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# EVALUATION OF SEISMIC CAPACITY OF NUCLEAR INSTALLATION EQUIPMENT BASED ON SEISMIC EXPERIENCE DATA

**Ayhan Altinyollar[1], Ovidiu Coman[2], Paolo Contri[3], Gregory S. Hardy[4], Tatsuhiro Yamazaki[5]**

[1] Nuclear Safety Officer, International Atomic Energy Agency, Vienna, Austria (a.altinyollar@iaea.org)
[2] Senior Nuclear Safety Officer, International Atomic Energy Agency, Vienna, Austria (o.coman@iaea.org)
[3] External Events Safety Section Head, International Atomic Energy Agency, Vienna, Austria (p.contri@iaea.org)
[4] Senior Principal, Simpson Gumpertz & Heger, CA, USA (GSHardy@sgh.com)
[5] Mechanical Engineer, Toyama, Japan (tatsu17162@gmail.com)

## ABSTRACT

Since 2005 the International Atomic Energy Agency (IAEA) in cooperation with some National Services operates an external event alert system. The alert system is able to identify potential damaging scenarios to nuclear installations related to external events. For severe events, the International Emergency Centre of the IAEA has procedures to subsequently alert the affected country. A new system has been under development since 2020.

In connection to the earthquake module of the alert system, IAEA launched a project to collect the records of the "stressors" affecting items of nuclear installations (structures, systems and components-SSCs) in the aftermath of earthquake events occurred in the region of nuclear (and non-nuclear) installation sites and populate a database with data on the affected items and the type of response which has occurred. The project also aims to develop a procedure for the use of new seismic experience data in seismic evaluation of nuclear installations by similarity, supported by the database of records and evidence.

Evaluation of seismic capacity of SSCs based on seismic experience data provides a significantly cheaper evaluation approach as compared with analysis and testing, and more insights into the safety margin of the equipment beyond the design basis. For seismic events, the process is addressed in IAEA (2021) and IAEA (2009).

The seismic evaluation procedure relies heavily upon new experience data from large earthquakes in Japan. A new set of similarity criteria have been developed in order to demonstrate the applicability of the new data from Japan to other international manufacturers' equipment.

## INTRODUCTION

The nuclear installations shaken by an earthquake ground motion accommodate valuable earthquake experience data. Seismic instrumentation systems installed in the free-field and in-structures of nuclear installations record the earthquake motions. Response of structure, system and components of the installation, either their failures or success behaviour, need to be collected and assessed. Seismic resistance, seismic margin, and damage modes of structure, systems, components should be assessed as a post-earthquake action. IAEA (2009) states that "All available information relating to actual earthquake experience at the site or at other industrial installations in the region should be obtained.". It also states that "Evaluation of the seismic capacity or fragility of systems and components should rely to a significant extent on earthquake experience data and test data. There is already a significant amount of data that have been obtained, evaluated, reviewed and incorporated into procedures.". Detailed guidance on conducting seismic safety evaluation programmes for existing nuclear installations are provided in IAEA (2020).

The use of the earthquake experience data in evaluation and the qualification (with more restrictions) of structure, system and components of existing and new nuclear installations has many advantages as it can be directly applied with ease in short time, high reliability, and least cost implications. Initially, earthquake experience data was developed and used to "verify" the capability of equipment, components, and distribution systems to perform their required functions when subjected to earthquake motions compatible with the SSE. Verification has evolved to qualification over the decades. For existing nuclear installations, seismic qualification and evaluation may be needed for replacements, upgrades, and new equipment/components for which seismic experience data is ideally suited.

The Seismic Qualification Utility Group (SQUG) was formed in 1982 and developed a database using earthquake experience and test experience to address Unresolved Safety Issue (USI) A-46. The United States Nuclear Regulatory Commission (U.S.NRC) categorized approximately 70 NPP units in the United States as "USI A-46 plants" in NUREG-1030. SQUG lead the efforts to collect data over the decades since its origin. Investigations of the behaviour of non-nuclear heavy industrial facilities when subjected to strong earthquake ground motions were performed and documented in a manner acceptable to the SQUG database peer review team and, consequently, if the data met the requirements established by the peer review team the earthquake experience data was added to the EPRI-SQUG database. International data continues to be added to the EPRI-SQUG Database. In addition, international institutions are developing Earthquake Experience Databases in parallel to the EPRI-SQUG Database: for example, EDF-France and CRIEPI-Japan.

The use of earthquake experience data for the seismic qualification of electrical and mechanical equipment has its origin in the NRC research program associated with USI A-46. The SQUG, with contributions from experts, developed the first version of the Generic Implementation Procedure (GIP) to utilize the earthquake experience data to demonstrate capacity of equipment and components. Electric Power Research Institute (EPRI) has taken over leadership and execution of the "SQUG" activities including the EPRI-SQUG Seismic Experience Database. GIP proposes a cost-effective way to seismically verify different classes of standard electrical and mechanical equipment, and cable tray, conduit, heat exchangers and tanks based on earthquake and generic testing experience in SQUG GIP (1992) and (2001).

The DOE Seismic Evaluation Procedure (DOE Report DOE/EH-0545) is adapted from the SQUG GIP in 1997 by incorporating DOE-specific requirements and guidance and broadening the application of the experience-based methodology to equipment classes not contained in the SQUG GIP (1992) and (2001). Masopust (1997) developed GIP-WWER in 1997 to verify seismic adequacy of the safe shutdown mechanical, electrical equipment and distribution systems of operating or constructed WWER-type NPPs, namely WWER-440/213.

IAEA launched a project on evaluation of seismic capacity of nuclear installation equipment based on seismic experience data in 2020. Project aims at developing guidelines and procedures for data collection, collection of new seismic experience data (earthquake experience and test data), and application of new seismic experience data in seismic evaluation of nuclear installations following existing methodologies.

## RECENT EARTHQUAKE EXPERIENCE DATA COLLECTION

Owners/providers of earthquake experience data are typically, nuclear and non-nuclear utilities, owners of plants which experienced significant earthquakes and recorded relevant data on SSC performance. The data is usually compiled through surveys of nuclear power plants, fossil-fuel and natural gas power plants, hydroelectric power plants, oil processing and refining facilities, water treatment and pumping stations, natural gas processing and pumping stations, manufacturing facilities and large commercial facilities.

There is already a significant amount of data that have been obtained, evaluated, reviewed and incorporated into procedures for seismic qualification at Design Basis Earthquake (DBE) levels and seismic evaluation for Beyond Design Basis Earthquake (BDBE) levels. Up to the 2000s, the vast majority of the earthquake experience data was obtained from non-nuclear facilities experiencing earthquakes. The non-nuclear facilities were heavy industrial and commercial facilities with equipment, components, and distribution systems the same or similar to those in nuclear facilities. Starting in the first decade of 2000, in addition to non-nuclear facilities, nuclear facilities (especially NPPs) were experiencing strong earthquake ground motions. The dominant location of such cases was in Japan. Earthquake experience data from Japan has been continually used to benchmark other data especially for the EPRI-SQUG database.

Earthquake experience data is organized into equipment classes. An equipment class is characterized by a group of similar equipment that share a range of physical, functional, and dynamic characteristics and whose performance in earthquakes has been demonstrated.

In all cases, the applicability of these earthquake experience data needs to be verified with regard to the specific nuclear installation being evaluated. In addition, specific issues to be considered are similarity, anchorage, peripheral attachments to equipment/components (e.g. I&C connections, power cables, piping, tubing, etc.), and seismic spatial interaction hazards – proximity and impact causing malfunction, impact from failed items, and flooding/spraying, etc.

Although significant seismic experience data has been collected and implemented in procedures for use in qualification and evaluation of equipment, components, and distribution systems, there is a need to collect additional seismic experience data to supplemental to existing sets of data, particularly data from strong motion earthquakes experienced in Japan that have affected NPPs.

Earthquake experience data have generally been collected in the detail and quality necessary to provide the information required for application to individual items. The earthquake experience data collection process includes stages such as: initiation of the process, walkdown planning, conduct of walkdown and documentation (see Figure 1). The data has traditionally been collected for an earthquake that occurred in the recent past. However, some of this data collection can be useful to establish the characteristics of the equipment in advance of a future earthquake. Obviously, the earthquake damage and the earthquake response can only be established following the earthquake.

Recently IAEA compiled earthquake experience data collected from Japanese nuclear power plants (NPPs); namely Kashiwazaki-Kariwa NPP Units 1, 6 and 7, Tokai NPP unit 2 and Onagawa NPP Units 1, 2, and 3. This data has been extracted from the Japan Nuclear Regulation Authority (NRA) database (open source data) (https://www.nsr.go.jp). Kashiwazaki-Kariwa NPP experienced the strong shaking in Niigataken-chuetsu-oki (NCO) Earthquake (Mw=6.8) in July 2007. Onagawa NPP experienced the strong shaking in Miyagi Ken Oki Earthquake (Mw=7.2) in 2005, Great East Japan Earthquake (GEJE) (Mw=9.0) in March 2011, and Miyagi Ken Oki Earthquake (Mw=7.1) in April 2011 (after shock of GEJE). Tokai NPP also experienced the shaking in the GEJE. Table 1 summarizes compiled earthquake experience data from Japan. Equipment categories are similar to the ones in SQUG GIP database.

The following information for each equipment is compiled:

- General information such as plant or facility name, unit #, building, experienced earthquake, plant or facility operating status during earthquake;
- Equipment identification (equipment ID, manufacturer, model number, weight, height, capacity, functions to be performed, equipment class, seismic class, safety class, equipment location within the building, etc.);
- Support details of equipment, e.g., anchorage; peripheral attachments (e.g., I&C, piping, HVAC duct, and power lines);
- Seismic interactions;

- Earthquake excitation at equipment support locations (the nearest floor response spectra) and at the ground motion level;
- Seismic performance; failed or succeeded performing its required function; identify function to be performed by the equipment/component during and/or after the shaking;
- Representative photographs and drawing showing the equipment and overall view;
- Other supporting or relevant documents.

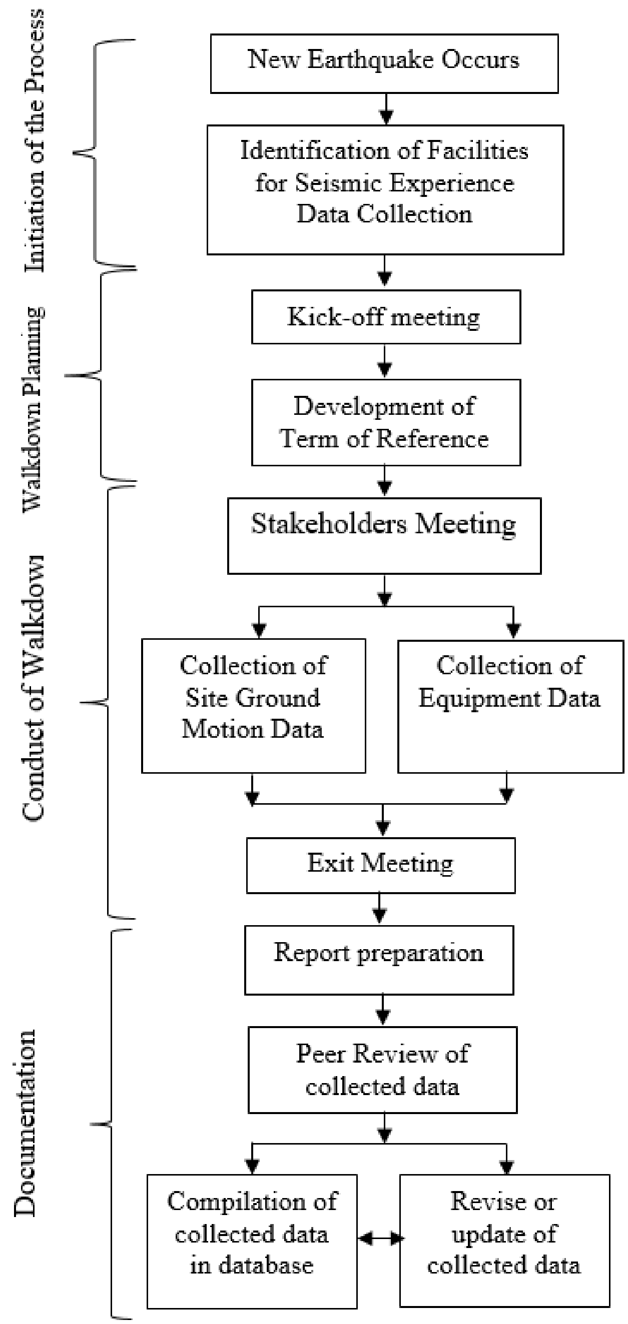



Figure 1. Earthquake experience data collection process.

Table 1: List of earthquake experience data compiled from Japan NRA database.

| No. | Equipment Class | Name of Nuclear Power Plant | Experienced Earthquake | Number of equipment |
|---|---|---|---|---|
| 1 | Fans | KK-6 (Kashiwazaki-Kariwa Unit 6) | NCO (Niigatakenn Cyuetsu Oki Earthquake, 16.07.2007, Mw=6.8, Japan) | 21 |
| | | KK-7 (Kashiwazaki-Kariwa Unit 7) | NCO | |
| | | T-2 (Tokai Unit 2) | GEJE (Great East Japan Earthquake, 11.03.2011, Mw=9.0, Japan) | |
| | | O-1 (Onagawa Unit 1) | GEJE | |
| | | | MKOE (Miyagi Ken Oki Earthquake, 16.08.2005, Mw 7.2, Japan) | |
| | | | MKOE-GEJE (Miyagi Ken Oki Earthquake, 07.04.2011, after shock of GEJE, Mw=7.1) | |
| | | O-2 (Onagawa Unit 2) | GEJE | |
| | | | MKOE | |
| | | | MKOE-GEJE | |
| | | O-3 (Onagawa Unit 3) | GEJE | |
| | | | MKOE | |
| | | | MKOE-GEJE | |
| 2 | Air compressor | KK-6, 7 | NCO | 12 |
| | | O-1, 2 | GEJE, MKOE, MKOE-GEJE after shock | |
| 3 | Battery | KK-6, 7 | NCO | 13 |
| | | T-2 | GEJE | |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 4 | Battery Charger and Inverter | KK-1, 6, 7 | NCO | 19 |
| | | T-2 | GEJE | |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 5 | Air Handler | KK-1, 6, 7 | NCO | 35 |
| | | T-2 | GEJE | |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 6 | Chillers | KK-1 | NCO | 9 |
| | | O-1 | GEJE, MKOE, MKOE-GEJE after shock | |
| 7 | Transformer | KK-1, 7 | NCO | 26 |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 8 | Vertical Pumps | KK-6, 7 | NCO | 36 |
| | | T-2 | GEJE | |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 9 | Horizontal Pumps | KK-6, 7 | NCO | 42 |
| | | T-2 | GEJE | |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 10 | Motor Generator | KK-6, 7 | NCO | 2 |
| 11 | Motor Control Center | T-2 | GEJE | 38 |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 12 | Low Voltage Switchgear | T-2 | GEJE | 18 |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 13 | Medium Voltage Switchgear (Metal | T-2 | GEJE | 15 |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 14 | Distribution Panels | KK6 | NCO | 20 |
| | | O-1, 2, 3 | GEJE | |
| 15 | Motor operate Valves | KK-6, 7 | NCO | 103 |
| | | T-2 | GEJE | |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 16 | Air operated valves | KK-6, 7 | NCO | 104 |
| | | T-2 | GEJE | |
| | | O-1, 2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 17 | Engine Generator | KK-6, 7 | NCO | 9 |
| | | T-2 | GEJE | |
| | | O-2 | GEJE, MKOE, MKOE-GEJE after shock | |
| 18 | Instrument racks | KK-6 | NCO | 21 |
| | | O-2 | GEJE, MKOE, MKOE-GEJE after shock | |
| 19 | Control and Instrumental | KK-6 | NCO | 25 |
| | | O-2, 3 | GEJE, MKOE, MKOE-GEJE after shock | |
| 21 | Low Pressure Storage Tank | KK-6, 7 | NCO | 23 |
| | | T-2 | GEJE | |
| | | O-2 | GEJE, MKOE, MKOE-GEJE after shock | |
| 22 | High Pressure Tanks and Heat exchangers | KK-1, 7 | NCO | 21 |
| | | T-2 | GEJE | |
| | | O-2 | GEJE, MKOE, MKOE-GEJE after shock | |
| 23 | Strainer | KK-6, 7 | NCO | 24 |
| | | T-2 | GEJE | |
| | | O-2 | GEJE, MKOE, MKOE-GEJE after shock | |
| | | | Total number of equipment | 636 |

## EXISTING METHODOLOGY FOR USE OF EARTHQUAKE EXPERIENCE DATA FOR SEISMIC SAFETY EVALUATION OF NUCLEAR INSTALLATION EQUIPMENT

To implement the use of earthquake experience data for assessing the seismic adequacy of a particular equipment component requires that the level of seismic excitation experienced by the components in the database during the earthquakes be estimated. It also requires that the equipment being evaluated and the set of data within that equipment class which underwent the strong motion earthquake have similar physical and functional characteristics and have similar support or anchorage characteristics. In the case of active items, it is also necessary in general to show that the item in the earthquake performed the same functions during or following the earthquake.

Seismic safety qualification ("screening evaluation") according to SQUG GIP (1992) involves the following steps:

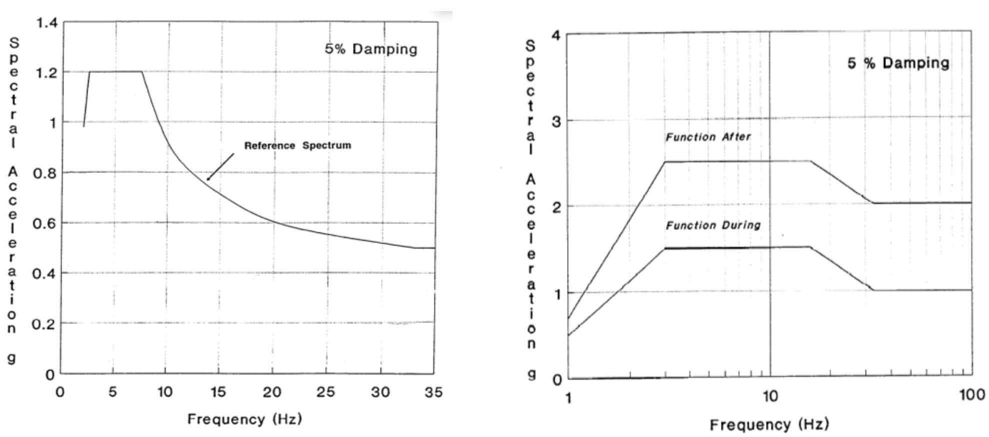
- Seismic capacity needs to be greater than seismic demand;
- Similarity to the equipment in the seismic experience databases needs to be checked (checking of caveats, based on walkdown and information available from documentation);
- Anchorage of equipment needs to be adequate (combination of inspection, analysis and judgment, based on walkdown and documentation);
- Potential seismic interactions need to be evaluated based on a walkdown.

SQUG GIP uses earthquake experience database for seismic capacity vs. demand screening. The seismic capacity of equipment is defined by the bounding spectrum if the applicable inclusion rules and caveats for the earthquake experience equipment class are met.

DOE and GIP-WWER procedures are modifications of the SQUG GIP and also include those same screening evaluations.

## COMPARISON OF CAPACITY SPECTRA

The first step in performing a safety evaluation based on the use of seismic experience data is performing the seismic capacity vs. seismic demand screening. For equipment being evaluated, seismic capacity can be represented by the SQUG reference spectrum documented in the SQUG GIP (1992) which is based on several large earthquakes which formed the basis for the SQUG experience database (see Figure 2 (on the left)). Seismic capacity of the equipment can also be represented by Generic Equipment Ruggedness Spectra (GERS) (see Figure 2 (on the right)), if available, based on data from seismic qualification testing




| Frequency (Hz) | 2.0 | 2.5 | 7.5 | 8.0 | 10 | 12 | 16 | 20 | 28 | 33 |
|---|---|---|---|---|---|---|---|---|---|---|
| Spectral Acceleration (g) | .98 | 1.2 | 1.2 | 1.13 | .90 | .80 | .68 | .59 | .53 | .50 |

| Frequency (Hz) | 1 | 3 | 16 | 33 |
|---|---|---|---|---|
| Function After (g) | 0.7 | 2.5 | 2.5 | 2.0 |
| Function During (g) | 0.5 | 1.5 | 1.5 | 1.0 |

Figure 2. Reference spectrum based on earthquake experience data of SQUG GIP (on the left) and GERS for motor control centre (on the right), (DOE Report DOE/EH-0545).

of nuclear power plant equipment. GERSs are developed for various equipment classes and generally have different caveats and restrictions from the classes using earthquake experience data. In existing seismic experience procedures, both reference spectrum or GERS can represent equipment seismic capacity if the applicable inclusion rules and caveats for the earthquake experience equipment class are met.

Within the framework of the subject IAEA project, floor response spectra are calculated for each equipment listed in Table 1 from the earthquake time histories associated with the nearest recordings at the facility floors. None of this equipment experienced failures due to the earthquake. Floor response spectra for each equipment class are developed for horizontal and vertical components.

Figure 3 presents a comparison picture of all floor response spectra (FRS) of in-structure records for the motor control centres collected during several Japanese earthquakes (See Table 1). Figure 3 also includes the reference spectrum and the GERS for Motor Control Centre (MCCs) which are documented in the SQUG GIP. SQUG GIP reference spectrum and GERS represent the seismic capacity of a MCC if the MCC meets the caveats for use of the Reference Spectrum and SQUG GERS respectively. MCCs were not damaged during listed earthquakes in Table 1. So, those FRSs can be taken as minimum capacity of the MCC. EPRI Report NP-5223-SL presents GERS capacity; namely 'Function After" and "Function Before" for MCC (see Figure 2 (on the right)). The "Function After" GERS can be used if it can be demonstrated that the starters, switches, and relays on the MCC that are critical to its safety function can be reset by operators following the earthquake. The "Function During" GERS can be used only if all the relays within the MCC have GERS greater than 4.5g within the amplified spectral region. Several of the MCCs listed in Table 1 have FRS which exceed the Reference Spectrum and GERS seismic capacity spectra which means those specific MCC have demonstrated higher capacity in specific frequency regions of the spectra. IAEA is currently verifying that the MCCs within Table 1 were all monitored for performance during the earthquake event and also reviewing similarity of these Japanese MCCs to other internationally made MCCs used at member states NPPs.

## CONCLUSION

This paper summarizes the efforts in the IAEA project on collection of seismic experience data and evaluation of seismic capacity of nuclear installation equipment based on seismic experience data. It discusses the usability and applicability of compiled seismic experience data from Japanese nuclear power plants. It is expected to be published in an IAEA TECDOC in 2023.

This new data from Japan nuclear installations is similar to shake table test data since in-structure records are available near to equipment and the performance of the equipment is well documented. In this regard, making a comparison of FRS for equipment class with the corresponding GERS class can be achievable.

The detailed evaluation of the new seismic experience data is currently being conducted. A key consideration is the applicability of that Japanese data to similar equipment manufactured in other countries. The IAEA project is actively reviewing this topic.

IAEA project has also been addressing the following issues:

- Necessity of new seismic experience data;
- Benefit of using high quality and high ground motion data;
- Specific floor response spectra at equipment level;
- Seismic code and manufacturing standard;
- How to use new earthquake experience data for safety evaluation.

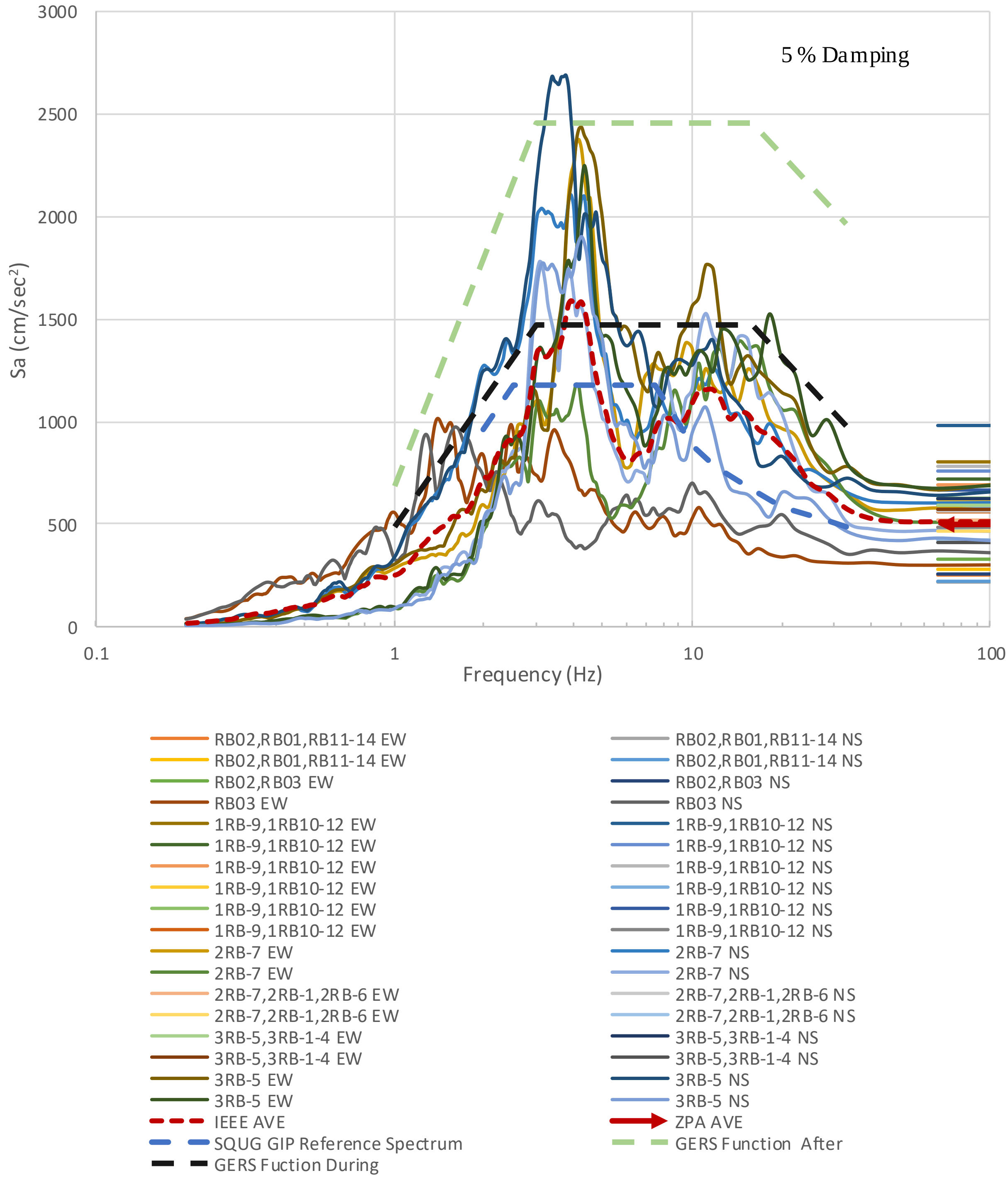



Figure 3. Comparison of response spectra for motor control centre.

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