ENERGY STORAGE AND EARTHQUAKES

DESIGN CONSIDERATIONS AND BEST PRACTICES TO OPTIMIZE BATTERY ENERGY STORAGE SYSTEM (BESS) DEPLOYMENT IN SEISMICALLY ACTIVE REGIONS

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Introduction

Grid resiliency in the face of natural disasters has been a concern as long as the power grid has existed. Natural disasters capable of damaging transmission and distribution infrastructure may also damage power generation infrastructure. An extreme example is the 2011 Tohoku Earthquake and Tsunami, where not only transmission and distribution infrastructure, but also significant generation assets, such as the Fukushima Daichi power plant, were damaged.[1] Recent years have seen a significant interest in distributed energy resources (DERs) as a method for ensuring local grid stability during outages elsewhere on the grid. While lithium-ion batteries are considered to preserve grid stability, their presence presents a fire risk in the battery energy storage systems (BESS) commonly used in both DERs and in grid-scale energy storage. Additionally, BESS may be disabled by damage to related hardware, such as the grid interconnection or communication and control systems.

To date, there has been scant research into the fire risk BESS present when subjected to an earthquake. However, IEEE has developed the standard *IEEE 693: IEEE Recommended Practice for Seismic Design of Substations*, which focuses on important grid electrical hardware and provides some guidance on safe BESS deployment.[2] Several studies have considered the hazards earthquakes pose to grid infrastructure, and significant research has considered the potential employment of BESS as tools for grid resilience after an earthquake.[3,4] This white paper begins with an overview of earthquake intensity and strength measurement, then describes common earthquake damage mechanisms. Next, it considers established BESS installation and performance testing mechanisms. Then it proposes recommendations for safe BESS deployment and

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[1] See references from Churchill et al 2014, eg Hollnagel & Fujita 2013; Null, 2017.
[2] *IEEE 693-2018: IEEE Recommended Practice for Seismic Design of Substations.*
[3] Aki H (2017) Demand-side resiliency and electricity continuity: experiences and lessons learned in Japan. Proc IEEE 105(7):1443–1455. https://doi.org/10.1109/JPROC.2016.2633780
[4] M. Nazemi, M. Moeini-Aghtaie, M. Fotuhi-Firuzabad, and P. Dehghanian, “Energy Storage Planning for Enhanced Resilience of Power Distribution Networks Against Earthquakes,” *IEEE Transactions on Sustainable Energy*, vol. 11, no. 2, April 2020.

operation in earthquake-prone regions. These include standards for substations and related infrastructure, a deep dive into vibrational concerns, and general structural considerations.

Earthquake Strength and Fundamentals

The Federal Emergency Management Agency (FEMA) applies what are known as *fragility curves*, denoting the failure probability of a component as a function of seismic parameters to assess the likelihood of damage. [5,6] The primary concerns when drawing fragility curves include:[7]

- Estimation of the most probable earthquake magnitude at the location of interest using historical earthquake catalogues.
- Determining the ground (soil) type at the location of interest.
- Estimation of a technical attenuation relationship suitably capturing the geotechnical characteristics at the location of interest.

There are several methods for estimating earthquake strength and ability to inflict damage. The best known is the *Richter Magnitude Scale*, based upon objective measurements of earthquakes' seismic waves using the formula[8]

$$M_L = log_{10}(\frac{A}{A_0(\delta)})$$

where M_L is the local magnitude, A is the maximum millimeters recorded on a seismograph, and $A_0(\delta)$ is the maximum amplitude at distance δ for a standard earthquake.[9] Many consider the Richter scale outdated and prefer the *Modified Mercalli Intensity Scale* (MMI scale), which correlates to a ground acceleration induced by the earthquake. The MMI scale is popularly used as it correlates to observed surface damage[10] and can be used as a predictive, planning tool.[11] Another method is the

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[5] Federal Emergency Management Agency (FEMA), "Multi-hazard loss estimation methodology: Earthquake model," Department of Homeland Security, FEMA, Washington, DC, 2003.

[6] M. Nazemi, M. Moeini-Aghtaie, M. Fotuhi-Firuzabad, and P. Dehghanian, "Energy Storage Planning for Enhanced Resilience of Power Distribution Networks Against Earthquakes," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 2, April 2020.

[7] M. Nazemi, M. Moeini-Aghtaie, M. Fotuhi-Firuzabad, and P. Dehghanian, "Energy Storage Planning for Enhanced Resilience of Power Distribution Networks Against Earthquakes," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 2, April 2020.

[8] https://pubs.usgs.gov/gip/earthq4/severitygip.html.

[9] Richter, C.F. 1935. An instrumental earthquake magnitude scale. Bull. Seism. Soc. Am., 25 : 1-32.

[10] https://pubs.usgs.gov/gip/earthq4/severitygip.html.

[11] M. Churchill, D. Bristow, and C. Crawford, "Increasing earthquake resilience for the power grid in southwestern British Columbia: integrated disaster planning for the shift from fuel to electric vehicles," *Natural Hazards*, vol.120, pages 9957–9976, https://doi.org/10.1007/s11069-024-06593-2, 2024.

moment magnitude scale, determined by quantifying the distance a fault slips and the area of that slip.[12,13,14]

Earthquakes generate seismic waves in the 0.01-10 Hz frequency range,[15] although frequencies as high as 100 Hz have been observed.[16] The MMI scale ranges from 0.05-0.60 g and ceases measuring intensities >0.60 g.[17] Above 0.60 g, extensive damage is considered probable, and complete damage is assured at 1.2 g.[18] In planning for earthquake intensity, the IEEE 693 considers *seismic qualification levels* based upon historical earthquake intensity as either high (>1.0 g), moderate (0.5-1.0 g), or low (<0.5 g).[19] Various governmental and professional organizations have published detailed risk maps for assessing earthquake risk, such as FEMA's fragility curves or related publications from the American Society of Civil Engineers (ASCE).[20],[21]

The period of time, in seconds, it would take a structure to undergo one complete cycle of free vibration (T)(inverse of seismic wave frequency) is a key consideration when evaluating an earthquake's surface effects on a structure. T's effects are quantified as follows:

$$T = 2\pi\sqrt{\frac{W}{Kg}}$$

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12 https://www.usgs.gov/faqs/moment-magnitude-richter-scale-what-are-different-magnitude-scales-and-why-are-there-so-many.

13 Hanks, T.C. and Kanamori, H. 1979. A moment magnitude scale, J. Geophys. Res., 84 : 2348-2350.

14 Kayal, J.R. Earthquake Magnitude, Intensity, Energy, Power Law Relations and Source Mechanism (2006).

15 Tosi, P., Sbarra, P., and De Rubeis, V., 2012. Earthquake sound perception. Geophysical Research Letters, vol 39 L24301, doi:10.1029/2012GL054382.

16 American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 6.

17 American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 4.

18 M. Nazemi, M. Moeini-Aghtaie, M. Fotuhi-Firuzabad, and P. Dehghanian, "Energy Storage Planning for Enhanced Resilience of Power Distribution Networks Against Earthquakes," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 2, April 2020.

19 IEEE 693-2018, 5.7 Seismic qualification levels.

20 ASCE 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Chapter 22: Seismic ground motion, long-period transition, and risk coefficient maps.

21 Different standards published by different professional organizations may use similar concepts as fragility curves but draw maps using different Richter, MMI, and frequency criteria. For example Telcordia Technologies Generic Requirements (GR-63-CORE), Section 4.4.1.1, for telecommunications infrastructure combines the Richter and MMI scale in mapping earthquake risk zones.

where W is the mass of the object, K is the object's stiffness, and g is the acceleration due to gravity.[22] The stiffness variable may vary widely for materials and depends upon many variables, including the inertias applied to the structure.[23]

Earthquake Damage

Ground shaking has been attributed to 90% of damage caused by earthquakes and is by far the most serious earthquake hazard.[24] Therefore, the bulk of attention in earthquake-prone regions focuses on methods to mitigate the effects of ground shaking. Other important hazards to consider are **tsunami**, soil **liquefaction**, **landslides**, **fault rupture**, and **lateral spreading**.[25] These other hazards are approached briefly:

- **Tsunami.** Avoid locating a BESS and related infrastructure in tsunami inundation areas. Documents such as ASCE 7-22 provide guidance on tsunami energy and inundation height and correlate it to geography.[26] ASCE 7-22, for example, advises on potential tsunami damage to shipping containers, like those commonly used as BESS housing containers,[27] and on good foundation design.[28] However, these considerations are strictly mechanical and ignore the risk of flooding to electrical or lithium-ion battery systems. If a BESS or related infrastructure must be sited in a tsunami inundation area, elevate it above the projected flooding height.[29] In regions with a high tsunami risk, BESS developments and their related electrical infrastructure should be spread out over a wide area, rather than concentrated in one location. This can limit damage caused by any one inundation event.[30] Additionally, BESS should be protected to avoid water ingress, both for risk of

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[22] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 4.

[23] C. Fu, D. Tong, and Y. Wang, "Assessing the Instantaneous Stiffness of Cracked Reinforced Concrete Beams Based on a Gradual Change in Strain Distributions," *Advances in Materials Science and Engineering*, Volume 2020, Article ID 7453619, https://doi.org/10.1155/2020/7453619.

[24] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 7.

[25] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 7.

[26] ASCE 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Chapter 6: Tsunami loads and effects.

[27] ASCE 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Chapter 6: Tsunami loads and effects, Section 6.11.6 Shipping Containers.

[28] ASCE 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Chapter 6: Tsunami loads and effects, Section 6.12 Foundation Design.

[29] M. Churchill, D. Bristow, and C. Crawford, "Increasing earthquake resilience for the power grid in southwestern British Columbia: integrated disaster planning for the shift from fuel to electric vehicles," *Natural Hazards*, vol.120, pages 9957–9976, https://doi.org/10.1007/s11069-024-06593-2, 2024.

[30] M. Churchill, D. Bristow, and C. Crawford, "Increasing earthquake resilience for the power grid in southwestern British Columbia: integrated disaster planning for the shift from fuel to electric vehicles," *Natural Hazards*, vol.120, pages 9957–9976, https://doi.org/10.1007/s11069-024-06593-2, 2024.

electric shock[31] and lithium fire. If water should ingress, the BESS must be able to properly vent in accordance with UL 9540 and UL 9540A. BESS developments are well-suited to providing resilience in DERs.

- **Liquefaction.** Despite the strong shaking experienced, liquefaction was blamed for the bulk of power grid damage during the 2011 Christchurch earthquake.[32] When possible, locate infrastructure outside liquifaction zones. Liquefaction zones can be identified by liquefaction hazard maps, usually issued by local authorities.[33] If siting outside a liquifaction zone is not possible, installers should take several precautions. For example, distribution and transmission infrastructure should be installed above ground and not buried.[34,35] Siting on reinforced mats may mitigate damage.[36] Another, more robust approach may be to harden liquefaction-prone soils using methods such as jet grouting.[37,38] As with tsunami risk, BESS should be protected to avoid contact with water, both for risk of electric shock[39] and lithium fire. Also, liquifaction must not impede venting.

- **Landslides.** Ideally, BESS should not be installed in regions with a substantial landslide risk. Landslides are the most common shaking-induced ground instability.[40] To date, recorded earthquake-induced landslides have been most common in regions without significant electrical infrastructure.[41] There is little record of landslides damaging deployed BESS. Landslides frequently damage

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[31] UL 9540, Section 10.15.

[32] M. Churchill, D. Bristow, and C. Crawford, "Increasing earthquake resilience for the power grid in southwestern British Columbia: integrated disaster planning for the shift from fuel to electric vehicles," *Natural Hazards*, vol.120, pages 9957–9976, https://doi.org/10.1007/s11069-024-06593-2, 2024.

[33] OSSPAC (2019) CEI hub mitigation strategies: increasing fuel resilience to survive Cascadia. Oregon Seismic Safety Policy Advisory Commission.

[34] Kwasinski A, Eidinger J, Tang A, Tudo-Bornarel C (2014) Performance of Electric Power Systems in the 2010–2011 Christchurch, New Zealand, Earthquake sequence. Earthq Spectra 30(1):205–230. https://doi.org/10.1193/022813EQS056M.

[35] M. Churchill, D. Bristow, and C. Crawford, "Increasing earthquake resilience for the power grid in southwestern British Columbia: integrated disaster planning for the shift from fuel to electric vehicles," *Natural Hazards*, vol.120, pages 9957–9976, https://doi.org/10.1007/s11069-024-06593-2, 2024.

[36] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 6.

[37] M. Churchill, D. Bristow, and C. Crawford, "Increasing earthquake resilience for the power grid in southwestern British Columbia: integrated disaster planning for the shift from fuel to electric vehicles," *Natural Hazards*, vol.120, pages 9957–9976, https://doi.org/10.1007/s11069-024-06593-2, 2024.

[38] OSSPAC (2019) CEI hub mitigation strategies: increasing fuel resilience to survive Cascadia. Oregon Seismic Safety Policy Advisory Commission.

[39] UL 9540, Section 10.15.

[40] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 7.

[41] Kwasinski A, Eidinger J, Tang A, Tudo-Bornarel C (2014) Performance of Electric Power Systems in the 2010–2011 Christchurch, New Zealand, Earthquake sequence. Earthq Spectra 30(1):205–230. https://doi.org/10.1193/022813EQS056M.

transmission lines[42] and roads.[43,44] In regions where an earthquake may limit access to damaged BESS developments, BESS operators and maintainers should store spare parts, tools, and emergency response equipment close to the BESS sites.

- **Fault rupture.** This is often known as *surface faulting* or *surface fault rupture*, to differentiate it as a surface hazard, as distinguished from the underground rupturing seismic faults, which create earthquakes.[45, 46] Surface faults are nearly unidimensional along the direction of the underground fault, and therefore affect a small surface area. Fault ruptures seldom damage buildings, but given their length, they may damage roads, transmission, and distribution lines.[47] As with landslide impacts, in regions where access to damaged BESS may be limited following an earthquake, BESS operators and maintainers should store spare parts, tools, and emergency response equipment close to BESS deployment sites. Unlike with landslides, siting on reinforced mats may mitigate fault rupture damage.[48]

- **Lateral spreading**. Lateral spreading describes a phenomenon where surficial soil permanently moves laterally due to earthquake shaking.[49] Lateral spreading usually occurs after liquefaction undermines soil integrity on a slope or cut.[50] The liquified soil then erodes, forming a cut in the slope or widening an existing cut.[51] Thus, lateral spreading is an additional hazard on top of those already posed in liquefaction zones. Building on sloped ground, especially near creeks or rivers, in

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42 Massie A, Watson NR (2011) Impact of the Christchurch earthquakes on the Electrical Power System infrastructure. Bull New Z Soc Earthq Eng 44(4):425–430.
43 M. Churchill, D. Bristow, and C. Crawford, "Increasing earthquake resilience for the power grid in southwestern British Columbia: integrated disaster planning for the shift from fuel to electric vehicles," *Natural Hazards*, vol.120, pages 9957–9976, https://doi.org/10.1007/s11069-024-06593-2, 2024.
44 OSSPAC (2019) CEI hub mitigation strategies: increasing fuel resilience to survive Cascadia. Oregon Seismic Safety Policy Advisory Commission.
45 Kayal, J.R. Earthquake Magnitude, Intensity, Energy, Power Law Relations and Source Mechanism (2006).
46 American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 6.
47 American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 6.
48 American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 6.
49 Wang, Y., Bartlett, S., & Miles, S. (2013). Earthquake Risk Study for the Critical Energy Infrastructure Hub in Oregon. Oregon Department of Geology and Mineral Industries, Open File Report O-13-9, page 39, 51.
50 Wang, Y., Bartlett, S., & Miles, S. (2013). Earthquake Risk Study for the Critical Energy Infrastructure Hub in Oregon. Oregon Department of Geology and Mineral Industries, Open File Report O-13-9, page 51.
51 American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 6.

regions with a liquefaction risk is highly discouraged.[52,53] When such construction is unavoidable, builders should employ similar mitigation methods as those employed for liquifaction.[54]

Established BESS Testing Requirements

UL 9540 is the leading standard for safe, effective BESS construction and installation. Its companion, UL 9540A, is the standard for BESS safety testing. Even the NFPA 855 Standard for the Installation of Stationary Energy Storage Systems references compliance with UL 9540 and UL 9540A as key to safe BESS installation. IEEE 693 provides some guidance on battery deployment in grid infrastructure in earthquake-prone regions, but this guidance is scant.[55] Because IEEE 693 guidance is scant, analogs are drawn from the standards for building other infrastructure, including substations, in earthquake-prone regions and from the vibrational standards associated with batteries in the transportation sector.

Most BESS are composed of battery *cells*, organized into *modules*, and installed in a BESS unit in a factory. The BESS unit is then transported to a site, where it is installed. UL 9540A testing involves a series of battery tests at each of these four levels as summarized by Underwriters Laboratories (UL):[56]

1. **Cell-level test.** Cell-level testing evaluates the thermal runaway characteristics of the cell as well as the composition and flammability of the gases.

2. **Module-level test.** Module-level testing evaluates the tendency of cell thermal runaway propagation, the heat and gas release rate of the module, and the potential danger of ignition or deflagration.

3. **Unit-level test.** Unit-level testing evaluates the likelihood of fire spread between modules, the unit's heat and gas release rates, and the potential for deflagration or re-ignition.

4. **Installation-level test.** Installation-level mainly evaluates the effectiveness of the fire protection system, as well as the heat and gas release rate of the system and the danger of deflagration or re-ignition.

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[52] OSSPAC (2019) CEI hub mitigation strategies: increasing fuel resilience to survive Cascadia. Oregon Seismic Safety Policy Advisory Commission.
[53] Wang, Y., Bartlett, S., & Miles, S. (2013). Earthquake Risk Study for the Critical Energy Infrastructure Hub in Oregon. Oregon Department of Geology and Mineral Industries, Open File Report O-13-9, page 11-12.
[54] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 6.
[55] IEEE 693-2018, Annex J, Station batteries and battery racks.
[56] UL 9540A, Section 1.

The concern of UL 9540A testing is to minimize the fire risk from deployed BESS. Key additions to the 2025 edition include requirements to ensure proper gas venting at the cell level,[57,58] that any cell-level gassing is non-flammable,[59,60] and that external module surface temperatures do not exceed cell venting temperatures.[61,62] Updates at the installation level concern sprinkler effectiveness.[63,64] UL 9540A provides guidance for differing humidity or temperature environments but does not address vibrational strains or other earthquake-related concerns.

Given these concerns, any design for earthquake-prone regions should ensure that vibrational hazards (or any other common earthquake hazards) will not adversely affect a BESS's ability to handle gas management or to deploy coolant during an adverse thermal event. Note that when all these components throughout the value chain travel through the stream of commerce, the primary guidelines for safe transportation and handling are the United Nations Manual of Tests and Criteria Subsection 38.3 (UN 38.3)[65] and relevant United States Department of Transportation (DOT) Regulations.[66]

UL 9540 requires BESS enclosures be sufficiently strong, "to resist the possible physical abuses that it will be exposed to during its transportation, installation and intended use."[67] The BESS enclosure also must meet durability requirements, including, among other things, "Severe conditions."[68] For these reasons, compliance with UL 9540 is inescapable, and UL 9540 calls for additional measures appropriate for the severe conditions that earthquakes may present. While UL 9540 does not mandate a specific testing standard for earthquake-prone regions, after such tests have been performed, a BESS fails UL 9540 if any of the following results:[69]

a) Explosion;

b) Fire;

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57 UL 9540A, Section 7.
58 *An inside look at the updates to UL 9540A: 2025: Key changes to the Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.*
59 UL 9540A, Section 7.
60 *An inside look at the updates to UL 9540A: 2025: Key changes to the Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.*
61 UL 9540A, Section 8.
62 *An inside look at the updates to UL 9540A: 2025: Key changes to the Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.*
63 UL 9540A, Section 10.3-10.5.
64 *An inside look at the updates to UL 9540A: 2025: Key changes to the Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.*
65 UN 38.3.
66 49 CFR §173.185 Lithium cells and batteries.
67 UL 9540, Section 9.1.
68 UL 9540, Section 7.2.
69 UL 9540, Section 37.4.3.

c) Combustible Concentrations (if applicable to technology);

d) Rupture (enclosure);

e) Electrolyte Leakage (external to enclosure);

f) Electric shock hazard (resistance below isolation resistance limits or dielectric breakdown);

g) Loss of protection controls.

Considerations for Electrical Infrastructure in Earthquake-Prone Regions

UL 9540 mandates BESS installers comply with other standards, as appropriate. Examples include IEEE 693, IEC 60980, and GR-63-CORE.[70] IEEE 693 incorporates methods such as load planning and load damping, which have been proven to mitigate earthquake vibrational damage in other infrastructure. These methods are applied to batteries by extension.[71] IEEE 693 advises the following considerations for low seismic qualifications, which are paraphrased below,[72] and recommends they be used for battery systems under normal conditions.[73]

a) **Anchorage.** Anchorage must withstand 0.2 times the equipment weight plus 0.16 times the weight of the equipment and support. The resultant load shall be combined with the maximum normal operating load and dead load to develop the greatest stress on the anchorage. ASCE 7-22 provides similar guidance for structural integrity.[74]

b) **Defined load path.** The equipment and its support structure shall have a well-defined load path. The manufacturer shall design the equipment such that it adheres to the characteristics described in IEEE 693. The load path shall not include sacrificial collapse members, materials that undergo non-elastic deformations, unrestrained translation, or rotational degrees of freedom, or solely friction-dependent restraints. ASCE 7-22 provides similar guidance for structural integrity.[75]

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[70] UL 9540, Section 37.4.1.
[71] IEEE 693-2018, Section J.8 Frequency or damping modifying devices or attachment.
[72] IEEE 693-2018, Section A.1.1.9 Low seismic qualification level.
[73] IEEE 693-2018, Section J.1.4 Low seismic qualification level.
[74] ASCE 7-22, Chapter 1, Section 1.4.4.
[75] ASCE 7-22, Chapter 1, Section 1.4.1.

c) **Conductor interface**. As discussed above, a slack and/or a flexible connection should be provided between the conductor and equipment. Guidelines for providing conductor slack are given in IEEE 1527.

IEEE 693 provides more general criteria on anchorages for Moderate and High-level seismic qualifications.[76] Such qualifications should prevent BESS from shifting during earthquakes.

a) Moderate qualification level:	0.81 g in each horizontal axis
	0.65 g in the vertical axis
b) High qualification level:	1.62 g in each horizontal axis
	1.30 g in the vertical axis

IEC 60980 and the related IEEE 344 focus on the safety of nuclear generation facilities and should be consulted when designing BESS to support or to supplement nuclear generation facilities in earthquake-prone regions.[77,78] GR-63-CORE concerns protecting telecommunications infrastructure and should be considered when designing BESS to support telecommunications infrastructure or when relevant telecommunications infrastructure is deemed essential to proper BESS operations.[79] When a related standard, such as IEC 60980, IEEE 344, or GR-63-CORE, applies to a development, facilities should be designed and constructed to comply with the most stringent standard.

Vibrational Considerations

Transportation guidelines provide details on BESS vibrational requirements, where the IEEE and UL standards are lacking. DOT regulations defer to the UN Manual of Tests and Criteria, Sub-Section 38.3 (UN38.3) for vibrational requirements governing larger battery systems, such as BESS.[80] UN38.3 prescribes several tests, some of which are deemed relevant to a standard in earthquake-prone regions.

- **Vibrational test.** This test consists of a 15-minute logarithmic sweep from 7 Hz to 200 Hz and back to 7 Hz, 12 times. From 7 Hz to 18 Hz, the acceleration should be 1 g and then should be increased to 2 g at 25 Hz. Afterward, a 2 g acceleration

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[76] IEEE 693-2018, Section A.1.5 Inherently acceptable.
[77] IEEE/IEC 60980-344-2020, *IEEE/IEC International Standard - Nuclear facilities - Equipment important to safety - Seismic qualification.*
[78] IEEE 344-2013, I*EEE Standard for Seismic Qualification of Equipment for Nuclear Power Generating Stations.*
[79] Telcordia Technologies Generic Requirements GR-63-CORE, Issue 3, March 2006.
[80] 49 CFR 173.185..

should be maintained until 200 Hz.[81] Consequently, the baseline vibrational standard for BESS in an earthquake-prone region should be 1g at 7-18 Hz acceleration, and 2 g at 25-200 Hz. Presumably, BESS that meet these criteria will perform properly at 18-25 Hz and >1 g but <2 g.

- **Shock test**. This involves a 50 g acceleration over 11 ms.[82]

The other UN38.3 tests (temperature, short circuit, and overcharge testing) are omitted because those hazards are more likely secondary rather than primary effects of an earthquake, and appropriate best practices are accounted for in other installation and operational guidelines. The UN38.3 Impact/Crush test applies to individual battery cells, rather than to a large battery or entire system, and therefore is not considered relevant here because a deployed BESS container would be crushed before individual cells covered by UN38.3 would be damaged.

In view of what is known about earthquake seismic frequencies and intensities, the UN38.3 vibrational and shock tests are relevant for ensuring a BESS is not damaged by vibrations during an earthquake. While UN38.3 is sufficient to ensure a deployed BESS is not damaged by an earthquake, the same cannot be said for associated components, such as BESS skids, connecting hardware, and nearby infrastructure such as substations. Cable joints pulling apart is a particularly common fault induced by earthquakes.[83]

IEEE 693 provides guidance on damping criteria that these components associated with a BESS should meet.[84] Such criteria are based upon historical earthquake activity in a region[85] and system operating voltages, as shown where IEEE 693 incorporates aspects of IEEE 1527.[86]

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[81] UN 38.3, Section 38.3.4.3.
[82] UN 38.3, Section 38.3.4.4.
[83] Massie A, Watson NR (2011) Impact of the Christchurch earthquakes on the Electrical Power System infrastructure. Bull New Z Soc Earthq Eng 44(4):425–430.
[84] IEEE 693-2018, Section A.1.2.6 Requirements for input motion for time history testing.
[85] IEEE 693-2018, Section A.1.2.6 Requirements for input motion for time history testing.
[86] IEEE 693-2018, Table A.2—Equivalent terminal forces for seismic qualification at performance level from IEEE Std 1527.

Table 1 – Table showing equivalent terminal forces (ETF) recommended on electrical infrastructure as a function of voltage and force direction. IEEE 693 requires ETF standards be divided by 2 for qualification.[87]

Table A.2—Equivalent terminal forces for seismic qualification at performance level from IEEE Std 1527

Voltage class	Direction	ETF	
		Moderate performance level (0.5 g)	High performance level (1.0 g)
< 110 kV < 90 kV DCV for surge arresters	Horizontal	None	None
110 kV to < 230 kV 90 to <180 kV DCV for surge arresters		750 N	1500 N
≥ 230 kV ≥ 180 kV DCV for surge arresters		600 N	1200 N
All	Vertical	None	None

IEEE 693 advises that substation batteries include the following best practices, which can be extrapolated to BESS. These criteria assume an appropriately IEEE 693-qualified rack[88,89] and are cited as follows:[90]

- All connections between cells and multi-cell modules shall be of the bolted type.
- Batteries shall employ spacers to maintain the correct separation between cells or multi-cell units.[91]
- Horizontal restraints on the battery rack shall be designed to prevent the cells from impacting the restraints. The restraints shall be positioned to prevent the cells from falling or toppling from the rack.
- Terminal cable connectors and cable connections between different levels or rows of cells shall have adequate slack to accommodate movement of the rack and conductor anchor points.
- Long cable runs, for example, from the battery's main terminal to the load or between racks on the opposite side of the battery room, shall be supported close to the battery connection to reduce stress on the battery terminal.

[87] IEEE 693-2018, Table A.2—Equivalent terminal forces for seismic qualification at performance level from IEEE Std 1527.
[88] IEEE 693-2018, J.6.2 Station batteries.
[89] IEEE 693-2018, J.6.4 Battery racks.
[90] IEEE 693-2018, J.6.2 Station batteries.
[91] UL 9540 and UL 9540A also provide significant guidance on cell, module, and BESS spacing.

Additionally, NFPA 855 A.4.1.4.1 recommends performing a failure mode and effects analysis (FMEA) when installing a BESS.[92] In earthquake-prone regions, cable joints pulling apart should be closely examined. BESS designs in these regions should electrically isolate disconnected electric cables in order to prevent ground faults or fire risk. BESS designs should also provide redundancy for automatic fire detection and suppression systems and communication and control circuits. Battery management and monitoring systems, including thermal warning systems, must remain in operation to prevent fire risk or other risk of damage to a BESS during and after an earthquake. Further considerations may be borrowed from DOT regulations, which limit the mass of lithium allowed in cells incorporated into the battery system and provide guidance on packaging individual cells.[93] UL 1741 should be considered for distributed BESS grid interconnection hardware.[94]

Structural Concerns

Construction best practices recommend avoiding construction adjacent to or over traces of known active faults.[95] However, that is not always practical. Often, BESS are deployed to ensure grid resilience in earthquake-prone regions, as demonstrated during the 2011 Tohoku earthquake.[96] Other times, the exact locations of fault lines are not well known. For example, the maps in the ASCE 7-22 and the digital hazard tool are very broad, even for well-studied regions like the California coast.[97,98]

For these reasons, BESS developers should never forget basic structural design considerations. The American Institute of Steel Construction considers **Continuity**, **Stiffness and Strength**, **Regularity**, **Redundancy**, and **Defined Yield Mechanisms** key structural considerations in earthquake-prone regions.[99] These considerations are addressed as follows:

- **Continuity.** All of the pieces that comprise a structure must be connected to each other with sufficient strength that when the structure responds to shaking, the

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[92] NFPA 855 A.4.1.4.1.
[93] 49 CFR 173.185.
[94] UL 1741, *Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources*.
[95] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 4.
[96] Aki H (2017) Demand-side resiliency and electricity continuity: experiences and lessons learned in Japan. Proc IEEE 105(7):1443–1455. https://doi.org/10.1109/JPROC.2016.2633780.
[97] ASCE 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Chapter 22: Seismic ground motion, long-period transition, and risk coefficient maps.
[98] https://ascehazardtool.org/.
[99] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, Section 2.10.

pieces do not pull apart and the structure is able to respond as an integral unit. This can generally be achieved by a proper seismic load-resisting system.

- **Stiffness and Strength.** Structures must have sufficient stiffness so that the lateral deformations experienced during an earthquake do not unnecessarily move forces to weaker parts of the structure (*P-Δ instability*) and cause collapse. P-Δ refers to an axial load (*P*) and a lateral displacement (*Δ*). The structure must also be strong enough that relatively small earthquakes do not weaken buildings, bringing them closer to their yield points and more prone to failure during a large earthquake. Methods for seismic strengthening for BESS deployments include anchoring, bracing, replacing live tank circuit breakers with more robust dead tank circuit breakers, hardening, and damping.[100]

- **Regularity.** Structure is configured such that lateral deformations due to shaking avoid excessive twisting and are relatively uniform throughout their heights. Due to the relatively small footprint and short height of BESS containers, this consideration is relatively unimportant but should be addressed in nearby larger and taller substations and transmission infrastructure.

- **Redundancy.** If a large number of seismic load-resisting elements are present in a structure, and some become damaged, others may still provide stability. Due to the relatively small footprint of BESS containers and electrical transmission infrastructure, this consideration is less important for an individual BESS container than it is for a larger building. However, spreading out generation assets (as with DERs) avoids a single point of failure in a power grid. Past studies indicate the optimal DER generator size for post-earthquake resilience is 400 kVA – 500 kVA, at 415 VAC.[101]

- **Defined Yield Mechanisms.** Often termed *capacity design*, the designer must decide which elements of a structure are going to yield under strong earthquake excitation. All other elements of the structure, such as gravity load-carrying beams, columns, and their connections, are proportioned so that they are strong enough to withstand the maximum forces and deformations that can be delivered to them by an earthquake. Due to the relatively small footprint of BESS containers and electrical transmission infrastructure, a recommended approach is to build strong skids and foundations for equipment and for yield mechanisms to install

[100] Wang, Y., Bartlett, S., & Miles, S. (2013). Earthquake Risk Study for the Critical Energy Infrastructure Hub in Oregon. Oregon Department of Geology and Mineral Industries, Open File Report O-13-9, page 11-12.
[101] Massie A, Watson NR (2011) Impact of the Christchurch earthquakes on the Electrical Power System infrastructure. Bull New Z Soc Earthq Eng 44(4):425–430.

excessively long, flexible connecting wires with disconnects.[102] As aforementioned, cable joints pulling apart is a particularly common fault induced by earthquakes.[103] The relatively low cost of these components makes them preferable to other BESS components as yield mechanisms.

Conclusion

In conclusion, developers should avoid siting BESS in regions most prone to earthquake damage where possible. However, this is often not an option due to poor geologic mapping or the specific need for energy storage in these earthquake-prone regions. As earthquakes are geological phenomena, and the primary earthquake hazard is ground shaking, BESS developers should first consult civil engineering guidance, such as ASCE 7-22. Because a BESS is part of a larger electrical grid or microgrid, IEEE 693, especially Annex J, Station batteries and battery racks, must be followed. To the extent IEEE 693 or other considerations merit adding additional operational requirements, BESS and their components should be subjected to these additional operational requirements when being evaluated for UL 9540 and UL 9540A compliance.

Assuming UL 9540 and UL 9540A compliance, damage to local interconnection, transmission, and distribution infrastructure is more likely than damage to actual BESS units. For example, cable joints pulling apart has been cited as the most common earthquake-induced grid failure. These systems should be designed to provide sufficient stiffness and strength to protect BESS units but flexibility and yield mechanisms at locations that enable safe disconnection and easy repair. In remote areas, BESS maintenance equipment and spare parts should be stored close to BESS developments as earthquake damage to transportation infrastructure may impede repair logistics.

[102] American Institute of Steel Construction, *Facts for Steel Buildings No 3: Earthquakes and Seismic Design*, page 16-17.
[103] Massie A, Watson NR (2011) Impact of the Christchurch earthquakes on the Electrical Power System infrastructure. Bull New Z Soc Earthq Eng 44(4):425–430.

About the Author

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As a P.E., he has developed conceptual designs and proposals and managed numerous projects involving grid-scale battery energy storage systems (BESS), energy storage research and development, renewables implementation, and heating, ventilation, and air conditioning (HVAC) projects for energy efficiency measures. Dr. Moye has developed battery emulator software for use in designing new battery cells, predicting long-term battery performance, and microgrid controls decision-making.

Additional Resources

Learn more about the engineering and operational challenges affecting battery energy storage systems, as well as solar and wind systems, in free, one-hour webinar on the Rimkus website. Register to watch the webinar here.