection can be included at a later date if SLR and storm levels in the future make that appropriate (e.g., designing foundations to support higher flood barriers in the future).

According to the confidence levels prescribed for climate model projections (e.g., CMIP5), there is much greater certainty associated with the near-term (mid-century) scenarios, after which uncertainties associated with the melting of ice sheets and land-based ice caps increasingly dominate. Design criteria should explicitly provide methods to address uncertainty, including future decision milestones for adaptation based on new information as scientific advances unfold. Because engineering works typically have a useful life far beyond the initial period of economic analysis, consideration of project adaptability is an important consideration in project development. These upfront analyses should determine how the SLR scenarios affect risk levels and plan performance and identify the design or operations and maintenance measures that could be implemented to minimize adverse consequences while maximizing beneficial effects (USACE 2013).

For these reasons, a mid-term outlook (e.g., less than the projected useful life of a project) may be appropriate. The project DFE can then be reevaluated following a planned interval based on the latest CISA at that time. Because the degree of uncertainty with regards to SLR increases exponentially with time, designing for, as an example, 100 years of SLR now may prove overly conservative or insufficient, whereas designing to mid-century (e.g., 50 years of SLR now) with the option of providing capital improvements later to adjust the DFE if necessary will provide more flexibility for climate adaptation.

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