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CURRENT STATUS ON ENHANCING SEISMIC PERFORMANCE VERIFICATION FOR UNDERGROUND RC STRUCTURES AT NPPS IN JAPAN

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ABSTRACT

An expanded version of the "Seismic Performance Verification Guidelines for Critical Underground Reinforced Concrete (RC) Structures in Nuclear Power Plants" was published by the Japan Society of Civil Engineers in October 2021 with a view to advancing the seismic performance verification of underground RC structures. These guidelines have systematically organized state-of-the-art technologies in earthquake engineering, concrete engineering, and geotechnical engineering for about 40 years. The latest advancement in performance verification methods for the structures are highlighted, with a particular focus on expanding seismic response evaluation methods for structures in densely deposited liquefiable ground, and the enhanced performance verification method using a three-dimensional (3D) nonlinear analysis.

INTRODUCTION

Nuclear power plants are required to maintain their functions, such as the seawater intake for reactor cooling, even during major earthquakes or emergencies. Therefore, underground RC structures such as water intakes, water intake channels, and seawater pipe ducts (Figures 1 and 2), are required to maintain interior space, support equipment and piping that are crucial for seismic safety, and maintain the ability to circulate water in the event of earthquakes with potential significant impacts on the entire facility. Since the 2011 Off the Pacific Coast of Tohoku Earthquake, Japan's safety regulations have undergone comprehensive revisions, and this includes the review and expansion of basic design ground motion provisions. Amidst this trend, more accurate and standardized methods for the seismic evaluation of critical underground RC structures are needed.

The Subcommittee on seismic performance verification of underground structures in the Japan Society of Civil Engineers (JSCE) conducted research activities enhancing seismic performance verification methods for critical underground RC structures from 2018 to 2021. The results were published in the 2021 edition of the "Seismic Performance Verification Guidelines for Critical Underground RC Structures in Nuclear Power Plants", which underwent revision and expansion in October 2018. Furthermore, cognizant of the knowledge widely used in Japan, the authors developed an English version of the guidelines and published it on the website of JSCE.

The objective of this paper disseminates the core knowledge employed in the guidelines and their optimal application for structural engineers. The paper first describes the current seismic performance verification method. Subsequently, research and development for establishing the guidelines are featured. Finally, the paper illustrates recent advances included in the 2021 version of the guidelines.

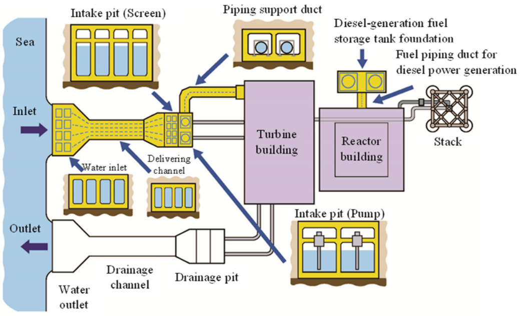


Figure 1. Example arrangement of nuclear power plant facilities
(Yellow color indicates critical underground RC structures)

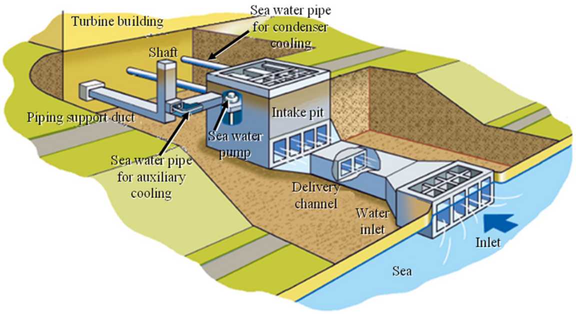


Figure 2. Layout example of a critical underground RC structure

SEISMIC PERFORMANCE VERIFICATION METHODS

The guidelines stipulate basic ideas to meet nuclear power regulations in the following ways. Seismic performance should be appropriately determined based on the performance requirements for a structure of interest, as determined by the performance verification for critical underground RC structures during an earthquake. Reference earthquake motion (S_S) shall be employed as the seismic action in the performance verification of underground RC structures during an earthquake. The seismic performance of an underground RC structure shall be specified as follows:

- An underground RC structure that requires the support of equipment and piping systems must maintain structural integrity without collapse under reference earthquake motion (S_S) and satisfy the conditions specified for the functional capability of its equipment and piping.
- An underground RC structure that requires the water-delivery function in the event of an emergency must maintain structural integrity without collapse under reference earthquake motion (S_S).

A typical flowchart of performance verification for underground RC structures that require the emergency water-delivering function is shown in Figure 3 (JSCE 2021). For performance verification during an earthquake, the performance settings are first discussed considering the performance requirements for a chosen structure and the design conditions. Secondly, methods of analysis and verification are selected based on the material properties, seismic action, and environmental impact. Finally, seismic performance verification is carried out distinctly depending on whether the structure requires the supporting function of certain equipment and piping systems or the structure requires the emergency water delivery function.

The latest version of the guidelines generalized the seismic performance verification method, integrating research findings and technical advancements. For instance, structural engineers can use the verification indices listed (Figure 3) to select the appropriate combination of structural analysis and verification indices. These combinations must be evaluated based on the accuracy of dynamic behavior representation and the scope of verification indices, particularly for failure modes extending beyond shear failure. Typically, advanced numerical analyses encompass a broader range of scenarios than simpler ones. Therefore, a material nonlinear analysis can effectively verify the shear capacity of underground RC structures. Furthermore, it provides guidance on maintaining the functionality of equipment and piping system support through the evaluation of anchorage capacity associated with local seismic damage to structural members as shown in Figures 4 and 5 (Nagata et al. 2020, 2021). The guidelines also incorporate a revised seismic performance verification method for existing underground structures strengthened with post-installed shear reinforcement. This demonstrates the practical application of a 3D macro-element nonlinear approach using laminar shell elements.

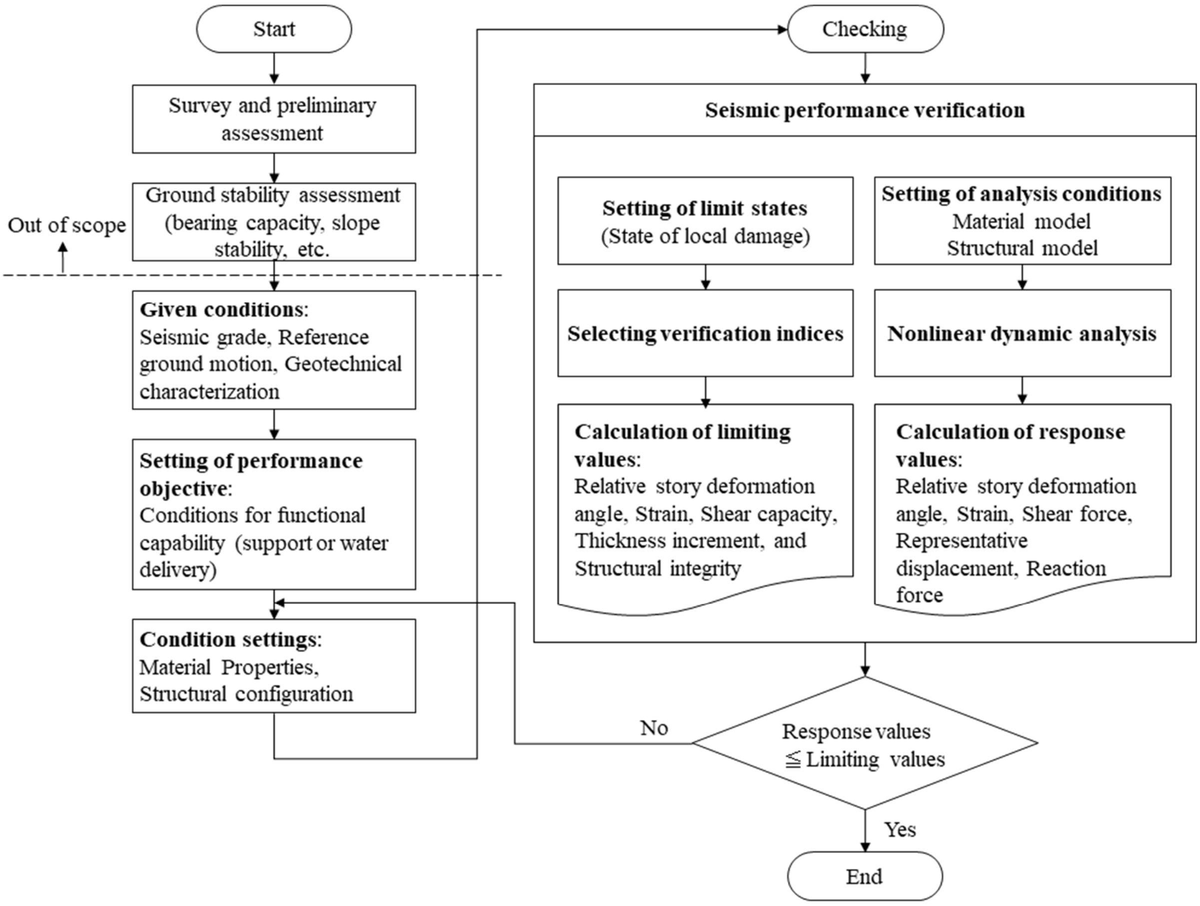


Figure 3. Flow chart of performance verification (water delivery function)

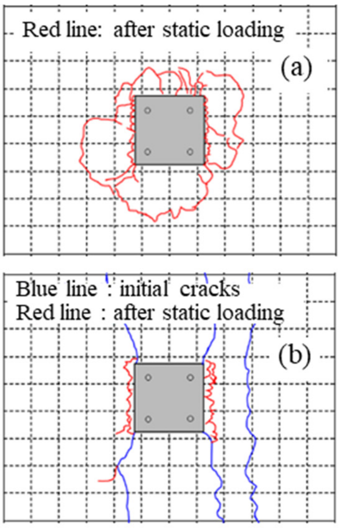


Figure 4. Damage state after static loading
(a) S-0 (without cracks) (b) S-1(with cracks)

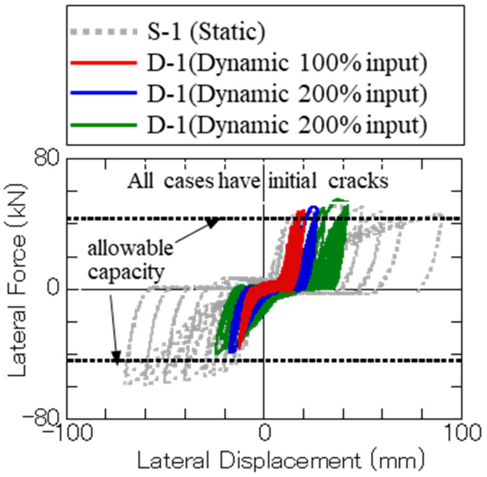


Figure 5. Hysteresis curves due to dynamic loading

RESEARCH AND DEVELOPMENT

General

The seismic performance verification, rooted in performance-based design, ensures the seismic safety of critical underground RC structures in Japan's nuclear power plants. This process leverages advanced knowledge and technology to address severe seismic conditions. Research on the seismic performance of underground RC structures commenced in the 1980s. This section provides a concise overview of the evolution of research and development on the seismic safety evaluation for underground RC structures.

Seismic Safety Assessment of Underground RC Structures (1980-1985)

Critical civil engineering structures, particularly underground RC structures, require a seismic design approach different from that of above-ground structures. Therefore, a simplified ground deformation method, which considers the dynamic response of underground RC structures as an alternative to the classic seismic coefficient method, was applied to the seismic safety evaluation method for underground RC structures to assess their seismic performance and their characteristics in 1985. However, the seismic safety evaluation method aimed to apply limit state design but adopted conventional allowable stress design (JSCE 1985).

Safety Verification Based on Limit State Design (1987-1992)

The seismic safety evaluation method marked a significant milestone by introducing the concept of performance verification. It clearly defined the performance requirements of the target structure and presented a method to verify its safety using the limit state design (LSD) method for safety verification. The LSD method also introduced novel techniques, such as the application of equivalent linear soil-structure interaction analysis for the seismic response of underground structures and the use of rational shear strength evaluation methods for RC members under distributed loads such as dynamic earth pressure (JSCE 1992).

Seismic Performance Verification (1997-2005)

A performance verification system was established, expanding on the concept introduced in the previous LSD to enable structures to undergo plastic deformation for safety against significant seismic forces (JSCE 2002). The system also favored dynamic nonlinear time-history analysis with soil-structure interaction to evaluate the seismic behavior of underground structures.

The preferred structural analysis model was validated through a comprehensive analysis of shaking table test data from one of the world's largest shaking tables and a large laminar shear soil box, in which one-third scale model RC structures are embedded approximately 5 m deep in dry sand with their bases fixed to the soil box. The seismic response analyses computed the plastic deformation of the model RC structures at an overburden depth of 3.0 m subjected to a maximum acceleration of approximately 1,100 Gal. Consequently, both macro-element and material nonlinear models accurately estimated relative story displacements, involving plastic deformation, yielding precise solutions for maximum and residual displacements (Ohtomo et al. 2003, Matsui et al. 2004, & Matsuo et al. 2021) as illustrated in Figure 6.

In addition (JSCE 2005), the system defined the application scope of total stress hysteresis modelling of saturated soil for soil-structure interaction analysis and settled the simultaneous input of horizontal and vertical ground motions in dynamic analysis, considering the minimal effects of vertical motions on underground structures. A method was introduced for determining member factors based on the relative story deformation angle of a structure for shear capacity verification.

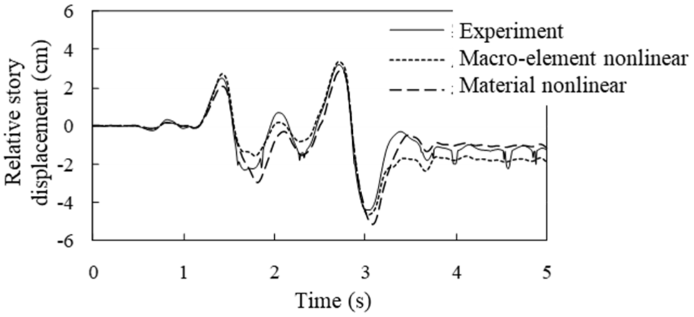


Figure 6. Time-history nonlinear dynamic response analysis with soil-structure interaction applied to a model RC structure experimental relative story displacement

Enhancement and Expansion of Seismic Performance Verification (2015-2018)

The enhanced system (JSCE 2018) introduced a 3D seismic response analysis of soil-structure interaction systems to enhance seismic performance verification and a displacement-based verification index (thickness increment of RC member) with a limit value to allow local damage while preserving structural integrity in shear capacity verification through material nonlinear analysis. This system also proposed an ultimate limit-state-oriented verification approach involving a pushover analysis with material nonlinearity, focusing on the overall seismic performance of a structure by defining limit values inclusive of both flexural and shear failure as depicted in Figures 7 and 8 (Shimabata et al. 2020).

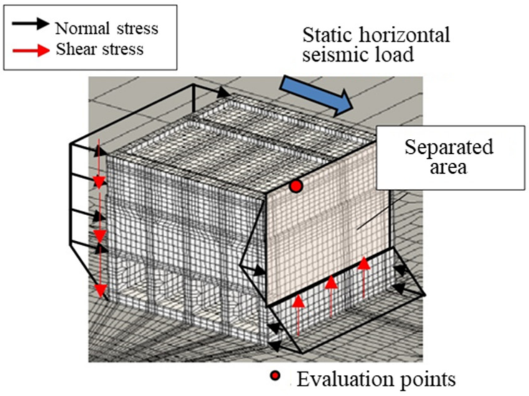


Figure 7. Static analysis model (seismic action)

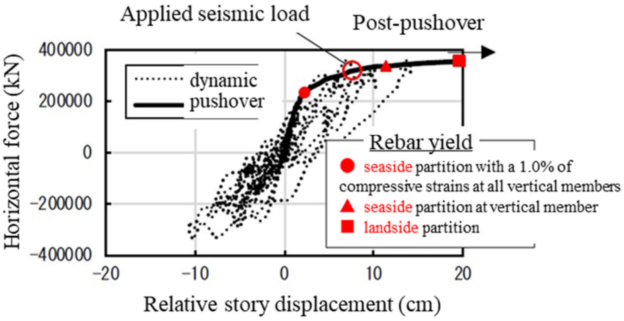


Figure 8. Load-displacement curves

RECENT ADVANCES

The latest research conducted from 2019 to 2021 broadens the range of available numerical analysis and verification methods. Key additions include: (1) A method for evaluating the seismic response of underground structures subjected to non-flow soil liquefaction. (2) An enhanced verification method using 3D material nonlinear analysis.

Evaluation method for seismic response of structures under soil softening

For the seismic performance verification of underground RC structures, response values are primarily calculated using nonlinear seismic response analysis. The effects of groundwater on dynamic soil properties must be considered in determining high groundwater levels in subsurface layers. Particularly, in saturated sand or granular layers, where the reduction in soil stiffness due to excess pore water pressure or soil liquefaction must be taken into consideration.

Recently, the implementation of strict safety reviews has led utilities to define stronger criteria for earthquake ground motions at nuclear sites, prompting investigation into potential soil liquefaction effects on underground RC structures, even in dense soils. Generally, the influence of soil liquefaction on underground structures poses a complex challenge in seismic design. The guidelines indicate a decrease in soil stiffness resulting from excess pore water pressure or liquefaction, even in saturated sand layers. The following experimental and numerical studies were conducted: centrifugal shaking table tests on a 3D RC shaft model in liquefiable layers, numerical analysis of these centrifugal models, and a seismic performance case study on a 3D soil and intake-pit interaction model. These studies explored the use of a total stress soil model for assessing the seismic performance of underground RC structures in scenarios involving local soil liquefaction and 3D configurations, in contrast with an effective stress soil model. They also demonstrate seismic performance verification while considering soil liquefaction in saturated, dense sand layers.

The centrifugal test can be used to evaluate the seismic performance of a dense sand deposit with 90% relative density. It provides insights into the deformation and damage of the RC shaft model (Figure 9). Results indicate that in the dense sand deposit, soil liquefaction is infrequent, even at shaking accelerations of 2,436 Gal. The excess pore water pressure does not reach its initial effective overburden pressure in the embedded shaft model. Additionally, the axial strain distribution of the shaft model exhibits a distinct inflection point at the boundary between the saturated and unsaturated layers (Figure 10). This indicates that the stiffness reduction in the saturated layer, followed by the upper unsaturated layer, leads to shear deformation in the shaft model (Watanabe et al. 2021).

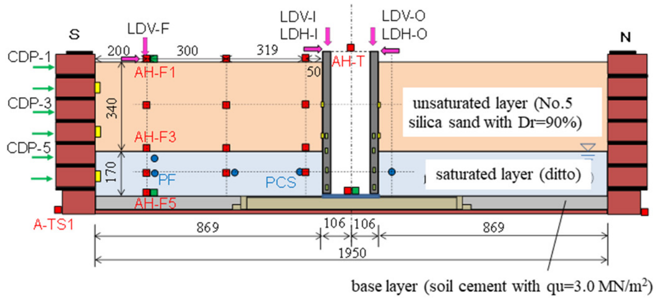


Figure 9. Centrifugal shaking table test

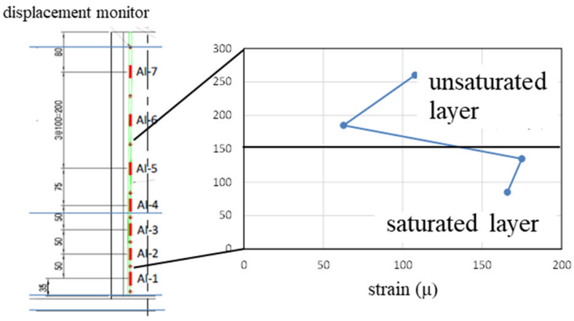


Figure 10. Principal strains along the shaft model

The case study explores the seismic performance of an existing intake pit model using a 3D nonlinear soil-structure interaction analysis with an effective soil model (JSCE 2021). The results reveal significant shear deformation at the boundary between the upper non-liquefied and lower liquefied layers during partial liquefaction. This indicates that large structural deformation can occur in both non-liquefied and fully liquefied states (Figure 11).

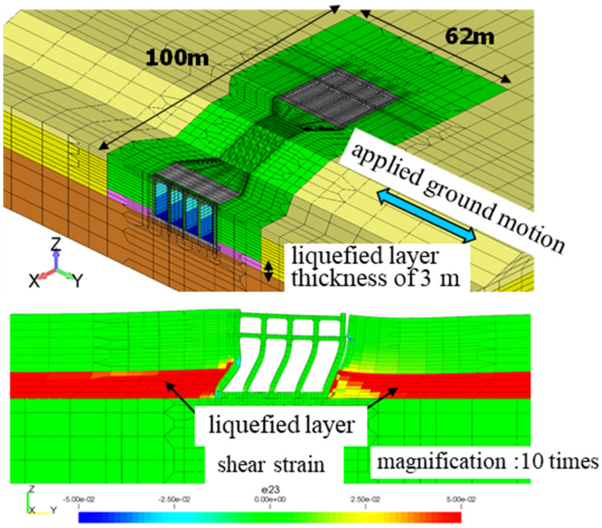


Figure 11. Dynamic behavior of an underground RC structure in dense sand which undergoes softening based on 3D nonlinear analysis with total stress soil model

Improvement of seismic performance verification method using 3D nonlinear analysis

The guidelines indicate that 2D or 3D nonlinear analysis can employ verification indices or limiting values, such as strains or displacements. These indices represent local material damage or detailed deformation, ensuring the integrity of underground RC structures.

Material nonlinear analysis provides reliable solutions beyond the ultimate state for flexural and shear failure modes in an RC frame without experiencing divergence. This allows for the adoption of alternative design indices such as strain or displacement, which can replace traditional shear capacity. However, material nonlinear analyses require prior validation using dependable test results. Currently, existing results solely validate 2D material nonlinear analysis, and there is limited evidence demonstrating the structural behavior of a full-sized RC member under reverse bilateral loading leading to shear failure. Full-scale RC members undergo systematic bilateral loading, as depicted in Figure 12 and Table 1 (Nagata et al. 2020, Sakashita et al. 2021).

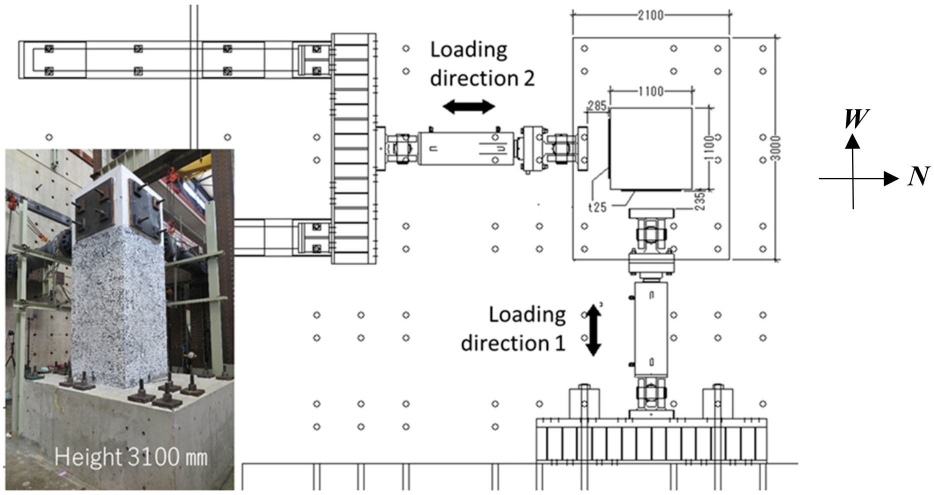
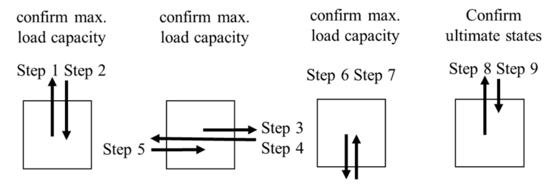
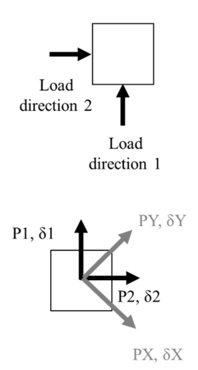
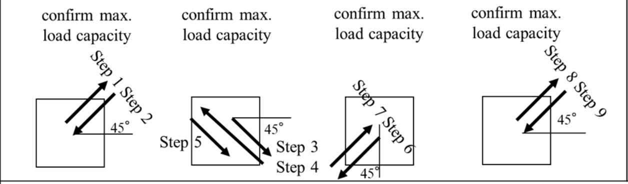
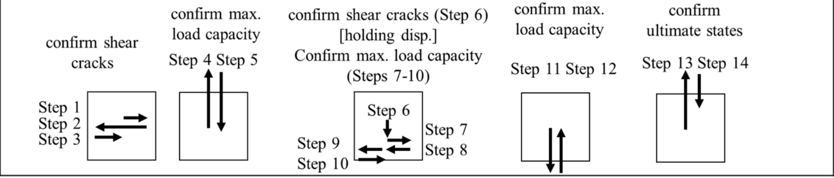
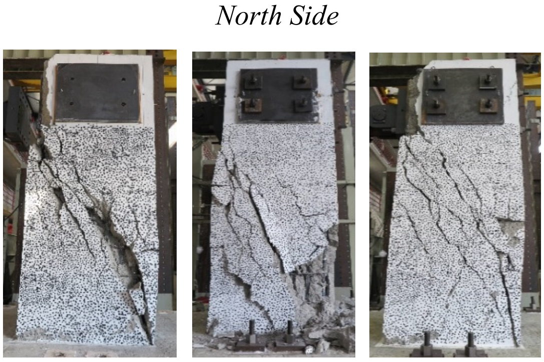


Figure 12. Loading condition to the RC member

Table 1: Loading patterns in the tests

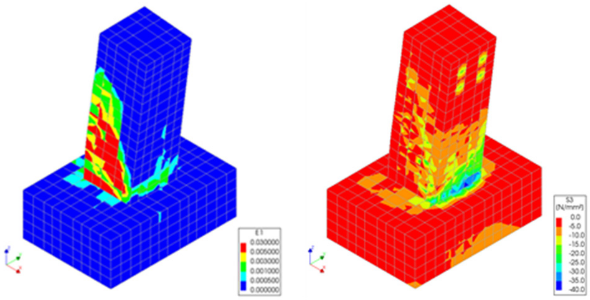
Case name	Loading history	Loading image
Loading pattern 1 N-1 P-1	 confirm max. load capacity Step 1 Step 2 confirm max. load capacity Step 5 Step 3 Step 4 confirm max. load capacity Step 6 Step 7 Confirm ultimate states Step 8 Step 9	 Load direction 2 Load direction 1 P1, δ1 PY, δY P2, δ2 PX, δX
Loading pattern 2 N-2-1	 confirm max. load capacity Step 1 Step 2 45° confirm max. load capacity Step 5 45° Step 3 Step 4 confirm max. load capacity Step 7 Step 6 45° confirm max. load capacity Step 8 Step 9 45°	
Loading pattern 3 N-2-2	 confirm shear cracks Step 1 Step 2 Step 3 confirm max. load capacity Step 4 Step 5 confirm shear cracks (Step 6) [holding disp.] Confirm max. load capacity (Steps 7-10) Step 6 Step 7 Step 8 Step 9 Step 10 confirm max. load capacity Step 11 Step 12 confirm ultimate states Step 13 Step 14	

Experimental results indicate that RC members experience greater compressive damage under unidirectional loading compared to diagonal loading (Figure 13). The shear capacity increases when initial cracks on the orthogonal surface of the RC member impede diagonal crack propagation. Subsequently, the 3D material nonlinear analysis assesses the structural performance of the RC members, confirming the accuracy and applicability of the analysis. In the subsequent sections, we discuss the load capacity, deformation behavior, and failure modes of the RC members, as depicted in Figure 14 (Shishikura et al. 2021). A numerical test evaluates the failure of a modified RC surface member analysis model (Komatsu et al. 2021).



(a)N-1 (b)N-2-1 (c)N-2-2

Figure 13. Damage to an RC member after loading



(a)maximum principal strain (b)minimum principal strain

Figure 14. Numerical results for bi-lateral loading

Numerical studies facilitate the development in advancing verification indices or limiting values for performance verification using material nonlinear analysis (Table 2). The developed verification indices include "Thickness increment of RC member" for out-of-plane shear failure mode and "Relative displacement on compressive edge" (Komatsu et al. 2023) for flexural and in-plane shear failures, each with specific limiting values (Figure 15). These indices are insensitive to local damage and meshing element geometry, thereby enhancing the precision of performance verification.

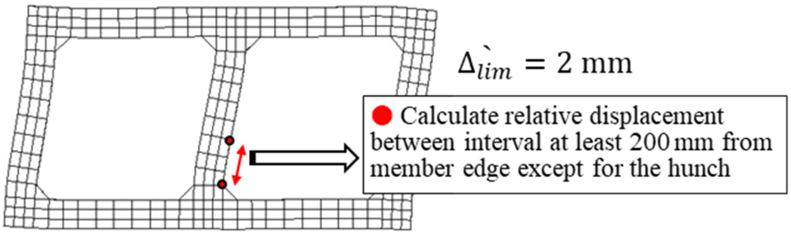


Figure 15. Calculation of relative displacement and its limiting values

Table 2: Verification indices for failure modes

Failure pattern	Direction	Failure mode	Verification index
Shear	Out of plane	Diagonal tension failure	Thickness increment of RC member
		Shear compression failure	Relative displacement on compressive edge
	In plane		
Flexural	Out of plane	Flexural compression failure	

CONCLUDING REMARKS

The current paper discusses the core knowledge employed in the guidelines and their optimal application for structural engineers. The latest version of the guidelines generalizes the seismic performance verification method by integrating research findings and other technical advancements. It provides a selection of the appropriate combination of structural analysis and verification indices, along with the evaluation of anchorage capacity associated with local seismic damage to structural members. The guidelines focus on dynamic nonlinear analysis with soil-structure interaction to evaluate the seismic behavior of underground structures. This approach is validated through a comprehensive analysis of shaking table test data. The analytical tool can be applied to a 3D ultimate limit-state-oriented verification approach, which involves a pushover analysis with material nonlinearity. The latest version further enables the application of seismic response evaluation methods for structures situated in densely deposited liquefiable ground. It also introduces an enhanced performance verification method using 3D nonlinear analysis.

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