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IEEE 693-Spectrum Compatible Optional Time History Usage Memo

Note. The use of the time histories packaged with this memo is optional, and need not be applied by the user in order to satisfy the requirements of the standard. The recommendations provided in this memo for selection and use of the time histories is optional, and need not be implemented. The user should ensure that the minimum requirements given in IEEE Std 693 are satisfied in order to obtain a valid qualification. Subduction zone earthquakes are not addressed in IEEE Std 693. A time history generated from a subduction seed record is primarily for information (or research purposes); it should not be applied in a seismic qualification test or analysis to claim that the equipment is qualified to resist a subduction zone earthquake.

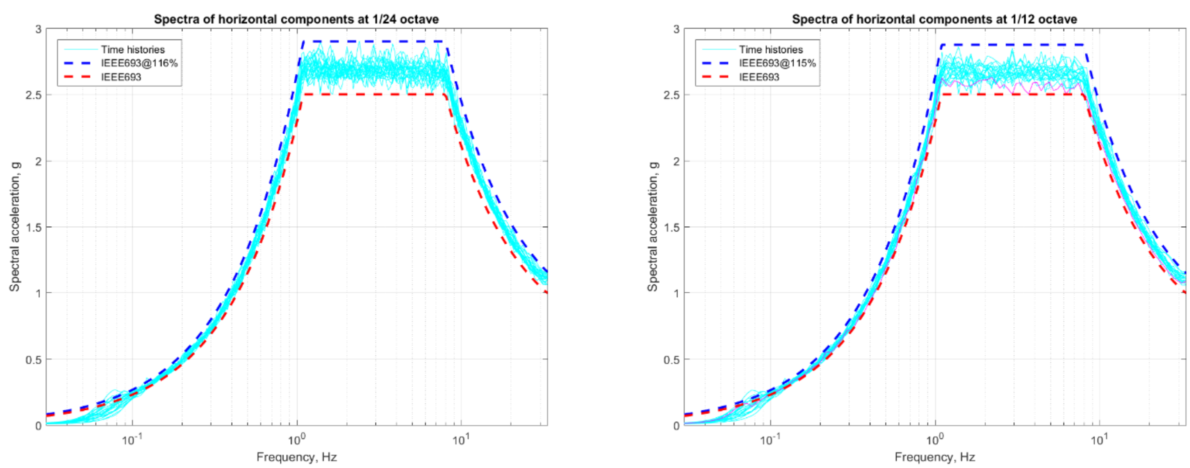
Background and motivation. A study conducted earlier on a number of strong motions [Takhirov et al. 2004] resulted in the development of a three-component strong motion called TestQke4IEEE. Based on a detailed analysis, the best candidate (seed motion) was selected from a set of 35 strong motions. TestQke4IEEE was developed from a historic record obtained during the 1992 Landers earthquake by matching its spectra to the current IEEE Std 693-2005 [IEEE 2005] spectra at 2% critical damping. The spectral matching was performed in a time domain. As a result, the TestQke4IEEE spectra closely matched the IEEE Std 693-2005 [IEEE 2005] spectra starting at about 0.3 Hz. For more than a decade, this strong motion has been successfully used for seismic qualification testing and analysis.

A new study [Takhirov et al. 2017a-c, EPRI 2017] was undertaken to address new developments in IEEE P693/D16 [IEEE 693 WG 2017], account for new strong-motion records from recent major earthquakes, and assess their effects on the spectral demand. The requirements for development of input motion time histories for use in shake-table testing and analysis given in IEEE P693/D16 [IEEE 693 WG 2017] are similar to those given in IEEE Std 693-2005 [IEEE 2005] except that spectral matching is performed at 5% instead of 2% damping, and the requirements for high cycle count and intermediate tolerance band checks have been eliminated. IEEE P693/D16 [IEEE 693 WG 2017] also describes the requirements for the design, analysis, and testing of seismic protective devices and equipment/device or equipment/structure/device systems. Such protected systems are required in IEEE P693/D16 [IEEE 693 WG 2017] to be subjected to multiple spectrum compatible time histories when those systems are qualified by analysis. The histories developed in this study include coverage of low-frequency demand issues so that the new time histories can be used with the new Annex W in IEEE P693/D16 [IEEE 693 WG 2017]. Although subduction earthquakes are specifically excluded from consideration in IEEE P693/D16, a spectrum compatible time history that satisfies the requirements of the draft standard has been developed in this project. This memo summarizes the major deliverables of the study and provides recommendations on using the time histories in seismic qualification by testing and analysis.

A set of eight IEEE 693-spectrum compatible time histories. A set of 410 records obtained during crustal earthquakes was studied to identify the best seed motions to be modified into IEEE 693-spectrum compatible time histories. An additional set of 65 records from subduction type earthquakes was studied to select a seed motion for a subduction type seed motion. In this extensive study, a number of parameters for each strong motion record were computed and analyzed. The parameters included: peak ground acceleration (PGA), peak ground velocity (PGV), root mean square (RMS) acceleration, cumulative energy (CE), specially introduced parameters estimating spectral proximity to the IEEE 693 spectrum, record's durations based on four definitions, number of cycles in each record, and number of cycles in the response of a single-degree-of-freedom system subjected to each record. In addition to the spectral accelerations of each horizontal component of the records, the RotD50 spectral accelerations were analyzed to estimate their proximity to the IEEE 693 spectrum. As a result, four crustal records and one subduction record were selected as seed motions. They were subsequently matched to the IEEE 693 spectrum in time domain by utilizing the commonly used procedure [Abrahamson, N.A. 1992; Al Atik et al 2010]. In addition to these four empirical IEEE 693-compatible time histories, three synthetic time histories were generated by using SimQke [Gasparini and Vanmarcke 1976]. The naming convention for the three-component time histories is presented in Table 1. The spectra of the IEEE 693-compatible time histories tightly envelope the IEEE 693 spectrum starting from 0.13 Hz as presented in Figure 1. They can be downloaded free of charge from the following link: **standards.ieee.org/downloads/693-2018_downloads.zip**.

Table 1. List of IEEE 693-spectrum compatible time histories developed in the study.

Seed motion, if any	Earthquake type	Name of IEEE 693-spectrum compatible time history
El-Centro, CA (1940)	Crustal	TestQke4IEEE5-1
Landers, CA (1992)	Crustal	TestQke4IEEE5-2
Chi-Chi, Taiwan (1999)	Crustal	TestQke4IEEE5-3
El Mayor-Cucapah, Mexico (2010)	Crustal	TestQke4IEEE5-4
CONSTITUCIONS/N4598, Chile, February 27, 2010	Subduction	TestQke4IEEE5-5
NA (synthetic)	NA	TestQke4IEEE5-6
NA (synthetic)	NA	TestQke4IEEE5-7
NA (synthetic)	NA	TestQke4IEEE5-8



(a) (b)

Figure 1. The developed time histories have spectra closely enveloping the IEEE 693 from 0.13 Hz to 33.3 Hz: (a) all spectra fit into a 16% strip above the IEEE 693 High PL at 1/24 octave resolution; (b) all spectra fit into a 15% strip above the IEEE 693 High PL at 1/12 octave resolution.

Filtered versions. Since the enveloping of the IEEE 693 spectrum starts from 0.13 Hz, all time histories developed herein impose a large displacement and velocity demand. It is worth noting that even the original TestQke4IEEE developed earlier [Takhirov et al 2004] also had a large displacement and velocity demand, because it was enveloping the IEEE 693 spectrum from about 0.3Hz. While this is acceptable for analysis, the time histories need to be filtered to meet the limitations of a shaking table. Therefore, two filtered versions were provided [Takhirov et al 2004] for high PL and high RRS testing. The same approach was followed in the current study and several filtered versions accommodating limitations of the majority of the shaking tables worldwide were provided [Takhirov et al, 2017c]. The filtered time histories and the report [Takhirov et al, 2017c] can be downloaded free of charge from the following link: standards.ieee.org/downloads/693-2018_downloads.zip.

Example of usage for seismic qualification by testing. To streamline a process of seismic qualification of high-voltage substation equipment, the IEEE Std 693-2005 [IEEE 2005] and its new draft version (IEEE 693 WG, 2017) permits to use a single time history in the seismic qualification by shaking table testing. In this case, based on the displacement limitations of the shaking table, a three-component time history will be selected from Table 2. Each file name has a value of high-pass filter's corner frequency and the peak displacement imposed by the filtered time history. For example, a file called 'TestQke4IEEE5-4X-0p785hz-4p887in.xlsx' contains a filtered version of the TestQke4IEEE5-4's X-component that is filtered with a corner high-pass filter of 0.785 Hz, which reduced the peak displacement to 4.887-in. For instance, the shaking table at the Pacific Earthquake Engineering Research Center, the University of California, Berkeley has ±5-in displacement limitation in both horizontal directions and ±2-in displacement limitation in the vertical direction. Therefore, the correct selection of the filtered versions of the IEEE 693-spectrum compatible time histories is as follows:

a. TestQke4IEEE5-4X-0p785hz-4p887in.xlsx for the X-axis of the shaking table,
b. TestQke4IEEE5-4Y-0p855hz-4p808in.xlsx for the Y-axis of the shaking table, and
c. TestQke4IEEE5-4Z-1p235hz-1p982in.xlsx for the Z-axis of the shaking table.

Table 2. List of IEEE693-spectrum compatible time histories filtered to meet limitations of majority of shaking tables.

	Displacement limit of shaking table			
TestQke	≤ 30in (750 mm)	≤ 8in (200 mm)	≤ 6in (150 mm)	≤ 5in (125 mm)
TestQke4IEEE5-4X.AT2	TestQke4IEEE5-4X-0p150hz-28p650in.xlsx	TestQke4IEEE5-4X-0p585hz-7p806in.xlsx	TestQke4IEEE5-4X-0p665hz-5p694in.xlsx	TestQke4IEEE5-4X-0p785hz-4p887in.xlsx
TestQke4IEEE5-4Y.AT2	TestQke4IEEE5-4Y-0p155hz-29p040in.xlsx	TestQke4IEEE5-4Y-0p572hz-7p704in.xlsx	TestQke4IEEE5-4Y-0p800hz-5p751in.xlsx	TestQke4IEEE5-4Y-0p855hz-4p808in.xlsx
TestQke4IEEE5-4Z.AT2			TestQke4IEEE5-4Z-0p665hz-5p733in.xlsx	TestQke4IEEE5-4Z-0p785hz-4p860in.xlsx
TestQke4IEEE5-5X.AT2	TestQke4IEEE5-5X-0p175hz-29p628in.xlsx	TestQke4IEEE5-5X-0p560hz-7p764in.xlsx	TestQke4IEEE5-5X-0p665hz-5p826in.xlsx	TestQke4IEEE5-5X-0p805hz-4p866in.xlsx
TestQke4IEEE5-5Y.AT2	TestQke4IEEE5-5Y-0p130hz-29p645in.xlsx	TestQke4IEEE5-5Y-0p550hz-7p753in.xlsx	TestQke4IEEE5-5Y-0p770hz-5p752in.xlsx	TestQke4IEEE5-5Y-0p795hz-4p829in.xlsx
TestQke4IEEE5-5Z.AT2			TestQke4IEEE5-5Z-0p685hz-5p846in.xlsx	TestQke4IEEE5-5Z-0p750hz-4p880in.xlsx
TestQke4IEEE5-6X.AT2	TestQke4IEEE5-6X-0p175hz-29p623in.xlsx	TestQke4IEEE5-6X-0p540hz-7p619in.xlsx	TestQke4IEEE5-6X-0p635hz-5p416in.xlsx	TestQke4IEEE5-6X-0p695hz-4p496in.xlsx
TestQke4IEEE5-6Y.AT2	TestQke4IEEE5-6Y-0p130hz-29p587in.xlsx	TestQke4IEEE5-6Y-0p410hz-7p894in.xlsx	TestQke4IEEE5-6Y-0p755hz-5p530in.xlsx	TestQke4IEEE5-6Y-0p790hz-4p873in.xlsx
TestQke4IEEE5-6Z.AT2			TestQke4IEEE5-6Z-0p570hz-5p743in.xlsx	TestQke4IEEE5-6Z-0p630hz-4p753in.xlsx

Table 2. List of IEEE693-spectrum compatible time histories filtered to meet limitations of majority of shaking tables (continued).

	Displacement limit of shaking table		
TestQke	≤ 4in (100 mm)	≤ 3in (75 mm)	≤ 2in (50 mm)
TestQke4IEEE5-4X.AT2	TestQke4IEEE5-4X-0p980hz-3p870in.xlsx		
TestQke4IEEE5-4Y.AT2	TestQke4IEEE5-4Y-0p965hz-3p878in.xlsx		
TestQke4IEEE5-4Z.AT2	TestQke4IEEE5-4Z-0p885hz-3p897in.xlsx	TestQke4IEEE5-4Z-0p950hz-2p963in.xlsx	TestQke4IEEE5-4Z-1p235hz-1p982in.xlsx
TestQke4IEEE5-5X.AT2	TestQke4IEEE5-5X-0p880hz-3p811in.xlsx		
TestQke4IEEE5-5Y.AT2	TestQke4IEEE5-5Y-0p900hz-3p920in.xlsx		
TestQke4IEEE5-5Z.AT2	TestQke4IEEE5-5Z-0p650hz-3p899in.xlsx	TestQke4IEEE5-5Z-0p760hz-2p800in.xlsx	TestQke4IEEE5-5Z-0p980hz-1p852in.xlsx
TestQke4IEEE5-6X.AT2	TestQke4IEEE5-6X-0p860hz-3p765in.xlsx		
TestQke4IEEE5-6Y.AT2	TestQke4IEEE5-6Y-0p850hz-3p842in.xlsx		
TestQke4IEEE5-6Z.AT2	TestQke4IEEE5-6Z-0p775hz-3p705in.xlsx	TestQke4IEEE5-6Z-0p985hz-2p816in.xlsx	TestQke4IEEE5-6Z-0p980hz-1p963in.xlsx

Example of usage for seismic qualification by analysis. In a case where the equipment is too big for a shaking table test or the testing demand exceeds the physical limitations of a shaking table, a seismic qualification by numerical analysis is recommended. To address the issue of seismic isolation and protection using seismic protective devices, see the special annex W in the new draft version (IEEE 693 WG, 2017).

Since variability in the response of nonlinear systems to different earthquakes is expected, an approach conservatively addressing this issue is needed. One of the possible approaches is commonly based on numerical simulations of the seismic performance of the equipment subjected to several time histories. Depending on the number of time histories used, the seismic qualification results are based on the (1) mean or (2) maximum of all responses. In the former case, the number of time histories is greater than that of the latter. In some practical applications of the approaches, the number of imposed time histories is limited to three for the approach based on the maximum, and to seven for the approach based on the mean response. Eight time histories matched to the same spectrum were used to evaluate these approaches by being imposed on the same nonlinear specimen in shaking table tests. The tests of the nonlinear system show that the response of the latter has large variations even for these time histories matched to the same spectrum [Takhirov et al 2017d].

To follow a conservative approach with consistent performance expectations, the following is recommended (assuming that the IEEE 693-spectrum compatible subduction time history is currently for information only and will be updated in the future):

1. When the mean response of several time histories is selected to follow, a usage of seven IEEE 693-spectrum compatible time histories (all empirical (excluding TestQke4IEEE5-5) and all three synthetic) is recommended;
2. When the maximum response of three time histories is selected to follow, usage of the empirical TestQke4IEEE5-4 and any two synthetic IEEE 693-spectrum compatible time histories is recommended.

All seismic qualification approaches are summarized in Figure 2.

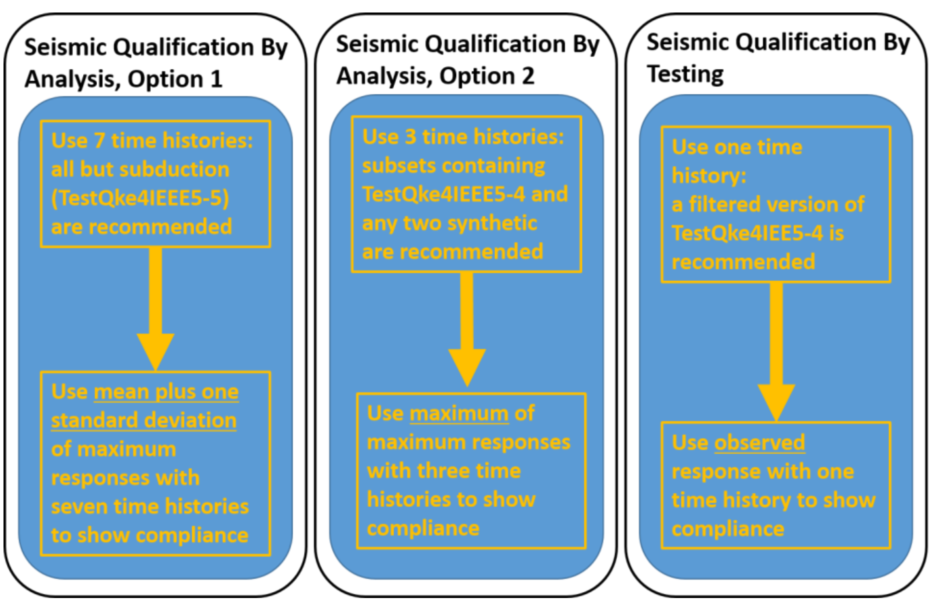


Figure 2. A summary of all approaches (options) for seismic qualification by analysis or testing.

Figure 2 Note: The mean plus one standard deviation concept of Seismic Qualification By Analysis, Option 1 is beyond the requirement of the standard and taking a mean of seven responses is recommended. If all recommendations are followed, the approach based on maximum of three responses has a tendency to be more conservative than the mean of seven responses.

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