



FURTHER DEVELOPMENT OF ISO 4917 STANDARD SERIES FOR THE DESIGN OF NUCLEAR POWER PLANTS AGAINST SEISMIC EVENTS

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ABSTRACT

The idea of developing a comprehensive ISO Standard Series for the design of nuclear power plants against seismic events – the ISO 4917 – was motivated under the impression of the catastrophic event in Fukushima in the year 2011 and in regard of many nuclear newcomer countries. The working basis for this new standard series was the German Safety Standard Series KTA 2201. These standards are the basis for the design and approval procedures of nuclear power plants in Germany and abroad. All parts were revised in 2011 to 2015, meeting the state of the art and were checked again in 2022. These standards were the starting point for the development of the comprehensive ISO Standard Series which is currently in progress. All documents were updated to the current state of the art and made compatible to international requirements by a working group of German and international experts from all over the world, Gersinska et al. (2022).

The first draft of the new developed ISO standard series ISO 4917 entitled “Design of Nuclear Power Plants against Seismic Events” comprises six parts at the beginning of work where part 1 “Principles” represent the basis for the following five parts. Part 2 concentrates on “Geotechnical Aspects”, part 3 on “Civil Structures”, part 4 on “Components”, part 5 on “Seismic Instrumentation” and part 6 on “Post Seismic Measures”.

All parts have been adapted to newly developed and existing IAEA guidelines. Many restricted clauses have been opened to accommodate major relevant national guidelines and code of practices. Several new aspects from other newly developed seismic design guidelines and recent research results have been incorporated in the new drafts.

In this paper the current stage of development of the ISO standard series ISO 4917 is presented. The further development of the different parts of the new ISO Standard Series is summarized and a time schedule is set for the ongoing work. In meantime this new series of standards of the project ISO 4917 “Design of nuclear power plants against seismic events” was developed further on. ISO Central Secretariat circulated the ISO 4917 parts 1, 3, 4 and 6 as draft international standard (DIS) to all ISO member bodies for voting and comment in 2023. The next step was the development of Final Draft International Standards (FDIS). Part 2 didn’t get the necessary support of 5 ISO member countries and was therefore rejected. Important recommendations of part 2 were integrated in part 3. Part 5 was accepted as Committee Draft (CD) in 2022 and actually is under further development to be prepared and accepted as draft international standard (DIS).

INTRODUCTION

In this paper the current stage of development of the ISO standard series ISO 4917 “Design of nuclear power plants against seismic events” is presented. In meantime this new series of standards of the project ISO 4917 was developed further on. The documents were made compatible to international requirements e.g. IAEA-

documents. Furthermore, some regulations were switched to recommendations in order to give the possibility for local characteristics and national preferences.

ISO Central Secretariat circulated the ISO 4917 parts 1, 3, 4 and 6 as draft international standard (DIS) to all ISO member bodies for voting and comment in 2023. The next step was the development of Final Draft International Standards (FDIS). Part 2 didn't get the necessary support of 5 ISO member countries and was therefore rejected. Important recommendations of part 2 were integrated in part 3. Part 5 was accepted as Committee Draft (CD) in 2022 and is under further development to be prepared and accepted as a draft international standard (DIS).

This paper is divided according to the 5 remaining parts of the ISO standard series and presents and discusses the major scientific and technical backgrounds.

Beyond Design Basis issues are only briefly addressed in ISO 4917. Reference is made to IAEA SSG-67 and other national regulations. Essentially, there is no internationally accepted common procedure or method for Beyond Design and it is still under discussion within IAEA. Countries apply different philosophies and measures. This is why no specific or detailed requirements regarding Beyond Design are proposed in ISO 4917.

PART 1: PRINCIPLES

The first part ISO 4917-1 contains principles for the determination of the design basis earthquake and general design requirements. The design requirements are specified more detailed in the other parts of this standard series. The safety objectives are controlling reactivity, cooling fuel assemblies, confining radioactive substances, and limiting radiation exposure. The general seismic design concept is based on the design basis earthquake (equivalent to safe shutdown earthquake (SSE) in other guidelines or SL-2 earthquake according to IAEA). Furthermore, an inspection level earthquake is considered and for high seismicity regions an operation basis earthquake (OBE) is recommended. The inspection level earthquake is defined as 0.4 times the design basis earthquake (however other factors may be justified).

1.1 Determining the Design Basis Earthquake

It is recommended to specify the design basis earthquake performing probabilistic and deterministic analyses to the extent reasonable. It is suggested how to compare and to use the results of both methods. The analyses should be performed according to IAEA SSG-9. This ISO standard gives basic requirements for the determination of the design basis earthquake. Furthermore, some concrete basic values are suggested, however most values can be defined by national regulators.

New in comparison to other guidelines is, that the standard proposes an inspection level earthquake. For low seismicity regions, this approach should be seen as an alternative to the OBE. For the design basis earthquake, seismic-engineering parameters are determined. These can be typically uniform hazard spectra, but also scenario-based response spectra or in well justified cases the results of fault rupture simulations. Strong motion duration is another seismic-engineering parameter to be evaluated. For soil sites, the influence of site response shall be evaluated by soil dynamic calculations.

1.2 General design requirements

The design basis comprises three seismic categories analogue to IAEA. For seismic category 1 it shall be verified that civil structures - regarding its load-bearing capacity and serviceability - and components - regarding its load-bearing capacity, integrity, and functionality - will be able to fulfil their respective safety related functions in case of a design basis earthquake. For seismic category 2 components and civil structures, it shall be verified, that they will not impair seismic category 1 components and civil structures during a design basis earthquake in such a way that they would not be able to fulfil their safety related functions. For seismic category 3, components and civil structures do not need to be designed for the design basis earthquake according to this standard.

Regarding verification procedures, general requirements are given related to the load combinations, combination of different excitation directions, basic aspects of structural modelling including soil-structure and structure-soil-structure interaction and variation in soil parameters. Besides, requirements for acceleration time histories and its application as well as analysis methods are given.

1.3 Other requirements

Further basic requirements are given to the seismic instrumentation and the inspection level, as well as post seismic measures. Briefly addressed are also secondary seismic effects, ground displacements and considerations regarding beyond design basis events.

PART 2: GEOTECHNICAL ASPECTS

ISO 4917-2 didn't get the necessary support of 5 ISO member countries and was therefore rejected. Important recommendations of part 2 were integrated in part 3.

PART 3: CIVIL STRUCTURES

Part 3 of the new ISO standard series specifies requirements for civil structures of nuclear power plants that must be met to achieve the safety objectives specified in ISO 4917-1. The verification of their load-bearing capacity in case of a seismic event which exceeds that of conventional buildings given in conventional standards is specified. Furthermore, requirements are given for the verification of the serviceability of civil structures as far as it is necessary for maintaining their safety-related functions in case of a seismic event. These are mainly deformation limits and crack-width limitations. This part includes regulations for the determination of building response spectra and a simplified method for the generation of response spectra is included. Specific methods and parameters that may vary from country to country, such as partial safety factors, combination factors or maximum damping values, are given as recommendations in annex A only and can be defined nationally.

3.1 Modelling of Structures, Analysis Methods, Building Response Spectra

Requirements for the modelling of civil structures are provided in ISO 4917-3. The building structures as well as the components have to be analysed by models which are able to describe the dynamic behaviour for the decisive frequency range excited by earthquakes. In the dynamic analysis of a building the influence of the subsoil and foundation on the vibration behaviour shall be considered. Fundamental instructions and references are given in ISO 4917-3.

The dynamic behaviour of structures is mainly influenced by the effective stiffnesses and masses as well as adequate damping values. The stiffness values should be determined on the assumption of linear elastic material behaviour considering possible stiffness reductions which result in unfavourable vibration effects, such as semi-rigid connections at frame corners. The material properties may be assumed based on static values that are given in the relevant national documents. Effective masses will be distinguished between permanent masses and temporary masses due to service and operational loads. Recommended combination factors are given for typical service and operational loads.

With regard to the damping behaviour three types of damping exist. First there is the material damping which results from micro-plastic processes inside the material and which is dependent mainly on the level of stress. Second there is the structural member damping which is the damping of e.g., a reinforced concrete slab, column or beam. Structural member damping is generally higher than material damping at comparable strain levels. Third there is the overall building damping which describes the damping of a total structure, consisting of many structural members, non-structural components, electrical and mechanical components, fittings, and connections. A large amount of damping results from friction and damping-radiation effects. Therefore, overall building damping is much higher than component damping at the same stress level.

The different damping ratios are provided according to the individual application. For building structures and sub-building structures the damping behaviour is mainly determined by overall building damping. So, the related damping ratios shall be applied for the verifications of the ultimate limit states (ULS with strength analysis), limit states of serviceability (SLS with service load analysis) and to determine building response spectra. Only for buildings in which the damping behaviour is determined predominantly by material and structural member damping, reduced damping ratios have to be considered to determine building response spectra.

According to the fundamentals of ISO 4917-1 the structural analyses may be carried out using the generally agreed procedures like the response spectrum method, the linear and non-linear time history method and the frequency response method. The quasi-static method as a simplified method may be applied, too. Details for the different analytic methods are specified, especially for the consideration subsoil-structure interaction and for the determination of building response spectra. These specifications correspond to the specifications for the dynamic analysis of components, given in ISO 4917-4. The results of these structural analyses will be used for further analysis of components (building response spectra as secondary response spectra) or for the verification of the building structure (internal forces and deformations).

3.2 *Verification of Seismic Actions*

ISO 4917-1 defines three classes of building structures and components with different verification demands: seismic category 1, 2 or 3. Only for components and building structures of category 1 and 2 seismic safety according to ISO 4917-1 is required. Generally, these components and building structures have to be verified with regard to their load bearing capacity and - if necessary - their integrity and serviceability. The verification procedures in ISO 4917-3 are based on the partial safety concept. The verifications for ultimate limit states and serviceability limit states are specified for reinforced concrete and pre-stressed concrete structures as well as for steel structures.

The permanent actions G_k (characteristic value), actions due to prestressing P_k (characteristic value), variable actions Q_k (characteristic value) and actions from design basis earthquake A_{Ed} have to be considered. The design value of the earthquake A_{Ed} has to be determined considering the mass-effect of the permanent actions and a percentage (combination value ψ_E) of the variable actions Q_k . Recommended combination values ψ_E as well as other combination values can be found in Annex A of ISO 4917-3.

For the ultimate limit states the action effects E_d have to be verified in such a way that $E_d \leq R_d$ where R_d represents the material specific design value of the bearing capacity as a function of the characteristic value of the material strength f_k and the respective partial safety factor γ_m from $R_d = R_k (f_k / \gamma_m)$. Recommended safety factors are given in Annex A of ISO 4917-3.

For the action effects of the design basis earthquake, it must be proven that a requirement-compliant use of the building can be ensured. Therefore, verifications in the limit states of serviceability with associated requirements (such as deformation and crack width constraints) must comply with $E_d \leq C_d$, where E_d is the design value of the earthquake action effect (e.g., stress, deformation) and C_d is the design value of the serviceability criterion (e.g. permissible stress, deformation or crack width) to meet the protective goals for earthquake loading. The serviceability criteria have to be specified plant-specific.

In order to provide adequate seismic margins for the most important structures and to avoid cliff edge effects, beyond design basis considerations shall be applied. This standard recommends that the beyond design basis earthquake shall be defined in accordance with national regulations and according to IAEA SSG-67.

PART 4: COMPONENTS

Part 4 of the new ISO standard series deals with the seismic design of mechanical and electrical plant components, including their supporting structures. It is the basis for the fulfilment of the safety-related requirements for the verification of the site-specific seismic safety of plant components.

In ISO 4917-4, the term mechanical components refers to components such as vessels, heat exchangers, pumps, valves, lifting gear, distribution systems and pipe lines including their support structures in as far as these components are not considered to be civil structures in accordance with ISO 4917-3. Liners, crane runways, platforms and scaffoldings are not considered as being part of these mechanical components.

The term electrical components refers to the combination of electrical devices including all electrical connections and their support structures (e.g. cabinets, frames, consoles, brackets, suspensions or supports). Supplementary to ISO 4917-4 reference is made to IEC/IEEE 60980-344 regarding the seismic qualification of electrical components.

4.1 Design Requirements

The general design requirements for components are specified in ISO 4917-1. They include classification of components, i.e., their assignment to the seismic category as well as general requirements regarding the verification of their earthquake safety. Ageing effects that might influence the verification objective shall be taken into account.

For the (in terms of safety) most important components of seismic category 1, it is required that they are able to fulfil their safety related functions in the case of seismic events. The safety related functions shall be specified individually for each component. Typical safety-related functions for the verification of components are explained in detail in Gersinska et al. (2022).

4.2 Verification procedure

The sequence of steps required for the verification is shown in Figure 1. Depending on the verification objective, individual steps of the verification procedure may be combined, provided, the detailing of the model allows this.

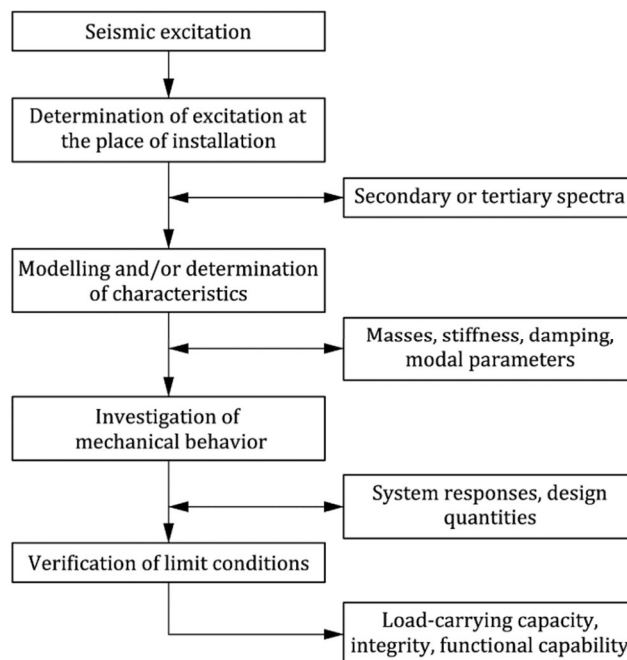


Figure 1. Part 4: Sequence of verification steps

For the verification of the limit states, the determined design values of the actions are to be compared with the allowable capacities in the appropriate design codes.

The four possible verification methods verification “by Analysis”, “by Testing”, “by Analogy” and “by Plausibility Considerations” are explained in detail in Gersinska et al. (2022). The verification methods to be used shall be defined for the plant components specific to their application.

PART 5: SEISMIC INSTRUMENTATION

Part 5 of this standard series describes the objectives of the seismic instrumentation: a) detecting and quantifying the seismic effects at the plant site and at the power plant itself, b) measuring the accelerations, recording the acceleration time histories and storing these data and c) enabling the comparison of these data with the design quantities basic to the design of the power plant.

5.1 *Requirements for the Seismic Instrumentation*

Immediately after a seismic event, the instrumentation shall display whether the plant walkdown inspection level, the inspection level or the shutdown level (OBE) is exceeded, which subsequently require measures defined in part 6. Therefore, the recorded acceleration time histories, the resulting response spectra as well as a comparison of the resulting response spectra with the free-field response spectrum or with the analytic building response spectra are made available. For the inspection level a comparison with the free-field response spectrum is relevant, as it is the design basis. Building response spectra can be used for the verification of the analytical models.

Requirements and recommendations are given for the location of the accelerographs. Besides the free-field accelerograph, at least three accelerographs shall be installed inside the reactor building. Multi-unit power plants are also addressed.

5.2 *Characteristics of the Instrumentation*

The characteristics of the instrumentation consider a temporary independent system operation in case of loss of external power supply, maintenance and testing of the instrumentation and technical characteristics of the accelerographs (acceleration sensor, recording device, data recording trigger and alarm trigger). Furthermore, recommendations regarding triggering, recording interval and data storage length are given.

5.3 *Actuation and Alarms*

The chapter actuation and alarm outlines recommendations for threshold values for data recording triggers, and interconnection between the accelerographs. The alarms regarding actuation of data measurement and recording, actuation of any one of the alarm triggers and loss of the external power supply to the instrumentation, shall be documented in the main control room or in a control room annex. Moreover, these alarms shall be interconnected to initiate a group alarm that shall be optically and acoustically announced in the main control room.

PART 6: POST-SEISMIC MEASURES

The new ISO standard series has the task of specifying safety-related requirements, compliance with which ensures that the precautions required by the state of science and technology are taken against damage during the construction and operating of the plant. To achieve these objectives, post-seismic measures are presented within the scope of part 6 of this standard that are based on the accelerations caused by the earthquake. After the occurrence of an earthquake, a concept of graduated measures depending on the recorded acceleration time history shall be applied. The process for post-seismic measures is structured in ‘Identification’, ‘Classification’, ‘Initial measures’, ‘In-depth measures’ and ‘Resulting measures’. A detailed description of these measures can be found in Gersinska et al. (2022). Figure 2 visualizes the workflow for the post-seismic measures. The main foreseen steps in the process are summarized in the following. The requirements are in line with IAEA guidelines.

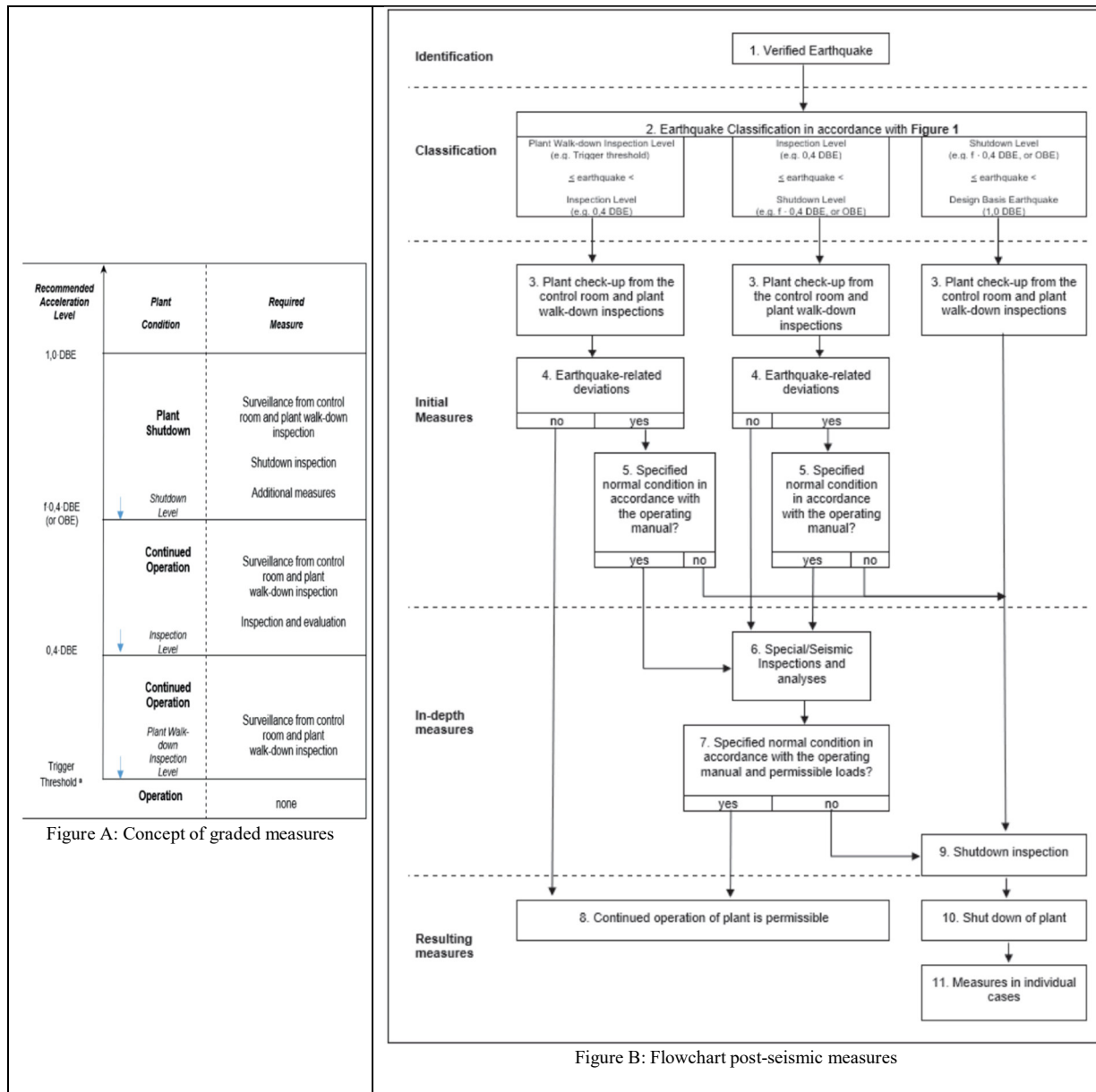


Figure 2. Part 6: Post-seismic measures

6.1 Identification

If a trigger threshold for data recording (see also part 1 and part 5 of the ISO series) is exceeded, the first step is the verification of the earthquake e. g. by evaluating the recorded time histories of institutions outside of the nuclear power plant to exclude faulty signals.

6.2 Classification

Regarding the response spectra generated from the recorded time histories, the earthquake shall be classified dependent on the design basis earthquake (DBE) respectively the operating basis earthquake (OBE) in:

1. **Plant walk-down inspection level:** Trigger threshold \leq earthquake \leq 0.4 DBE
2. **Inspection level:** 0.4 DBE \leq earthquake $\leq f \cdot 0.4$ DBE (or OBE)
3. **Shutdown level:** $f \cdot 0.4$ DBE (or OBE) \leq earthquake $<$ 1.0 DBE

The inspection level of the plant corresponds to 0.4 DBE. It is typically an earthquake intensity, which is less than the OBE (typically $f \cdot 0.4 = 0.6$ DBE) and where inspections and investigations should be initiated after an earthquake below OBE level. The factor f may be assumed as equal to 1.5. For $f > 1.5$, individual plant-specific verification must be provided. All given acceleration levels are just recommendations based on German practice (KTA) and may be adjusted country specific. Other types of earthquake intensity measures (e.g., cumulative absolute velocity (CAV) values) may also be specified additionally in a specific country. Recent investigations have shown a rather low correlation between CAV and seismic damage/risk. This is why there are no recommended CAV-values for classification of earthquakes. But of course, these may be defined country specific.

If the inspection level is decisively exceeded only for frequencies above a predetermined plant specific upper bound frequency (e.g., 16 Hz), the status of the plant shall be evaluated by engineering-based considerations. For the length of these activities, a continued operation of the plant is permissible. The rationale for the upper bound frequency (typically 16 Hz) is that:

- For the majority of safety-related SSCs (with a few exceptions), the essential frequencies for design are typically the ones up to 16 Hz;
- Typically, due to the filtering of the earthquake waves in the (softer) subsoil and in the (non-rigid) building and incoherency effects from the foundation, no relevant high-frequency vibrations should occur in the building. Thus, recorded high frequency motions are mostly false measurements or vibrations from other sources.
- High-frequency vibrations have hardly any appreciable energy content and can therefore hardly cause any damage (see Figure 3). Even in idealised systems, these vibrations are dissipated by slight plastic deformations.
- 16 Hz has been chosen conservatively, in analogy to considerations for airplane impact analysis (APC). There is a typical nonlinear displacement of <1 mm associated with a frequency $f > 16$ Hz.

The specific value of 16 Hz is a typical recommended value in ISO 4917 and may be adjusted site or country specific.

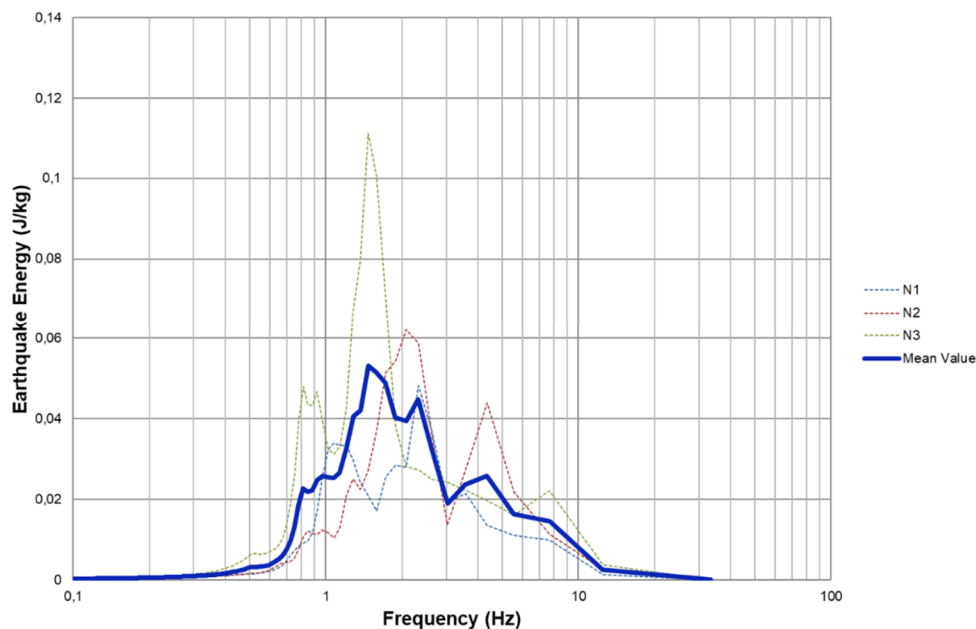


Figure 3. Energy spectra (input energy) for typical earthquake time histories

CONCLUSIONS

The new standard series ISO 4917 entitled “Design of Nuclear Power Plants against Seismic Events” is in its final stage of development. It comprises of five parts and is based on IAEA safety standards and guidelines, providing detailed design and analysis procedures for Structures, Systems and Components (SSCs). Its application is restricted to nuclear power plants with water cooled reactors. However, the methods described can also be adapted analogously to other nuclear structures.

Part 1 of ISO 4917 represents the basis for the following parts and gives principles for the determination of the design basis earthquake and general design requirements. The design requirements are specified more detailed in the other parts of this standard series.

Part 2 didn't get the necessary support of 5 ISO member countries and was therefore rejected. Main important recommendations of part 2 were integrated in part 3.

Part 3 of ISO 4917 defines the demands on the seismic design of civil structures which exceeds those of conventional buildings given in conventional standards. So, with respect to the fundamentals of ISO 4917-1 the structural analysis including the determination of building response spectra occupy an important part. Parameters that may vary from country to country, such as partial safety factors, are given as recommended values in an annex and can be defined nationally.

Part 4 of ISO 4917 provides requirements for the design of mechanical and electrical plant components, including their supporting structures. It is the basis for the fulfilment of the safety-related requirements for the verification of the site-specific seismic safety of plant components. Design requirements are given followed by different verification procedures.

Part 5 of ISO 4917 describes the objectives of the seismic instrumentation of this standard series. The characteristics of the instrumentation are defined and recommendations for the actuation and alarm outlines for threshold values for data recording triggers, and interconnection between the accelerographs are given.

Part 6 of ISO 4917 presents post-seismic measures that are based on the accelerations caused by the earthquake. After the occurrence of an earthquake, a concept of graduated measures depending on the recorded acceleration time history shall be applied.

Recent developments in IAEA and international guidelines and standards (e.g. IAEA SRS No 66, SSR-2/1, TECDOC-1956 and ANSI/ANS-2.26-2004) have been accounted for in the latest revision of this ISO code. Compared to usually more general, extensive and comprehensive IAEA guidelines, ISO 4917 is more specific, clear and focused. It is practical to use for the nuclear industry and authorities as it regulates all necessary items in a sufficiently focused manner. All parts together form a comprehensive, consistent and complete seismic design guideline series compatible and in line with other IAEA and ISO standards. The standard series suggests specific design values, but at the same time is open for national requirements and regulations.

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