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Diversification of Seismic Design of Components of Nuclear Power Plants with Improvement of Static Seismic Coefficient considering Ductility Factor

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ABSTRACT

In Japanese regulatory guide for seismic design of nuclear power plants, the combination of the design by the dynamic response analysis with design basis earthquake and the design by the design basis seismic static coefficient (DSC) is required.

This paper proposes new static seismic design methodology with newly defined DSC derived from elastoplastic time historical seismic response analysis of components and allowable ductility factor to prevent damage to components. The process of the seismic response analysis to obtain the ductility factor considering load-deflection characteristic of components and definition of the allowable ductility factor based on the actual experiences are also described.

It is expected that the new procedure will help diversify the existing seismic design system, which is based on equivalent elastic design, as well as increase the reliability of seismic design to deal with the uncertainty of the seismic motion.

1. Introduction

The Component and Piping systems (hereinafter, referred to as “the Component”) in the Nuclear Power Station (hereinafter, referred to as “the NPS”) in Japan are required seismic design based on the combination of the static force seismic force and the seismic force which is based on the seismic response analysis with the basis ground motion and the ground motion for elastic design (NRA(2014)). The present seismic design of the Component have great ruggedness and reliability and no damage of the safety-related facilities in the Kashiwazaki-Kriwa NPS (hereinafter, referred to as “the KK NPS”) and the Fukushima-daiichi NPS (hereinafter, referred to as “the 1F NPS”) have been observed in the Nigataken-chuetsu-Oki earthquake (hereinafter, referred to as “the NCO earthquake”) in 2007 and the 2011 off the pacific coast of Tohoku Earthquake (hereinafter, referred to as “the GEJE”) in recent years.
While, on setting the basis ground motion recently,
① Introducing the fault model to consider “ground motion by specific hypocenter each the NPS site”
② Introducing inside land crustal ground motion recorded on the national rationally “earthquake motion by non-specific hypocenter”
－are demanded on the design stage of the Component considering uncertainty of earthquake as a natural phenomenon is become larger concern.

2. The issue and outlook of seismic design for NPS

2.1 excess of the basis ground motion

After “code of seismic design for nuclear plant” (hereinafter referred to as “ the guidance of judgement for seismic design”) published by Nuclear Safety Commission in 1978, it is decided to use the DBE and static seismic force which is considered past earthquakes occurrence situations the nature of active fault around the site and static ground motion for setting ground motion considered for the NPS seismic design. The way of thinking is the same as the new standards for the regulation by recent nuclear regulation authority. In this period, the development of evaluation for the seismic force based on the accumulations of new knowledge about seismology and seismic engineering such as introduction of the fault models has been conducted. However, it is necessary to consider that Earthquake is natural phenomenon and has uncertainty, therefore in the future, there is a risk that observed ground motion could exceed DBE. The correspondence of the back-fit against the existing NPS by the present standard regulation was limited to confirmation seismic safety only. It is important to construct the policy for insurance of safety in the case of earthquake which exceed the DBE

2.2 The seismic design for the Component

The seismic design of the Component in the NPS are based on the standards of regulation which the details are based on "the technical code for seismic design of nuclear power plant" (hereinafter referred to as "JEAC4601"). The time history response analysis using DBE or spectrum modal analysis are applied to seismic response analysis (but it is possible to adapt static analysis by maximum response acceleration of building and structure for seismic analysis of the Component with stiff structure). Seismic response analysis are conducted by multibody system model or one-degree-of-freedom model, therefore the elastoplastic behavior of the Component are limited to the range which is able to be handles as the equivalent linear model and it is possible to say that the criteria is set with sufficient tolerance against plastic region.

In the KK NPS which ground motion exceeded DBE, no damage to or loss of function of safety related components caused by the earthquake was found actually. It may be because sufficient tolerance was due to that by present seismic design system. However, if earthquake might exceed DBE, it is necessary that the tolerance is arranged in the policy for insurance safety.

2.3 defense in depth concerned with seismic design

After the accident in the 1F NPS, various considerations concerned with defense in depth have been conducted by each organization. The ground motions which exceeded DBE in the each NPS have been recorded as stated above and it is necessary to discuss about how to reflect it as policy of defense in depth against this situation. In the revise code of judgement for seismic design in 2006, the remaining risk was decided to consider and it is provided to reflect probability safety analysis PSA for earthquake in seismic design. However, no discussion whether to consider that the situation exceeded DBE for design of each component or not have been conducted.

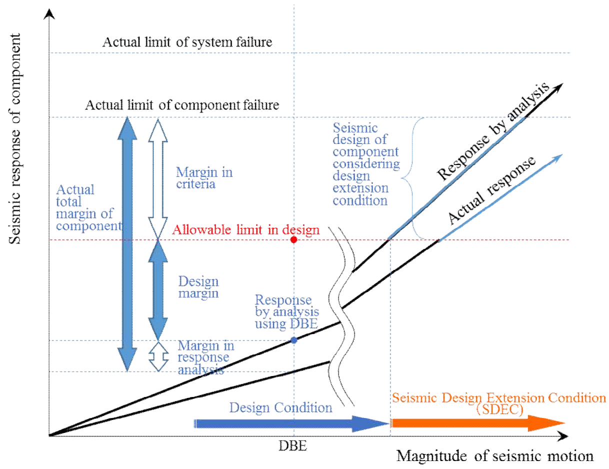


Fig. 1 Safety margin in the current seismic design and design extension condition

Here, in the Safety Guide of IAEA, the situation exceeded assumption for the design is defined "Design Extension Condition" and reflecting it in the design of the facility is required. No requirement about seismic design is in it, however it might be necessary to see the situation of the earthquake exceed DBE as Design Extension Condition and introduce seismic design, which is consider it.

Fig.1 shows that concept of the tolerance in the present seismic design system and increase of seismic response of the component in case ground motion exceed DBE. In the present seismic design, because the seismic response analysis of the component based on DBE is conducted ("Response by analysis using DBE" in Fig.1) and it is compared with the criteria ("Allowable limit in design" in Fig.1), both criteria which design tolerance is equivalent for that of analysis value against allowable value and analysis procedure have tolerance.

Therefore, even if ground motion exceed DBE is assumed, seismic response of the component will not exceed allowable limit immediately. If seismic response of the component is less than or equivalent for to the allowable limit, it is considered that it is within "design situation". In this paper, it was defined that the situation assumed ground motion exceeded that is "Seismic Design Extension Condition" (hereinafter referred to as " SDEC").

According to Safety Guide of IAEA, design procedure of the component aimed at assurance safety in the SDEC has to construct immediately.

3. Elastoplastic behavior and ductility factor of the component

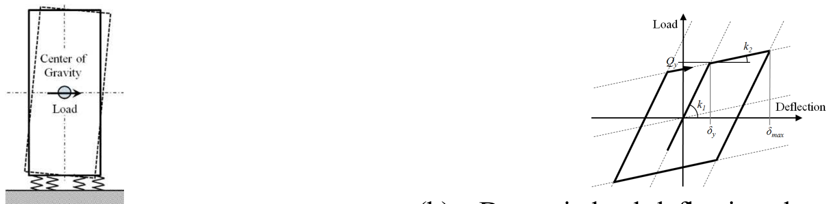
3.1 Concept of the ductility factor

In the conventional structural design of the Component, stress generated with seismic acceleration and relative deflection is focused and we confirm that it is in the tolerable range with the proportional analysis. In contrast, in this study ductility factor which is as criteria of the component's damage limit is introduced and seismic design procedure is discussed, which relates ductility factor to static seismic coefficient.

That is to say, the procedure of structural evaluation based on the load that is the structural design procedure considered actual strength (tenacity on their elastoplastic) is discussed. In this case, the response deflection as the evaluation index can preserve function at the earthquake by comparing it with allowable ductility factor.

Again, considering uncertainty of the earthquake as natural phenomenon, the design procedure complements seismic design based on basis ground motion and has properties to develop seismic safety.

3.2 Evaluation the responded ductility factor and the ductility factor spectrum



(a) one-degree-of-freedom system

(b) Dynamic load-deflection characteristic (Bi-linear model)

Fig.2 Elastoplastic response analysis

As seen in Fig. 2(a), when a seismic load acts on the gravity center of the component installed on the elastic body, such as the ground, the position of the gravity center moves due to the deformation of the support and component itself. If this seismic response deflection exceeds the yield limit (yield deflection), and plastic deformation occurs at that part to decrease the stiffness, whereupon, the deflection increases drastically. This paper provides the model which is simplified (Fig.2(b)) load-displacement characteristics by bi-linear model.

$$k_1 = \frac{4\pi^2}{T^2}\frac{W}{g} \quad \text{—— (1)} \qquad Q_y = Sc\,W \quad \text{—— (2)} \qquad \mu = \frac{\delta_{max}}{\delta_y} \quad \text{—— (3)}$$

At Fig.4, Q_y is yield load, δ_y is yield deformation, δ_{max} is maximum deformation, primary rigidness k_1 is elastic rigidness and secondary rigidness k_2 is plastic rigidness. The equation (1) between Natural cycle T and k_1. W is weight of center of the mass and g is gravity. In the relational expression (2) between Q_y and W, seismic intensity giving yield load is called static seismic intensity or *Sc*. As shown previous section, ductility factor μ is defined ratio of δ_y to δ_{max} as described in the equation (3).

By performing the elastoplastic analysis and inputting any seismic motion to bi-linear model, load-deflection response according to the characteristics of the seismic motion and maximum ductility factor in the earthquake duration is obtained. Fig.3,4 shows the load-deflection hysteresis response characteristic (Fig.4), which is obtained by the observation records (Fig.3(a)) on Kashiwazaki-Kariwa Unit 1 R/B under NCO Earthquake in 2007.

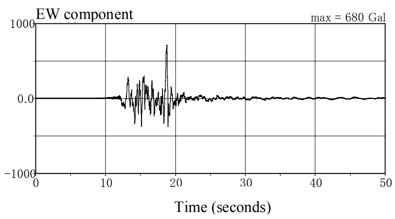


Fig.3 Example of seismic ground motion

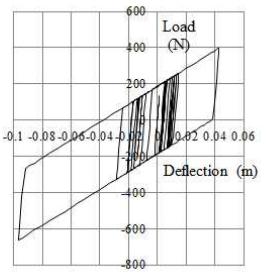


Fig.4 Example of load-deflection hysteresis

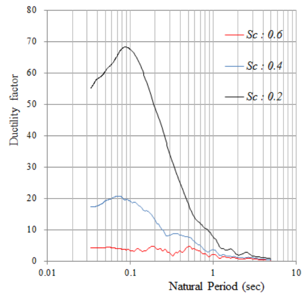


Fig.5 Example of ductility factor response spectrum

In addition, the ductility factor spectrum is obtained by calculation the same way (see Fig.5).

The level of ductility factor affecting the maintenance of function of the component is statically understood when spectrum of ductility factor obtained from static seismic coefficient Sc for the design and observation records and the status for damage or loss of function are compared in the damage situation of the NPS component.

4. Improvement of the static seismic design

In this paper, by setting static seismic coefficient which is met allowable ductility factor, static seismic design procedure is proposed the Component.

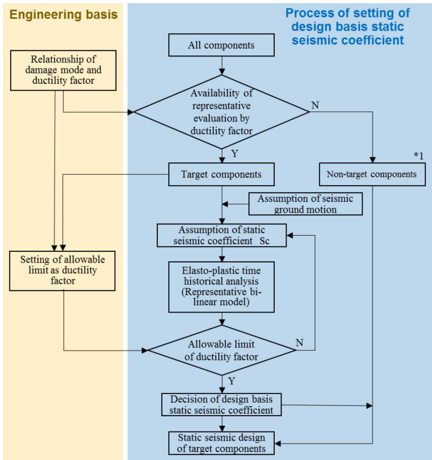
4.1 Abstract of the static seismic procedure

Fig.6 shows the step of the procedure for static seismic design procedure based on allowable ductility factor.

At first, designer need to select the Component which can be adapted this procedure. As shown in section 4.3, there is the Component which can not be adapted this procedure according to type or damage mode of the Component, so that the target component should be selected. The Component which can't be represented damage or loss of function by ductility factor such as chattering rely, relative displacement in earthquake and contact inner parts, etc. needs to be designed individually.

Next, the input ground motion is selected.The basis ground motion in the NPS is considered as one of ground motion assumed examples for the design are showed in section 5. When the ductility factor spectrum is derived by the input ground motion, static seismic coefficient or Sc is set and Elastoplastic time historical analysis is conducted by bi-linear model. Till the spectrum which derived by above procedure is analyzed within increment of the static seismic coefficient or Sc, till it is smaller than allowable ductility factor. And Sc to conform to allowable ductility factor will be found. Furthermore, static seismic coefficient for the design is set with taking conservation into the consideration and adapted each static seismic design.

The adaption of static seismic design with allowable ductility factor is shown at section4.3, and setting of allowable ductility factor is shown at section 4.4.



*1: A component, whose damage modes are not associated with the ductility factor, should be non-target component. Examples of these damage modes are wearing of bearings, ratcheting fatigue, contact of internal parts, short circuit of electrical equipment, relay chattering, etc.

Fig.6 Procedure of setting of design basis static seismic coefficient

4.2 Target of performance

While dynamic seismic design that considered the uncertainty of the basis ground motion and set target ground motion over the basis ground motion is generally demanded elastic design, the static seismic design aims at preventing damage or loss of the function of the Component. The evaluating system propose elastoplastic response of the components under alternate load realistically by adapting the evaluation based on the load deflection elastoplastic response.

4.3 application of the static seismic design by allowable ductility factor

The response and allowable ductility factor is evaluated by one-degree-of-freedom model. Through one-degree-of-freedom model is utilized for the design of any components, the Component in the NPS has various type.

Therefore, application of static seismic design based on allowable ductility factor is considered as per each system of the Component in this section.

4.3.1 The models for seismic design of the Component

The seismic design procedure for the system of the Component is described in “The technical code for seismic design of the NPS (JEAC 4601-2008)” (JEA(2008)) published by the Japan Electrical Association. And the inspection of the Component was conducted on the KK NPS under the NCO earthquake (IAEA(2011)). Table 1 shows the examples as analysis models adapted to the design of the Component and the weakest part.

4.3.2 Application of static seismic design with allowable ductility factor

1) The one-degree-of-freedom model

Many self-standing and dynamic components are represented by one-degree-of-freedom model. These components are designed displacement of the support or break of the bolt as the weakest part and can be

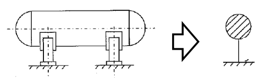
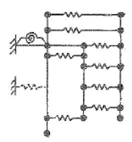
applied to static seismic design. The target components are the vessels, heat exchangers, horizontal pumps, vertical pumps (short and high strength), fans (high strength), diesel engine generators motors, HVAC, etc.
Dynamic components out of these facilities, continued function of them have to be evaluated separately.

2) The multibody system model

It is considered that the Component designed by the multibody system model, basically need to adapt the other procedure, can be analyzed by one-degree-of-freedom model and designed by this procedure in case of focused on the weakest part causing loss of function of the Component and on vibration mode affecting the Components.

The long vertical pumps are met this case. Maintenance of function of the component is confirmed in order to prevent loss of function for all parts except the weakest part.

Table 1 Examples of the major models of components for seismic analysis and typical vulnerable parts

Type of components	Model for seismic design	Vulnerable part and the damage mode
Tanks	One-degree- of-freedom model 	Anchor bolts (Shear fracture, plastic deformation)
Vertical pumps (long body)	2D multi-mass system model 	Anchor bolts (Shear fracture, plastic deformation) Bearings (Wearing)
Piping system	3D multi-mass system model 	Support structure (plastic deformation) Piping (Ratcheting fatigue)

3) The application against damage mode

The static seismic design procedure is effective for preventing damage of the part of the component or loss of function due to plastic deflection by earthquakes. The phenomenon such as loss of the function of the pump bearings, piping ratcheting fatigue, malfunction by the contact of internal parts of the equipment (turbine blade contact) or loss of electrical function such as electrical short circuit and chattering rely can't be applied this procedure. However, even if the damage mode corresponds with above damage mode, such as damage of the bearing of the pump, by clarifying the relation between load-deflection characteristic and damage evaluation parameter (surface pressure in case of the bearing), the maintenance function can be represented in allowable ductility factor.

4.4 Setting of the allowable ductility factor

4.4.1 The statistical arrangement of the components damaged by earthquake

As shown in section 3.2, seismic design based on the static seismic coefficient which is set in each NPS, become reasonable. It is rational that static seismic coefficient which is decided from the ductility factor spectrum shown in Fig.5 is set uniformly to adapt the allowable ductility factor.

It is considerable that allowable ductility factor is evaluated by analysis it each kind or type of the component but it will be reasonable to be defined allowable ductility factor by arrangement statistics knowledge in the NPS under earthquake.

Here, the level of the allowable ductility factor is considered widely the components in the KK NPS under the NCO earthquake on 2007. The samples of the low seismic class component which assumed that those ductility factors are high are selected and are evaluated the ductility factor.

1) The comparison of the components that have the same specification

In the KK NPS, it is found between components that degree of damage is different, though they are installed closely and have the similar seismic response characteristics.

The filtered water tanks (N.3 and No.4) are the same property On the No.5 yard and are installed closely. While the base bolts of the No.4 filtered water tank were damaged, the base bolts of the No.3 tank were not damaged. The ductility factor of them were 30. ― ①

2) The analysis of the components maintained the function

Next, the ductility factors of the undamaged components are considered. The components confirmed the relatively high ductility factor were Unit 7 main transfer (ductility factor was 14), Unit 6 station transfer (ductility factor was 12) and No.3 filtered water tank (ductility factor was 30).― ②

4.4.2 The setting of the allowable ductility factor

As a result of previous consideration, ① it is confirmed that the threshold of ductility factor of the component suffered damage is 30 and ② when the component's function is maintain even ductility factor being excess about 10, the threshold of ductility factor which damage the component in fact is considered no less than about 20～30. It is considered and proper that the allowable ductility factor taken account of conservation is set about 10.

Since the data obtained and analyzed for the ductility factor limit in the KK NPS, similar data from other NPSs or general industries will be required for further analysis of the ductility factor. It will be effective to conduct various test aimed at allowable ductility factor and analysis the past test.

5. Example of design in the KK NPS

Under the new regulatory Requirements for nuclear power station that was effective in July 2013, it is prescribed that the Specialized Safety Facility should be installed against Air Plane Crush or act of terrorism and also robustness against the seismic ground motion beyond basic seismic ground motion is required.

To improve that robustness of the Specialized Safety Facility, static seismic coefficient procedure, which is considered diversity of the seismic design procedure, is described below.

5.1 Setting of the input ground motion

The target of the static seismic coefficient procedure is to prevent the Component from damaging or losing their function, and considerable deflection of the Component are allowed, so that it is necessary to be assumed that the input ground motion is large considerably large. It is considerable that the diversity of uncertainty of the earthquake as natural phenomenon can be improved.

Here, the basis ground motion are need to set in the basis of the two viewpoints "the ground motion set by the specific hypocenter each site" and "the ground motion without setting by the specific hypocenter for each site" under the present regulation (NRA(2014)). The input ground motion for this procedure is considered above requirement.

5.1.1 The ground motion set by the specific hypocenter for each site

The ground motion set by the specifying hypocenter for each site is set in the basis of the ground motion in consideration of uncertainty to the earthquake that is expected that have a great influence on the site. Therefore, the input ground motion to calculate the ductility factor is unique for each site.

The ground motion set by the specific hypocenter each site in the basis ground motions for the KK NPS is considered the F-B fault and the Nagaoka plain western margin fault zone on 2007 and the parameters of the hypocenter included stress drop and fault slope angle about the each fault is set conservatively in the basis of the scientific knowledge (Ss-1 ~ Ss-7).

The input ground motion adapted for the static seismic design is need to be more than basis ground motion considerably and it is rational that it is set by twice the basis ground motion from easy viewpoint. Here, the twice waves of the S_S-1 and S_S-2 of the basis ground motions which have large maximum acceleration were the objects of consideration and these are set as Ss-1* and Ss-2* (See Fig.7, 8).

In principal, although the ground motion is considered by result of the seismic analysis for building as the Specialized Safety Facility, Ss-1* and Ss-2* which were set in the concept of free rock surface, were used in this consideration conveniently. Therefore, the result in this paper, comparing results analyzed by the response of the building, is considered extremely conservative result.

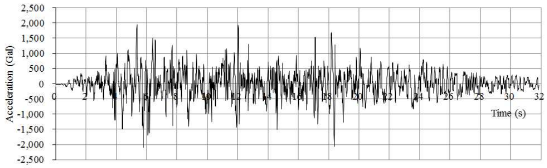


Fig.7 Seismic ground motion of Ss-1*

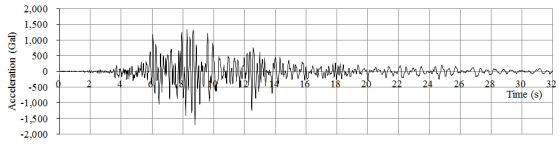


Fig.8 Seismic ground motion of Ss-2*

5.1.2 The ground motion set by the non-specific hypocenter

In setting the ground motion set by the non-specific hypocenter on the KK NPS, the past inside land srustal ground motion (the near earthquakes) which are difficult to connect the hypocenter and the active fault are extracted as the ground motion considered and the ground motion based on the motion of the 2004 south of Hokkaido Rumoi Sub-prefecture earthquake which is above the ground motion set by the specific hypocenter each site in part of cycle is added as the basis ground motion of Ss-8 based on observation records and ground property.

On the other hand, the input ground motion is set to consider the seismic design for the Specialized Safety Facility based on the national observation records at the ground level.

The selected ground motions are the 60 waves synthesized three dimension (See Fig.9) which have high acceleration higher rank and released as the data of Strong-motion Seismograph Networks（K-NET、KiK-net） published by National Research Institute for Earth Science and Disaster Resilience (See Fig.9).

1) Recording start time：from 1996 to April 2016

2) the maximum acceleration（the maximum acceleration synthesized three dimension） ：from 500 to 5000 Gal

3) distance from the epicenter：from 0 km to 30 km

These ground motions are ground motion which observed on the ground and have large acceleration compared to the response of the basis ground motion in the building of the Specialized Safety Facility.

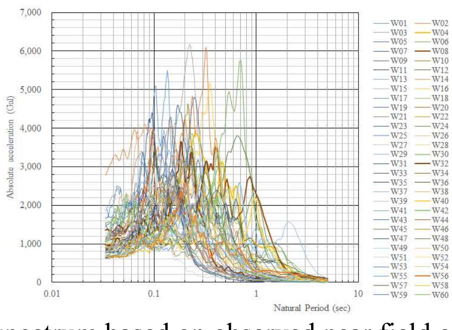


Fig.9 Seismic response spectrum based on observed near field earthquake ground motion

5.2 Evaluating the ductility factor and setting static seismic coefficient

5.2.1 The ground motion set by the specific hypocenter each site

elastoplastic analysis by input the Ss-1* and Ss-2* to bi-linear model using a one-degree-of-freedom system response of one-degree-of-freedom was performed (dumping factor in the elastic region : 0.05, secondary stiffness : 0.05 times the primary stiffness) and the spectrum of the responded ductility factor was calculated. (See Fig.10,11).

It is confirmed that the responded ductility factor exceeds 50 in the case of static seismic coefficient (Sc = 0.6) in some natural frequency of the Component which has seismic class S. Achieving the allowable ductility factor (10) suggested in the previous section, the static seismic coefficient of the Component in the Specified Safety Facility for seismic class S is expected upper 1.5. However, the Ss-1* and Ss-2* could be small static seismic coefficient so that these are ground motions on the free rock surface, therefore the static seismic coefficient applied to actual design is considered to be smaller than that.

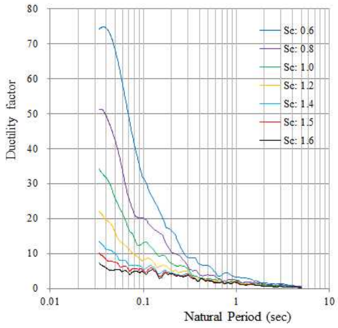


Fig.10 Ductility factor response spectrum (Ss-1*)

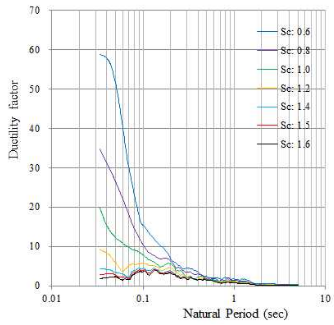


Fig.11 Ductility factor response spectrum (Ss-2*)

5.2.2 The ground motion set by the non-specific hypocenter

For the 60 ground waveform of near earthquake extracted in section 5.1.2, elastoplastic analysis using a one-degree-of-freedom bilinear model is conducted (dumping factor in the elastic region : 0.05, secondary stiffness : 0.05 times the primary stiffness) and the spectrum of response ductility factor was calculated (see Fig.12～14).

Based on the response ductility factor spectrum, maximum response ductility factor is approx. 100 at the static seismic coefficient of 0.6 (=Sc) for the Component of seismic class S at present. If the seismic coefficient of approx. 1.2 is applied, the response ductility factor of 60s wave is lower than 10 within the three times of the standard deviation (3σ). If applied 1.5, it is confirmed that all 60s response ductility factor are lower than 10.

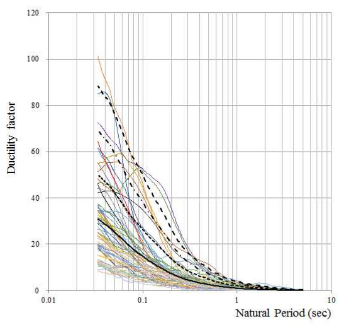


Fig.12 Ductility factor response spectrum (Sc 0.6)

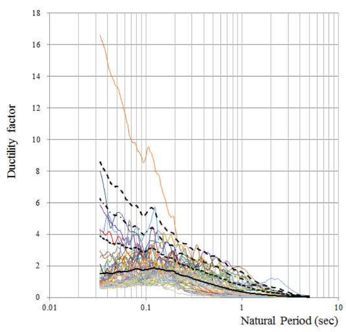


Fig.13 Ductility factor response spectrum (Sc 1.2)

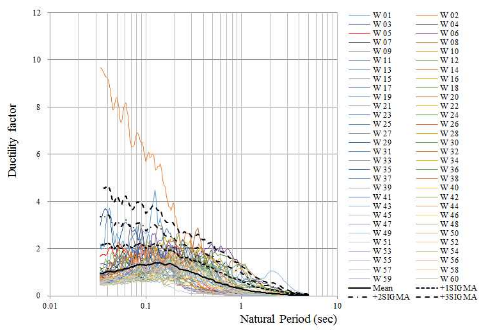


Fig.14 Ductility factor response spectrum (Sc 1.5)

Therefore, it is considered that 1.2～1.5 as the static seismic coefficient is required for the design of the Component which is seismic class S adapted 10 as the allowable ductility factor in the previous section.

5.2.3 Setting the static seismic coefficient adapted allowable ductility factor

The static seismic coefficient adapted ductility factor to 10 for the Specialized Safety Facility in the KK NPS is considered as an example. The input ground motion is twice the basis ground motion that the static seismic coefficient is the above 1.5 and is observation records on the ground of national large earthquakes that the static seismic coefficient is 1.2～1.5 and the both adapted the allowable ductility factor (10). Accordingly, it is considered that setting static seismic coefficient to 1.5 is effective for the diversity and the robustness design of seismic class S as the Specified Safety Facility.

6. CONCLUSION

The static seismic coefficient adapted the allowable ductility factor is set in this paper and the static seismic design procedure of the Component was suggested. Through analysis about situation of the components in the KK NPS suffered by the NCO Earthquake and the 1F NPS suffered by the GEJE of Tokyo Electric Power Holdings Inc., the level of the ductility factor and static seismic coefficient adapted to the allowable ductility factor is considered.

This procedure adapts new idea that the function is maintained by focus on the load-deflection characteristic of the Component with taking elastoplastic characteristic of the Component and the alternative characteristic of the ground motion into consideration against present dynamic design which the basis ground motion in the NPS present is demanded structural strength within elastic generally.

The earthquake is needed to be considered the uncertainty because the earthquake is natural phenomenon and it cannot be denied that the earthquake which exceeds the basis ground motion in a part of cycle will happen from the past experience. The procedure suggested in the paper is to put the backup in the case that the earthquake will happen and is to give new diversity and conservation to seismic design system at present. In addition, it is considered that the procedure contributes to understanding of the situation of the components suffered by the earthquake and judgement of restart operating after the earthquake.

It is expected to improve further knowledge about the allowable ductility factor by analysis the damage situation in the other NPS and the general industry, conducting test focused on the ductility factor and analysis the past test's results.

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