SEISMIC PERFORMANCE VERIFICATION GUIDELINES FOR CRITICAL UNDERGROUND REINFORCED CONCRETE STRUCTURES IN NUCLEAR PLANTS -2021-

DRAFT

August 2023

Japan Society of Civil Engineers

Committee of Civil Engineering of Nuclear Power Facilities

本ファイルは、「原子力発電所屋外重要土木構造物の耐震性能照査指針」2021年版（条文とその解説）を英訳したものである。国外での耐震設計・研究、国内での英文作成、国外への情報発信などに広く活用してもらうことを目的として、ドラフトを公開することとした。正式には、後日、技術付属書を添付した日英版として刊行する計画としている。

This published draft represents an English translation of provisions and their comments involved in the 2021 version of the "Seismic Performance Verification Guidelines for Critical Underground Reinforced Concrete Structures in Nuclear Power Plants". We have decided to prepare the draft with the purpose of having it widely used for overseas seismic design and research developing related English technical documents, and disseminating information overseas. We will officially release the Japanese-English version with a dozen of technical annexes at a later date.

This manuscript has been proofread and partly edited by Uni-Edit (https://uni-edit.net/) with a level of easy for a native-speaker of English to read in addition to no obvious mistakes.

Seismic Performance Verification Guidelines for Critical Underground Reinforced Concrete Structures in Nuclear Power Plants -2021-

CONTENTS

CHAPTER 1 GENERAL

1.1 Scope of Application

(1) The present guidelines shall be used for the performance verification of critical underground reinforced concrete (RC) structures at nuclear plants that may be subjected to seismic action as well as RC structures that require an equivalent level of seismic safety.

(2) The structures covered by the guidelines include:

1) Underground RC structures that require the functioning of supporting of equipment and piping systems classified as seismic grade “Class S” and
2) Underground RC structures that require a seawater delivery function in the event of an emergency (hereafter referred to as "emergency water delivery function").

[Commentary]

(1)

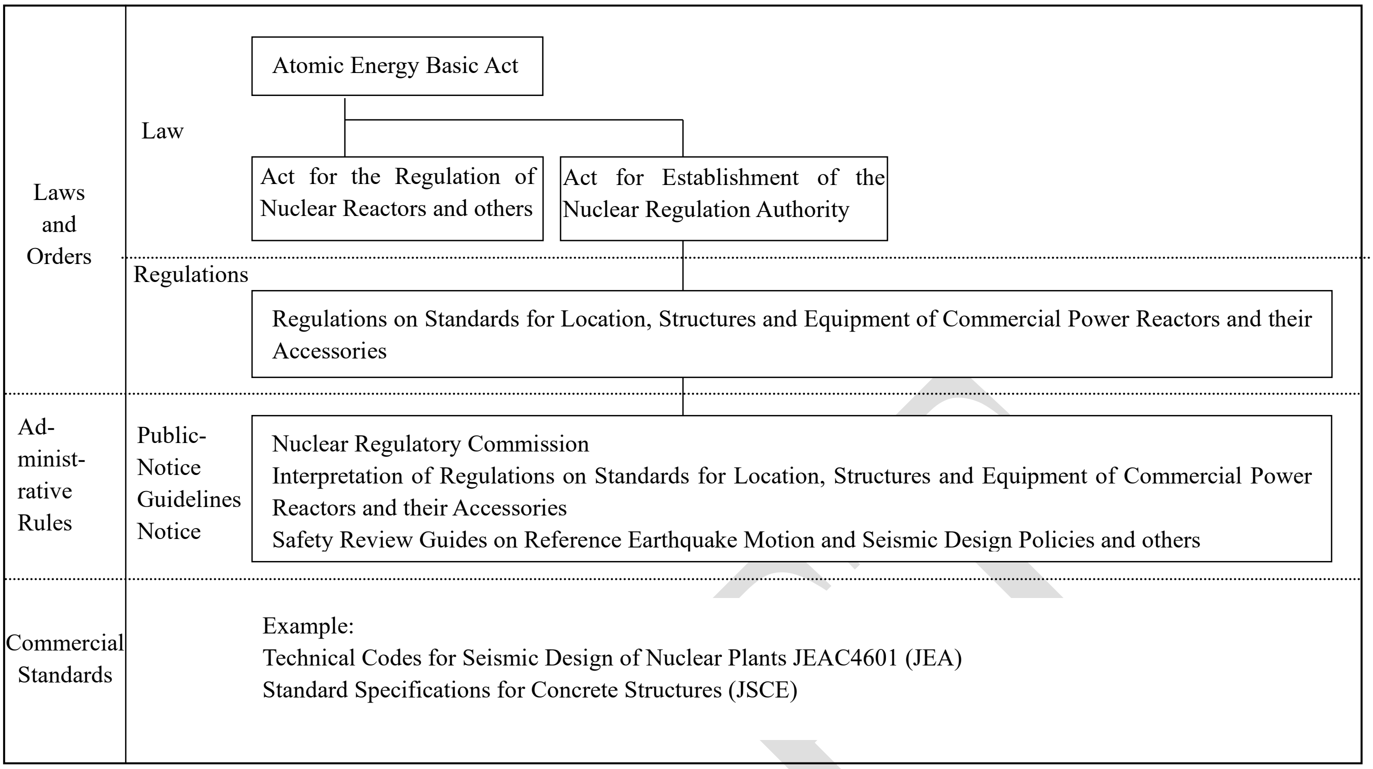
The present guidelines provide the principles of seismic performance verification for critical underground RC structures at nuclear power plants (hereinafter referred to as "underground RC structures"). The structural configurations of underground RC structures commonly feature lines along the longitudinal direction and solid figures. These structural forms have relatively large shear rigidity in their longitudinal or depth direction, and their seismic behavior is biased towards the weak axis direction of their structure, which has lower shear rigidity. Therefore, the transverse sections of these structures are generally examined for seismic performance verification, and emphasis is accordingly placed on the application of two-dimensional seismic response analysis throughout these guidelines. Seismic performance verification of the longitudinal direction of structures should be performed separately as needed. Furthermore, if seismic performance verification using two-dimensional analysis is judged to be unsound from an engineering point of view, the three-dimensional seismic response analysis can be employed.

Other RC structures at a nuclear plant (*e.g.*, tsunami protection facilities and reprocessing facilities) that require equivalent seismic safety levels to underground RC structures are designed in accordance with the same design practice, *i.e.*, the principles of these guidelines are applied to such structures. Foundation structures that are handled as mass concrete in design practice (*e.g.,* diesel-generation fuel storage tank foundations, stack foundations, refueling tank foundations) are beyond the scope of these guidelines because the seismic stability of such foundations is considered under the rigid body assumption.

The seismic stability of the supporting ground where the underground RC structures are to be constructed should be examined as required. An impact of possible ground surface displacement on an underground RC structure is also beyond the scope of these guidelines. (Technical commentary on this issue can be found in a separate guideline volume.) Although the guidelines should be applied for performance verification at the design stage of yet to be constructed structures, they can also be applied to an existing structure under the condition that aging has had a minor impact. Thus, specific considerations for existing structures, including the material factor for the concrete used for performance evaluation and the effects of repair, are provided in the present guidelines where appropriate. In addition, strengthening effects may be considered in the seismic performance verification of certain existing structures about seismic upgrading.

In addition to the various methods of performance evaluation outlined in these guidelines, other tools for structural analysis and experimental approaches may also be valid for use in seismic performance verification. These methods are provided in “The Safety Verification Manual on Seismic Design of Important Outdoor Civil Structures in Nuclear Power Plants” (September 1992, Nuclear Civil Engineering Committee of the Japan Society of Civil Engineers (JSCE) (hereinafter referred to as the "the Manuals (1992)". These tools and approaches may be used for the performance evaluation of underground RC structures if they are able to properly assess the real structural performance of individual designs.

In Japan, the regulatory system necessary for ensuring nuclear safety has already been established. The laws and regulations and administrative rules of the regulatory system concerning the seismic design of underground RC structures are shown in Commentary Figure 1.1-1. Commercial standards (or recommendations/guidelines released by academic societies) can also be found in Fig. 1.1-1. The laws and regulations and administrative rules specify the rules that must be complied with for nuclear safety; commercial standards, on the other hand, are used as criteria for evaluating the sufficiency of these rules.



Commentary Figure 1.1-1 Regulatory system and commercial standards for underground RC structures

In addition to these guidelines, the seismic performance verification of an underground RC structure should essentially comply with, refer to, and apply the following regulations and recommendations:

"Regulations on Standards for Location, Structures and Equipment of Commercial Power Reactors and Their Accessories" (hereinafter referred to as "Regulations on Installation Permission Standards"); Nuclear Regulation Commission, July 8, 2013 (revised on April 1, 2020) (in Japanese).

"Interpretation of the Regulations on Standards for Location, Structures and Equipment of Commercial Power Reactors and Their Accessories" (hereinafter referred to as "Interpretation of the Regulation"); Nuclear Regulatory Commission, June 19, 2013 (revised on April 21, 2021) (in Japanese).

"Regulations on Technical Standards for Commercial Power Reactors and Their Accessories" (hereinafter referred to as "Technical Standards Regulation"); Nuclear Regulation Commission, July 8, 2013 (revised on April 1, 2020) (in Japanese).

"Interpretation of the Regulation on Technical Standards for Commercial Power Reactors and Their Accessories"; Nuclear Regulatory Commission, June 19, 2013 (revised on July 21, 2021) (in Japanese).

"Safety Review Guide on Reference Earthquake Motion and Seismic Design Policy" (hereinafter referred to as "Safety Review Guide for Seismic Design Policy"); Nuclear Regulatory Commission, June 19, 2013 (revised on April 21, 2021) (in Japanese).

"Construction Authorization Safety Review Guide for Seismic Design" (hereinafter referred to as "Safety Review for Construction Authorization Guide"); Nuclear Regulatory Commission, June 19, 2013 (revised on March 31, 2020) (in Japanese).

"Technical Codes for Seismic Design of Nuclear Plants Japan Electric Association Code (JEAC4601-2015)" (hereinafter referred to as "JEAC4601-2015"); Japan Electric Association (JEA), 2016 (in Japanese).

"Japanese Architectural Standard Specification for Reinforced Concrete Work JASS5N (2013) (Reinforced Concrete Construction at Nuclear Power Plant Facilities)"; Architectural Institute of Japan (AIJ), 2013 (in Japanese).

"Technical Guidelines for Seismic Design of Nuclear Plants JEAG4601-2015" (hereinafter referred to as "JEAG4601-2015"); JEA, 2015 (in Japanese).

"Technical Guidelines for Seismic Design of Nuclear Plants -Classification of Importance-, Allowable Stress- JEAG4601 Supplement 1984" (hereinafter referred to as "JEAG4601-1984 Supplement-1984"); JEA, 1984 (in Japanese).

"Technical Reports on Assessment Methods for Geological and Geotechnical Explorations and Tests and Seismic Stability of Ground at a Nuclear Power Station" (hereinafter referred to as the "JSCE Reports on Assessment Method for Seismic Stability of Ground"); Nuclear Power Civil Engineering Committee, Japan Society for Civil Engineers (JSCE), August, 1985 (in Japanese).

"The Safety Verification Manual on Seismic Design of Important Outdoor Civil Structures in Nuclear Power Plants" (hereinafter referred to as the "the Manuals (1992)"); Nuclear Power Civil Engineering Committee, JSCE, September, 1992 (in Japanese).

"Guideline and Recommendation for Seismic Performance Verification of Underground Reinforced Concrete Structures in Nuclear Power Plants"; Nuclear Power Civil Engineering Committee, JSCE, June, 2005 (hereinafter referred to as "Guidelines, Manuals, Examples, Technical Commentaries 2005") (in Japanese).

"Standard Specifications for Concrete Structures 2002 [Structural Performance Verification]", JSCE (hereinafter referred to as "Specifications [Structural Performance Verification]").

"Standard Specifications for Concrete Structures 2017 [Principles of Earthquake Resistance Design]", JSCE (hereinafter referred to as "Specifications [Principles of Earthquake Resistance Design]") (in Japanese).

"Standard Specifications for Concrete Structures 2018 [Maintenance, Construction, Design]", JSCE (hereinafter referred to as "Specifications [Maintenance, Construction, Design]") (in Japanese).

"Standard Specifications for Concrete Structures 2017 [Construction]", JSCE (hereinafter referred to as " Specifications [Construction]") (in Japanese).

"Standard Specifications for Concrete Structures 2007 [Design]", JSCE (hereinafter referred to as "Specifications [Design]").

"Standard Specifications for Concrete Structures 2012 and 2017 [Design]", JSCE (hereinafter referred to as " Specifications [Design]") (in Japanese).

"Standard Specifications for Concrete Structures 2017 [Test Methods and Specifications]", JSCE (in Japanese).

"Technical Commentaries for Revision of Standard Specifications for Concrete Structures 2007, 2012, and 2017", JSCE (in Japanese).

"Verifications of Seismic Performance of In-ground LNG Structure", Energy Committee, Concrete Library 98, JSCE, December, 1999.

"Recommendations on Evaluation of Structural Sound Function for Underground Reinforced Concrete Structures in Nuclear Power plants", Nuclear Power Civil Engineering Committee, JSCE, October, 2012 (hereinafter referred to as the "Recommendations on Evaluation of Structural Sound Function") (in Japanese).

"Common Specifications for Infrastructures 2016 [Principals, Performance and Actions, Structural Planning]", Structural Engineering Committee, JSCE (in Japanese).

"Seismic Performance Verification Guidelines, Manuals and Examples for Underground RC Structures in Nuclear Power Plants” (revised in October, 2018), Nuclear Power Civil Engineering Committee, JSCE, June, 2018 (hereinafter referred to as "Guidelines, Manuals, Examples, Technical Commentaries 2018") (in Japanese).

As these regulations and recommendations are revised, seismic performance verification should essentially comply with, refer to, and/or apply the content of the most recent versions of these documents. In addition, these regulations and recommendations must be fully examined and understood for valid application.

(2)

To effectively ensure the seismic safety of nuclear power plants, their various facilities are classified into seismic design grades as explained in Commentary Table 1.1-1 (cited from "Chapter 2 Seismic Grade Classification" (JEAC4601-2015)). It should be noted that underground RC structures are only *indirectly* involved with the seismic safety of these facilities (cited from Commentary Table 1.1-2, "Seismic Grade Classification in Chapter 2" (JEAC4601-2015)) and they are normally dealt with outside the scope of seismic grade classification. On the other hand, according to the nuclear equipment category (cited from Tables 1.1-3 and "Chapter 2 Seismic Grade Classification" (JEAC4601-2015)), Underground RC structures constitute a part of the system that guarantees the seismic safety of a nuclear power plant, and thus an underground RC structure *indirectly* supports the primary and secondary equipment that *directly* ensure seismic safety. In other words, the structure plays an *indirect* supporting structural role that supports the primary and secondary equipment (referred to as “direct support structures”). Accordingly, an underground RC structure ensures seismic safety equivalent to that of the primary and secondary components in terms of functionality. The primary equipment, secondary equipment, and direct support structures are classified into Class S, Class B, and Class C seismic grades, and the seismic grades of underground RC structures are established in accordance with these facilities. Various equipment and piping systems that have been classified as Class S are commonly installed on the floors or walls of facilities that have been classified as Class S, B, or C. Of these, the present guidelines will focus on the support function of facilities classified as Class C. Accordingly, the present guidelines define such a function simply as “support” without designating it as *direct* or *indirect* to avoid confusion.

Considering the above, the following two RC structure types represent the underground RC structures covered by these guidelines:

1) Underground RC structures that require the functioning of supporting equipment and piping systems classified as seismic grade “Class S”, and
2) Underground RC structures that require an emergency water delivery function.

The various underground RC structures covered in these guidelines are listed in Commentary Table 1.1-4. For example, the underground RC structures corresponding to a reactor cooling water system facility (emergency cooling water intake equipment) include intakes and sea water delivery channels that require a seawater flow function, piping support ducts that require the support of Class S equipment and piping systems, and intake pits that require both water delivery and support functions. A layout and bird's-eye view of a typical underground RC structure are illustrated in Commentary Figures 1.1-2 and 1.1-3, respectively.

Commentary Table 1.1-1 Definitions for seismic grade classification

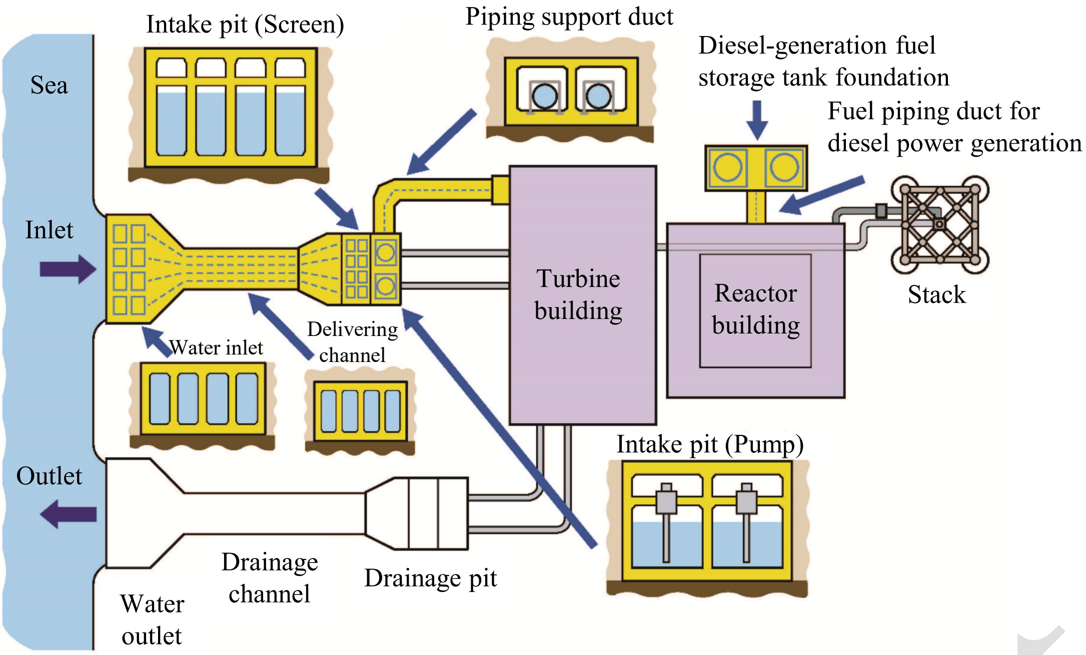
Class S	Nuclear structures or components with built-in radioactive material or directly related to a facility with built-in radioactive material. This includes structures and components that are potentially hazardous and could release radioactive material externally due to loss of functionality, those required to prevent such situations from happening, those required to reduce the impact of the release of radioactive material externally during the onset of an accident, and those that have a significant influence on the accidental release of radioactive material.
Class B	Any of the above nuclear structures or components that have a minor impact on seismic safety
Class C	Nuclear structures or components that require the same degree of seismic safety as general industrial facilities, excluding Class S and Class B structures.

Commentary Table 1.1-2 Functional classification

Class S	(i) Equipment and piping systems that contribute to the "reactor coolant pressure boundary" (as defined in "Safety Review Recommendations for Safety Designs for Light Water Reactors"). (ii) Equipment for storing spent fuel. (iii) Facilities for rapidly adding negative reactivity to an emergency shutdown of a nuclear reactor and facilities for establishing the shutdown of a nuclear reactor. (iv) Facilities that remove decay heat from the core after reactor shutdown. (v) Facilities acting as pressure barriers in the event of damage to the reactor coolant pressure boundary and directly preventing the release of radioactive material. (vi) Facilities for controlling the external release in the event of an accident involving the release of radioactive material other than the facilities covered by (i) to (v).
Class B	(i) Facilities directly connected to the reactor coolant pressure boundary with or capable of incorporating primary coolant. (ii) Facilities with built-in radioactive waste except for cases where the built-in amount is small or the effects of radiation on the public due to damage are sufficiently small compared to the annual exposure dose outside supervised areas, depending on the storage method. (iii) Facilities related to radioactive material other than radioactive waste and having the potential to cause excessive radiation exposure to the public and employees when damaged. (iv) Facilities for cooling spent fuel. (v) Facilities for controlling the release of radioactive material to the outside and not belonging to Class S.
Class C	Facilities not belonging to Class S or Class B.

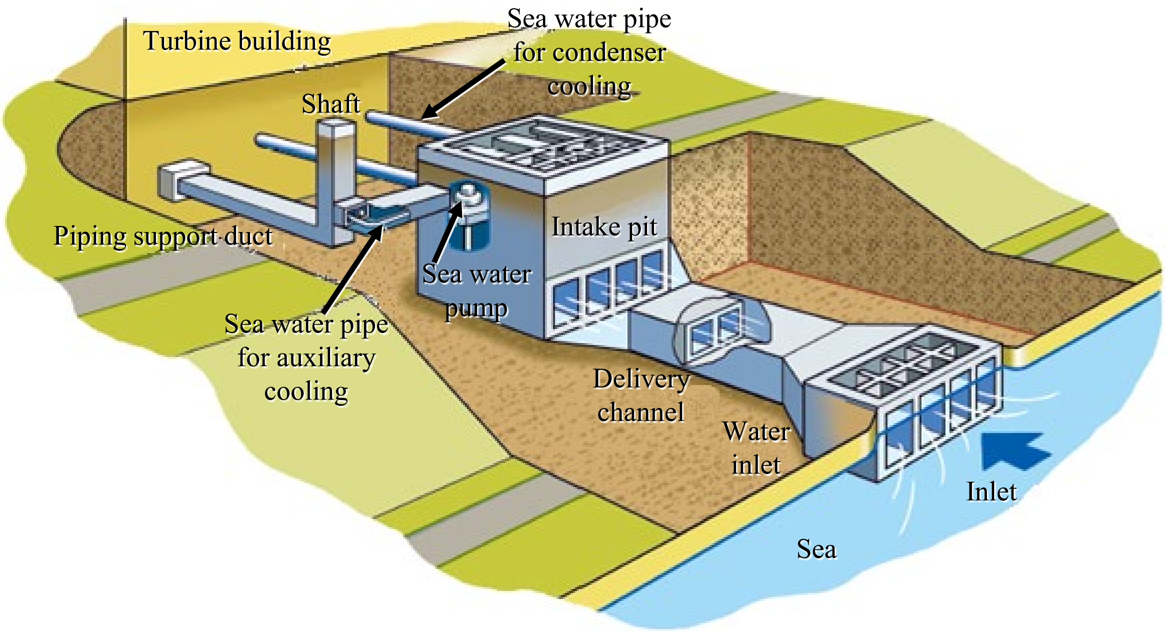
Commentary Table 1 1-3 Facility category (cited from Tables 1.1-3 and "Chapter 2 Seismic Grade Classification" (JEAC4601-2015)

Primary equipment	Equipment directly related to the functions required for the safety assurance of a nuclear power plant.
Secondary equipment	Equipment indirectly related to the functions required for the safety assurance of a nuclear power plant and having an ancillary role to the primary equipment.
Direct support structures	Support structures attached directly to the primary or secondary equipment or directly bearing the load of these facilities.
Indirect support structures	Support buildings or structures such as reinforced concrete or steel frame structures that carry loads transferred from the direct support structures.
Facilities deemed to have consequential impact	Facilities that could consequentially impact the facilities of higher seismic grades when damaged.



Commentary Figure 1.1-2 Example arrangement of nuclear power plant facilities

(Yellow color indicates critical underground RC structures)



Commentary Figure 1.1-3 Layout example of a critical underground RC structure

Commentary Table 1.1-4 Facilities and functions related to typical critical underground RC structures

Equipment Systems and their Functions		Typical Underground RC Structures and their Functions	
Class S	○Reactor cooling water system equipment (common equipment for pressurized-water reactors (PWRs) and boiling-water reactors (BWRs) Removes the decay heat (residual heat) of the reactor and supplies sufficient cooling water required to cool the emergency equipment and piping systems in the event of an emergency.	Water delivery	○Water inlet and water delivery channel Ensures the required amount of cooling water in the event of an emergency. ○Intake pit (screen section and others) Ensures the required amount of cooling water in the event of an emergency.
		Support	○Intake pit (pumping room) Safely supports the equipment (*e.g.*, pumps) in the event of an emergency. ○Piping support duct Safely supports piping in the event of an emergency.
	○Emergency power supply equipment (common equipment for PWRs and BWRs) Supplies the necessary power to safely shutdown the reactor as well as the power to operate the engineered safety equipment in the event of a loss of the external power supply system.		○Diesel-generation fuel storage tank foundation Safely supports the oil tank for diesel power generation in the event of an emergency. ○Fuel piping duct for diesel power generation Safely supports the oil piping for diesel power generation in the event of an emergency.
	○Safety injection system and auxiliary water supply facilities (PWR facilities) Removes decay heat (residual heat) by injecting boric acid water into the reactor core in the event of an emergency; the auxiliary water supply facilities work by feeding water to the secondary system of the steam onset unit in the auxiliary water supply system in the event of an emergency.		○Fuel replacement water storage tank foundation and condensate tank foundation Safely supports the respective tank to secure, for example, boric acid water to remove decay heat in the event of an emergency. ○Fuel replacement water piping duct and condensate piping duct Safely supports the respective piping in the event of an emergency.
	○Emergency gas processing facilities (BWR facilities) Safely processes gaseous radiation material generated in the reactor building thereby maintaining internal negative pressure in the event of an emergency.		○Emergency gas processing-piping duct Safely supports the piping to prevent air leakage from the emergency gas processing-piping in the event of an emergency. ○Stack foundation Safely supports the stack to prevent air leakage from below the limit altitude in the event of an emergency.

1.2 Definitions

The following terms are defined for general use in the present guidelines:

- Critical underground RC structure

  Generic term referring to underground RC structures that require the supporting function of special equipment and piping systems classified as seismic grade Class S and also underground RC structures that require an emergency water delivery function.
- Reference earthquake motion S_S

  An earthquake ground motion defined as appropriate for the assumption that such a motion would very rarely occur, generating a subsequent severe impact on given nuclear facilities during their service period with regard also to the geological and geotechnical structures nearby the nuclear power plant site based on the seismology and seismic activity in the vicinity of the plant site. Reference earthquake motion S_S should be defined as an earthquake ground motion on an outcrop rock surface.
- Outcrop rock surface

  A free surface hypothetically assumed to have no subsurface layers or no structures on the bedrock surface. The bedrock surface is idealized to be almost horizontal and be a half-space without significant difference of surface elevation. "Bedrock" refers to firm ground with a shear wave velocity (V_s) of approximately $V_s = 0.7$ km/s or more and with insignificant weathering.
- Performance requirements

  Levels of performance required from facility owners as well as socially accepted standards, considering the importance and application of a facility, its operating conditions, and the surrounding environment. These should be intelligible to the public.
- Performance objectives

  The engineering interpretation of the performance requirements, expressed as various factors that comprehensively satisfy the performance requirements.
- Seismic performance

  Performance objectives related to the earthquake resistance capability of a structure during and after an earthquake.
- Durability performance

  Performance objectives related to the durability of a structure at the end of its design life.
- Performance verification

  A check that a specified structure satisfies the relevant performance objectives.
- Crisis resistance

  In the case of general infrastructure, the capability of a structure to reduce the probability of devastating economic and/or social activity by managing the disruptive failure of the entire structure, even if an unexpected event occurs and despite the completion of the performance verification stage. In the case of underground RC structures, the capability of a structure to avoid losing the cooling function of a reactor by preventing the structural damage consecutively impacting priority nuclear systems, even if the response resultants of the structure exceed the allowable limit state.

・Verification item

Limit state or failure mode of a structure or the members of a structure that need to be checked. A more descriptive expression of the performance objectives to feasibly check the performance of a structure. Each verification item has a corresponding response value and limiting value.

・Response value

A value representing the dynamic responses of a structure (*e.g.*, stress resultant, strain) under seismic action.

・Limiting value

The value to be checked to determine whether a performance objective is satisfied.

・Design life

The period specified in the design for which the structure and/or structural members will satisfy the specified performance requirements.

・Macro element nonlinear analysis

A method of structural analysis (finite element analysis) in which a structural model is typically divided into an array of beam or shell elements and the stress resultants are calculated using nonlinear properties with respect to the member section force defined in the respective element. In the case of a beam element of reinforced concrete, the relationship between the flexural moment and the curvature is used to express the nonlinear properties of the beam elements.

・Material nonlinear analysis

A method of structural analysis (finite element analysis) in which a structural model is typically divided into an array of two- or three-dimensional solid elements and the stress resultants are calculated using nonlinear properties with respect to the stress-strain curves defined in the respective element. In the case of a structural analysis of a reinforced concrete structure, various constitutive laws for cracked concrete, reinforcing bars, and the bond characteristics between them are applied.

・Pushover analysis

A method of structural analysis in which loads or displacements are loaded incrementally onto a structural model until the member or structure reaches its ultimate state (load-carrying capacity). Pushover analysis is typically carried out using only monotonic loading but cyclic loading can be used as needed.

・Relative story deformation angle

Value obtained by dividing the horizontal relative displacement between the upper and lower slabs of a structure by the distance between the slabs.

・Repair

Maintenance measures primarily intended to restore or improve the durability of a structure or to restore the mechanical capability of an earlier age of the structure.

・Strengthening (seismic upgrade)

A maintenance measure to restore or improve the structural performance of a structure, such as load-carrying capacity and/or stiffness.

CHAPTER 2 PERFORMANCE SETTINGS FOR CRITICAL UNDERGROUND REINFORCED CONCRETE STRUCTURES

2.1 General

Seismic performance shall be appropriately determined in accordance with the performance requirements for a structure of interest as determined by the performance verification for critical underground RC structures during an earthquake.

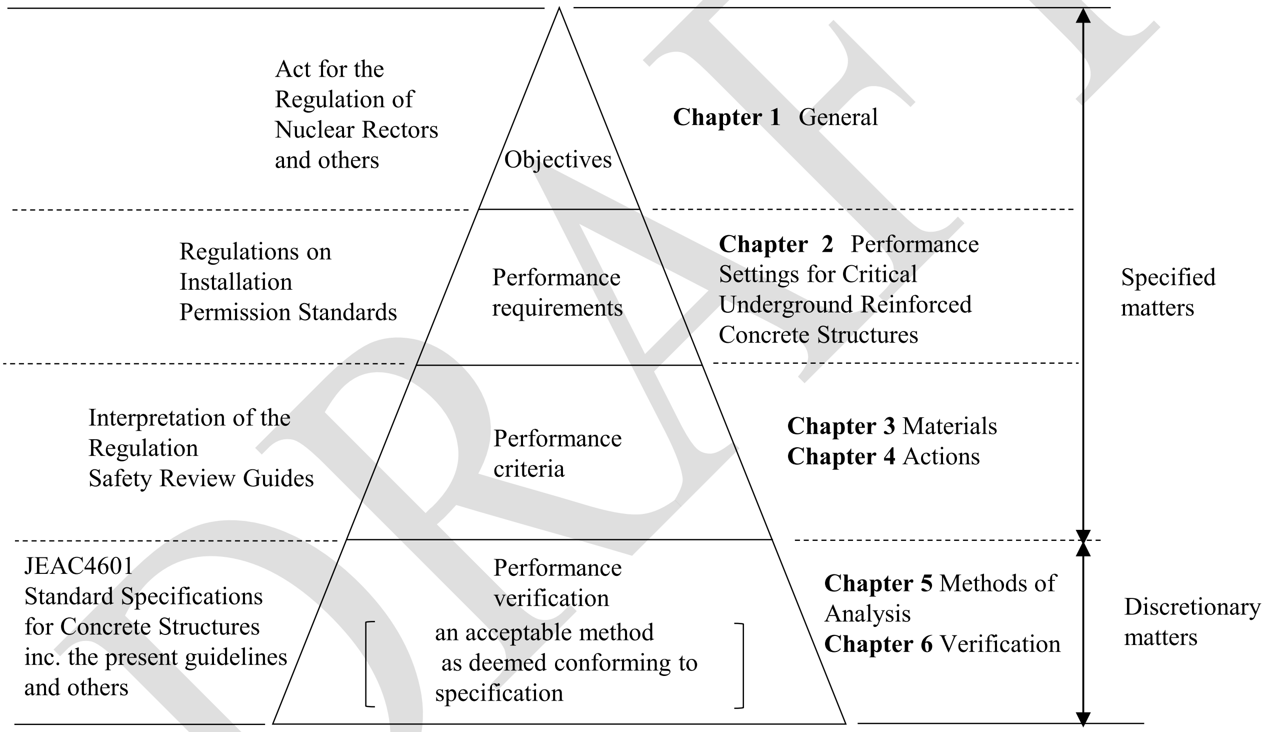
[Commentary]

In the design stage of civil engineering structures, including critical underground RC structures, it is a guiding principle that the performance requirements for the safety, serviceability, restorability, and durability of a structure are identified, and verification is carried out in a reasonable manner. Of these performance requirements, the present guidelines primarily cover performance verification for earthquakes (*i.e.*, seismic performance verification) that would seriously affect the safety requirements of a nuclear power plant. The guidelines exclude direct examination of the time dependent variation of seismic performance over the design life of a structure; however, the guidelines specify durability-related performance requirements and performance objectives as a prerequisite for ensuring acceptable time dependent variation of seismic performance over the design life of a structure. The present guidelines address durability performance verification as a prerequisite for seismic performance verification, in particular providing verification methods in **Chapter 6** of the manuals. (NOTE: The Japanese version of the present guidelines are published as one volume with their manuals and examples. Hereinafter, “the manuals” refers to the one in the same volume.)

Performance-based design is a design method that allows design engineers to discretionarily select a suitable method of checking whether the performance requirements have been satisfied by assuming that the selected method meets the requirements in an adequately reliable manner while also clearly defining the required performance. In other words, performance-based design is intended to promote the adoption of new materials and technologies.

Generally, the concepts underlying performance-based design can be expressed in a hierarchized structure, as shown in Commentary Figure 2.1-1, with reference to “Common Specifications for Infrastructures [Performance and Action]” as an example. The first class designates the "objective" and the function conforming to the "objective" of the structure. The second class then determines the "performance requirements" that satisfy the function. Based on this, the third class defines the performance using a technical expression that can be checked using a suitable engineering method or else it is "performance specified". "Performance specified" may be equivalent to the "performance objective" defined in the guidelines. Finally, the fourth class verifies fulfillment of the “performance requirements” (*i.e.*, performance verification). The "performance verification" basically employs the limit state design method. Here, the first, second, and third classes have corresponding regulations that must be observed. On the other hand, the "performance verification" in the fourth class allows design engineers to discretionarily select the method of confirming “performance verification” as long as a verification method with an appropriate scope of application is selected, *i.e.*, one regarded as “an acceptable method” or “deemed as conforming to specification".

Based on the performance-based design concept, regulatory documents, standards, and other relevant factors, seismic performance verification for underground RC structures can be adapted to the hierarchized structure according to their roles and the scope of application. The chapters of the present guidelines are organized in accordance with such a structure. Of these, various analysis and verification methods are provided in **Chapters 5 and 6** in the manuals as specific examples of applicable methods.



Commentary Figure 2.1-1 Hierarchized structure of performance-based design

The "performance requirements" are intended to convey the principle of “performance”, expressing the content of the performance settings in a manner that is intelligible to the public. The "performance objectives" are an engineering interpretation of the performance requirements, expressing all the factors that must be considered to satisfy the performance requirements in engineering terminology. The performance objectives are determined by combining the assumed load action with an acceptable limit state of the structure. Each performance objective is broken down into a “verification item” (*i.e.*, the “limit state” or “failure mode” of a structure) with regard to practical verifiability, and hence the actual process of checking is performed for a corresponding “verification item”. The definitions and examples of these performance expressions are described in Commentary Table 2.1-1. The performance requirements and performance objectives are described in this chapter, and the verification items are described in detail in **Chapter 6 Verification**.

Commentary Table 2.1-1 Performance expressions

Performance	Definition	Examples
Performance requirements	The performance required for a structure from both social and economic perspectives. It is intended to convey the general principle of the required “performance”.	The pumping function of an intake pit must continue to operate. The water delivery function of the sea water piping for a piping support duct must continue to operate.
Performance objectives	The performance levels technically achievable to meet the performance requirements. It combines the assumed load action with an acceptable limit state of a structure expressed in engineering terms.	For a reference earthquake motion Ss: 1) A given structure does not collapse. 2) A given structure satisfies the constraints for the functional capability of its equipment and piping.
Verification item	The limit state or failure mode to be examined for verification. It is described for each performance objectives as specific items (limit states or failure modes) that can be checked.	The member of a structure does not reach its limit state, *e.g.*, flexural failure or shear failure.

2.2 Performance Requirements for Critical Underground RC Structures

(1) The performance requirements for underground RC structures shall be determined for either the supporting function of Class S equipment and piping systems or the emergency water delivery function, depending on their role, objective, and importance as follows:
  1) Underground RC structures that require the functioning of supporting will have the supporting function for equipment and piping systems.
  2) Underground RC structures that require the emergency water delivery function will have the water delivery function (sea water) established for cooling.

(2) Seismic performance and durability performance shall be determined in the performance requirements for underground RC structures as objective engineering standards.

[Commentary]

(1)

The “Installation Authorization Standards Regulation” provides that nuclear power reactor facilities of the highest seismic grade must retain safety functionality against possible seismic action that may have a major impact on the nuclear power plant during their service period. Accordingly, ensuring the required level of performance during an earthquake is to be set as the ultimate performance requirement, even for the underground RC structures covered by the present guidelines.

To ensure the seismic safety of a nuclear power plant, it is essential to control the release of radioactive substances into the environment in the event of an emergency. To achieve this, nuclear power plants must implement 1) a function to “shut down” their reactors, 2) a function to “cool down” their reactors, and 3) a function to “confine” radioactivity, even in the event of an emergency. For these functions, the reactor cooling water system facilities are responsible for function 2) above, *i.e*., to “cool down” the reactors. Underground RC structures represent civil engineering structures that require the support of seismically important equipment and piping, for example, reactor cooling water system equipment or water delivery systems in an emergency. Therefore, the performance requirements should be specified in relation to the safety function of the supporting facilities or the equipment that could be subjected to consequential impact distinct from the function of the structure itself.

Underground RC structures may differ in their performance requirements from structures that belong to the same system (*e.g.,* emergency cooling water intake equipment), such as intakes and intake channels that require the water delivery function during an emergency or intake pits and piping support ducts that require that require the support function. Accordingly, the performance requirements are to be independently determined according to the categories of either the support function of equipment and piping or the water delivery function.

For structures that require supporting equipment, their performance requirements are to be determined such that the functioning of the supporting equipment can be ensured. Structures requiring the water delivery function during an emergency include intakes that are part of the emergency cooling water intake equipment and water delivery channels connecting the coastline to the pump room. These structures will directly provide seawater for cooling. Given the function of the emergency cooling water intake equipment, the equivalent performance requirements of the relevant equipment and piping (*e.g*., seawater pumps and seawater pipes) should be applied to the overall structure. This determines the performance requirements such that the function of seawater delivery for cooling can be ensured for structures that require it during an emergency.

The water storage function (with no excessive water leakage) may be required for certain structures. This requires that underground RC structures such as intake channels and intake pits must store cooling water when tsunami-induced undertows are created near the shore. When examining such structures for seismic performance verification, the water storage function must be considered as a performance requirement.

(2)

The function and performance for the equipment and systems in an underground RC structure must be established over the design life of the structure. Here, seismic performance as well as durability performance should be established for underground RC structures to ensure seismic safety over their design life. For seismic performance, the performance objectives should be specified such that an underground RC structure can sustain sufficient structural safety against loading actions during an earthquake. For durability performance, the performance objectives should be specified such that the required seismic performance can be demonstrated over the design life of the structure. Here, the term "design life" refers to the period over which the performance requirements for a structure must be met, being determined by a nuclear power operator based on social and economic factors.

The durability performance of an underground RC structure is to be determined such that material degradation due to environmental impact would have little effect on seismic performance over the design life of the structure. The carbonation of concrete or penetration of chloride ions into concrete may result in material deterioration such as reinforcing bar corrosion, the onset of cracking, and reduction of the reinforcing bar cross-sectional area. In addition, freezing and thawing actions can cause material deterioration, such as the reduction of concrete quality. These may affect seismic performance depending on the degree of severity. Therefore, the performance objectives of durability performance are to be specified such that the extent of these material deteriorations would have little or minor effect on seismic performance over the design life of a structure.

Three types of environmental impact, carbonation, the intrusion of chloride ions, and freezing and thawing action, should be considered for the durability performance of underground RC structures. The presence of carbon dioxide in the air necessitates examination of the carbonation of concrete for the underground RC structures commonly exposed to the atmosphere. These structures may be in contact with seawater or soil containing seawater and may also be exposed to airborne salt. Accordingly, the intrusion of chloride ions should be considered in the durability performance assessment of such underground RC structures. In addition, freezing and thawing action should be considered for underground RC structures in cold regions because of the temperature change.

2.3 Seismic Performance

(1) Reference earthquake motion S_S shall be employed as the seismic action in the performance verification of underground RC structures during an earthquake.

(2) The seismic performance of an underground RC structure shall be specified as follows:

1) An underground RC structure that requires the support of equipment and piping systems shall maintain structural integrity without collapse under reference earthquake motion S_S as well as satisfy the conditions specified for the functional capability of its equipment and piping.

2) An underground RC structure that requires the water delivery function in the event of an emergency shall maintain structural integrity without collapse under reference earthquake motion S_S.

[Commentary]

(1)

The technical code JEAC4601-2015 classifies underground RC structures mainly as "indirect support structures", for which the guidelines drop the term *indirectly* as discussed in **Section 1.1 Scope of Application** of **Chapter 1**. This results in using identical reference earthquake motions for structures as those used for the earthquake resistant design of "primary equipment", "secondary equipment", or "direct support structures" that could be significantly affected by damage to an underground RC structure. The reference earthquake motion is to be defined in accordance with the provisions of the “Interpretation of the Regulation”.

(2)

Underground RC structures are classified as one of the following four types of system: 1) reactor-cooling-water system equipment, 2) emergency-power-supply equipment, 3) safety-injection-system and auxiliary-water-supply equipment, and 4) emergency gas-processing equipment (see Commentary Table 1.1-4). According to the technical code "Chapter 2-Seismic Grade Classification in JEAC4601-2015", the systems labeled 1) to 4) above are classified as seismic grade Class S. In addition, the performance requirements for underground RC structures are specified distinctly as either support function or emergency water delivery function. These discussions permit the performance objectives for underground RC structures to be specified for their respective required functions. The performance requirements for various structures and the performance objectives being developed are described in Commentary Table 2.4-1.

The functional capability for equipment and piping should be confirmed under the reference earthquake motion S_S for the underground RC structures requiring the support function of Class S equipment and piping systems. For this purpose, an underground RC structure needs to secure installation space, and the structure should provide the required load-carrying capability. Usually, the load-carrying capability can be ensured by demonstrating that the structure maintains its structural integrity without collapse. Accordingly, the performance objectives for the underground RC structures requiring the support function of Class S equipment and piping systems should be specified such that the structure can maintain its structural integrity without collapse under reference earthquake motion S_S. In addition, restrictions on the functional capability of equipment and piping presented by mechanical or electrical engineers are to be examined during verification.

The systems of underground RC structures requiring the water delivery function in the event of an emergency are classified as Class S; therefore, the water delivery function should be secured to ensure proper functioning of the system. This can be achieved with reference to the load-carrying capability of the structure. Thus, the performance objectives should also be specified such that the structure can maintain its structural integrity without collapse under reference earthquake motion S_S for underground RC structures requiring the water delivery function

After the Great East Japan Earthquake, civil engineering communities have recognized the importance of ensuring crisis resistance such that a structure will never experience catastrophic damage even if the intensity of a seismic event exceeds the design earthquake ground motion. In the case of underground RC structures considered as a part of the seismic risk management at a nuclear power plant, it is desirable to avoid structural collapse due to the exceedance of the specified limit state defined in the verification process that may affect the upper system and result in the loss of the cooling function of a reactor. Currently, no concepts have been yet established for designing and building power plant facilities (facilities and their environment) to achieve crisis resistance; however, crisis resistance may be approached via seismic design planning. It is also possible to examine crisis resistance using certain measures, *e.g.*, preventing the brittle failure of a structure by identifying its failure limits using a pushover analysis or controlling the structural damage of an underground RC structure from the interference of possible recovery activities during accident management. In any case, the fracture behavior of individual facilities and structures as well as their consequences need to be understood to comprehensively enhance crisis resistance.

Commentary Table 2.4-1. Required performance for critical underground RC structures developed from the performance requirements for a nuclear power plant during an earthquake

Capabilities of a nuclear power plant during an earthquake		Capabilities of equipment and piping systems		Capabilities of Underground RC structures		
				Structures	Performance requirements	Performance objectives
Securing safety for a nuclear power plant during an earthquake includes: To "shut down", to "cool down" a reactor, and to "confine" radioactivity.	Equipment, buildings, and other objects that execute a "shut down", "cool down", or "confine" function normally operate without any effect from seismic action. ↓ Seismic grade classifications: Class S ・Facilities with the functionality required to shut down a reactor and cool down a reactor core in response to a possible event due to seismic action. ・Facilities that are directly related to equipment that could diffuse radioactive substances to the exterior due to the loss of functionality. ・Facilities necessary to mitigate the impact of accidents resulting from the loss of function and reduce the impact of radiation on the environment.	Class S equipment and piping highly integrated into an underground RC structure ↓ To "shut down" (1) Emergency-power-supply facilities The facilities that supply power are required to safely shut down a reactor in the event of a loss of the external power supply system and to operate the engineered safety facilities. (Common for PWR and BWR) To "cool down" (2) Reactor-cooling-water-system facilities In the event of an emergency, the facilities remove the reactor decay heat (residual heat) and supply sufficient cooling water to cool the emergency nuclear equipment. (Common for PWR and BWR) to "confine": (3) Emergency gas-processing facilities The facilities safely process the radioactive waste gas generated inside the reactor building in an emergency, while maintaining negative pressure. (Peculiar for BWR)	Performance requirements for equipment and piping during an earthquake: To ensure the pumping capability of pumps. To ensure the water delivery capability of pipes. To ensure the liquid storage function of tanks. To ensure the ventilation capability of pipes. To ensure the functioning of stacks. Performance objectives for equipment and piping: For reference earthquake motion Ss: Piping maintains required functionality under the load conditions considering loads under normal operation and loads arising from transient abnormalities and accidents during operation and seismic action under the reference earthquake motion. ・Even when plastic strain develops in the facilities under a loading as described above, the amount of strain remains at a very small level. Thus, the facilities should have sufficient safety margin in their load carrying capacity to remain unaffected in their functionality as required for the facilities. ・Equipment establishes the required functions or dynamic function against dynamic responses induced by reference earthquake motion Ss. Specifically, the allowable limits shall be established as functional capability acceleration as determined by verification tests.	Underground RC structures that require the supporting function of Class S equipment and piping. ・Intake pits (Common for PWR and BWR) Diesel-oil-pipe duct (Common for PWR and BWR) ・Piping-support ducts (Common for PWR and BWR) ・Emergency gas-processing-pipe duct (Peculiar for BWR) ※Tanks and stack foundations (massive concrete) are beyond the scope of these guidelines.	To safely support equipment and piping (Assurance of support function) The equipment and piping maintain operation without loss of functionality (Notes) Underground RC structures are civil engineering structures that require the supporting function of seismically important equipment and piping or the water delivery function of seawater in case of an emergency. Their seismic design requirements are to be established in view of the safety function of the support structures and facilities being possibly affected by significant damage distinct from the overall structural functions. ("JEAC4601-2015")	For reference earthquake motion Ss: (1) Structures maintain structural integrity without collapse. (2) Structures satisfy the requirements for the functional capability of equipment and piping as an underground RC structure. (In coordination with mechanical and/or electrical engineering input) ↓ (1) Verification using relative story deformation angle, shear capacity, and other factors. (2) Checking equipment and piping conditions.
				Underground RC structures that require the emergency water delivery function ・Water delivery channel, intake pits (Common for PWR and BWR)	Delivering the required amount of sea water (Securing the form of cross-section needed to deliver sea water)	For reference earthquake motion Ss: (1) Structures maintain structural integrity without collapse. ↓ (2) Verification using relative story deformation angle, shear capacity, and other factors.

2.4 Steps for Performance Verification

For performance verification during an earthquake, the performance settings are first discussed considering the performance requirements for a considered structure and the design conditions. Second, methods of analysis and verification are selected based on the material properties, seismic action, and environmental impact. Finally, seismic performance verification is carried out in a distinct manner depending on whether the structure requires the supporting function of certain equipment and piping systems or whether the structure requires the emergency water delivery function.

[Commentary]

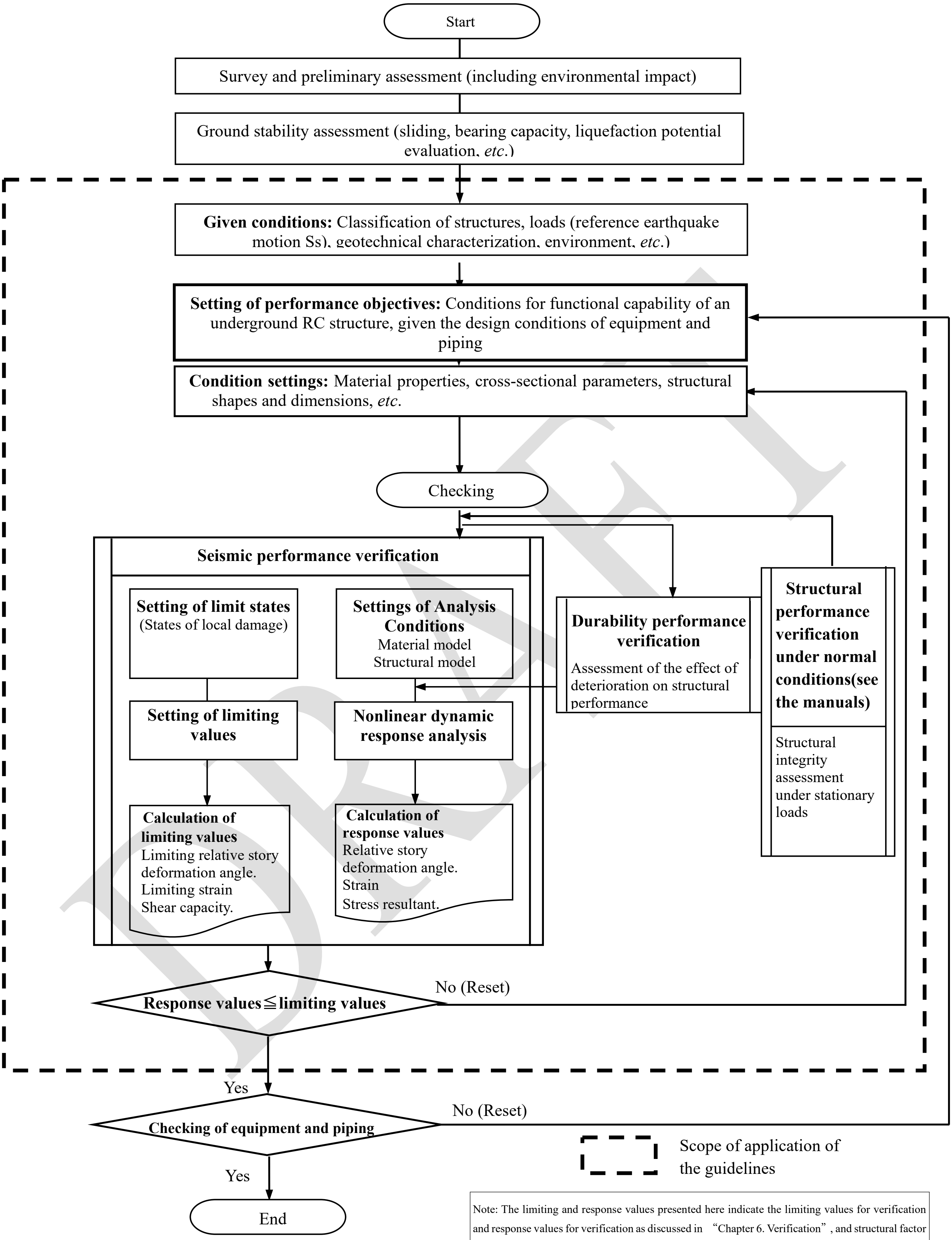
Typical flowcharts of performance verification for both underground RC structures requiring the support function of equipment and piping system as well as the emergency water delivering function are shown in Commentary Figures 2.6-1 and 2.6-2, respectively. As clearly indicated, the present guidelines cover the steps in the box with the bold-dashed-line based on the assumption that a survey, preliminary assessment, and ground stability assessment have already been implemented at a site.

The main objective of performance verification for the underground RC structures requiring the support function of Class C equipment and piping system is to establish the functional capability of its equipment and piping under the assumed load conditions as shown in Commentary Figure 2.6-1. This specifies the constraints required for an underground RC structure as the “conditions given” to ensure functional capability of their equipment and piping. In addition, matters incapable of being directly checked are to be examined as part of an integrity evaluation of the equipment and piping system outside the flow of the underground RC structure verification process. Specifically, in the underground RC structures requiring the support function, the seismic safety of equipment and piping is to be evaluated based on the floor response acceleration. The performance settings for an underground RC structure may be reset depending on such floor response evaluations. These steps complete the verification including verification for the seismic safety of the equipment and piping. From the viewpoint of streamlining the structural design process, it is desirable to check the seismic safety of equipment and piping using a coupled-structural-system analysis that is incorporated into the process of the overall structure, but such numerical computation is not possible at present. Thus, the guidelines identify the boundaries between the equipment and piping and an underground RC structure, providing a framework for the checking process. For example, if equipment is anchored to a certain part of a structural member that was damaged during an earthquake, the impact of the damage on the anchor or the equipment and piping should be examined using an appropriate approach.

On the other hand, performance verification for the underground RC structures requiring the emergency water delivering function can be carried out in accordance with the use and purpose of the structure, and the verification is considered complete without assessment of the seismic safety of the equipment and piping, as indicated in Commentary Figure 2.6-2.

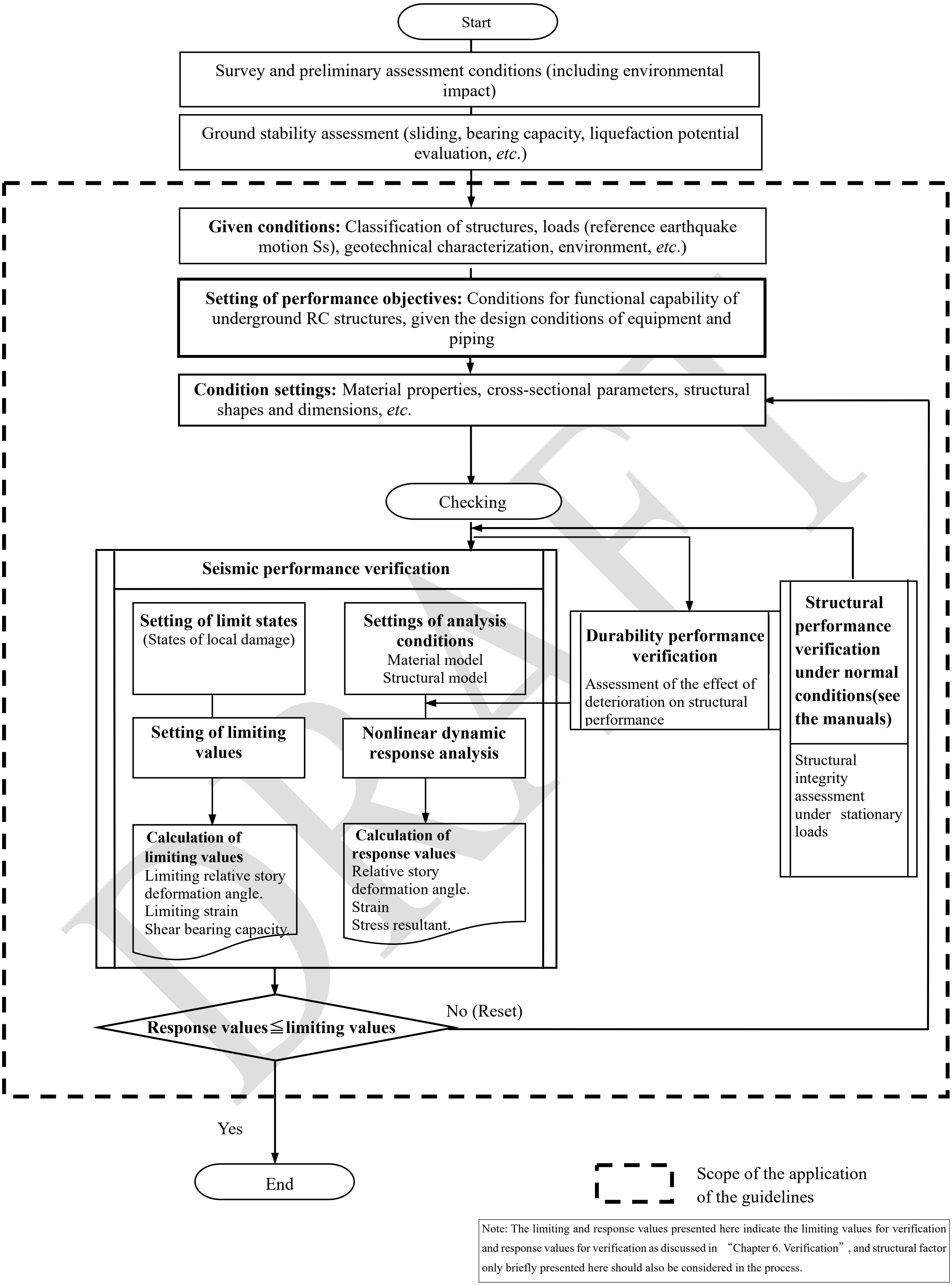
Aging related to the carbonation of concrete, intrusion of chloride ions, and freezing and thawing action may degrade the seismic performance of underground RC structures. Ideally, the seismic response analysis conducted during seismic performance verification should consider the state of aging about the design life of a structure; however, the current methods of structural analysis are unable to model this. Accordingly, the present guidelines ensure seismic performance through the independent verification of durability performance and seismic performance. Hence, limit states, such as “aging condition having little or minor effects on the seismic performance of a structure", are determined during the durability performance verification. This verification confirms the assumption made during the seismic performance verification that the conditions of a structure (*e.g.*, material properties, bond characteristics between reinforcing bar and concrete, and stiffness) are the same as immediately after completion of the structure.

Although the present guidelines only cover performance verification in the event of an earthquake, underground RC structures are essentially required to ensure water delivery functionality for cooling seawater even under normal conditions (*i.e.*, under stationary loading). In other words, it needs to be ensured that the quality of materials assumed during the seismic performance verification of an underground RC structure is unaffected by the continuous action that would have occurred under normal conditions. In addition, the structural design of underground RC structures for normal conditions needs to be streamlined. Therefore, the contents of structural performance verification under normal conditions are also provided in **Chapter 6** of the manuals.



Note: The limiting and response values presented here indicate the limiting values for verification and response values for verification as discussed in "Chapter 6. Verification", and structural factor only briefly presented here should also be considered in the process.

Commentary Figure 2.6-1 Flow chart of performance verification (support function)



Note: The limiting and response values presented here indicate the limiting values for verification and response values for verification as discussed in "Chapter 6. Verification", and structural factor only briefly presented here should also be considered in the process.

Commentary Figure 2.6-2. Flow chart of performance verification (water delivery function)

CHAPTER 3 MATERIALS

3.1 General

Material properties shall be determined using characteristic values of the materials and mechanical properties, such as the stress-strain relationship, according to the application to determine the structural response values and estimate the limiting values.

[Commentary]

When structural analysis is carried out during seismic performance verification for a critical underground RC structure, the material properties of the soil, concrete, and reinforcing bar are required to assess the loads (*e.g.,* earth pressure and self-weight), structural responses, and limiting values of the structure. "Material properties" refers to the characteristic values of a material (such as concrete strength) and a mechanical model of a material (such as the constitutive law of concrete). In the present guidelines, the mechanical properties of materials mainly cover the flexural moment-curvature relationship of the cross section of a reinforced concrete member used in macro element nonlinear analysis and the stress-strain relationship (in a compressional, tensile, or shearing field) used in material nonlinear analysis. Most mechanical models of a material have one characteristic value as the parameter of the model. Providing the characteristic values of a material often enables the evaluation of its limiting values using an appropriate formula, whereas structural response analysis requires a mechanical model of the material. These mechanical properties should be established considering the accuracy and limitations of the formulas used to calculate the limiting values and the tools for structural analysis used in the verification process. Since the characteristic values of a material are usually scattered to some extent, they should be specified under the most unfavorable conditions of the structure. The mechanical property models are described in **Chapter 5. Methods of Analysis**.

Safety verification for existing structures offers narrower uncertainty factors for the construction work than for the design stage. The measured values of material properties also usually have variations depending on the data acquisition method. Accordingly, properly managed construction and data acquisition methods allow the characteristic values of materials to be successfully employed as measured values.

3.2 Material Properties of Concrete, Reinforcing Bar, and Soil

(1) Characteristic values for concrete materials shall be determined based on tested values obtained using actual concrete materials and mix proportions.

(2) Characteristic values for reinforcing bars shall be determined based on tested values obtained using actual reinforcing bars.

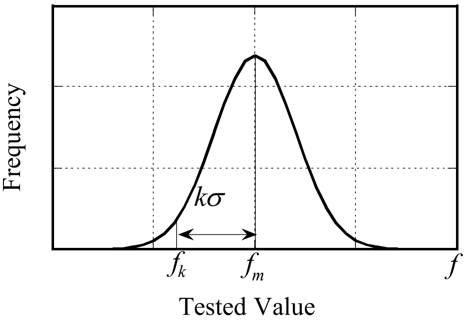
(3) Characteristic values for soil materials shall be determined based on tested values obtained from *in situ* tests at the site and laboratory tests of samples taken from the site.

[Commentary]

(1)

Concrete with appropriate mix proportions (such as strength, slump, *etc.*) has relatively little variation in its inherent material properties; however, its actual material properties under practical mix proportions can vary depending on the conditions of the aggregate and mixer kneading. Accordingly, the characteristic values for concrete materials are to be determined based on tested values obtained using actual materials and mix proportions.

The material properties of concrete are characterized by compressive strength, tensile strength, bond strength, Young's modulus, Poisson's ratio, stress-strain curve, *etc*. They can also be characterized by thermal properties, drying shrinkage, and creep, depending on the environmental conditions around the structure of interest. Concrete material properties that are not time dependent are to be generally determined based on strengths obtained from 28-days tests; however, they may be determined based on tests using other appropriate ages depending upon factors such as the duration of the principal loading, the construction schedule, materials, mix proportion, and construction technique.



Commentary Figure 3.2-1 Concept of Characteristic Values

Characteristic values for concrete strength may generally be obtained using Eq. (3.2-1), which has been established by probability to have tested values less than the characteristic value and distribution shape of tested values in consideration of the variation arising from the manufacturing process of concrete.

$$f_k = f_m - k\sigma = f_m(1 - k\delta) \qquad (3.2\text{-}1)$$

where f_k is the characteristic value, f_m is the mean of tested values, σ is the standard deviation, δ is coefficient of variation of tested values, and k is the factor.

The other characteristic values for concrete material are to be essentially in accordance with the “Specification [Design Edition]”. The following is an outline of the respective characteristic values provided in the “Specification [Design Edition]”.

a. Compressive strength

The characteristic values for the compressive strength of concrete are to be specified such that the probability of a tested value being smaller than a characteristic value be less than or equal to 5%. When this is the case and a normal distribution is assumed, then the coefficient k becomes 1.645 (see Commentary Figure C3.2-1)

Characteristic values for the compressive strength of concrete are, in general, to be based on 28-days tests in accordance with JIS A 1108 "Method of Test for Compressive Strength of Concrete". Specimens should be prepared in accordance with JIS A 1132 "Methods of Making and Curing Concrete Specimens". When JIS A 5308 "Ready-Mixed Concrete" is used, however, the nominal strength specified by the purchaser may be used as the characteristic compressive strength of the concrete.

When testing compression strength using drilled concrete cores to identify the characteristic values of the strength of existing structures, JIS A 1107 "Method of Sampling and Testing for Compressive Strength of Drilled Cores of Concrete" should be followed. The use of measured results in the verification of existing structures is provided for in the "Recommendations on Evaluation of Structural Sound Function" and "JEAC 4601-2015". The conditions and methods for incorporating them into the safety factors are described in **Chapters 2 and 3** of the manuals.

b. Tensile strength

The characteristic values for the tensile strength of concrete are to be determined using appropriate tests or Eq. (3.2-2). Tests for the tensile strength of concrete are to be carried out in accordance with JIS A 1113 "Method of Test for Splitting Tensile Strength of Concrete."

$$f_{tk} = 0.23 f'^{2/3}_{ck} \tag{3.2-2}$$

where f_{tk} is the tensile strength of concrete and f'_{ck} is the basic design strength.

c. Bond strength

The characteristic values for the bond strength of concrete are to be determined using appropriate tests. Alternatively, deformed bars that meet the provisions of JIS G 3112 "Steel Bars for Concrete Reinforcement" may be obtained using:

$$f_{bok} = 0.28 f'^{2/3}_{ck} \tag{3.2-3}$$

where f_{bok} is the bond strength of concrete and is less than or equal to 4.2 N/mm^2.

d. Flexural cracking strength

The flexural cracking strength of concrete may be obtained using:

$$f_{bck} = k_{0b} k_{1b} f_{tk} \tag{3.2-4}$$

where

$$k_{0b} = 1 + \frac{1}{0.85 + 4.5(h/l_{ch})}, \tag{3.2-5}$$

$$k_{1b} = \frac{0.55}{\sqrt[4]{h}} \quad (\geq 0.4), \tag{3.2-6}$$

and k_{0b} is the coefficient representing the relation between tensile strength and flexural cracking strength on account of the tension softening characteristics of concrete, k_{1b} is the coefficient representing the reduction in crack strength caused by drying, heat of hydration, *etc*., h is height of the member (m) and l_{ch} is the characteristic length (m) ($l_{ch} = G_F E_c / f^2_{tk}$), E_c is Young's modulus, G_F is fracture energy, and f_{tk} is tensile strength. Fracture energy and Young's modulus are to be obtained in accordance with "f" and "g" below.

e. Stress-strain curve

Several curves have been developed for various stress-strain behaviors. It is desirable to select an appropriate stress-strain curve after reviewing their features and limitations. When examining ultimate limit states under the large deformation of a structure, it is advisable to use a stress-strain curve that can be expected to provide an elaborate solution in the softening region. In general, concrete surrounded by hoops or shear reinforcement is known to have greater compressive strength and ultimate strain on account of the confining effect of those reinforcements. If such a confining effect of reinforcement is identified via experiment, the experimental results may be used as the stress-strain curve. Appropriate hysteresis curves consisting of unloading and reloading curves should be selected based on previous studies or experiments.

Since the stress-strain curves under biaxial or triaxial stress differ from those under uniaxial stress, the effect of such stress is to be taken into consideration for examination of the ultimate limit states. In addition, a concrete constitutive model, which will be provided later in the present guidelines, is required to handle stress-strain curves under biaxial or triaxial stress.

The stress-strain relationship of concrete used for earthquake response analysis is described in **Chapter 3**, "3.2 Calculation of response values using material nonlinear analysis" of the manuals.

f. Tension softening properties

Fracture energy, G_F, of normal concrete may be obtained using:

$$G_F = 10(d_{\max})^{1/3} \cdot {f'_{ck}}^{1/3} \qquad (3.2\text{-}7)$$

where d_{max} is the maximum size of coarse aggregate (mm), and f'_{ck} is the characteristic value of compressive strength (basic design strength).

g. Young's modulus

The Young's modulus of concrete is to be obtained from appropriate tests. The test is to be conducted in accordance with JIS A 1149 "Method of Test for Static Modulus of Elasticity of Concrete". In general, the values of the Young's modulus for concrete may be taken to be equal to that shown in Commentary Table 3.2-1 provided in the "Specification [Design Edition]".

Commentary Table 3.2-1. Young's modulus of normal concrete

f'_{ck} (N/mm^2)	18	24	30	40	50	60	70	80
E_c (kN/mm^2)	22	25	28	31	33	35	37	38

h. Poisson`s ratio

The Poisson`s ratio of concrete may, in general, be set as 0.2 within the elastic range.

(2)

In general, the strength of reinforcing bars varies in quality even when the manufacturing process is properly controlled. Thus, the material properties of reinforcing bars are to be determined based on the strengths obtained by tensile tests, including reinforcing bars specified by JIS (the Japanese Industrial Standards).

The material properties for reinforcing bars are determined by yield strength, tensile strength, and the stress-strain relationship under tension, compression, and shear. In addition, the thermal properties are to be considered as material properties in accordance with the environmental conditions of the structure of interest. The material properties for reinforcing bars are to be specified in accordance with the “Specification [Design Edition]”. These specifications are outlined below:

a. Tensile yield strength and tensile strength

The characteristic values of tensile yield strength and the tensile strength of reinforcing bars are to be determined based on the strengths obtained from tensile tests. The tensile tests of reinforcing bars are to be carried out in accordance with JIS Z 2241 “Metallic Materials-Tensile Testing-Method of Test at Room Temperature”.

In general, reinforcing bars that meet JIS provisions have lower limit values specified as their characteristic values. The nominal cross-sectional area of a reinforcing bar specified in JIS may be used for the purposes of design.

b. Compressive yield strength

The characteristic values of the yield strength of reinforcing bars in compression may be taken to be the same as that in tension.

c. Stress-strain curve

The stress-strain curve of reinforcing bars is to be assumed to have a suitable form for the purpose of structural analysis. Several stress-strain curves have been developed, including a fully elastoplastic model with tensile yield points and a bilinear model with secondary stiffness connecting tensile yield and tensile strength points. The heterogeneously developed stress and strain of reinforcing bars in concrete increase at the crack position and decrease elsewhere. Thus, recent studies have formulated the stress-strain relationship of reinforcing bars as an average stress-strain curve. When analyzing concrete areas in which cracks are dispersed, the use of such a model improves the accuracy of the analytical results. Preferably, a hysteresis curve consisting of unloading and reloading curves should be selected from an appropriate model based on previous studies or experiments.

d. Young's modulus and Poisson's ratio

It is a principle that the Young's modulus of reinforcing bars is to be determined from the results of the stress-strain curve obtained by the tests for tensile yield strength. Reinforcing bars that meet JIS provisions may generally be set as 200 kN/mm^2. Similarly, the Poisson`s ratio for reinforcing bars, in general, may be set as 0.3.

(3)

In general, geotechnical profiles vary from site to site with variation in soil properties as well. Therefore, the characteristic values for soil materials are to be determined based on strengths and moduli obtained from *in situ* tests as well as laboratory tests of undisturbed samples taken from the site. The characteristic values of the soil parameters may also be taken from proven data specified in geotechnical recommendations or standards or previous test data available elsewhere in certain cases in which the applicability of the tools for structural analysis or the estimation accuracy of seismic actions or limiting values clearly conform to the safety requirements of the verification process.

In situ tests and laboratory tests to determine the material properties of soil parameters are to be conducted in accordance with the "Report on Soil Stability Evaluation Method of JSCE" (Part 3, Ground Survey and Testing Method) or "JEAG 4601-2015". Testing practices are to be carried out in accordance with widely recognized standards such as JGS (Societies of Geological Engineering Standards) or JIS.

CHAPTER 4　ACTIONS

4.1 General

For performance verification under seismic action, the actions likely to occur during the design life of a structure shall be determined according to the performance requirements and concerning the level of intensity experienced by the structure. The seismic action shall be specified using earthquake motions established based on the seismicity and ground characteristics around the site.

The performance requirements for a structure shall be identified according to the actions expected to occur during the design life of the structure.

[Commentary]

In the present guidelines, "action" refers to any event that could cause stress and/or deformation of a structure or members of a structure, as well as any change in material properties over time due to deterioration. Typical combinations of actions and actions required for structural performance verification under normal conditions and durability performance verification are described in **Section 4.2 Combinations of Actions**. Actions to be considered in seismic performance verification and the reference earthquake motion for seismic action are described in **Section 4.3 Seismic Action in Seismic Performance Verification**.

Seismic action refers to the effects of a reference earthquake motion on any dynamic behavior of a critical underground RC structure. The reference earthquake motion is to be established in accordance with "The Interpretation of the Regulation" and defined under the conditions given for seismic performance verification, being deliberately determined in accordance with appropriate provisions other than the present guidelines. The reference earthquake motion adopted as the seismic action for an instance of seismic performance verification is to be determined based on the performance requirements for the underground RC structure of interest as discussed in **Section 2.3 Seismic Performance**.

4.2 Combinations of Actions

(1) Combinations of actions shall be determined considering the characteristics of individual actions, the probability of their simultaneous occurrence, and the degree of their impact on the limit state.

(2) <u>Environmental actions that induce material deterioration such as carbonation, chloride ion intrusion, and freezing and thawing action shall be determined, in principle, based on field observation data at the site.</u>

(3) Permanent and variable actions shall be accounted for in durability performance verification and structural performance verification under normal conditions.

[Commentary]

(1)

In the present guidelines, the combinations of actions tabulated in Commentary Table 4.1-1 should be generally specified according to the performance verification being conducted.

Commentary Table 4.1-1 Combinations of design actions

Seismic performance verification	Permanent action + seismic action (variable action is excluded)
Durability performance verification	Permanent action＋variable action
Structural performance verification for normal conditions	Permanent action＋variable action

In the present guidelines, load actions are generally divided into permanent actions, variable actions, and seismic actions. Permanent action refers to a load that acts continuously on a structure and has variability of negligible magnitude compared with the average magnitude. Permanent action includes self-weight (dead load), installation load, overburden load, permanent imposed load, earth pressure at rest, exterior hydrostatic pressure, and interior hydrostatic pressure. underground RC structures are constructed in coastal areas, where the groundwater level depends on the sea level. Hydrostatic pressure acts on these structures below the groundwater level, thereby varying with the sea level of the tide; however, the sea water level can be seen as stationary over the long term. This results in hydrostatic pressure being considered a permanent action here. Variable action refers to a load that varies frequently or continuously and the variations are of non-negligible magnitude compared with the average load. Variable actions include variable loading due to the effect of temperature, snow loading, and vehicle traffic; however, when snow fall is frequently observed in a cold region, the snow load should be considered a permanent action.

For typical loading actions other than seismic action, their characteristic values are to be determined so as to provide the most unfavorable conditions for the limit states of a structure considering the expected variation of the individual loads during the design life, the combinations of actions, and the limit state being examined.

The action considered during verification is firstly selected from one of seismic action, structural performance verification under normal conditions (permanent action + variable action), or environmental action. Next, the combinations of actions are specified according to the category of verification. Finally, the characteristic values for the respective actions are evaluated and then multiplied by action factors to define the design action. Commentary Table 4.1-2 outlines the type of and calculation methods for the load actions under consideration. Specific characteristic values may be obtained based on design drawings or the “Specifications [Design Edition]”, or from elsewhere; however, specific values are to be used if they have been obtained from testing or observed data.

Commentary Table 4.1-2. Outline of load (action) types and calculation methods

Type		Load	Method of Calculation
Permanent action	Stationary load	Self-weight	The volume of the structure multiplied by the unit weight of the material based on the design drawings.
		Equipment and piping load	The loads specified by the mechanical designs *etc*., calculated from the weight of equipment and piping.
		Overburden load	The weight of the ground above the crown of the structure.
		Permanent imposed load	The weight of objects permanently placed above the ground surface.
	Earth pressure at rest		The direction (positive or negative) in which the earth pressure at rest contributes to the stress resultant and accounting for the extent of variation. Specifically, the coefficient of earth pressure at rest uses upper and lower limits to determine appropriate action factors.
	Exterior hydrostatic pressure		Hydrostatic pressure based on the groundwater level.
	Interior hydrostatic pressure		Hydrostatic pressure acting on the inner wall of a structure, such as that generated by a water delivery channel or an intake pit.
Variable action		Variable imposed load	The live load of traffic transferred to the structure.
		Snow load	Calculation based on the design depth of snow above the ground, unit design weight of snow, and gradient of the structure’s surface.
		Effect of temperature	If the effect of temperature is a subsidiary load, the rigidity of the structure may be reduced by 50% of the total cross-sectional rigidity in calculating thermal stresses.
Seismic action[*1]		Horizontal earthquake ground motion	The time history accelerations are specified in accordance with provisions other than the present guidelines. They are also used as given conditions in the present guidelines.
		Vertical earthquake ground motion	Time history accelerations are specified as given conditions in the same manner as the horizontal earthquake ground motions. The seismic coefficient of vertical ground motion is generally set to be 50% of the horizontal maximum acceleration amplitude of the reference earthquake motion defined at the site rock outcrop surface.
		Dynamic water pressure	Appropriately modeled by dynamic response analysis.

* 1) In principle, structural analysis is carried out via time-history earthquake response analysis in the present guidelines. When other methods are used for structural analysis, the seismic action should be treated as follows:

Dynamic earth pressure	Dynamic earth pressure is, in principle, estimated using dynamic response analysis. Other methods may be used if proven tools are available.
Inertial force	The effect of a horizontal motion is calculated by multiplying the horizontal acceleration response of a structure obtained from dynamic analysis by its mass. The effect of a vertical motion is determined using a seismic coefficient equal to 50% of the horizontal maximum acceleration amplitude for the reference earthquake motion at the site.
Dynamic water pressure during an earthquake	Dynamic water pressure during an earthquake can be estimated using Westergaard’s formula and other proven methods.

(2)

Environmental actions examined during performance verification are to be identified about the environmental conditions in which the structure of interest is constructed. The constructed environments of the underground RC structures in Japan have carbonation, intrusion of chloride ions, and freezing and thawing processes as their associated environmental actions; however, the actual environmental conditions may differ.

For the carbonation of concrete, the required conditions (*e.g.*, the wetting conditions) are first determined to estimate depth of carbonation. Carbonation-induced deterioration, which frequently occurs on concrete structures almost everywhere in Japan, should be considered as an environmental action.

For the intrusion of chloride ions, parameters such as the outdoor temperature, humidity, dry-wet cycle conditions, and the distance from a shoreline are determined based on field observation data to assess the diffusion of salinity from the concrete surface to the interior. Japanese nuclear power plants constructed on the coast need to consider the intrusion of chloride ions for their associated environmental actions.

For freezing and thawing action, freezing days and freezing and thawing action frequency are determined based on a survey of local weather conditions (*e.g.*, outdoor temperature); however, freezing and thawing action need not be considered in environments where no freezing actions are observed.

Concerning durability performance verification, an estimation of the cracking width of a developed crack in a concrete structure is required as a prerequisite condition for the consideration of the intrusion of chloride ions. This requires a load action to calculate the cracking width.

(3)

In addition to individual variable actions, the simultaneous action of the effect of temperature and variable imposed loading can be considered. All other combinations, *e.g.*, the effect of temperature and snow load, snow load and variable load, *etc.*, are not considered because the probability of their simultaneous occurrence is judged to be negligible.

In durability performance verification, the checking of concrete cracks is to be the first item. The reason for this is that this information is required to set the diffusion coefficient for chloride ions in subsequent verification of chloride-induced deterioration. In addition, if the cracking width is below or equal to the allowable value, the crack can be ignored for the verification of carbonation.

Structural performance verification under normal conditions can be carried out via the stress-centered checking of strengths of reinforcing bar and concrete. This verification method assumes that the rigidity of the structural members is higher than that in seismic performance verification, which considers the large deformation of structural members. Therefore, the effect of temperature should be accounted for in verification under normal conditions.

Commentary Table 4.3-1 shows the combinations of actions (loads) considered in durability performance verification and structural performance verification under normal conditions. The data in the table are supplemented with the following outlines:

a. Individual variable action

Characteristic values for a subsidiary variable load, snow load, and the effect of temperature may be determined to be one-half of the load estimated using commonly accepted methods.

b. Combination of the effect of temperature and a variable load

Significantly small probabilities of the simultaneous occurrence of these loads can further reduce the characteristic values already modified according to "a" above. This reduction factor can be generally assumed to be 0.7. In this case, the method for calculating the characteristic values for each load are:

1) Variable imposed load: $9.8\ \mathrm{kN/m^3} \times 0.5 \times 0.7 = 3.43\ \mathrm{kN/m^2}$

2) Effect of temperature: (estimated effect of temperature) $\times 0.5 \times 0.7$

Commentary Table 4.3-1 Combinations of load actions for durability performance verification and structural performance verification under normal conditions

Type of combinations	Variable action		
	Variable imposed load	Snow load	Effect of temperature
a. Individual variable actions	Applicable	N/A	N/A
	N/A	Applicable	N/A
	N/A	N/A	Applicable
b. Combination of the effect of temperature and a variable load	Applicable	N/A	Applicable

4.3 Seismic Action Considered in Seismic Performance Verification

(1) Seismic action shall be evaluated by time-history seismic response analysis with soil-structural interaction using a reference earthquake motion.

(2) The combination of permanent action and seismic action shall be considered in the seismic response analysis.

[Commentary]

(1)

The seismic action considered in seismic performance verification is evaluated based on a time-history seismic response analysis with soil-structure interaction using a reference earthquake motion defined at the site rock outcrop surface. As shown in **Chapter 5. Methods of Analysis** of the present guidelines, the dynamic behavior of an underground RC structure during an earthquake should be, in principle, evaluated using nonlinear time-history seismic response analysis that can handle soil and structure interaction.

For reference earthquake motions, the effects of the combined response values of horizontal and vertical seismic actions are to be appropriately considered in accordance with the provisions of "The Interpretation of the Regulation".

The effects of seismic action on an underground RC structure are generally dominated by the horizontal earthquake ground motion. The relatively large stiffness and load carrying capacity along the longitudinal direction means that the transverse-section perpendicular to the water flow governs the seismic responses of intake pits and piping support ducts under horizontal earthquake motions from all directions. This seismic response characteristic usually leads to idealization of the structure in two- dimensions, and then a time-history earthquake response analysis is performed for in-plane excitation. On the other hand, when the seismic response of the transverse-section of a structure is insignificant or when the response behavior of a structure needs to be rigorously evaluated, an appropriate method of performance checking about the seismic action needs to be conducted based on a longitudinal-section model or a three-dimensional model as needed. In seismic response analysis using a three-dimensional model, orthogonal horizontal input motions are usually required; however, if the predominant direction of the earthquake ground motions can be distinguished from the less dominant directions, a single input motion may be applied. It should be noted that even if the earthquake ground motion is applied in a single direction, multiple-axis responses may develop in certain structural configurations.

If the horizontal and vertical components of the earthquake ground motions used for verification are both given by time-history accelerations, a seismic response analysis should be performed under simultaneous input motions. The effects of vertical earthquake ground motions (upward and downward directions) should be considered in accordance with “The Interpretation of the Regulation”. When examining the effects of vertical earthquake ground motions as vertical seismic coefficients, two types of seismic coefficient, those in the upward and downward directions, should be adopted.

(2)

In seismic performance verification, the permanent action is set as the initial load on the structure being examined and the seismic action is then examined under that condition. In the event of a seismic action, the response of the structure may enter a nonlinear region, and thus the stresses and strains caused by each of the permanent action and the seismic action cannot be superimposed. Therefore, the initial state of the stress and strain in the structure developed from the permanent action is to be first calculated, and then the time-history earthquake response analysis is to be carried out using a reference earthquake motion. These steps enable the superimposition of the permanent action and seismic action. Furthermore, since the probability of the simultaneous occurrence of the seismic action and variable action is judged to be considerably small, any variable action can be ignored in the seismic performance verification.

Seismic action also includes dynamic earth pressure and ground deformation acting on a structure. These should be estimated using the soil properties or appropriate soil parameters prepared for seismic response analysis.

In general, soil properties significantly vary with the type of ground, the inhomogeneous nature of ground, and the extent of soil compaction for filled ground. “Soil properties” here refers to several generic terms such as the coefficient of earth pressure at rest, shear wave velocity, stress-strain relationships, and hysteresis loop parameters. Soil properties are also scattered depending on the method used in the *in situ* or laboratory tests. Therefore, it is essential to determine the characteristic values for soil properties in such a way that the effects of the characteristic values on a structure would be the most unfavorable, including the shear deformation and stress resultant (shear force, flexural moment, and axial force). Generally, the mean value of the tested data for soil properties (equivalent to the statistical median) does not match their characteristic values. When soil properties have been determined to provide a safer estimation on the failure mode of a structure (bending or shear), a single set of soil properties may be used. When the specified soil properties are deemed to be dangerous for the structural responses yielded at the characteristic value setting stage, it is advisable to establish multiple sets of soil properties based on the mean values of available tested data or proven data obtained from previous research.

In addition, dynamic water pressure is considered as a seismic action for water storage structures. In the seismic response analysis for these structures, dynamic water pressure is to be estimated either by modeling storage water as an array of added masses or by discretizing the storage water into an arrangement of fluid elements. Detailed methods are provided in **Section 2.2 "Calculation of Response Values Using Macro Element Nonlinear Analysis**" of the manuals.

CHAPTER 5 METHODS OF ANALYSIS

5.1 General

Appropriate tools for structural analysis using reliable and accurate models shall be selected to calculate response values in seismic performance verification for critical underground reinforced concrete (RC) structures.

[Commentary]

The structural analysis methods to be used in seismic performance verification can be generally divided into linear and nonlinear analyses depending on the nonlinear stress-strain behavior of the soils and structures of interest, including damping. Much experience in linear analysis has enabled the calculation of structural responses with a reliable solution close to the linear stress-strain behavior of structural members. Nonlinear analysis, on the other hand, has a wider scope of application than that of linear analysis but the analytical results are frequently scattered to some extent. Therefore, it is essential to confirm the applicability of nonlinear analysis before using it. Commonly used structural analyses for the seismic performance verification of underground RC structures and methods of deterioration prediction for durability performance verification are provided in **Section 5.2 Selection of Structural Analysis**. In addition, preferable structural analyses for seismic performance verification are discussed in **Section 5.3 Structural Analysis for Calculating Response Values in Seismic Performance Verification**. Methods of prediction to estimate the deterioration of concrete for structural performance verification under normal conditions and durability performance verification are described in **Chapters 6 and 7** of the manuals, respectively.

5.2 Selection of Analysis

(1) Appropriate tools for structural analysis shall be selected to calculate response values for seismic performance verification in accordance with the verification conditions associated with the geotechnical characterization and the structure, the nonlinear behavior of the soil-structure interaction, and the relevant limit states.

(2) Appropriate methods for the prediction of the deterioration mechanism of concrete induced by environmental action shall be employed to determine the design values.

[Commentary]

(1)

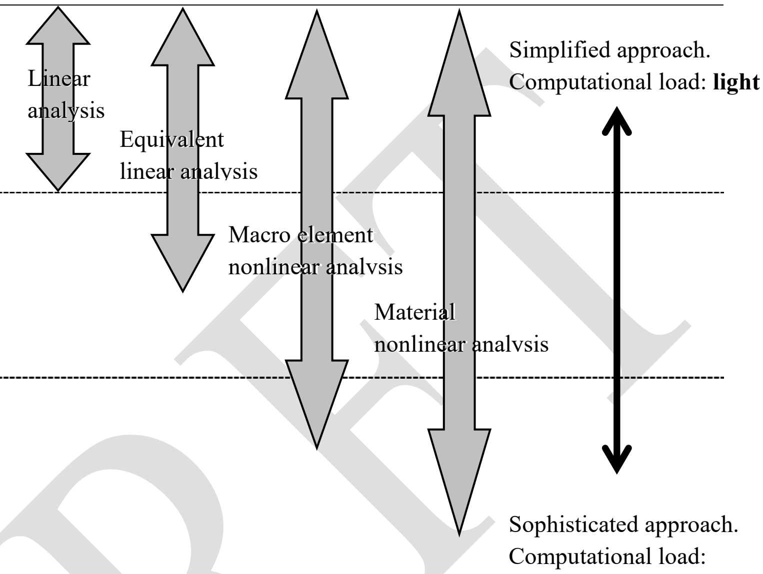
The structural analysis tools to be used in the seismic verification should specify reasonable dimensions from an engineering perspective according to the verification conditions associated with the geotechnical characterization and the structure. Two-dimensional analyses are generally used in seismic performance verification for underground RC structures because the transverse-sections of these structures have relatively low shear rigidity under horizontal seismic forces and are conservatively considered in the verification process. On the other hand, the selection of three-dimensional structural analysis is advantageous for evaluations of seismic responses in the longitudinal direction and structures that exhibit complicated dynamic behavior. The dimensions for structural analysis can be selected by considering the earthquake motions to be applied and the profiles of soils, rocks, and/or structures (refer to **Chapter 1** of the manuals).

Accurate assessment of the dynamic behavior of a structure (deformation and/or stress resultants) during and after an earthquake is required to efficiently check the seismic performance of an underground RC structure. For this purpose, it is essential to use tools for structural analysis that are capable of calculating the actual dynamic behavior of a structure as accurately as possible. Thus, the applicability and accuracy of the selected structural analysis method is to be confirmed through highly reliable experimental verification in advance (see **Section 3.3.2** of the manuals). This step, however, may be skipped if the method has been verified elsewhere.

The types of structural analysis used in seismic response analysis can be generally divided into linear, equivalent linear, and nonlinear analyses depending on how they handle the dynamic nonlinear behavior of soils and structures, including damping. Appropriate tools for structural analysis should be selected depending on the limit state being examined. Generally, the use of a sophisticated analysis method provides more accurate verification than the use of a simplified analysis method. This leads to the recommendation of nonlinear time-history seismic response analysis as an appropriate tool for structural analysis; however, simplified analyses have sufficient technical documentation and many practical demonstrations, thereby having proved their validity in practice. Therefore, the present guidelines permit the use of simplified analysis for verification. Since items such as the calculated outputs, accuracy, and the scope of application differ between structural analysis tools, *i.e.,* between linear analysis, equivalent linear analysis, and nonlinear analysis, the most preferable tool should be selected according to the limit state to be examined. Commentary Table 5.1-1 shows the descriptive correlations between seismic performance categories with their limit states and favorable tools for structural analysis as an example. Generally, sophisticated analyses cover the application scope of simplified analyses.

In calculating response values, it is important to select tools for structural analysis whose reliability and accuracy has been verified and to realistically idealize the examined structure as well as its surrounding soil and/or rock layers. Generally, such idealization allows more essential response behavior to be assessed on account of the soil-structure interaction, leading to reliable verification. As a result, the structural design is further streamlined. Accordingly, it is emphasized that the soil and/or rock layers, structures, and their interfaces should be discretized depending on the site conditions and structural configurations in an appropriate manner. In addition, special care must be paid to matching the performance objectives specified according to **Chapter 2 Performance Settings for Critical Reinforced Concrete Structures** and the feature and application scope of the mechanical properties used in the selected tool for structural analysis.

Commentary Table 5.1-1 Correlation between seismic performance and analysis tools

Performance objectives		Tools for structural analysis to be selected
Category	Limit state	
1	Members of a structure will not reach yield strength.	
2	A structure will not reach maximum bearing capacity.	
3	A structure will maintain structural integrity without collapsing.	

(2)

For durable performance verification, a method of prediction capable of representing the concrete deterioration due to environmental action such as carbonation, the intrusion of chloride ions, or freezing and thawing action is to be used, and the respective design values are to be determined.

In an examination of carbonation, a prediction method of carbonation depth should be used that considers the quality and environmental conditions of the concrete. Generally, the $\sqrt{t}$ law, or square root relationship between time and carbonation depth is to be used. When factoring in a reduction in the possible effect of carbonation due to rainfall, the method of infiltration of water may be used.

Concerning the intrusion of chloride ions, this can be physically treated as a diffusion phenomenon allowing the chloride ion content to be predicted. The prediction method derived from a solution of the one-dimensional diffusion equation should be used. When setting the limit state described as "No cracks due to reinforcement corrosion will occur", the degree of corrosion of steel over time should be predicted considering variations of the chloride ion content around the position of reinforcement, and then the presence or absence of cracks due to corrosion should be checked. Currently, no methods are available to accurately assess the degree of corrosion of steel and the subsequent onset of cracks. Therefore, these predictions are to rely on empirical methods based on recorded data, provided in **Chapter 5** of the manuals.

When frost damage sustained by concrete is concerned, no appropriate prediction methods have yet been established to estimate deterioration induced by freezing and thawing action over time based on actual environmental conditions and/or mix proportion conditions. Accordingly, the deterioration of concrete quality due to freezing and thawing action should be assessed using appropriate indices such as the relative dynamic elastic modulus obtained from a laboratory material test using concrete test specimens of the same mix proportion (JIS A 1148 (Method A) "Concrete Freezing and Thawing Action Test Method (Underwater Freezing and Thawing Action Test Method)").

The cracking width of the concrete will limit the scope of application of these prediction methods. Therefore, estimating the cracking width triggered by permanent and variable loads should be carried out prior to the assessment of individual environmental actions, and thus the scope of application of the above methods of deterioration prediction should be confirmed.

It has been recommended that "In maintaining the underground RC structures, appropriate remedial measures shall be taken to satisfy the performance requirements throughout the design life by carrying out inspection and predicting the degradation of structural performance considering the progress of deterioration even before the defects on concrete surface becomes apparent” (see the "Recommendations on Evaluation of Structural Sound Function"). This requires using an appropriate prediction method to meet such requirements. In addition, the above prediction methods may be applied to members or parts of existing structures where repair or serviceability restoration are assumed. The effects of repair materials and cross-sectional repairing materials may vary depending on the quality of the concrete to which these methods are applied and the conditions during construction. Therefore, the effects on the deterioration prediction methods should be appropriately considered by identifying the actual concrete quality and construction conditions of the structures of interest.

5.3 Structural Analysis for Calculating Response Values in Seismic Performance Verification

(1) Time-history seismic response analysis with dynamic soil-structure interaction shall be used to calculate the response values for seismic performance verification.

(2) Constitutive models of materials used for the time-history seismic response analysis shall demonstrate the nonlinear stress-strain behavior of soils and structures, including damping.

[Commentary]

(1)

The performance of an underground RC structure depends heavily on the site response during an earthquake. Accordingly, seismic response analysis with soil-structure interaction should be used to calculate the response values of an examined structure. The analysis is expected to represent the dynamic stress-strain behavior of the soils and structures and their interaction behaviors. In addition, ensuring seismic safety with structural ductility constitutes a basic issue in the verification process provided in the present guidelines because response values may exceed the elastic limit in a stress-strain curve. This enables the application of time-history seismic response analysis using step-by-step time integration to appropriately evaluate the absorption of input energy through the hysteresis curve due to structural deformation and the deformation characteristics of the nonlinear behavior of structural members.

Static analysis may be used to calculate response values if the seismic coefficient approach has been validated. This is discussed in **Chapter 4 "Seismic Performance Verification Using Pushover Analysis"** of the manuals.

(2)

Commentary Table 5.2-2 shows the classification of the tools for structural analysis with respect to the constitutive models of the materials. Although the application of nonlinear structural analysis is treated in the present guidelines, linear structural analysis is presented for the purposes of comparison.

Commentary Table 5.2-1 Classification of seismic response analyses with soil-structure interaction

Classification of tools / Item		Seismic response analysis			
		Linear analysis		Nonlinear analysis	
Material Model	Soil	Equivalent linear analysis using strain dependent rigidity and damping		Nonlinear models based on total stress or effective stress	
	Structure	Initial rigidity	Equivalent rigidity (degraded stiffness)	Macro element nonlinear model	Material nonlinear model
Response values to be calculated		Stress	Flexural moment/ axial force	Flexural moment, axial force curvature, relative story displacement	Flexural moment, axial force, concrete strain on the compression edge, curvature, relative story displacement
			Shear force	Shear force	Shear force shear strain

▢ Suggested toll for structural analysis

In discretizing the geotechnical and structural profiles into finite element meshes, the following points should be considered when setting the constitutive models of the materials for the soil and structure as well as the mechanical model of the interface between the two:

(i) Material models of soil elements

Soil elements should retain appropriate constitutive models of materials capable of properly assessing dynamic soil properties depending on their strain levels assumed from the intensity of the reference earthquake motions used for verification. The effect of groundwater on the dynamic soil properties is to be considered in case of a high groundwater table in the subsurface layers. In particular, the decrease of soil stiffness due to the generation of excess pore water pressure or soil liquefaction should also be appropriately considered in the saturated sand layers (details of which are provided in **Section 1.3** of the manuals).

(ii) Material models of structural elements

The basic intention is to ensure the seismic safety of structures during verification using energy absorption from input ground motion through the hysteresis curve due to structural ductility. Consequently, the structural elements require appropriate constitutive models of materials capable of properly assessing concrete cracks and reinforcement yield under the combination of permanent loads and earthquake ground motions.

(iii) Material models of the interface elements between soil and structure

Complicated behavior such as sliding and separation may occur at the interface between the soil and structure depending on the strength of the reference earthquake motion used for verification and the magnitude of the relative shear rigidity between the subsurface layers and the cross-section of the structure. These will affect the global dynamic response of the structure. Therefore, the interface elements between soil and structure require appropriate models capable of representing this behavior.

CHAPTER 6　VERIFICATION

6.1 General

Verification shall be carried out by setting appropriate verification items, using appropriate safety factors, and confirming that the response values for verification do not exceed the limiting values. A set of verification items and their indices (limiting values) shall be specified according to the tools selected for structural analysis and used to calculate the response values and performance objectives.

[Commentary]

The principle of seismic performance verification is to conform with the "Specification [Design Edition]." Chapter 6 contains **Section 6.2 Prerequisites of Verification** followed by a detailed description of seismic performance verification in **Section 6.3 Safety Factors** and **Section 6.4 Seismic Performance Verification**". The tools for structural analysis used to calculate the response values are described in **Chapter 5 Methods of Analysis** and the manuals. For descriptions of the performance objectives and limit states, see **Chapter 2. Performance Settings for Critical Reinforced Concrete Underground Structures**.

6.2 Prerequisites of Verification

(1) Verification of an underground RC structure under seismic action shall be carried out on the assumption that durability and structural performance under normal conditions have been verified in advance.

(2) For durability performance verification of an underground RC structure, appropriate verification items and their indices (limiting values) shall be specified to demonstrate that material degradation due to environmental action would have an insignificant effect on the structure's seismic performance over its design life for three types of environmental action: carbonation, the intrusion of chloride ions, and freezing and thawing action.

[Commentary]

(1)

The performance required of a structure must be maintained over its design life, and hence the present guidelines assume that both durability and structural performance under normal conditions have already been verified. Durability performance verification and structural performance verification under normal conditions are described in **Chapters 6 and 7**, respectively, of the manuals.

(2)

Irreversible deterioration of a concrete structure generally shows most significantly at the end of the design life of the structure. The seismic performance of the structure should be checked, taking into consideration the state of deterioration at the time of checking; however, it is difficult to perform seismic response analysis even under the assumption of aging of the structure. Therefore, demonstration of the insignificant impact of deterioration on seismic performance at the end stage of a structure's design life allows for the exclusion of the temporal change associated with the seismic performance.

The deterioration condition with insignificant effects on the seismic performance is defined as the condition that does not have cracks from reinforcing bar corrosion and in which the concrete has retained its required quality. Under this condition, a set of verification items and indices (limiting values) can be determined. The present guidelines specify that the following three deterioration mechanisms are to be checked to verify the durability performance of a structure: carbonation, chloride-induced deterioration, and freezing damage.

The progress of reinforcing bar corrosion due to concrete carbonation or the intrusion of chloride ions generates cracks in the concrete and further deterioration results in peeling; however, the condition just before the onset of cracking is widely accepted to experience little reinforcement corrosion as well as exhibiting the unchanged dynamic behavior of the original reinforced concrete structure.

In coastal environments where underground RC structures are in service, the speed of intrusion of chloride ions is generally much faster than the rate of concrete carbonation. Thus, in many cases the former is the dominant deterioration mechanism, which can be accordingly regarded as the primary deterioration mechanism. Thus, the limiting values for verification are to be determined such that no cracks be generated by reinforcing bar corrosion due to the intrusion of chloride ions. In addition, the depth of carbonation should be checked in such a way that the depth of carbonation stays within the concrete superficial layer, thus eliminating its effect on the progress of reinforcing bar corrosion due to the intrusion of chloride ions. When the progress of carbonation seems to have been slowed by rainfall or similar weather conditions, the verification process is to be carried out by focusing on reinforcing bar corrosion.

For freezing and thawing action, the quality of concrete is generally examined using the relative dynamic elastic modulus.

The methods of calculation for the above-mentioned limiting values are presented in "**Chapter 5 Durability Performance Verification**" of the manuals.

6.3 Safety Factors

(1) Seismic performance verification shall employ five safety factors: the structural factor, material factor, action factor, structural analysis factor, and member factor.

(2) Appropriate values of the safety factors shall be determined based on the methods used to calculate the response and limiting values as well as the verification items corresponding to the performance requirements.

[Commentary]

(1)

The basic concept of seismic performance verification can be expressed as:

$$\gamma_i \cdot \frac{S_d}{R_d} \leq 1.0 \qquad (6.2\text{-}1)$$

where S_d is the response value for verification ($S_d = S(\gamma_f, \gamma_m) \cdot \gamma_a$), R_d is the limiting value for verification ($R_d = \frac{R(\gamma_m)}{\gamma_b}$), S is the characteristic value of the response value, R is the characteristic value of the limiting value, γ_i is the structural factor, γ_m is the material factor, γ_f is the action factor, γ_a is the structural analysis factor, and γ_b is the member factor

When setting the safety factors, partial safety factors should be considered related to both the response values and limiting values depending on relevant uncertainties such as the material properties and/or actions. The basic concepts guiding safety factor settings are as follows:

The structural factor is to be determined by considering the importance of a structure, as determined by the social impact of the structure reaching the limit state. Advisably, underground RC structures of relatively high importance should allow the structural factor to be generally taken as greater than or equal to 1.0.

The material factor is to be determined by considering the unfavorable deviations of material strength from the characteristic values, the difference between test specimens and actual structures, the effects of material properties on the specific limit state, and time dependent variation of materials.

The action factor is to be determined by considering the unfavorable deviation of actions (loads) from the characteristic values, uncertainty in the evaluation of actions, time dependent variation of actions over the design life of a structure, the effect of actions on the limit state, and variation of environmental actions.

The structural analysis factor is to be determined by considering the uncertainty of computational accuracy of calculating response values through structural analysis, the difference between realized models and actual structures, and other uncertainties involved in the computation of response values.

The member factor is to be determined by considering the uncertainties in the computation of the capacities of members, the severity of the dimensional error of members, the importance of members, and the effects on the entire structure of a member reaching certain limit states.

Multiplication and division of the safety factors are used to guard against unfavorable deviation, and this arithmetic operation should be appropriately applied according to the relevant verification indices, such as the load carrying capacity, stress, deformation, and strain.

(2)

The safety factor is to be defined in each seismic performance verification, durability performance verification, and structural performance verification under normal conditions. Although a set of safety factors and the terms used to refer to the response values may differ between performance verification categories (for example, “response value” is usually designated by “design value” when it does not apply to seismic performance verification), the principle guiding the safety factor settings should conform to that of seismic performance verification. Standard values for the safety factors are provided in the manuals.

In examining the seismic performance of existing structures, the characteristic values for materials may be judged as the design basis strength, and the material factor may be deduced from the values determined at the design stage if the construction process of the structure has been confirmed to have been properly managed.

The safety factors to be considered for durability performance verification are to be distinctly determined from those for seismic performance verification because they involve reference to specified limit states associated with the generation of reinforcement corrosion due to carbonation or the intrusion of chloride ions, crack development due to reinforcement corrosion, and quality deterioration due to freezing and thawing action. These safety factors include the material factor, the safety factor considering the computational accuracy of the design equation concerned with durability (equivalent to the assessment of response values), and the structural factor. They also include the safety factor for the prediction accuracy of the carbonation velocity factor and the design chloride ion diffusion coefficient. Determining these safety factors for durability performance verification requires consideration of the constructability of concrete, the accuracy of the respective deterioration prediction methods, and the importance of the structure.

When verification is carried out using strains calculated from material nonlinear analysis, the assessment of the response values is affected by uncertainty, unfavorable deviation, and error accounted for by the material factor and the member factor because of the considerable influence of nonlinear material properties on calculating the response values. On the other hand, the assessment of limiting values is also affected by the uncertainty of the computational accuracy of structural analysis, accounted for by the structural analysis factor. This means that the safety factors examined in seismic performance verification using material nonlinear analysis need to be appropriately determined depending on the associated set of verification items and indices (limiting values), taking the principle of the safety factors discussed above into consideration.

6.4 Seismic Performance Verification

(1) For the reference earthquake motion Ss, a set of verification items and indices (limiting values) to demonstrate that an underground RC structure "maintains its structural integrity without complete collapse of structure" shall be appropriately determined according to the tools for structural analysis used for the calculation of the response values.

(2) In the seismic performance verification of the transverse-section of a structure, a set of verification items and indices (limiting values) shall be generally used as follows:

- Flexural failure: concrete strain on the compression edge at the time of concrete peeling or the corresponding amount of deformation (limit curvature/limit relative story deformation angle);
- Shear failure: shear capacity of a structural member.

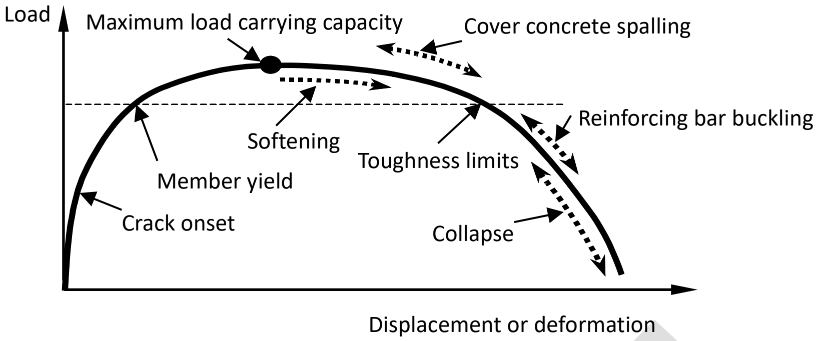
(3) The use of material nonlinear analysis may permit use of verification indices (limiting values), such as strains, to represent the local damage of materials or detailed deformation behavior.

(4) Structures requiring the support of equipment and piping systems shall be checked using a set of verification items and indices (limiting values) as well as other given function-related indices (limiting values) to ensure the functional capability of such installations.

[Commentary]

(1)

Commentary Figure 6.3-1 shows a schematic load-deformation relationship for a simple rigid frame box structure with flexural yielding failure preceding shear failure of its members. The area of the cover concrete spalling in Commentary Figure 6.3-1 is defined as the limit state for flexural failure considering the applicability of macro element nonlinear analysis and the ease of illustrative understanding. Previous experimental studies and examples of seismic damage have shown that reinforced concrete structures retain their ductile nature without rapid softening and compressive buckling of reinforcing bars unless cover concrete spalling occurs. Thus, the limit state defined in such a way is expected to avoid the occurrence of fatal damage, such as the complete collapse of the structure.



Commentary Figure 6.3-1 Illustration of the process of flexural failure of a reinforced concrete structure

The “Specification [Design Edition]” defines the following three seismic performance standards that should be met by a structure:

Seismic Performance Standard 1: full functional capacity during an earthquake and operational without having undergone repair after the earthquake.

Seismic Performance Standard 2: full functional capacity can be restored in a short to moderate time and structure remains operational without strengthening.

Seismic Performance Standard 3: the entire system of a structure does not collapse due to the seismic force.

In general, the state of Seismic Performance Standard 1 is equivalent to structural behavior within the elastic range or before reinforcing bar yield along its load and displacement curve. This state is judged to have little effect on the earthquake resistance capability of a structure unless the state enters Seismic Performance Standard 2. This enables the safe use of Seismic Performance Standard 1 for trend monitoring and repair in a normal maintenance routine. In addition, the seismic performance that "structures maintain structural integrity without complete collapse" (which is described in **Chapter 2 Performance Settings for Critical Reinforced Concrete Underground Structures** of the present guidelines) is generally equivalent to Seismic Performance Standard 3.

Most verification practices are examined against the failure of the cross-section of structural members by setting a set of verification items for flexural failure and shear failure for individual sections/parts or the overall structural members. In addition, checking for local material damage also needs to be considered based on the stress-strain outputs from finite element analysis. On the other hand, the use of a pushover analysis allows checking of the overall behavior of a structure by calculating the limiting values representing its horizontal loads or displacements. This broadly evaluates the overall behavior of the structure and makes no distinction between the failure modes such as flexural failure or shear failure associated with the cross-section of a member.

(2)

For underground RC structures, the performance objectives are specified such that the floor slabs will not collapse, and the sidewalls and partition walls will not lose capacity in accordance with the seismic performance where "the structure maintains structural integrity without complete collapse ".

This can be satisfied by preventing the transformation of the state of plastic deformation into the state of near collapse (hereinafter referred to as "transformation of the structure to a near collapse state") and shear failure of the cross-section of the members. In checking the seismic performance in the transverse-section direction of an RC underground structure, respective verification indices (limiting values) may be specified for the amount of deformation corresponding to the transformation of the structure to a near collapse state from flexural failure and the shear capacity of a member.

Verification indices for flexural failure may include the relative story deformation angle and curvature in addition to concrete strain on the compression edge. The deformation angle is obtained by dividing the relative displacement between the upper and lower horizontal members constituting the story by the distance between the same members. The seismic performance of a simple rigid frame box structure having shear deformation modes can be easily checked based on the deformation angle. On the other hand, the curvature or the concrete strain on the compression edge should be carefully selected when an irregular deformation is surmised; the possible deformation stems from the complex shape of the structure or the localized deflection around the center of the member length, possibly due to earth pressure. Even when such local deformation is specified as a verification index (limiting value), however, it is still desirable to assess the degree of deformation of the overall structure using a macro deformation index such as the relative story deformation angle.

On the other hand, shear failure is characterized by an abrupt reduction in the load carrying capacity of the members after the onset of failure. In particular, the out-of-plane shear failure of sidewalls and partition walls is significantly brittle compared with ductility-related failure such as flexural failure. Accordingly, shear failure must be avoided in statically determined structures. Shear failure of sidewalls and partition walls generally leads to loss of the inner space of the structure, but macro element nonlinear models are incapable of evaluating the state beyond shear failure. Therefore, the limit state for shear failure is to be specified such that no shear failure occurs in any member of the structure.

(3)

Material nonlinear models can simulate the damage process in more detail compared with macro element nonlinear models and have the advantage of extended capability to handle the complex shape of the members or structure. Three-dimensional configurations can also be used. The present guidelines offer a choice in the specification of verification indices based on the use of material nonlinear analysis because there is accumulated experience using this type of analysis in both research and practice, improving its reliability and capability. Material nonlinear models use a wide variety of constitutive laws to model elastic-plastic mechanical properties of concrete, reinforcing bars, and their boundaries. Therefore, verification indices should be selected and corresponding limiting values should be determined in consideration of the scope of application of the material nonlinear models.

When a verification item depends on a limit state discussed in the durability performance verification, it is necessary to consider the dependency of the durability when determining the limiting values.

If studies by multiple researchers have proposed rational and reliable evaluation methods for calculating limiting values through experimental validation, they may be applied for verification.

(4)

Concerning the seismic performance of structures that require functioning of support for nuclear components and piping networks, it is required that they "satisfy the constraints against structural dimensions to establish functional capabilities of equipment and piping system (*e.g.* establishing the operation of equipment and the elastic deformation of piping) provided through technical coordination with mechanical engineers."

Alternative limit states may be assumed to ensure the functional capability of equipment and piping systems in certain underground RC structures that require to support installations ranked as seismic grade Class S. The limit state may be specified as bearing more moderate damage than that of the limit state associated with the seismic performance that a structure "maintains its structural integrity without complete collapse ". Additional verification indices may also be needed to ensure the functional capability of the equipment and piping. For instance, the following verification indices may be selected: floor response accelerations to ensure the functional capability of intake pumps, the relative story displacement between floors through which intake pumps are installed, and the relative displacement between piping supports. In addition, the effects of the local damage sustained by a structure on the anchorage capability of equipment and piping should be examined as needed.

原子力発電所屋外重要土木構造物の耐震性能照査指針・マニュアル・照査例（2021年版）　原子力土木シリーズ5

令和3年10月25日　初版印刷・発行

編　集　者　〒160-0004 東京都新宿区四谷一丁目(外濠公園内)　土木学会原子力委員会
委員長　中村　晋
発　行　者　〒160-0004 東京都新宿区四谷一丁目(外濠公園内)
公益社団法人　土木学会　専務理事　塚田幸広
発　行　所　公益社団法人　土木学会
〒160-0004 東京都新宿区四谷一丁目(外濠公園内)
電話　03-3355-3441番(代表)　Fax　03-5379-0125

978-4-8106-1052-9