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SEISMIC CAPACITY OF SQUG OUTLIERS SUBJECT TO HIGH FREQUENCY ACCELERATIONS – AN UPDATED APPROACH

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ABSTRACT

The Seismic Qualification Utilities Group (SQUG) Generic Implementation Procedure (GIP), (SQUG, 2001) is a widely accepted method of seismic qualification for mechanical and electrical equipment. The GIP was developed by surveying and recording the effects of strong motion earthquakes on various types of equipment mounted in power plants and other industrial facilities. Based on this experience data, the seismic capacity of equipment in each equipment class was developed and is represented by the "Bounding Spectrum". The SQUG process assesses equipment against various screens to check for compliance against the evidence from experience data.

The SQUG GIP capacity-versus-demand screen requires that the seismic demand response spectrum be enveloped, with allowance for small exceedances, by the Bounding Spectrum. If this screen is not met, the equipment is classed as an outlier and is subject to additional evaluation for acceptance. Pending successful outlier resolution, the equipment can continue to the next screen.

Where the design response spectrum exceeds the SQUG Bounding Spectrum, additional costly measures for outlier resolution such as shake table testing or seismic isolation may be required. This is specifically a problem as new probabilistic methodologies for seismic hazard assessment developed subsequent to the publication of the SQUG GIP, have led to the specification of design basis earthquake response spectra, for new nuclear power plants, that have significantly higher frequency content.

This paper aims to update the higher frequency seismic capacity of equipment covered by the GIP based upon research undertaken by the Electric Power Research Institute (EPRI) subsequent to the publication of the GIP. This paper outlines the development of this research, provides a detailed analysis of the seismic capacity of equipment, and develops an argument for adopting this outlier resolution technique.

INTRODUCTION

The SQUG GIP (SQUG, 2001) is a widely accepted method of seismic qualification through experience data and has been used in the UK previously with acceptance by the Office for Nuclear Regulation (ONR). It was developed as a solution to NRC Unresolved Safety Issue USI-A46 and is based upon experience data from various plants, including nuclear, petrochemical, water treatment, and fossil-fuel.

The SQUG GIP is essentially an experience-based screening process that examines each piece of equipment in turn and checks for compliance to various criteria, e.g., seismic capacity versus demand, caveats, anchorage, and interaction effects. The SQUG GIP capacity-versus-demand screen requires that the seismic demand response spectrum be enveloped, with allowance for small exceedances, by the Bounding Spectrum, Reference Spectrum or Generic Equipment Ruggedness Spectrum (GERS), depending on the selected screening method (Method A or Method B). Method A is selected where the demand is characterised by the ground response spectrum, the equipment is mounted below about 12m (40 feet) above the effective grade and the natural frequency is greater than about 8Hz. Method B is selected where the demand is characterised by an In-Structure Response Spectrum (ISRS) and the equipment is located at any elevation and with any natural frequency. If the capacity-versus-demand screen requirement is not met, the component is classed as an outlier and is subject to additional evaluation for acceptance. Pending successful outlier resolution, the equipment can be selected for use.

Equipment is also subject to adherence to the SQUG Caveats, Appendix B of the SQUG GIP. The intent of the caveats should be met when evaluating an item of equipment; the wording of the caveat need not necessarily be met provided the intent is met. Engineering judgment is permitted to determine whether the specific seismic concern addressed by the caveat is met. Moreover, anchorage and interaction effects must also be considered.

Pending a successful SQUG walkdown (i.e., no outliers identified, or all outliers resolved) following installation of the equipment, the equipment can be considered seismically qualified. In accordance with SQUG GIP Section 2.4, the walkdown is to be undertaken by a Seismic Review Team (SRT) consisting of at least two Seismic Capability Engineers (SCEs), one of whom must be a licensed professional engineer.

New probabilistic methodologies for seismic hazard assessment developed subsequent to the publication of the SQUG GIP, led to the specification of design basis earthquake response spectra, for new nuclear power plants, that have significantly higher frequency content.

As part of a joint effort between industry and regulators, EPRI undertook studies to identify the significance of this higher frequency content in the response of nuclear safety-related structures, systems and components (SSCs). These studies have extended the experience of the dynamic response of equipment in higher frequencies.

EPRI 1025287 (EPRI, 2013) was produced prior to detailed testing of vibration sensitive components. However, it has been approved for use by the U.S. Nuclear Regulatory Commission (USNRC). EPRI 1025287 summarises the available data at the time of production, in particular EPRI 1015108 (EPRI, 2007) which outlines that high-frequency vibratory motions are generally not damaging to the large majority of structures, components and equipment. The evidence shows that, in general, it is relative displacement that causes damage to equipment and high-frequency motions are associated with very low, non-damaging relative displacements. The report outlines that a potential exception to this is vibration-sensitive components, such electrical components, whose output signals could be affected by high-frequency vibrations. Further testing has since been completed following the production of EPRI 1025287.

EPRI investigations (EPRI, 2007) also identified that brittle materials such as ceramic insulators and cast-iron elements may be vulnerable to high-frequency motions. These items will be identified as part of the SQUG screening and verification walkdown and should be evaluated separately where relevant.

The following definitions will be used throughout this paper:

- Low-frequency refers to the range less than 10Hz on a response spectrum.
- High-frequency refers to frequencies greater than 10Hz.

This paper aims to update the higher frequency seismic capacity of equipment based upon research undertaken by EPRI subsequent to the publication of the SQUG GIP. This could reduce or remove the need for traditional outlier resolution options where an ISRS is not bounded by the SQUG capacity spectra in the higher frequency ranges.

SQUG SEISMIC CAPACITY

The SQUG seismic capacity is based upon data from four historic earthquakes: San Fernando (1971), Imperial Valley (1979), Coalinga (1983) and Chile (1985) as detailed in (SSRAP, 1991) and listed in Table 1. The SQUG Reference Spectrum is based upon these four historic earthquakes, as illustrated in Figure 1.

Table 1 - List of Representative Response Spectra used to Develop the SQUG Reference Spectrum

Database Site	**Average Horizontal Ground Acceleration (g)**
1971 San Fernando (Sylmar) earthquake	0.5
1979 Imperial Valley (El Centro) earthquake	0.42
1983 Coalinga earthquake	0.5
1985 Chile (Llolleo) earthquake	0.55

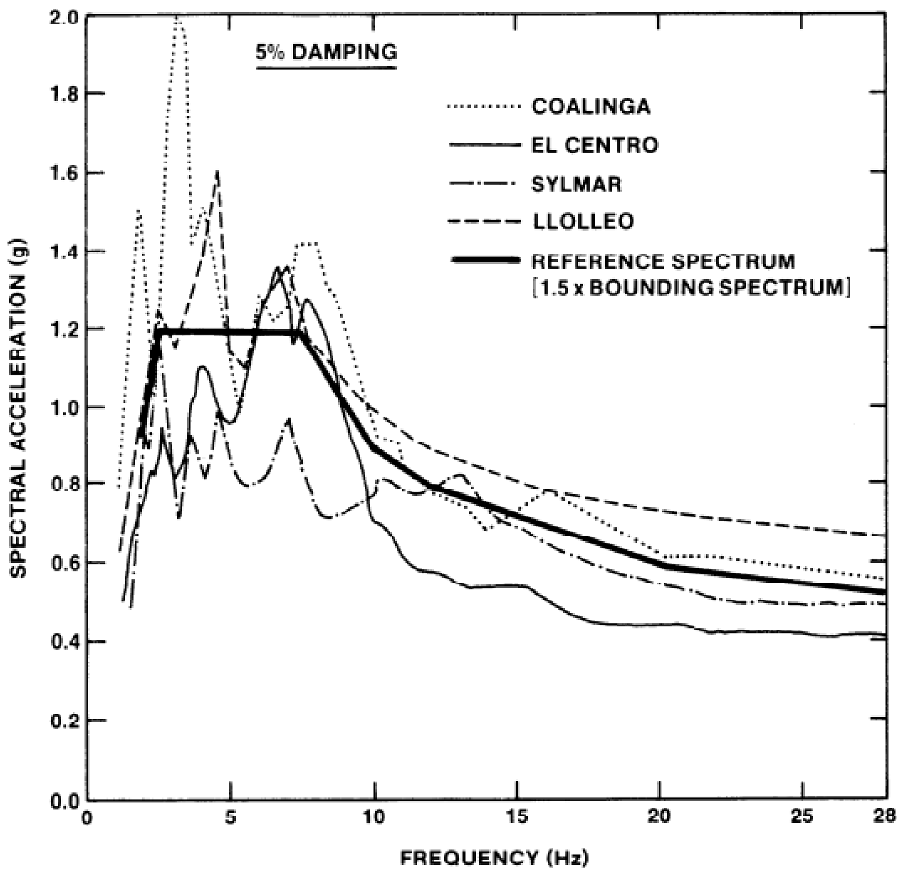

Figure 1 - Basis of Seismic Capacity, taken from Figure A-1 of (SSRAP, 1991)

The Senior Seismic Review and Advisory Panel (SSRAP) judged that a Reference Spectrum which provides a reasonable description of the ground motion level to which the earthquake experience data demonstrate seismic ruggedness, could be obtained by averaging and smoothing these four representative response spectra. A significant number of database equipment in each of the equipment classes was subjected to ground motion similar to that represented by the Reference Spectrum. It should be noted that the average database site spectra in Figure 1 are considered to represent free-field spectra and do not directly relate the seismic input to the database equipment. The database equipment would have seen input which might have been either greater or smaller than the free-field spectra would indicate.

As floor spectra were not available in the database plants and because realistic floor spectra are often not available for nuclear power plants, SSRAP emphasised the comparison of database free-field spectra with free-field ground spectra for nuclear power plants. However, it was recognised that some structural amplification of floor spectra over free-field spectra might occur even at low elevation (generally less than about 12m (40 feet) above grade) in these nuclear power plants and that this amplification might exceed that in the database plants. For this reason, the database spectra were divided by a factor of 1.5 to obtain a Bounding Spectrum for comparison with free-field horizontal ground spectra at nuclear power plants. This 1.5 factor was to account for the possibility that floor spectra within about 12m (40 feet) above grade in the nuclear power plant might be amplified over the ground spectra of the database plants.

Thus, the resultant Bounding Spectrum is directly applicable for comparison with ground spectra. When compared to ISRS, this Bounding Spectrum may be increased by a factor of 1.5 to bring it back up to the Reference Spectrum. Both the Bounding Spectrum and the Reference Spectrum are defined in terms of the 5% damped horizontal response spectrum.

Figure 2 provides the Bounding Spectrum and Reference Spectrum (1.5 x Bounding Spectrum), along with values of frequency (Hz) and spectral acceleration (g) in the range 2Hz to 33Hz. The values at 33Hz are extended out to 100Hz.

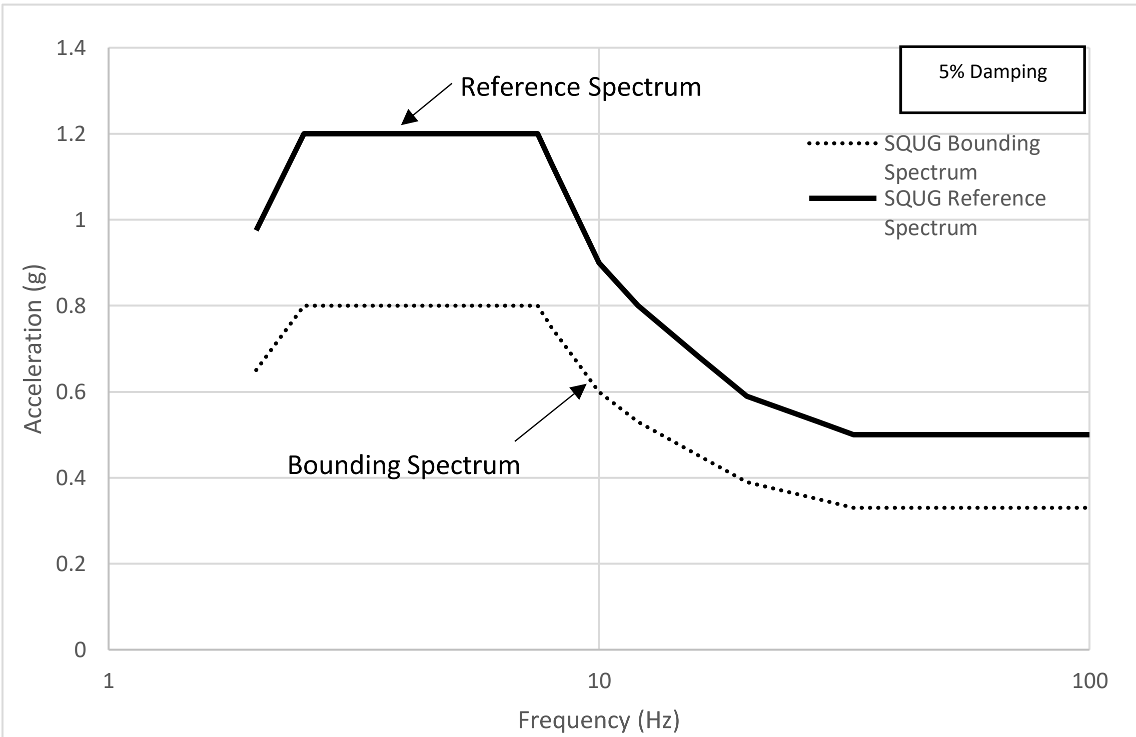

Figure 2 - SQUG Reference Spectrum and Bounding Spectrum (SQUG, 2001)

CURRENT METHODOLOGY FOR OUTLIER RESOLUTION

An outlier is a piece of equipment which does not meet all the screening guidelines provided in the SQUG GIP. Where outliers are identified, additional work in the form of outlier resolution is required to seismically qualify the equipment. Section 5.3 of the GIP outlines the following methods of outlier resolution:

1. Expansion of equipment class on a specific area of interest
2. Modification of equipment to bring it within the scope of SQUG
3. Replacement of equipment with pre-qualified or SQUG compliant equipment
4. Detailed analysis to more carefully evaluate equipment capacity or demand
5. In-situ testing of equipment areas of interest
6. Shake table testing of equipment
7. Determine alternative method for safe shutdown of plant
8. Use information not available at the time of the Screening and Verification Walkdown

The above traditional outlier resolution methods can be time consuming, resource intensive and increase seismic qualification costs. Therefore, there are significant benefits associated with developing a further outlier resolution method for the seismic capacity-versus-seismic demand screen.

DISCUSSION

The various documents examined as part of this paper provide a pathway for extension of the SQUG Reference Spectrum (and therefore Bounding Spectrum) peak spectral acceleration in the high-frequency range.

The SQUG GIP (SQUG, 2001) capacity-versus-demand screen requires that the seismic demand response spectra be enveloped, with allowance for small exceedances, by the Bounding Spectrum, Reference Spectrum or GERS, depending on the screening method used (Method A or Method B). If this requirement is not met, the component is an outlier. The outlier is subject to additional evaluation for acceptance. For example, the small exceedance criteria in the GIP is conservative.

Subsequent to publication of the SQUG GIP (SQUG, 2001) and EPRI NP-6041 (EPRI, 1991) the new probabilistic methodology for seismic hazard assessment led to specification of design basis earthquake response spectra for new nuclear plants that had significantly higher frequency content. This was identified as a generic issue, GI-199, (USNRC, August 2010) and led to a joint effort between industry and regulators to research the significance of these high-frequency exceedances for safety-related structures, systems and components. GI-199 was later subsumed into the post-Fukushima Near-Term Task Force Recommendation 2.1.

The results of the GI-199 research efforts were published in EPRI 1015108 (EPRI, 2007) and EPRI 1015109 (EPRI, 2007). EPRI 1015108 examined the sensitivity of structures, systems and components (SSCs) to seismic motions in the greater than 10Hz frequency range. The results showed that these motions are potentially significant only for certain high-frequency sensitive components. In general, it was found that it is relative displacement that causes damage to structures, systems and components, except for certain sensitive components, and high-frequency motions are associated with low, non-damaging relative displacements. EPRI 1015109 provided methods to identify and evaluate high-frequency sensitive components.

The industry plan for response to NTTF 2.1, endorsed by the USNRC, was published in EPRI 1025287 (EPRI, 2013). The report summarised the results of the first phase of testing in the High Frequency Program. Phase 1 of testing concluded that the sensitivity of contact devices to high-frequency vibrations is generally device specific and that further testing, Phase 2, was required to provide more general conclusions.

Results of the EPRI High-Frequency Program, Phase 1 and Phase 2, were published in EPRI 3002002997 (EPRI, 2014). The testing program considered the previous results developed for the GERS, referenced in the SQUG GIP. At the time of development, the GERS testing was completed predominately in the low-frequency range, 4-16Hz. The primary conclusion of the testing program was that whilst some components are sensitive to vibration, there was no unique high-frequency sensitivity identified. Some components are sensitive to vibration in general, but sensitivity is not increased in the high-frequency region. Moreover, in all cases where chatter occurred in a high-frequency test, chatter also occurred in the low-frequency test at an equal or lower input motion level.

Further guidance for high-frequency capacity determination is given in EPRI 3002004396 (EPRI, 2015) and Section 5.3 of that report discusses capacity determination. If capacity is known in the low-frequency region it may be used as the capacity in range above 16Hz. In other words, the peak spectral acceleration capacity based on low-frequency testing may be extended into the high-frequency region and is conservative with respect to high-frequency test results.

The peak spectral acceleration for the original GERS testing had an upper frequency limit of 16Hz and the new testing was completed for the 16Hz to 40Hz range, justifying the extension of the GERS peak capacity above 16Hz. However, the peak of the SQUG Reference Spectrum is between 2.5Hz and 7.5Hz. It has been judged that the gap between the 7.5Hz and 16Hz is insignificant to the proposed procedure as it has been shown that, in general, it is relative displacement that causes damage to equipment and the capacity in the higher frequency ranges is equal to, if not greater than the capacity in the lower frequency ranges. Displacements decrease as the frequency increases and therefore equipment capacity in the 2.5Hz-7.5Hz range would govern the higher frequency capacity and the range between 7.5Hz to 16Hz could be considered within the spectral acceleration comparison. Similarly, it has been judged that for motions above the testing limit of 40Hz, the lower frequency capacity of the SQUG Reference Spectrum will be applicable as the relative displacements are significantly lower in the ranges above 40Hz. It is worthwhile to note that Phase 1 testing was completed up to 64Hz and no concerns were identified, as reported in EPRI 3002004396 (EPRI, 2015).

Although the testing primarily focussed on electrical components, the proposed methodology can be applied to all types of equipment covered by the SQUG GIP. As discussed above, the evidence has shown that in general it is relative displacement that causes damage to equipment. This is consistent with the findings of EPRI 1015108 (EPRI, 2007).

What this means for use of the SQUG GIP (SQUG, 2001) is that for the capacity-versus-demand screen, the spectral acceleration in the 2.5Hz-7.5Hz range of the Reference Spectrum, may be used for comparison to the peak spectral acceleration of the seismic demand spectra, for all frequencies above 2.5Hz. This could be done as an outlier resolution or as meeting the intent of the caveat. The SRT should have knowledge of the above reports when applying this approach.

In addition, EPRI have been consulted regarding this approach and outlined that EPRI 1019200 (EPRI, 2009) discusses the extension of the SQUG Bounding/Reference Spectrum plateau region into the higher frequencies. The approach discussed in EPRI 1019200 has been endorsed and accepted by the U.S. Nuclear Regulatory Commission (NRC) under the approval of EPRI 3002000704 (EPRI, 2013) as advised by EPRI.

PROPOSED OUTLIER RESOLUTION

It is proposed that seismic capacity versus demand outliers can be resolved by comparing the peak spectral acceleration of the seismic capacity spectrum against the peak spectral acceleration of the seismic demand spectrum in the frequency ranges above 2.5Hz i.e., a comparison between the peak of the Bounding/Reference Spectrum and the peak of the relevant SSRS above 2.5Hz.

The first step in the SQUG screening process is to check that seismic capacity exceeds demand. Should the demand exceed capacity then an alternative method for capacity versus demand comparison is required. It is proposed that a comparison of peak spectral accelerations can provide the alternative method of capacity versus demand comparison.

CONCLUSION

This paper has reviewed recent developments undertaken by EPRI examining the effects of high-frequency accelerations on mechanical and electrical equipment. As a result of this review, this paper has proposed an option for outlier resolution which can be used as part of the SQUG seismic capacity-versus-demand screen.

The developments, which have been undertaken since the publication of the SQUG GIP, provide new experience and data from recent earthquakes and shake table testing. These data have been endorsed and accepted by the NRC for the justification of seismic qualification of equipment following revised site specific ISRS which contain higher frequency motions.

EPRI report 1015108 examined the effects of frequencies greater than 10Hz on mechanical and electrical equipment using analytical and empirical evidence. The report provided a basis for all further research and concluded that short duration, high-frequency excitations do not have a significant impact on the majority of mechanical and electrical equipment, with the exception of some potential high-frequency sensitive equipment such as relays. The evidence presented indicated that, in general, it is relative displacement that causes damage to equipment and high-frequency motions are associated with very low, non-damaging relative displacements.

Following on from previous research, EPRI developed a list of potential high-frequency excitation sensitive subcomponents and created a High Frequency Test Program to identify criteria for comparison of fragility levels. This program was completed over two phases, reported in EPRI 3002002997, and concluded that where chatter occurred in a high-frequency test, chatter also occurred in the low-frequency test at an equal or lower input motion level. The reports outlined that test capacity values from the shake table testing completed as part of the EPRI GERS and SQURTS programs can be extended from the 4-16Hz range to the high-frequency range up to 40Hz. These GERS data are the same GERS data referenced in the SQUG GIP.

A summary of EPRI's High Frequency Test Program, provided in EPRI 3002004396, concluded that new data have demonstrated that equipment have greater capacity against high-frequency excitations than low-frequency excitations. Therefore, by comparing the peak spectral acceleration of the capacity spectrum in the low-frequency ranges against the peak spectral accelerations of the demand ISRS in the frequency ranges above 2.5Hz, capacity-versus-demand outliers can be resolved. Provided the peak spectral acceleration of the SSRS is lower than that of the SQUG Reference Spectrum, the capacity versus demand outlier can be resolved.

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