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The Impact of Extreme Events on Electrical Substation Infrastructure in Coastal Areas

C. BOWEN, C. JERGENSEN, P. SOMBOONYANON
Burns & McDonnell
USA

SUMMARY

Keeping an electrical substation operational is one of the top priorities for every utility. For substation structural designs, utilities often refer to ASCE 113, which is generally based on ASCE 7-05 edition with modifications to better suit substation designs. Although ASCE 113 outlines design procedures for extraordinary events such as extreme winds and earthquakes, it does not have any provisions for extreme events such as tsunamis and hurricanes. ASCE 7 includes provisions for hurricane wind and hurricane flood loadings, however, it is not until the latest version of ASCE 7, the 2016 edition, that the provisions for tsunami loadings were added to the standard. In this paper, load characteristics for extreme events in coastal areas including tsunamis and hurricanes are first presented based on ASCE 7-16. Then, a case study is performed to compare the total base shear of an example substation control enclosure for different extreme event load components. An inland extreme wind event with a design wind speed of 115 mph is used as the baseline event as it covers most areas in the United States. Not only does this comparison provide utilities with a better understanding of how the aforementioned events affect substation structural designs, but the perspective gathered through this case study can be utilized to better define utilities' acceptable risks. Substation design considerations due to these extreme events addressed in various standards are also discussed.

KEYWORDS

Extreme events, Tsunami loadings, Hurricane loadings, ASCE 7, ASCE 113, Substation structure design

cbowen@burnsmcd.com

INTRODUCTION

The reliability and resiliency of the electric grid is one of the primary concerns of an electric utility. While there are many challenges in maintaining a robust infrastructure, severe weather-related events in coastal areas pose a threat to the electric grid that may catch utilities unprepared. Not only have these extreme events occurred with greater frequency recently, but loadings from these extreme events may exceed the threshold to which utilities typically design their substation infrastructure. Section 2.2 of FEMA P-55 Vol. I [1] "*Coastal Construction Manual*" provides an extensive list of major coastal flood and wind events, nearly 50 events, occurred throughout the United States coastal areas from 1900 to 2010. These extreme events were triggered by hurricanes, typhoons, other storms, and tsunamis. In addition, Robertson [2] describes several past tsunamis events in detail along with their associated damages.

ASCE 7 sets minimum load requirements for the design of buildings and other structures. For substation structural designs, utilities often refer to ASCE 113 [3], "*Substation Structure Design Guide.*" This guide is based on ASCE 7-05 [4] with modifications to better suit electrical substation designs. While the guide outlines extreme events such as high winds or earthquakes, it does not provide any provisions related to extraordinary events such as tsunamis or hurricanes. Many designers commonly refer to requirements outlined in ASCE 7 and ASCE 24-14 [5] "*Flood Resistant Design and Construction*" for flood and hurricane loadings. However, it is not until the latest edition of ASCE 7, 2016 edition [6], that provisions for tsunami loadings were introduced.

Although each coastal extreme event, tsunami and hurricane, is triggered by a different source and their load characteristics are addressed in separate sections of standards, there are some similarities among these events in the nature of how the loads cause damage to structures. Loads imposed to structures during a tsunami event are similar to those during a flood event and can occur in the form of uplift, surcharge, and lateral pressures. A hurricane event produces high winds and can also cause a storm surge resulting in area floods, but normally in a smaller magnitude compared to a tsunami event.

This paper first describes load characteristics of two extreme events, tsunami and hurricane, affecting coastal areas. Then, a case study is performed to compare loadings on an example substation control building subject to 1) an inland extreme wind event, as a baseline 2) a tsunami event, and 3) two different hurricane categories. Other substation design considerations subject to tsunami and hurricane loadings are also discussed.

TSUNAMI LOADINGS

Tsunami load determination is outlined in ASCE 7-16, Chapter 6. It should be noted that it is only applicable to five states in the United States: Alaska, Washington, Oregon, California, and Hawaii due to the tsunami models utilized in the development of this chapter. For other regions where a tsunami is determined to be a threat, ASCE 7-16 suggests that the site-specific procedure as outlined in Section 6.7 could be developed for use in conjunction with this chapter. Another resource outlining general procedures to numerically evaluate tsunami models can be found in NOAA Technical Memorandum OAR PMEL-135 [7] "*Standards, Criteria, and Procedures for NOAA Evaluation of Tsunami Numerical Models.*" Tsunami effects introduce many loading considerations to substation structural designs including hydrostatic loads, hydrodynamic loads, debris impact loads, and foundation design considerations, which will be further examined in more detail.

Hydrostatic Loads

ASCE 7-16 Section 6.9.1 instructs designers to evaluate reduced net weight caused by buoyancy. While many structural elements of an electrical substation may not be subject to the buoyancy force due to their configuration, e.g., steel columns supporting electrical equipment, any enclosed space, like a substation control building and its anchorages, is vulnerable to uplift caused by buoyancy and should be designed accordingly. When in consideration, the buoyancy force is determined as follows:

$$F_v = \gamma_s V_w \quad \text{[ASCE 7-16, Eq. 6.9-1]}$$

Where: γ_s = minimum fluid weight density for design hydrostatic loads
V_w = displaced water volume

Hydrostatic unbalanced lateral force develops on a wall element because of differences in water level on either side of the wall, irrespective of the wall orientation to the tsunami flow direction. ASCE 7-16 Section 6.9.2 also requires designers to include unbalanced hydrostatic lateral forces in a design of any structural wall having a two- or three-sided perimeter configuration regardless of length, which can be computed as follows:

$$F_h = \frac{1}{2}\gamma_s b h_{max}^2 \quad \text{[ASCE 7-16, Eq. 6.9-2]}$$

Where: b = width subject to force
h_{max} = maximum inundation depth above grade plane at the structure

In addition to forces described above, other hydrostatic surcharge pressures from a tsunami event should be considered when applicable. For example, dead load plus a residual water surcharge needs to be considered for all horizontal floors below the maximum inundation, as outlined in ASCE 7-16 Section 6.9.3. Also, during both incoming and outgoing tsunami flow, water elevation on opposite sides of a wall may be developed resulting in a differential surcharge pressure on the foundation that needs to be considered in a design, as outlined in ASCE 7-16 Section 6.9.4.

For simplicity and comparison purposes, only an unbalanced lateral force is considered as part of hydrostatic loadings for a tsunami event with variables defined in a case study later.

Hydrodynamic Loads

Hydrodynamic loads develop when fluid flows around objects within its flow path, which should be considered for substation structure designs. ASCE 7-16 Section 6.10 gives both a simplified and detailed equation to calculate hydrodynamic lateral forces. For a detailed design method as outlined in ASCE 7-16 Section 6.10.2, it considers factors such as drag forces on buildings and components, loads on vertical structural components, hydrodynamic loads on perforated walls, and walls angled to the flow. In this paper, the simplified equivalent uniform lateral static pressure equation, as outlined in ASCE 7-16 Section 6.10.1, is considered and is equal to:

$$p_{uw} = 1.25 I_{tsu} \gamma_s h_{max} \quad \text{[ASCE 7-16, Eq. 6.10-1]}$$

Where: I_{tsu} = importance factor for tsunami forces

Debris Impact Loads

Tsunamis can transport a large volume of debris. Virtually anything within its flow path that can float given the inundation depth and that cannot withstand the water flow becomes debris. ASCE 7-16 Section 6.11 requires designers to include the effects of debris impact forces where the minimum inundation depth is 3 ft or greater. Debris impact loads for structure designs are determined based on debris types, such as wood logs and poles, floating vehicles, and submerged tumbling boulders and concrete debris in the surrounding area that would be expected to reach a site during a tsunami event. ASCE Section 6.11.2 thru 6.11.4 outline design requirements for debris impact loads for each debris type. For larger objects, such as shipping containers, ships, and barges, the process to perform a site hazard assessment is detailed in ASCE 7-16 Section 6.11.5. However, utility operators may elect to consider the simplified method for debris impact static load as detailed in ASCE 7-16 Section 6.11.1 as follows:

$$F_t = 330 C_o I_{tsu}$$ [ASCE 7-16, Eq. 6.11-1]

Where: C_o = debris orientation coefficient

When the debris impact load is computed based on the above simplified equation and when it is determined that a site location is not in an impact zone for shipping containers, ships, and barges, then ASCE 7-16 Section 6.11.1 allows the debris impact load to be reduced by 50%.

HURRICANE LOADINGS

Hurricanes derive their energy through the evaporation of water from the ocean surface, which ultimately recondenses into clouds and rain when moist air rises and cools to saturation. These hurricanes are the primary source of wind and flood damages on structures.

Hurricane Wind Loads

For extreme wind loadings on substation structures, utilities commonly refer to design procedures outlined in ASCE 113, which references the same wind maps as ASCE 7-05. The ASCE 113 wind design procedures are the same as those outlined in ASCE 7-05 with modifications to better suit substation designs. ASCE 7-05 defines hurricane-prone regions with two criteria for the United States and its territories as:

1. The U.S. Atlantic Ocean and Gulf of Mexico coasts where the basic wind speed is greater than 90 mph, and
2. Hawaii, Puerto Rico, Guam, Virgin Islands and American Samoa

It should be noted that these criteria are not defined in ASCE 113. For ASCE 7-16 edition, the first criteria has been revised to the same defined areas where the basic wind speed for Risk Category II buildings is greater than 115 mph.

Hurricanes are normally measured by the Saffir-Simpson hurricane wind scale based on the 1-minute maximum sustained wind speed. While all hurricanes produce high winds and cause property damages, hurricanes rated Category 3 and higher are known as major hurricanes. The Saffir-Simpson hurricane wind scale and its equivalent 3-second gust wind speed along with anticipated property damages are presented in Table 1.

Category	1-min Maximum Sustained Wind Speed (mph)	3-s Gust Wind Speed (mph)	Type of Damage
1	74-95	89-116	Minimal
2	96-110	117-134	Moderate
3	111-129	135-159	Extensive
4	130-156	160-189	Extreme
5	>157	> 189	Catastrophic

Table 1: Hurricane Intensity Scale

Based on ASCE 7-16 wind map for Risk Category II buildings, a wind design considering 3-s gust wind speed of 115 mph is sufficient for most substations within the continental United States. From the Table 1 above, this same wind speed is considered as a hurricane Category 1. ASCE 7 and ASCE 113 do not have a separate design procedure for extreme wind or hurricane events. The wind design procedure in these standards is primarily based on a 3-s gust design wind speed. For the case study performed in this paper, the design wind speed of 115 mph (or hurricane Category 1), covering most areas in the United States, is utilized as a baseline for comparison purposes to other extreme events. Wind loadings from hurricane Category 3 with a 3-s gust wind speed of 150 mph on the same example building will also be computed and then compared in the case study.

The wind velocity pressure based on ASCE 7-16 is defined as:

$$q_z = 0.00256 K_z K_{zt} K_d K_e V^2 \qquad \text{[ASCE 7-16, Eq. 26.10-1]}$$

Where: K_z = velocity pressure exposure coefficient
K_{zt} = topographic factor
K_d = wind directionality factor
K_e = ground elevation factor
V = design wind speed

Then, the calculated wind velocity pressure is multiplied with a product of gust factor, *G*, and force coefficient, C_f. For simplicity, wind loadings computed for the case study in this paper conservatively assume a force coefficient, C_f, of 2.0 for square or rectangle surfaces as outlined in Table 3-9 of ASCE 113. This value of the force coefficient includes wind loadings for both windward and leeward walls contributing to the total building base shear. For gust factor, *G*, both ASCE 7-16 and ASCE 113 allow a value of 0.85 for rigid structures.

Hurricane Flood Loads

When considering flood loads due to hurricane events, ASCE 7 and ASCE 24 are commonly utilized for substation structural designs as ASCE 113 does not contain any provisions for flood loading. There are two types of floods, 1) riverine flooding caused by runoff from rainfall or snowmelt and 2) coastal flooding influenced by storm surges caused by hurricanes or other storm types. For coastlines, flood zones are identified in three main areas separated by wave height: V-zone, A-zone, and X-zone, as shown in Figure 1 below.

***Source: FEMA P-55 Vol. I [1]**

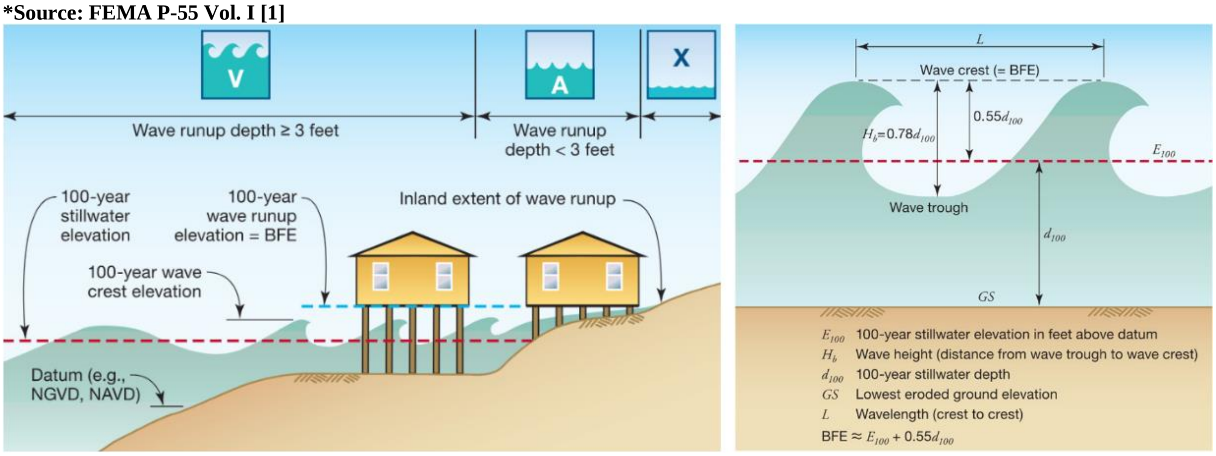

Figure 1*: Flood hazard zones and terminologies

Load determinations for flood loading are very similar to load determinations for tsunami loading. The two key parameters used for computing flood loadings are flood depth and flood velocity. Similar to tsunami loading, flood loads introduce hydrostatic loading, hydrodynamic loading, debris impact loading and scour effects to structures. In addition, flooding events impose wave loading to structures.

Hurricane Flood Hydrostatic Loads

Hurricane flood hydrostatic loading imposed to substation structures is derived the same way as hydrostatic loading imposed during a tsunami event including buoyancy, lateral forces and surcharge pressures.

Hurricane Flood Hydrodynamic Loads

Dynamic effects of moving water during flood events are permitted to be converted into equivalent hydrostatic loads by increasing the DFE for design purposes by an equivalent surcharge depth, d_h, on the headwater side and above ground level only, equal to the equation below.

$$d_h = \frac{aV^2}{2g} \qquad \text{[ASCE 7-16, Eq. 5.4-1]}$$

Where:	V	=	flood velocity
	a	=	drag coefficient or shape factor
	g	=	acceleration due to gravity

Hurricane Flood Wave Loads

Wave loads are a result from water waves propagating over the water surface and striking structures or components. ASCE 7-16 Section provides equations to determine a maximum pressure, Pmax, and net forces, Ft, resulting from a normally incident breaking wave on vertical walls in the following equations:

$$P_{max} = C_p \gamma_s d_s + 1.2\gamma_w d_s \qquad \text{[ASCE 7-16, Eq. 5.4-5]}$$

$$F_t = 1.1\, C_p \gamma_s d_s^2 + 2.4\gamma_s d_s^2 \qquad \text{[ASCE 7-16, Eq. 5.4-6]}$$

Where:	P_{max}	=	maximum combined dynamic and static wave pressures
	F_t	=	net breaking wave force per unit length
	C_p	=	dynamic pressure coefficient
	γ_w	=	unit weight of water
	d_s	=	still water depth at base of a building

Hurricane Flood Impact Loads

Impact loading due to a hurricane flood event is calculated much differently than impact loading due to a tsunami event, and the objects assumed to create impacts on structures are much smaller. ASCE 7-16 provides an equation for determining an impact load based on an assumed object weight of 1,000 lbm as follows:

$$F = \frac{\pi W V_b C_I C_O C_D C_B R_{max}}{2g\Delta t} \qquad \text{[ASCE 7-16, Eq. C5.4-3]}$$

Where:	W	=	debris weight, assumed 1,000 lbm
	V_b	=	velocity of object (assumed equal to velocity of water)
	g	=	acceleration due to gravity
	Δ_t	=	impact duration, suggested 0.03s
	C_I	=	importance coefficient
	C_O	=	orientation coefficient, equal to 0.8
	C_D	=	depth coefficient
	C_B	=	blockage coefficient
	R_{max}	=	maximum response ratio for impulsive load

CASE STUDY

In this section, a case study is performed to compare loadings from two coastal extreme events, tsunami and hurricane, to an inland extreme wind event as a baseline. The extreme wind event with a design wind speed of 115 mph for Risk Category II buildings is selected because it applies to most areas in the United States based on the wind map provided in ASCE 7-16. The case study considers loads from each extreme event imposed to an example substation control building with dimensions of 12' (W) x 40' (L) x 12' (H). Using equations outlined in previous sections, design assumptions and results are presented in sections below.

Tsunami Loadings

Design assumptions for tsunami loading include fluid weight density, γ_s, of 62.4 lbf/ft^3 and inundation depth, h_{max}, of 3 ft. Based on the dimensions of the example control building listed above, the uplift force, F_v, caused by buoyancy is approximately equal to 90 kips. The hydrostatic unbalanced lateral force, F_h, subject to the long side of the example building, b = 40ft, is equal to 11.2 kips. For the hydrodynamic loads of the Risk Category II building, I_{tsu} = 1.0, the value of p_{uw} is equal to 234 lbf/ft^2, resulting in total lateral force, F_{uw}, of 28.1 kips. The debris impact load, F_t, is computed to be 214.5 kips with debris orientation coefficient, C_o, of 0.65. For this case study, it is assumed that the site is not located in an impact zone for shipping containers, ships, and barges; therefore, the debris impact load can be reduced by 50% as outlined in ASCE 7-16 Section 6.11.1, resulting the final value of 107.3 kips. All tsunami load components are shown in Figure 2.

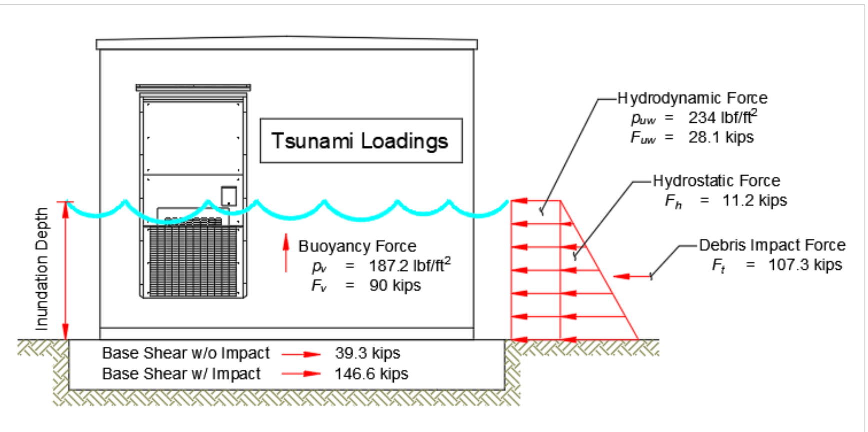

Figure 2: Tsunami Load Components and Total Base Shear

Hurricane Wind Loadings

Wind loadings on buildings are typically determined in accordance with ASCE 7-16 Chapter 27 through Chapter 30 depending on an applicable design procedure with different wind pressures exerted on different zones. As mentioned previously, this case study conservatively assumes a uniform wind pressure for an entire building surface based on the design procedure outlined in ASCE 113 assuming a force coefficient, C_f = 2.0 for square or rectangular surfaces, gust factor, G = 0.85, velocity pressure exposure coefficient and wind directionality factor, K_z = K_d = 0.85, and a value of 1.0 for both the topographic factor and ground elevation factor, K_{zt} = K_e = 1.0. For an inland extreme event with a design wind speed of 115 mph for Risk Category II buildings (equivalent to a Category 1 hurricane event - wind only), this results in a wind pressure of 20.8 lbf/ft^2, resulting in a total base shear of 20 kips. For a Category 3 hurricane with a design wind speed of 150 mph, this wind pressure increases to 35.4 lbf/ft^2, resulting in a total base shear of 34 kips. Wind load components are shown in Figure 3.

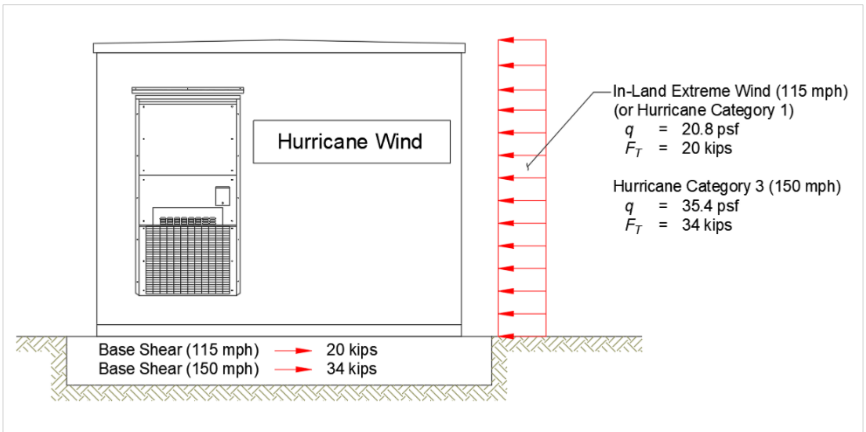

Figure 3: Hurricane Wind Loadings and Total Base Shear

Hurricane Flood Loadings

For this case study, an assumed design flood depth is equal to 3 ft resulting in the same hydrostatic load as the tsunami with the inundation depth of 3 ft, 11.2 kips. It is also assumed that the crest of reflected wave is at the design flood elevation, coefficient of drag, *a* = 1.25, and the flood velocity is equal to 10 ft/s. With these assumptions, an equivalent surcharge depth, d_h, is computed to be 1.94 ft, resulting in a total dynamic force on a building wall of 14.5 kips. For computing wave loads, a value of 3.2 is used for dynamic pressure coefficient, C_p, with a still water depth, d_s, of 1.36 ft; therefore, the total wave load is equal to 45.7 kips. For computing flood impact load, importance coefficient, C_I, depth coefficient, C_D, blockage coefficient, C_B, and maximum response ratio for impulsive load, R_{max}, are assumed to be equal to 1.2, 0.25, 1.0, and 0.4, respectively. The computed flood impact load is equal to 1.6 kips. It should be noted that the total base shear is computed assuming coastal A-zones with the load combination of 0.5W + 1.0Fa in accordance with ASCE 7-16 Section 2.3.2. All hurricane flood load components are shown in Figure 4.

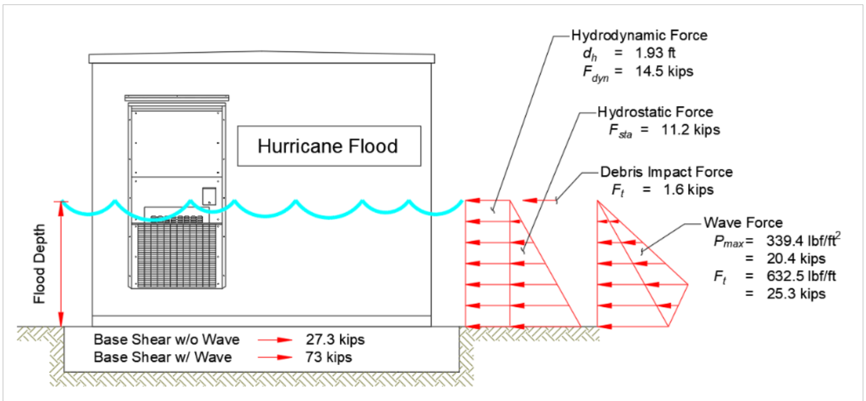

Figure 4: Hurricane Flood Loadings and Total Base Shear

Building Base Shear Comparison

From the case study results for each extreme event, the total building base shear loads are then compared using an inland extreme event with a design wind speed of 115 mph as the baseline event, as shown in Figure 5. Based on the design assumptions listed above, the findings are as follows:

- For a tsunami event with the inundation depth of 3 ft, the total base shear is nearly two times higher than the baseline event when excluding the debris impact load.

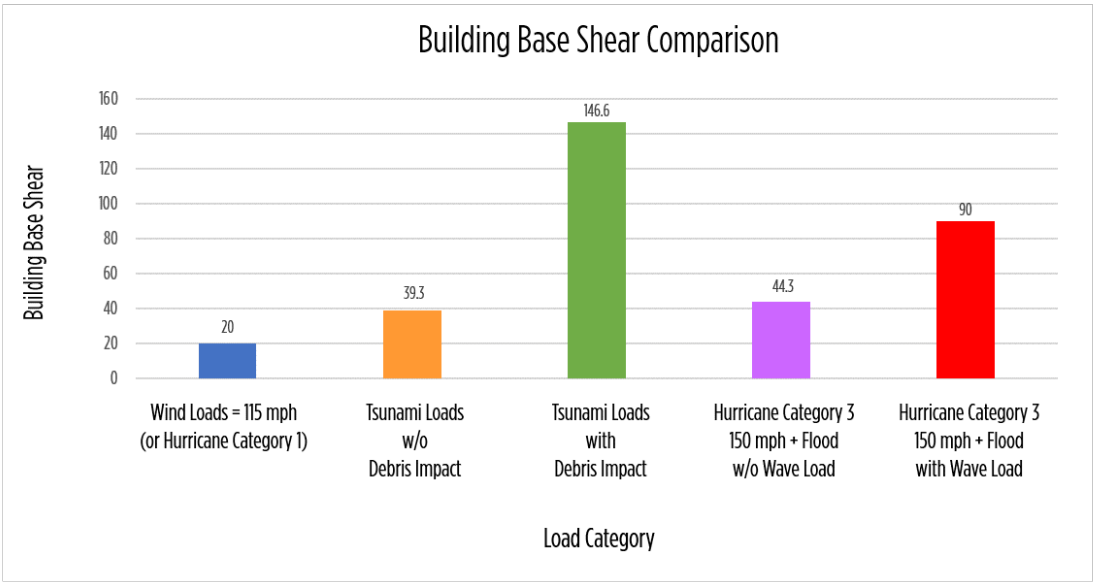

Figure 5: Building Base Shear Comparison

- For the same tsunami event, the total base shear is more than seven times higher than the baseline event when considering the debris impact load, even with 50% reduction in the force due to its location outside an impact zone for shipping containers, ships, and barges.
- For a hurricane Category 3 with a design wind speed of 150 mph, the total base shear contributing from wind and flood loads (excluding wave load) is approximately two times higher than the baseline event.
- For the same hurricane Category 3, when considering all load components, the total base shear is more than four time higher than the baseline event.

It is obvious that tsunami debris impact load and hurricane flood wave load components significantly contribute to the total base shear. Since there is no standard providing guidelines to utilities for designing their substation infrastructures under these extreme events, the comparison from this case study could provide guidance as to how utilities choose to include or exclude each load component that best suits their acceptable risk. Also, it should be noted that results from the case study are based on variables and design assumptions listed in this paper. Different variable values and design assumptions may yield different outcomes.

SUBSTATION DESIGN CONSIDERATIONS

Although many design recommendations outlined in various codes and standards are geared toward building structures rather than substation structures, there are still several aspects that could still be applied to substation applications. Particularly, those suggestions are applicable to a control enclosure that is similar to an enclosed building and contains many electrical components critical to substation operations. Some suggestions and considerations that utilities could adopt to better prepare, harden, and protect their assets during these extreme events include:

- Water infiltration can cause damages to electrical equipment, particularly in a control enclosure. Therefore, it is recommended that building envelopes, such as doors, windows, and skylights, be designed to resist the "E" missile load as specified in ASTM E1996. The doors should be tested in accordance with ASTM E1886.
- According to ASCE 24-14 Section 2.5, due to concerns regarding erosion and scour during flood events, slab-on-grade foundations are not recommended in coastal high hazard areas and coastal A zones.

- When deep foundations are used, erosion and scour should be considered in the design as they can increase loads on foundations due to higher foundation reveal and reduction in embedment depth.
- Section 3.3.1.2 of FEMA 543 [8] suggests that within 3,000 feet of the ocean, protective coatings thicker than normally provided should be specified.

CONCLUSION

Extreme events in coastal areas, such as tsunamis and hurricanes, pose a threat to the electrical grid infrastructure, especially with its more frequent occurrence. For substation structure designs, utilities often refer to ASCE 113. Although extreme wind loadings and the wind design procedure are addressed in ASCE 113, effects from hurricanes including both high winds and floods are excluded from this guide. In addition, ASCE 113 does not have any provisions for tsunami loadings. In this paper, load characteristics and its effects from two extreme events, tsunami and hurricane, are presented based on ASCE 7-16. Then, a case study was performed to compare a total building base shear of an example substation control building among different extreme events. The inland extreme wind event with a design wind speed of 115 mph for Risk Category II was used as a baseline since it covers most areas in the United States. Based on results from the case study, the total base shear from tsunami and hurricane events are approximately two times higher and can be as much as more than seven times higher than the baseline event. Through a better understanding of the design requirements and its effects, utilities can design substations to be more resilient and better prepared for the next coastal extreme event.

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