Transactions of the 17th International Conference on
*Structural Mechanics in Reactor Technology (***SMiRT 17***)*
Prague, Czech Republic, August 17 –22, 2003
Paper # K06-6

Concept of Performance Based Seismic Design Guideline Underground Reinforced Concrete Structures in Nuclear Power Plants in Japan

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ABSTRACT

Japanese seismic safety assessment guidelines for important underground reinforced concrete structures were substantially revised based on performance oriented design in May 2002. The paper introduces the outlines of the historical background, basic concept, structural analytical methods, assessment procedures, example of assessment and safety factors, which were incorporated in the guidelines. The decisive incentive of the wholesale revision was the damages incurred by underground culvert-type reinforced concrete structures in the Great Kobe Earthquake in January 1995. Two–box-type culvert models with a scale of 1:2.5 with respect to actual structures were dynamically tested in a laminar sand box placed on a large shaking table. The dynamic structural analytical methods were verified in light of the experimental evidences.

KEY WORDS: nuclear power plant, seismic design, seismic assessment, reinforced concrete duct, intake water pit, emergency cooling water, underground structure, soil-structure interaction, laminar shear box, shaking table, dynamic analysis, structural analysis, limit states design, partial safety factor, important civil engineering structure, durability, salt attack, accountability

INTRODUCTION

In line with a transition of JSCE(Japan Society of Civil Engineers) Concrete Design Standards[1] to what we call performance based safety assessment, corresponding Guidelines for Seismic Assessment of Important Civil Engineering Reinforced Concrete Structures[2] (referred to as the Guidelines hereafter),which are mostly underground box-type ones, were substantially revised in May 2002. Taking valuable lessons we have learned from the Great Kobe Earthquake(17. Jan. 1995) into consideration and basing on the experimental results obtained by large reinforced concrete box models embedded in a large laminar shear sand container excited on a huge shaking table, state-of- the-art technological information as well as experiences were incorporated in the Guidelines.

The focal points to be mentioned are; 1) Required and demanded performances for seismic as well as durability evaluation are clearly identified. 2) Non-linear dynamic soil-structure interactive analyses based on time history earthquake waves are recommended as a primary structural analytical tool. 3) Ultimate seismic structural performances are evaluated in terms of either compressive fiber strain in concrete or shear deformation angle of the structural component. 4) Effects of deteriorations due to aging are implicitly included in the framework of seismic safety assessment.

HSTORICAL BACKGROUND OF THE GUIDELINES

JSCE's Concrete Design Standard adopted the limits states design in 1986[3] for the first time in Japan. After extensive research as well as comprehensive survey for four years, "Safety Assessment Manual for Seismic Design of Important Civil Engineering Structures in Nuclear Power Stations"[4] was published by JSCE's Nuclear Power Civil Engineering Committee in September 1992 consistent with the above Standard.

In the meantime in January 1995 the killer earthquake of Great Kobe occurred devastating a variety of reinforced concrete structures including underground ones. In the wake of the Earthquake, JSCE critically reviewed the then available seismic design codes organizing adhoc task forces. A consensus was reached within JSCE that the structures should be safety-checked against multi-levels of design earthquakes depending on the importance as well as performances required of the structures, and that a certain degree of damages shall be allowed in the case of the strongest postulated earthquakes. In 1996, tentatively revised standard of RC structures was drafted by JSCE as a separate volume, which was authorized in December 2003 with substantial modifications[5]. The concept of the new JSCE Concrete Design Standard was first embodied in "Guidelines for Structural Safety Performance Assessment of In-ground LNG Reinforced Concrete Tanks"[6] in December 1999. Seismic Design Guidelines for railway[7] and public road bridges[8] soon followed suit.

JSCE made a wholesale transition of the Concrete Design Standard from the limit states concept to performance based design in March 2002. Soon after that the Guidelines in question was published in May 2002.

OUTLINES OF PERFORMNCE BASED SAFETY ASSESSMENT(PBSA)

Gist of PBSA consists in that the performances required of the target structures are to be identified clearly, for which a rational methodology should be presented to guarantee them. Because of the increasing public demands on accountability of the safety design to utilities, the procedures should be understandable to the general public. Taking into account of the design life of the structure, effects of aging on the seismic structural performance should be incorporated in one way or others. The basic flow of the performance based assessment is shown in Fig.1. Without elaborating on details of the limiting states and the individual partial safety factors, the basic idea of the flow is applicable to any other types of design or safety assessment methods whether allowable or limit states design.

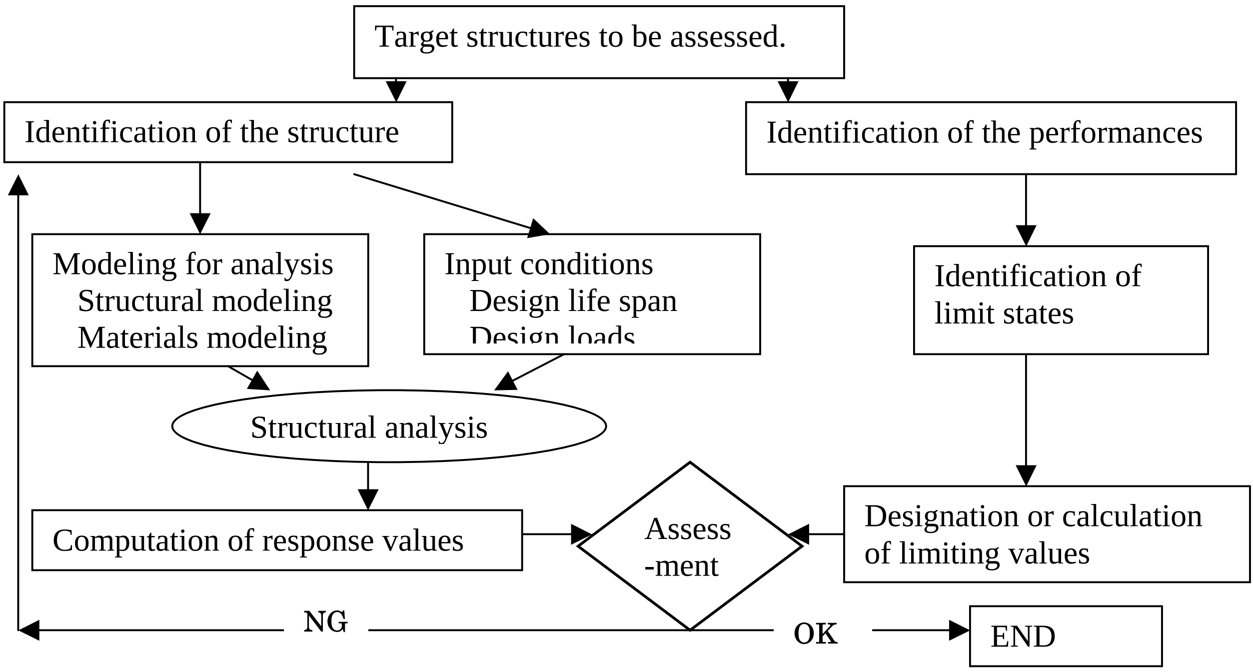


Fig. 1 Basic flow of performance based safety assessment

SPECIFICS OF THE GUIDELINES FOR IMPORTANT CIVIL ENGINEERING RC STRUCTURES IN NUCLEAR POWER PLANTS

Three fundamental countermeasures must be fulfilled in case of emergency in nuclear power plants. They are to scram and cool the reactor and to contain radioactive substances within a confined area. Most of the civil engineering structures such as intake water pits and underground reinforced concrete ducts to accommodate emergency cooling water pipes are required of playing the role of cooling the reactor. However, the structures in question are not classified per se as the most important category in terms of seismic design except for emergency cooling water channels in which water flows directly. Therefore, the important civil engineering structures are divided into two categories; One is to support or protect the most important equipment or piping and the other is to function as the most important structure by itself. Both are required to check against the strongest earthquake of S2. The general performances required of the structures are described in the super ordinate Guidelines of JEAC 4601-1987[9]. Since the description is rather qualitative, the performances should be interpreted in physical terms so that their structural performances could be compared with the analytically obtained response values, which we defined as target performances. Target as well as required performances are listed in Table 1.

The design earthquakes are specified also in JEAC 4501-1987[9]. Basically, two types of earthquakes, S1 or S2, are considered depending on the importance of the structures to be designed. Combinations of the loads to be taken into account in design are summarized in Table 2.

Performances for seismic behavior and those for durability are not interrelated in the Guidelines. Salt attack to reinforcing steel is a major concern to durability and seismic capacity of the RC structures, which are buried under salty ground or in direct contact with seawater. The width of the cracks in concrete due to normal operating loads should be considered as an initial condition in estimate of ingress of chloride ion. Other factors to affect durability such as carbonation and freeze-thaw damage should be checked wherever they are needed.

Table 1. Required and target performances for important civil engineering structures against S2 earthquakes.

Types of structures	Required performances (JEAC)	Target performances
To support As class equipment or piping *Intake water pit *Duct for accommodation of emergency cooling water	1) To support safely the equipment and/or piping 2) Not to impair function of the supporting items	Designed against S2 1) Not to collapse 2) The functions demanded to support the supporting items a. Shear deformation angle of the structure, shear capacity etc b. Other conditions demanded from the supporting items
Intake water channel for emergency cooling water	To secure the capacity of water flow needed to cool the reactor in emergency	Ditto above excluding b

Table 2. Combinations and items of loads to be considered in design.

Category of performance	Classification of load
Seismic	Permanent + earthquake
Durability	Permanent+ variable

Load classification	Items of loads
Permanent	Dead, equipment / piping, soil cover, superimposed, static earth pressure etc.,
Variable	Temperature effect, variable superimposed, water pressure, snow etc.,

DYNAMIC ANALYTICAL METHODS

Various analytical methods have been employed to compute the response behavior of RC embedded structures due to earthquake effects. Historically speaking, an equivalent static linear approach was first introduced mainly for above ground structures, assuming the dynamic earthquake force as an equivalent static inertia load. For underground structures what is called response displacement analysis has also been utilized such as based on the function of complex numbers and equivalent linear models. In this analysis response displacement of soil due to earthquakes is calculated by finite element dynamic analysis, for which the structural deformation response is estimated by the imposed maximum displacement of soil.

Current trend is that a kind of time history FEM response analysis is pursued on stepwise time integration scheme for which non-linear properties of soil and reinforced concrete are incorporated in the constitutive equations. Table 3. lists the applicable analytical methods in accordance to the levels of target structural performances. In the Guidelines we recommend to use a total stress approach for soil based on the commonly used Ramberg-Osgood model together with Masing's histeresis damping rule. If the behavior of soil is to be investigated in detail, an effective stress approach can also be applied [10]. For reinforced concrete box type structures, non-linear characteristics of reinforced concrete can be considered either by non-linear moment-curvature hysteresis loops of reinforced concrete beam members subjected to axial forces if any [11], or by material non-linear models of plain concrete and reinforced concrete elements [12]. The interface between the soil and the surface of the structure embedded may slip and/or open in the large deformation level of soil. To take the phenomenon into account, special interface elements can be arranged either by slip elements[12] or rigidity reduced soil elements[13].

Fig. 2 illustrates a comparison of experimental results for relative displacements between the top and bottom slabs of a RC duct model embedded in a laminar shear box exited on a large shaking table, the outline of which is illustrated on the right hand side of Fig. 2 [14]. The analysis was conducted using a total stress model for soil and a member level non-linear model for reinforced concrete. The analysis can be judged as valid enough to estimate the dynamic response of embedded box type RC structures.

As a reinforced concrete structure deteriorates due to aging effect, its seismic performance degrades gradually with time. However, since it is extremely difficult to correlate the aging effect of a structural member to seismic performance, the Guidelines allow that original seismic performance is maintained up to the time when the degradation due to aging remains within a limit that is considered not to affect the seismic performance. Since the main portion of the structures is buried under ground, cracking due to corrosion of steel becomes a major concern.

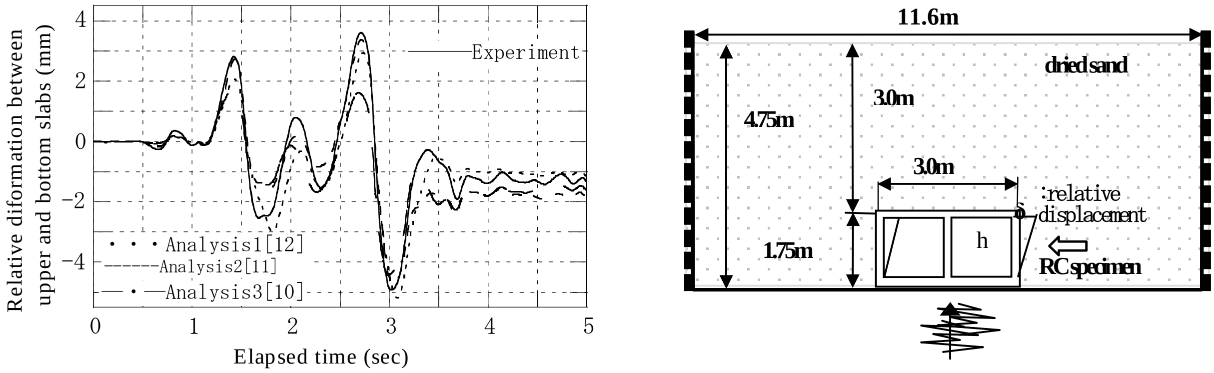


Fig. 2. An example of experimental and analytical responses of relative deformations of a duct mode and a sketch of laminar shear box with RC model embedded.

Table 3. Seismic response analytical methods to comply with the seismic performances required.

Target performances		Items to be checked in safety assessments	Analytical tools and its applicability
States	Limit states		
1	Each structural member remains within elastic limit (up to yielding).	Max. normal stress in concrete and steel Max. shear stress in concrete	Elastic linear analysis
2	The structure does not reach the maximum load capacity.	Items above plus Maximum shear force in the member Maximum moment in the member	Equivalent linear analysis
3	The structure does not collapse.	Items above plus Max. curvature, deflection and shear deformation angle of the structural member	Non-linear analysis in member level(1)
		Items above plus Maximum strain in concrete and steel	Non-linear analysis in material level(2)

(1) Reinforced concrete (RC) portions of the structure are divided into linear members, for which non-linear moment curvature hysteretic characteristics of the respective RC elements are considered in two-dimensional FEM analysis.
(2) Non-linear constitutive equations of plain concrete and those of cracked non-linear RC elements are used for RC structure in two-dimensional FEM analysis..

OUTLINES OF SESMIC SAFETY ASSESSMENT

Seismic safety assessments are performed according to the flow in Fig. 3.

The fundamental concept of safety assessment adopted in the Guidelines is similar to that applied in the limit states design, which is expressed in the following inequality.

$$\gamma_i S_d / R_d \leqq 1.0$$

S_d – Response values for assessment { = S(γ_f, γ_m) γ_a }
R_d – Limiting values for assessment { = R(γ_m)/ γ_b }
S - Characteristic response values
R - Characteristic limiting values
γ_i - Structure importance coefficient
γ_f - Load factor
γ_a - Coefficient for structural analysis
γ_m- Material coefficient
γ_b- Member coefficient

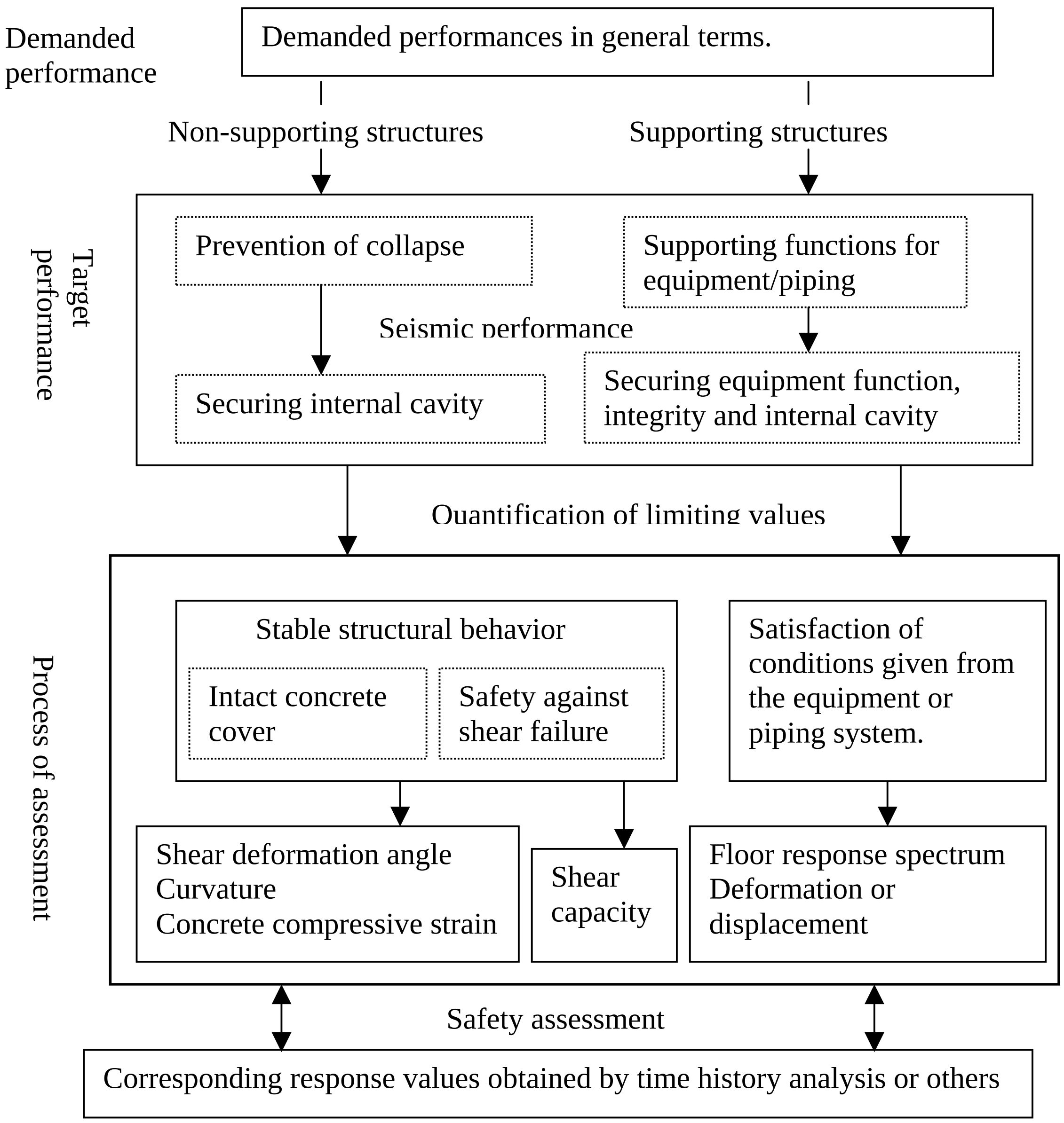


Fig. 3 Flow of seismic safety assessment

Table 4. Partial safety coefficients employed in the Guidelines.

Items of assessment			Flexural failure dominant		Shear failure dominant	
			Resp. Value	Limit value	Resp. value	Limit value
Material coefficient γ_m	Concrete		1.0	1.0	1.0	1.3
	Reinforcing steel		1.0	1.0	1.0	1.0
	Soil		1.0	-	1.0	-
	Bending & axial force	Concrete	-	-	-	1.1
		Reinf. steel	-	-	-	1.3
	Shear	Concrete	-	-	-	1.3*
		Reinf. steel	-	-	-	1.1
	Deformation / strain		-	1.0	-	-
Load factor γ_f			1.0	-	1.0	-
Coefficient of structural analysis γ_a			1.2	-	1.05	-
Structure importance coefficient γ_i			1.0		1.0	

* This value must be increased by 20% when the member is subjected to repeated loads in high stress ranges.

The critical tasks of safety assessment are to identify the limit states in compliance with the target performances, and to determine rational safety factors. The response values are calculated independently as characteristic values. Referring to JSCE Concrete Design Standards, the partial safety coefficients given in Table 4. are provisionally provided in the Guidelines.

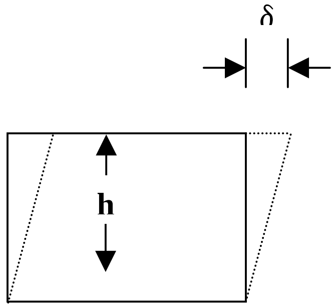
Target performances are translated into the items of assessment, for which corresponding limiting values are provided (Table 5.). Since majority of the important out-door civil engineering structures are a kind of box culvert, the relative displacement between the top and bottom slabs divided by the height of the box (shear deformation angle, δ /h) is specified. Further discussions on the limiting values of shear deformation angle are found in references [15],[16]. Shear deformation of angle of 1% is unconditionally allowed.

For the structures other than box culvert type, for which shear deformation angle is difficult to define, limiting concrete compressive strain in compression fiber is specified as $10,000\times10^{-6}$ or 1%. This strain value is selected based on the post-peak compressive strain of concrete, which still retains about 10% of the uniaxial compressive strength. Also, experiments demonstrate that up to this level of compressive strain the cover concrete remains without spalling.

Table 5. Summary of target performance, items of assessment and limiting values

Target performance	Items of assessment	Limiting values
To ensure not to collapse.	Shear deformation angle	Limiting angle ≦ 1% *
	Compressive strain in compression fiber	Limiting strain ≦ 1%
	Shear force	Shear capacity
To sustain functions of the supported equipment or piping	Response acceleration of the supporting floor	Corresponding limiting acceleration
	Response deformation of the supporting floor	Corresponding limiting deformation

*Limiting values higher than 1% can be allowed depending on the structural properties.



Deformation angle
= δ / **h**

As for the assessment against shear failure, not the deformation or strain, but the conventional approach based on shear load carrying capacity is applied due to the lack of experimental data to substantiate deformation oriented safety check. Design formula to estimate the shear capacity are presented in the Guideline taking into account the experimental results obtained specifically for this purpose[17].

For special cases when demands are imposed from the side of equipment or piping, response floor accelerations and/or deformational behavior of the supporting structures are required to be notified to the designers of the equipment.

AN EXAMPLE OF SEISMIC SAFETY ASSESSMENT FOR TWO-BOX CULVERT

The sample structure taken up for an example is a two-box type culvert to accommodate and support emergency cooling seawater pipes, which constitute a part of core cooling equipment classified as **As**. Table 6. summarizes the performances to be assessed.

Table 6. Seismic performances to be evaluated

Required performance	To safely support the seawater pipes during and after the prescribed design earthquakes, maintaining the function of water flow.
Target performance	To assure that the structure does not collapse against design earthquake **S2**

The cross section of culvert to be checked is sketched in Fig. 4. The cover soil over the duct is a sand layer with a depth of 10 m. The bottom slab is fixed firmly to hard rock bed. Ground water table is located at the level of top face of upper slab. Deformed bars with diameters of 19 mm and 16 mm are arranged with a spacing of 15 cm as main and distribution reinforcements, respectively. Characteristic compressive strength and Young's modulus of concrete are 24 N/mm^2 and 25 kN/mm^2, respectively. Yield strength and Young's modulus of steel are 345 N/mm^2 and 200 kN/mm^2, respectively.

Input design earthquake wave in horizontal direction with a maximum acceleration of 600 Gal is given as a time history scheme. Maximum vertical acceleration of 300 Gal is also considered as an equivalent inertia force.

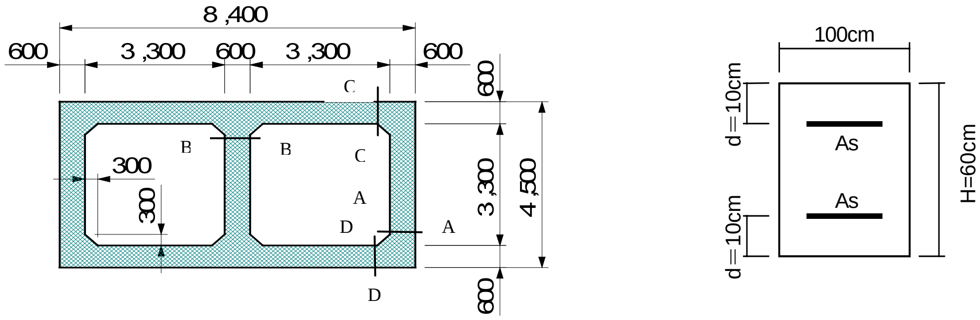


Fig. 4 Cross section and main reinforcement arrangement of the duct to be assessed.

Two-dimensional seismic response analysis was applied to a combined soil-structure interaction system, taking into account the material non-linearity of the structure and soil. The duct and the soil were represented by plane strain elements. Fixed and mixed boundary conditions were employed to the sides and the bottom of the structure, respectively. Mesh division of the FEM model is illustrated in Fig. 5. The soil portion was so divided that the finer meshes were located in the vicinity of the structure embedded. On both sides of the structure enough area of soil was extended to eliminate the effect of side boundary conditions. Division of the structure portion was made so that the position of main reinforcing bars coincided with the centroid of elements. Joint slip elements were inserted along the outer periphery of the structure.

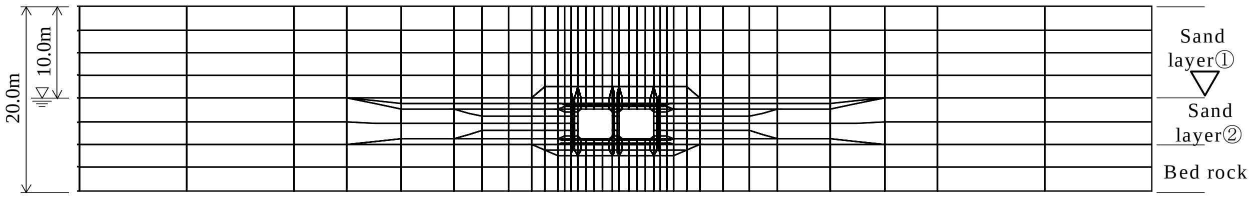


Fig. 5 Mesh division of FEM model for coupled soil and RC duct

To express the non-linear response of soil, Ramberg-Osgood model was used for total stress hysteresis scheme. Initial shear moduli were assumed as 165 MN/m^2 and 184 MN/m^2 for unsaturated and saturated sand layers, respectively. Corresponding value for bedrock was given as 1000 MN/m^2. Initial damping factor for soil was taken as 2.0 %. Poisson's ratio of 0.4995 was used to account for the effect of groundwater in the saturated sand layer.

Table 7. Results of safety assessment for concrete strain and deformation of the duct

Assessment based on compressive strain in concrete		Assessment based on overall shear deformation angle	
Max. compressive strain ε	$8.5\text{x}10^{-4}$	Max. shear deformation angle θ	0.0029
Structural analysis coefficient γ_a	1.20	Structural analysis coefficient γ_a	1.20
Comp. strain for checking $\varepsilon_d=\varepsilon\gamma_a$	$1.0\text{x}10^{-3}$	Shear angle for checking $\theta_d=\gamma_a\theta$	0.0035
Limiting compressive strain ε_r	$1.0\text{x}10^{-2}$	Limiting shear angle R	0.01
Structure importance coefficient γ_i	1.00	Structure importance coefficient γ_i	1.00
Safety index $\gamma_i\varepsilon_d/\varepsilon$	0.10	Safety index $\gamma_i\theta_d/R$	0.35
Safety judgment	OK	Safety judgment	OK

Table 8. Results of safety assessment for shear capacity of the members (See Fig. 5 for the sections checked)

Items	A-A	B-B	C-C	D-D
Structural analysis coefficient γ_a	1.05	1.05	1.05	1.05
Shear force V_d (kN)	814	532	644	591
Limiting shear force V_{yd} (kN)	1281	922	1173	1330
Structure importance coefficient γ_i	1.00	1.00	1.00	1.00
Safety indexγ_i V_d/ V_{yd}	0.64	0.58	0.55	0.44
Safety judgment	OK	OK	OK	OK

Based on the assessment flow in Fig. 4, safety check was performed in regard to concrete compressive strain and overall shear deformation angle (Table 7). Similar check for shear capacity is summarized in Table 8. As can be seen from the tables, the designed duct satisfies the seismic safety requirements with an ample margin. The safety indices range from 0.10 to 0.64, inferring that the structure in question has a room to further economize the design.

FUTURE WORKS

Following issues are needed to be further investigated in order to generalize the Guidelines. 1) Linkage of structural and durability assessments as unified Guidelines. 2) Development of a methodology to expand the concept to retrofit the existing structures.

ACKNOWLEDGEMENT

The foregoing study is a part of the joint research entitled "*Development Study on Verification Method of Seismic Performance of Underground Reinforced Concrete Structures in Nuclear Power Stations (Part-2)*", which was supported by Electric Power Industry in Japan in the period 1997 through 2001. The authors are very grateful to the concerned of the industry. They also appreciate valuable advice given by the committee organized in JSCE chaired by Prof. Hajime Okamura, President of Kochi Institute of Technology.

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