JANSI-FDE-03

Assessment Methods for Nuclear Power Plant against Fault Displacement

(Provisional Translation of Main Text)

September 2013

On-site Fault Assessment Method Review Committee
Japan Nuclear Safety Institute

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Contents

1. Introduction

One of the major regrets about the accident that occurred at Fukushima Daiichi Nuclear Power Station on March 11, 2011 was that we were not able to consolidate our knowledge due to weak coordination across the areas concerned with tsunami measures, such as “seismic analysis”, “tsunami analysis”, “civil engineering design”, “component design” and “safety design”. With deep reflection on this point, it is extremely important to consider comprehensive measures by coordinating relevant areas, consolidating our knowledge, and grasping a complete picture in various activities to improve nuclear safety in the future.

For on-site fault assessment, it is really necessary to put together scientific and engineering wisdom and review the safety of facilities in a comprehensive manner. In Japan as an earthquake country, a great deal of studies and researches into earthquakes have been accumulated in the areas of both science and engineering over the years. The world’s leading highest level of knowledge has been accumulated. To improve nuclear safety, it is considered vital to draw on all intellectual resources for full utilization.

From the above perspective, this report shows the procedure to comprehensive assessment of plant safety against fault displacement, drawing on all knowledge in the areas of “geomorphology”, “geology”, “geophysics”, “seismology”, “geotechnology”, “earthquake engineering”, “structural engineering”, “nuclear safety engineering”, and so forth. In other words, this report does not focus just on whether an on-site fault may be an active fault. Rather, it is intended to show a scientific and engineering framework to examine “whether it has a significant impact on the safety functions of important nuclear power plant facilities” when there is ground deformation due to fault movement in the ground on which they are sited.

This report summarizes the procedure from the estimation of fault displacement to the assessment of plant safety against displacement, which has not conventionally been made clear. It does not contain detailed analyses or specific study examples. These details will be deliberated further in the future.

We hope that this report will contribute to the improvement of nuclear safety.

2. Definition

As described in 1. Introduction, this study shows the procedure to comprehensive analysis of plant safety against fault displacement, drawing on all knowledge in the areas of “geomorphology”, “geology”, “geophysics”, “seismology”, “geotechnology”, “earthquake engineering”, “structural engineering”, “nuclear safety engineering”, and so forth.

For a cross-cutting study like this, it is important to clarify the definitions of the terms and share them with the parties concerned. For this purpose, the terms with different definitions from one area to another have been sorted out to establish a framework for a coordinated study. Thus, some of the terms used in one area may not always be used in the same way in other areas.

Table 2-1 shows the definitions of the terms used in this report.

Fault-related terms and their definitions have been put together and sorted out in Appendix A.

Table 2-1: Definitions of Terminology

Term	Definition
Fault	A discontinuous plane created by the fracture of rocks, along which relative displacement has occurred
Active fault	In general, a fault that has repeatedly been active in recent geological ages and may possibly be active in the future. A fault that cannot be denied being active since the Late Pleistocene. In recognizing active faults, a fault, which made no displacement or deformation in geological layers or geomorphic surfaces of the last interglacial period or before, can be set outside the scope of consideration.
Earthquake source fault	A fault that is considered to have caused an earthquake
Surface earthquake fault	A fault that has come up to the ground surface
Master fault	Same as an earthquake source fault
Splay fault	A fault that is formed diverging from an earthquake source fault and has a potential to be active in the future due to the activity of the earthquake source fault
Secondary fault	A fault that is formed secondarily in association with the activity of an earthquake source fault although no geotectonic association with the earthquake source fault and the possibility of its displacement cannot be denied in the future by the activity of the earthquake source fault
Landslide	Phenomenon in which materials of a slope slide by gravity
On-site fault	A fault, the outcrop of which exists on the site of a nuclear power plant, or the existence of which has been confirmed by boring survey, etc.
Ground deformation	Displacement bordering with a fault plane (hereafter referred to as displacement or fault displacement) and continuous deformation, such as inclination (hereafter referred to as deformation)
Geological field	Geological environment at the relevant site in the past and present, e.g., formation environment, geological structure formation process, and stress field.
Fault gouge	Fine-grained materials formed by fault movement
Ground deformation analysis	Analysis to examine the deformation (displacement and/or deformation) of the foundation ground of a reactor building, etc.
Enforced displacement analysis	Analysis in which the displacement is input as a displacement vector at the boundary of the model
Foundation ground stability analysis	Analysis to verify that the support function of the foundation ground of a reactor building , etc. is not significantly affected by seismic motion or ground deformation, including the examination of a slip safety factor as well as the stress state of the ground

An earthquake occurs upon displacement or fracture of an earthquake source fault. When the scale of displacement is major, it will come up to the ground surface as a surface earthquake fault. Active faults are the traces of activities of earthquake source faults that had repeatedly appeared at the ground surface, which include “master faults” and “splay faults”.

A “secondary fault” is a fault that is formed secondarily in association with the activity of an earthquake source fault although no geotectonic association with the earthquake source fault and the possibility of its movement cannot be denied in the future by the activity of the earthquake source fault

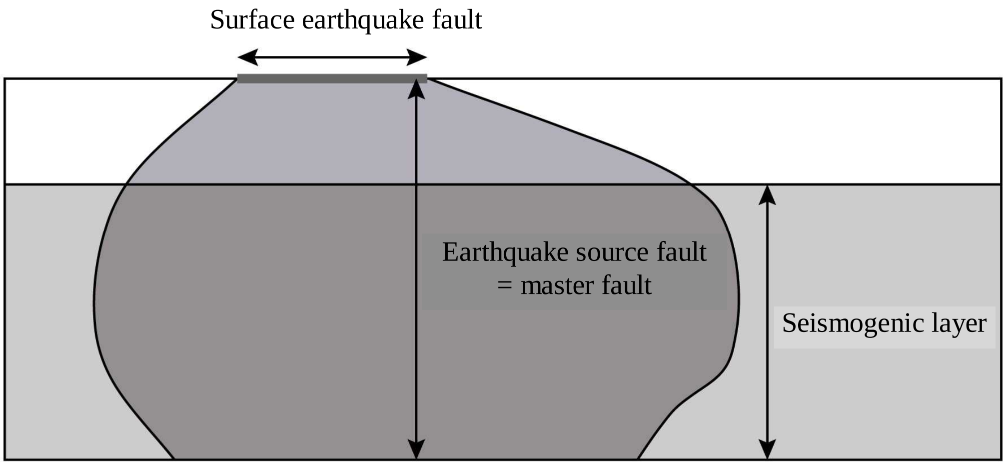

Figure 2-1: Schematic Diagram of Relationship between Earthquake Source Fault and Surface Earthquake Fault

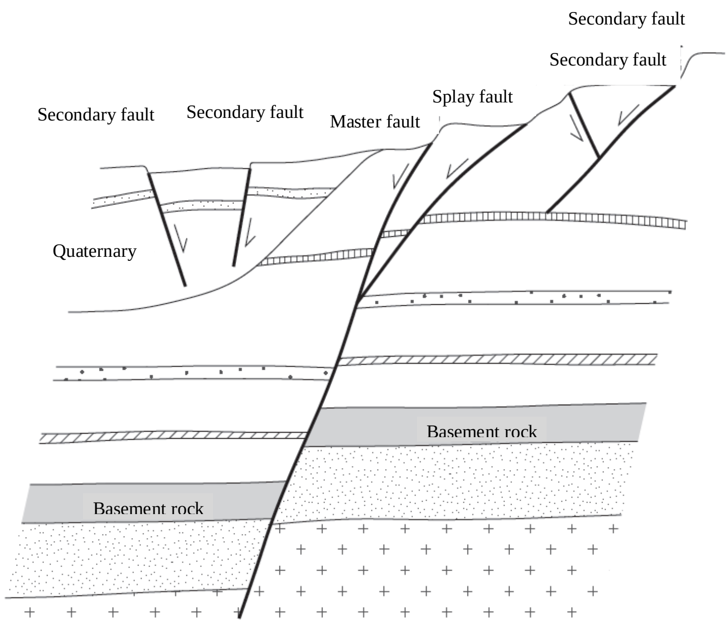

Figure 2-2: Conceptual Diagram of Surface Earthquake Fault Distribution

3. Scope of Application

(i) This study shows the framework of the safety assessment of a nuclear power plant against on-site fault displacement. When considering the impact of on-site faults in the event of an earthquake, seismic motion (quake) and ground deformation (discontinuous displacement and continuous deformation) come into question. This report focuses on the latter, i.e., ground deformation.

(ii) An on-site fault is a fault, the outcrop of which exists on the site of a nuclear power plant, or the existence of which has been confirmed by boring survey, etc. When the displacement of this fault cannot be denied in the future, it has the potential to affect the facilities. In this study, both displacement and deformation will be considered as a direct or indirect effect on the facilities. The safety assessment of a nuclear power plant against on-site fault displacement, which takes account of both impacts, will be referred to as “safety assessment against fault displacement”.

- Direct impact: Impact due to discontinuous displacement of the ground (hereafter referred to as “displacement”)
- Indirect impact: Impact due to continuous deformation, such as inclination (hereafter referred to as “deformation”)

(iii) In this study, those faults whose possibility of movement cannot be denied in the future will be considered. In other words, those faults that have possibility of passively moved by seismic activities (secondary faults) will be considered in addition to active faults (master faults and splay faults) that are regarded as earthquake sources. After considering the possibility of the fault movement in question, the impact of its displacement on the facilities will be analyzed when the possibility of displacement cannot be denied. On the other hand, those faults that can be denied to have been active since the Late Pleistocene are regarded not to move in the future.

(iv) On-site faults confirmed at the outcrop on the bed rock surface are considered. When there is no evidence on the bed rock surface, the occurrence of new faults does not have to be considered.

(v) This study focuses on the important facilities mainly among power reactor facilities concerned with “shutting down”, “cooling” and “containing”. For example, these include reactor buildings and components and piping systems in them. This study is also considered applicable to important civil engineering structures, and other nuclear-related facilities.

(vi) The analysis methods shown in this report have been developed primarily for application to existing plants. These methods can also be referenced in the design of new plants.

4. On-site Fault Assessment Policy

The basic idea is to ensure that "the safety functions of the reactor facilities would not significantly be affected" by earthquakes and/or tsunamis, as well as other natural phenomena than earthquakes and tsunamis. Safety against displacement will also be assessed taking account of its effect on these safety functions.

4.1 Safety Assessment of Plant against Fault Displacement

The flowchart of safety assessment against fault displacement is shown in Figure 4-1.

(i) Grasp the distribution, properties, and activity of on-site faults through geological surveys. Select the secondary faults whose movement cannot be denied in the future.

(ii) Estimate the displacement of the selected secondary faults by the method described in Section 4.2 to set the design basis displacement δa that is equivalent to the design basis event for other natural phenomena. In doing so, the probabilistic fault displacement hazard analysis, in which the fault in question is regarded as a secondary fault, will be referenced. Here, referencing means to estimate the annual frequency of exceedance of δa based on the probabilistic fault displacement hazard analysis so as to verify that the estimated value meets the reference value shown in the next section. Use the method described in Chapter 6 to perform a stability evaluation of foundation ground in the event of fault displacement so as to verify that the foundation ground will retain the function to support the buildings and structures.

(iii) In estimating the design basis displacement δa, perform an enforced displacement analysis by the method described in Chapter 8 with the obtained ground displacement as a condition input to the analysis model of the buildings and structures. Separately, determine the impact of seismic motion on the buildings and structures to grasp the effect of both displacement and seismic motion on the buildings and structures, thereby confirming that the safety functions will not significantly be affected in comparison with the allowable limits described in Chapter 7. The deformation and inclination of building mat slabs, etc., and the relative displacement between the buildings will be used as input conditions for reviewing components and piping systems.

(iv) Use the deformation, inclination, and relative displacement between the buildings obtained in the foregoing examination of the buildings and structures to estimate the effect on components and piping systems. Use the method described in Chapter 9 to analyze safety against displacement. When it is anticipated that the safety functions may be affected, safety improvement measures need to be taken.

(v) Since the uncertainty of fault displacement is considered to be greater than that of other natural phenomena, the impact on the facilities arising from the displacement exceeding the design basis displacement δa will be examined from the perspective of risk assessment. That displacement will be referred to as the beyond design basis displacement δb. In this case, an analysis will be performed based on the actual strength of each piece of equipment to estimate its impact on the functions required of the facilities. When the functions required of the facilities are considered to be affected, mitigation measures will also be considered. Probabilistic fault displacement hazard analysis in this stage is intended to refer the annual frequency of exceedance of δb from the perspective of risk assessment.

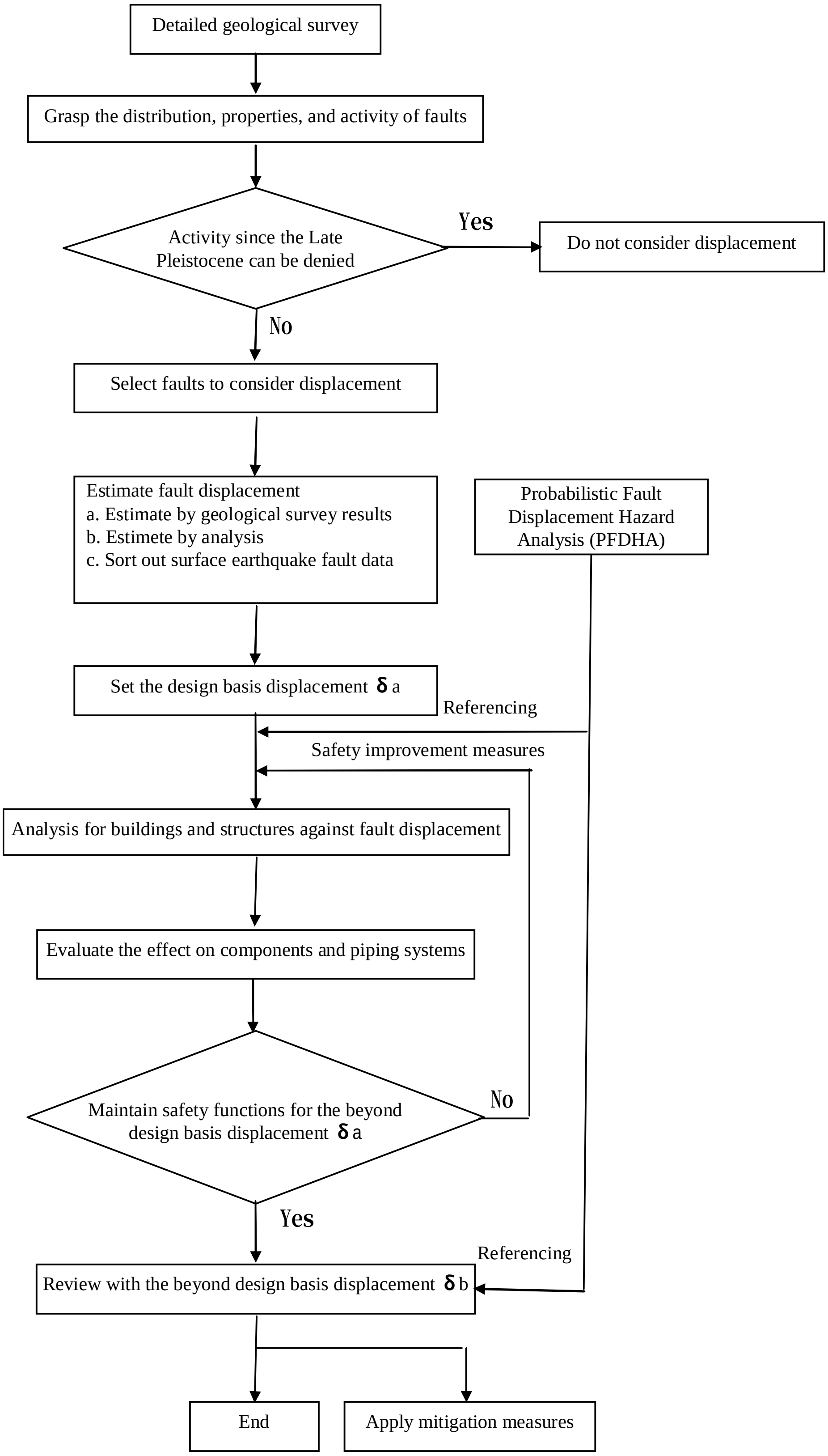

Figure 4-1: Flowchart of Assessment

4.2 Estimating Fault Displacement

4.2.1 Basic Approach

(i) It is reasonable to treat fault displacement in an approach consistent with earthquakes, tsunamis, and other natural phenomena that are taken into account in deliberating how to ensure nuclear power plant safety. It should be verified that the maintenance of safety functions would not significantly be affected even if fault displacement should occur in the ground in the event of an earthquake.

(ii) The activity and origin of an on-site fault need to be studied in a scientific and reasonable manner. When different opinions arise as to its activity and origin, however, it is important to show that its effect on the facilities can be estimated through an engineering analysis even when the fault displacement occurs.

(iii) For a nuclear power plant, since the location of installations is decided based on a detailed study, no active fault exists beneath the reactor building. In this report, the secondary fault that exists immediately beneath the reactor building and the possibility of its displacement cannot be denied is considered, and its displacement will directly be applied to the reactor building. The effects of other on-site secondary faults and master faults that exist both on and off the site on the ground on which the reactor facilities are sited will also be analyzed

(iv) Core damage frequency (CDF) of 10^{-4} (per year) has been specified as a performance goal to ensure nuclear power plant safety. Based on this, the probability (frequency) of natural phenomena has been discussed.

(v) With regard to seismic motion, it is required to perform a seismic hazard analysis to show what level of exceedance probability is comparable to the Design Basis Earthquake Ground Motion Ss. The probability (frequency) of Ss is set to be 5×10^{-4} to 10^{-5} (Nuclear Power Plant Seismic Design Engineering Codes JEAC4601-2008). In the examination guide regarding tornadoes, the annual probability of exceedance of the maximum wind velocity of the design basis tornado is considered to be 10^{-5} (tentative) as new regulatory standard. Based on these, in this report, annual frequency of exceedance of 10^{-4} to 10^{-5} (per year) is assumed for design basis fault displacement. This fault displacement will be referred to as the design basis displacement δa.

(vi) For this design basis displacement δa, it is necessary to ensure the safety functions of a nuclear power plant, i.e., “shutting down”, “cooling” and “containing”.

(vii) Since the uncertainty of fault displacement is considered to be larger than that of other natural phenomena, the impact on the facilities arising from fault displacement exceeding the design basis displacement δa (beyond design basis displacement δb) will be examined.

4.2.2 Estimating Displacements (δa and δb) for Analysis

It is usual that a large number of faults exist both on and off the site. Out of these, the faults for which the effect of displacement will be estimated are classified as shown below. Faults whose activity since the Late Pleistocene is denied are considered not to move in the future.

(i) Secondary fault immediately beneath the reactor building
Estimate the displacement of the secondary fault in question in the event of an earthquake and apply this displacement to the facilities.

(ii) Secondary faults not immediately beneath the reactor building
Estimate the displacement of the secondary fault in question in the event of an earthquake to analyze the effect of this displacement on the facilities (ground deformation, such as the inclination of the ground).

(iii) Master faults and splay faults that exist on and off the site
Estimate the displacement of the master fault in question in the event of an earthquake to evaluate the effect of this displacement on the facilities (ground deformation, such as the inclination of the foundation ground). Also examine whether the on-site secondary faults will be displaced by the displacement of the master fault. When they are displaced, (i) or (ii)

should be considered.

(1) Design basis displacement δa

The design basis displacement δa will be estimated in a comprehensive manner by any of the methods (a, b, c) listed below or by appropriately combining them.

a. Estimation by geological survey results

When past fault activity data is available from on-site geological surveys, δa will be estimated based on it. Specifically, it can be estimated as displacement or deformation per activity from trench surveys, etc., or can be computed from the cumulative displacement and the number of activities.

b. Estimation by analysis

If no geological survey results are available as shown in a above, δa can be estimated using the analysis method described below. In this case, the per-activity displacement of master faults that exist on and off the site will be estimated and the δa of the secondary fault immediately beneath the facilities will be estimated based on it by analysis. The per-activity displacement of a master fault can appropriately be estimated based on the geological survey results or the empirical relationship between the master fault displacement and the magnitude of earthquake.

c. Probabilistic fault displacement hazard analysis

Based on the above mentioned estimations (a. and b.), an appropriate δa is set based on engineering judgment. The annual frequency of exceedance of this δa will be estimated based on the probabilistic fault displacement hazard analysis to compare with the reference value of 10^{-4} to 10^{-5} (per year).

(2) Beyond design basis displacement δb

In view of the uncertainties involved in natural phenomena, the impact on the facilities arising from any displacement (beyond design basis displacement δb) exceeding the design basis displacement δa will be examined. Examples of estimation of the impact of δb on the buildings and structures include investigating whether the total fracture of building mat slab will totally occur.

In this report, secondary fault displacements were newly analyzed based on the data sorted out for past surface earthquake faults. Based on this, it has been confirmed that secondary fault displacements are considered to be up to 30cm within the scope of this study. Thus, this value can be set as δb. The annual frequency of exceedance of this value can be estimated based on the results of the probabilistic fault displacement hazard analysis. The appropriateness of this value can also be verified for application.

In this report, two types of displacement are used, i.e., δa and δb. When it can be verified that the safety functions originally required for δa can be met by δb, the analysis using δa can be omitted.

(3) Deformation Analysis

For deformation analysis by δa, the displacement of master faults on and off the site and that of on-site secondary faults will be estimated in a manner similar to (1) above. The deformation of the foundation ground can be determined by evaluation based on computational analysis.

The impact of the displacement of the secondary fault immediately beneath the facilities is greater than that of the deformation of foundation ground due to the displacement of the secondary fault distantly located. For deformation analysis by δb, only the former will be considered.

4.2.3 Comparison of Fault Displacement with Other Event

The estimation of δa and δb in comparison with other events (natural phenomena) is shown in

Table 4-1.

As mentioned earlier, the location of facilities is decided based on a detailed geological investigation. Thus, the locations of the faults to analyze are clear. The regions (positions) in which certain impact is expected can be specified. Depending on the region, the impact on the safety-related facilities of the plant can be mitigated by the redundancy of the systems, for example. Therefore, fault displacements have characteristics that are different from other natural phenomena. On the other hand, the uncertainties anticipated for them are greater than those of other natural phenomena, including epistemic uncertainties as to whether the analysis condition (displacement) itself would occur. Thus, it is effective to analyze the impact on the facilities, assuming δb as an amount of displacement, to assess the risk the anticipated level may have on plant safety with a view to cover mitigation measures.

Table 4-1: Positioning of Estimation of δa and δb

	Evaluate basis event	Event exceeding evaluate basis	Status of standards concerning the estimation of event occurrence frequency
Fault displacement	Assessment against the design basis displacement δa	Assessment against the beyond design basis displacement δb	Collection of JAEE papers (Note 1)

	Design basis event (Note 5)	Event exceeding design basis	Status of standards concerning the estimation of event occurrence frequency
Seismic motion	Assessment against the Design Basis Earthquake Groun Motion Ss	Seismic risk analysis Seismic margin analysis	Earthquake PRA Standards (Note 2)
Tsunami	Assessment against the Design Basis tsunami	Tsunami risk analysis Tsunami resistance margin analysis	Tsunami PRA Standards (Note 3)
Tornado	Assessment against the reference tornado	—	JNES outsourced research (Note 4)

(Note 1) Takao, M., et al.: Application of Probabilistic Fault Displacement Hazard Analysis in Japan, Journal of Japan Association for Earthquake Engineering, Volume 13, No. 1, 2013, pp17-36

(Note 2) Implementation Standard Concerning the Seismic Probabilistic Safety Assessment of Nuclear Power Plants: 2007(AESJ-SC-P006:2007)

(Note 3) Implementation Standard Concerning the Tsunami Probabilistic Risk Assessment of Nuclear Power Plants: 2011(AESJ-SC-RK004:2011)

(Note 4) Research Study on the Impact of Tornadoes on Nuclear Facilities (February 2011), FY2010 Outsourced Research Result Report, Japan Nuclear Energy Safety Organization (JNES)

(Note 5) Hazard analysis in the examination/analysis of the new regulatory standards by NRA is referencing the exceedance probability of the Design Basis Earthquake Ground Motion Ss and the Design Basis tsunami with regard to seismic motion and tsunami. For tornadoes, it is referencing the greater of the “maximum wind velocity in the past” and the “maximum wind velocity corresponding to the annual exceedance probability based on the hazard curve.”

5. Fault Survey Method and Classification

5.1 Fault Survey Method

Figure 5-1 shows the flowchart of the on-site fault activity estimation method.

For fault activity estimation t, special attention should be paid to making comprehensive decisions based on the knowledge of “geomorphology”, “geology”, “geophysics” and so forth.

As shown in this flowchart, the “overlying strata method” is used for activity estimation. In this method, when any strata in or before the last interglacial period are distributed, the existence of activities since the Late Pleistocene is determined as to whether the strata have been displaced or deformed by any fault.

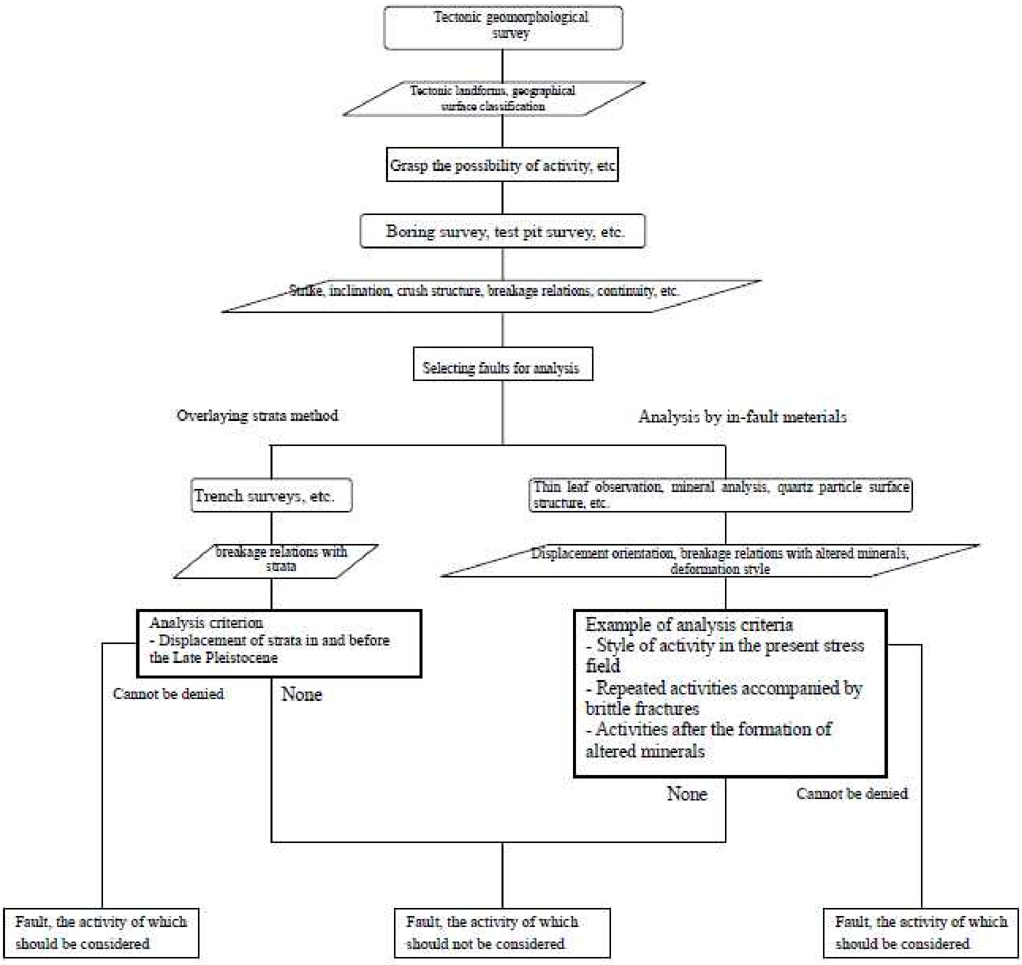

Figure 5-1: On-site Fault Activity Estimation Method

The concept of the overlying strata method is shown in Figure 5-2. As shown in the right of this figure, when Stratum B covering the top of the fault is not displaced or deformed by the fault, it is determined that there have been no activities at least since the sedimentation of Stratum B. In other words, it is determined that this fault is not an active fault if Stratum B is older than the Late Pleistocene.

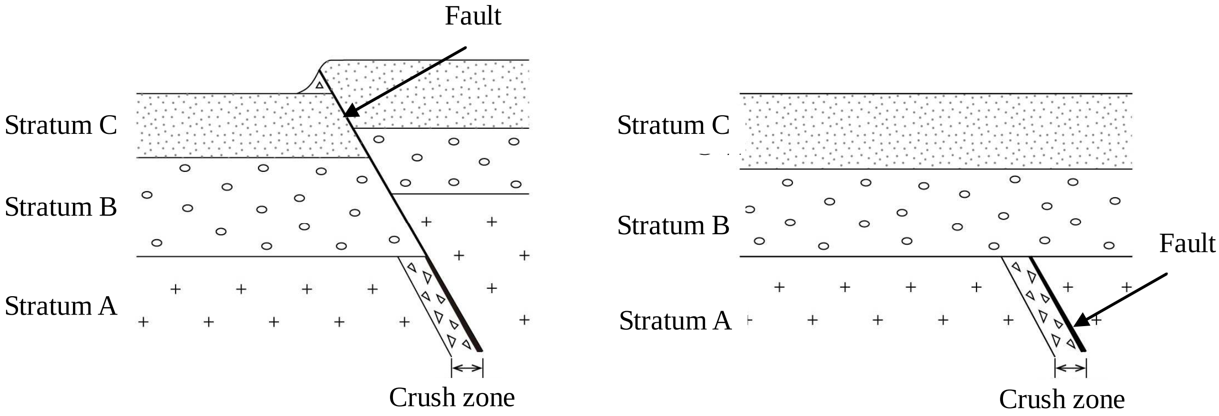

Figure 5-2: Conceptual of Overlying Starta Method

When there are no overlying strata, a decision will be made in a comprehensive manner based on the “analysis of in-fault materials” or the geological structure development process.

Attention should be paid to the following points in examining in-fault materials:

・Whether the pattern of activity is consistent with the present stress field.

・Whether repeated activities accompanied by brittle fractures can be recognized. Whether the fault has been formed in an environment involving plastic deformation and has been active since then.

・Whether any activities after the formation of altered minerals can be recognized. Whether the fault has been active after being affected by generative or hydrothermal activities in deep underground.

5.2 Fault Classification

Based on the above-mentioned detailed geological survey, faults will be classified into the following four types (see Chapter 2 and Figure 2-2):

・Master Faults

・Splay Faults

・Secondary Faults

・Other Faults

Generally, this sort of mechanical classification may sometimes be difficult. For example, different opinions often arise in connection with the recognition of fault activities and their origins. These include the decision on fault properties based on the deep underground fault distribution profile, the decision on activity based on the state of consolidation in the fault crush zone, and the estimation of depositional ages of volcanic ashes, etc., used for the estimation of those of strata. For any fault that cannot be denied being active, the fault in question will be considered as a secondary fault in this study. Its effect on the facilities will be estimated taking account of displacement.

Where there are different opinions about the activity and origin of the fault in question, scientific and rational investigation should be promoted in regard to its activity and origin in parallel with the assessment against fault displacement.

6. Methodology of Estimation of Fault Displacement

6.1 Estimation by Field Study

When the fault's past activity data is available from on-site geological surveys, its displacement will be estimated based on it. Specifically, it can be estimated as displacement or deformation per activity based on trench surveys, etc., or displacement per activity that can be computed based on the cumulative displacement and the number of activities

6.2 Sorting out Data on Surface Earthquake Faults

Based on the surface earthquake fault data observed in Japan, secondary fault displacements have been sorted out as shown in the figure below (see Appendix B).

Fourteen earthquakes of Mj6.5 or higher that have occurred since about 120 years before were selected for analysis. These surface earthquake faults whose displacements are in harmony with the activity sense of earthquake source faults were presumed to be structural faults and secondary faults appeared near these faults were selected for sorting out their displacements. Eight earthquakes of Mj6.8 to 7.3 were accompanied by these secondary faults with displacements ranging roughly from 0.1m to 0.3m.

In terms of the relationship between the magnitude of earthquake and secondary fault displacements, displacements range from 0.1m to 0.2m for Mj6.8 to Mj7.0 and 0.2m to 0.3m for Mj.7.2 to Mj.7.3, except for the Mikawa Earthquake. It is possible to estimate corresponding secondary fault displacements by identifying the size of the master fault based on these data.

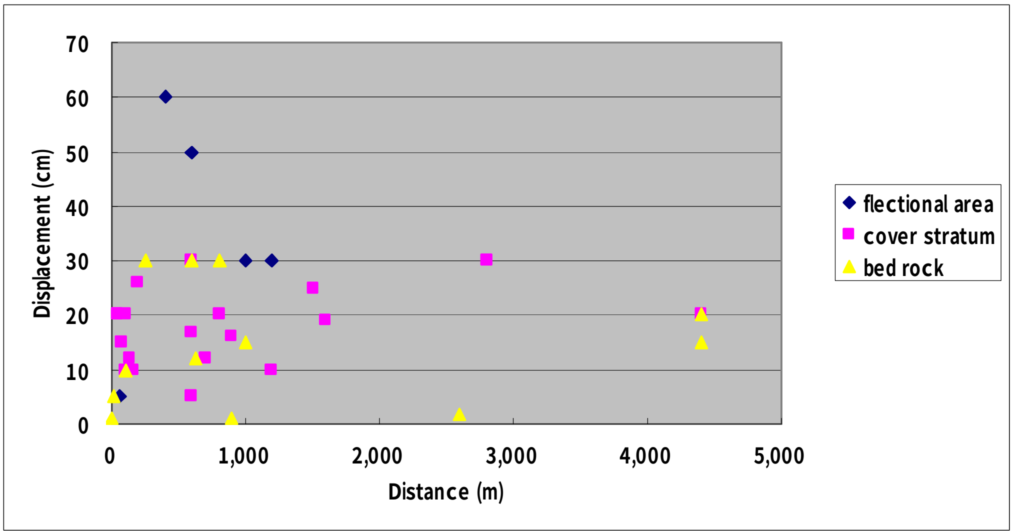

Figure 6-1: Distance from Master Faults and Displacement of Secondary Faults

For this study, documented fault displacements corresponding to tectonic landforms were recog l as master faults or splay faults, while those not corresponding to tectonic landforms were recog l as secondary faults (see Chapter 2).

Doc nted fault displacements are considered to have left remarkable displace Flection area in the records of geological surveys. Even if a detailed resurvey is performed at this p Cover stratum f time, landforms have changed due to artificial modifications or natural erosion. In particula Bedrock highly likely that minor fault displacements have ceased to exit. It is difficult to recognize minor faults that are not recorded at this point of time. Considering that largest displacements have essentially been recorded immediately after earthquakes, it is possible to understand that this figure shows the largest values of secondary faults although it was prepared to sort out approximately 120 years of data in Japan.

It is necessary to note that this figure includes the displacement of overlying strata as well as that of bedrock. According to the data on bedrock and overlying strata, however, there is no significant difference and the displacements are roughly 30cm or less. The appearance of surface earthquake faults is considered to vary depending on the size or location of the asperity of earthquake source faults, crustal stress fields, physical properties, geological structures, and landforms. However, this figure can be referenced for the beyond design basis displacement δb in connection with fault displacements that are expected to occur in the future.

The particularly large values in the above figure may have reflected the activity of the master faults aligned in an echelon arrangement in a "flectional area" during the Northern Izu Earthquake or Mikawa Earthquake. The area in which these were recorded is located at a junction of neighboring earthquake source fault segments. Since the strike of both earthquake source faults changes sharply by 30 degrees or more, it is referred to as a "flectional area." For fault displacement assessment, it is necessary to note that fault displacement in a "flectional area" like this is likely to be larger, necessitating future research and study.

6.3 Displacement Estimation by Analysis

6.3.1 Outline of Fault Displacement Analysis Methods

Here, major methods for analytically determining on-site fault displacement, including advanced ones, are outlined. The effect of displacement will be estimated first by using the analysis methods conventionally used in the engineering area. It is desirable to use advanced analysis methods complementarily as many of which are still in the study phase to make comprehensive decisions on analysis results.

(1) Dynamic Approach

As a method to estimate on-site fault displacement, dynamic model-based approach can be thought of. In this method, fault parameters, such as the fracture propagation rate, amount of displacement, and seismic source time function, can be obtained as a result of analysis just by giving the stress-slip relationship on the fault plane. Since the 1970s, analysis based on this approach has continuously been performed using the finite difference method (Reference 1), boundary integral equation method (Reference 2), and finite element method (References 3 through 7). Initially, the main objectives were to understand the occurrence and development of fault ruptures, and reproduce seismic motions near the ground surface. Following the damage done by surface earthquake faults in the 1995 Hyogo-ken Nambu Earthquake and 1999 Taiwan Chi-chi Earthquake, however, it draws attention as a displacement analysis method in recent years. In the finite element method, for example, those mechanisms suitable for fracture problems, such as the particle discretized scheme finite element method (PDS-FEM) (Reference 8), may be used in addition to those using joint elements when modeling faults. Figure 6-2 shows the image of the model.

In principle, it is an ideal model that allows for reproducing the movement of a fault and that of the ground in the vicinity of the building in single model for simultaneous consideration of dynamic effect. When the model for analysis is made to have resolution sufficient to analyze the deformation of the ground near the building, however, a certain means are needed because analysis is difficult with ordinary computer capacity. The further development of this approach is desirable, e.g., investigation concerning the calibration of the stress-slip relationship on the fault plane.

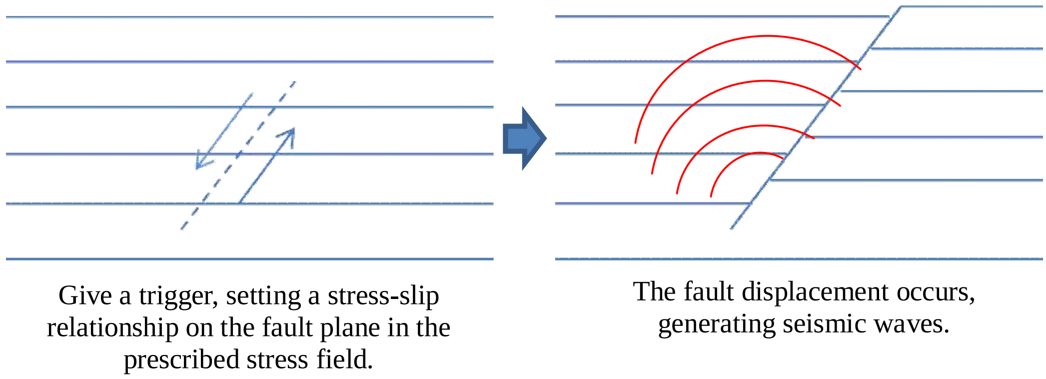

Figure 6-2: Image of Dynamic Approach

(2) Static Approach

Enforcement displacement resulting from fault dislocation will be applied statically to the boundary of the target area in which the effect on the facilities will be analyzed to compute the displacement and/or deformation of the analysis area. Enforced displacement applied to the boundary of the analysis area is computed using the elastic theory of dislocation, etc., as shown in Figure 6-3. In the elastic theory of dislocation, other faults and buildings within the analysis area will not be modeled. Subsequent ground deformation analysis will be described Section 6.3.2.

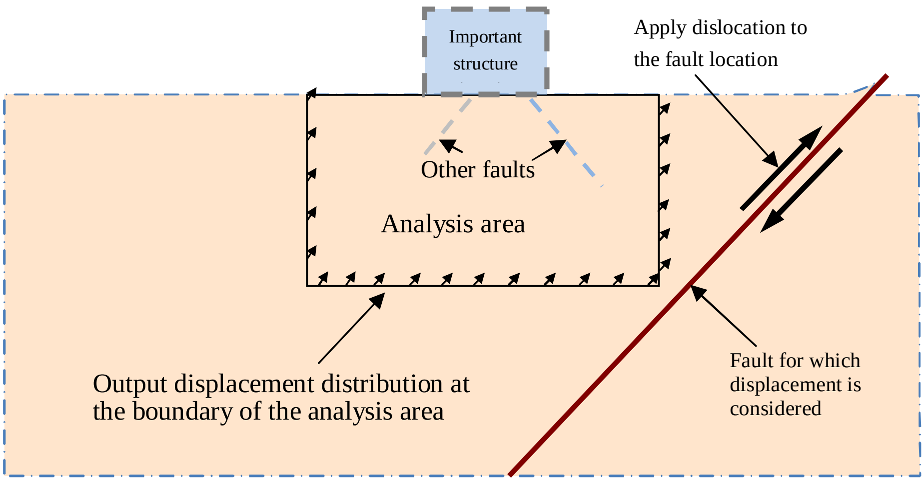

Figure 6-3: Computing Displacement in the Boundary of the Analysis Area

(3) Approach by Granular Material Models

Both dynamic and static approaches are generally based on the finite element method. In recent years, however, granular material models of the distinct element method (DEM) are used for analysis (References 9 through 12). The distinct element method can render slips and breaks at all contact points representing granular materials, making it easy to reproduce fracture phenomena. Figure 6-4 shows an example of analysis by the distinct element method in static approach.

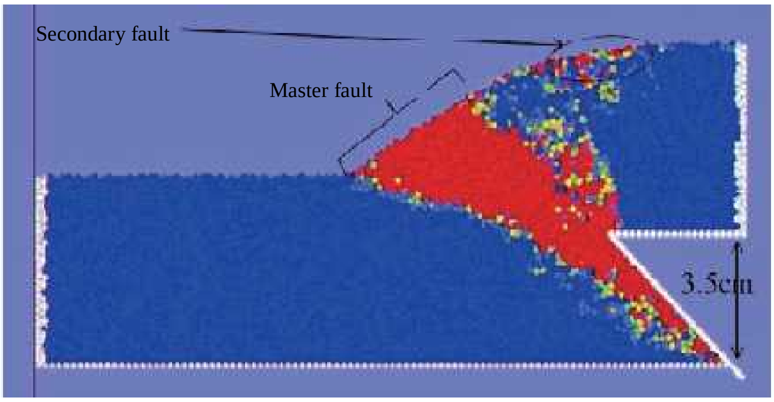

Figure 6-4: Example of Analysis by the Distinct Element Method (Arai, et al., 2013)

References

＜Finite Difference Method＞

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＜Boundary Integral Equation Method＞

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6.3.2 Ground Deformation Analysis Method

Here, the steps are described to analyze the deformation (displacement and/or deformation) and stability of the building foundation ground affected by both fault displacement and seismic motion during an earthquake.

(1) Analyzing Ground Deformation due to On-site and Near-site Fault Displacement

The methods for analyzing ground deformation due to fault displacement and seismic motion include advanced ones, such as the dynamic approach and granular material analysis described in the previous section. Here, however, the method by the static approach applying conventional methods is described.

In the current stability analysis of a reactor building foundation ground, the ground including faults is modeled in detail and the verification seismic motion is input to verify ground stability by the finite element method. The ground deformation analysis method described in this section is the method that uses the ground model of this finite element method. The area accounted for by this ground model will hereafter be referred to as the analysis area.

In the heading of this section, “on-site” and “near-site” are used distinctively. In terms of analysis, however, there are no significant differences in the treatment of both.

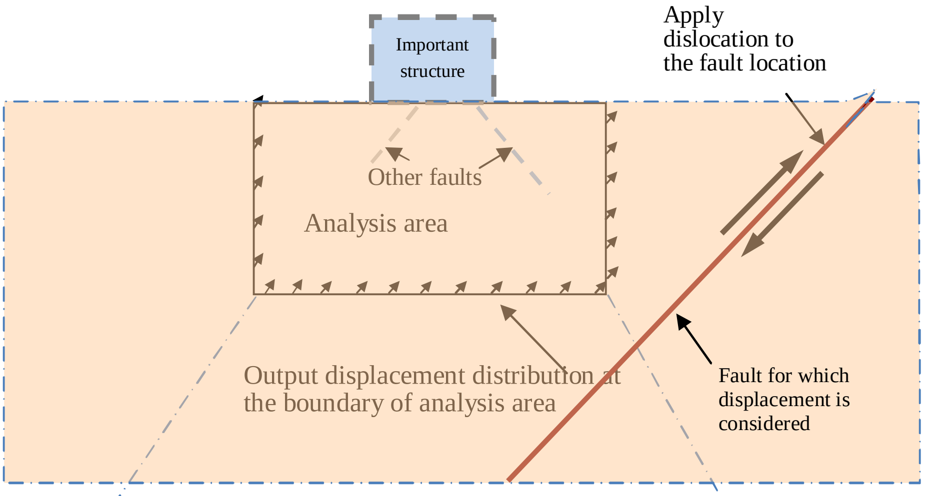
This method statically applies enforced displacement to the boundary of the analysis area. To determine the enforced displacement applied to the boundary, the aforementioned elastic theory of dislocation and other are used.

Figure 6-5 shows the image of the ground deformation analysis method in which the amount of displacement at the boundary is determined using the elastic theory of dislocation. This example represents an image in which near-site fault dislocation is considered. When on-site faults are considered, the model shown in Figure 6-6 can be used.

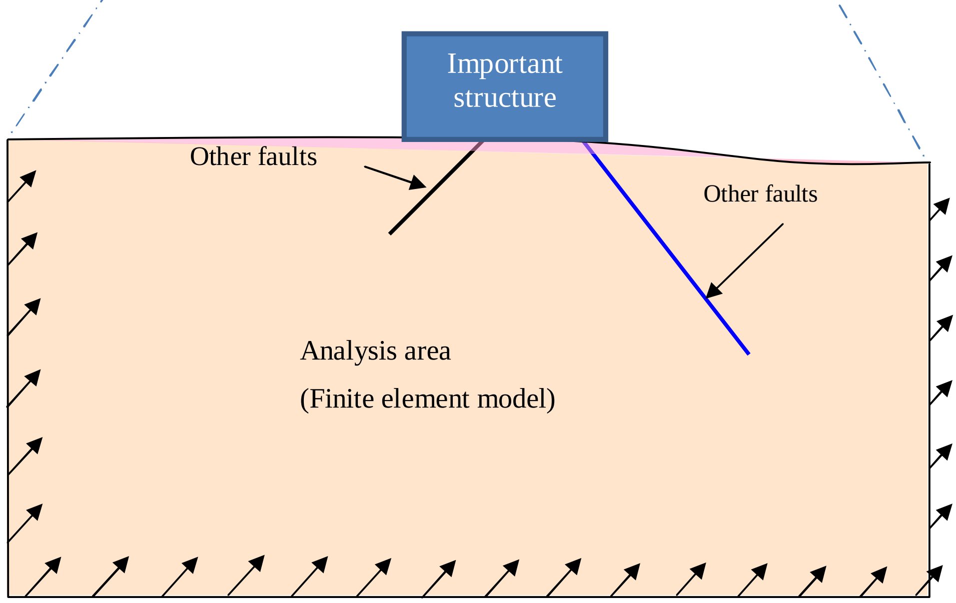
Other than the method using the elastic theory of dislocation, there is also a method in which the amount of dislocation determined in Sections 6.1.1 and 6.1.2 is applied directly to the model boundary as a vector in the fault orientation.

The items to be evaluated by the ground deformation analysis described in this section are:

- Displacement or deformation of the building foundation ground.
- Stress distribution, strain distribution, and local safety factor distribution in the building foundation ground.



Compute the boundary displacement in the analysis area with the elastic theory of dislocation.
(Other faults or buildings within the analysis area are not modeled)



Statically apply the boundary displacement computed with the elastic theory of dislocation to the finite element model in the analysis area.

Figure 6-5: Image of Ground Deformation Analysis with the Elastic Theory of Dislocation
(When near-site faults are considered)

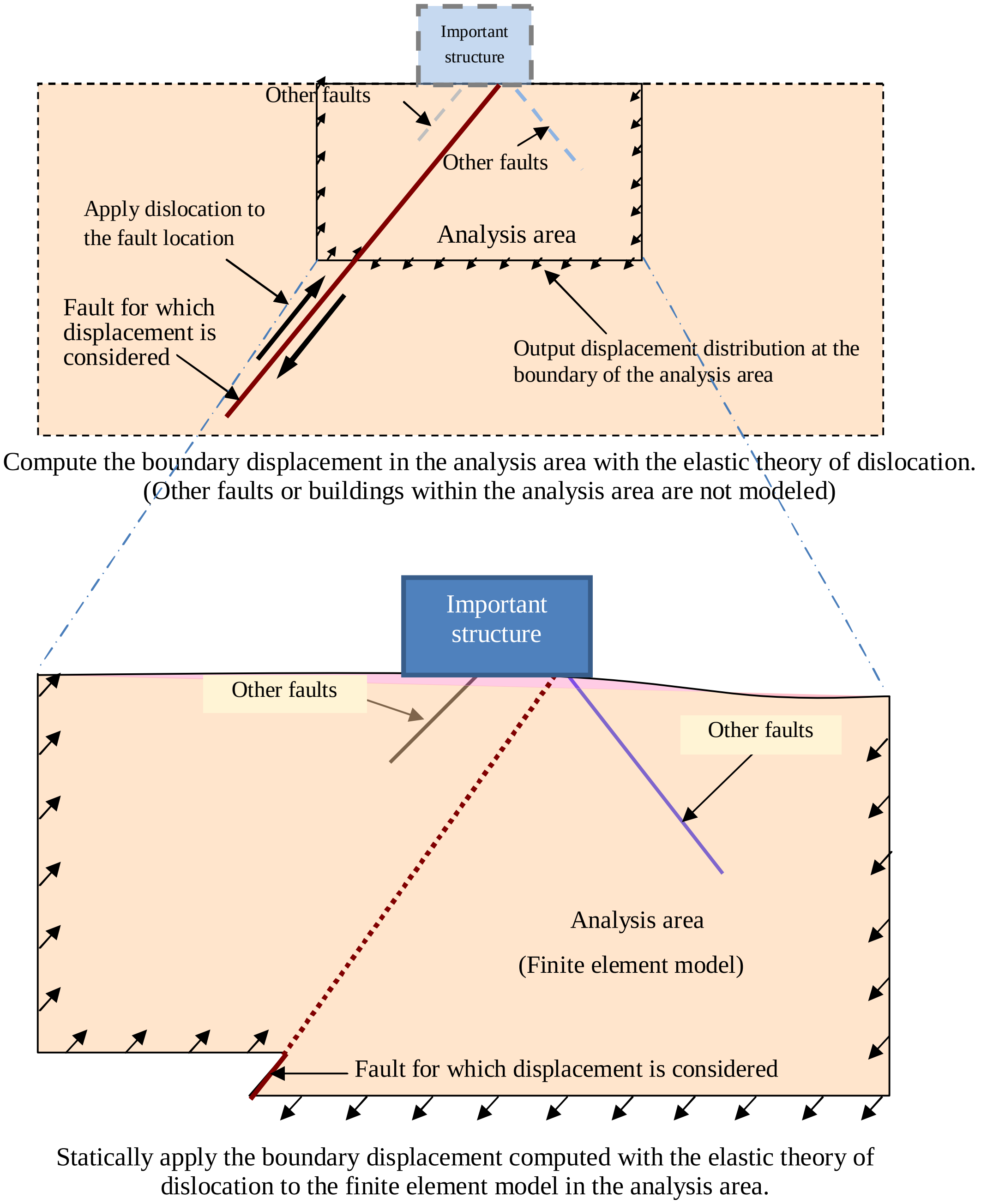


Figure 6-6: Image of Ground Deformation Analysis with the Elastic Theory of Dislocation (When on-site faults are considered)

(2) Analyzing Ground Deformation due to Seismic Motion

In the current stability analysis of a reactor building foundation ground, the ground including faults is modeled in detail and the verification seismic motion is input to verify ground stability by the finite element method. The results are output with respect to the following items as described in the foregoing section:

- Displacement or deformation of the building foundation ground.
- Stress distribution, strain distribution, and local safety factor distribution in the building foundation ground.

(3) Steps to Analyze the Deformation and Stability of the Building Foundation Ground

The steps to analyze the deformation and stability of the building foundation ground are shown in Figure 6-7.

a. Analyzing the Deformation of the Building Foundation Ground

To take account of both fault displacement (dislocation) and seismic motion (quake) with regard to the displacement or deformation of the ground beneath the building, the ground displacement and/or deformation estimated in (1) and (2) above can be added up for analysis. The same is applicable to the stress distribution, strain distribution, and local safety factor distribution in the building foundation ground, and the foundation ground should be verified to be sound for these analysis items.

Since there are a wide variety of analysis methods, it is desirable to use a few methods, including advanced ones, in addition to the above. Based on these analyses, the design basis displacement δa will be set.

Based on the probabilistic fault displacement hazard analysis, moreover, the annual frequency of exceedance of δa will be estimated to verify that it meets the target value.

b. Analyzing the Stability of the Building Foundation Ground

Current stability analysis of a foundation ground is performed from a perspective different from the above. Here, the sliding safety factor will be estimated from the stress caused by the Design Basis Earthquake Ground Motion Ss, and the inclination of the building due to ground deformation associated with an earthquake will be estimated to confirm that the foundation ground is stable against the seismic motion and that the ground deformation resulting from the seismic motion is within the extent that would not impair the facilities.

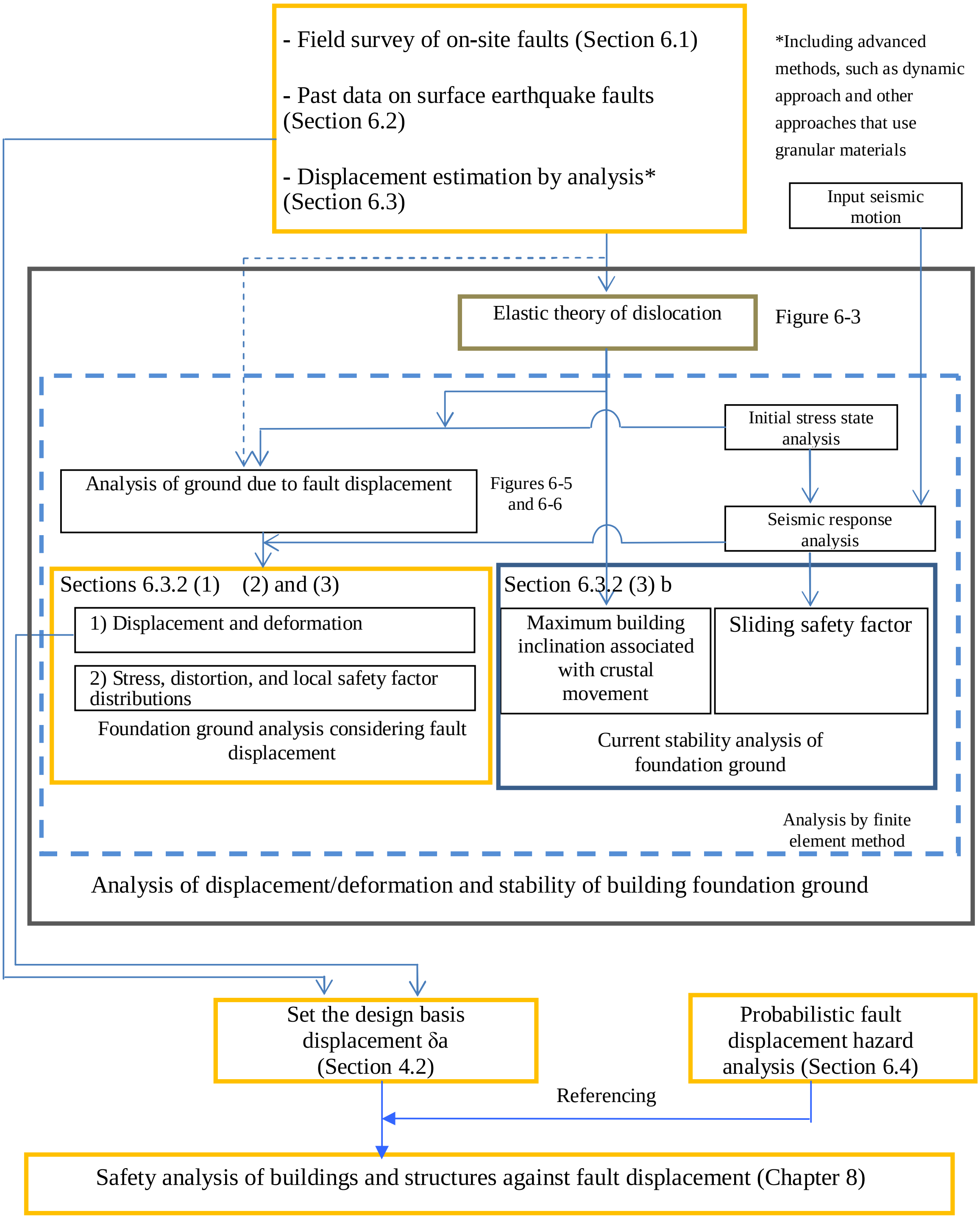


Figure 6-7: Steps to Analyze the Displacement/Deformation and Stability of the Building Foundation Ground

6.4 Probabilistic Fault Displacement Hazard Analysis

6.4.1 Introduction

A methodology to estimate fault displacement at ground surface in association with an earthquake probabilistically (Probabilistic Fault Displacement Hazard Analysis (PFDHA)) was proposed by Youngs, et al. (2003). In Japan, it has also been applied based on domestic data by Takao, et al. (2013).

Youngs, et al. (2003) showed evaluation procedure based on diverse data on normal faults in the U.S. Lateral faults and reverse faults have been analyzed by Petersen, et al. (2011) and Robb, et al. (2011), respectively. Takao, et al. (2013) showed evaluation formulas based on Japanese earthquakes associated with lateral faults and reverse faults.

Although the IAEA guideline (IAEA Safety Standard No.SSG-9) requires PFDHA for problems posed by capable faults at existing nuclear power plant facilities (Appendix F), PFDHA has been applied to a limited number of cases. Examples in which PFDHA has actually been applied include the case of Diablo Canyon Power Plant (2011) (Appendix C-3).

For probabilistic analysis, two types of uncertainties can basically be taken into account, i.e., aleatory uncertainties and epistemic uncertainties. Aleatory uncertainties can be evaluated by applying the probability density function or the cumulative distribution function. On the other hand, epistemic uncertainties mean those resulting from inadequate knowledge or data, e.g., when different opinions are expressed by experts. Epistemic uncertainties are generally modeled using logic tree branches and the weight given to them. If expert opinions vary, the logic tree method can be applied.

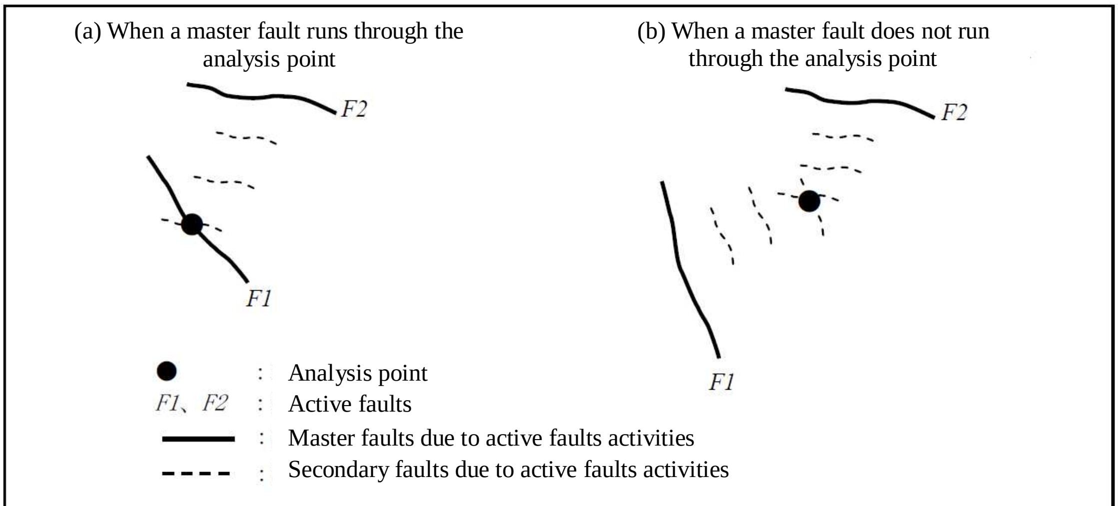
6.4.2 Outline of Probabilistic Fault Displacement Hazard Analysis

PFDHA is a method to estimate the frequency at which fault displacement exceeds a certain value per year (hereafter referred to as the annual frequency of exceedance). The result is expressed in a fault displacement hazard curve.

Youngs, et al. (2003) showed two approaches, i.e., the earthquake approach and displacement approach. The earthquake approach referenced the probabilistic seismic hazard analysis proposed by Cornell (1968). On the other hand, the displacement approach uses the characteristics of fault displacement observed at a target analysis point. Here, the earthquake approach will be used as a more generic approach.

In the earthquake approach, the annual frequency of exceedance of fault displacement is estimated as a sum of the frequency of displacement of two types of faults. One is the displacement of master faults and the other is the displacement of secondary faults. Master faults are defined as the faults closely related to earthquake source faults among other surface earthquake faults. Secondary faults are defined as the fault displacements that occurred at the ground surface although it cannot be said that they are closely related to earthquake source faults. Or it can be said that they are the fault displacement that occurred secondarily or subordinately in association with the activity of an active fault at places away from the active fault. Takao, et al. (203) did not consider the correspondence to tectonic landforms shown in Section 6.2 when recognizing secondary faults.

Figure 6-8 shows the concept of estimating the annual frequency of exceedance when a master fault runs through the analysis point (a) and when a maser fault does not run through the analysis point (b). In the case of (a), it is necessary to estimate both the fault displacement that will occur immediately above the F1 fault due to its activity and the fault displacement that will occur secondarily due to the activity of the F2 fault at a place away from those faults. In the case of (b), however, the fault displacement immediately above the faults does not have to be estimated. It is good enough just to estimate the fault displacement that will occur secondarily due to the activities of the F1 and F2 faults at a place away from them.



In the case of (a), both the displacement of the master fault when F1 becomes active and the displacement of the secondary fault when F2 becomes active will be estimated.
Annual frequency that the fault displacement at the analysis point exceeds d: v(d) = v(d)p1 + v(d)d2
In the case of (b), the displacement of the secondary fault when F1 and F2 become active will be estimated.
Annual frequency that the fault displacement at the analysis point exceeds d: $v(d) = v(d)_{d1} + v(d)_{d2}$
$v(d)_{p1}$: Annual frequency that the displacement of the main fault running through the analysis point exceeds d
$v(d)_{d1}$: Annual frequency that the displacement of the secondary faults associated with the activity of the i^{th} active fault (Fi) exceeds d

Figure 6-8: Concept of Estimation of Annual Frequency of Exceedance of Fault Displacement by Takao, et al (2013)

The outline of the computation of the annual frequency of exceedance of fault displacement due to the master fault as proposed by Takao, et al (2013) is shown in Figure 6-9. The computation of the annual frequency of exceedance of fault displacement due to the secondary fault is outlined in Figure 6-10. The estimation formulas used in respective figures were proposed by Takao, et al. (2013).

Examples of computation by the methods proposed by Takao, et al. (2013) assuming two cases of active faults are shown in Appendix C-1. The examples are for two cases: one with a fault length of 20km and an average activity interval of 5000 years and the other with a fault length of 80km and an average activity interval of 1000 years. As a reference, Figure 6-11 shows an example a hazard curves of a secondary fault when a 20km-long active fault (moment magnitude Mw=6.5) with an average activity interval of 5000 years becomes active.

In this case, the annual frequency of exceedance is 10^{-5} or below regardless of the distance from the master fault. If some displacement is set deterministically, it can be decided that it would be estimation on the safe side. From this figure, the annual frequency of exceedance of a fault displacement of 30cm is found to be 5×10^{-6} to 10^{-7} depending on the distance from the master fault.

In these examples of PFDHA computation, the computational cell is set as 500m x 500m. Since dependency on the cell size (the smaller the cell gets, the smaller the probability of occurrence of secondary faults will be, resulting in a small annual frequency of exceedance) is known, an appropriate computational cell needs to be set taking account of the cell size of the target facilities in a specific application.

$$v(d)_{p1} = P_0 \times P_{1p} \times P_{2p} \times P_{3p}$$

P_0: Activity rate of the active fault (per year)
P_{1p}: Probability that the fault displacement due to the master fault occurs at the ground surface when the active fault becomes active
P_{2p}: Probability that the fault displacement occurs at the analysis point when fault displacement due to the master fault occurs at the ground surface
P_{3p}: Probability that the fault displacement exceeds a certain value when fault displacement due to the master fault occurs at the analysis point

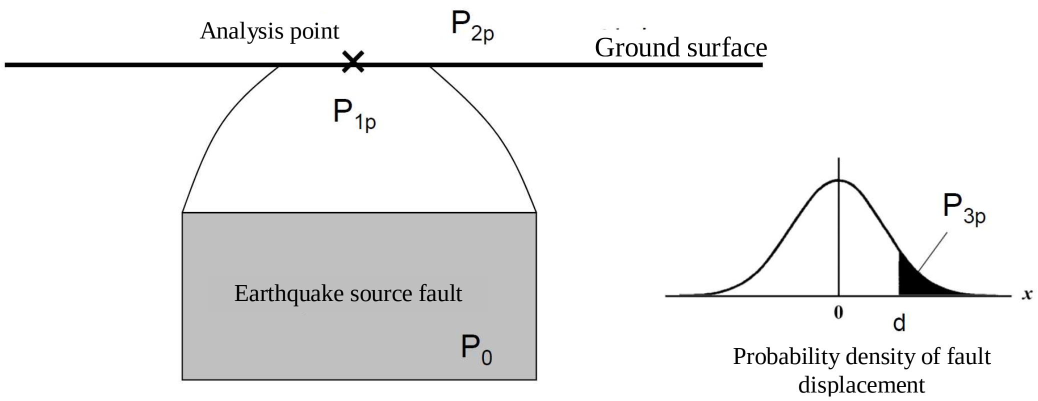
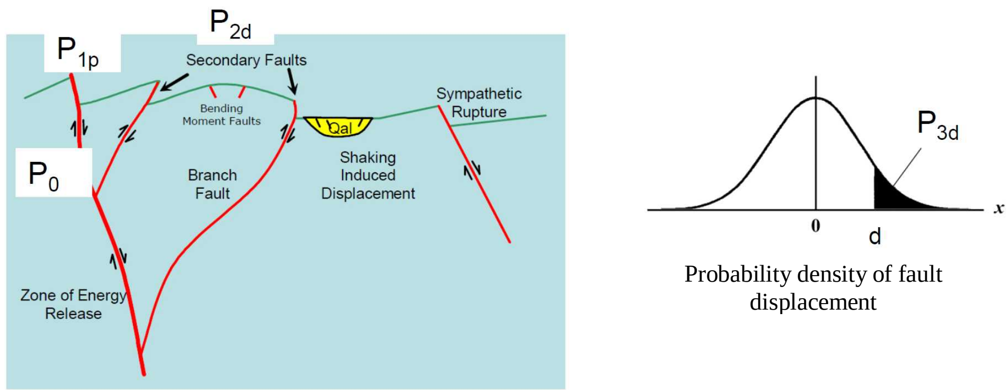


Figure 6-9: Outline of Computation of Annual Frequency of Exceedance of Fault Displacement due to Master Fault as Proposed by Takao, et al. (2013)

$$v(d)_{d1} = P_0 \times P_{1p} \times P_{2d} \times P_{3d}$$

P_0: Activity rate of the active fault (per year)
P_{1p}: Probability that the fault displacement due to the master fault occurs at the ground surface when the active fault becomes active
P_{2d}: Probability that the fault displacement due to the secondary fault occurs at the ground surface at the analysis point when the active fault becomes active
P_{3d}: Probability that the fault displacement exceeds a certain value when fault displacement due to the secondary fault occurs at the analysis point



The figure on the left by J.A. Treiman (2009)
Figure 6-10: Outline of Computation of Annual Frequency of Exceedance of Fault Displacement due to Secondary Fault as Proposed by Takao, et al (2013)

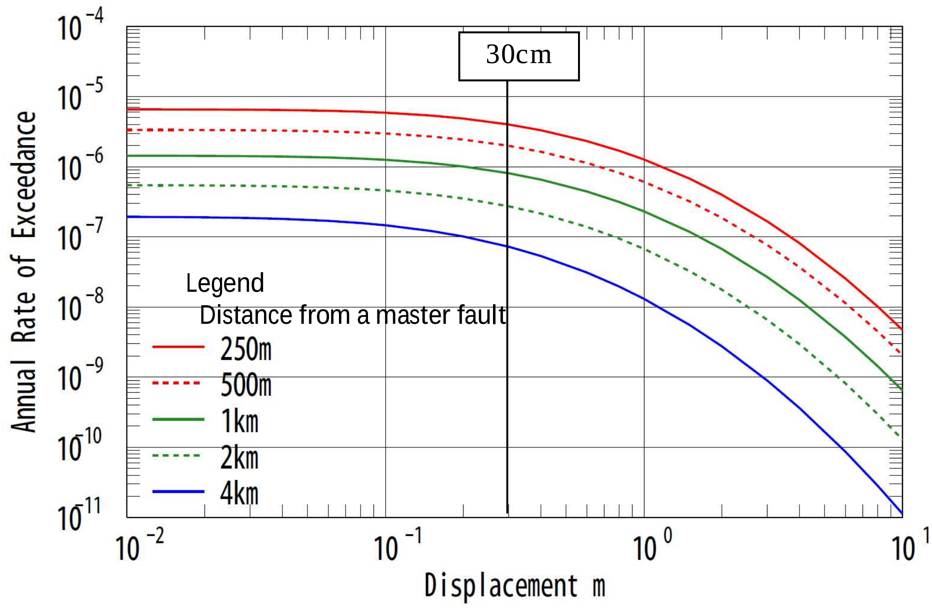


Figure 6-11: Fault Displacement Hazard Curve (Secondary Fault) (When Mw=6.50)

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6.4.3 Issues Concerning the Expansion of Application and the Improvement of Accuracy of Hazard Analysis

(1) Issues Concerning the Expansion of Application

The uncertainty of fault displacement hazards arises from epistemic uncertainties as mentioned earlier. It is modeled using logic tree branches and the weight given to them and expressed as the width of a fault displacement hazard curve (fractal hazard curve). It is considered important for the expansion of application of PFDHA that options are provided to allow for appropriate setting of logic tree branches and that these options cover almost all future possibilities.

To estimate the probability of occurrence, Takao, et al. (2013) used a 500m x 500m cell like Youngs, et al. (2003). However, the probability of occurrence depends on the cell size. The results plotted based on the formula proposed by Petersen, et al. (2011) are shown in Figure 6.12. Making the cell size smaller will result in a smaller probability of occurrence. It is considered as one condition for the expansion of application of PFDHA to clarify this sort of trend with regard to Japanese data.

To estimate the distribution of secondary fault distribution, Takao, et al. (203) also applied the modeling (e.g., function forms) proposed by Youngs, et al. (2003) as it is. Its appropriateness and the ways to decide on parameters may need to be reconsidered.

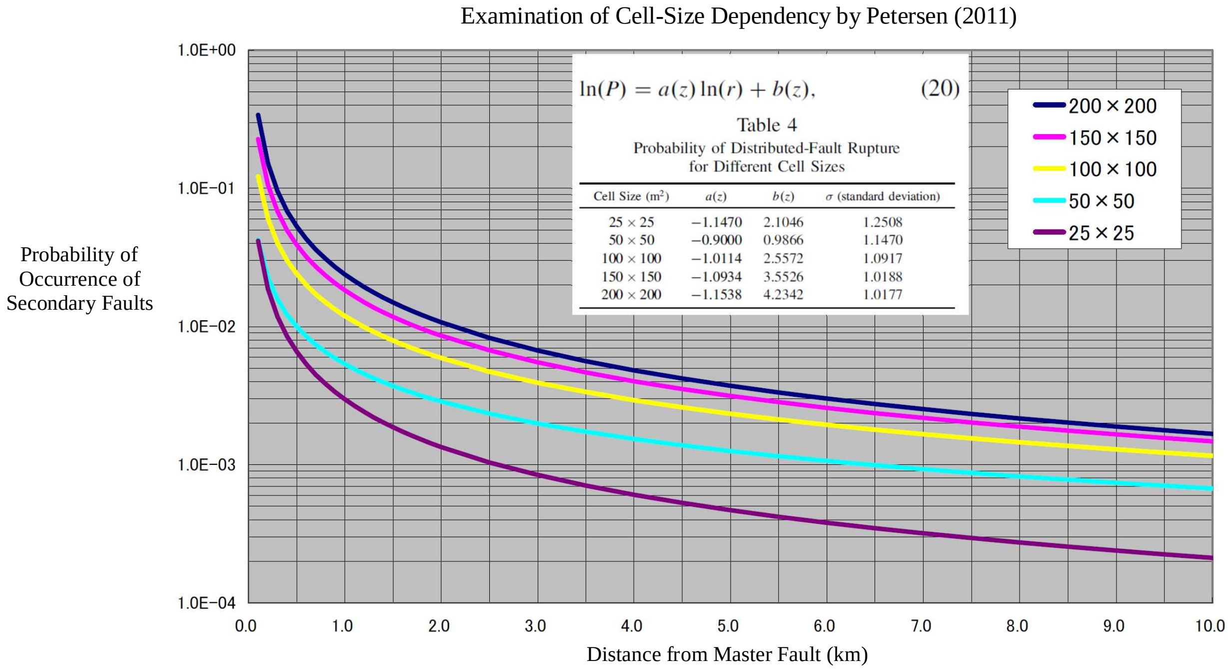


Figure 6-12: Examination of Cell-Size Dependency by Petersen, et al. (2011)

(2) Issues Concerning the Improvement of Accuracy

It is considered important to accumulate field survey data and utilize the results of experiments and numerical analyses so as to complement data inadequacy and improve analysis accuracy. In case a surface earthquake fault appears in association with an earthquake, it is important to conduct field surveys that will contribute to improving the accuracy of this analysis method, e.g., accuracy of the empirical formula regarding the attenuation of fault displacement.

6.5 Issues Concerning Fault Displacement Analysis

Major issues concerning fault displacement analysis include the following:

(i) Nuclear power plants are sited on bedrock. The displacement information essentially required is the information about fault displacement in bedrock. However, it has to be said that little information is currently available about displacement in bedrock. Displacements recorded in surface earthquake faults include those that occurred both in overlying strata and bedrock. In general, it is difficult to discuss the quantitative relationship between fault displacements on bedrock and those in overlying strata. Thus, it is necessary to accumulate survey data, indoor experiments on fault displacement, and analytic evaluations. In “flectional areas” in which different earthquake source fault segments will join with one another by sharply changing their strikes, fault displacement is likely to be larger. It is, therefore, necessary to study and research fault displacements in “flectional areas.”

(ii) With regard to the analysis of fault activities (ground deformation as a result), various studies and researches are currently under way, including advanced method. It is necessary to promote the upgrading and practical application of them. The conditions (e.g., physical properties and stress states) of the ground are extremely important as analysis conditions. Thus, it is necessary to upgrade the ways to obtain the data and utilize the data obtained through geological and ground surveys and seismological observation in the planning, design, and construction of nuclear power plants.

(iii) Studies on the probabilistic fault displacement hazard analysis began recently. Its application needs to be expanded while its accuracy needs to be improved. It is also necessary to promote a series of studies, such as fragility analysis and accident sequence analysis, for plant-wide risk assessment against fault displacement hazards (fault displacement PRA).

7. Load Combinations and Allowable limits

With regard to load combinations and allowable limits, buildings and structures should have a margin in the ultimate state (deformation acceptability and ultimate strength) as the whole structure against the effect of fault displacement in addition to the stationary load, operating load and seismic loads. Components and piping systems should maintain the functions required for the facilities against the loading condition combining the effect of fault displacement in addition to operating and seismic loads.

The effect of fault displacement will be evaluated based on amount of displacement at its anticipated location, which is considered to work statically in one direction.

7.1 Load Combinations and Allowable limits of Buildings and Structures against Fault Displacement

The building for assessment is the reactor building containing important equipment to the safety of a nuclear power plant. Other buildings and structures containing important equipment to the safety than the reactor building will also be assessed.

In addition to the load arising from fault displacement, the stationary load, operating load, and seismic load will be combined. Here, the seismic load is the load arising from the earthquake corresponding to the design basis displacement δa. The idea about the allowable limits is described below.

- Design basis displacement δa

  Buildings and structures should have a sufficient margin of deformation acceptability (deformation at the ultimate strength) as the total system, and adequate safety margin against the ultimate strength.

- Beyond design basis displacement δb

  Buildings and structures should maintain the shape as the whole structure without leading to total fracture.

7.2 Load Combinations and Allowable limits of Components and Piping Systems against Fault Displacement

The equipment to be assessed among components and piping systems is important equipment to the safety of a nuclear power plant. Specifically, it will be the components and piping systems (Class 1, 2 and MC) which are specified in the Codes for Nuclear Power Generation Facilities – Design and Construction Codes (Japan Society for Mechanical Engineers, JSME S NC1-2012) from the perspective of structural design and the components and piping systems of seismic class S (classified as highest importance), which are specified in the Nuclear Power Plant Seismic Design Engineering Codes (Japan Electric Association, JEAC4601-2008) from the perspective of seismic design.

With regard to load (stress) combinations and acceptable standards, acceptable standards must be met for the load combinations specified according to the classification of components in accordance with JSME S NC1-2012. When combining with the load from seismic motion, the combination specified in JEAC4601-2008 will be followed.

The working loads (stress) to be specifically combined include the dead weight, pressure, external mechanical force, thermal stress, and seismic force. Along with these, the stress arising from the impact of inclination, deformation, or relative displacement resulting from fault displacement will be estimated.

The allowable stress will be based on the permissible level that has been specified for each of the failure modes (e.g., ductile fracture, plastic collapse, buckling, fatigue fracture and progressive deformation). The allowable stress specified for each operating mode (operating modes I through IV) will also be applicable. The idea about the allowable limits is that the functions required of components and piping systems will be maintained for both δa and δb.

Here, it will be verified based on analysis or test results that the functions of the facilities (e.g., the function to maintain internal fluid) will not be affected by excessive deformation, cracking, or damage even when a considerable portion of a static component yields, resulting in plastic deformation. It will also be verified based on analysis or test results that the performance of a dynamic component will not decline beyond the system's allowable level due to plastic deformation of moving parts. Chapter 9 outlines these.

For individual analysis using the beyond design basis displacement δb, safety analysis will be performed taking account of the redundancy of the system or the effectiveness of consequence mitigation measures.

8. Safety Assessment of Buildings and Structures against Fault Displacement

8.1 Scope of Application

"8. Safety Assessment of Buildings and Structures against Fault Displacement" will be conducted when assessing the effect of seismic fault displacement to buildings and structures. The displacement of buildings and structures computed in the process of the safety assessment will be used for the safety assessment of components and piping systems against fault displacement.

The buildings and structures to be analyzed will be the reactor building containing the facilities of seismic importance Class S. Other buildings and structures containing Class S facilities than the reactor building will also be assessed.

Examples of scope of application are shown in Figure 8.

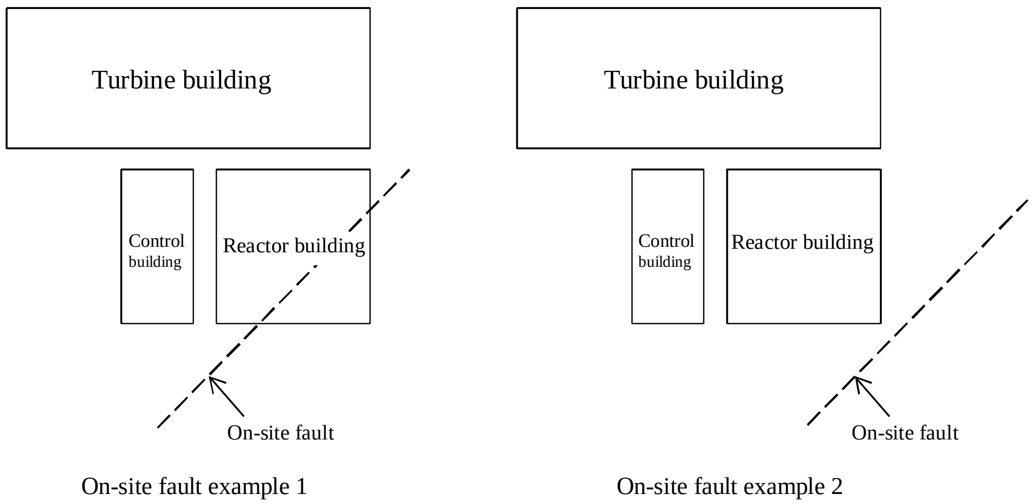


Figure 8-1: Scope of Application

8.2 Assessment Policy

For the safety assessment of buildings and structures (collectively "building(s)"), the target building and surrounding ground will be modeled using a three-dimensional discrete system. The seismic load and fault displacement will be applied to this analysis model to compute the resulting displacement, stress, and so forth that will be generated in the building. The safety of the building against displacement will be estimated based on the computation results.

In general, safety important buildings, including reactor buildings, have reinforced concrete structures. See Appendix D-1 for the fracture properties of reinforced concrete members of mat slabs and others when they are subjected to seismic displacement.

8.3 Material Constant

As the material constant for the building and ground, the value measured in testing will be used. If the material constant is not measured in testing, any of the following values can be used:

・Values that are set in the design stage

・Values that are shown in the Atomic Energy Society of Japan's "Implementation Standard Concerning the Seismic Probabilistic Safety Assessment of Nuclear Power Plants: 2007."

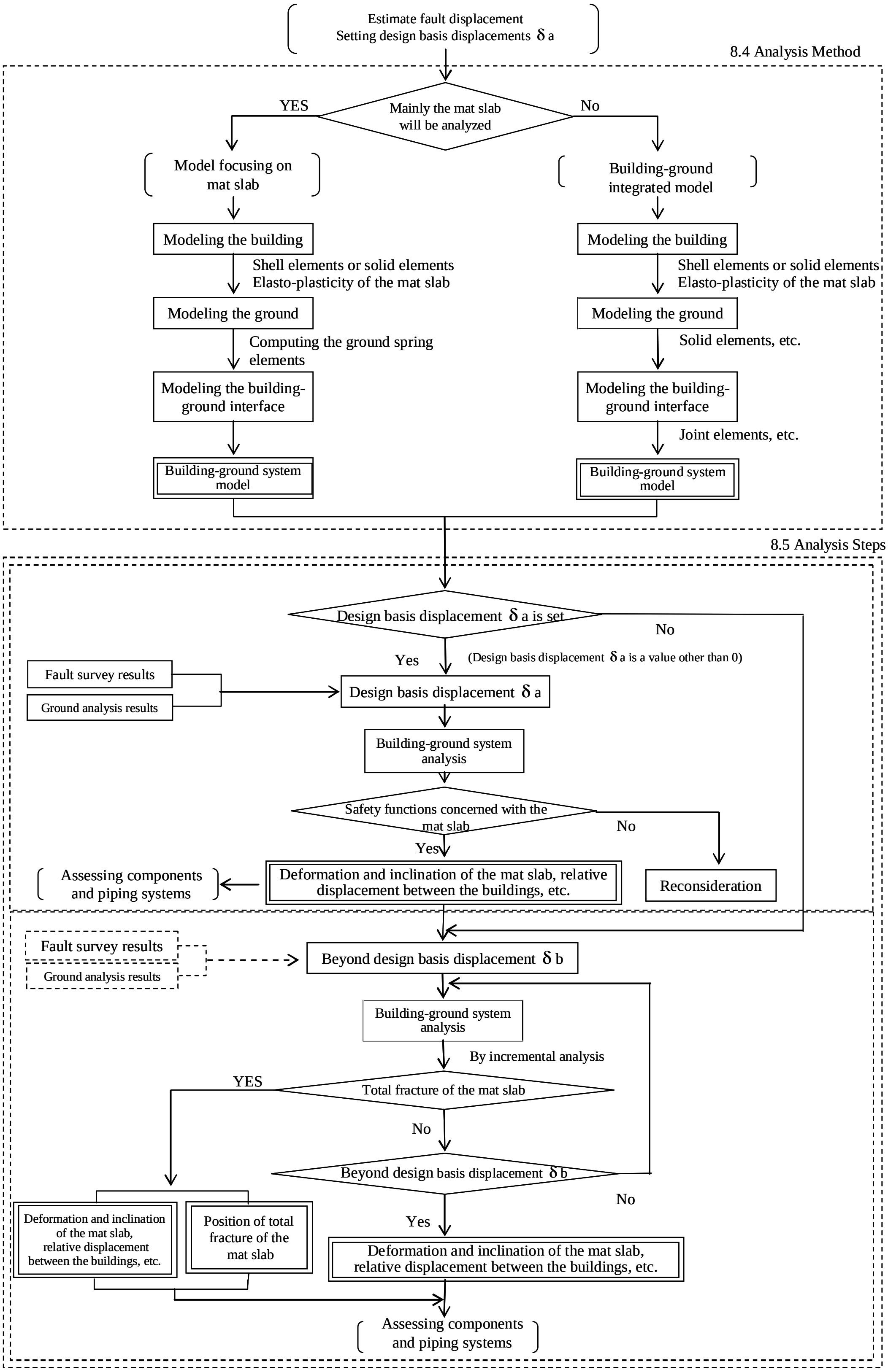


Figure 8-2: Flowchart of Safety Assessment of Buildings against Fault Displacement

8.4 Analysis Method

8.4.1 Analysis Models

(1) Types of Analysis Models

Two analysis models can be used depending on the purpose of analysis, peripheral ground conditions, and so forth.

- Model focused on mat slab
- Building-ground integrated model

(2) Model focused on mat slab

When analyzing the rotating angle of the whole building against fault displacement, the "model focused on mat slab" can be used. The "model focused on mat slab" is based on shell or solid elements for the mat slab. The foundation ground will be modeled with the equivalent spring elements. In this case, the equivalent ground spring elements will be estimated as a combined or independent spring. An example of the analysis model is shown in Figure 8-3.

For analysis, the elasto-plasticity of the mat slab, separation and sliding between the building and ground will be considered as necessary.

Fault displacement will be applied as boundary displacement in the horizontal and vertical directions of the ground spring

(3) Building-Ground Integrated Model

When analyzing the safety of the whole building against displacement, including the mat slab and the rotating angle of each level of the building, the "building-ground integrated model" can be used. The "building-ground integrated model" will be modeled with shell or solid elements for the mat slab and building. The ground will be modeled with solid elements, etc. Between the building and ground, elements in which separation and sliding can be considered, such as joint elements, will be inserted. The fault plane will be modeled with joint elements, etc. The area of the ground will be set within a range not be affected by buildings. An example of the analysis model is shown in Figure 8-4.

Fault displacement will be applied as boundary displacement in the horizontal and vertical directions.

For analysis, the elasto-plasticity of the mat slab, separation and sliding between the building and ground will be considered as necessary.

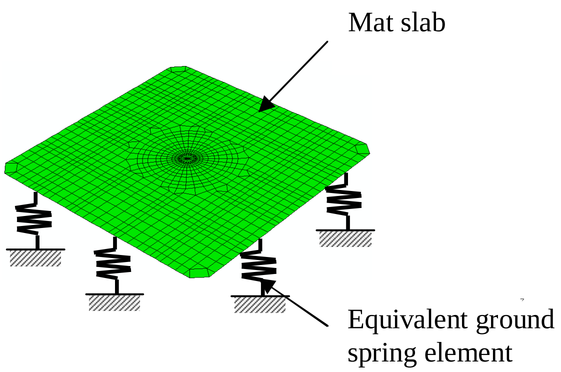


Figure 8-3: Model Focused on Mat Slab (Example)

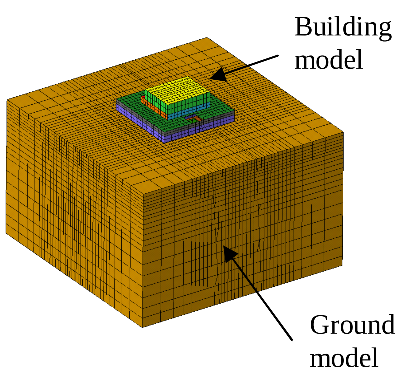
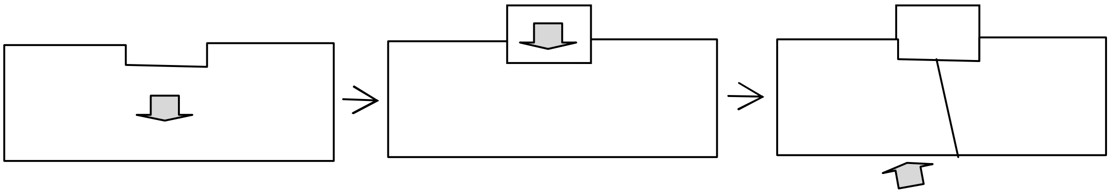


Figure 8-4: Building-Ground Integrated Model (Example)

8.4.2 Analysis Steps

Considering constant stress (ground stress and building's dead weight), dead weight analysis and seismic analysis will be performed. An example of analysis steps is shown in Figure 8-5



Step 1: Analyze effect of the ground's dead weight

Step 2: Analyze effect of the building's dead weight

Step 3: Perform seismic analysis (displacement, etc.)

Figure 8-5: Analysis Steps

8.4.3 Outputting Analysis Results

To analyze the stability of the building against displacement, the stress or strain generated in each element and the deformation at each joint will be output.

8.5 Analysis Steps

8.5.1 Analysis against the Design basis displacement δa

(1) Target of Application

When the on-site fault displacement (design basis displacement δa) has been determined as not zero based on survey results, or the results of analysis of the ground to building system with using the ground deformation analysis model, the safety of the building against displacement will be analyzed according to steps described below.

(2) Loading Conditions

Loading conditions below will be considered.

・Consider the condition in which fault displacement (horizontal and vertical displacement) is applied independently.

・Consider the condition in which the seismic force of an earthquake and fault displacement are applied simultaneously.
In this case, the seismic force will be corresponding to the earthquake that is expected to cause the design basis displacement δa.

(3) Estimating the Allowable limit

Buildings and structures should have a sufficient margin of deformation acceptability (deformation at the ultimate strength) as the total system, and adequate safety margin against the ultimate strength of the buildings and structures.. Specifically, it will be verified that the stress and strain of the mat slab and the earthquake resistant walls are within the allowable limit.

(4) Output for assessment of Components and Piping Systems

As analysis results, the deformation and inclination of the mat slab, etc., the relative deformation between the buildings, and others will be output for the safety assessment of components and piping systems.

8.5.2 Analysis against the Beyond design basis displacement δb

(1) Target of Application

With respect to the beyond design basis displacement δb, the steps described below will be used to assess the safety of the building against displacement.

(2) Loading Conditions

- Consider the condition in which fault displacement (horizontal and vertical displacement) is applied independently.
- Consider the condition in which the seismic force of an earthquake and fault displacement are applied simultaneously.

When the beyond design basis displacement δb is set as a value that takes into account uncertainties over the design basis displacement δa, the seismic force corresponding to the earthquake that is expected to cause the design basis displacement δa will be considered.

Here, fault displacement will be applied incrementally and the upper-bound of displacement applied will be the beyond design basis displacement δb.

(3) Estimating the Allowable limit

Buildings and structures should maintain the shape as the whole structure without leading to a total fracture. Specifically, it will be verified whether the mat slab and earthquake resistant wall does not lead to total fracture (i.e., fracture across the span of the mat slab or earthquake resistant wall).

(4) Output for assessment of Components and Piping Systems

As analysis results, the deformation and inclination of the mat slab, etc., the relative deformation between the buildings and others will be output for the safety assessment of components and piping systems against fault displacement.

When the foundation leads to total facture before the fault displacement reaches δb (beyond design basis displacement), the fault displacement that caused the total fracture will be indicated as the limit displacement. As analysis results of the limit displacement, the displacement and inclination of the mat slab, the displacement of each part of the buildings, etc., will be output. Fractured zone will be specified and the relative displacement within and between the structures will be output for the safety analysis of components and piping systems against fault displacement.

8.6 Trial Analysis of Buildings and Structures against the Fault Displacement

To estimate the effect of fault displacement on the reactor building, a trial analysis was performed. The results of trial analysis of a BWR reactor building is shown in Appendix D-2 while those of a PWR reactor building is shown in Appendix D-3.

In the trial analysis of the BWR reactor building, two cases were considered by setting the rigidity of the foundation ground as Vs=500m/s (soft rock) and 1500m/s (hard rock). An elasto-plastic analysis was performed with the building-ground integrated model in the event of a maximum of 30cm of reverse fault displacement directly under roughly the center of the reactor building. In the trial analysis of the PWR reactor building the rigidity of the foundation ground is assumed Vs=1600m/s in the event of 30 cm normal fault displacement on the outside of the containment vessel.

Figure 8-6 shows the BWR analysis model and result (deformation) while Figure 8-7 shows the PWR analysis model and result (deformation). Here, deformation scale is enlarged 10 times.

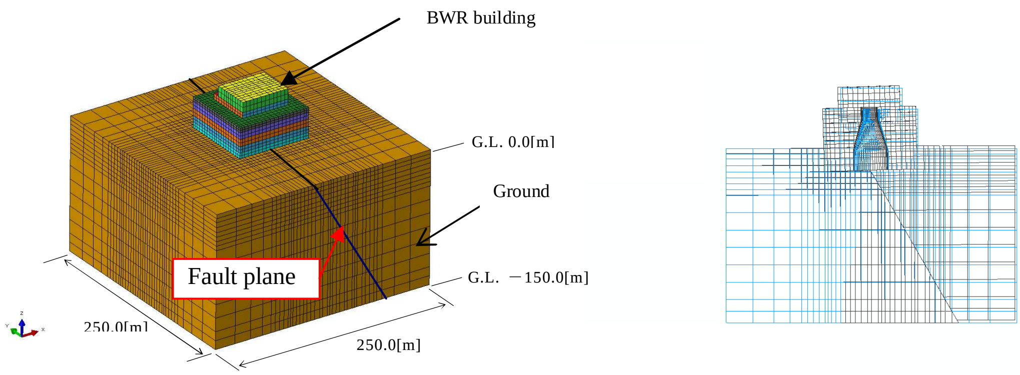


Figure 8-6: BWR Trial Analysis Model and Result (deformation, enlarged 10 times)

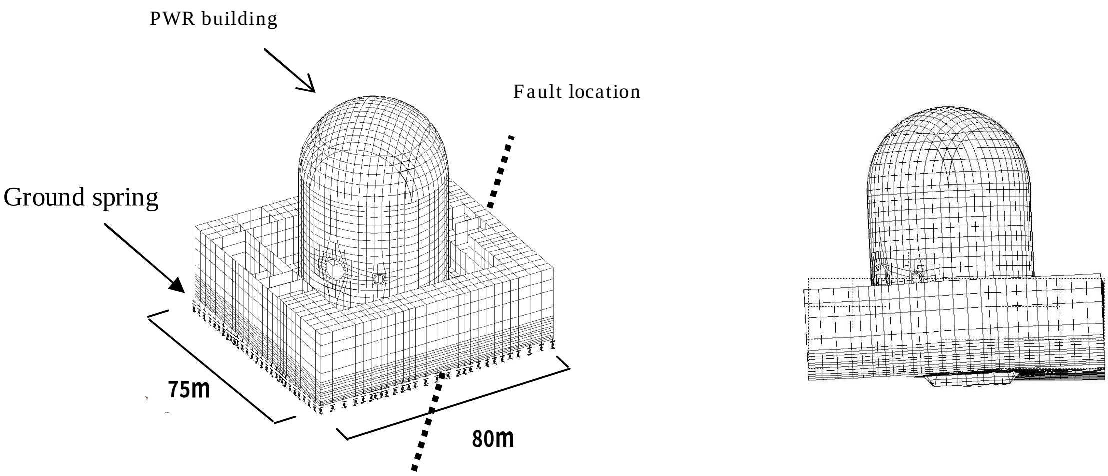


Figure 8-7: PWR Trial Analysis Model and Result (deformation, enlarged 10 times)

Although these trial analyses were performed for certain limited cases, it was found that ground-building integrated analysis is possible for a fault displacement of 30cm or so, making it possible to grasp the trend of the stress and deformation occurring to the mat slab, earthquake resistant wall, etc. of the reactor building. According to these results, the stress in the building tends to be greater in the case of the hard ground when the same displacement is assumed. As for the effect of fault displacement, the out-of-plane shear stress tends to be more severe than the bending moment. However, it is expected that the stress and deformation in the building will be different depending on the amount, direction (normal, reverse, or strike fault), and the location of the faulting relative to the building, ground conditions, and the type of the building (the type of reactor, the thickness and shape of the mat slab, the arrangement of the earthquake resistant walls, etc.)

8.7 Issues on the Safety Assessment of Buildings and Structures against Displacement

In the safety analysis of buildings and structures, the behavior of the building due to fault displacement, etc., will be analyzed through elasto-plastic analysis taking account of the elasto-plasticity of the ground, fault plane slips, separation and sliding between the building and ground, and the elasto-plasticity of the building. Based on this, the safety against displacement will be assessed.

The method used here is a combination of conventional methods. To develop and refine the method described here, the following issues can be pointed out:

(i) Loading

Here, the displacement of the secondary fault due to an earthquake is applied statically and the seismic force arising from the earthquake is applied statically as well. However, it is desirable that these can be considered simultaneously and dynamically. This sort of load analysis remains to be addressed in the future.

(ii) Stress Analysis

There are a variety of stress analysis methods and none of them are specified here. When performing elasto-plastic analysis, however, it is general to use laminated shell elements for the analysis of each part of the building due to limited computational time. Laminated shell elements allow for detailed analysis against the bending moment and axial force. The evaluation concerning the out-of-plane shear stress has to depend on evaluation by conventional experimental formulas. If computational time is ignored, it is possible to apply solid elements that can express shapes of each part of the building exactly basis in elasto-plastic analysis. Accuracy of analysis will be improved by applying solid elements, etc. in elasto-plastic analysis as computer capacity improves.

(iii) Allowable Limit Evaluation

The allowable limit of the mat slab for the beyond design basis displacement δb is the total fracture of the building. In some cases, however, it is difficult to estimate a total fracture in detail by analysis. In this case, there is no choice but to depend on conservative evaluation. The approach to developing analysis method concerning total fractures of the building will be established.

(iv) Fragility Evaluation

For the safety assessment of buildings and structures, a deterministic method has been provided to evaluate safety against the fault displacements estimated based on various studies. When fault displacement is estimated probabilistically, however, it is necessary to establish ~~a~~ probabilistic method to assess the safety against fault displacement in line with it. The method to analyze fragility against the fault displacement will be established in the future based on the method presented here.

9. Safety Assessment of Components and Piping Systems against Fault Displacement

9.1 Scope of Application

When considering the effect on the nuclear power facilities arising from on-site fault displacement caused, assessment is required to verify that the safety functions of “shutting down,”, “cooling” and “containing” can be maintained.

In this chapter the method is shown to analyze the effect on components and piping systems from the inclination and deformation of buildings and structures due to on-site fault displacement and the associated relative displacement between the buildings and structures.

The analysis described here is based on the premise that the shape of the buildings and structures as a whole can be maintained. Cases in which the support functions of components and piping systems are lost are outside the scope of analysis. The equipment to deal with severe accidents, etc. is also outside the scope of individual analysis. The idea about the analysis described in this study may be helpful in future analyses.

9.2 Analysis Policy

9.2.1 Equipment to Assess

Equipments to assess are those important to safety of nuclear power plants. Specifically, it will be the components and piping systems (Class 1, 2 and MC) which are specified in the Codes for Nuclear Power Generation Facilities – Design and Construction Codes (Japan Society for Mechanical Engineers, JSME S NC1-2012) from the perspective of structural design and the components and piping systems of seismic class S, which are specified in the Nuclear Power Plant Seismic Design Engineering Codes (Japan Electric Association, JEAC4601-2008) from the perspective of seismic design. These codes are the latest at present. However, it should be noted that older versions will be used for regulatory compliance because engineering evaluation by the regulatory body is behind the schedule.

9.2.2 Conditions for Analysis of Components and Piping Systems Affected by Fault Displacement

As the conditions for the analysis of components and piping systems, the inclination and deformation of the buildings and structures due to fault displacement, the relative displacement between the buildings and structures, and the seismic force[*1] arising from the anticipated earthquake will be taken into account in addition to operating loads.

With regard to the inclination, deformation, etc. of the buildings and structures for which the impact on components and piping systems is considered, the values calculated in the process of safety assessment of the buildings and structures. The maximum inclination and deformation anticipated will be the levels at which the support functions as the indirect support structures for the target equipment can be maintained.

*1: Inertial force and force due to seismic relative displacement

9.2.3 Screening the Equipment to Analyze

Based on the levels of the anticipated maximum inclination, deformation,, etc., described in 9.2.2, the effect on components and piping systems will roughly be estimated. It is considered possible to put the equipment for which a minor impact is anticipated outside the scope of the safety assessment against fault displacement. Equipments on which the inclination or deformation of the buildings and structures are considered to have a minor impact are as follows.

(i) Equipment installed in the area not affected by the inclination or deformation of the buildings and structures

(ii) Equipment that will apparently receive minor impact because of the dimensions of the components and piping systems and the interfaces with the indirect support structures (e.g., reactor pressure vessel, core internals, components on floor)

(iii) Equipment that will apparently receive minor impact compared to the seismic forces considered in previous analyses or seismic design without consideration of fault displacement.

(iv) Equipment with larger margin for the allowable limit compared to the ultimate limit of the indirect support structures (buildings, structures, etc.) (e.g., PCV liner)

Flowchart of safety assessment of components and piping systems against on-site fault displacement is shown in Figure 9-1.

Representative equipments of BWR and PWR affected by fault displacement and the summary of the impact evaluation are shown in Tables 9-1 and 9-2. Furthermore, a general structure and impact evaluation method for representative equipment of BWR and PWR are compiled in Appendix E-1.

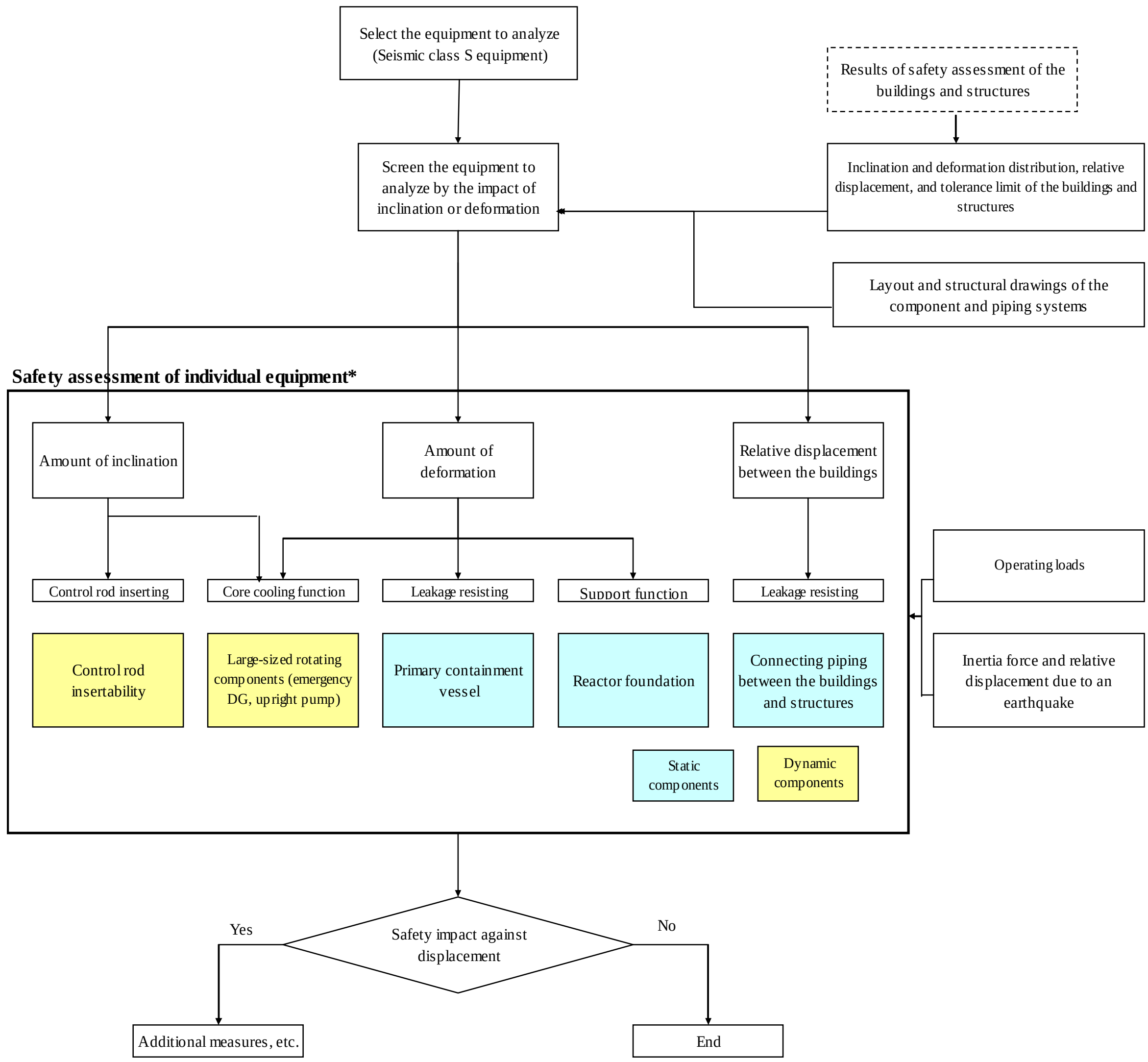


Figure 9-1: Flowchart of Safety Assessment of Components and Piping Systems against Fault Displacement

Table 9-1: Equipment Anticipated to be Affected by Fault Displacement and Summary of evaluation: BWR

(Representative) equipment or part anticipated to be affected		Impact of fault displacement on buildings and structures considered in equipment analysis*1			Impact on equipment	Seismic loads considered in conventional seismic analysis				Seismic loads newly considered due to on-site fault displacement *1			
						Primary stress	Secondary stress			Primary stress		Secondary stress	
		Inclination	Deformation	Relative displacement between connecting parts		Seismic inertia force	Seismic relative displacement	Maintenance of dynamic functions	Maintenance of electric functions	Component force/ deflection due to inclination	Bearing reactive force	Frame deformation	Relative deformation
Static component	Reactor, in-core components/ supports	○	—	—	Occurrence of dead weight component force along inclination	○	—	—	—	○	—	—	—
	Tanks and heat exchangers/ supports	○	—	—		○	—	—	—	○	—	—	—
	Refueling machine, reactor ceiling crane/fall prevention devices	○	—	—		○	—	—	—	○	—	—	—
	Reactor pedestal	—	○	—	Impact of building deformation on support displacement and indirect support functions	○	—	—	—	—	—	○*2	—
	PCV pedestal (Mark-I, II)/ Concrete anchorage zone	—	○			○	—	—	—	—	—	○*2	
	PCV liners	—	○	—	Liner deformation due to building deformation	○	—	—	—	—	—	○	—
	Spent fuel pool/liners	—	○	—	Increase in reactive force working on piping penetrations from connecting piping	—	—	—	—	—	—	○	—
	RCCV/piping penetrations	—	○	○		○	—	—	—	—	○	—	—

	Connecting piping/pipes	—	—	◎	Increase in displacement between supports	○	○	—	—	—	—	—	◎
	Connecting piping/pipe supports and anchors	—	—	◎	Increase in reactive force due to piping deformation	○	—	—	—	—	—	—	◎
	Conduits/cables	—	—	○	Occurrence of tension on cables	—	—	—	—	—	—	—	○*2
Dynamic component	Control rod insertability	○	—	—	Increase in frictional force due to channel box deflection during CR insertion	—	—	○	—	○	—	—	—
	Emergency DG (long horizontal rotating machine)	—	○	—	Occurrence of moment on rotating machine shafts due to deformation between support point	○	—	—	—	—	○	—	—
	Upright pump (long vertical rotating machine)	—	○	—		○	—	○	—	—	○	—	—
Electric component	Electric counter	○	—	—	Occurrence of dead weight component force along inclination (no impact on electrical functions)	○	—	—	○	○	—	—	—

*1: Impact of fault displacement ○: Minor, ◎: Major *2: Consideration required when structure deformation due to fault displacement has an impact on indirect support functions of components

Table 9-2: Equipment Anticipated to be Affected by Fault Displacement and Summary of evaluation: PWR

(Representative) equipment or part anticipated to be affected		Impact of fault displacement on buildings and structures considered in equipment analysis[*1]			Impact on equipment	Seismic load considered in conventional seismic analysis				Seismic loads newly considered due to on-site fault displacement [*1]			
						Primary stress	Secondary stress			Primary stress		Secondary stress	
		Inclination	Deformation	Relative displacement between connecting parts		Seismic inertia force	Seismic relative displacement	Maintenance of dynamic functions	Maintenance of electric functions	Component force/ deflection due to inclination	Bearing reactive force	Frame deformation	Relative deformation
Static component	Primary coolant equipment (reactor vessel, in-core structures, steam generator, primary coolant pump, pressurizer)/ nozzles, supports, concrete anchorage zones	○	○	—	Occurrence of dead weight component force along inclination. Decline in pullout resistance of frame (support anchors)	○	—	—	—	○	—	○[*2]	—
	Tanks and heat exchangers/ supports	○	—	—	Occurrence of dead weight component force along inclination	○	—	—	—	○	—	—	—
	Spent fuel pit crane, polar crane/fall prevention devices	○	—	—	Occurrence of dead weight component force along inclination	○	—	—	—	○	—	—	—
	Refueling water pit, condensate pit/liners	—	○	—	Liner deformation due to building deformation	—	—	—	—	—	—	○[*2]	—
	Spent fuel pit/ liners	—	○	—		—	—	—	—	—	—	○[*2]	—
	PCCV/piping penetrations	—	○	○	Increase in reactive force working on piping penetrations from connecting piping	○	—	—	—	—	—	○[*2]	—

	Connecting piping/pipes	—	—	◎	Increase in displacement between supports	○	○	—	—	—	—	—	◎
	Connecting piping/pipe supports and anchors	—	—	◎	Increase in reactive force due to piping deformation	○	—	—	—	—	—	—	◎
	Conduits/cables	—	—	○	Occurrence of tension on cables	—	—	—	—	—	—	—	○*2
Dynamic component	Control rod insertability	○	—	—	Increase in frictional force due to inclination during CRDM insertion	—	—	○	—	○	—	—	—
Dynamic component	Emergency DG (long horizontal rotating machine)	—	○	—	Occurrence of moment on rotating machine shafts due to deformation between support point	○	—	—	—	—	○	—	—
Dynamic component	Upright pump (long vertical rotating machine)	—	○	—	Occurrence of moment on rotating machine shafts due to deformation between support point	○	—	○	—	—	○	—	—
Electric component	Electric counter	○	—	—	Occurrence of dead weight component force along inclination (no impact on electrical functions)	○	—	—	○	○	—	—	—

*1: Impact of fault displacement ○: Minor, ◎: Major *2: Consideration required when structure deformation due to fault displacement has an impact on indirect support functions of components

9.2.4 Safety Assessment Method for Individual Equipments against Fault Displacement

The ideas about the load combinations and allowable limits applied to the safety assessment of individual equipment are described below. The assessment method described here is based on JSME S NC1-2012 and JEAC4601-2008 that are used in current structural design and seismic design. It is considered to provide conservative analysis results against inclination, deformation, etc., due to on-site fault displacement.

When the safety cannot be confirmed with the conservative analysis method described here, the improvement of the analysis methods will be considered.

(1) Load Combinations

In addition to the seismic load (the load from the earthquake) and the operating load considered in conventional seismic design, the loads from the inclination, deformation, etc., due to on-site fault displacement will be taken into account. In other words, the loads (i) through (iii) will be assumed to work simultaneously.

(i) Operating load *1

(ii) Load from the earthquake *1

(iii) Inclination and deformation of the buildings and structures, and the relative displacement between the buildings and the structures due to on-site fault displacement

*1: To be determined based on the service condition specified in JSME S NC1-2012 and JEAC4601-2008. The combination with the accident load is not required, assuming that the occurrence frequency of fault displacement is equivalent to that of Ss.

(2) Allowable limit

With regard to the type of stress contributing to fracture, the impact of inclination will be considered as stress proportional to external force in the primary stress analysis. In the analysis of the secondary stress arising from restraint of neighboring sections or self-restraint, the impact of deformation and the relative displacement between the buildings and structures will be taken into account.

The seismic load considered in conventional seismic design is the inertia force from the quake and the seismic relative displacement. The allowable limit is set including the stress repeatedly applied by earthquake. The deformation and relative displacement of the buildings and structures caused by the on-site fault is the displacement working statically in one direction, which will newly be analyzed this time. In the assessment, however, it will be treated as secondary stress like seismic relative displacement. It can be estimated conservatively and simply by using the example of allowable stress shown in JSME S NC1-2012 and JEAC4601-2008.

The allowable stress is specified for each fracture mode. Table 9-3 shows an example of the allowable stress for JEAC4601-2008 Class 1 piping in the service conditions Ds (when combined with the Design Basis Earthquake Ground Motion Ss).

Table 9-3: Example of Allowable Stress of Class 1 Piping

Stress class / Service condition	Primary stress (membrane + bending)	Primary stress (torsion, bending + torsion)	Primary + secondary stress range	Primary + secondary + peak stress
Ds	When short-term mechanical loads other than earthquake is included Min[$3S_m$, $2S_y$]	Stress from torsion $0.73S_m$ When the above is not met, stress from bending + torsion $2.4S_m$	$3S_m$	Cumulative fatigue coefficient≦1.0

(S_m: Design stress intensity, S_y: Design yield point)

In general, the secondary stress arising from the impact of deformation and relative displacement will be redistributed and weakened as a result of deformation, which will not immediately cause fractures. Accordingly, a allowable limit can be specified to verify the safety functions of individual components and piping systems depending on the extent of deformation and relative displacement.

9.2.5 Points of Attention for Individual Analysis

(1) Connecting Pipes

The important piping installed inside the building has a certain safety margin against the inclination and deformation of the building. However, there are many connecting pipes between the buildings and structures on the site, where on-site fault displacement has a relatively significant impact on seismic safety.

As to the assessment standards for the piping systems anticipating displacement due to on-site faults, JSME S NC1-2012 and JEAC4601-2008, in which the method to estimate the impact of relative displacement is specified, will also be applied to consideration and evaluation of the magnitude and direction of the anticipated displacement and the way of restraint between the facilities in the piping route.

The elasto-plastic analysis method can be applied to allow for analysis based on earthquake (seismic motion) and impact assessment of relative displacement between the buildings and structures due to fault displacement.

The examples of trial assessment of the impact on connecting pipes from relative displacement between buildings are shown in Appendix E-2.

(2) Support Structures

Support structures, such as containers, pipes, pumps, and valves, will receive direct impact of the seismic load in addition to the inclination and deformation arising from fault displacement. By applying JSME S NC1-2012 and JEAC4601-2008 for assessment, however, it is considered that they have a certain safety margin.

As for the anchor zones of large-sized equipment, such as the reactor containment vessel and the reactor pedestal, it is possible to improve the accountability of seismic safety by performing detailed assessment utilizing the information shown in (4) below and applying the elasto-plastic analysis method.

(3) Dynamic Components

Among dynamic components, attention needs to be paid, in particular, to long rotating equipment, such as emergency DG and upright pumps, for damage to shaft bearings and others caused by the moment arising from floor deformation, etc. To this end, the information about the functional limit acceleration, etc., that have been confirmed by the verification tests conducted on large-sized shaking table, can be referenced.

(4) Reference Information

As for the safety assessment of components and piping systems against fault displacement, codes and standards concerning structural design and seismic design can be applied. Here, the concept of assessment taking account of the impact of fault displacement has been put together based on the concepts of JSME S NC1-2012 and JEAC4601-2008.

As to the assessment of the impact of inclined buildings on components, useful examples are shown in the report on Kashiwazaki Kariwa Nuclear Power Station published after the Niigata-ken Chuetsu-oki Earthquake by Tokyo Electric Power Co.

Other than these, there are numerous reports on the component soundness evaluation after the Chuetsu-oki Earthquake. The policy on individual assessment in the event of exceedance of the design basis seismic motion and examples of application of the elasto-plastic analysis method to the seismic safety assessment of piping systems and components have been put together and the report can be referred below.

・Reports on Soundness Evaluation of Rector Components after Chuetsu-oki Earthquake (April 2008, April 2009, April 2010, March 2012), Japan Nuclear Technology Institute
http://www.gengikyo.jp/archive/soundnessreport.html (in Japanese)

According to many data of fatigue tests which were collected with the condition of pre-strain in this report, it was conformed that approximately 10% cyclic strain indicated no notable change of fatigue life. If this result is applied to fault displacement assessment, allowable stress condition which is shown in section 9.2.4, seems to be remained sufficient safety margin actually against one direction static displacement.

9.3 Assessment Summary and Issues

As the impact of ground displacement/deformation on components and piping systems via the building mat slab, the safety of individual facilities against inclination, deformation, and relative displacement between buildings and structures was assessed. Since most of the safety important equipments of a nuclear power plant are installed inside the reactor building, fault displacement is considered to have a minor impact on the inclination and deformation of the components and piping systems via the ground and building.

With regard to the connecting pipes between the buildings and structures that receive a relatively significant impact from displacement, it is possible to apply JSME S NC1-2012 and JEAC4601-2008 to estimate the impact of relative displacement and use the elasto-plastic analysis method for detailed assessment.

As a result of detailed assessment of the impact of fault displacement on piping systems, it is possible to absorb displacement by modifying piping routes and support structures when hardware measures are required. As to measures for very low probability events, it is necessary to examine the effectiveness of the measures in a comprehensive manner, including software and human actions in terms of accident management, taking into account maintenance risks and costs, newly arising from the hardware measures.

10. Summary

The Committee has been activity for five months since its start in March this year. Since its initial objectives have largely been achieved, this report was put together as a roundup. Achievements and issues to be solved are summarized below.

10.1 Summary of Achievements

This study shows the framework of the safety assessment of a nuclear power plant against on-site fault displacement. It is appropriate to assess the safety of a nuclear power plant in the event of an earthquake, taking account of the effect of ground displacement on the plant's safety functions. In this report, the assessment procedure of plant safety against displacement is summarized, which has not been proposed previously.

(1) Policy on On-site Fault Analysis

(i) An on-site fault is a fault, the outcrop of which exists on the site of a nuclear power plant, or the existence of which has been confirmed by boring survey, etc. When the movement of this fault cannot be denied in the future, it has the potential to affect the facilities. In this study, both displacement (discontinuous displacement) and deformation (continuous deformation, such as the inclination of the ground) are considered to affect on the facilities. The safety assessment of a nuclear power plant against on-site fault displacement will be referred to as "the safety assessment against fault displacement."

(ii) Faults that are likely to move in the future include secondary faults and active faults (master faults and splay faults).

(iii) At a nuclear power plant, detailed information about on-site faults and active faults both on and off the site has been obtained through in-depth geological surveys. Based on this, those faults that may move in the future will be selected. The displacement of on-site faults will be estimated by the results of geological surveys on the selected on-site faults and analytic evaluation concerning the displacement of on-site faults associated with the activities of active faults on and off the site, or making engineering judgment based on them.

(iv) To ensure the safety of nuclear power plants, design basis have been specified against natural phenomena, such as earthquakes, tsunamis, and tornadoes. A fault displacement equivalent to the design basis of other natural phenomena will be considered using an annual frequency of exceedance of 10^{-4} to 10^{-5} (per year) as a reference. This fault displacement will be referred to as the design basis displacement δa. For this design basis displacement δa, it will be verified that the safety functions of a nuclear power plant, i.e., "shutting down", "cooling" and "containing" can be ensured. When it is anticipated that the safety functions may be affected, safety improvement measures should be taken.

(v) Since the uncertainty of fault displacement is considered to be greater than that of other natural phenomena, the effect on the facilities arising from fault displacement exceeding the design basis displacement δa will be examined. That fault displacement will be referred to as the beyond design basis displacement δb. The analysis by δb will be performed from the perspective of risk assessment in the event of exceedance of the design basis. In this case, an analysis will be performed based on the actual strength of each piece of equipment to estimate its effect on the safety functions of the facilities. When the safety functions of the facilities are considered to be affected, mitigation measures can also be taken.

(2) Estimating Displacements for Analysis

(i) The design basis displacement δa will be estimated in a comprehensive manner by any of the methods listed below or by appropriately combining them.

- Estimate the displacement of the fault that is likely to move in the future based on the geological survey results.
- Estimate the displacement by analysis when on-site secondary faults move by the activities of active faults on and off the site.

・ Estimate the appropriate displacement based on engineering judgment in reference to the probabilistic fault displacement hazard analysis

(ii) The analysis methods to estimate the effect of active faults include a variety of methods including advanced ones. In this study, however, the conventional methods based on the FEM analysis are described as examples. For specific application, it is desirable to use a few methods for analysis.

(iii) The beyond design basis displacement δb will be assumed from the perspective of risk assessment.

(iv) In this study, the displacement of secondary faults in surface earthquake faults associated with past earthquake is sorted out. Although it represents approximately 120 years of data in Japan, it can be referenced for the beyond design basis displacement δb.

In connection with the probabilistic fault displacement hazard analysis, moreover, examples of computation for two cases are shown (fault length of 20km with average activity interval of 5000 years and fault length of 80km with average activity interval of 1000 years).

(3) Safety Assessment of Buildings and Structures against Fault Displacement

The flowchart of safety assessment of buildings and structures in the event of displacement/deformation of the foundation ground of the buildings and structure is shown for a series of analysis, including analysis models, load combinations and allowable limits, and outputting response to components and piping systems. Trial analyses were performed to assess the effect of up to 30cm fault displacement directly under BWR and PWR reactor buildings to grasp the trend of stress, displacement, etc., occurring to the mat slab and others.

(4) Safety Assessment of Components and Piping Systems against Fault Displacement

Concerning to the inclination and deformation of buildings and the associated relative displacement between the buildings due to the event of displacement/deformation of the foundation ground, the flowchart of safety assessment of components and piping systems is shown by the load combination and allowable limit etc. of the selected representative equipments to be affected by fault displacement. Since most of the important equipment is installed inside the reactor building, fault displacement is considered to have a minor impact on the inclination and deformation of the components and piping systems via the ground and building. With regard to the connecting pipes between the buildings and structures that receive a relatively significant impact from displacement, it is possible to apply the codes and standards of the Japan Society of Mechanical Engineers and the Japan Electric Association to estimate the impact of relative displacement and use the elasto-plastic analysis method for detailed analysis.

10.2 Issues to be addressed

Issues to be addressed concerning on-site fault survey, displacement analysis, and the assessment of affect on facilities are summarized below.

(i) As nuclear power plants are sited on bedrock, information about fault displacement in bedrock is required. However, at present little information is available about displacement of secondary faults on bedrock. Thus, it is necessary to accumulate survey data, indoor experiments on fault displacement, and analytic evaluations. In “flectional area” in which different earthquake source fault segments will join with one another by sharply changing their strikes, fault displacement is likely to be larger. It is, therefore, necessary to study and research fault displacements in “flectional area”.

(ii) With regard to the analysis of fault activities (ground deformation as a result), various studies and researches are currently under way, including advanced method. It is necessary to promote the upgrading and practical application of them. In particular, the conditions (e.g., physical properties and stress states) of the ground are extremely important as analysis conditions. It is necessary to upgrade the ways to obtain the data

(iii) As for the probabilistic fault displacement hazard analysis, its accuracy needs to be improved and its application needs to be expanded. It is also necessary to promote a series of studies, such as fragility analysis of buildings and structures as well as components and piping systems and accident sequence analysis, for plant-wide risk assessment against fault displacement hazards (fault displacement PRA).

(iv) For the safety assessment of buildings and structures against fault displacement, elasto-plastic analysis by the building-ground integrated model is used. However, how to apply the displacement and seismic force arising from the earthquake and evaluate the out-of-plane shear stress remain to be established. Accuracy of analysis needs to be improved by upgrading the analysis method. It is also necessary to establish a method to analyze the total fracture of the mat slab.

(v) As a result of detailed individual analysis of the affect of fault displacement on piping systems, it is possible to absorb displacement by modifying piping routes and support structures when hardware measures are required. As to measures for very low probability events, it is necessary to examine the effective of the measures, including software and human actions in terms of accident management, taking into account new maintenance risks, costs, etc. arising from the hardware measures comprehensively.

(vi) From the perspective of defense in depth, it is important to improve the accountability of plant risks, in comparison with the safety goals, paying attention to their impact on the probability of resulting in core damage or containment damage. In risk quantification, continuous efforts are expected to reduce uncertainties in data. Furthermore, it is also expected to find a way to improve resilience (flexible and strong organizational response capacity) while the organizations and personnel concerned with nuclear energy identify the risks arising from external events in an extensive manner.

Experts from the relevant organizations need to steadily accumulate research data. Other relevant societies, such as the Atomic Energy Society of Japan, the Japan Society of Civil Engineers, and the Japan Association for Earthquake Engineering, need to promote cross-cutting discussions beyond their specialty areas. For example, the Atomic Energy Society of Japan has put together the ideas about "seismic safety" and "nuclear safety." They are expected to promote discussions as an extension of them. It is also desirable for the Nuclear Regulatory Agency to participate in discussion with the societies to incorporate new knowledge and information into the regulations.

The Japan Nuclear Safety Institute will follow up this report even after the end of this Committee and endeavor to solve the issues for the improvement of nuclear safety, asking the organizations and personnel concerned for cooperation as necessary.

Reference

On-site Fault Assessment Method Review Committee

■Members, Presenters, and Secretariat

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Member	Daiei Inoue	Research Advisor Emeritus, Central Research Institute of Electric Power Industry
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	Katsuichirou Hijikata	Strategy Planning Division, JANSI (up to the end of March 2013)
	Kazuta Hirata	Nuclear Safety Division, JANSI

■ Date of Meeting

1st Committee Meeting	March 8, 2013
2nd Committee Meeting	April 10, 2013
3rd Committee Meeting	May 17, 2013
4th Committee Meeting	June 19, 2013
5th Committee Meeting	July 17, 2013
6th Committee Meeting	August 6, 2013

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