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Tsunami Assessment Method for Nuclear Power Plants in Japan

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Chapter1 Preface

It is well known that Japan is highly earthquake-prone; the earthquakes cause damage to human lives, public facilities, industrial facilities, and houses. In particular, the damage caused by tsunamis generated by submarine earthquakes is greater than that by ground shaking due to an earthquake because of the high density of human population and commercial activities in the low-lying coastal areas. Consequently, safety measures in the event of a tsunami have been recognized as an important issue.

The frequency of tsunami occurrence is low; tsunami waves are different from the wind waves that are usually observed on the seashore. The 1983 Mid Japan Sea earthquake tsunami occurred during the daytime; however, this is not always the case. Since observations of tsunamis are rare, it is considerably difficult to clarify its characteristics. New properties of tsunamis are recognized during every occurrence, thereby contributing to the progress in tsunami research. For example, until the occurrence of the 1983 Mid Japan Sea earthquake tsunami, it was widely believed that a tsunami would be amplified only at the inner part of a V-shaped bay such as the Rias coast. However, as a result of this tsunami, it was observed that a tsunami could be amplified even at a flat coastline under certain conditions. Moreover, new phenomena such as soliton fission, lens effect, and multiplex reflection were recognized. In 1993, the Southwest Hokkaido earthquake tsunami occurred in the Japan Sea; the maximum run-up height of this tsunami exceeded that of the 1983 Mid Japan Sea earthquake tsunami. Further, new phenomena such as capturing by an island and localized change in run-up height in complicated topography were recognized.

To date, safety assessments for nuclear power plants have been carried out based on “the Guideline about Safety Design for Light Water Nuclear Power Generating Facilities” cited by the Nuclear Safety Commission of Japan. [The guideline only states ”(the effect by) tsunami should be considered in design”. That does not state “the design tsunami should be determined by numerical simulation”.] By referring to the guideline, the design tsunami has been determined site by site by a numerical simulation based on information regarding the maximum historical tsunami and the greatest influenced submarine active fault induced tsunami. Accordingly, the safety design has been implemented based on the tsunami thus determined. It is considered that the guideline by the Nuclear Safety Commission of Japan will not create problems in the near future for the following two reasons: various safety insurances have been considered in the process of tsunami evaluation, and the latest information has been taken into account for the assessment.

On the other hand, as described above, tsunami evaluation techniques are presently being improved. In order to enhance the safety and reliability of coastal nuclear power plants, it is important to incorporate the new findings obtained from recent studies into the assessment method.

From the abovementioned viewpoints, by organizing recent findings and the progress of technology, a standard assessment method is proposed in this paper for the evaluation of the tsunami model for the safety assessment of nuclear power plants in Japan.

In this paper, “tsunami assessment/tsunami evaluation” implies the “evaluation of water level by the design tsunami.”

[Reference]

Nuclear Safety Commission of Japan (1990): *Guideline about Safety Design for Light Water Nuclear Power Generating Facilities* (in Japanese).

Chapter2 Tsunami sources and tsunami phenomena for assessment

In this paper, water rise and fall of tsunamis directly generated by earthquake fault motion are considered.

[Description]

(1) Tsunami sources for assessment

Tsunamis can be generated by earthquakes, volcanic eruptions or collapses, landslides, or meteorite impacts. An earthquake can induce a submarine landslide; however, the possible location of occurrence is quite limited in such cases. For example, if there is a large submarine valley off the coast of the mouth of a large river, the sediment transported from the river mouth is often in an unstable condition, and an earthquake could trigger a large-scale landslide. Hence, there is a possibility that a landslide-induced tsunami and an earthquake-induced tsunami might have occurred simultaneously in the past. We can consider that such landslide-induced tsunamis are included in the analysis of earthquake-induced ones. One reason is that a tsunami source model for a historical tsunami can reproduce historical tsunami run-up heights, and the other is that the simultaneous occurrence can be considered to have been accounted for in Aida's indexes. Aida's indexes represent the comparison results of the calculation results and actual historical tsunami run-up heights–see Section 4.2.2. Thus, the landslide-induced tsunami is excluded in this paper. Further, volcano- and meteorite-induced tsunamis are also excluded because they are infrequent events in comparison with earthquake-induced ones (Imamura, 1998).

As mentioned above, only earthquake-induced tsunamis that are directly caused by faulting are studied in this paper. However, tsunamis to which a fault model can be applied, but have no earthquake shaking records -a result of uncertainty regarding whether or not they were caused by faulting - can be an additional subject in this paper.

(2) Tsunami phenomena for assessment

A tsunami not only causes water rise and water fall but also results in a flow of seawater. This flow can result in the following types of damages: movement or turnover or breakage of caissons that are under construction, scattering of wave-eliminating blocks, uprooting of trees in the coastal woods, damage to fishing boats by eddies in harbors, run-off and scattering of timber from timber ponds, scouring or banking by sand movement, damage to structures by floating materials, and contamination of seawater. However, the primary agent of damage is water rise; this phenomenon results in disasters such as inundation and flood.

From the viewpoint of risk management for tsunami at nuclear power plants, the evaluation of the maximum water rise and fall is the most important issue; this is because important facilities provided for safety purposes and water intake should be protected. It is assumed that the effects of the other phenomena are less important than that of the water level.

Therefore, only the water level of tsunamis, which is characterized by water rise and fall, is dealt with in this paper.

[Reference]

Imamura, F. (1998): *Development of tsunami numerical analysis in 15 years and its future*, Kaiyo, Extra No.15, pp.89–98 (in Japanese).

Chapter3 Outline of a tsunami assessment method

3.1 Overall procedure

The overall policies for a tsunami assessment method are as follows:

(1) Tsunami source for the design tsunami

Among the various possible scenario tsunamis for each area, the one causing the maximum water rise and fall to the target site is selected as the “design tsunami.” The design water level is defined as the sum of the “design tsunami” and an appropriate tidal condition.

(2) A consideration policy with regard to the uncertainties of scenario tsunamis

In order to account for the uncertainties regarding a tsunami source in the model, a large number of numerical calculations are carried out under various conditions within a reasonable range. This is referred to as a “parametric study.” Each results of the parametric study are termed as scenario tsunamis. For the model to the target site, the tsunami causing the greatest damage to the target site is selected among the scenario tsunamis.

(3) Method for verifying the design tsunami

The design tsunami is verified by using the following criteria.

The design tsunami height exceeds all the recorded and calculated historical tsunami heights at the target site.

In the vicinity of the target site, the envelope of the scenario tsunami heights exceeds all the recorded and calculated historical tsunami heights.

(4) Method for verifying the assessment procedure based on historical tsunamis

Before the abovementioned steps are carried out, a numerical calculation system is verified by performing numerical calculations on historical tsunamis.

[Description]

In this paper, the assessment is carried out according to overall policies. The procedure of the assessment is shown in Fig.3-1.

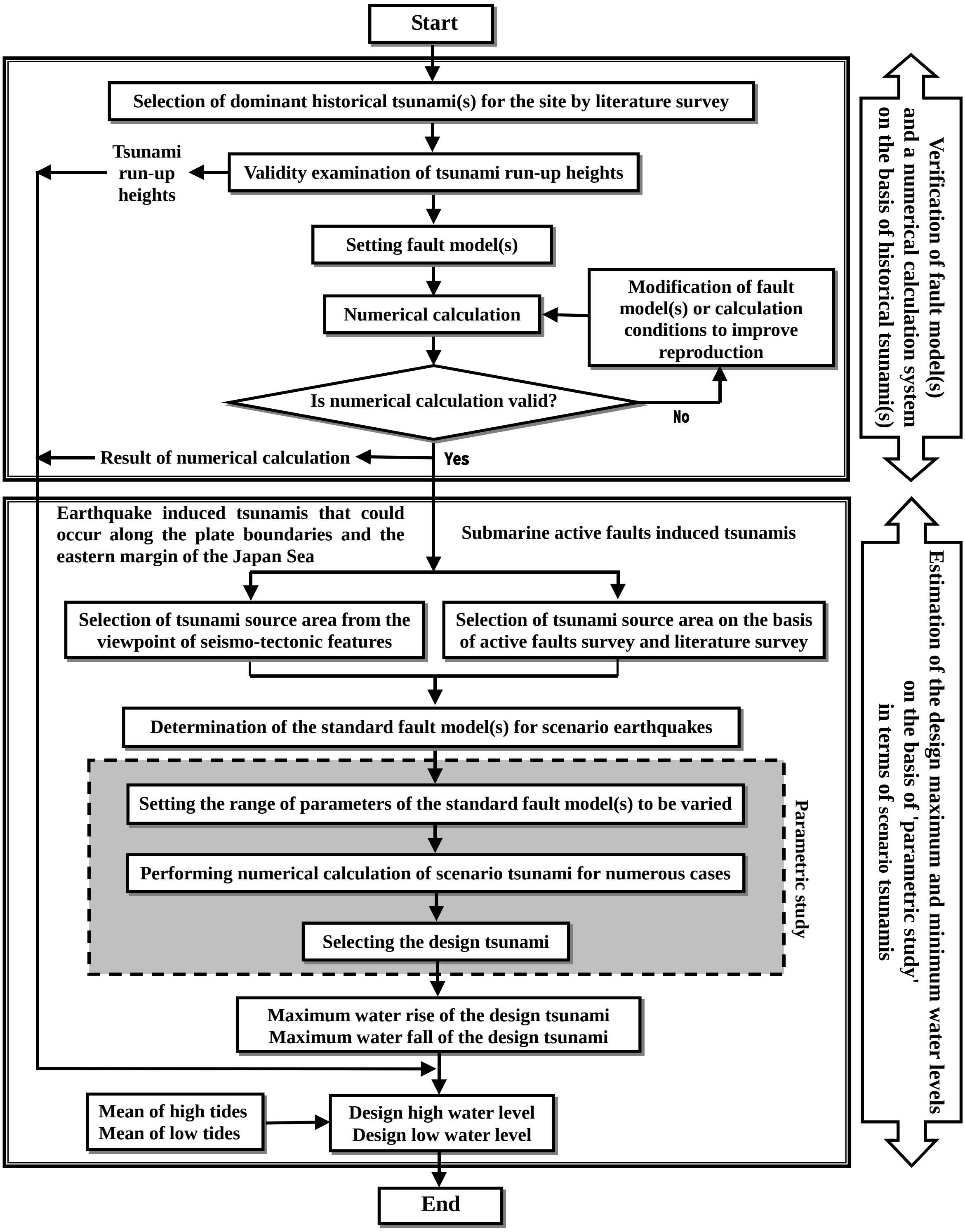

Fig.3-1 Flowchart for the assessment of the design tsunami

(1) Tsunami source for the design tsunami

In the assessment of the water level of the design tsunami for nuclear power plants, historical tsunamis and earthquake-induced tsunamis generated by submarine active faults have been considered so far. Thereafter, using the data acquired from the 1993 Southwest Hokkaido earthquake tsunami, it was suggested that the tsunamis occurring along the plate boundaries and the eastern margin of the Japan Sea must be considered. Since this is for the purpose of reference, tsunamis in these areas have been gradually investigated.

On the other hand, with regard to general coastal facilities, "Report on Disaster Prevention Facilities Project for Eastern Margin of the Japan Sea" and "Report on Disaster Prevention Facilities Project for Pacific Coastal Area" by the Ministry of Agriculture, Forestry and Fisheries, etc., were published. In these reports, the investigations on not only the historical tsunamis but also the tsunami occurring along the plate boundaries and the eastern margin of the Japan Sea were described.

From the viewpoint of the reliability of the tsunami design nuclear power plants, and with the abovementioned conditions for the recent tsunami assessment method, earthquake-induced tsunamis that can occur along plate boundaries, the eastern margin of the Japan Sea, and as a result of submarine active faults are considered in this paper.

(2) A consideration policy on the uncertainties of scenario tsunami

The uncertainties and errors listed below are included in the numerical simulation of the design tsunami. These uncertainties and errors should be taken into account such that the water level of the design tsunami is not underestimated.

1) Uncertainties of the tsunami source model
2) Errors in the numerical calculation
3) Errors in the submarine topography and coastal landform data

It is rather difficult to estimate each parameter quantitatively. Further, it is also difficult to select one tsunami source from many scenario tsunamis. In this paper, the following procedure is adopted.

1) Scenario earthquakes with various conditions within a reasonable range are set based on standard fault model
2) A large number of numerical calculations for scenario earthquakes are performed. This is termed as a "parametric study."
3) Each results of the numerical calculation in 2) are termed as a "scenario tsunami."
4) For the design, the tsunami responsible for the maximum water rise and the maximum water fall to the target site is selected among the scenario tsunamis.

It is assumed that the design tsunami height, which is evaluated by a parametric study, sufficiently exceeds all the historical tsunami heights.

(3) Method for verifying the design tsunami

It is assumed that the design tsunami, which is developed in this paper, should have a sufficient height that exceeds the historical tsunami heights. However, the verification of this requirement is not carried out for all Japanese coasts. In principle, the design tsunami should satisfy the following two points in order to confirm its adequacy.

1) At the target site, the height of the design tsunami should exceed all the calculated historical tsunami heights.
2) In the vicinity of the target site, the envelope of the scenario tsunami heights should exceed all the recorded historical tsunami heights (see Figure3-2). “The vicinity of the target site” should be appropriately set taking into account the following three points: the number of run-up heights by the dominant historical tsunami, the distribution of run-up heights by the dominant historical tsunami, and the similarities between submarine topography and coastal landform. Here, the historical tsunamis that have no recorded tsunami run-up heights in the vicinity of the target site can be excluded from consideration.

However, if the following three points are satisfied, the abovementioned criteria need not be met: existence of a tsunami run-up trace by the dominant historical tsunami at the target site, slight variation between submarine topography and coastal landform, and the design tsunami exceeding the historical tsunami run-up height at the target site.

In this framework, in which the design tsunami is compared with the historical tsunamis, it might appear as though their heights are identical. However, it is confirmed the height of the design tsunami that is obtained in this paper is twice that of historical tsunamis on an average.

From the following reasons, both 1) and 2) are needed for confirmation of adequacy:

a) With respect to the calculation results of the historical tsunamis at the target site that are applied to 1), even if a calculation reproduces the recorded historical tsunami heights well on average, which implies K = 1.0, there is a 50% possibility that the true historical tsunami heights are not exceeded. That is because uncertainties and errors exist. In other words, it is possible that the calculated heights do not exceed the recorded historical tsunami heights.
b) If the calculation results increases proportionally considering uncertainties and errors, the possibility of a) could decrease. However, a method of determining the additional value has not been quantitatively established.
c) Based on a) and b), the best method for solving 1) is to directly compare the total scenario tsunami heights with recorded historical tsunami heights in the vicinity of the target site.

With respect to 2), the design tsunami is not directly verified at the target site. In fact, it is verified indirectly by confirming the adequacy of the considered method for uncertainties and errors in the vicinity of the target site.

As shown in Figure3-2, it is necessary that all the scenario tsunami heights exceed all the recorded historical tsunami heights. Since the tsunami sources of the historical tsunamis may differ from that of the design tsunami, it is not necessary to compare the design tsunami with the neighboring recorded historical tsunami heights.

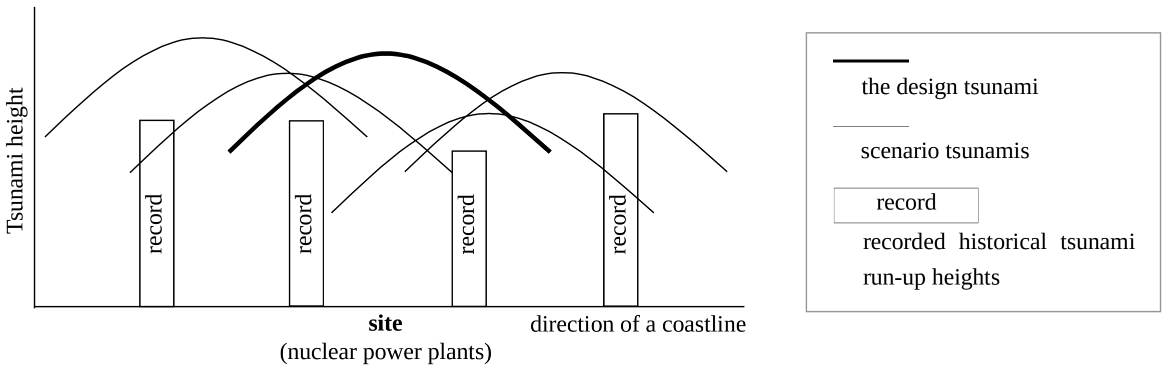

Figure3-2 Relationship between scenario tsunamis and recorded historical tsunami-run up heights

(4) Method for verifying the assessment procedure based on historical tsunamis

For the design of nuclear power stations, historical tsunamis and earthquake-induced tsunamis by submarine active faults have been considered, and the one causing greater damage to the target site has been selected so far. In contrast, in this paper, the location of a historical tsunami differs from its position in previous studies because newly defined tsunami sources such as along the plate boundaries and the eastern margin of the Japan Sea are applied to the assessment procedure.

The method for verifying the assessment procedure is as follows.

Firstly, a historical tsunami is positioned in the verification data for ensuring the accuracy of the design tsunami, as mentioned above. In this paper, in order to verify the height of the design tsunami, the calculation results of the design tsunami should exceed recorded and calculated historical tsunami heights. Historical tsunamis are adopted as the criterion for accuracy because their heights include uncertainties and errors in the tsunami sources and propagation processes. Further, these uncertainties and errors are considered in the design tsunami.

Secondly, a historical tsunami is positioned in the verification data for the accuracy of the fault models, submarine topography models, coastal landform models, and numerical simulation processes. In this paper, the design tsunami is obtained on the basis of a numerical simulation. Further, it is necessary to confirm that the numerical simulation adequately reproduces historical tsunamis in some manner. Since many tsunami have occurred in Japanese coastal areas, considerable data exist on the historical tsunami heights for the purpose of verification. Hence, historical tsunami heights are suitable as a verification tool of the tsunami source, etc. Aida (1977) proposed K and κ as indexes for the fitness in space between historical tsunami heights and calculated tsunami heights. Aida's indexes are introduced in this paper because they are widely used in Japan.

Concretely, K and κ over a wide area should satisfy the following conditions.

$0.95 < K < 1.05$ and $\kappa < 1.45$

If K does not satisfy this condition, the calculation results should be enlarged K times in order that the calculation results of the historical tsunamis can reproduce the run-up heights of these historical tsunamis. The validity of the tsunami is then confirmed as given in (3).

3.2 Basic concepts

In principle, numerical simulation should be carried out to assess the following basic matters in compliance with the overall policies.

(1) Historical tsunamis

Historical tsunamis include near- and far-field tsunamis.

(2) Scenario tsunamis

Scenario tsunamis include near-field tsunamis including the tsunamis that are generated by scenario earthquakes along plate boundaries, the eastern margin of the Japan Sea, and the submarine active faults. If necessary, the scenario tsunamis also include far-field tsunamis.

(3) Moment magnitude of the earthquakes assumed to occur along the plate boundaries and the eastern margin of the Japan Sea.

The maximum moment magnitude of the earthquakes assumed to occur along the plate boundaries and the eastern margin of the Japan Sea are on the scale of the maximum historical earthquake in each water area.

(4) Moment magnitude of the earthquakes assumed to occur due to submarine active faults

The moment magnitude of the earthquakes assumed to occur due to submarine active faults are estimated based on the relationship between the active fault length and earthquake scale.

(5) Parametric study

For the design tsunami, the uncertainties of the tsunami sources are taken into account by a parametric study.

(6) Numerical simulation/Numerical calculation

The maximum water rise and fall are determined by numerical simulation.

(7) Tidal conditions

For the design of the high and low water levels, the means of the high and low tides, respectively, are added to the calculation results.

(8) Resonance in a harbor and the response with an intake passage

If necessary, the effect on resonance in a harbor and response with an intake passage are examined.

The underlined terms are defined in Section 3.3 and 4.1.2.

[Description]

(1) Historical tsunamis

In the past, many historical tsunamis caused considerable damage to Japanese coastal areas; these include not only near-field tsunamis but also far-field tsunamis. The 1960 Chilean earthquake tsunami is an example of a far-field tsunami that occurred at a foreign coast and propagated to the Japanese coast. Generally, in terms of the damages caused by historical tsunamis, the effects of near-field tsunamis are greater than those of far-field tsunamis. Hence, near-field tsunamis are more important from a design viewpoint. On the other hand, 200 near-field tsunamis and 50 far-field tsunamis are cited in Watanabe (1998). Far-field tsunamis cannot be neglected in the design because the number of far-field tsunamis is substantial and the largest historical tsunami in some region is actually a far-field tsunami.

Consequently, in this paper, both near- and far-field tsunamis are considered as sources of historical tsunamis.

(2) Scenario tsunami

With respect to near-field tsunamis, the calculated water level at the target site is greatly variable for a parametric study, whereas, with respect to far-field tsunamis such as a Chilean and Cascadian tsunamis that have considerable effect on the Japanese coast, the calculated water level at the target site differs only slightly by a parametric study, for example, refer to Takaoka (2001). Moreover, for the Chilean and Cascadian region, it is assumed that the largest possible tsunami in each region has already occurred.

Accordingly, in most cases, a near-field tsunami is sufficient as a source of a scenario tsunami. In some cases, if it is assumed that a far-field tsunami may be larger than a near-field tsunami, the former, mainly Chilean and Cascadian tsunamis, should be considered.

(3) Moment magnitude of earthquakes assumed to occur along the plate boundaries and the eastern margin of the Japan Sea

It is general for seismotectonic map that the maximum magnitudes of scenario earthquakes are assumed to be equal to those of historical earthquakes. This paper uses the Hagiwara Map, given by Hagiwara (1991). Further, in the Hagiwara Map, the maximum magnitudes of the scenario earthquakes are assumed to be equal to the maximum magnitude of the historical earthquakes in each region. Thus, the moment magnitudes of the scenario earthquakes are equal to or greater than that of the maximum historical earthquake tsunami; further, the fault model of the maximum historical earthquake tsunami should reproduce its run-up heights. In this paper, the uncertainty of the moment magnitude is not directly considered; instead, it is considered indirectly by a parametric study.

(4) Moment magnitude of the earthquakes assumed to occur due to submarine active faults

The relationship between inland active fault length and its earthquake size is shown by studies such as Matsuda

(1975) and Takemura (1998). Consequently, for the earthquakes assumed to occur at submarine active faults, the maximum moment magnitude is decided based on the active fault length and appropriate scaling law, in principle.

(5) Parametric study

Firstly, a parametric study of the dominant factors of the standard fault model should be carried out. Secondly, by using the fault model with the greatest effect on the target site, a parametric study of the subordinate factors should be carried out. These procedures enable us to efficiently carry out such parametric studies. Here, certain factors that have a small degree of uncertainty can be excluded.

By considering the characteristics of the water areas, the factors for a parametric study should be appropriately selected among the fault position, depth of upper edge, strike direction, dip angle, dip direction, slip angle, combination of segments, etc. The details are described in Section 4.3.5.

The range of the parametric study is set within reasonable limits. If it is possible for a factor to process statistics-based historical earthquakes and tsunamis, the range of the parametric study can function as the standard deviation.

With regard to far-field tsunamis, the parametric study should be carried out based on the procedure for near-field tsunamis.

The method of setting the tsunami sources is described in Section 4.

(6) Numerical simulation/Numerical calculation

At the target site, it is possible to assess the water level of the designed tsunami using a simplified estimation formula and numerical simulation. The simplified estimation formula is useful to narrow down the tsunami sources for

the numerical simulation. However, this method lacks rigidity; for example, it does not consider the effects of submarine topography and coastal landforms. As a result, in most cases, a simplified estimation formula cannot be applied for a conclusive assessment of the water level of the designed tsunami. Thus, in this paper, the water level of the designed tsunami should essentially be assessed by a numerical simulation. Further, a suitable numerical simulation method should be adopted in order to assess the maximum water rise and fall at the target site. The details are described in Section 5.

(7) Tidal conditions

For the high water level of the design tsunami, the mean of the high tides should be added to the calculation results. For the low water level of the design tsunami, the mean of the low tides should be added to the calculation results. This approach for the high water level of the design tsunami is also employed by the Agricultural Structure Improvement Bureau, Ministry of Agriculture, Forestry and Fisheries etc. (1996, 1997).

However, for efficiency, this approach assumes that the maximum water rise and fall are simultaneously calculated based on the appropriate tidal condition in; subsequently, the means of the high and low tides are added.

Hence, this approach is not applicable to the case in which a numerical simulation is carried out on the basis of the mean of the high tides for the assessment of the high water level of the design tsunami.

(8) Resonance in a harbor and response with an intake passage

When the predominant period of the tsunami and the natural period of free oscillation for the harbor are equal, the water rise and fall may be amplified by resonance in a harbor regardless of the magnitude of the earthquake. The effect of resonance in a harbor is included in the numerical simulation method shown in Section 5. It is desirable that such resonance is investigated if necessary by using, for example, a numerical simulation based on a moment magnitude that is smaller than the maximum one.

Because variation in the water level may occasionally be amplified at the target point due to the response with an intake passage, it is desirable that such response is investigated if necessary.

3.3 Definition of terms

The main terms used in this paper are as follows:

(1) Design water level

"Design water level" indicates the "design high water level" and "design low water level," which are the tsunami water levels used for the design. The "design water level" is defined as the sum of the "design tsunami" and an appropriate tidal condition.

(2) Scenario tsunami for design

"Scenario tsunami" is a tsunami generated due to an scenario earthquake along the plate boundaries, the eastern margin of the Japan Sea, or submarine active faults. Around Japan, the plate boundaries are located at the Japan Trench, southern Kurile Trench, and Nankai Trough.

(3) Design tsunami

"The design tsunami" is selected among the scenario tsunamis at each area as the tsunami that has the maximum influence on the target site in terms of the maximum and minimum water levels. Sometimes, the tsunami sources that give rise to the maximum and fall to the minimum water levels are different.

(4) Standard fault model

"Standard fault model" is a model for generating a scenario earthquake in a numerical simulation. Thus, a standard fault model can generate a scenario tsunami. The standard model for the parametric study is defined as a "standard fault model", which should be determined appropriately considering characteristics of each sea area.

(5) Parametric study

"Parametric study" is a method of taking into account the uncertainties of tsunami sources in the design. A "parametric study" is defined as a study in which a large number of numerical calculations under various conditions. The conditions of a scenario earthquake are set based on a standard fault model and varied within an appropriate range. Each of the calculation results is a scenario tsunami.

(6) Scenario tsunamis

A group of scenario tsunamis obtained by a parametric study is defined as "scenario tsunamis."

(7) Design high water level/design low water level

These are defined as follows:

"Design high water level" = "Maximum water rise" + "Mean high tide"

"Design low water level" = "Maximum water fall" + "Mean low tide'"

(8) Maximum water rise/Maximum water fall

These terms are defined as follows:

"Maximum water rise" = maximum water rise calculated from the tidal level when the simulation is carried out based on the proper tidal level

"The maximum water fall" = calculated maximum water fall from the tidal level when the simulation is carried out based on the proper tidal level

[Description]

For “scenario tsunami,” “scenario tsunamis,” “‘design tsunami,” “standard fault model,” and “parametric study,” the concept diagram is shown in Figure3-3.

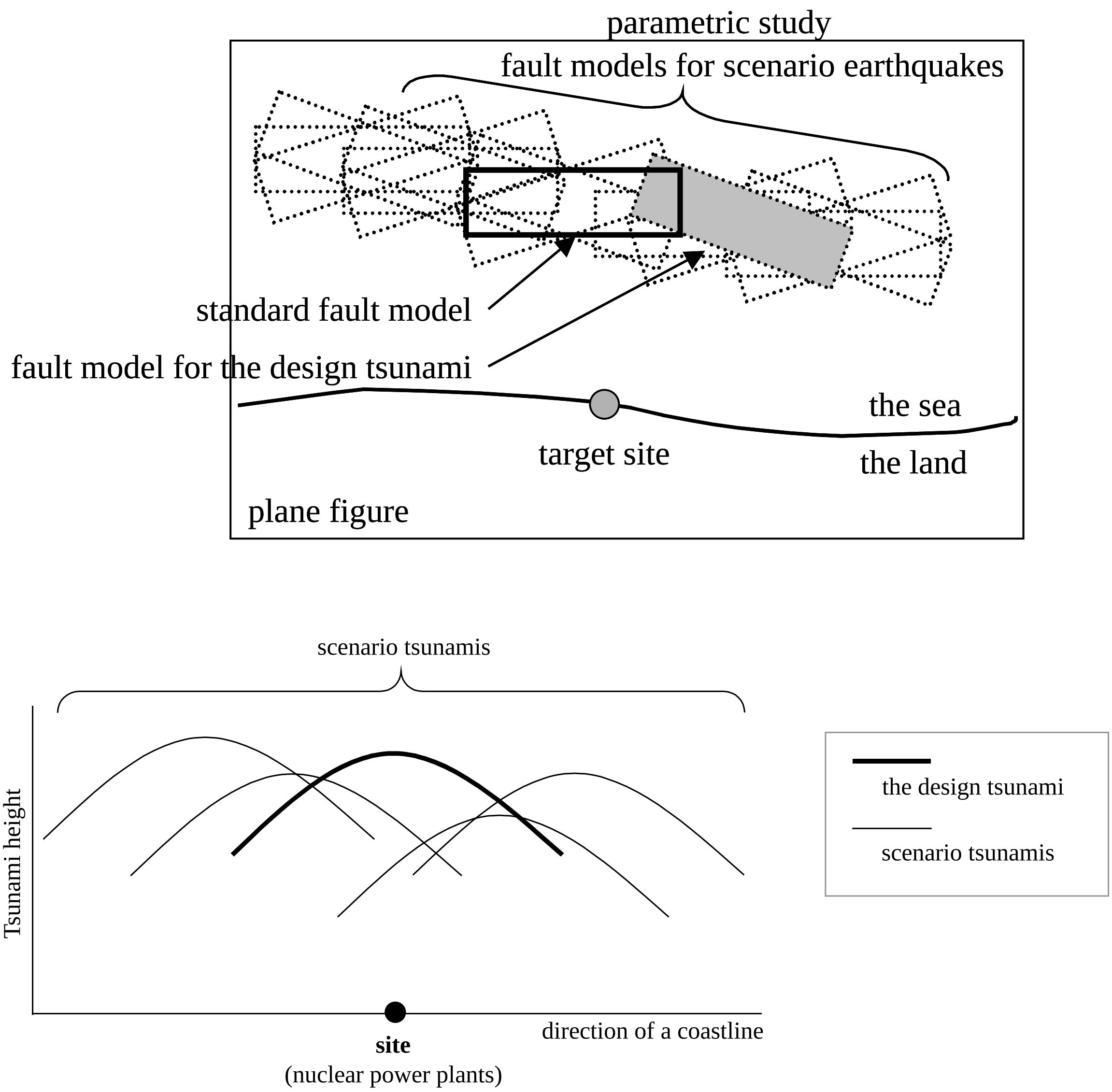

Figure 3-3 Concept diagrams of the design tsunami and related terms

[References]

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Chapter4 Setting fault models for tsunami sources

4.1 Basic concepts

4.1.1 Classification of tsunami sources for assessment

The tsunami sources evaluated in the tsunami assessment of nuclear power plants are classified as follows:

(1) Historical tsunami

(2) Scenario tsunami

[Description]

The overall policy of the assessment of the water level of the design tsunami is shown in Section 3.1.

The term "historical tsunami" is utilized for verifying the validity of the design tsunami and tsunami water level evaluation method including the fault model, modeling of the submarine topography and shoreline, and the numerical calculation system.

In contrast, the evaluated design water level is based on "scenario tsunamis" with various uncertainties taken into account, which can be classified as shown in Table 4-1. The concept of this classification is based on the data compiled in 1999 by the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion attached to the Prime Minister's office (now a part of the Ministry of Education, Culture, Sports, Science and Technology). The method of determination of the standard fault model for the scenario tsunami in each classification is described in Section 4.3.

Table 4-1 Classification of scenario tsunami

Classification	Sea area	Types of earthquakes
tsunamis due to earthquakes along the plate boundaries	sea areas related to the subduction of the Pacific Plate	・ typical interplate earthquakes ・ tsunami earthquakes (slow earthquakes) ・ intraplate earthquakes with a reverse fault ・ intraplate earthquakes with a normal fault
	sea areas related to the subduction of the Philippine Sea Plate	・ typical interplate earthquakes
tsunamis due to earthquakes in the eastern margin of the Japan Sea	eastern margin of the Japan Sea	・ shallow inland earthquake(*)
tsunamis due to earthquakes in the submarine active faults	(entire area around Japan)	・ shallow inland earthquake

(*) In the eastern margin of the Japan Sea, a clear plate boundary is not formed considering that earthquakes with two opposing dip directions have occurred in the area. Therefore, the tsunami source is modeled in accordance with earthquakes that occur within the upper crust. See Section 4.3.1 for the definition of "shallow inland earthquake."

4.1.2 Expression for earthquake size

In principle, the earthquake scale for setting the fault parameters are expressed by the moment magnitude Mw in the tsunami assessment.

[Description]

A wide variety of scales have been proposed for expressing the size of earthquakes. Various values of magnitude have been estimated for the same earthquake because the definitions of the scales differ from each other. It has been pointed out that there are systematic differences among the magnitudes obtained using different scales.

For a detailed evaluation of tsunamis by a numerical calculation, the basic scale used to express the magnitude of the earthquake is the moment magnitude M_w. In addition, a tsunami magnitude scale *Mt* is applicable for the preliminary estimation of the tsunami height.

(1) Moment magnitude M_w

M_w defined by Kanamori (1977) is directly connected to the seismic moment M_0, which is defined as a function of the various quantities of the fault parameters; therefore, it is a physical expression of the size of the seismic faulting.

$$\log M_0\ (\mathrm{N\cdot m}) = 1.5\, M_w + 9.1$$

$$(\log M_0\ (\mathrm{dyne\cdot cm}) = 1.5\, M_w + 16.1)$$

where $M_0 = \mu LWD$

L : fault length

W: fault width

D: slip amount (see Section 4.1.3)

μ: rigidity modulus (see Section 4.1.4) of the medium in the vicinity of the hypocenter.

Because M_w reflects the long-period components of seismic waves (mainly a periodic band with a period longer than approximately 10 s) and is adequate for expressing phenomena with large wavelengths, such as tsunamis, the earthquake magnitude is basically expressed by using the M_w scale for a detailed evaluation of tsunamis by numerical calculation.

It should be noted that the definition of the Japan Meteorological Agency magnitude M_J is based on the maximum amplitude of seismic waves with a period of 5 s or less recorded by middle-period or short-period seismographs. Since M_J cannot express the magnitude correlation between giant earthquakes (the so-called “saturation phenomenon;” compiled by Utsu et al. (2001)), and it cannot directly reflect the physical magnitude of the seismic faulting, its application for the evaluation of tsunamis is considered to be more suitable in this paper.

(2) Tsunami magnitude Mt

Mt defined by Abe (1981) and Abe (1999) is expressed by the following equations with an amplitude *H* of the tsunami recorded on tide gauge records (or run-up heights) and the distance from the tide gauge station to the earthquake epicenter Δ.

Mt is defined as having a good correlation with M_w of the tsunamigenic earthquakes and functions as a scale for estimating the magnitude of an earthquake with a tsunami record.

Definition equation of M_t using tide gauge records (Abe (1981))

$$M_t = \log H + \log \Delta + 5.80$$

$$M_t = \log H_2 + \log \Delta + 5.55$$

where *H*: maximum single crest or trough amplitude of the tsunami waves based on the tide gauge records (m)

H_2: maximum double amplitudes of the tsunami waves based on the tide gauge records (m)

Δ: distance from the earthquake epicenter to the tide station along the shortest oceanic path (km)

Definition equation of M_t using run-up height (Abe (1999))

$$M_t = 2 \log H_m + 6.6$$

$$M_t = 2 \log H_{max} + 6.0$$

where H_m: maximum value of the local-mean run-up height (m)

H_{max}: maximum run-up height in the entire area (m)

Relationship between M_t and M_w

$M_t = M_w$ (Pacific; Abe (1985))

$M_t = M_w + 0.2$ (Japan Sea when *Mt* is determined using tide gauge records; Abe (1985))

$M_t = M_w + 0.4$ (Japan Sea when *Mt* is determined using the run-up height; Abe (1999)).

4.1.3 Modeling fault motion

In order to express the tsunami source, the faulting should be properly modeled to reflect the characteristics of the tsunamigenic earthquake.

[Description]

The spatial distribution of the initial sea level fluctuations of the tsunami is assumed to be equal to that of the vertical deformation of the sea bottom by faulting. Further, in the process employed for estimating the initial sea bottom deformation, a rectangular fault plane model with a uniform slip is generally adopted. With respect to permanent deformation by faulting, a rectangular fault model with a uniform slip can be described by the following nine parameters (see Fig. 4-1).

- Horizontal positions of reference point *(N, E)*
- Fault length L ・Strike direction θ
- Fault width W ・Dip angle δ
- Slip amount D ・Slip angle λ
- Depth of upper edge of the fault plane d

Among the parameters above, L, W, and D can be related to M_0 by the following equation.

$$M_0 = \mu LWD$$

where μ : rigidity modulus of the medium in the vicinity of the fault

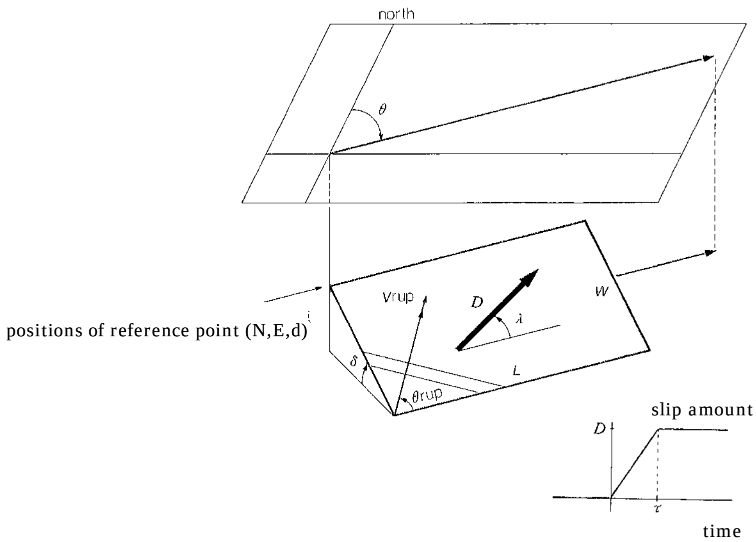


Fig.4-1 Fault parameters (modified from Sato (1989))

In recent years, researches for developing more detailed fault models of the historical earthquakes have been carried out by applying the tsunami waveform inversion analysis in order to take into account "asperity," or an area where the slip on the fault surface is locally significant. (see Section 1.1.3).

The actual crustal deformation can be reproduced more precisely by a combination of multiple faults with different parameters. In such cases, the crustal deformation obtained from each fault may be linearly added.

When the fault size is large, there are cases in which the primary focus is on the temporal change in the submarine fluctuations by faulting. In such cases, additional fault parameters such as the time required for fault slip (rise time) τ, rupture propagation velocity V_{rup}, and propagation mode of rupture are considered.

4.1.4 Rigidity of medium near the fault

The rigidity modulus of the medium in the vicinity of the fault should be appropriately set depending on the earthquake generation area, focal depth, etc.

[Description]

The rigidity modulus μ of the medium in the vicinity of the fault can be calculated by using the following equation.

$$\mu = \rho V_s^{\,2}$$

where V_s : the S-wave velocity and ρ is the density of the medium

Because the rigidity modulus affects the estimation of M_w of historical tsunamis, it is essential to set an approximate value of the rigidity modulus in the evaluation of tsunamis. With respect to the tectonics in the neighborhood of Japan, studies of seismic velocities using artificial sources were extensively carried out in and after the 1950s, and the overall figure will now be elucidated.

It is known that the exact value of the rigidity modulus of the medium in the vicinity of the fault varies in the horizontal and vertical directions. However, for tsunami evaluation, the values listed in Table 4-2 can be used as a standard.

Table 4-2 Standard values of the rigidity modulus of the medium in the vicinity of the focus

Location	Rigidity modulus
・Continental plates in south-west Japan ・Eastern margin of the Japan Sea ・Shallow levels of plate boundaries (when the entire fault surface exists within a depth of less than 20 km)	3.5×10^{10} N/m^2 (3.5×10^{11} dyne/cm^2)
・Oceanic plates ・Deep levels of plate boundaries (when the entire fault plane exists within a depth of greater than 20 km)	7.0×10^{10} N/m^2 (7.0×10^{11} dyne/cm^2)
・Central portion of plate boundaries (when the entire fault plane exists across a depth of 20 km).	5.0×10^{10} N/m^2 (5.0×10^{11} dyne/cm^2)

4.2 Setting source of historical tsunamis

4.2.1 Selection of target tsunami

Based on the literature survey, etc., the historical tsunami that is assumed to have exerted the greatest influence on the target site is selected as the evaluation target.

[Descriptions]

Among the historical tsunamis assumed to have exerted considerable influences on the evaluation point, the tsunamis for which the reliability of the run-up height records is verified are chosen as the evaluation targets.

(1) Reliability of the run-up height records

The run-up heights of tsunamis older than the 1896 Meiji Sanriku earthquake tsunami have been assumed by researchers on the basis of old records, documents etc.; the reliability of the data must be closely examined. In the case of the run-up heights of comparatively recent tsunamis that occurred after 1896, the investigation method should focus on the heights mentioned in individual documents and their reliability.

If the reliability of any run-up height is doubtful, the accuracy of the data must be re-examined based on the original document. Further, if the reliability is too low, they can be eliminated when the goodness of fit is evaluated.

(2) Literature survey

The following literatures are available for surveying historical tsunamis.

- Watanabe, H. (1998): *Comprehensive List of Tsunamis to Hit the Japanese Islands [Second edition]*, University of Tokyo Press, pp. 238 (in Japanese).
- National Astronomy Observatory (ed.):, *Chronological Scientific Tables*, Maruzen Co., Tokyo (in Japanese).
- Usami, T. (2003): *Materials for Comprehensive List of Destructive Earthquakes in Japan* [Latest Edition] , University of Tokyo Press, pp. 605 (in Japanese).
- Utsu, T. (1982): *Catalog of large earthquakes in the region of Japan from 1885 through 1980*, Bulletin of Earthquake Research Institute, University of Tokyo, Vol. 57, pp. 401–463 (in Japanese).
- Utsu, T. (1987): (in Japanese).
- Kayano, I. and Utsu T. (2001): *Table of large earthquakes in Japan, Encyclopedia of Earthquakes [Second Edition]*, edited by Utsu, T., Asakura Publishing Co., Tokyo, pp. 569–641 (in

Japanese).

- Abe, K. (1988): *Tsunami magnitude and the quantification of earthquake tsunamis around Japan*, Bulletin of Earthquake Research Institute, University of Tokyo, Vol. 63, pp. 289–303 (in Japanese with English abstract).
- Abe, K. (1999): *Quantification of historical tsunamis by the Mt scale*, *Zisin*, Second Series, Vol. 52, pp. 369–377 (in Japanese with English abstract).
- Investigation report by research institutes such as universities etc., and public agencies such as Japan Meteorological Agency etc.
- Scientific literatures by researchers (for example, a series of historical tsunami research literature by Dr. Hatori)

(3) Extraction of tsunamis for detailed evaluation

For detailed evaluation, it is possible to extract a tsunami from two or more tsunamis by using a simplified prediction equation. For such a simplified prediction technique, there are methods, including that of Abe (1989), that employ the following equations.

$$\log Ht = M_w - \log\Delta - 5.55 + C$$
$$\log Hr = 0.5\,M_w - 3.3 + C$$

where Ht: local-mean tsunami height in intervals of several tens of km (m)

Hr: maximum value of local mean height (m)

M_w: moment magnitude

Δ: distance along the shortest oceanic path from the epicenter to the observation point (km)

C: regional constant (C = 0 for the tsunamis in the Pacific Ocean and C = 0.2 for the tsunamis in the Japan Sea)

However, an evaluation that employs the simplified prediction technique may lack accuracy because the influences of the water depth at the source location and coastal topography are not taken into account. Therefore, it is desirable to carry out a detailed evaluation by a numerical calculation if the results of narrowing by a simplified prediction equation indicate that there are two or more historical tsunamis that are assumed to exert a considerable influence at the target site.

4.2.2 Evaluation of goodness of the fault model

The goodness of the fault model as the tsunami source should be evaluated by Aida's indexes K and κ.

[Descriptions]

(1) Aida's indexes K and κ

Aida (1977, 1978) evaluates the goodness of the fault model based on the geometric average K and geometric standard deviation κ. The indexes K and κ by Aida (1978) have been applied as indexes of fitness in space between the recorded and computed tsunami heights. The defining equations of K and κ are given as follows.

$$\log K = \frac{1}{n}\sum_{i=1}^{n}\log K_i$$

$$\log \kappa = \left[\frac{1}{n}\left\{\sum_{i=1}^{n}\left(\log K_i\right)^2 - n\left(\log K\right)^2\right\}\right]^{1/2}$$

where n: number of data for evaluation,

$K_i = R_i / H_i$

R_i : recorded tsunami height at i

H_i : calculated tsunami height at i

Since the estimated error of κ depends on the number of samples, the number of samples should be stated for reference in calculating K and κ.

(2) Points to be noted

When the reliability of the run-up heights is doubtful, the accuracy of the records must be re-examined on the basis of the original document. If their reliability is determined to be low, they can be eliminated when evaluating the goodness of fit.

Since the tide gauge records may provide smaller amplitudes than the run-up heights depending on the period of the tsunamis and the response characteristics of the tide gauges, when the highest tide gauge record is adopted as a substitute for the run-up height, the systematic differences between the tide gauge records and run-up heights must be carefully considered.

4.2.3 Setting fault model of historical tsunamis

> The fault parameters of the fault model of the historical tsunamis should be set in such a way to reproduce the distribution of tsunami heights along the coast.

[Descriptions]

In general, a fault model that can explain the seismic waves is not always consistent with that which can explain the run-up heights of a tsunami. Needless to say, it aims at the evaluation of the tsunamis considered in this paper. When the fault model of the historical tsunami is set, it is important to also set the fault parameters in order to effectively explain the distribution of the tsunami heights along the coast well.

(1) General

When the fault model of the historical tsunami is set, the fault parameter is set in such a manner that the run-up heights of the tsunamis along the coast can be satisfactorily explained. In other words, the fault parameters should be set so that geometric average K by Aida becomes nearly 1.0, and the geometric standard deviation κ may acquire as low as possible.

It is recommended to use the following conditions as a good rule of thumb for K and κ of wide areas:

$0.95 < K < 1.05$

$K < 1.45$

These conditions are essential in order to enable an explanation of the overall trend of the run-up height distribution over a wide area; further, they are also important for ensuring satisfactory reproducibility in the vicinity of the target site.

When the run-up heights for evaluating the reproducibility are selected taking the target site into careful consideration, the following criteria are considered.

1) The distance from the site is short.
2) The coastal and sea bottom topographies around the site are similar.
3) The number of run-up heights necessary for calculating K and κ should be statistically reliable.

If the tide gauge records can be referred, the fault parameters should be set so that the wavelength, phase, etc., of the tsunami can be expressed.

When abundant records are available for recent tsunamis as well as the earthquakes that caused them, various characteristics of the earthquake can be referred. These characteristics include aftershock distribution, focal mechanism solution, crustal deformation before and after the earthquake, etc.

(2) Fault model of historical tsunamis proposed by research literature

In the case of major historical tsunamis, fault models that can explain tsunamis have been proposed in research literature, and it is possible to refer to these models when evaluating such tsunamis. The literature edited by Sato (1989) has a collection of such fault models from around Japan.

Among these models, the ones from particularly old sources may be inaccurate in the light of recent seismological findings in terms of consistency of the depth of plate boundaries, etc. The parameters of the fault model should be collected with discretion.

Among the fault models that can explain tsunamis proposed in research literatures, there exist models that can explain tide gauge records but not run-up heights. Since the tide gauge records may provide smaller amplitudes than the run-up heights depending on the period of the tsunamis and the response characteristics of the tide gauges, when the fault model set using the tide gauge records is adopted, the systematic differences between the tide gauge records and run-up heights must be carefully considered.

4.3 Setting source of scenario tsunamis

4.3.1 Basic concepts

(1) Types of earthquakes accompanied by tsunamis

Types of earthquakes accompanied by tsunamis should be considered for setting the scenario tsunami source.

(2) Scaling law

The relationship between the moment magnitude *Mw* and fault model parameters should be determined in accordance with the appropriate scaling law that conforms to the tectonics, the types of earthquakes accompanied by tsunamis, etc.

[Description]

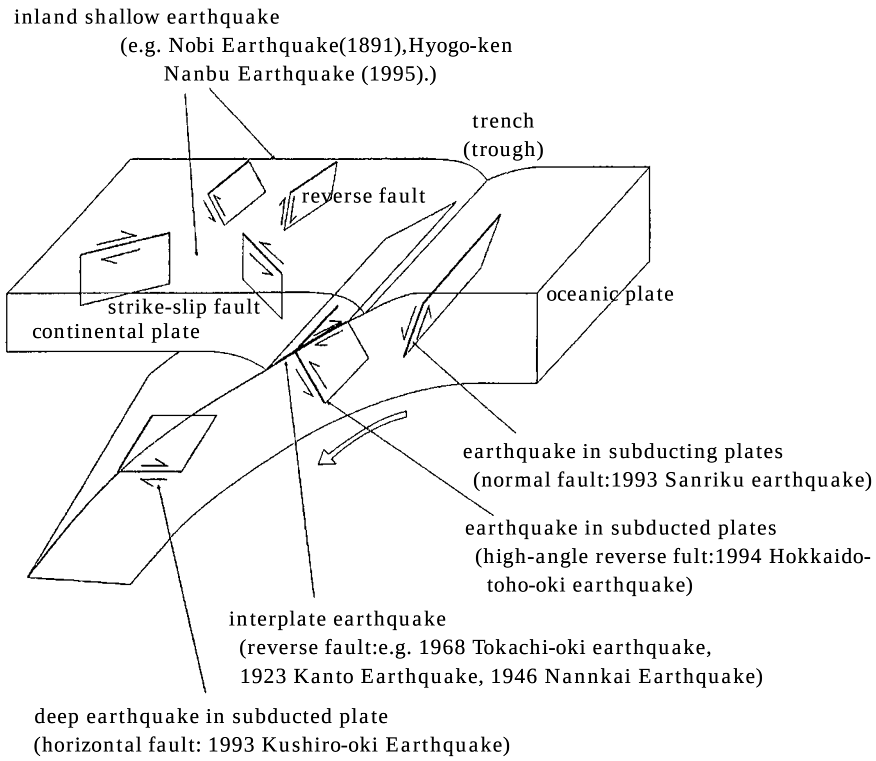
(1) Types of earthquakes accompanied by tsunamis

The types of earthquakes accompanied by tsunamis that have occurred in the Japanese archipelago and surrounding areas can be categorized as follows (see Fig. 4-2):

1) Earthquakes along plate boundaries

- 1-1) Interplate earthquakes caused by subducting plates
- 1-1-a) Typical interplate earthquakes with a reverse fault
- 1-1-b) Tsunami earthquakes (slow earthquakes)
- 1-2) Earthquakes in subducting plates
- 1-2-a) Intraplate earthquakes with normal fault in subducting plates
- 1-2-b) Intraplate earthquakes with reverse fault in subducting plates

2) Shallow inland earthquakes (*)



There are interplate earthquakes (plate boundary earthquakes), earthquakes within subducting (subducted) plates, and shallow inland earthquakes, and others.

(*) As referred herein, 'inland' denotes the continental crustal area from the viewpoint of tectonics and covers the continental plate excluding the plate boundaries or their extremely close areas. This is different from the geographical segmentation of land and

Fig.4-2 Types of earthquakes in the Japanese archipelago and the surrounding area
(Edited by the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion of the Prime Minister's Office (1999))

Based on the types of earthquakes described above, the fault model can be defined with respect to each location and type of earthquake accompanied by a tsunami.

The tsunami earthquake referred in this paper indicates that "the interplate earthquakes occur near the plate boundary close to the trench axis, and slip occurs slowly with extensive fault movement," as shown by Tanioka and Satake (1996).

(2) Scaling law

The following three concepts regarding the scaling law of the fault parameters related to M_w are introduced (see Fig. 4-3).

1) No limit on fault length L, fault width W, or slip amount D

$\mathrm{Log}M_0(\mathrm{Nm}) = 1.5M_w + 9.1, \qquad M_0 = \mu LDW$

M_0: seismic moment

μ: rigidity of the medium near the earthquake source

L: fault length

W: fault width

D: fault slip amount

The above relations indicate that if M_w increases by 0.1, M_0 becomes $10^{0.15}$ times larger. In the case of drawing no line on L, W and D, if M_w increases by 0.1, then every L, W and D becomes larger by $10^{0.05}$ or 1.12 times.

2) Setting limit on width W of the fault plane

When W reaches the upper limit, L and D increase by $10^{0.075}$ = 1.19 times as M_w increases by 0.1.

3) Setting limit on length L and width W of the fault plane

When L and W reach the upper bound, D increases by $10^{0.15}$ or 1.41 times as M_w increases by 0.1.

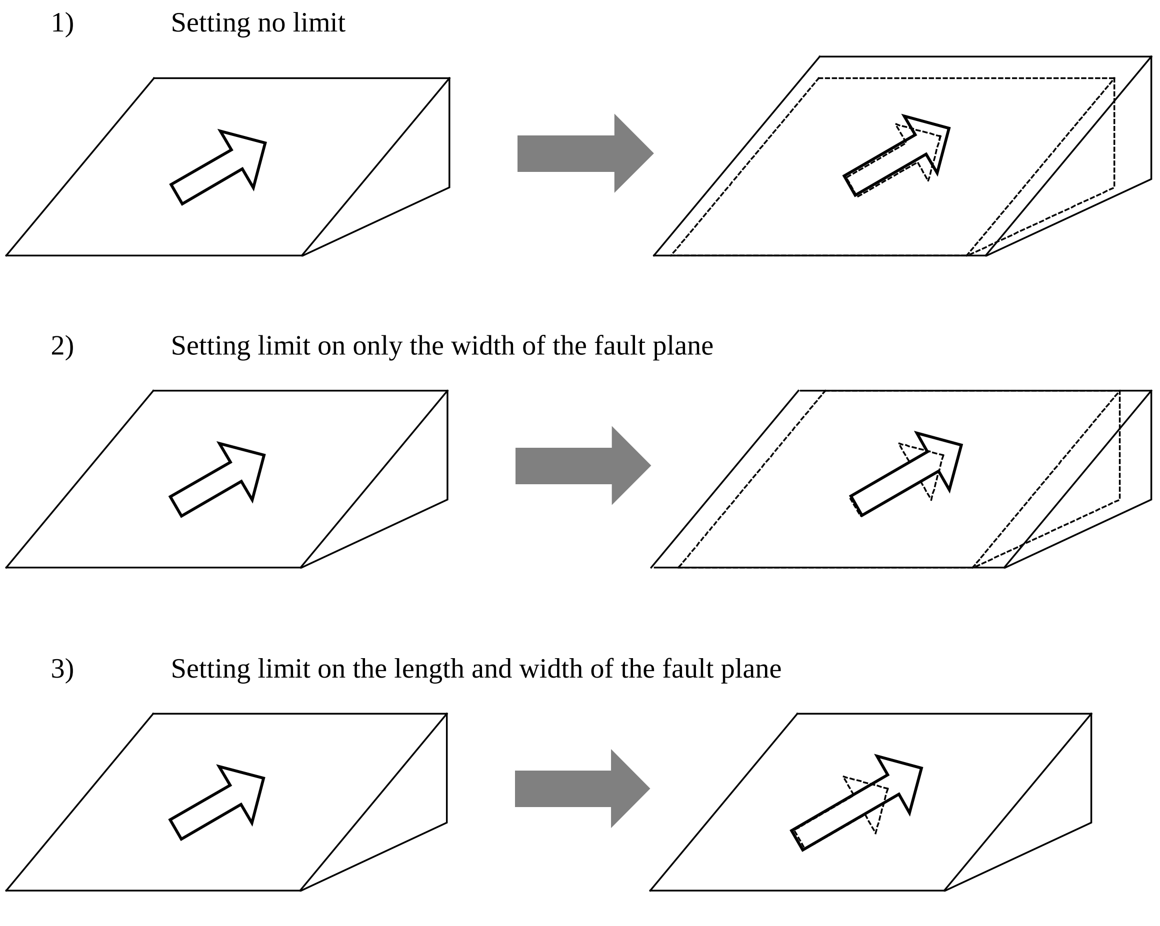


Fig. 4-3 Three scaling laws

These three scaling laws are applied to the following cases, respectively.

1) Setting no limit:

When the area of the rupture caused by the earthquake is small as compared to the existing weak plane and the length and width is less than their upper limits.

2) Setting limit only on the width of the fault plane:

When the depth of the seismic layer is limited and the rupture caused by the earthquake extends to the upper limit of the depth of the seismic layer (submarine active fault, normal fault in intraplate, etc.).

3) Setting limit on the length and width of the fault plane:

When the length of the fault plane and depth of the seismic layer are limited and the rupture caused by the earthquake extends to the upper limits of both the length and depth of the seismic layer.

With regard to the evaluation of the scenario tsunami, the appropriate scaling law that conforms to the seismo-tectonic features, types of earthquakes accompanied by tsunamis, etc., should be applied.

4.3.2 Setting tsunami sources for earthquakes along plate boundaries

(1) Evaluation range

Tsunamis resulting from possible future earthquakes along plate boundaries should be evaluated.

(2) Standard fault model

On the basis of the scaling law, considering the location of occurrence and type of earthquake, the standard fault model that corresponds to the assumed magnitude M_w should be introduced.

(3) Source region

Characterization of tsunami sources should be based on the idea of seismotectonics. In addition, the source region of the standard fault model may be introduced at an appropriate region in accordance with the type of earthquake, based on seismological knowledge such as the conditions that caused historical earthquakes, etc.

(4) Maximum moment magnitude

In each source region, the maximum moment magnitude of the standard fault model shall be equal to or greater than the moment magnitude M_w of the fault model that can employ this value to reproduce the maximum run-up height of recorded historical tsunamis.

[Description]

(1) Evaluation range

Along areas such as the Pacific coasts where earthquakes have repeatedly occurred along the plate boundaries, the assumed largest earthquake/tsunami in each tsunami source region would have already occurred. However, tsunamis resulting from possible future earthquakes along plate boundaries should be evaluated, and the tsunami source should be introduced on the basis of seismotectonics.

The source areas of tsunamis resulting from earthquakes along the plate boundaries can be classified into the following two neighboring sea areas in Japan on the basis of plate tectonics and the earthquake characteristics as well as the knowledge of the fault model that expresses them.

1) Subduction zone of Pacific plate

2) Subduction zone of Philippine plate

Therefore, the tsunamis resulting from earthquakes occurring along plate boundaries are separated into the two categories shown in Table 4-1, and the tsunami sources are introduced in this paper.

(2) Standard fault model

On the basis of the scaling law considering the place of occurrence and type of earthquakes that generate tsunamis, the standard fault model (see Section 3.3) that corresponds to the assumed magnitude M_w will be introduced. The method of determining the standard fault models, etc., is shown in Appendices 1 and 2.

In this paper, fault parameters that differ from one sea area to another are adopted; this is to ensure that the characteristics of the fault model that can explain the recorded historical tsunami run-up height and the characteristics of the earthquake and fault model obtained from various studies on various seismological subjects can be represented.

In the sea areas along the Japan Trench, southern Kurile Trench, and Nankai Trough, tsunamis repeatedly occurred in the past; hence, considerable information on the geometric configuration of plate boundaries, etc., has been obtained. A standard fault model that reflects the characteristics of every sea area can be introduced by applying the scaling law to the fault model that explains the recorded historical tsunami run-up heights.

In this section, the concept for limited regions is presented; however, when an scenario tsunami of another sea area is evaluated, a standard fault model can be introduced on a similar basis.

(3) Source region

The characterization of tsunami sources should be based on the idea of seismotectonics.

In the Japanese archipelago and surrounding areas, various characterization charts that show seismotectonics on the basis of varying viewpoints have been proposed. One of these charts is the characterization chart of the seismotectonics edited by Hagiwara (1991) in which the characterization covers over the entire sea area; this chart can be applied to the tsunami evaluation (see Fig. 4-4).

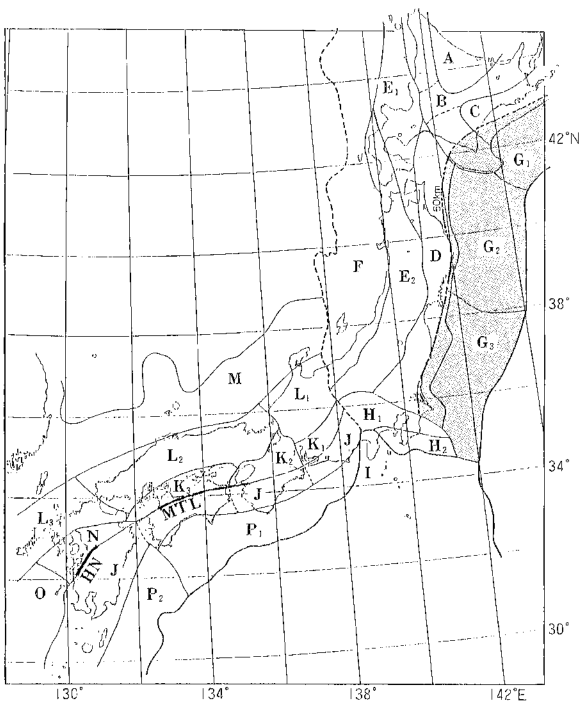


Fig. 4-4 Characterization chart of seismotectonics edited by Hagiwara (1991)

The characterization chart of seismotectonics edited by Hagiwara (1991) was compiled using comparatively large tectonic blocks on the basis of topographical, geological, or geophysical similarities. However, from the viewpoint of the conditions under which earthquakes/tsunamis occurred in the past, earthquakes of a particular magnitude and type have not always occurred in each tectonic block.

Therefore, in the actual evaluation of an scenario tsunami, it must be possible to introduce the source area of the standard fault model in a tsunami source region, which has been determined on the basis of a detailed rational evaluation; such a selection must depend on the type of tsunami, which is based on seismological knowledge such as conditions during the occurrence of historical earthquakes, etc. The tsunami source region of each standard fault model is shown in Appendices 1 and 2.

(4) Maximum moment magnitude

Depending on the sea areas, M_w of the fault model that explains the earthquake ground motion and that of the fault model that explains the recorded historical tsunami run-up height do not always coincide (see the Appendix shown below). Since this paper focuses on the evaluation of a tsunami, the maximum moment magnitude of the standard fault model assumed for every location of occurrence and/or type of earthquake should be equal to or greater than the M_w value of the fault model that can explain the maximum recorded historical tsunami run-up height. The maximum moment magnitude of each standard fault model is shown in Appendices 1 and 2.

There are various methods of defining the maximum magnitude of the earthquake that can occur in each tectonic segment. However, in the seismotectonic characterization chart edited by Hagiwara (1991), the method of evaluation is proposed on the basis of the maximum magnitude of the historical earthquakes.

As mentioned above, the value of M_w should be equal to the magnitude of the fault model with which the numerical model can reproduce the recorded historical tsunami run-up height in this paper; however, the method by which the maximum magnitude is assumed follows the method of Hagiwara (1991) (using the maximum magnitudes given in the historical records as the expected maximum magnitude).

【Appendix】

In the case of the earthquakes that occurred in recent years, the relationships between the M_w value determined by a seismic wave analysis and the M_w value that is assumed in this research for reproducing the tsunami run-up heights are shown in Figure-A1. In particular, the Pacific Ocean shows a trend in which the M_w value of the tsunami generally exceeds the M_w value of the earthquake. The following two points are considered to be the reasons for such a trend.

(a) There exists a trend in which the historical tsunami run-up heights are generally recorded as being larger than the half-amplitudes of the tide gauge. Accordingly, the seismic moment of the fault model that reproduces the recorded historical tsunami run-up heights must be assumed to be larger than that of the fault model that reproduces the tide gauge records. Since the fault model used to explain the tsunami is also often defined to reproduce the tsunami run-up heights, its moment magnitude M_w is assumed to be larger than the seismic moment magnitude M_w that is assumed to be consistent with the tide gauge records.

(b) In the case of an equivalent size of the seismic moment, the maximum tsunami run-up height used in the heterogeneous slip distribution on the fault is generally larger than that used in the uniform slip. It is assumed that fault movement includes this heterogeneity in practice; however, as a fault model with a uniform slip is assumed for every earthquake, as shown in Figure-A1, a large slip should be defined in order to reproduce the recorded historical tsunami run-up heights. Hence, the M_w values of tsunamis tend to be larger than those of the earthquakes.

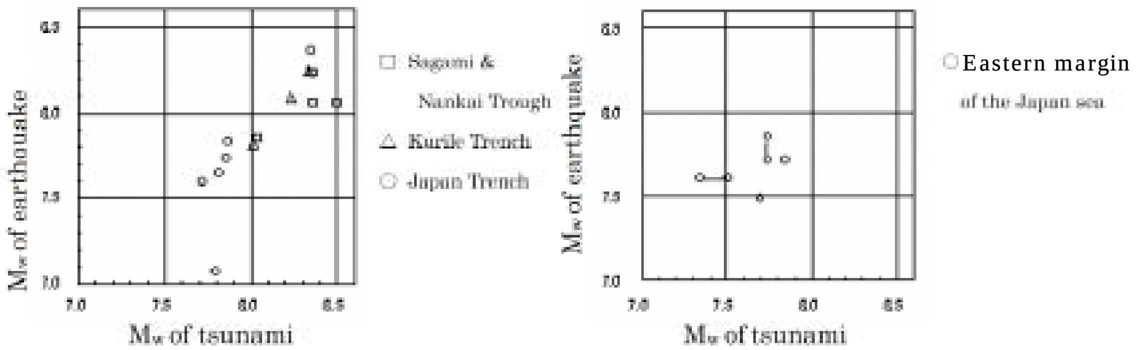


Figure-A1 Comparison between M_w of a tsunami and an earthquake

4.3.3 Setting tsunami sources along the eastern margin of the Japan Sea

(1) Evaluation range

Tsunamis resulting from possible future earthquakes along the eastern margin of the Japan Sea should be evaluated.

(2) Standard fault model

On the basis of the scaling law, considering the location of occurrence and type of earthquake, the standard fault model that corresponds to the assumed magnitude M_w should be introduced.

(3) Source region

Characterization of tsunami sources should be based on the idea of seismotectonics. In addition, the source region of the standard fault model may be introduced at an appropriate region in accordance with the type of earthquake, based on seismological knowledge such as the conditions that caused historical earthquakes, etc.

(4) Maximum moment magnitude

In each source region, the maximum moment magnitude of the standard fault model shall be equal to or greater than the moment magnitude M_w of the fault model that can employ this value to reproduce the maximum run-up height of recorded historical tsunamis.

[Description]

(1) Evaluation range

It is estimated that a mature plate boundary plane has not been formed along the eastern margin of the Japan Sea; however, after considering M7.5-class earthquakes and tsunamis that occur almost continuously from the west of Hokkaido to the west of Niigata, the scenario tsunami based on the knowledge of seismotectonics are evaluated separately from the tsunamis generated by earthquakes due to submarine active faults.

(2) Standard fault model

On the basis of the scaling law considering the location of occurrence and the type of the earthquakes that generate tsunamis, the standard fault model corresponding to the assumed magnitude M_W is set. The method of estimating the standard fault model, etc., is shown in Appendix 3.

It is estimated that a mature plate boundary plane has not been formed along the eastern margin of the Japan Sea; hence, the earthquakes that have occurred in this sea area have variable dip directions. A standard fault model is set by considering the uncertainties of parameters such as the dip angle by considering the limit of the thickness of the seismogenic layer and applying the scaling law as proposed by Takemura (1998), given by the following equation.

$$\log L = 0.75M_W - 3.77$$

L : fault length (km)

M_W : moment magnitude

(3) Source region

The tsunami source regions are assumed based on seismotectonics.

Therefore, in the actual evaluation of an scenario tsunami, the source area of the standard fault model should be set in a tsunami source region that has been determined using a detailed rational analysis depending on the type of tsunami; this is based on the seismological knowledge such as the conditions under which the historical earthquakes occurred, etc. The tsunami source region of each standard fault model is shown in Appendix 3.

(4) Maximum moment magnitude

The maximum moment magnitude of the standard fault model assumed for all locations of occurrence of and/or types of earthquakes should be equal to or greater than the M_W value of the fault model that can explain run-up heights of the maximum historical tsunami.

4.3.4 Setting tsunami sources on submarine active faults

(1) Evaluation range

Tsunamis resulting from possible future earthquakes on submarine active faults should be evaluated.

(2) Standard fault model

The standard fault model that corresponds to the assumed magnitude M_W should be set on the basis of the properties of the individual submarine active fault and the appropriate scaling law.

(3) Source region, etc.

Position, fault length L, and strike direction θ of the standard fault model should be set by the individual submarine active fault investigation for each target site, literature survey, etc.

(4) Maximum moment magnitude

The maximum moment magnitude in submarine active faults model should be set on the basis of length of submarine active faults to assess.

[Description]

(1) Evaluation range

Large-scale damages caused by tsunamis generated by earthquakes at submarine active faults are not known so far; however, for the purpose of verification, resulting from possible future earthquakes in submarine active faults should be evaluated.

The tsunamis generated by earthquakes at submarine active faults that are assumed in this paper should be considered with respect to the entire sea area around Japan; this analysis would be separated from that for the seismotectonic regionalization of the sea area shown in Sections 4.3.2(1) and 4.3.3(1).

However, because submarine active faults in the vicinity of trenches of the Pacific side are considered to be related to the earthquakes along plate boundaries, they may not need to be considered as tsunami sources due to earthquakes on submarine active faults.

In addition, along the eastern margin of the Japan Sea, the submarine active faults in the neighboring seas from the west of Hokkaido to the west of Niigata need not be considered as tsunami sources of the “tsunamis generated by earthquakes at submarine active faults” if the scale of these tsunamis is less than the scale of the scenario tsunamis, based on seismotectonics, as shown in Section 4.3.3.

The following literatures are available for surveying submarine active faults.

- Hydrographic Department, Japan Coast Guard: Basic map of the sea in the coastal waters
- Hydrographic Department, Japan Coast Guard: Basic map of the sea in the continental shelf areas
- Hydrographic Department, Japan Coast Guard: Submarine structural chart, bathymetric chart, and report of survey
- The Research Group for Active Faults of Japan (1991): New edition, Active Faults of Japan, University of Tokyo Press, 437p.
- Geological Survey of Japan: Geological Atlas of Japan (2nd edition)
- Geological Survey of Japan: Various marine geology maps

It is possible to extract a tsunami source for a detailed evaluation from two or more active faults by using a simplified prediction equation. For this purpose, methods including that of Abe (1989) (see Section 4.2.1) can be employed.

However, an evaluation that employs the simplified prediction technique might be lacking in strictness because the influences of the water depth at the tsunami source and coastal topography are not taken into account. Therefore, it is desirable to carry out a detailed evaluation by a numerical calculation if the results of the simplified prediction equation indicate that there are two or more tsunami sources in the submarine active faults that are assumed to exert considerable influence on the target site.

(2) Standard fault model

Depending on the properties of the individual submarine active faults, the standard fault model that corresponds to the assumed magnitude M_W will be set based on the appropriate scaling law. The method used to assume the standard fault model for submarine active faults is shown in appendix 4.

In this paper, the standard fault model is adopted for tsunamis generated by earthquakes at submarine active faults by representing uncertainties of parameters such as the dip angle, etc., considering the thickness limit of the seismogenic layer, and applying the scaling law as given by Takemura (1998).

(3) Source region, etc.

The fault locations of submarine active faults, fault length L, and strike direction θ are set by the investigations of individual submarine active fault or literature surveys of the target site. The dip angle δ and other parameters can be set on a similar basis as the fault length L and strike direction θ if they are accurately determined from an investigation of the individual submarine active fault or literature surveys of the target site.

(4) Maximum moment magnitude

In principle, for tsunamis generated by earthquakes on submarine active faults, the maximum moment magnitude is set on the basis of the active fault length and the appropriate scaling law.

The following equation by Takemura (1998) expresses the relationship between the active fault length L

and M_W.

$$\log L = 0.75 M_W - 3.77$$

where L : fault length (km)

M_W : moment magnitude

By convention, in order to estimate the scale of earthquakes occurring at active faults, the following equation by Matsuda (1975) has been popularly used for expressing the relationship between L and M_J.

$$\log L = 0.6 M_J - 2.9$$

where M_J : Magnitude according to the Japan Meteorological Agency

As described in Takemura (1998), at an M_J value of 6.8 or higher, Takemura's equation and Matsuda's equations are nearly the same when M_W is converted into M_J. Therefore, in this paper, M_J and M_W are related by the following equation for earthquakes assumed to occur at submarine active faults.

$$M_W = 0.8 M_J + 1.16$$

4.3.5 Parametric studies

In principle, the parametric study is carried out on the maximum water rise and fall for the main factors that have uncertainties among the various conditions of the fault model. The range of parametric studies should be appropriately set based on the degree of uncertainty.

[Description]

On the basis of the standard fault model, numerical calculations are carried out with parameters varied for the factors having uncertainties among the various model conditions; the scenario tsunami is then be evaluated.

The scenario tsunami is evaluated by appropriately setting the factors for carrying out the parametric study, and it is important that it is set within a reasonable range. When statistical estimate of a factor was made from historical earthquakes and tsunamis, the standard deviation can be used for the range of the parametric study.

(1) Procedure for the parametric study

The parametric study concerning the dominant factors of the standard fault model should be carried out. Subsequently, a parametric study concerning subordinate factors should be carried out by using the fault model with the greatest effect on the target site.

(2) Factors of parametric study

In principle, the parametric study should be carried out on the factors shown in Table 4-3 using the standard fault model; however, some factors that exhibit a slight uncertainty can be excluded.

Table 4-3 indicates the concept for limited sea areas; however, it is also possible to apply the same procedure for assessing the scenario tsunamis of other sea areas.

(3) Range of parametric study

The range of the parametric study is basically set with reasonable limits. For those factors that statistical analysis can be made from historical earthquakes and tsunamis, the standard deviation can be used as a range of the parametric study.

The ranges for the tsunami sources of earthquakes assumed to occur along the eastern margin of the Japan Sea and submarine active faults, are indicated in the standard fault model for some factors that exhibit a large uncertainty (see Appendix 3 and 4); the parametric study should be carried out by using this range as a reference.

Table 4-3 Parameters of the standard fault model

Name of sea area	Types of earthquakes	Parameters of the standard fault model						
		Fault position	Depth of upper edge of the fault plane (d)	Strike direction (θ)	Dip angle (δI)	Dip direction	Slip angle(λ)	Combination of segments
Along the Japan trench	Typical interplate earthquakes	○	○	○	○	—	○ #3	—
	Tsunami earthquakes (slow earthquakes)	○	○	○	○	—	○ #4	—
	Normal fault earthquake in the subducting plate	○	○	○	○	—	— be fixed at 270 degrees	—
Along the Nankai trough	Typical interplate earthquakes	○	○	○	○	—	○ #3	○
Eastern margin of the Japan Sea	Earthquakes that occur within the upper crust	○	○	○	○	○ west dip east dip	— be fixed at 90 degrees	—
Submarine active faults	Earthquakes that occur within the upper crust	—	○ #1	—	○ #1	○ #2	○ #4	—

#1 : Can be fixed, if determined through a survey.

#2 : If it is unknown, both directions have to be set.

#3 : Slip angle is to be set in conjunction with strike direction taking variation of slip direction into account.

#4 : Slip angle is to be set in conjunction with dip angle taking variation of stress field into account.

○: ○ is an item that should be taken into consideration in 'parameter study'.

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Chapter5 Numerical simulation

5.1 Basic concepts

For assessing the design water level, the numerical calculation method that can accurately evaluate the maximum water rise and fall at the target site should be adopted.

[Descriptions]

(1) Selection of the appropriate numerical calculation model

A fundamental framework for applying the governing equations and a numerical scheme that can accurately evaluate the maximum water rise and fall at the target site under adequate conditions of the initial water surface and boundary must be used.

The method of selecting the numerical model will be discussed in detail in Section 5.2.

(2) Adequate execution of numerical calculation

The computation domain, grid size, computation time step, bathymetry data, coefficients in governing equations, and simulating time are appropriately determined according to the spatial tsunami shape and topography of the sea areas along with the sources and target site.

The execution method of the numerical calculation will be discussed in detail in Section 5.3.

5.2 Selection of numerical simulation model

5.2.1 Governing equations and numerical scheme

When the numerical calculation is carried out, factors such as accuracy with regard to the phenomena to be calculated and necessary computation time should be taken into account, and the appropriate governing equations and numerical scheme should be selected.

[Description]

(1) Governing equations for tsunami evaluation

Since the tsunami has a longer wavelength as compared to the water depth, the long-wave theory is applied. The following theories are suggested with respect to the long-wave theory. They are based on two-dimensional equations that are derived from three-dimensional governing equations by integrating in the vertical direction. One of them should be selected in accordance with the objective phenomena.

[1] Linear long-wave theory

This is applied under the condition that the ratio of the wave height to the water depth is sufficiently small. The equations of motion comprises an unsteady term and a pressure term (hydrostatic distribution). When the bottom friction cannot be ignored, a friction term should be considered.

[2] Nonlinear long-wave theory (shallow water wave theory)

This is applied under the condition that the ratio of the wave height to the water depth is not small (the nonlinearity cannot be ignored). The equations of motion comprises an unsteady term, a pressure term (hydrostatic distribution), and an advection term; with these terms, the steepning of the wave front in shallow water can be considered. In general, since friction with the sea bottom cannot be ignored, a friction term is expressed. The horizontal eddy viscosity term may be considered if necessary.

[3] Dispersive wave theory

This is applied under the condition that the curvature of the tsunami wave increases with propagation, the vertical acceleration of the water particles cannot be ignored, and wave dispersion appears. The dispersion term is referred to as the linear dispersing wave theory and nonlinear dispersive wave theory when it is added to theory [1] and theory [2], respectively. The linear dispersive wave theory is applied for the calculation of the far-field tsunami propagation.

With respect to near-field tsunamis, if a tsunami is accompanied by soliton fission, wave breaking occurs before or after run-up. Even if the soliton fission had forced an increase in the run-up heights, this factor is accordingly taken into account by setting the slip of the fault model to be larger, provided the run-up heights were derived from calculations using the same governing equations and numerical scheme employed in setting the fault. Consequently, in discussing the water level, the nonlinear dispersive theory might not be needed in principle. It was proposed that the dispersive wave theory is better suited to the entire numerical area, which includes the tsunami source and the coastal area, since it can evaluate the tsunami wave shape more precisely than with the nonlinear wave theory without reference to soliton fission. This is because the dispersive term has the effect of suppressing the leaning of wave front in the deep and shallow sea areas (Iwase et al. (1998), Hara et al. (1998)). In the future, the dispersive wave theory is expected to facilitate the development of a more precise and practical numerical model than the nonlinear long wave theory by including a damping term due to wave breaking.

In addition, the numerical model for tsunami propagation is based on two-dimensional models as described above. However, if a particular local topographic feature such as a precipitous slope or a small valley acts as the maximum run-up point, as was observed with Monai on Okushiri Island during the Hokkaido Nansei-Oki Tsunami, a three-dimensional numerical model may be necessary for such areas (Yoneyama and Matsuyama (2001)).

(2) Governing equations and numerical scheme for near-field tsunami propagation

For nearshore tsunami propagation, where the water depth is shallower than 200 m, the governing equations of the nonlinear wave theory should be selected (Shuto (1986)). In such a case, an explicit finite difference scheme with a staggered leapfrog method is generally adopted because the analysis method of the numerical error caused by the finite difference scheme is nearly established.

In actual practice, either the method of Goto and Ogawa (1982) (hereinafter referred to as the Goto method) or the method of Tanaka (1985) (hereinafter referred to as the Tanaka method) is applied. Both are nonlinear wave theories, but have slight differences as shown in Table 5-1.

Table 5-1 Comparison between Goto method and Tanaka method

		Goto method	Tanaka method
Governing equation	Advection term	Conservation type	Non-conservation type
	Friction term	Manning type	General friction type
	Horizontal eddy viscosity term	Introduced if necessary	Introduced
Numerical scheme	Alignment of variables	Staggered scheme	Staggered scheme
	Difference in pressure term	Leapfrog scheme (Discretization error have accuracy to the second degree because both space and time are from a central difference.)	Leapfrog scheme
	Difference in advection term	1^{st}-order upstream difference scheme with accuracy of 1^{st} order	Lax-Wendroff scheme with accuracy of 2^{nd} order
	Difference in friction term	Approximated implicitly	Approximated explicitly (time forward difference)
	Difference in horizontal eddy viscosity term	-	Approximated explicitly (time forward difference)

However, since it has been verified that there is very little difference between both methods except under special conditions when the sea bottom slope is less than 1/100 and the period is less than 5 minutes, the use of either method does not pose a practical problem.

In addition, it is possible to apply other numerical calculation methods (for example, the finite scenario method). In such a case, it should be verified that the accuracy of the method is equal to or better than that of the abovementioned method by a prior analysis of the numerical error.

(3) Governing equations and numerical scheme for the far-field propagation of tsunamis

In the case of the far-field propagation of a tsunami, the linear theory can be applied because the wave height is small when compared to the water depth. However, when the initial tsunami profile has a wide range with respect to the frequency components, the wave velocity varies slightly for each frequency at the deep water; further, since it propagates for a long time, the delay of the shorter wave is larger. Therefore, in order to reproduce this effect, it becomes necessary to apply governing equations that include the dispersion term. Furthermore, for far-field tsunamis, the Coriolis force must be considered in the equations of motion. In addition, since the effects of the spherical earth cannot be ignored, a spherical coordinate system must be adopted. For a numerical scheme, the alignment of variables is performed by a staggered leapfrog scheme while the explicit difference method is adopted for the equation of continuity. An implicit difference calculus is generally adopted for the equations of motion.

5.2.2 Initial conditions

> In principle, the initial water level in a numerical calculation should be equal to the vertical slip amount of the sea bottom, calculated on the basis of the fault model.

[Description]

(1) Vertical slip amount distribution on the sea bottom

The vertical slip amount distribution of the sea bottom—the initial condition for the numerical simulation of the tsunami—is generally evaluated by using the Mansinha and Smylie (1971) method. This method is based on the theory of elasticity under the conditions of isotropy and homogeneity. Therefore, the Mansinha and Smylie (1971) method may be adopted to evaluate the fault slip amount distribution of the sea bottom in this paper.

In addition, it must be noted that the result is obtained under the conditions that Poisson's ratio ν of the ground is 0.25 (Lame's constants μ and λ are equal). The Okada (1985) method has higher versatility, and it is applicable to the calculation of the vertical slip amount of the sea bottom if either ν is not equal to 0.25 or the fault has a tensile component.

(2) Duration of fault movement

The duration of the fault movement that generates a large tsunami is assumed to be approximately several tens to 120 s. In such a case, the duration has no significant effect on the results of the numerical simulation of the tsunami as compared to the case in which the sea bottom is displaced instantaneously (Aida (1969), Iwasaki et al. (1974)). Consequently, both the methods—with and without a consideration of the duration—may be applicable. When an instantaneous vertical slip amount distribution is assumed on the water surface, a short-period oscillation might occasionally occur in the numerical results. This oscillation can be ignored if it disappears when the duration of the fault movement is considered.

When $CT_V/L > 4\times10^{-2}$, the dynamic slip of the sea bottom should be considered in the governing equations (Imamura (1989)). Here, C represents the wave velocity; T_V, the time duration of the fault movement; and L, the wavelength in the direction of the width of the fault.

(3) Setting the initial conditions

The vertical slip amount distribution of the sea bottom in Section (1) is generally given for the initial water surface as an initial condition; this is the fundamental method of tsunami generation. When the dynamic effects of the fault motion are considered in a mass conservation equation, the initial water surface is still water.

In addition, any initial flux (integrated flow in a depth) should be set as zero in either case, i.e., with or without the dynamic effects of the fault motion.

5.2.3 Boundary conditions

When carrying out the numerical calculations, the following boundary conditions associated with the computational region, submarine and coastal topography, structures, etc., should be properly applied:

(1) Offshore boundary conditions

(2) Onshore boundary conditions

(3) Overflow boundary conditions

[Description]

(1) Offshore boundary conditions

Since the computational region is finitely determined, open boundaries are artificially provided on the offshore and two sides. Appropriate boundary conditions need to be applied so that the behavior of the tsunami is free from the artificial reflection from the boundaries. In this paper, the offshore boundary and two side boundaries are referred to as the offshore boundaries.

1) Boundary conditions for a tsunami propagating from the inner to the outer areas of the computational region:

The conventional method for expressing the discharge flux using the progressive wave conditions (Aida (1969), Aida (1970, 1974), Iwasaki and Yo (1974)) is adopted. The method that uses free transmission conditions was proposed for situations in which this condition is not satisfied; this method was based on the method of characteristics (Goto and Ogawa (1982)).

The other free transmission conditions can be considered by setting a virtually complete reflecting wall at the open boundary. The transmitted wave height at this boundary is assumed to be one half of the standing wave height at the virtually complete reflecting wall (Hino et al. (1988)). In such a case, if the wall is properly positioned, results can be obtained with high accuracy (Imamura (2001)).

Both the methods, i.e., the method of the characteristics and that of the virtually complete reflection wall, can be applied to the case in which the tsunami propagates from the outer to the inner areas of the computational region. However, the latter can be applied under the conditions that the incidence angle to the offshore boundary is nearly a right angle.

2) Method of inputting a tsunami at the offshore boundary in the near-field ocean:

In case of the calculation of a far-field tsunami in the coasts of Japan, the tsunami motion is calculated in accordance with the linear dispersive wave theory formulated using the spherical coordinates system under the initial condition that was obtained using the fault model for the coasts of a foreign country. The incident tsunami component may be used for the offshore boundary of the computational region in the near-field domain (at identical positions in the far-field tsunami domain).

The time series of the tsunami estimated from the data recorded at a tidal station can be used as an input for the offshore boundary condition.

(2) Onshore boundary conditions

The boundary conditions between the sea and land should be applied in accordance with the following conditions.

1) Complete reflection condition

When the tsunami run-up onto land is not considered, a vertical wall with an infinite height should be positioned on the coastal line, and the discharge flux in the direction perpendicular to the coastal line should be assumed to be zero. In other words, a complete reflection condition should be applied. However, when this condition is applied, the water depth must be sufficient so that the sea bottom at the seaside region adjacent to the coastal line is not exposed during the run-down of the tsunami. If the water depth is low, the boundary conditions at the run-up front, which are discussed in the following section, can be used by taking the exposure of the submarine surface during the run-down into account.

2) Boundary conditions at the run-up front

When considering the tsunami run-up onto sloping land or run-down into a shallow sea exposing the sea bottom, the topography is approximated in the form of steps with the mesh size, and the existence of water in the topography at the tsunami front is judged at every time step. In practical works, the method of Iwasaki and Mano (1979) is extensively used. This method can be summarized as follows:

- The tsunami front is located at the boundary between the cell in which the sum of the water depth and maximum still water depth at the cell boundaries (four sides) is positive, and the cell in which the sum is either zero or negative.
- The total water depth at the cell boundary for calculating the discharge flux is given as the sum of the still water depth at the cell boundary and the higher water depth in the two neighboring cells.
- The discharge flux is estimated using the momentum equation by assuming that the line connecting the water level of the wave front and the bottom height in the neighboring cell gives the surface slope to a first-order approximation. When the total water depth is zero or negative, the discharge flux should be assumed to be zero.
- When the total water depth approaches zero, the advection term is neglected.

Kotani et al. (1998) proposed a modified method for determining the total water depth and an advection term for estimating the discharge flux in the run-up calculation.

(3) Overflow boundary conditions

The boundary conditions for the case in which the tsunami flows over the breakwater, sea dike, seawall revetment, and other structures should be applied according to the following conditions.

1) When the breakwater, etc., are modeled by the ground height as a part of the topography:

In this case, the boundary conditions at the run-up front described in the previous section can be applied to the boundary conditions in which the tsunami flows over the breakwater, etc.

2) When the breakwaters, etc., are modeled by the boundaries between cells:

[1] Honma formula (Honma (1940))

When breakwaters or sea dikes exist in the computational region and the water level exceeds the crest elevation, the discharge that flows over the structure is estimated using the following formulae in accordance with the overflow conditions (Iwasaki et al. (1981), Goto and Ogawa (1982)).

(Complete and incomplete overflows)

$$q = \mu h_1 \sqrt{2gh_1} \qquad h_2 \le \frac{2}{3} h_1$$

(Submerged overflow)

$$q = \mu' h_2 \sqrt{2g(h_1 - h_2)} \qquad h_2 > \frac{2}{3} h_1$$

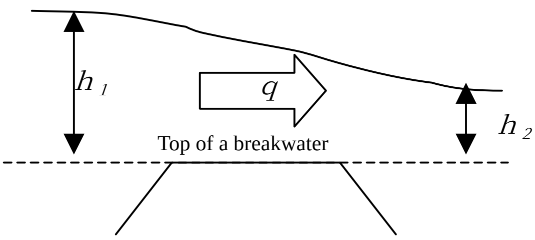

Fig. 5-1 Description of Honma formula

where h_1 and h_2 are the water depths in front of and behind the structure on the top of the structure, respectively; μ = 0.35, μ' = 2.6μ ; and g is the gravitational acceleration.

If the water does not flow over the breakwater and sea dike, the complete reflection condition setting of the vertical wall is assumed and the discharge flux in the direction perpendicular to the structures is assumed to be zero.

[2] Aida formula (Aida (1977))

When a seawall exists on the coastal line, the volume of overflow onto the dry bed of the seawall can be estimated using the following broad-crested weir formula and the flow rate coefficient as is the case with a submerged breakwater.

$$q = C_1 H_1 \sqrt{g \Delta H}$$

where H_1 is the water level on top of the revetment; ΔH, the water level difference at the discontinuous position; and C_1 = 0.6.

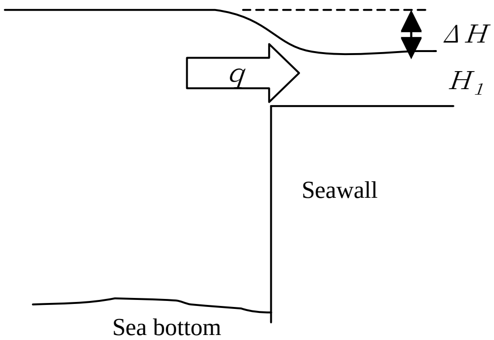

Fig. 5-2 Description of Aida formula

5.3 Details of numerical calculation

5.3.1 Setting the computational region and spatial mesh sizes

The computational region and spatial mesh sizes used for the numerical calculation should be properly determined after taking the size of tsunami source region, horizontal scale of the tsunami profile, characteristics of the submarine and coastal topographies, structures around the target site, etc., into account.

[Description]

The computational region of the tsunami that includes the tsunami source should be set up such that refraction (including lens effects), reflection (including multiple reflections), diffraction, seiche, trap effects, run-up, etc., which have considerable effects on the maximum water rise and fall at the respective site, can be reproduced with high accuracy.

In the tsunami calculation, the method of connecting computational regions with varying mesh sizes in accordance with the tsunami profile and topographical conditions is used from this viewpoint. The calculation of the tsunami is performed simultaneously within the connecting computational regions. In other words, the wavelength of a tsunami in the open sea is of the order of several tens to several hundreds km, and it decreases as the water depth decreases. It is necessary to successively change finer mesh sizes to meet the above conditions. In addition, since the topography in the vicinity of the seashore is usually complicated, the spatial mesh size must be properly set up in accordance with the characteristic topography of the seashore concerned or the scale of the artificial structures, as well as the spatial scale of the tsunami profile.

When setting and connecting the computational regions and spatial mesh sizes, the following aspects must be carefully considered.

(1) Spatial mesh sizes

In order to obtain the computational results with sufficient accuracy in each region with different mesh size, the spatial mesh sizes should be determined as follows. The descriptions shown below are fairly effective rules to be followed when a numerical calculation model is applied with a staggered scheme and a leapfrog differential method, which is the most popular method. Appropriate values of the mesh size should be determined after thoroughly examining the relationship between the scenarios and mesh sizes and the calculation errors when other numerical calculation models such as the finite scenario method are applied.

1) In tsunami source region

The mesh sizes in the tsunami source region should be determined considering the dimensions of the tsunami source region and the spatial scale of the tsunami profile.

As a rule of thumb, when the mesh sizes are determined in conformity with the spatial scale of the tsunami, the method proposed by Hasegawa et al. (1987), in which the mesh size is set to 1/20 of one wavelength of the tsunami, may be adopted.

2) In the sea area in the tsunami propagation process

In sea areas where the tsunami propagates, the mesh size should be determined by focusing on the refraction phenomena generated by the submarine topography in addition to the spatial scale of the tsunami profile.

When the submarine topography is simple, the rule of thumb for determining the mesh size is the same as that described in 1). In regions where the effects of the refraction phenomena appear predominant, the mesh size may have to be less than 1/100 of one wavelength of the tsunami.

3) In the sea area in the vicinity of the target site

In the sea area in the vicinity of the concerned site, the mesh size should be determined by focusing on the spatial scale of the tsunami, sea bottom slope, submarine and coastal topography, size and the shapes of structures such as breakwaters, etc. Under the condition that the coastal topography is not as complicated and the effects of the structures are insignificant, it is fairly accurate to gradually reduce the mesh size from 100 m at a water depth of 50 m or shallower to approximately 25 m at the coastal line.

In the case of ports and harbors, it is known that the water level in the ports and harbors can be calculated with a good accuracy if a mesh size of about 1/5 of the port entrance width or less is used for the vicinity of the port entrance (Inagaki et al. (2001)).

When the vicinity of the concerned site is located in a V-shaped bay, it is necessary to determine the mesh size in accordance with the ratio of the mean tsunami wavelength Lv in the bay to the bay length *l*. When Lv/*l* < 6, a mesh size that is less than 1/100 of the wavelength of the tsunami or seiche induced may be required for the bottom of the bay (Inagaki et al. (2001)).

4) In tsunami run-up area

The mesh size Δx of the tsunami run-up area under the conditions of an uncomplicated topography may be determined by the following formulae using the land slope α, the tsunami period T, and the gravitational acceleration g.

$\Delta x / \alpha g T^2 \leq 7 \times 10^{-4}$ (In the case of Manning's coefficient of roughness, n = 0.03 $m^{-1/3}s$)

$\Delta x / \alpha g T^2 \leq 4 \times 10^{-4}$ (If the friction term is not taken into account, refer to Goto and Shuto (1983))

(2) Connection of regions with varying spatial mesh sizes

With respect to the calculations used for connecting the regions, the spatial mesh sizes between the neighboring regions must be carefully changed. The connecting of regions with excessively different mesh sizes may cause errors; these errors are accumulated in the regions with smaller mesh sizes (the smaller region). This is because it is impossible to propagate a tsunami component with a short wavelength generated in a smaller region into a larger region, and it remains within the smaller region. The limit wavelength that can be reproduced in each region is twice the mesh size. It is necessary to reduce the mesh sizes by 1/3 or 1/2, etc.

The computation may become unstable if the connecting boundary on the lateral side intersects the coastline at an acute angle. This is because the reflected wave from the coastline reaches the lateral side boundary immediately; further, the difference between the actual and calculated results for a region with a larger mesh size is large where the numerical results are obtained for an outer region with a rough topography.

5.3.2 Setting computational time steps

The computational time steps should be properly set after considering the calculation stability, etc.

[Description]

By using the spatial mesh sizes, which are set in conformity to the concept discussed in Section 5.3.1, the time intervals are set so as to satisfy the CFL conditions shown below with the calculation stability, etc. General stable conditions exist in the wave motion numerical calculation. The following are conditions for the horizontal 2-dimensional numerical calculations.

$$\Delta t \leq \frac{\Delta x}{\sqrt{2gh_{\max}}}$$

where Δx: mesh size

Δt: time step

h_{max}: maximum water depth

g: gravitational acceleration

In general, calculation regions with different mesh sizes are connected and the numerical calculation is carried out all together with the time intervals set to be constant. Firstly, the value of Δt that satisfies the CFL conditions in each region with uniform Δx is determined; finally, the minimum Δt is adopted as the time interval.

However, when the calculation is actually performed in practice, numerical errors and nonlinearity of the phenomena interfere. Hence, Δt must be set at a small value as compared to $\Delta x / \sqrt{2gh_{\max}}$ with an allowance provided. In particular, in the case of calculations with a high-speed current occurring during the run-down of the tsunami, the flow velocity becomes greater than the wave celerity of the tsunami, $\sqrt{gh_{\max}}$; this might result in a divergence of the calculation.

5.3.3 Topographic data

In principle, topographic data used for the calculation should be prepared in accordance with the latest submarine topographical maps, land topographical maps, etc.

[Description]

(1) Bathymetry data

As a result of the recent development of an echo-sounding technique and satellite positioning technique applied to a wide area, the measuring technique of the water depth distribution has been remarkably improved. Hence, from the viewpoint of a higher accuracy of calculations for numerical simulations of historical and scenario tsunamis, the water depth data used should be prepared in accordance with the latest measurement results.

In the case of the bathymetric data, nautical charts and base maps of the sea from the Hydrographic and Oceanographic Department, Japan Coast Guard, and Expert Grid Data for Geography: 1 km, Bathymetry Integrated Random Data Set of the Japan Hydrographic Association, etc., are readily available. If echo-sounding has already been carried out in the vicinity of the assessed spot, the survey data can be used.

If a wide oceanic area of an ocean such as far-field tsunami, etc., is investigated, the 5-Minute Girded Earth Topography Data by NOAA (1988), etc., can be utilized. If the wide bathymetric area is investigated, the 2-Minute Girded Earth Topography Data by Smith and Sandwell (1997a, 1997b) can be utilized.

(2) Topographical data in the inundation area

Topographical data of the land used as the inundation area should be basically prepared in accordance with the latest topographical maps. For such data, the numerical maps of the Geographical Survey Institute and Japan Map Center can be utilized. However, it should be noted that the geographical accuracy in the vicinity of the coast is not necessarily satisfactory.

(3) Past topographical data

Some cases in which the artificial changes due to the structures, etc., which did not exist when the historical tsunamis hit, are included in the latest topographical data. In this case, if the water level of the scenario tsunami is compared with the run-up height at the assessed spot and the reproduction calculation of the water level of the historical tsunami is carried out, the topographical data before the above artificial changes should be used only for the above changed portions.

Furthermore, with respect to the coordinate system that serves as a reference for the abovementioned topographical digital data, the Japan geodetic system is used for data recorded in Japan, while the world geodetic system WGS84 is used for the data from American satellites. When they are used in combination, these facts must be carefully considered (Imai (2000), Sengoku et a1. (2000), Takahashi (1999)).

5.3.4 Various coefficients, etc.

Various coefficients and water depth related to the tsunami head, used for the numerical calculations should be appropriately chosen by referring to documents, etc.

[Description]

(1) Coefficients related to the friction term

The coefficients of the friction term should be chosen with reference to Table 5-2.

Table 5-2 Coefficients assigned to the friction term

Name of coefficient	Values reported in documents	Values used frequently for the assessment of the water level of the design tsunami of nuclear plants
Manning's coefficient of roughness n ($m^{-1/3}s$)	Iwasaki and Mano (1979): 0.03 for the sea area Goto and Sato (1993): 0.025 for the sea area Kotani et al. (1998): Inundation area: High-density residential district: 0.08 Medium-density residential district: 0.06 Low-density residential district: 0.04 Forest area: 0.03 Agricultural area: 0.02	Sea area: 0.03 Inundation area: 0.03
Friction coefficient k_b	Tanaka (1985): Deep sea area: 0.0026 Shallow sea area: 0.005–0.01 Inundation area: 0.01–0.5	Deep sea area (usually deeper than 15 m): 0.0026 Shallow sea area (usually shallower than 15 m): 0.00637 Inundation area: 0.01

However, when the friction coefficient is varied in accordance with the water depth, the current velocity field may yield unnatural results if the variation is discontinuous. Hence, it is recommended to set the friction coefficient such that a smooth variation is ensured.

(2) Coefficient of eddy viscosity

If the coefficient of eddy viscosity is smaller than 10 m^2/s (10^5 cm^2/s), the water fall ratio for a coefficient of eddy viscosity of zero is about 5% or less. Hence, if the water level change is subject to assessment, 10 m^2/s (10^5 cm^2/s) can be used as the actual maximum value of the coefficient of eddy viscosity. In Tanaka's method, 10 m^2/s (10^5 cm^2/s) is empirically used as the coefficient of eddy viscosity.

(3) Water depth related to the tsunami head

Theoretically, when the water depth at the tsunami head section becomes zero, the portion is judged to be the area that is not under water.

However, in practice, a small water depth remains due to numerical calculation errors, and the redundant calculations may sometimes continue. In addition, since the head-end section of the inundated tsunami is extremely small, the denominators of the friction and advection terms become very small and the numerical calculation tends to diverge.

Therefore, [1] the "minimum water depth" is carefully set to prevent the execution of the calculation by regarding the head-end water depth as zero. Moreover, [2] the "virtual water depth" is carefully set in order to prevent the water depth substituted for the friction and advection terms from achieving a value smaller than a certain water depth.

Imazu et al. (1996) researched the minimum water depth and virtual water depth; this work can be referred to for setting the water depth.

5.3.5 Reproduction time

The reproduction time should be appropriately set after taking the tsunami characteristics, topographical conditions, etc., into account.

[Description]

A tsunami does not always cause the maximum water rise or fall with the first wave. Moreover, the rise times of their maximum rise and fall vary in accordance with the time series of water-level changes at the wave source, topographical conditions, etc., in the vicinity of relevant locations.

For example, when the resonant oscillations inside the bay are excited or the reflection waves of the first wave from the opposite bank and a subsequent tsunami are superimposed, either a maximum water rise or the maximum water fall may occur. Hence, it is important to select a reproduction time that is suitable for analyzing these phenomena.

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Chapter 6. Postscript

Various uncertainties and errors exist in the process of tsunami assessment. It is rather difficult to quantitatively estimate them in sequence; further, it is also difficult to select a tsunami source from many scenario tsunamis. Instead of directly taking into account uncertainties and errors, the tsunami assessment method with a parametric study is proposed. According to the proposed method in this paper, a large number of numerical calculations are carried out under various conditions within a reasonable extent. The proposed method is verified by comparing and examining the typical historical tsunamis in Japan. In order to ensure the validity of the proposed method, the design tsunami is selected as the highest among all the historical and possible future tsunamis at the site.

With regard to future challenges, tsunami effects other than tsunami water levels, such as tsunami wave force and sand movement by a tsunami, are specified. Considerable research is in progress in these areas. In the near future, it is expected that the introduction of the results of these studies into the design of nuclear power plants will help to improve its efficiency and reliability.

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Appendix-1 Manner of Determination of Standard Fault Model - along the Japan Trench and southern Kurile Trench -

Sea area

Category	Sea area
1st category	In the vicinity of plate boundaries
2nd category	Sea area related to subduction zone of Pacific plate
3rd category	Along the Japan Trench and southern Kurile Trench

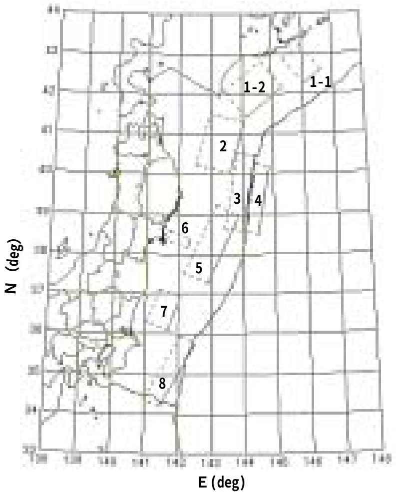
Characteristics of earthquakes and fault models

- Typical inter-plate earthquakes, tsunami earthquakes and normal fault earthquakes in the subducting plate are generated this area.
- Every earthquake type has its own characteristics with respect to the parameters of a fault model.
- Strike corresponds to the depth contour line of the trench.
- Slip direction is approximately the same as the direction of the relative movement between two plates.

Basic concept of setting fault models

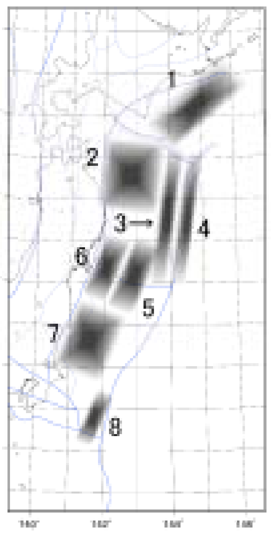
- A standard fault model is to be set depending on the fault position and magnitude M_w on the basis of the fault model that reproduces the historical tsunami run-up heights.

Fault models of historical tsunamis



Region No.	L (km)	W (km)	D (km)	δ (°)	λ (°)	μ (×10¹⁰N/m²)	M0 (×10²⁰N・m)	Mw	Year in which the tsunami occurred
1-1	60	100	2.2	27	115	5.0	6.6	7.8	1973
1-2	130	100	3.5	20	115	5.0	22.8	8.2	1952
2	150	100	6.0	20	80	5.0	45.0	8.4	1968
3	210	50	9.7	20	75	3.5	35.6	8.3	1896
4	185	50	6.6	45	270	7.0	42.7	8.4	1933
5	210	70	4.0	15	85	5.0	29.4	8.2	1793
6	26	65	2.0	20	85	7.0	2.4	7.5	1978
7	100	60	2.3	10	85	5.0	6.9	7.8	1938
8	200	50	6.5	20	95	3.5	22.8	8.2	1677

Maximum historical M_w

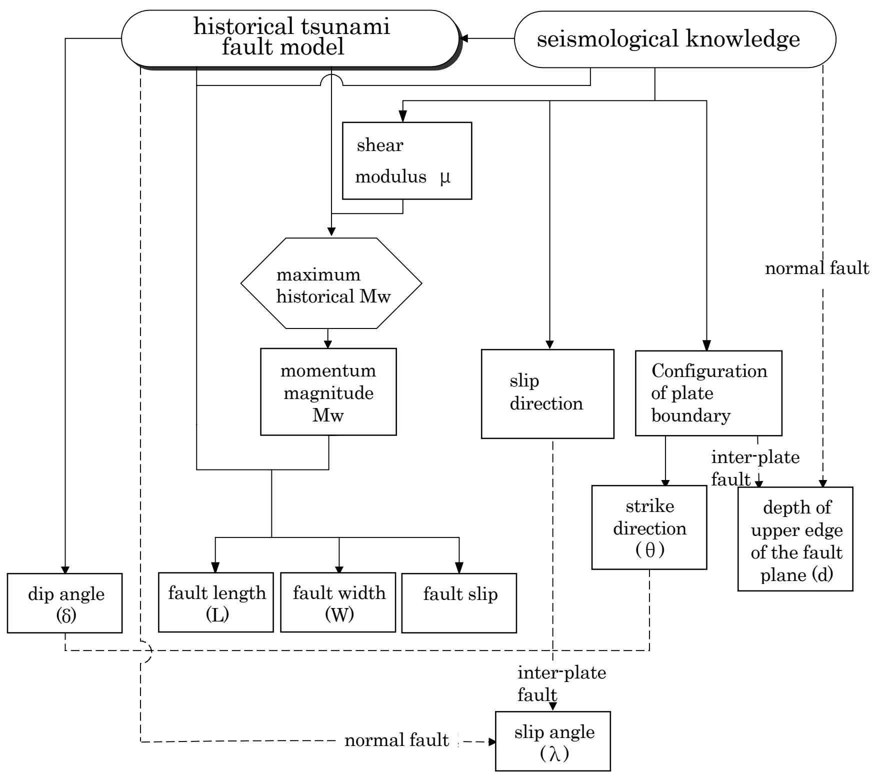


Region No.	Maximum historical M_w	Year in which the tsunami occurred
1	8.2	1952
2	8.4	1968
3	8.3	1896
4	8.6	1933
5	8.2	1793
6	7.7	1978
7	7.9	1938
8	8.2	1677

How to create a fault model

Parameter	Method
Length (L)	A suitable scaling law is applied to the historical tsunami fault model that has been set and is able to efficiently reproduce the historical tsunami.
Width (W)	Same as above.
Slip (D)	Same as above.
Depth of upper edge of the fault plane (d)	- Inter-plate earthquake: Depth is to be determined on the basis of the depth of the upper surface of the subducting plate. - Normal fault earthquake: Depth is set to zero.
Strike direction (θ)	Strike direction is set according to the strike direction of the upper surface of the subducting plate.
Dip angle (δ)	Same as the historical tsunami fault model
Slip angle (λ)	- Inter-plate earthquake: Slip angle is decided on the basis of the strike and slip direction. - Normal fault earthquake: Same as the historical tsunami fault model.
Shear modulus (μ)	3.5 × 10^{10} (N/m²) when depth is less than 20 km 7.0 × 10^{10} (N/m²) when depth is more than 20 km 5.0 × 10^{10} (N/m²) when the fault model extends over both regions.
Scaling law	- Inter-plate earthquake: Width should have an upper limit when the depth exceeds 50 km. - Normal fault earthquake and tsunami earthquake: Upper limit of the width is 50km.

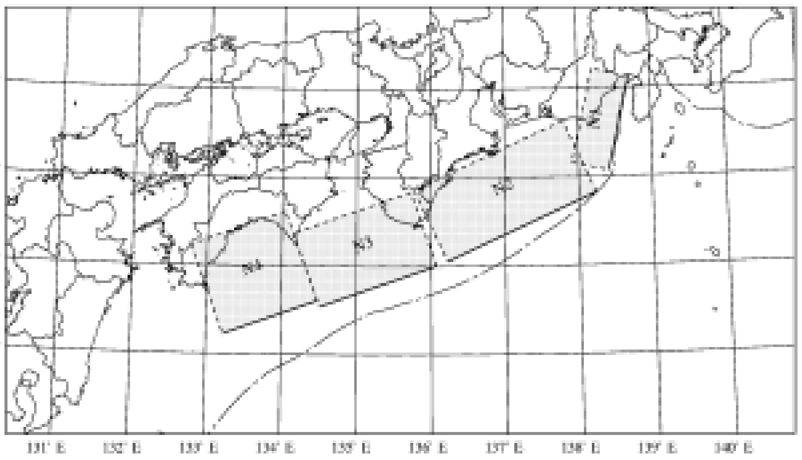
Determination flow of parameters of the standard fault model



Appendix-2 Manner of Determination of Standard Fault Model - along the Nankai Trough -

Sea area	1st category	In the vicinity of plate boundaries	Characteristics of earthquakes and fault models	・ Slip and combination of segments are the only items that can be changed because historical tsunami run-up heights can be reproduced by the fixed-area fault model.
	2nd category	Sea area related to the subduction of the Philippine Sea plate		
	3rd category	Along the Nankai trough	Basic concept of setting fault models	・ Fixed-area fault model is applied to the surface of Philippine Sea plate.

Fault models of historical tsunamis



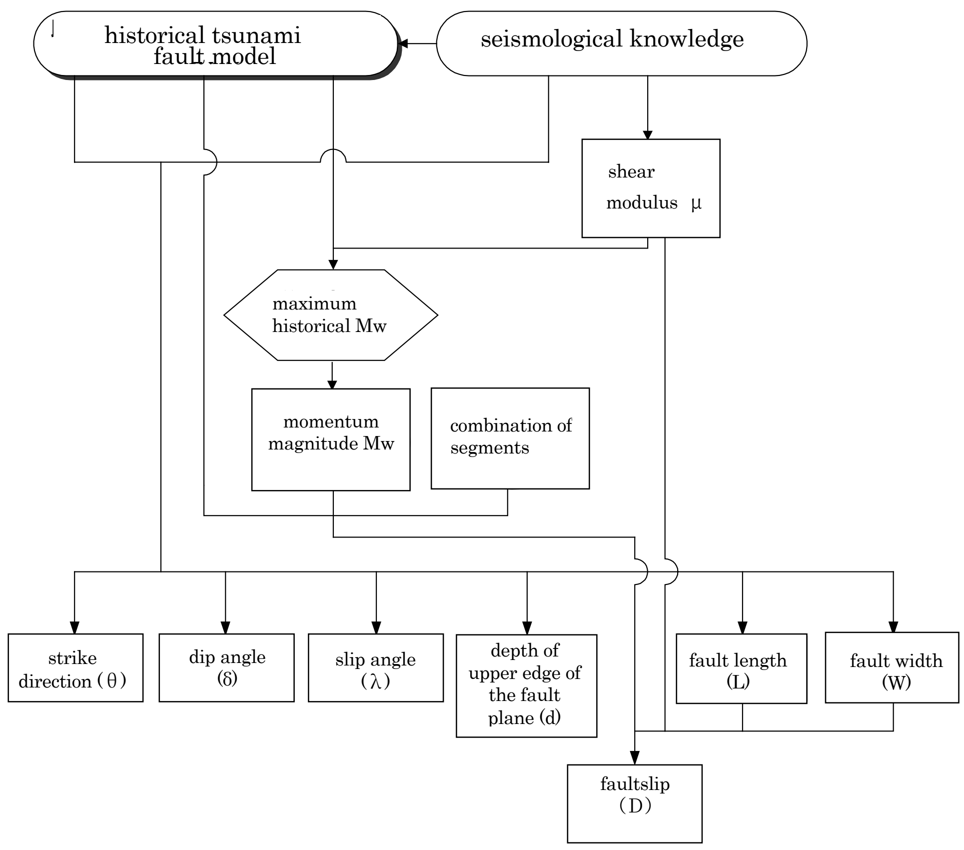
Seg-ment	Mw	area S (km^2)	L (km)	W (km)	d (km)	θ (°)	δ (°)	λ (°)	Year in which the tsunami occurred according to the reference model
N1	8.1	6000	120	50	5	193	20	71	1854, 1707
N2	8.5	20500	205	100	5	246	10	113	1854, 1707
N3	8.4	15500	155	100	8	251	12	113	1707
N4	8.5	15000	125	120	11	250	8	113	1707

Maximum historical *Mw*	Destribed in the above table

How to create a fault model

Length (L)	Same as the historical tsunami fault model
Width (W)	Same as the historical tsunami fault model
Slip (D)	Slip is determined according to *Mw* because area is fixed.
Depth of upper edge of the fault plane (d)	Same as the historical tsunami fault model
Strike (θ)	Same as the historical tsunami fault model
Dip angle (δ)	Same as the historical tsunami fault model
Slip angle (λ)	Same as a historical tsunami fault model
Shear modulus (μ)	3.5×10^{10} (N/m^2) when depth d is less than 20 km 7.0×10^{10} (N/m^2) when depth d is more than 20 km 5.0×10^{10} (N/m^2) when the fault model extends over both regions.
Scaling law	Area of the segment is fixed. Combination of segments and slip are changeable.

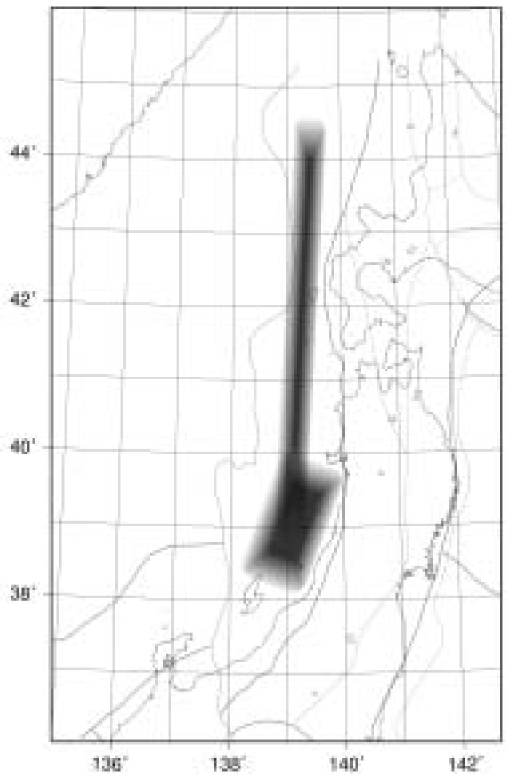
Determination flow of parameters of the standard fault model

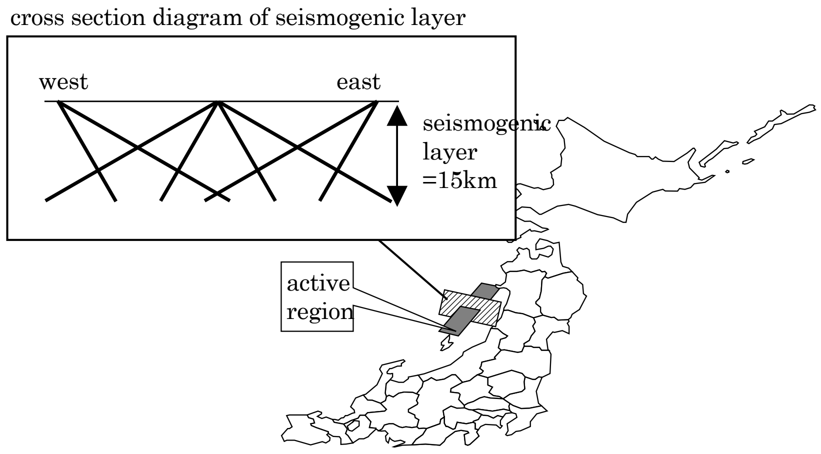


Appendix-3 Manner of Determination of Standard Fault Model - Eastern margin of the Japan Sea –

Sea area	Eastern margin of the Japan Sea	Characteristics of earthquakes and fault models	・ Takemura's formula(1998) can be applied to this sea area as the relationship between the length(L) and magnitude(Mw). ・ Earthquakes in this region are shallow ones and the thickness of the seismogenic layer has an upper limit. ・ Both west-dip and east-dip earthquakes have occurred. ・ Strikes agree with the depth contour line and faults are characterized as pure thrust faults.
		Basic concept of setting fault models	・ Takemura's scaling law is applied by taking the thickness of the seismogenic layer into account.

Location



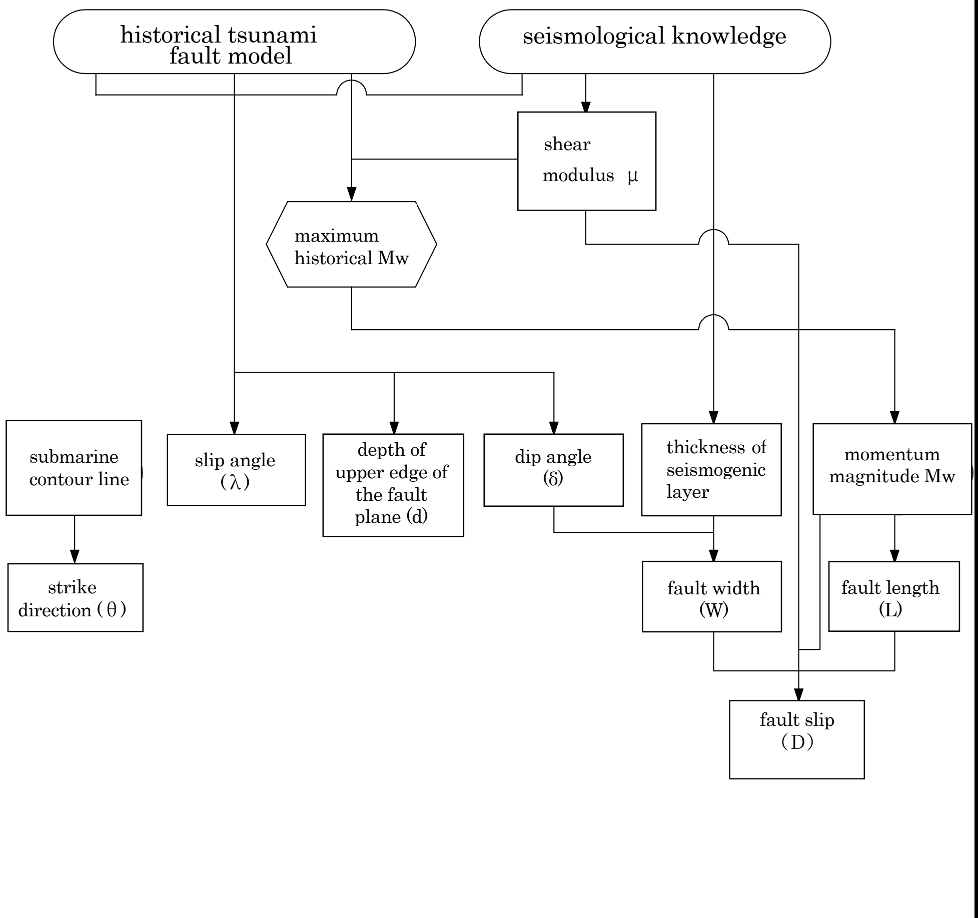


Maximum historical *Mw*	・ Darkened region in the above figure is the active area. ・ The maximum historical *Mw* is 7.8 (1993 Southwest Hokkaido earthquake).

How to create a fault model

Length (L)	See the description of 'scaling law' given below.
Width (W)	Width is set on the basis of the thickness of the seismogenic layer and the dip angle.
Dislocation (D)	$D = M_0 / \mu LW$ where $\log M_0$ (N・m) = $1.5Mw + 9.1$
Depth of upper edge of the fault plane (d)	0 km
Strike (θ)	Strike is determined by depth contour line.
Dip angle (δ)	Set from 30° to 60° West dip and east dip should be taken into account.
Slip angle (λ)	Fixed at 90°
Shear modulus (μ)	3.5×10^{10}(N/m^2)
Scaling law	1) $W <$ "thickness of the seismogenic layer" / $\sin\delta$ $W = 2L/3$ $L \propto W \propto D$ 2) $W >$ "thickness of the seismogenic layer" / $\sin\delta$ $W =$ "thickness of the seismogenic layer" / $\sin\delta$ $\log L$ (km) = $0.75Mw - 3.77$ (Takemura's formula) $L \propto D$

Determination flow of parameters of the standard fault model



Appendix-4 Manner of Determination of Standard Fault Model - Active Submarine Fault –

Sea area	Active submarine fault	Characteristics of earthquakes and fault models	・ We have not experienced large-scale tsunamis due to active submarine faults. ・ Thickness of seismogenic layer has an upper limit. ・ Crustal structure in the sea area is the same as that in the land area. ・ Dip angle is high.
		Basic concept of setting fault models	・ Takemura's scaling law is applied by taking the thickness of the seismogenic layer into account.
Location	・ Location should be set on the basis of the results of an active fault survey.		
Mw	・ *Mw* is calculated by using the scaling law and length *L*.		

How to create a fault model

Length (L)	Length is to be set on the basis of the results of an active faults survey.
Width (W)	Width is set on the basis of the thickness of seismogenic layer and dip angle.
Slip (D)	$D = M_0 / \mu LW$ where $\log M_0 (\mathrm{N \cdot m}) = 1.5Mw + 9.1$
Depth of upper edge of the fault plane (d)	0 km
Strike (θ)	On the basis of the result of active fault survey
Dip angle (δ)	On the basis of the earthquake focal mechanism solutions, or set from 45° to 90° .
Slip angle (λ)	Determined by strike direction, dip angle and direction of principle stress axis.
Shear modulus (μ)	3.5×10^{10}(N/m²)
Scaling law	1) $W <$ "thickness of the seismogenic layer" / sin δ $W = 2L / 3$ $L \propto W \propto D$ 2) $W >$ "thickness of the seismogenic layer" / sin δ W = "thickness of the seismogenic layer" / sin δ $\log L$ (km) = $0.75Mw - 3.77$ (Takemura's formula) $L \propto D$

Determination flow of parameters of the standard fault model