Comparison and Research on Seismic Design Practice for Electric Substation Equipment in China, Japan, USA and Europe

Z Guan\textsuperscript{1}, Q Zhu\textsuperscript{2}, X Fan\textsuperscript{3}, M Cao\textsuperscript{4}, B Yuan\textsuperscript{1}, H Wang\textsuperscript{1} and J Ren\textsuperscript{1}

\textsuperscript{1}College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 200090, China
\textsuperscript{2}Institute of New Electrical Materials, Global Energy Interconnection Research Institute, Beijing 102211, China
\textsuperscript{3}State Grid Shanxi Economic Research Institute, Taiyuan, Shanxi 030001
\textsuperscript{4}China Electric Power Research Institute, Beijing 100055, China

Email: guanzzhen@163.com

Abstract. This paper compares the key aspects, i.e. the objectives, methods of seismic qualification, site classification and required response spectra (RRS) of GB 50260, JEAG 5003, IEEE Std 693 and IEC 62271-300. This study provides an understanding of the similarities and differences among Chinese, Japanese, U.S. and European seismic design practice. In terms of the performance objectives, site assignments and RRS, IEEE Std 693 and IEC 62271-300 present numerous similar standards, although there are many minor differences in the detailed provisions, while GB 50260 and JEAG 5003 are different in definition of ground types and determination of design response spectra. Among the four codes, the IEEE standard is generally the most restrictive, particularly at higher qualification levels. The four have strengths as well as shortcomings, and may benefit from learning each other’s experience. This study may provide linkages among these standards for seismic qualification, as well as potential modifications and unification of these criteria, which could result in better performance.

1. Introduction
Power system is an important part of lifeline engineering, in which electric equipment is the most basic component. The malfunctioning or destruction of electric equipment may cause the failure of power plant, substation or transmission line during the seismic event. A series of earthquakes, notably the 1960 Valdivia earthquake (Mw = 9.5), 1971 San Fernando earthquake (Mw = 6.6), 1976 Tangshan earthquake (Mw = 7.8), 1989 Loma Prieta earthquake (Mw = 6.9), 1994 Northridge earthquake (Mw = 6.7), 1995 Great Hanshin earthquake (Mw = 6.9), 1999 Jiji earthquake (Mw = 7.6), 1999 İzmit earthquake (Mw = 7.6), 2008 Sichuan earthquake (Mw = 7.9), 2010 Chile earthquake (Mw = 8.8), 2011 Tōhoku earthquake (Mw = 9.0), 2013 Lushan earthquake (Mw = 7.0), 2015 Illapel earthquake (Mw = 8.3), 2016 Sumatra earthquake (Mw = 7.8), 2016 Ecuador earthquake (Mw = 7.8), 2017 Papua New Guinea earthquake (Mw = 7.9), 2017 Chiapas earthquake (Mw = 8.2), 2017 Central Mexico earthquake (Mw = 7.1), 2017 Jiuzhaigou earthquake (Mw = 6.5) and 2017 Iran–Iraq earthquake (Mw = 7.3) caused major damage to substation equipment.

Due to the sudden and unpredictable occurrence, there are no effective measures to prevent earthquakes from happening. Many countries with high seismic hazards have made efforts to develop seismic
qualification standards for substation equipment, such as “IEEE Recommended Practice for Seismic Design of Substations” (IEEE 693-2005), “Guide for Seismic Design of Electrical Equipment” (JEAG 5003-2010)2 and the IEC standards. IEEE 693 has become the leading seismic qualification standard for electric equipment in high seismic hazard areas of North America such as the Western U.S., Canada and Mexico. JEAG 5003 is the national seismic qualification guide for electric utilities in Japan. Unlike IEEE 693 and JEAG 5003 providing in a single document, the IEC standards provide a suite of seismic qualifications, covering different types of electric equipment or part of the qualification process found in substations, e.g., IEC 60068-2-3:1991, IEC 60068-2-6: 2007, IEC 60068-2-47: 2005, IEC 60068-2-57: 2013, IEC 60255-21-1:1998, IEC 62271-300:2006, IEC 62271-207:2012 and IEC 62271-210:2013. The IEC standards are widely adopted in Europe, providing an alternative to IEEE 693. China is also an earthquake-prone area. After 1976 Tangshan earthquake, China began to work on seismic standards for electric equipment. The 2009 revision of “Seismic qualification for high-voltage switchgear and controlgear” (GB/T 13540-2009), the 2010 revision of “Code for aseismic design of electrical facilities in industrial plants” (GB 50556-2010) and the 2013 revision of “Code for seismic design of electrical installations” (GB 50260-2013) are the current seismic qualification standards for substations, power generating and transmission equipment in China.

At present, IEEE 693 and the IEC standards have become the most influential international standards in the world. JEAG 5003 and GB 50260 are the representative standards in Asia. Since different areas have different historic seismic activity, the seismic design practice varies from one standard to another. Since these codes have largely modeled based on their own national seismic-resistant practice, investigations into these representative seismic qualification standards is important to understand their seismic effects and substation practice in these countries.

Fujisaki2 gave a comparison of the key aspects of IEEE 693 and IEC 62271 Part 300 which applied to circuit breaker seismic qualification, and found that their overarching objectives were the same but some of the methods of qualification employed differ somewhat. IEEE 693 in general, represented the stricter standard. Regarding the comprehensive comparison of the seismic qualification procedures for the electrical substation equipment in the leading seismic design standards, there are few studies.

This paper presents a comparison of seismic design criteria and practices employed in Chinese, Japanese, U.S. and European codes for electric equipment, i.e., the seismic objectives, seismic qualification levels, site class, seismic design response spectrum and seismic design requirements. It is intended to provide information for the effectiveness of present design and construction practices in China, Japan, US and Europe, as well as potential modifications to Chinese practices that could result in better performance in future events.

2. Performance objectives and seismic qualification levels

The objectives of these practices are to allow manufacturers to design their electrical equipment to meet functional requirements and secure individual equipment. The objectives of these practice in different countries are slightly different. IEEE 693 and GB 50260 both share the same two-level seismic fortification objectives: qualified equipment should remain functional under the design earthquake, and should be undamaged (IEEE) or repairable (GB 50260) under rare earthquakes. According to the seismic importance and characteristics of electric utilities, power facilities in GB 50260 are divided into important and general facilities. GB 50260 provides that the seismic fortification level of important facilities should be improved by 1 degree against general facilities but further improvement no longer needs when their seismic fortification level is 9 degrees or above. JEAG 5003, IEC 62271-3002 and IEC 62271-2075 define a single seismic fortification level, i.e., the functionality of the equipment is not impaired when subjected to a design earthquake. It is noted that the IEC standards covering an equivalent scope shall include IEC 62271-300 and a number of others, each of which shall involve in several vital supplementary.

Although the overall performance objectives of these standards are largely similar, the definition of the design earthquake and the acceptance criteria influence the seismic performance of equipment qualified by any standard. The performance objectives and qualification levels in standards from different
countries are presented in table 1.

Table 1. Objectives and seismic qualification levels on Chinese, Japanese, U.S. and European seismic design practice.

| Codes       | Objectives                                                                 | Seismic Qualification Levels                                                                 | Probabilistic Seismic Hazard                                                                 |
|-------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| GB 50260    | No damage under occasional earthquake, and repairable damages under rare earthquake. | The seismic precautionary intensity is 6 degree, 7 degree, 8 degree and 9 degree based on earthquake intensity zoning map (GB18306-2015) and on significance of structures in electric utilities. | (a) occasional earthquake: with probability of exceedance 10% in 50 years (i.e., 475-year return period). (b) rare earthquake: with probability of exceedance 2% in 50 years (i.e., 2475-year return period). |
| GB 50556    | The equipment should not be undamaged, and is expected to continue to function under basic earthquake. | The seismic precautionary intensity is 6 degree, 7 degree, 8 degree and 9 degree.               | 10% probability of exceedance in 50 years (i.e., 475-year return period)                        |
| JEAG 5003   | The equipment does not malfunction or fail in the event of an earthquake.    | The seismic qualification levels are classified as service level and ultimate level.             | (a) moderate earthquake: with probability of exceedance 10% in 50 years (i.e., 475-year return period). (b) strong earthquake: with probability of exceedance 2% in 50 years (i.e., 2475-year return period). |
| IEEE 693    | When subjected to an earthquake described by the required response spectrum (RRS) level, a qualified equipment is completely undamaged and expected to continue to function; when subjected to an earthquake described by the performance level (PL), which is twice the RRS level, the equipment can perform acceptably, but may experience some minor damage, e.g., minor yielding or permanent deformation of ductile components. | Three qualification levels are low, moderate, and high according to the user desired qualification level. If the PGA is at or below 0.1g, the level is classified as low. If the PGA is greater than 0.1g but equal or less than 0.5g the level is classified as moderate. If the PGA is greater than 0.5g the level is classified as high. | 2% probability of exceedance in 50 years (i.e., 2475-year return period)                        |
| IEC 62271-300, IEC 62271-207. | During and after the seismic event, the equipment should withstand seismic stress and maintain its specified function, without failure on the | The qualification levels are termed low, moderate, and high defined by anchoring the standard broad-band spectral shapes. | 10% probability of exceedance in 50 years (i.e., 475-year return period) |


GB/T 13540 encloses the main circuits as well as on the control and auxiliary circuit, including the relevant mounting structures. For ductile components, minor permanent deformations are acceptable.

GB/T 13540 is originated from IEC 62271-207, and have the same general performance objective. From Table 1, it can be observed that IEEE 693 has the strictest objective and seismic qualification level, compared to Chinese, U.S. and European standards. For the performance objective, GB 50260, GB 50556 and JEAG 5003 just provide fundamental objectives, but lack the detailed performance objectives of the main and auxiliary equipment.

3. Site class
Site class and site coefficient are two parameters needed for designing response spectra. Site class can be estimated using average standard penetration test blow counts (N-SPT), shear wave velocity (V_s) or average undrained shear strength (S_u) of a certain depth of top soil deposit, among which V_s is one of the most important parameters to represent the stiffness of the soil layers. China, Japan, U.S. and Europe have their own provisions to define site classes, which are a little different from each other.

The Chinese site classes are defined in “Code for seismic design of buildings” (GB 50011-2010, 2016 Edition), and classified into I, II, III and IV in accordance with the equivalent shear wave velocity of the soil layer and the overburden thickness (between 0 and 20 m). Site class I is subdivided into two categories, namely I_0 (rock) and I_1 (stiff soil or soft rock). Since site class III and IV are designated to soft site, if electric utilities are founded on such soft site, an earthquake disaster may be serious. Therefore, GB 50260 implicates that site selection for power plants and substations should choose area such as stable rock, stiff soil as well as dense and homogeneous medium-stiff soil with a high-density and wide-open area, which is favorable for earthquake resisting, and should avoid disadvantage area, such as soft soil, liquefied soil, strip-producing spur, etc. site class II is widely distributed, and is the leading example of site in China.

The building standard law of Japan (BSLJ) gives provisions for seismic design of foundations. The construction sites in Japan are classified as three-classes, i.e., stiff soil, medium-stiff soil and soft soil simply depending on the characteristic period (T_s), which is related to the number of soil layers from the soil foundation surface to the bedrock, the shear wave velocity and the thickness of the mth soil layer.

In U.S., the National Earthquake Hazards Reduction Program (NEHRP) provides a framework for seismic regulations according to site classes (A-F) defined for similar seismic responses. The site classes A, B, C and D are assigned to hard rock, rock, very dense soil and soft rock, and stiff soil, with site conditions of V^3_{s0} (average shear wave velocity for the upper 30 m of the subsurface, i.e., effective shear wave velocity) >1500 mS^-1, 760-1500 mS^-1, 360-760 mS^-1 and 180-360 mS^-1 respectively. Site class E is involved in a soil profile with V^3_{s0} <180 mS^-1 or any profile with more than 3 m of soft clay defined as soil with PI (plasticity index) >20, w (moisture content) ≥40%, and S_u (average undrained shear strength) <25 kpa, while the identification of site class F requires site-specific evaluations.

Eurocode 8 (EC8) is widely used in Europe, and also uses the V^3_{s0} for site class characterization. The near-surface materials are classified as type A, type B, type C, type D, type E, type S_1 and type S_2 according to the value of V^3_{s0}. Comparison of Site classification in Chinese, Japanese, U.S. and European codes is represented in Table 2.
| Codes | Site class or soil profile type | Description | GB 50011, China | NEHRP, USA | Eurocode 8, Europe |
|-------|---------------------------------|-------------|----------------|-----------|------------------|
|       |                                 |             | I              | A         | C                |
|       |                                 |             | stiff soil or rock | Hard rock | Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface |
| I     | medium-stiff soil                |             | 250 ≤ $v_s$ < 500 | $T_g$ = 0.4 | Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters |
| II    | medium-soft soil                 |             | 150 ≤ $v_s$ < 250 | $T_g$ = 0.6 | Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil |
| IV    | Soft soil                        |             | $v_s$ ≤ 150    | $T_g$ = 0.8 | $v_s$ > 800 |
| I     | Stiff soil                       |             | $v_s$ ≥ 1500   | -         |               |
| II    | medium-stiff soil                |             | 760 ≤ $v_s$ ≤ 1500 | -         |               |
| III   | Soft soil                        |             | 360 ≤ $v_s$ ≤ 760 | -         |               |
| A     | Rock                             |             | 180 ≤ $v_s$ ≤ 360 | -         |               |
| B     | Very dense soil/soft rock        |             | $v_s$ < 180    | -         | $v_s$ < 180 |
| C     | Stiff soil                       |             | $v_s$ ≥ 300    | -         | $v_s$ ≥ 300 |
| D     | Soft soil                        |             | $v_s$ ≥ 180    | -         | $v_s$ ≥ 180 |

Table 2. Site classes according to GB 50011-2010, NEHRP and EC8
A soil profile consisting of a surface alluvium layer with $v_{s}^{30}$ values of class C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $v_{s}^{30} > 800$ m/s.

Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI>40) and high water content.

Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A-E or S1.

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**S1**

- Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI>40) and high water content.

- Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A-E or S1.

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**S2**

- Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A-E or S1.

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a) the characteristic period.
b) The equivalent shear wave velocity of the soil profile, in m/s.
c) A time-averaged shear wave velocity to a depth of 30 m, in m/s.

About all, site characterization can be defined by many parameters (namely, the shear wave velocity, standard penetration test blow counts, average un-drained shear strength, characteristic period, thickness of site overlying layer, etc.), it is mainly based on single-index or double-index evaluation method. U.S. and Europe adopt the single-index evaluation method, i.e. the average shear-wave velocity of ground in the upper 30m ($v_{s}^{30}$) for site classification. While Japan only adopts the characteristic period for site class assignments. China employs the double-index estimation depending on the equivalent shear-wave velocity ($v_{s}$) and the overlaying thickness of soil profile ($d_{ov}$). Comparison of site classification for the seismic codes in China, U.S. and Europe is presented in Figure 1, where the subscript “U.S.” indicates the NEHRP site classes, and “Eur.” indicates the Eurocode 8 site classes.

![Comparison of the site classification schemes among Chinese, U.S. and European seismic codes](image)

Here, GB 50011 of China defines “rock” sites as those having shear-wave velocity of 500 m/s, lower than that in NEHRP and Eurocode 8 (shear-wave velocity of 800 m/s). The shear-wave velocity for the “soft” site in GB 50011 is 150 m/s, also lower than that in NEHRP and Eurocode 8 (shear-wave velocity of 180 m/s). There are also some differences in the definition of the reference site, i.e. GB 50011 class I, BSLJ class I, NEHRP Class B and Eurocode 8 Class A as their own reference sites. From Figure 1, it can be seen that 1) site class I defined in GB 50011 (shear wave velocity ranging from 360 m/s to 760 m/s) corresponds to NEHRP class CD and Eurocode 8 class BC; 2) Eurocode 8 class A is equivalent to GB 50011 I0, and roughly equivalent to NEHRP class A and class B; 3) Eurocode 8 class B, class C and class D corresponds to NEHRP class C, class D and class E, respectively.
Since the shear wave velocity is one of the most important input parameters to represent the stiffness of the soil layers\(^\text{10}\), it is widely used as an effective predictor for seismic site characterization in the world. However, there are many differences in the methods for shear wave velocity determination, e.g., the calculation method, thickness of site overlaying layer and selection of the calculated initial surface (GB 50011 and NEHRP adopt the ground surface, while BSLJ and Eurocode 8 employ basic plane as their calculated initial surfaces). In addition, compared to BSLJ, NEHRP and Eurocode 8, GB 50011 uses double-index evaluation method for site classification, therefore small variations in the shear wave velocity or the thickness of site overlaying near the boundaries of the site classes may cause site type saltation, which cause characteristic site period saltation. In Japan, U.S. and Europe, the thickness of site overlaying layer is taken as an auxiliary criterion, but not a necessary index for site class assignments.

In order to better design the reference earthquake spectra, our site classification should be study carefully and consider the appropriate definition of seismic site characterization. It is better to adopt continuous site classification profiles.

4. Design spectral response

The use of seismic response spectra as a means for qualifying equipment has become the most widely accepted and powerful method. Designing response spectra at ground surface, site class and site coefficient are two needed parameters. A response spectrum is a plot of maximum response (displacement, velocity, or acceleration) versus a system characteristic (frequency or period and damping ratio) for a single degree-of-freedom oscillator for a particular applied load\(^2\). For non-reference-site conditions, site coefficient is used to adjust for site class effects, which is based on soil type (site class) and given in seismic regulations. According to the seismic risk analysis for different seismic intensity of Chinese Site Class II\(^1\), the fortification intensity 8 level (design basic acceleration of ground motion of 0.3 g) of GB 50260 roughly corresponds to the moderate seismic level of IEEE Std 693 and IEC 62271-300, while the fortification intensity 9 level of GB 50011 roughly corresponds to the high seismic level of IEEE Std 693 and IEC 62271-300. Here the characteristic periods in GB 50260 are assigned to use the values from the 1st design seismic group.

For electrical equipment, the damping ratio is usually assumed to be 2\%, and the theoretical response spectrum should be computed at 2\% damping. The maximum response is plotted as a function of period at a damping ratio of 2\% and the reference site conditions based on the U.S., European, Chinese and Japanese seismic codes, showing in Figure 2. The damping ratio can be changed to develop a family of response spectra.

![Moderate required Response spectra](image)
Figure 2. Comparison of the response spectra among U.S., European, Chinese and Japanese codes for seismic design of electrical installations, 2% damping

Note: $g$ is the gravitational acceleration.

From Figure 2, it can be seen that the response spectra are all defined as a piecewise function, divided into three or four segments. Compared to U.S., European and Chinese seismic codes, the elastic response spectra of BSLJ do not have the increase section. For the 1st design seismic group of GB 50260 and GB 50556, the characteristic period values for Site Class I₀, Site Class I₁, Site Class II, Site Class III and Site Class IV are 0.2 s, 0.25 s, 0.35 s, 0.45 s and 0.65 s respectively. GB/T 13540 adopts IEC 62271-207, and their site characteristic period values are 0.42 s. The site characteristic periods of IEEE Std 693, IEC 62271-300 and BSLJ are assigned to be 0.91 s, 1.4 s and 0.6 s respectively.

In addition, regarding the required response spectra (RRS) for moderate levels, the heights of the plateau of the spectra in GB 50260, GB 50556, GB/T 13540, IEEE Std 693 and IEC 62271-300 are 0.95 g, 0.88 g, 0.85 g, 0.81 g and 0.85 g respectively. As for high levels, the heights of the plateau of the spectra in GB 50260, GB 50556, GB/T 13540, IEEE Std 693 and IEC 62271-300 are 1.27 g, 1.18 g, 1.4 g, 1.62 g and 1.4 g respectively. Compare to U.S., European and Japanese seismic codes, the characteristic period values are a little small, particularly for rock or hard soil (Site Class I and Site Class II), and the height and width values are also small, especially at higher levels. Figure 2 indicates that IEEE Std 693 has strict qualification requirements and methods, particularly at higher seismic qualification levels.

5. Conclusions

By comparing these standards, it can be concluded that the objectives, seismic qualification levels, site class definitions and RRS of JEAG 5003, GB 50260 are different from those of IEEE Std 693 and IEC 62271-300, while IEEE 693 and IEC 62271-300 share the similar performance objectives, methods of qualification and response spectra. IEEE 693 and IEC 62271-300 have become the two influential and authoritative international codes, and are widely adopted in North America and Europe. The IEEE standard in general, represents the strictest standard.

While the performance objectives of JEAG 5003, GB 50260, IEEE Std 693 and IEC 62271-300 are similar, they differ fundamentally in the specification of the qualification methods, particularly in the provisions defining when testing is required and what tests are needed. They also differ significantly in the seismic margin provided by qualifications. Each standard referring to the performance objectives, methods of qualification and design of seismic response spectra is based on its in situ survey data (such as geology, lithology and soil conditions) and its development level of science and technology. Each
standard has merits as well as shortcomings, and each may benefit from adopting some of the provisions of the others. With globalization, it is beneficial to streamline these standards for the benefit of electrical equipment manufacturers and users. As the continuous discussions, research, development, and mutual understanding, the four standards may improve and unify some standards for seismic qualification, which plays an important role in cost cutting and time saving.

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