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Structural Design of Substation Steel Structures: Seismic Load Considerations

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SUMMARY

Electrical substations, critical to both power transmission and distribution, are vital assets of the national power grid. One often overlooked but integral component of a substation's design is the structures that support each piece of electrical equipment. These steel structures must be held to strict design standards to ensure the proper usage of all electrical substation equipment to avoid dangers such as fault hazards. One environmental force that is particularly unpredictable and fierce is that caused by seismic activity or earthquakes. Steel substation structures follow some of the same seismic design philosophies as more commonly acknowledged structures such as buildings and bridges, but remain vastly different in many aspects. There is ambiguity in the field regarding the proper standards and methods for the seismic design of substation steel structures. This paper will identify two useful standards for seismic design of substation structures and will summarize the loading considerations and design requirements of each. The first is the American Society of Civil Engineers Standard 7-10 "Minimum Design Loads for Buildings and Other Structures" or ASCE 7-10, which is primarily used for building design. However, ASCE 7-10 also provides some provisions for nonbuilding structures. For substation structures, the designer can make some assumptions in order to apply ASCE 7-10 in most cases, but this code may not capture every necessary element of substation structure design. The second of these codes is the American Society of Civil Engineers Manuals and Reports on Engineering Practice No. 113 "Substation Structure Design Guide" or ASCE 113, which was developed specifically for the design of substation structures. ASCE 113 provides a comprehensive look at substation structure design considerations but may lack specific design provisions for the design of steel structures for seismic requirements. In this paper, the author will examine the design philosophies present in both ASCE 7-10 and ASCE 113 and explain the process for the determination of seismic loads on substation structures. A design example will step the reader through the process of seismic load determination for structural analysis and design in accordance with each code. This will give a side-by-side comparison of the results from the differences in provisions each code offers for seismic criteria and will provide insight on how the use of each code will affect design. Together, these codes can be used in for a complete and effective design while ensuring the safety of the substation as a whole and the reliability of the national power grid.

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KEYWORDS

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Introduction

For an effective seismic design, it is important to understand the nature and behaviour of seismic forces and how they can impact a structure. Seismic forces are not simple to analyze. Their behavior is often unpredictable. In a seismic event, the ground moves in all directions, as a wave-like force propagates though the earth, from the focus outward. A structure experiences the effects of the seismic event from the ground up, as the force is transferred from the earth to the foundation and through the structure. ASCE 7 and ASCE 113 offer several different methods for analyzing how seismic forces affect structures. It is not completely accurate to model a seismic force on a structure as a simple static force, because seismic forces are dynamic in nature. However, in most cases, for substation steel structures, it is acceptable to make conservative assumptions in order to simplify external seismic forces to an equivalent static force. This is known as the equivalent lateral force method. This paper will assume the use of the equivalent lateral force method for analysis of seismic forces.

Seismic Base Shear

As outlined in ASCE 7-10 Section 12.8.1, to perform an equivalent lateral force analysis, you must determine the seismic base shear for a structure. The seismic base shear is defined in Equation 12.8-1 as the seismic response coefficient C_s times the effective seismic weight of the structure.

$$V = C_s W \qquad (12.8\text{-}1)$$

ASCE 7-10 Equation 12.8-1

In most cases of substation structures, the effective seismic weight is simply the dead load of the structure itself and any equipment it supports. The seismic response coefficient is defined by ASCE 7-10 Equation 12.8-2 as the short period design spectral response acceleration parameter S_{DS} divided by the term R/I_e, where R is the response modification factor given for nonbuilding structures in Tables 15.4-1 and 15.4-2 and I_e is the seismic importance factor.

$$C_s = \frac{S_{DS}}{\left(\frac{R}{I_e}\right)} \qquad (12.8\text{-}2)$$

ASCE 7-10 Equation 12.8-2

This seismic base shear as defined by ASCE 7-10 is comparable to the seismic design force F_E defined in ASCE 113 as the design spectral response acceleration S_a times the earthquake importance factor, and I_{MV}, divided by R, all multiplied by the dead load.

$$F_E = (S_a/R)W(I_{FE})(I_{MV}) \qquad (\text{Eq. } 3\text{-}10)$$

ASCE 113 Equation 3-10

For most substation structures, single mode behaviour can be assumed and I_{MV} can be taken as 1.0. Essentially, the only difference in these two formulas is the use of S_{DS} versus S_a.

Design Response Spectrum

In order to understand the relationship between S_a and S_{DS}, we will take a look at a Seismic Response Spectrum. This is essentially a map of the acceleration of an object as a response to a seismic force versus the fundamental period. A response spectrum can be generated for a given geographic area based on historical earthquake data. The graphic below shows a typical response spectrum. You can see from the graphic that the spectral response acceleration, which is a function of the ground motion, increases dramatically and then plateaus from a period of zero seconds to T_s. This is the short-period range of the response spectrum. After T_s, the acceleration decreases at a function of the structure period. The design spectral response acceleration S_{DS} is simply that value of S_a at the short-period plateau, or the maximum value S_a will take for any given period. For the purpose of substation structure designs, it is generally appropriate to assume that S_a is at a maximum value of S_{DS}, but if a more precise analysis is desired, the actual value of S_a can be determined if the fundamental period of the structure is known.

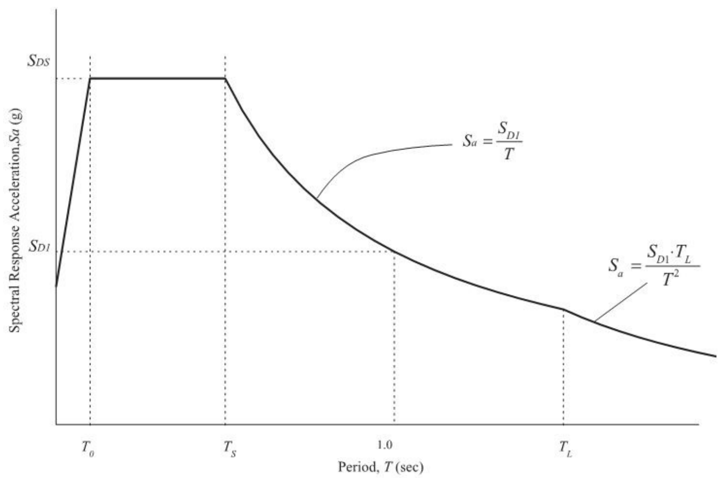


FIGURE 11.4-1 Design Response Spectrum.

Reproduced from ASCE 7-10 Figure 11.4-1 with permission from ASCE

Importance Factor

While the presence of both the importance factor and response modification factor is consistent between ASCE 7-10 and ASCE 113, these factors can take different values depending on which code is used. In ASCE 7-10, as defined in Table 1.5-2, the seismic importance factor I_e depends only on the risk category of the site. The Risk Category in ASCE 7-10 Table 1.5-1 is dependent on the occupancy type. Risk categories are assigned to indicate the severity of a potential collapse, with a higher category indicating a more critical structure. For example, essential facilities are considered as Risk category IV, while structures whose failures present low risk to human life are considered as Risk Category I. For substation structures, a Risk Category of III is typically appropriate. The earthquake importance factor I_{FE} defined in ASCE 113 depends not on the risk category but on the component being analyzed. A metric of risk is inherent but not explicit in the importance factor of ASCE 113. Structures and equipment essential to operation are assigned a 25% higher importance factor than all other structures and equipment, per Section 3.1.7.2. It is also interesting to note that the importance factor for anchorages are higher than that for structures and equipment. We will return to this later on in this paper.

Response Modification Factor

As defined in Tables 15.4-1 and 15.4-2 of ASCE 7-10 and Section 3.1.7.3 of ASCE 113, the response modification factor depends on the type of structure to be analyzed. This factor is essentially a reduction to the seismic design force that accounts for the inherent ductility of a structure. The response modification factor is in the denominator of the seismic design force equation, such that a larger response modification factor results in a smaller seismic design force. For example, an ordinary moment frame such as an H-frame dead-end structure has a higher response modification factor than a section of rigid bus or a station post insulator because a moment frame is more ductile in nature and will therefore absorb or dissipate more of the energy from a seismic event before failure occurs.

Design Spectral Acceleration Parameters

Once all applicable factors have been established, the design spectral acceleration parameter S_{DS} must be determined. This is defined by ASCE 7-10 in Equation 11.4-3 as 2/3 times S_{MS} and by ASCE 113 in Equation 3-6 as 2/3 F_a multiplied by S_s. This is consistent because ASCE 7-10 defines S_{MS} in Equation 11.4-1 as F_a multiplied by S_s. F_a is known as the site coefficient and is given in ASCE 7-10 Table 11.4-1 and ASCE 113 Table 3-12 as a function of both the site class and S_s. The site class reflects the measured soil properties found on site and is defined by ASCE 7-10 in Section 20.3 and Table 20.3-1. For instance, a site with hard rock would be in Site Class A, while a site with soft clay soil would be in Site Class E. S_s is known as the mapped Maximum Considered Earthquake (MCE) spectral response acceleration parameter. This value can be found from USGS maps for the MCE in any given location. Fundamentally, seismic base shear is calculated by starting with the maximum response acceleration that could be expected in a given area and adjusting that value through the use of multiple factors to account for risk, structure ductility, and soil type.

Analysis and Design

For the purpose of structural analysis and design of substation steel structures, it is generally accepted to apply the seismic base shear value to each member or component of the structure as a static lateral load in each horizontal direction. ASCE 113 Section 6.7 states that 80% of that horizontal force should be applied in the vertical direction to each member or component. For the equivalent lateral force method, once the seismic forces are known, a structural analysis can be performed similar to with any other load case.

Connections and Anchorage

Connections and anchorage are especially critical during seismic events. If a structure failure occurs in a member, steel yielding can allow for a ductile failure in which energy has dissipated before a break. However, if a seismic-related failure occurs in a connection, if careful consideration is not taken, the failure can be brittle in nature and the results can be catastrophic. In order to mitigate brittle failures at connections, it is recommended to design connections and anchorage for ductile behavior. When this may be difficult, it is generally acceptable to apply an overstrength factor to connection and anchorage loads. ASCE 7-10 provides values for the overstrength factor Ω_0 for nonbuilding structures in Tables 15.4-1 and 15.4-2. ASCE 113 does not include provisions for an overstrength factor, but the higher values of I_{FE} for anchorages may account for this consideration.

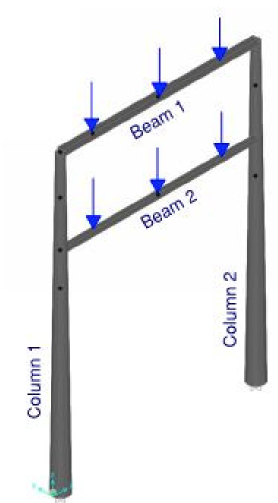
Design Example

Now that we have introduced the aspects of seismic design for substation steel structures, let us put this into perspective with a design example. We will perform the design using ASCE

113 as well as ASCE 7-10 and compare the results between the two codes. We will assume the use of the LRFD method.

Assume that we have a H-frame dead-end structure, as shown in the graphic below, with the following properties:

- Dead Load of Column 1: 2000 lb
- Dead Load of Column 2: 2000 lb
- Dead Load of Beam 1: 1000 lb
- Dead Load of Beam 2: 1000 lb
- Dead Load of Equipment at Each Attachment Point: 500 lb
- S_s from USGS MCE Map: 0.75 g
- Site Class: D



ASCE 113

Importance Factor

This structure is considered essential to operation of the substation.

- Thus, from Section 3.1.7.2, I_{FE}=1.25 except for anchorage, for which I_{FE}=2.0.

Response Modification Factor

- This structure can be considered a moment-resisting steel frame, for which R=3.0 in Section 3.1.7.3.

Seismic Design Lateral Force Coefficient

- From Table 3-12, For S_s = 0.75 and Site Class D, F_a = 1.2.

- From Equation 3-6, S_{DS} = 2/3 x F_a x S_s = 2/3 x 1.2 x 0.75 = 0.6g.

- S_a = S_{DS} = 0.6g, from Equation 3-8.

- From Equation 3-10, assuming single mode behavior, $F_E = S_a/R \times I_{FE} \times I_{MV} = 0.6g/3.0 \times 1.25 \times 1.0 = \underline{0.25g.}$

Thus, the lateral seismic coefficient is 0.25 times the weight of each component, and the vertical seismic coefficient is 0.8 times that.

- $F_{Ev} = 0.8 \times 0.25g = \underline{0.2g}$

ASCE 7-10

Importance Factor

- For Risk Category III, $I_e = 1.25$.

Response Modification Factor

- For steel ordinary moment frames, according to Table 15.4-1, R=3.5

Seismic Design Lateral Force Coefficient

- From Table 11.4-1, For $S_s = 0.75$ and Site Class D, $F_a = 1.2$
- $S_{MS} = F_a \times S_s = 1.2 \times 0.75 = 0.9g$
- $S_{DS} = 2/3 \times S_{MS} = 2/3 \times 0.9g = 0.6g$
- $C_s = S_{DS}/(R/I_e) = 0.6g/3.5 \times 1.25 = \underline{0.214g}$

Thus, the lateral seismic coefficient is 0.214 times the weight of each component, and the vertical seismic coefficient is 0.8 times that.

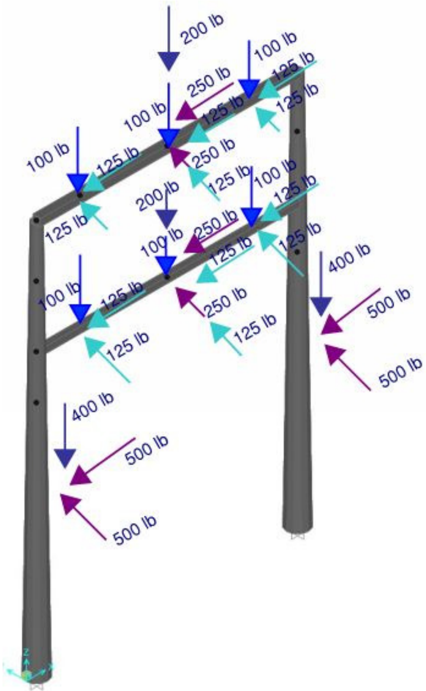
- $F_{Ev} = 0.8 \times 0.214g = \underline{0.171g}$

Design Results

From a comparison of the results from both design approaches, it can be seen that the primary difference here is the response modification factor. In our case, this leads to a higher seismic coefficient with ASCE 113 than with ASCE 7-10. For the sake of a more conservative design, we will use the seismic coefficients from ASCE 113. To find the seismic force on each member, we will multiply the seismic coefficient by the weight of each respective member. The seismic forces on each member are summarized below and shown in the graphic.

- Horizontal Seismic Load on Column 1: 2000 lb x 0.25g = <u>500 lb</u>
- Horizontal Seismic Load on Column 2: 2000 lb x 0.25g = <u>500 lb</u>
- Horizontal Seismic Load on Beam 1: 1000 lb x 0.25g = <u>250 lb</u>
- Horizontal Seismic Load on Beam 2: 1000 lb x 0.25g = <u>250 lb</u>
- Horizontal Seismic Load at Equipment at Each Attachment Point: 500 lb x 0.25g = <u>125 lb</u>

- Vertical Seismic Load on Column 1: 2000 lb x 0.2g = <u>400 lb</u>
- Vertical Seismic Load on Column 2: 2000 lb x 0.2g = <u>400 lb</u>
- Vertical Seismic Load on Beam 1: 1000 lb x 0.2g= <u>200 lb</u>
- Vertical Seismic Load on Beam 2: 1000 lb x 0.2g = <u>200 lb</u>
- Vertical Seismic Load at Equipment at Each Attachment Point: 500 lb x 0.2g = <u>100 lb</u>



Once all equivalent static seismic forces are known for each member, a static structural analysis and design can be performed. It is important to remember to apply appropriate load factors and combinations per ASCE 113 and ASCE 7-10 as well as to design for ductile connections or apply an appropriate overload factor.

<u>Conclusion</u>

In conclusion, it can be seen that both codes contain similar provisions for seismic load determination and can be used with design assumptions to produce comparable designs. Our design example yielded nearly identical results with the only fundamental difference being in the response modification factor. This may not always be the case for different input conditions or if different design assumptions are made, but it is easy to see the similarities in the provisions that each code offers for seismic design of substations steel structures. With appropriate design assumptions, either ASCE 7 or ASCE 113 can be used for a safe and effective seismic design.

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