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NEW DEVELPOPMENT OF AN ISO STANDARD SERIES FOR THE DESIGN OF NUCLEAR POWER PLANTS AGAINST SEISMIC EVENTS

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ABSTRACT

Under the impression of the catastrophic event in Fukushima in the year 2011 and in regard of many nuclear newcomer countries, the development of a comprehensive ISO Standard Series for the design of nuclear power plants against seismic events seams vital. The working basis for this new standard series is the German Safety Standard Series KTA 2201 (Elsche et al. 2013 and Henkel et al. 2013), which will be extended and adjusted with respect to requirements of an international ISO standard series.

The first draft of the new developed ISO standard series ISO 4917 entitled “Design of Nuclear Power Plants against Seismic Events” comprises six parts where part ISO 4917-1 “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”. In this paper the technical and scientific background and the current stage of development of the ISO standard series ISO 4917 is presented. The proposal for these new series of standards for the project ISO 4917 “Design of nuclear power plants against seismic events” were accepted as Committee Drafts by ISO for the parts 1, 2, 3, 4 and 6. Part 5 is accepted in the work program as preliminary working item and needs further development to be accepted as committee draft too. This part was also reviewed by ISO and the open questions were resolved by the designated working group. The current status and the major scientific and technical backgrounds of all these code drafts will be presented and discussed in this paper.

INTRODUCTION

The development of a first comprehensive Standard Series for the design of nuclear power plants against seismic events in Germany started in the year 1975 with the KTA 2201 part 1. In the following years 5 further parts followed. These standards have proved reliable being the basis for the design and approval procedures of nuclear power plants in Germany and abroad. All parts were brought to the state of the art in the years 2011 to 2015. Now, these standards are the starting point for the development of a comprehensive ISO Standard Series which is currently in progress. All documents now are 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. This work is sponsored by a project from the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and managed by TÜV SÜD Industrie Service GmbH in Germany.

This paper is divided according to the 6 parts of the ISO standard series and presents and discusses the major scientific and technical backgrounds.

PART 1: PRINCIPLES

Part one of the new ISO 4917 standard series 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. 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). If the seismic instrumentation displays an earthquake, inspection measures follow depending on the level of exceedance or non-exceedance.

1.1 Determining the Design Basis Earthquake

The design basis earthquake shall be specified by evaluating the deterministic and the probabilistic analyses in accordance with IAEA SSG-9. This ISO standard gives basic requirements for the determination of the design basis earthquake. Complementary to IAEA SSG 9 a deterministic and probabilistic assessment is recommended, and it is suggested how to compare and to use the results of both methods. Furthermore, some concrete basic values are given, 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.

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 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

Part 2 of ISO 4917 deals with the determination and application of subsoil properties governing the seismic design of nuclear power plants. So, requirements for the subsoil investigation are specified. The subsoil conditions shall be evaluated based on expert reports concerning geology, seismology and subsoil. Geotechnical surveys and investigations shall be carried out in accordance with the Eurocodes.

Furthermore, ISO 4917-2 comprises analytical procedures concerning the determination of dynamic subsoil properties. The dynamic subsoil properties are characterized by data of the individual soil layers like dynamic shear modulus, Poisson's ratio, material damping, density and shear wave velocity. Finally, ISO 4917-2 deals with possible changes of the subsoil that might occur as secondary effects of earthquakes, regarding permanent vertical deformations as well as a simplified evaluation of soil liquefaction.

PART 3: CIVIL STRUCTURES

Part 3 of ISO 4917 applies to civil structures of nuclear power plants with water cooled reactors to achieve the safety objectives specified in ISO 4917-1. It specifies the requirements for civil structures that must be met for the verification of their load-bearing capacity (stability) in case of a seismic event which exceed those of conventional buildings given in conventional standards. Additionally, requirements are specified pertaining to the verification of the serviceability of civil structures as far as necessary for maintaining their safety-related function in case of a seismic event (e.g., deformation and crack-width limitations). With respect to the fundamentals of ISO 4917-1, the structural analysis includes the determination of building response spectra as 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.

3.1 Structure Analysis - Modelling of Structures, Analysis Methods, Building Response Spectra

Fundamental requirements for structural modelling are provided in ISO 4917-1. So, the building structures including subsoil as well as the components have to be analysed by models which are able to describe the structural behaviour for the decisive frequency range excited by earthquakes. Accordingly, a three-dimensional model will not be necessary in general.

The dynamic structural behaviour mainly will be 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 regarding possible stiffness reductions which result in unfavourable vibration effects, such as semi-rigid connections of frame corners. The necessary material data may be assumed according to static values given in the relevant national documents. Effective masses will be distinguished between acting masses and temporary masses due to service and operational loads in consideration of the verification concept.

With regard to the damping behaviour three types of damping exist:

- Material damping: damping, which results from micro-plastic operations inside (measured in the laboratory) and which is dependent on the level of stress.
- Component damping: damping of a structural component, such as plate or beam structure. Component damping is higher than material damping at strain level.
- Structural damping: damping of a total structure, consisting of many structural components including the effect of such non-structural components, fittings, connections, and radiation effects. Structural damping at the same stress level is much higher than component damping.

In ISO 4917-3 different damping ratios are provided according to the individual application. For building structures and sub-building structures the damping behaviour is mainly determined by structural 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 component 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 usual dynamic analytic methods like the response spectrum method, linear and non-linear time history method or frequency response method. Also, the quasi-static method as a simplified method may be applied. Details for the different analytic methods are specified in ISO 4917-3, especially for the consideration subsoil–structure interaction and for determining 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 vertical actions including permanent actions and a percentage of the variable actions Q_k (combination value ψ_E). The combination value ψ_E as well as other combination values can be found in ISO 4917-3.

For 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 $R_d = R_k (f_k / \gamma_m)$.

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.

Additionally, beyond design consideration are given in a special annex of ISO 4917-3.

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 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).

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.

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 which verification of components is required are:

- Load-bearing capacity (stability) for the component and its support including the building structure interaction loads.
- Integrity of the components, based on requirements in accordance with the component-specific standards.
- Functionality, which shall be differentiated between whether the functionality of the component shall be achieved after or during and after the earthquake. Furthermore, it shall be differentiated between active and passive functionalities. An active functionality of a component ensures that the specified movements can be performed and that the electrical functions are maintained. A passive functionality of a component means that permissible deformations and movements are not exceeded. Also, false signals should not appear in electrical equipment.

Ageing effects that might influence the verification objective shall be taken into account.

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.

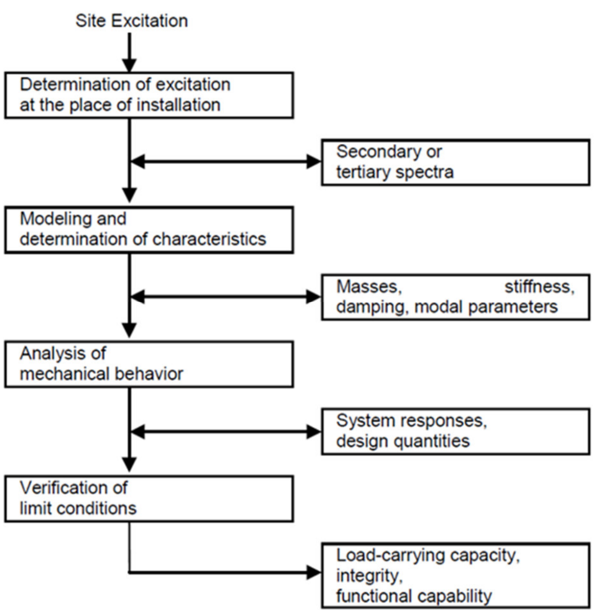

Figure 1. Part 4: Sequence of verification steps

The following four verification methods are permissible, either individually or in combination. The verification methods to be used shall be defined for the plant components specific to their application.

4.2.1 Verification by Analysis

The basic requirements regarding verification by analysis are specified in ISO 4917-1 and include the combination of excitation directions, modelling, determination and use of acceleration time histories, and superordinate aspects of the analysis methods. Either the quasi-static method, the response spectrum method or the time history method shall be used. In well substantiated cases, simplified procedures are permissible. For pipelines, installation guidelines may be used as a substitute, provided, their technical basis includes the load case earthquake. Non-linearities are allowed to be considered in the analyses.

4.2.2 Verification by Testing

When choosing the verification by testing it must be specified whether the limit values resulting from the design requirements can be determined during the test. Requirements regarding the test object, excitation, system characteristics and parameters, the analysis of the mechanical behaviour and determination of the stress, the verification of limit conditions and the combination of several verification steps are specified.

4.2.3 Verification by Analogy

A verification by analogy shall be based on reference results from analysis or experimental verifications that were performed on similar, type-identical components, or on quantitatively documented results for the respective component with regard to its behaviour under other actions, provided, these results are suited to make comparisons.

4.2.4 Verification by Plausibility Considerations

A verification by plausibility considerations shall be based on factual experience regarding the behaviour of similar, type-identical components in nuclear or non-nuclear facilities during earthquakes that have actually occurred or on factual experience from earthquake verifications for similar, type-identical components that enable an evaluation of the design planning or mechanical design of other components with regard to earthquake safety.

PART 5: SEISMIC INSTRUMENTATION

The objectives of the seismic instrumentation described in part 5 of this standard series, are: 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 annunciated 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'. Figure 2 visualizes the workflow for the post-seismic measures. The main foreseen steps in the process are summarized in the following.

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 ≤ earthquake ≤ 0.4 DBE
2. **Inspection level:** 0.4 DBE ≤ earthquake ≤ $f \cdot 0.4$ DBE (or OBE)
3. **Shutdown level:** $f \cdot 0.4$ DBE (or OBE) ≤ earthquake < 1.0 DBE

The factor f may be assumed as equal to 1.5. For $f > 1.5$, individual plant-specific verification must be provided.

6.3 Initial measures

Independent of the earthquake classification, a plant check-up from the control room as well as plant walk-down inspections shall be conducted. Within the framework of this safety measure, possible deviations due to the earthquake can be detected and need to be documented.

When exceeding the inspection level, a plant shutdown inspection shall be performed, and the plant shall be shut down.

Assuming the earthquake is classified as 'Plant walk-down inspection level' and no earthquake-related deviations are detected, there is no need for in-depth measures and continued operation of the plant is permissible. In case of the earthquake classification 'Inspection level' and no earthquake-related deviations were discovered, it is possible to proceed immediately to the in-depth measures.

If the earthquake classification is not 'Shutdown level' and earthquake-related deviations were detected, it shall be investigated whether the specified normal condition is maintained in accordance with the operating manual. These conditions are considered to be complied if the corresponding requirements specified in the operating manual are met and no restriction of the specified normal operation can be determined due to the earthquake-related deviations.

Provided, the specified normal condition is observed, the plant is allowed to continue operation while in-depth measured are executed. If the specified normal operation condition is not observed, shutdown inspection shall be performed, and the plant should be shut down.

6.4 In-depth measures

Depending on the results of the initial measures and the earthquake classification, in-depth measures must be carried out.

For earthquakes classified as inspection level or lower, where in-depth measures are necessary, first a special plant inspection team which is familiar with the conditions of the plant prior to the earthquake shall conduct a special/seismic inspection of the entire plant. Special attention must be paid to Seismic category I components and the influence of earthquake-related deviations of Seismic category IIa components on them.

If there are any earthquake-related deviations detected on Seismic category I components, additional exemplary Seismic category I components are to be investigated where the earthquake is the governing load case and that are highly stressed. The investigations include an analysis of the action effects due to the earthquake or non-destructive examinations at the previously identified locations of highest load. Additionally, the load cycles during the earthquake need to be evaluated.

Furthermore, under the actual operating condition, the function of the terminating elements of the reactor protection system, the components of the emergency power supply and the emergency system shall be inspected.

After the special/seismic inspections and analyses, the specified normal conditions in accordance with the operating manual and the permissible loads are to be ensured. If this is considered as ascertained, continued operation of the plant is permissible. In the case that the special/seismic inspections and analyses have detected a deficiency, the shutdown inspections shall be performed which means the availability of the systems necessary for a safe shutdown shall be checked and, if required, made available.

6.5 Resulting measures

The continued operation of the plant is permissible if the specified normal operation condition has been established by the previous measures. Assumed this condition is not upheld the shutdown of the plant shall be prepared and additional measures are required in individual cases.

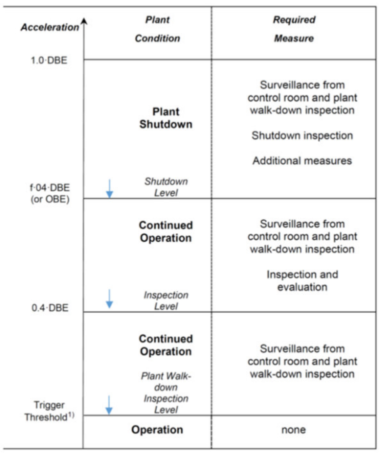

Figure A: Concept of graded measures

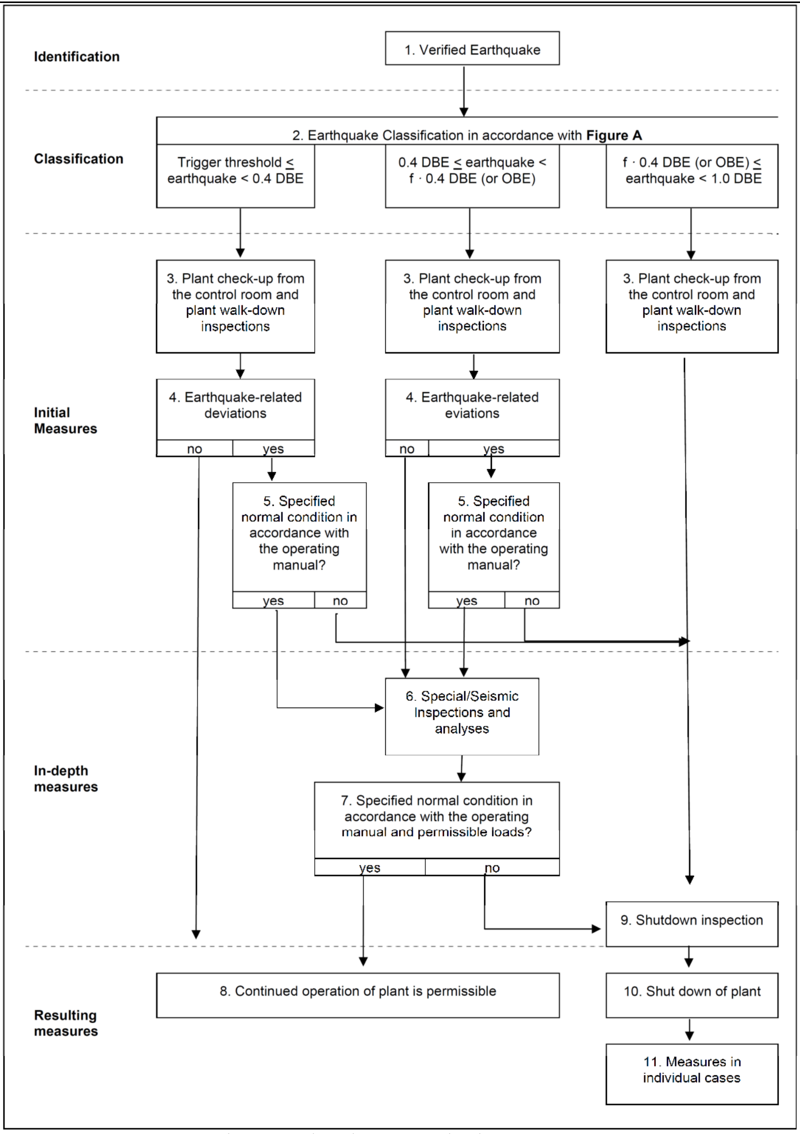

Figure B: Flowchart post-seismic measures

Figure 2. Part 6: Post-seismic measures

SUMMARY/CONCLUSIONS

A new standard series ISO 4917 entitled "Design of Nuclear Power Plants against Seismic Events" is under development. It comprises six parts and will be based on IAEA safety standards and guidelines and will provide 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 five 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 of ISO 4917 deals with the determination and application of subsoil properties governing the seismic design of nuclear power plants. The requirements for the subsoil investigation are specified. The subsoil conditions shall be based on expert reports concerning geology, seismology and the subsoil. Analytical procedures concerning the determination of dynamic subsoil properties are presented. Possible changes of the subsoil are reflected that might occur as a result of earthquakes regarding permanent vertical deformations as well as basic principles for the evaluation of soil liquefaction.

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.

All six parts together form a comprehensive, consistent and complete seismic design guideline series compatible and in line with other IAEA and ISO standards.

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