
Seismic design examples based on ISO 23469

Exemples de dimensionnement basés sur l'ISO 23469



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2. www.iso.org/directives

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT), see the following URL: [Foreword - Supplementary information](#)

The committee responsible for this document is ISO/TC 98, *Bases for design of structures*, sous-comité SC 3, *Loads, forces and other actions*.

Introduction

ISO 23469:2005 provides guidelines to be observed by experienced practicing engineers and code writers when specifying seismic actions in the design of geotechnical works. It might not be so easy for code writers and practitioners to utilize ISO 23469, because that it offers advanced philosophy and general framework of seismic design. The purpose of this Technical Report (TR) is to provide seismic design examples based on ISO 23469 for demonstrating how to utilize ISO 23469 in actual seismic designs to the code writers and the practitioners. The implementation of ISO 23469 will secure the rationality of seismic safety evaluation of the infrastructures in the world, and this TR aims at promoting the implementation.

ISO 23469 is essentially a guideline itself. Therefore, this TR should contain not explicit guidelines but design examples without using the term 'guideline'. Thus, this TR is expected to demonstrate the utilization of ISO 23469 by providing design examples with detailed explanation from the viewpoint of conformity with ISO 23469 for a kind of guidance rather than to provide the detailed recommendation of specific methodologies.

Through the development of this Technical Report, it is concluded that ISO 23469 has been and is going to be an essential and useful guideline of seismic design of geotechnical works for experienced practicing engineers and code writers.

Seismic design examples based on ISO 23469

1 Scope

This Technical Report provides seismic design examples for geotechnical works based on ISO 23469:2005 in order to demonstrate how to use this ISO standard. The design examples are intended to provide guidance to experienced practicing engineers and code writers. Geotechnical works include buried structures (e.g. buried tunnels, box culverts, pipelines, and underground storage facilities), foundations (e.g. shallow and deep foundations, and underground diaphragm walls), retaining walls (e.g. soil retaining and quay walls), pile-supported wharves and piers, earth structures (e.g. earth and rock fill dams and embankments), gravity dams, tanks, landfill and waste sites.

ISO 23469 addresses important issues for seismic actions for designing geotechnical works, including effects of site-specific response, ground displacement, soil-structure interaction and liquefaction, in a systematic manner within a consistent framework. This International Standard presents a full range of methods for the analysis of geotechnical works, ranging from simple to sophisticated, from which experienced practicing engineers can choose the most appropriate option for evaluating their performance. Therefore, this Technical Report includes well-chosen design examples that consider these important issues and covering in a balanced way the wide range of the methods of analysis and the types of model which can be used to evaluate seismic actions of geotechnical works.

2 Purpose and policy of collecting design examples

2.1 Purpose of collecting well-chosen examples

This Technical Report aims at collecting design examples that are basically conformable with ISO 23469. They are expected to be design examples dealing with important things need to be covered in ISO 23469 from the point of view of performance-based design approach. This TR should be well-balanced in included design examples;

- Focusing evaluation of reference earthquake ground motions with detailed description as a common issue.
- Having combination of simplified and detailed analyses.
- Based on simplified equivalent static analysis and detailed analysis for retaining walls, buried structures or earth structures.
- Focusing consideration of soil displacements for pile foundations and buried structures.
- Focusing evaluation of effects of liquefaction for retaining walls, earth structures, pile foundations.
- Focusing consideration of spatial variation in the ground motions for long bridges, buried structures, or dams.
- Based on site specific dynamic response by 1-D analysis.
- Based on detailed dynamic analysis by 2-D or 3-D analysis.

2.2 Concept and policy of choosing and composing

To realize the prescribed purpose of this TR, the basic concept of it is targeting to cover major distinguishing and important issues of IS23469 by all the design examples contained in this TR. Thus, the following points are another requirement for choosing and composing design examples.

- Design examples written with cares for readers in terms of conformity with requirement and recommendation in ISO 23469
- The TR should consist of several well-chosen design examples which cover the key issues of the ISO 23469 with well balance between them.
- The TR is anticipated to be well balanced among Japan, Northern America, and Europe.
- For description of manuscript, each design example is requested to
- Be cared in terms of conformity with requirement and recommendation in ISO 23469
- Have stress on methodology recommended by WG
- Be within 20 pages for a complete example and 8 pages for a sub-example basically

2.3 Development and result

After discussing the policy of collecting and choosing design examples, WG10 also had developed an expected table of contents from arguments through three Working Group meetings held in 2006 and correspondence with consideration of design practice situation in member's countries and regions. After registration of NP12825 in the end of this year, the WG10 repeatedly requested all the WG members and participants of the meetings to provide possible design examples for this Technical Report. The table of contents of the TR of design examples was almost fixed and the drafting persons for the examples were assigned in 2008 through more four WG meetings; eight examples for the first stage of specifying seismic action were expected to be prepared by three persons from Japan and one from Turkey and 28 examples for the second were hopefully to be prepared by 17 persons from Japan, three from USA, one from Greece, and one from Italy.

This NP was officially approved with the submission, in 2008, of the first Working Draft of TR12825 containing six examples, but the NWI was subsequently re-numbered as 12930 from an administrative reason. The third and final Working Draft of TR12930, which was developed through another three meetings in two years for waiting design examples to be offered from countries other than Japan was submitted to TC98/SC3 in the end of 2010 then accepted as a Draft Technical Report with a request of addition of description for a few points. The last two year period was mainly aimed at collecting examples from countries excepting Japan. Notwithstanding the total number of attendees in thirteen WG meetings is 87 and they came from Japan, USA, Greece, France, Poland, Canada, Turkey, Italy, South Africa, Germany, Morocco, Romania, and Russia (in order of total number of attendees), only prescribed persons were merely expected. Probably because that the preparing a manuscript is a tough job with few personal incentive; i.e. a completely volunteer work.

2.4 General conclusion of TR12930 obtained through its development

Eventually seven examples for the first stage and 15 examples for the second stage were successfully collected from thirteen persons consisting of eleven from Japan, one from USA, and one from Greece. The total number of the 22 well-chosen design examples can almost cover major distinguishing and important issues of IS23469 as targeting at the beginning. Through the process of preparing and editing the drafts, it was clarified that IS23469 is useful for evaluation, assessment and review in the seismic design. Furthermore, it was demonstrated that assessment for conformity with IS23469 in can be conducted in terms of provisional sentences according to Clause 3 of this TR. Thus, it is concluded that IS23469 has been and is going to be an essential and useful guideline of seismic design of geotechnical works for experienced practicing engineers and code writers.

2.5 Editors, authors and reviewers

This Technical Report has general remarks and 22 well-chosen design examples written in over 200 pages with 60 thousand words. Reviewing and editing all the manuscripts require tremendously hard works as well as the authors preparing them. Thus, the contributions of editors, authors and reviewers are shown here.

2.5.1 Editors

Prof. Shinichiro Mori, Ehime University, Japan, Convener of ISO/TC98/SC3/WG10

Prof. Kohji Ichii, Hiroshima University, Japan

The editors mainly reviewed and checked the conformity with ISO 23469 in all the manuscripts prepared by authors and added conformity codes corresponding sentences or paragraphs in their ends when necessary. The editors also revised hard-to-understand, confusing or complicated English expressions, written by some Japanese authors, by modifying the expressions and covering logical gaps.

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2.5.3 Reviewers

The reviewers were basically the members of TC98/SC3/WG10 including 16 members for development of IS23469 from 12 member bodies/countries and additional 24 members from 7 member bodies/countries. They also provided great contributions throughout the development as well. The members of TC98/SC3 were also potentially to be reviewers. The mirror committee of WG10 in Japan with 34 members had been also reviewing as well as preparing the activity prior to each step in this work item.

3 Assessment for conformity with ISO 23469

Assessment of a design with regard to conformity with ISO23489 is made based on the conformity with each provisional sentence in this ISO standard.

In the main text of each sub-sub-clause for a design example, a sentence or a paragraph corresponding to a specific requirement which is provided in a sentence using “shall” in ISO 23469, shall be ended with a corresponding “code” written in parentheses for being checked in terms of conformity with provisional sentences in ISO 23469. A specific recommendation is provided in a sentence using “should” as well. Therefore, this Technical Report adopts a code description in which a code of abbreviation consists of numerals and an alphabet. In the code, consecutive numerals stand for clause, sub-clause, and sub-sub-clause, respectively in principle. An alphabet in capital letter stands for “shall” and that in lower-case letter stands for “should” in appearing order. For examples, the third sentence using “shall” in the sub-sub-clause 6.2.1 in ISO 23469 corresponds to “(621C)” and the first sentence using “should” in sub-sub-clause 8.1.4 corresponds to “(814a).” Exceptionally, zero is placed in the place for sub-clause like “(520A).”

Provisional sentences using “shall” or “should” are extracted from the main body of ISO 23469 with partial reduction if acceptable and shown in appearing order as shown in Annex A.

4 First stage of specifying seismic actions - Determination of site-specific earthquake ground motions demonstrated by design examples

For designing geotechnical works, reference earthquake motions are needed to specify as seismic actions at the first stage. In order to evaluate the reference earthquake ground motions, the motions at the firm ground are evaluated by a seismic hazard analysis based on probabilistic or deterministic approach. As the reference earthquake motions, earthquake motions at the surface of the free field or/and at a certain depth within the subsoil can be evaluated by site response analyses.

The probabilistic approach is more appropriate for the evaluation of seismic actions at scale a nation or region. In general, the probabilistic approach in some case could lead to an underestimation of local seismic action comparing with the deterministic approach. (Grooso S. and Mourgeris M. 2009a and 2009b)

Probabilistic seismic hazard analysis as probabilistic approach shall be used to determine earthquake ground motion for evaluating serviceability. The earthquake ground motion for evaluating safety shall be determined by either probabilistic or deterministic analysis is used to determine. The seismic hazard analysis should capture the characteristics of the ground motion based on the earthquake magnitude, fault type and distance with or without site parameters. More detail seismic hazard analysis should capture the near source effects and directivity effects and should be based on seismic source parameters, including the geometry of seismic faults, propagating of the fault rapture over the seismic fault, attenuation of earthquake motions from the seismic fault, and deep basin effects. The uncertainties in the model parameters of the seismic fault, attenuation relations, and deep basin effects shall be considered appropriately (621A, 621B, 621C 622a, 622b, 622c).

The seismic hazard analysis method includes empirical, semi-empirical, and theoretical method, and a combination of these methods, and shall be chosen, consistent with the degree of refinement required for analysis of the geotechnical works, based on the importance of structures, and the available information on seismic faults and deep basin structures in the vicinity of a site. Results of seismic hazard analysis, ie NEHAP in USA etc. may be available over a country or region from relevant authorities giving the representative values of earthquake ground motion for use in the subsequent analysis. (622A)

Some examples to evaluate seismic hazard analyses in term of probabilistic and deterministic approach are described in Subclause 4.2. Furthermore, some examples for site response analysis are described in Subclause 4.3.

4.1 General

4.1.1 Methodology for empirical method in deterministic approach and examples

The simplest method among empirical methods is to combine an attenuation equation of an intensity of earthquake motions at firm ground with the amplification characteristics of a site of interest. As for the indices of the intensities of the earthquake motions for design, such as maximum acceleration, maximum velocity and amplitudes of response spectra, the attenuation equations of the indices are obtained by regression analyses using earthquake motion records in terms of the magnitude of earthquakes and the hypocentral distance. Using the attenuation equations, a designer can estimate the indices of earthquake ground motions during scenario earthquakes. Recent accumulation of observed earthquake motion records led to upgraded attenuation equations that can consider the regional peculiarity or the mechanism of earthquake source. This methodology has advantages: It is easy to evaluate the characteristics of earthquake ground motion. It has been used for a long time for probabilistic hazard analysis corresponding estimated values to mean values of observed motions. (622a)

An equation developed according to a theoretical formula of earthquake ground motion is adopted as an attenuation equation. A source spectrum, $S(T)$ consists of the terms representing both the effect of fault scale as the magnitude M and the influence of rock stiffness in the source region, where T is the object frequency.

$$S(T) = a(T)M + c(T) \quad (1)$$

The term representing the propagation of earthquake motion waves consists that of the non-elasticity attenuation and that of geometrical damping as the following equation. The hypocentral distance X represents the minimum distance from fault and the object site. Therefore, the accuracy of the focal location and area is required for more accurate estimate in focal region. (622a)

$$P(T) = -\log X - b(T)X \quad (2)$$

Adding the term associated with the relative amplification to the average ground, the final form of the attenuation equation becomes as follows.

$$\log F(T) = S(T) + P(T) + G(T) = a(T)M + c(T) - \log X - b(T)X + d(T) \quad (3)$$

For example, attenuation equations of acceleration response spectra have been developed using earthquake ground motion records of inland earthquakes observed from 1978 to 2003. Estimated acceleration response spectra as per the attenuation equations are shown in Figure 1. The equations can clearly express the difference of amplification characteristics depending on the types of ground.

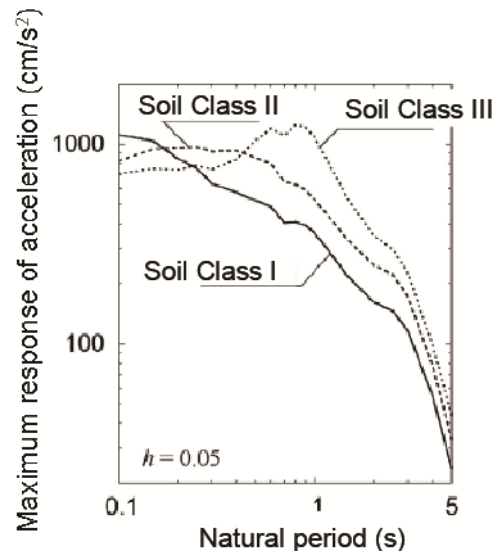


Figure 1 — Acceleration response spectrum obtained by attenuation equation

Further as variables of the fault parameters such as hypocenter depth and the earthquake type, etc. might be added to this equation. The term of the geometrical damping might be assumed $0.5\log X$ instead of $\log X$ by considering for propagating the surface wave. The form of the attenuation equation is assumed including coefficients such as a , b , c , and d . The coefficients are evaluated by the regression analysis based on the observed seismic records. The attenuation equation has the characteristics to be applicable to evaluate the motion on the specific ground which is the same ground with that observed seismic records by used of the regression analysis. If the ground is a engineering bedrock, the characteristic value at ground surface is obtained by magnifying the amplification coefficient to the value at the engineering bedrock. (622a)

4.1.2 Examples

First of all, detail of fault plane according to fault zone between Ohoita plane and Yufuin is modeled for two planes with east part and west part based on the evaluation of the Headquarters for Earthquake Research Promotion. The fault length in east part is set to be 27 km, and the length in west part is set to be 14 km as shown in Fig.2. Moreover, this fault zone has been evaluated as the normal fault whose plane inclines the north side. The dip angle around ground surface has been known as 70 degrees based on survey. The dip angle of the fault plane was assumed to be 60 degrees considering tendency to grow the dip angle of the normal fault in the surface ground. Based on the data by the Japan Meteorological Agency, the upper and lower bound depth among fault parameters in the east part were set to 2km, 15km respectively. Those in the west part were set to 3km, 15km respectively. Therefore, the fault width in the east part and the west becomes 15km and 13km respectively. Next, fault area S required for determining the magnitude becomes $5.9 \times 10^2 \text{ km}^2$ by use of the specified fault length and width in the east and west part as the mentioned above. Based on the experimental relationship between the magnitude and the investigated fault plane in the past earthquakes, the magnitude M was set as 6.8. Minimum distance from fault plane to the design object site is set as 2km under the assumption that the value is the same with the upper bound depth of the fault plane. (622a)

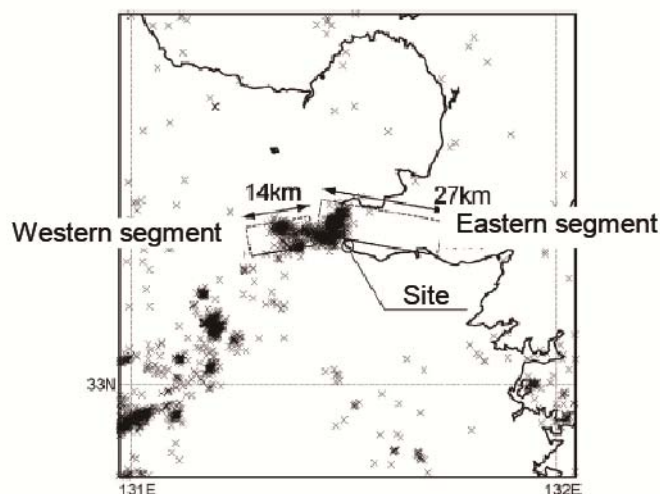


Figure 2 — Fault model at the object site

Acceleration response spectrum among the variable of earthquake ground motion is chosen to determine the seismic action on the geotechnical works. The design acceleration response spectrum at the site whose ground type is characterized as I kind is evaluated by use of the attenuation equation as mentioned above in 4.1.1. The spectrum is shown in Figure 3. As for the applicable lime of the empirical method, it has a difficulty to take into account of the investigated site-specific characteristics in terms of the fault parameters and the ground condition directly. Moreover, it can not apply to evaluate an extremely large-scale earthquake that the strong motion record has not been obtained. (623B)

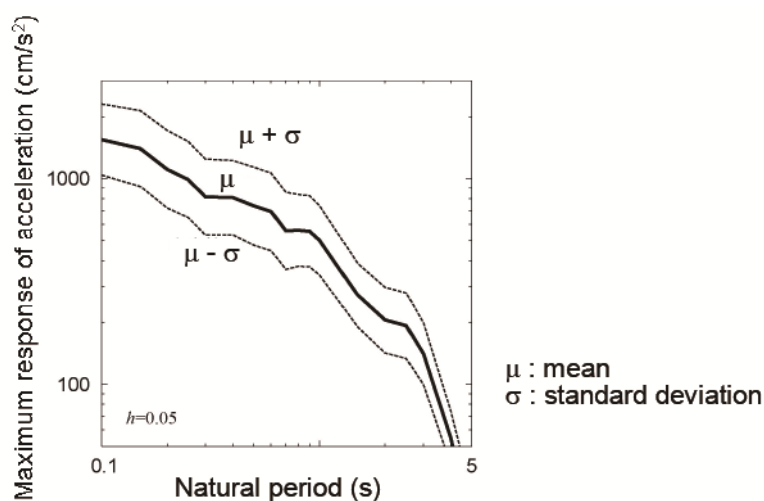


Figure 3 — Estimated acceleration response spectrum for M with 6.8, and X with 2km

4.2 Site-specific seismic hazard analysis evaluation

Site-specific seismic hazard analysis evaluation is conducted either by probabilistic approaches or deterministic ones. In general,

4.2.1 Probabilistic approach- Probabilistic seismic hazard analysis with focus on Fourier amplitude and group delay time

4.2.1.1 Outline

In general, strong ground motions are determined by three effects, namely, the source effect, the path effect and the site effect as shown in Figure 4. The source effect is defined as the effect of the rupture process of the earthquake. The path effect is defined as the effect of the materials along the propagation path from the source to the bedrock beneath the site. The site effect is defined as the effect of sediments below the site down to the bedrock. Here, the bedrock is defined as a layer with a shear wave velocity over 3000 m/s (In many cases it corresponds to fresh granite in Japan). (622a)

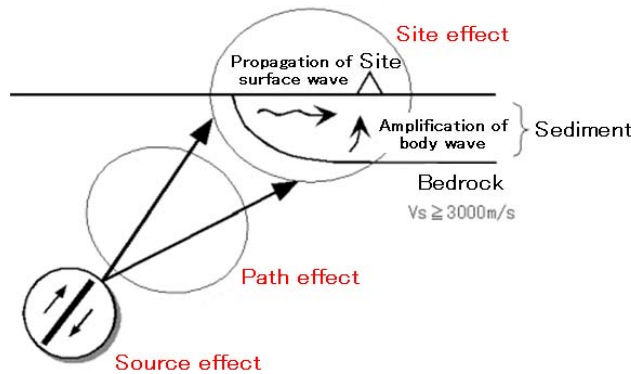


Figure 4 — Source, path and site effects

In general, the Fourier amplitude of a ground motion observed at the ground surface $O(f)$ is the product of the source effect $S(f)$, the path effect $P(f)$ and the site effect $G(f)$. (622a)

$$O(f) = S(f)P(f)G(f) \quad (4)$$

On the other hand, the group delay time of a ground motion observed at the ground surface $t_{gr}^O(f)$ is the sum of the source effect $t_{gr}^S(f)$, the path effect $t_{gr}^P(f)$ and the site effect $t_{gr}^G(f)$ (SAWADA *et al.*, 1998).

$$t_{gr}^O(f) = t_{gr}^S(f) + t_{gr}^P(f) + t_{gr}^G(f) \quad (5)$$

The group delay time is defined as the derivative of the Fourier phase with respect to angular frequency and it roughly corresponds to the arrival time of each frequency component (COHEN, 1995).

The probabilistic seismic hazard analysis (PSHA) described here (NAGAO *et al.*, 2005) is intended to deal with the source, path and site effects as strictly as possible by focusing on the Fourier amplitude and the group delay time of earthquake ground motions. The analysis uses the records of earthquake ground motions at the site of interest to account for the site effects as accurately as possible. It can generate ground motion time histories corresponding to a given annual probability of exceedance.

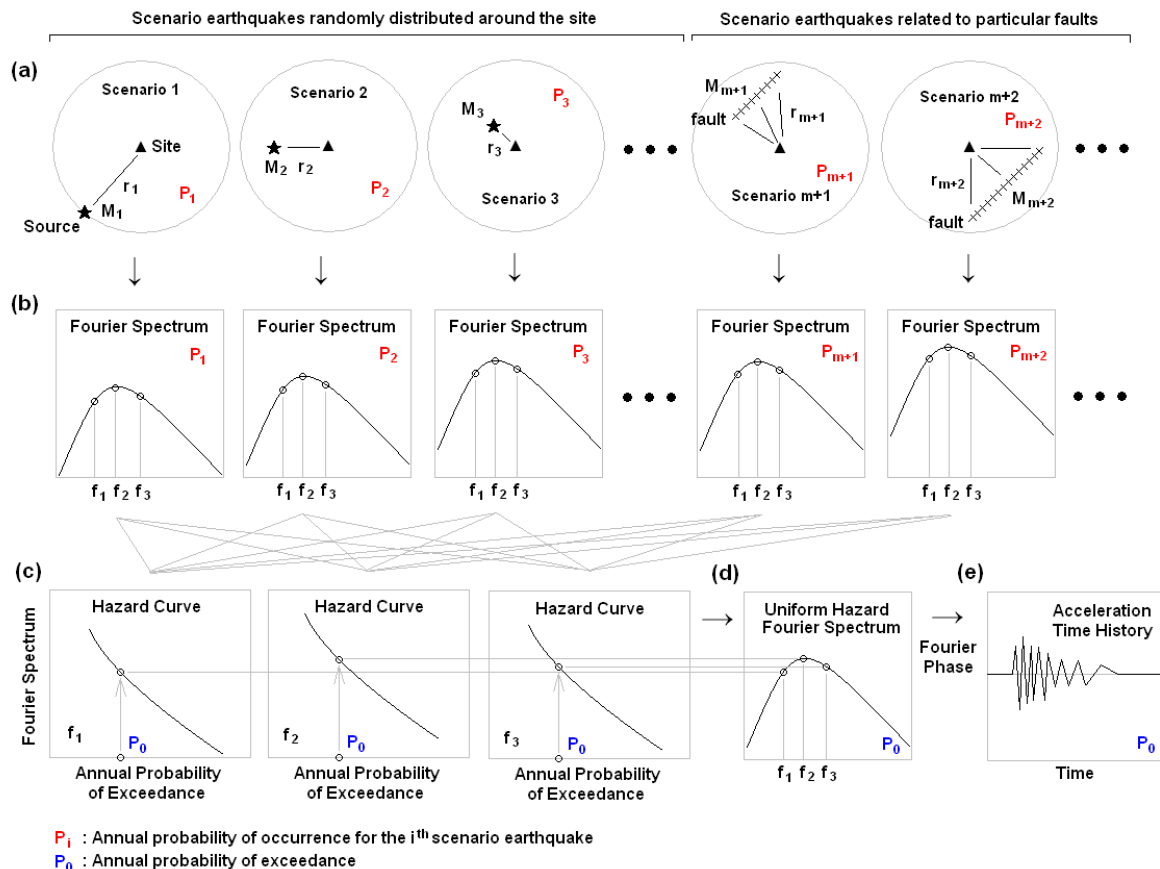


Figure 5 — Overview of the present PSHA

The overview of the present PSHA is shown in Figure 5. First, all the possible earthquake scenarios have to be considered. The scenario earthquakes fall into two categories. One is the scenario earthquakes randomly distributed around the site (background earthquakes) (Scenarios 1, 2, ..., m in Figure 5 (a)). The other is the scenario earthquakes that are related to particular faults such as active faults or plate boundaries (Scenarios $m+1$, $m+2$, ..., n in Figure 5 (a)). For each scenario, the annual probability of occurrence has to be assigned. Then, for each earthquake scenario, the Fourier amplitude spectrum at the site of interest is evaluated as shown in Figure 5 (b), taking into account the source effect, the path effect and the site effect as described later. Based on the Fourier amplitude spectra thus obtained and the relevant annual probability of occurrence, the “hazard curve” (relation between the Fourier amplitude and the annual probability of exceedance) can be obtained for each frequency (Figure 5 (c)) (the detailed procedure will be described later). If the Fourier amplitude corresponding to a given annual probability of exceedance is plotted as a function of frequency, it is called the “uniform hazard Fourier spectrum” (Figure 5 (d)). Finally, if the uniform hazard Fourier spectrum is transformed back into the time domain, it will give the ground motion time history corresponding to the annual probability of exceedance p_0 (Figure 5 (e)). For this transformation, the Fourier phase of a record at the site of interest can be used. (622c)

4.2.1.2 Evaluation of Site Amplification Factor

In this article, the amplification of Fourier amplitude spectrum caused by the sediment is called “the site amplification factor”. The evaluation of the site amplification factor is crucial in the present PSHA. It is recommended to evaluate the site amplification factor based on the seismograms obtained at the site of interest. The detailed procedure to evaluate the site amplification factor based on the seismograms is described in 4.2.2).

4.2.1.3 Earthquake scenarios and probability of occurrence

Two kinds of scenario earthquake are considered. One is the scenario earthquakes randomly distributed around the site (background earthquakes) and the other is the scenario earthquakes that are related to particular faults such as active faults or plate boundaries. For the former type of the earthquakes, a domain is assumed in which the seismicity is uniform. It is often assumed that sufficiently large earthquakes can be attributed to known faults and background earthquakes have smaller magnitudes. In the example described later, it is assumed that background earthquakes have JMA (Japan Meteorological Agency) magnitudes less than 7.

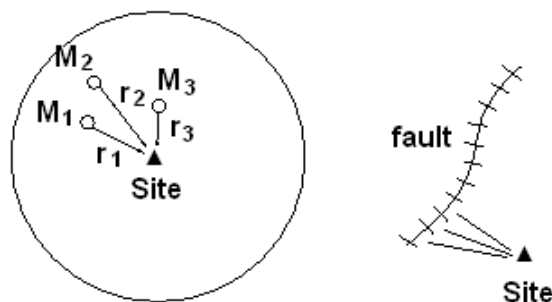


Figure 6 — Scenario earthquakes randomly distributed around the site (background earthquakes; left) and those related to particular faults (right)

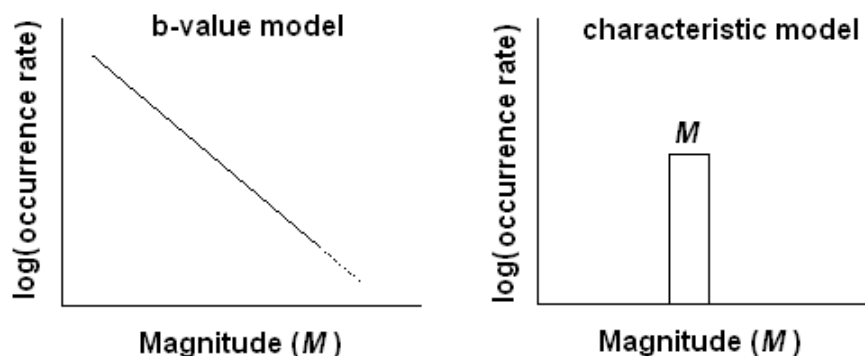


Figure 7 — Probability models for background earthquakes (left) and those for the earthquakes related to particular faults (right)

For both type of earthquakes, the annual probability of occurrence should be specified. For the background earthquakes, the earthquake catalogues are used to evaluate the annual probability of occurrence as a function of earthquake magnitude. First, the relation between the earthquake magnitude (M) and the occurrence rate of the earthquakes (N) above the magnitude is modelled as

$$\text{Log}(N) = a - bM \quad (6)$$

The model is called the “b-value model”. Taking the derivative of both sides of the equation (6), it can be shown that the logarithm of the occurrence rate of the earthquakes in the range ($M, M+dM$) is also linearly related to the earthquake magnitude. This relation is shown in Figure 7 (left). The parameters a and b should be determined based on the earthquake catalogue in the region. The annual probability of occurrence of the earthquakes can be determined to be consistent with the occurrence rate.

For the scenario earthquakes related to active faults, the earthquake magnitude and the annual probability of occurrence can be specified based on geological and geomorphological information. The earthquake

magnitude is typically evaluated based on the length of the fault. The annual probability of the earthquake is typically evaluated based on the length of the fault and the slip rate of the fault. For the scenario earthquake related to plate boundaries, the earthquake magnitude and the annual probability of occurrence can be evaluated based on the information on historical earthquakes.

In general, time-dependent annual probability can be incorporated in the analysis. In the example described later, time-independent annual probability is considered for simplicity, *i.e.*, the occurrence of earthquakes is assumed to be a Poisson process.

4.2.1.4 Evaluation of Fourier amplitude spectra

For each earthquake scenario, the Fourier amplitude spectrum (either at the outcrop of a firm ground or at the ground surface) at the site of interest should be evaluated, taking into account the source effect, the path effect and the site effect (Figure 5(b)). (623B)

For the background earthquakes, the Fourier amplitude spectrum can be obtained as the source spectrum multiplied by the path effect and the site amplification factor. As for the site amplification factor, refer to 1)-2).

The source spectrum can be assumed to follow the ω^{-2} model (Aki, 1967). According to the ω^{-2} model, the acceleration Fourier amplitude spectrum of a seismic wave radiated from a fault (source spectrum) can be expressed as follows.

$$S(f) = C \frac{M_0}{4\pi\rho V_s^3} \frac{(2\pi f)^2}{1 + (f/f_c)^2} \quad (7)$$

Where

M_0 : seismic moment,

f_c : corner frequency,

ρ : density in the bedrock,

V_s : shear wave velocity in the bedrock,

C : constant.

The seismic moment is defined as follows (Aki, 1966)

$$M_0 = \mu A D_0 \quad (8)$$

Where

μ : rigidity in the bedrock,

A : area of the fault,

D_0 : slip on the fault.

The constant C is the product of the radiation coefficient (in the example shown below, 0.63 is used as an averaged value), the amplification due to free surface (=2) and the coefficient representing the partition of seismic energy into two horizontal components (in the example shown below, 0.71 is used based on the assumption that the energy is equally partitioned into two horizontal components). Figure 8 shows the displacement, velocity and acceleration source spectra following the ω^{-2} model.

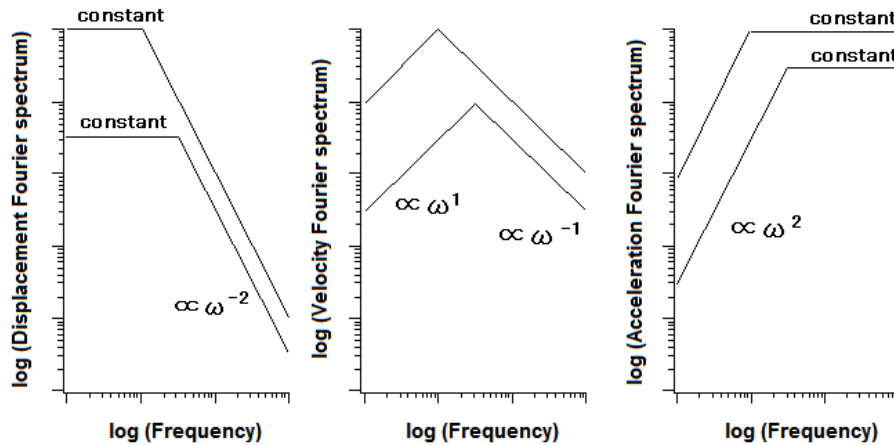


Figure 8 — Source spectra which follow the ω^{-2} model

As for the path effect, it is a common practice to take into account both the geometrical spreading and the inelastic damping as follows:

$$P(f) = \frac{1}{r} \exp(-\pi f r / QV_s) \quad (9)$$

Where

r : hypocentral distance,

Q : Q value along the propagation path.

For the earthquakes related to particular faults, it is preferable to consider fault finiteness to estimate the Fourier amplitude spectrum at the site. This can be achieved by introducing a fault model and applying the semi empirical approach. In the semi empirical approach, a Green's function (a ground motion from a small earthquake) should be prepared, taking into account the source, path and site effects, and then superposed according to the fault model. In this process, again, the site amplification factor evaluated in 1)-2) is utilized. Details of the semi empirical approach can be found in Subclause 4.2.2). As for the Fourier phase of the Green's function, the Fourier phase of a record from a small to medium-sized earthquake at the site of interest can be used, based on the assumption that the rupture process does not have significant effects on the Fourier phase for a small to medium-sized earthquake. Although the Fourier phase of the Green's function does not have any effect on the Fourier amplitude of the calculated ground motion, it will be used to determine the Fourier phase of the calculated ground motion, which will be useful for the generation of the ground motion time history corresponding to a given annual probability of exceedance at the final step.

4.2.1.5 Evaluation of uniform hazard Fourier spectrum

Now we have evaluated the Fourier amplitude spectra for n scenario earthquakes and the relevant annual probability of occurrence. Let us consider one particular frequency for a while. Let n' ($< n$) denote the number of scenarios for which the Fourier spectrum at the frequency exceeds a given value x . If we sum up the annual probability of occurrence for the n' scenarios, then it will give the annual probability that the site experiences a Fourier spectrum exceeding x at the frequency. This is called the "annual probability of exceedance" and denoted here as $p(x)$. If $p(x)$ is plotted against x , it is called the "hazard curve" (Figure 5(c)). Then, let us find x corresponding to a given annual probability of exceedance p_0 and denote it by x_0 . If we plot x_0 as a function of frequency, it is called the "uniform hazard Fourier spectrum" (Figure 5(d)). (623B)

4.2.1.6 Evaluation of ground motion time history

If the uniform hazard Fourier spectrum is transformed back into the time domain, it will give the ground motion time history corresponding to the given annual probability of exceedance p_0 (Figure 5(e)). This transformation can be achieved simply by applying an appropriate Fourier phase. To determine the Fourier phase, it is recommended to carry out the disaggregation of hazard (Bazzurro and Cornell, 1999), that is, to determine the most dominant earthquake scenario at a given level of Fourier amplitude. This process is illustrated in Figure 9. In general, the total annual probability of exceedance corresponding to a given level of Fourier amplitude is the sum of the contributions from several scenarios as shown in Figure 9. In the disaggregation, the scenario with the largest contribution is selected. The selected scenario may be dependent on the frequency. So far, it is recommended to consider the frequency range which is most important for the design of geotechnical works. For the inverse Fourier transform, the Fourier phase of the ground motion from the most dominant scenario can be used. If a scenario earthquake from a fault is most dominant, the Fourier phase of the ground motion from the fault predicted by the semi-empirical method can be used. If background earthquakes are most dominant, the Fourier phase of a record from a small to medium-sized earthquake at the site of interest can be used for the inverse Fourier transformation, based on the assumption that the rupture process does not have significant effects on the Fourier phase because of the relatively small size of the earthquake. (623B)

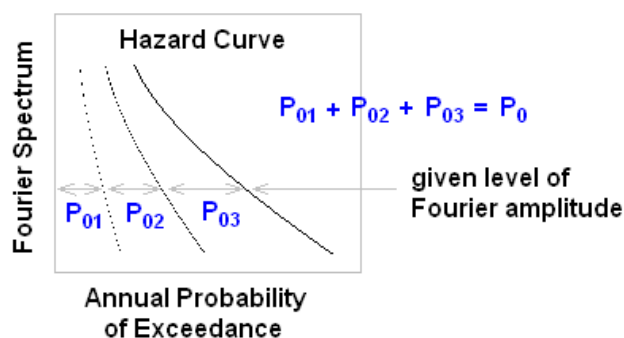


Figure 9 — Source spectra which follow the ω^{-2} model

4.2.1.7 Example of application

In this section, an example of the application of the present PSHA (NAGAO et al., 2005) is described. The analysis is applied to Kanto region, Japan. The targeted area is shown in Figure 10. Mesh A includes the Port of Tokyo. Mesh B includes Miura Peninsula. In this example, the site amplification factor for each mesh was evaluated as an average for several strong motion stations included in the mesh for demonstrating purpose. In practice, the site amplification factors should be evaluated based on the seismograms obtained at the site of interest. The evaluated site amplification factors are shown in Figure 11. These site amplification factors were evaluated at the outcrop of a firm ground. The site amplification factor for Mesh A is characterized by a relatively large amplification at lower frequencies. This is due to the thick sediments in the Kanto basin. The site amplification factor for Mesh B is relatively small for lower frequencies because Mesh B mainly covers the Miura Peninsula, which is outside the Kanto basin.

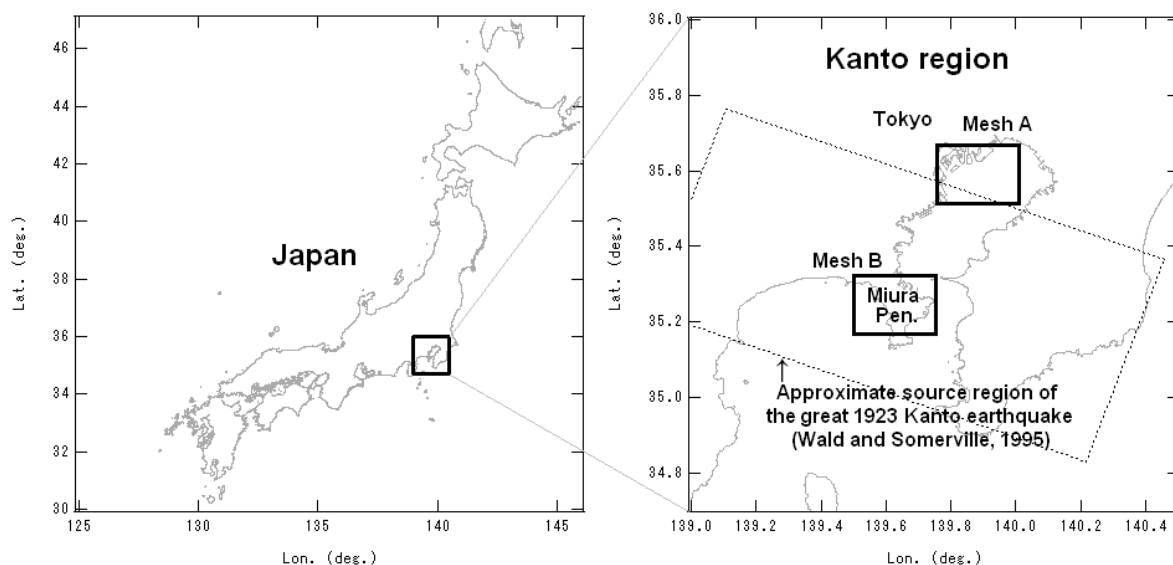


Figure 10 — Targeted area

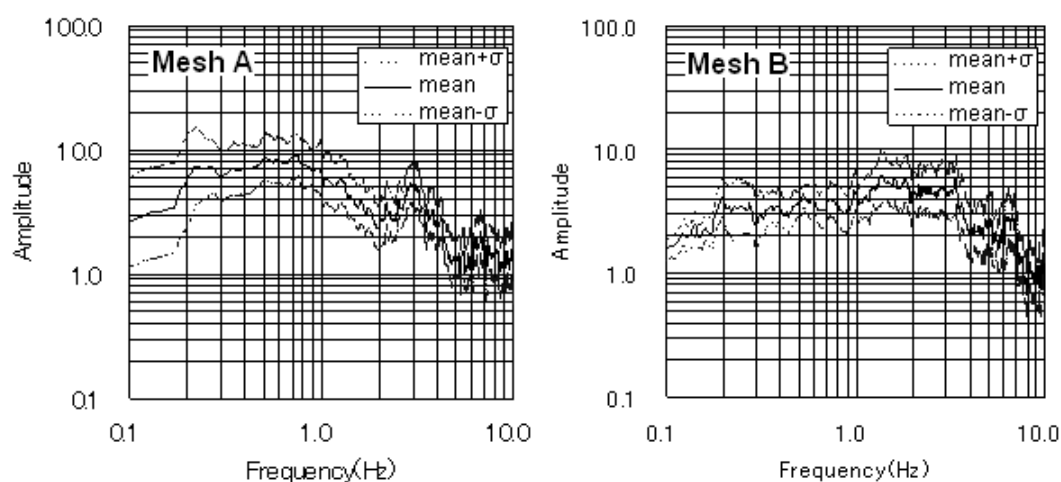


Figure 11 — Site amplification factors evaluated for Mesh A (left) and Mesh B (right)

As for the background earthquakes, two domains were considered. One domain is within 100km from the mesh (more strictly, from the center of the mesh) and 3-20 km deep. The other domain is within 100km from the mesh and 20-60 km deep. The seismicity was assumed to be uniform within the domains. The parameters for the b-value model were determined based on relevant earthquake catalogues. For these earthquakes, the seismic moments and the corner frequencies were estimated based on empirical relations (NAGAO *et al.*, 2005). The Fourier amplitude spectra at the sites for these earthquakes were calculated as a product of the source, path and site effects.

As for the earthquakes related to known faults, two kinds of earthquake were considered. One is the recurrence of the 1923 Kanto earthquake, which is a huge subduction earthquake and the other is the earthquake from active faults. For these earthquakes, fault models were introduced and the ground motions at the sites were calculated using the semi empirical method.

Approximate source region of the 1923 Kanto earthquake (Wald and Somerville, 1995) is shown in Figure 10. Source parameters shown in Table 1 (NAGAO *et al.*, 2005) were used to account for the recurrence of this earthquake. Based on the results of the waveform inversion, (Wald and Somerville, 1995), two asperities (relatively small regions on the fault where the slip and the slip velocity are especially large) were considered.

The locations of the asperities were determined based on the inversion results. The rupture starting point was randomly distributed along the bottom of the asperities.

Table 1 — Source parameters for the recurrence of the 1923 Kanto earthquake

Total area	9100km ²
Strike	290°
Dip	25°
Total moment	1.07×10^{21} Nm
Average slip	3.56m
Average stress drop	3.0MPa
Area of asperity	2002 km ² (22%)
Average slip on asperity	7.12m
Return period	162 years
Annual probability of occurrence	6.17×10^{-3}



Figure 12 — Active faults considered for the example hazard calculation

As for the earthquakes from active faults, 21 active faults within 100 km from the site were considered as shown in Figure 12. The earthquake magnitudes were evaluated based on the length of the fault. The annual probability of each earthquake was evaluated based on the length of the fault and the slip rate of the fault. The annual probability ranged from 4.34×10^{-6} to 3.15×10^{-3} .

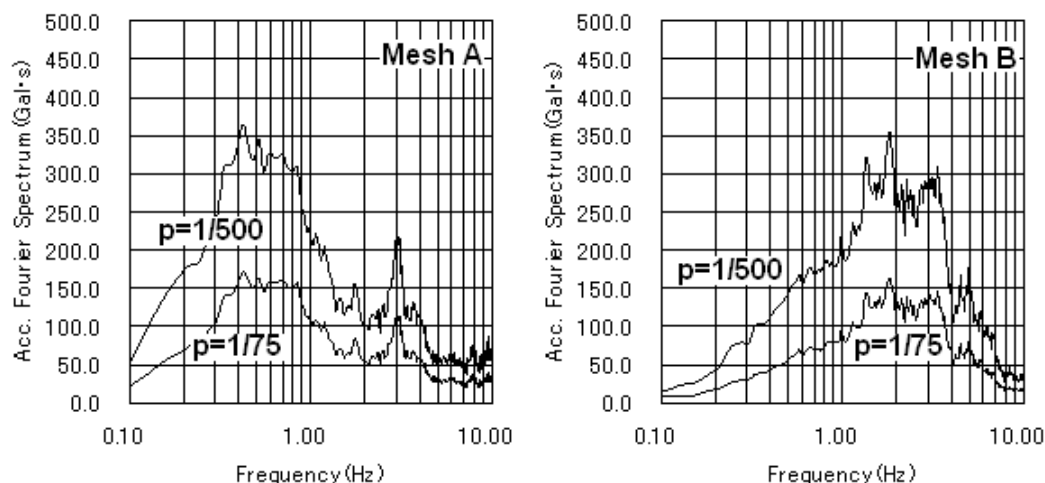


Figure 13 — Uniform hazard spectra for Mesh A (left) and Mesh B (right)

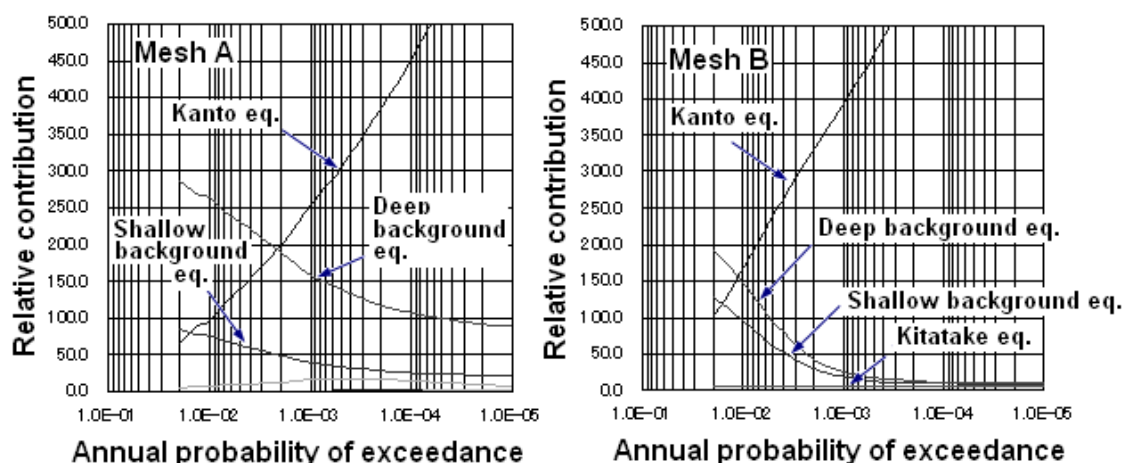


Figure 14 — Relative contributions from the scenarios for Mesh A (left) and Mesh B (right)

Uniform hazard spectra evaluated for Mesh A and Mesh B for the annual probability of exceedance of 1/75 and 1/500 are shown in Figure 13. These spectra were evaluated at the outcrop of a firm ground. For Mesh A, frequency components around 0.3-0.9 Hz are predominant. For Mesh B, frequency components around 1.0-4.0 Hz are predominant. These characteristics are consistent with the gross characteristics of the subsurface structure.

Relative contributions from the scenarios for Mesh A (left) and Mesh B (right) as functions of the annual probability of exceedance are shown in Figure 14. At the annual probability of 1/75, the contribution from the deep background earthquakes is dominant at both Mesh A and Mesh B. At the annual probability of 1/500, the contribution from the recurrence of the Kanto earthquake is dominant at both Mesh A and Mesh B. These results were used to determine the Fourier phase to obtain ground motion time histories.

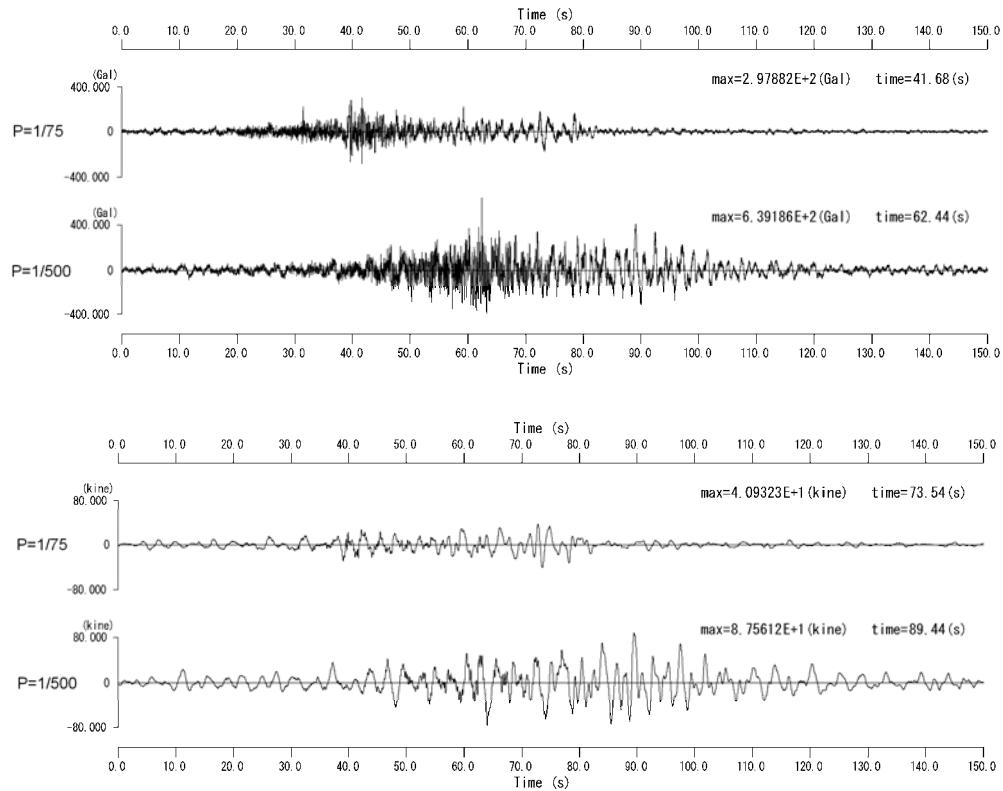


Figure 15 — Acceleration (top) and velocity (bottom) time history for Mesh A

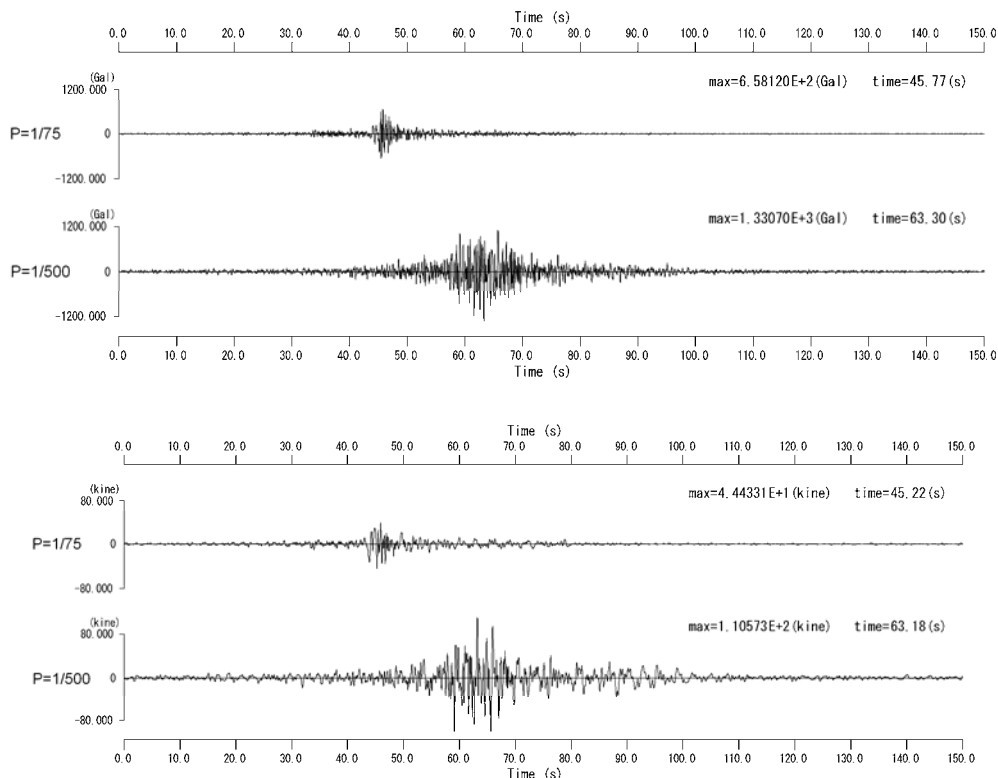


Figure 16 — Acceleration (top) and velocity (bottom) time history for Mesh B

Acceleration and velocity time histories corresponding to the annual probability of exceedance of 1/75 and 1/500 for Mesh A and Mesh B are shown in Figure 15 and Figure 16, respectively. These time histories were evaluated at the outcrop of a firm ground. The time histories for Mesh A are characterized by the predominance later phases, which can be attributed to the sediments in the Kanto basin. The ground motions for the annual probability of 1/500 have longer duration than those for the annual probability of 1/75 because, at the annual probability of 1/500, the contribution from the Kanto earthquake becomes predominant and the phase characteristics is affected by the rupture process of the Kanto earthquake. Thus, the phase characteristics of an earthquake ground motion are affected both by the source effect and the site effect. The present probabilistic seismic hazard analysis can incorporate both of these effects.

4.2.2 Site-specific approach on earthquake motions probabilistically evaluated in a LNG tank design considering a specific active fault

4.2.2.1 General procedure and design example

Guideline for Performance-Based Structural Evaluation for LNG Underground Tank was issued by Committee on Civil Engineering in Energy and Power Industries in Japan Society of Civil Engineers in 1999. The outline to evaluate the reference earthquake motion shown in the Guideline for using not only a probabilistic approach but also the combined method of the deterministic approach with probabilistic approach is described. By considering the required seismic performance for LNG underground tank, two or more levels of the earthquake ground motion are determined. First, the earthquake ground motion which occurs either once or twice during the service period is defined as Level 1 Earthquake Ground Motion. (513A)

The strongest earthquake ground motion among the realistic motion whose occurrence possibility at the object site during the service period is small is defined as Level 2 Earthquake Ground Motion. Moreover, the earthquake ground motion is specified for a few levels if necessary. As an example, the level of the motion is defined as Level 2L in case that a probability of occurrence during the service period is relatively low. The level of the motion is defined as Level 2H in case that probability of occurrence during the service period is extremely low. The design earthquake ground motion is defined at the engineering bedrock. The variable of the motion is specified as the acceleration response spectrum. The time history is evaluated by simulated earthquake motion consistent with the response spectrum. Here, Level 1 Earthquake Ground Motion is defined based on probability of occurrence in the service period. Moreover, Level 2 Earthquake Ground Motion is defined as the evaluated result at the object site to specify the scenario earthquake with the possibility generating strong earthquake ground motion by considering the occurrence probability in the service period. As the method to evaluate Level 1 and Level 2 Earthquake Ground Motions, probabilistic approach and deterministic approach are adopted.

Procedure to evaluate design earthquake ground motion described in the guideline is shown in Figure 17. In this procedure, both probabilistic approach and deterministic approach are required. Furthermore, the observed seismic record around the object site is requested to be used effectively.

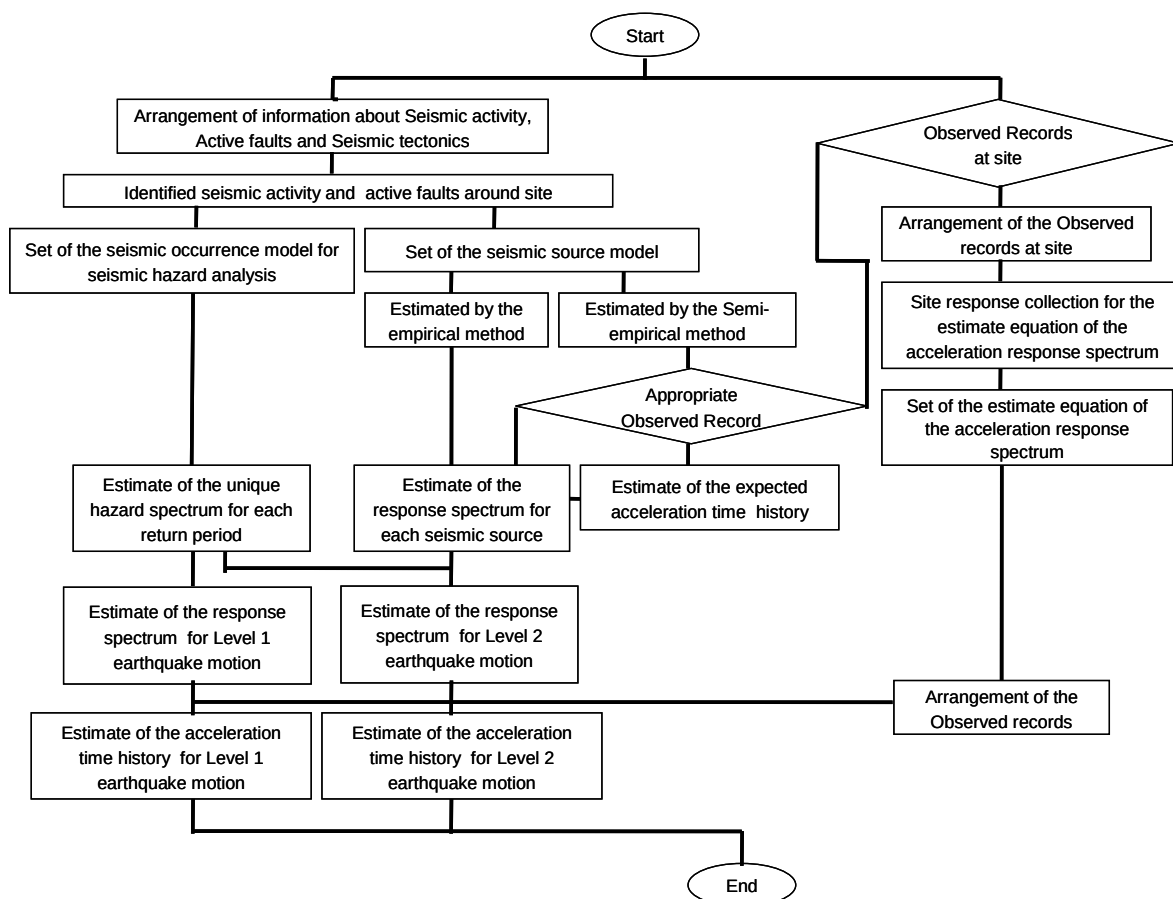


Figure 17 — Procedure of evaluating design earthquake ground motion as per LNG Design Code

In order to evaluate Level 1 earthquake motion by probabilistic approach, the occurrence probability for the service period has to be specified. As an example, 80% probability of occurrence in a 50-year period (corresponding to 31-year return period), or 50% probability of occurrence in a 50-year period (corresponding to 71-year return period) is used. The uniform hazard spectrum of 80% probability of occurrence in a 50-year period is shown in Figure 18 as an example of Level 1 Earthquake Ground Motion (F site at Tokyo Bay). The maximal acceleration is about 150 m/s^2 .

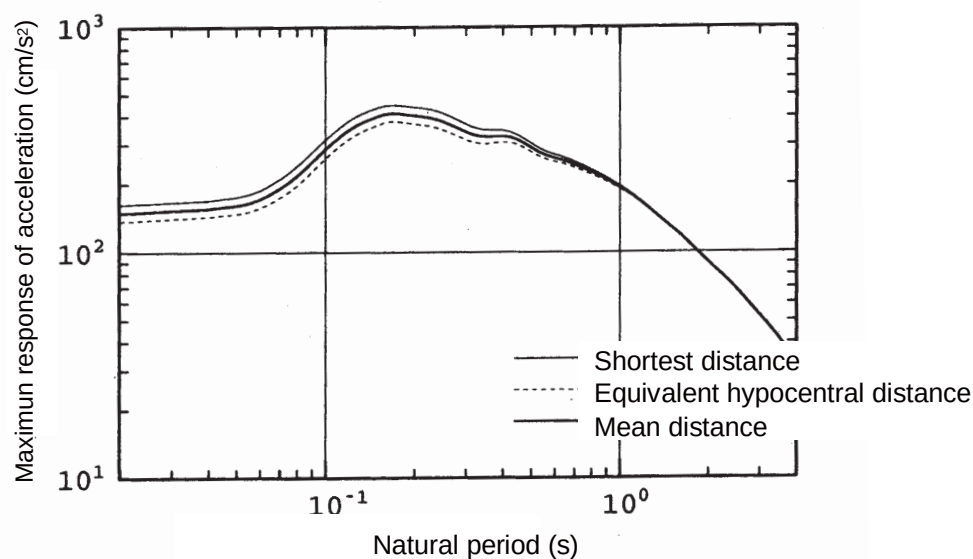


Figure 18 — Uniform hazard acceleration response spectrum for the occurrence probability 80% in 50 years

The scenario earthquake has to be modelled to evaluate Level 2 Earthquake Ground Motion as the deterministic approach. When the South Kanto Earthquake (the magnitude by Japan Meteorological Agency magnitude is 7.9) is taken into account as the scenario earthquake, the projection of the fault plane onto the ground surface is shown in Figure 19.

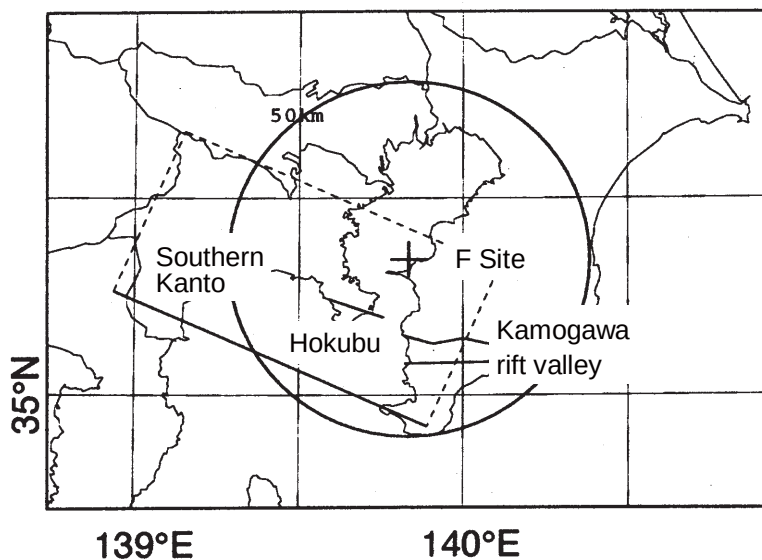


Figure 19 — Projection of the fault plane to the ground surface of the scenario earthquake

The acceleration response spectrum evaluated by not only attenuation equation method but also stochastic Green's function method are shown in Figure 20.

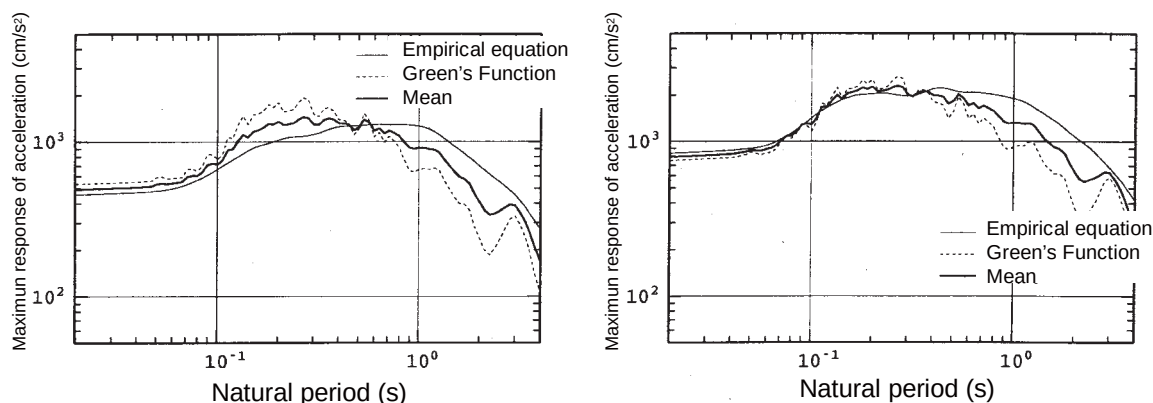


Figure 20 — Acceleration response spectrum evaluated by not only the attenuation equation but also stochastic green function method

Considering the probabilistic approach described later, the response spectrum for Level 2L, and Level 2H Earthquake Ground Motion are shown in Figure 21. Level 2L Earthquake Ground Motion is evaluated based on average Spectrum for scenario earthquake. Level 2H Earthquake Ground Motion is evaluated based on average plus standard deviation ($\mu + \sigma$) for scenario earthquake. As for the referred uniform hazard spectrum for Level 2L, and 2H Earthquake Ground Motions, probabilities of occurrence in a 50-year period are from 30% to 15% and from 15% to 5% respectively. The maximal acceleration of Level 2L Earthquake Ground Motion is evaluated as about 4.5 m/s^2 and the maximal acceleration of Level 2H Earthquake Ground Motion is evaluated as about 7.2 m/s^2 .

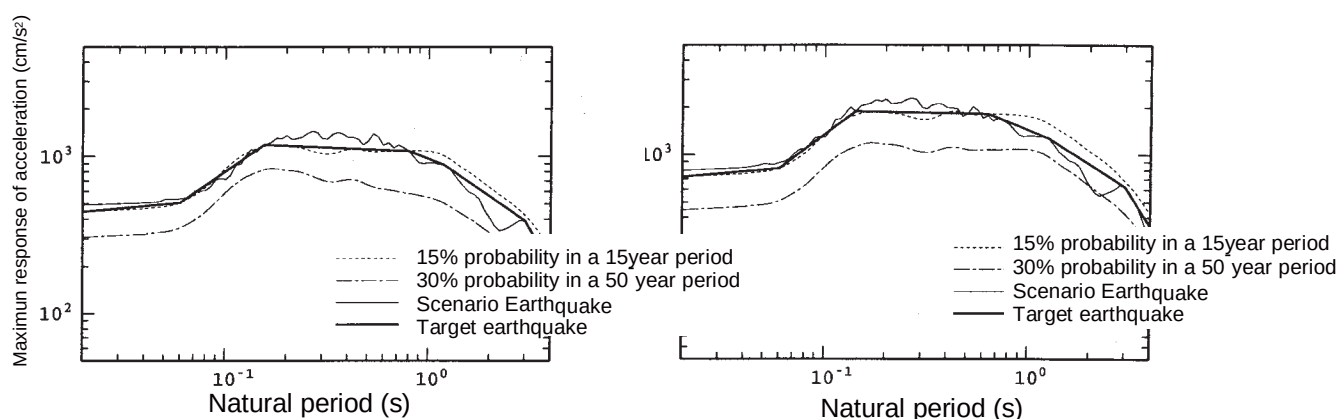


Figure 21 — Response spectrum for Level 2L, and Level 2H earthquake motion

4.2.3 Deterministic approach - Theoretical ground motion estimation based on hypothetical scenario earthquakes

4.2.3.1 Methodology for theoretical ground motion estimation

It is better to use observed ground motion information for estimating strong ground motion. However, it is rare case that we have some records with enough information at the target site. Especially for the shake map project, it is difficult to have plane information from observation records. To solve this problem, we need to assume sedimentary structure model of target area and theoretically simulate ground motions from the source fault to the target sites.

Two-stage calculation technique is popular for the theoretical simulation. First, ground motion is simulated on the engineering bedrock on which we do not need to care about non-linear site response. And next, surface ground motion is evaluated considering non-linear site response.

Evaluating ground motion at the engineering bedrock, it is ideal if we can make minute model of seismogenic zone and sedimentary structure and calculate seismic wave propagation caused by fault rupture process. However, popular methods we use for simulating wave propagation; i.e. 3-D finite difference method (GRAVES, 1996; PITARKA, 1999), require a grid model as shown in Figure 22. The methods have limitation because of finiteness of model possible and capacity of computer. At present, limitation of model is about several dozen meters. It defines limitation of shortest period to calculate around 0.5 to 2 second, depending minimum shear wave velocity of the model. Accordingly, we have to employ stochastic Green's function method introduced in section 1) for short period ground motion estimation. Stochastic Green's function methods with theoretical site response are proposed (ONISHI and HORIKE, 2000; KAGAWA, 2004) that calculate site amplification from sedimentary structure model assumed at sites. The methods are frequently used for shake map project and ground motion simulation without observed records. Main disadvantage of Stochastic Green's function method with theoretical site response is accuracy in long period range. First, the method does not treat surface wave generation and propagation because it does not consider irregular boundaries of sedimentary layers. And it does not take account of near and intermediate terms of ground motion.

To overcome the disadvantage, a hybrid method is popularly employed. The hybrid method uses a 3-D FE method for a longer period range and a stochastic Green's function method for a shorter period range. The hybrid addition is a sum of both two results weighted with the amplitude of a high-pass or a low-pass filter for each frequency. The amplitudes of the two filters are complementary for each other in order to keep the sum of the two values a unity. The filters are called 'a pair of matching filters'. It is preferable to set the central frequency of the transition zone of the matching filter, which is considered to be a boundary between deterministically and stochastically characterized ranges of frequency in terms of seismic ground motion. However, the boundary frequency is currently popular to be set approximately 1 Hz, slightly lower than the transition zone.

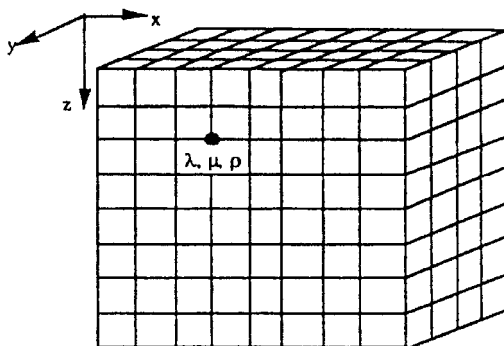


Figure 22 — Image of 3-D finite difference method

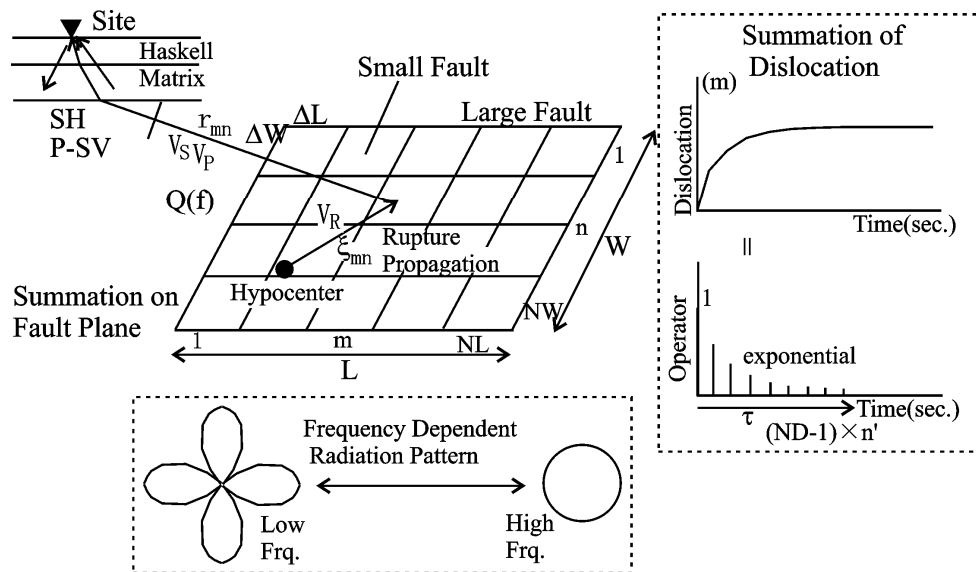


Figure 23 — Explanatory diagram of stochastic Green's function method with theoretical site response

4.2.3.2 Recipe for strong ground motion estimation

It is difficult to predict complicated fault rupture process of hypothetical earthquake. However, we are on the road to understanding the general characteristics of fault rupture process from statistical analyses of past earthquakes. Modelling asperities is a problem in progress. An asperity is the area where tectonic stresses accumulate and then they are released by strong seismic wave radiation through a fault slip dislocation in an earthquake event. It takes important role on generating strong ground motions. Using the information from the analyses, a recipe for strong ground motion estimation is proposed (IRIKURA and MIYAKE, 2001; IRIKURA et al., 2004). The recipe provides average feature of fault rupture and its parameters with their variation. Characteristic Source Model, the model of an entire fault plane and asperities in the plane as rectangular-shape areas, is employed in the recipe. On the other hand, Stochastic Source Model is popular in the world. The model has slip distributions as complicated as analysed source slip of real earthquakes. In Japan, Characteristic Source Model is popular because the model is more convenient for assuming a rupture scenario of a future earthquake than a complicated source model. Especially it works well in associating asperities with large deformation areas along the target active fault and setting worst scenario to the site considering forward directivity or focusing effect. (621C, 622a, 622b, 622A)

It is confirmed that the dominant feature of observed ground motions are simulated by Characteristic Source Model as well as the original complex slip model due to the real earthquake. The recipe for a general crustal earthquake (IRIKURA et al., 2004) is explained as follows:

Step 1: Fault Rupture Area ($S = LW$)

Fault length, L is assumed as the first variable of a target earthquake. Fault width, W is secondly assumed considering the maximum width defined by thickness of seismogenic zone and a dip angle. Eventually, fault rupture area, S is calculated by the production of L and W .

Step 2: Seismic Moment (M_0)

Seismic moment, M_0 is determined from fault rupture area, S using the following three-stage scaling laws.

$$S \text{ (km}^2\text{)} = 2.23 \times 10^{-15} \times M_0^{2/3} \text{ for } M_0 < 7.5 \times 10^{25} \text{ dyne*cm: Self Similar} \quad (10)$$

$$S \text{ (km}^2\text{)} = 4.59 \times 10^{-11} \times M_0^{1/2} \text{ for } M_0 \geq 7.5 \times 10^{25} \text{ dyne*cm: Width } W \text{ saturates.} \quad (11)$$

$$S \text{ (km}^2\text{)} = 5.30 \times 10^{-25} \times M_0 \text{ for } M_0 \geq 7.5 \times 10^{27} \text{ dyne*cm: Slip } D \text{ Saturates.} \quad (12)$$

Step 3: Average Stress Drop ($\Delta\sigma_c$)

The value is evaluated from the crack theory (Eshelby, 1957).

$$\Delta\sigma_c = \frac{7\pi^{1.5}}{16} \frac{M_0}{S^{1.5}} \quad (13)$$

Step 4: Combined Area of Asperities (S_a)

An empirical relationship between seismic moment, M_0 and combined area of asperities, S_a (Somerville et al., 1999; IRIKURA and MIYAKE, 2001) are used. Average ratio of S_a to M_0 is approximately 0.22.

$$S_a = 0.22M_0 \quad (14)$$

Step 5: Stress Drop in Asperity ($\Delta\sigma_a$)

The value is evaluated by multiplying average stress drop, $\Delta\sigma_c$ and inverse number of area ratio derived in Step 4. The treatment is based on the asperity theory. The process introducing short-period level (Dan et al., 2001) is also used for evaluating stress drop in asperity. In the case, area ratio changes from the value 0.22 to satisfy the relationship mentioned in Step 4.

Step 6: Number of asperities (N) and their location

Number of asperities depends on the number of fault segmentation. The location of the asperities is set where accumulated surface deformation is large. The location of asperities due to late events might be an example, if the recurrence period of the target earthquake is short enough. We expect back-slip monitoring by GPS network for this purpose.

Step 7: Average Slip Ratio in Asperity (D_a)

Average slip ratio in asperity against average slip over the fault is evaluated considering the number of asperities assumed in Step 6. According to dynamic fault rupture simulations, the ratio tends to decrease with the number of asperities. Average value 2.0 is generally used. The value corresponds to the case of two asperities from statistical analysis.

Step 8: Effective Stresses in Asperity ($\Delta\sigma_a$) and Background ($\Delta\sigma_b$)

Effective stresses in asperity approaches to stress drop in asperity, Step 5. Effective stress in background slip is assumed about one fifth of the effective stresses in asperity from dynamic fault rupture simulations.

Step 9: Slip Velocity Function

Kostrov-type slip velocity function is generally employed. Maximum slip velocity is assumed from effective stresses. Slip duration is estimated from asperity size and rupture velocity. The results from dynamic fault rupture simulations are also used for the confirmation.

(Other Parameters) Rupture Starting Point

Rupture starting and terminating points are assumed from branching feature of target fault system (NAKATA et al., 1998).

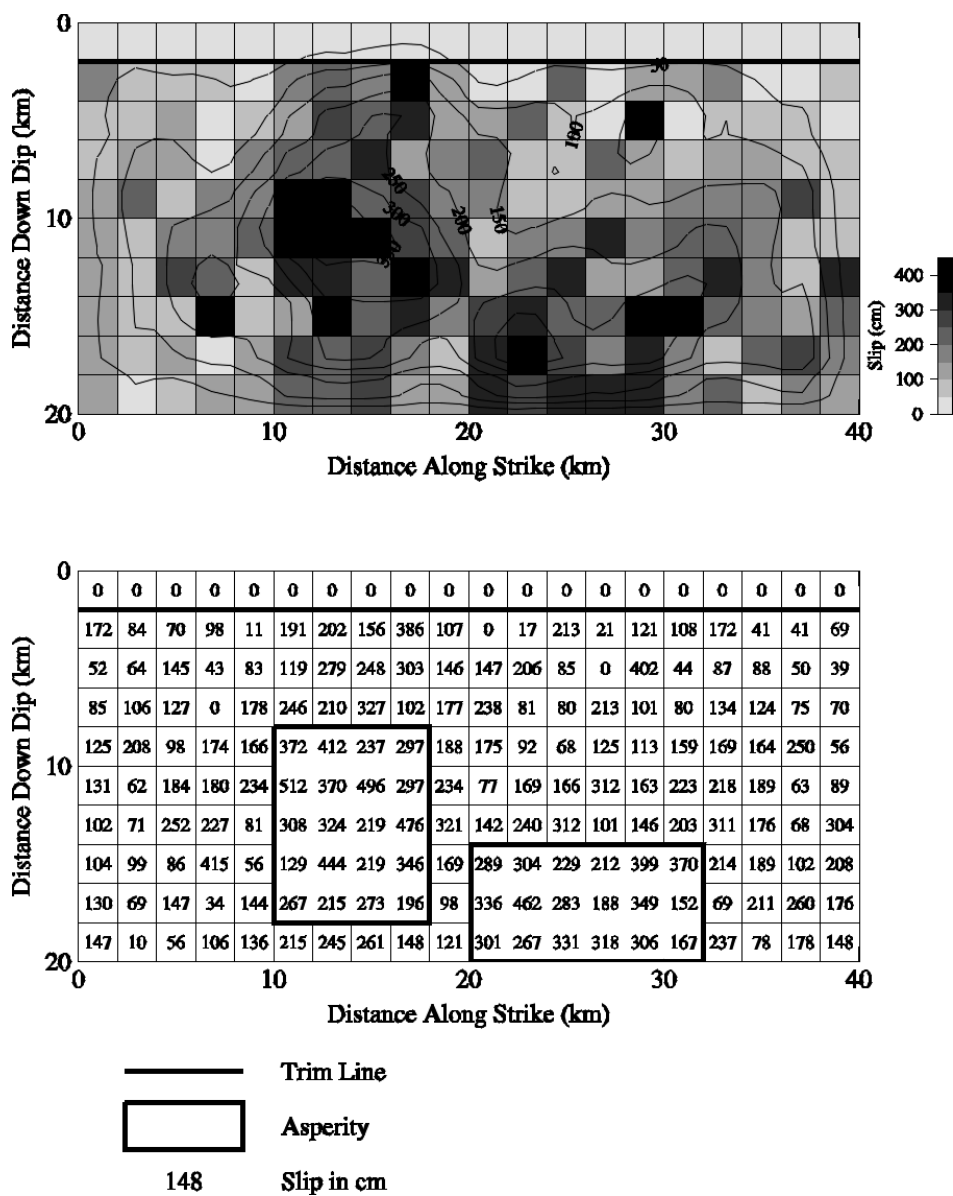


Figure 24 — Extracting a characteristic source model from a complex slip distribution derived from a source inversion analysis

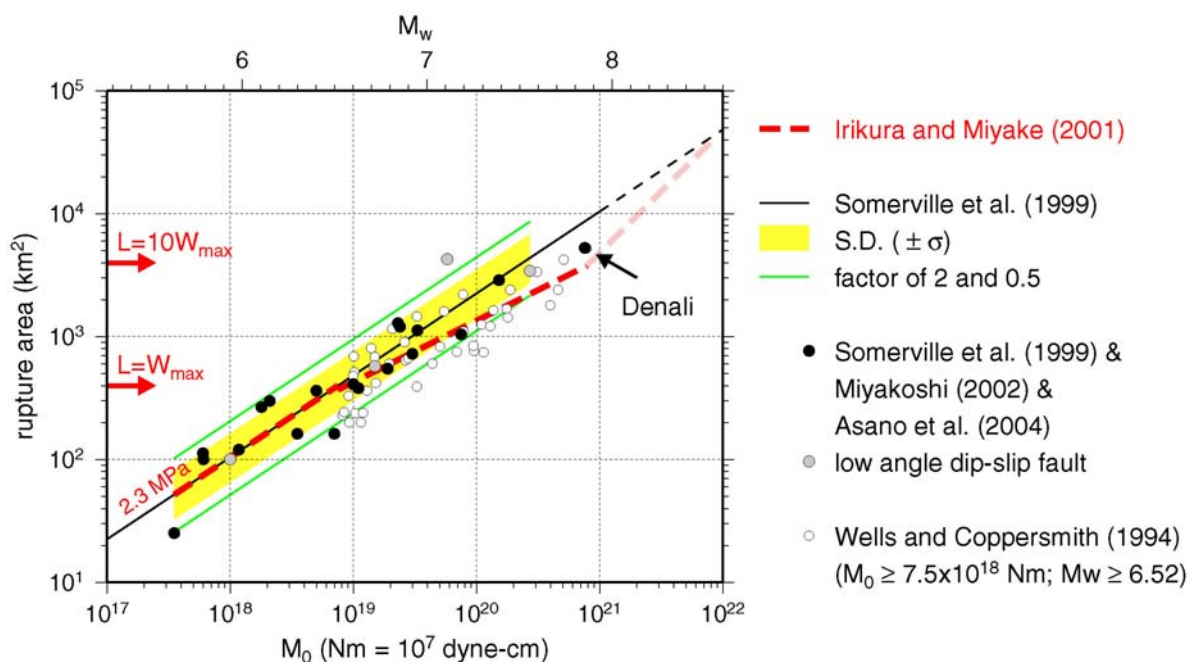


Figure 25 — Three-stage scaling models after IRIKURA et al. (2004)

4.2.3.3 Sedimentary structure model

The accuracy of sedimentary structure model affects much on the simulations of theoretical seismic wave propagation. The structure model is divided into two categories depending on the calculation methods mentioned in 2-1). One is shallow structure from surface to engineering bedrock. And the other is deep structure beneath the engineering bedrock. Physical parameters of body wave velocities, density and attenuation are required for both structure models. Parameters for non-linear site response; i.e. G - γ and h - γ properties are additionally required for shallow structure model. Irregular layered boundary model is required for calculation of 2-D or 3-D wave propagation in the deep structure. (623A, 645A, 645B)

Shallow structure models are constructed from borehole information; i.e. soil tests and logging data. It is desirable to construct a well-arranged database of borehole information gathering high quality borehole information. However, it is difficult to have homogeneous information with necessary quantity and high quality data. Interpolation from given data is generally employed to cover the wide target area supported by mesh information of soil classification and land utilization. In general borehole exploration, PS-logging of seismic waves and soil tests for non-linear site response are rarely conducted. Empirically derived relationships with standard penetration test (N-value) are employed to estimate the parameters above. It is better to use individual relationships derived from local data, however, the relationship of neighbouring area or nation wide standard relation ship is popular in practical case. (631A, 641A)

As for deep structure model, spa well drilling is the quite rare example of deep boreholes. Directly obtained information down to bedrock is lacking. Geophysical explorations are conducted to estimate deep sedimentary structure model. The most convenient technique to survey underground structure in wide area is the method using gravity anomaly, however, accuracy of data decreases in sea area. Density structure is derived from the gravity anomaly survey. Survey technique that gives highest resolution is seismic reflection survey. It uses large artificial seismic source and costs more than other survey techniques. Therefore, the area where seismic reflection surveys were conducted is limited. Another application of artificial seismic source is seismic refraction survey. It can briefly estimate sedimentary boundary structure in wide area. Using the surveys, pressure wave structure is estimated, since the artificial seismic source generally radiates. Shear waves, however, are mainly affected on strong ground motion. Shear wave structure is assumed from microtremor observation. Microtremor consists of surface waves that are sensitive for shear wave structure. (631A, 641B, 645A, 645B)

The physical explorations are not conducted to cover the target area, but the information is along a survey line or at a point. A sedimentary basin model is constructed after interpolating given data. For simulating seismic wave propagation in irregular sedimentary structure, we need model of not only sediments beneath the target site but also basin structure with surrounding mountains. The model shall be confirmed through simulations of observed small earthquake records. The records are published from some organizations at present and we can easily use them.

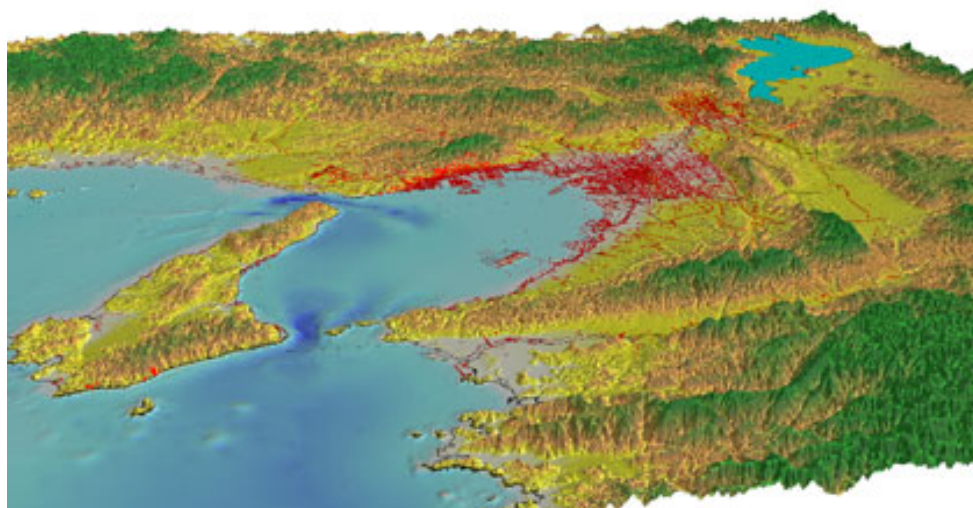


Figure 26 — Distribution of boreholes included in the database of Kansai Geo-informatics Network (2008)

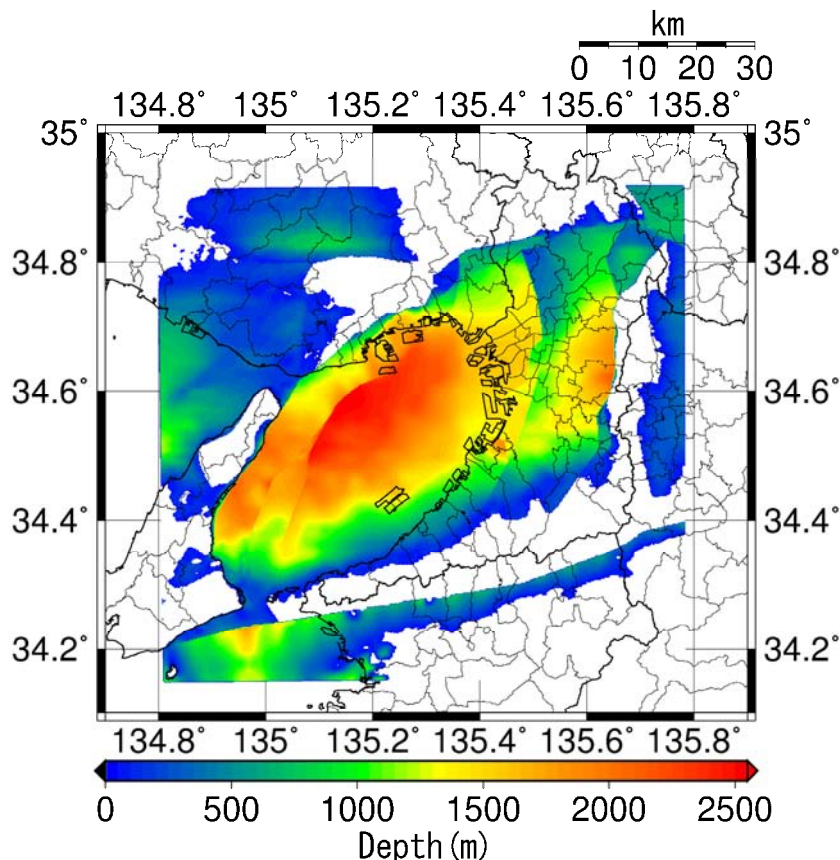


Figure 27 — Sedimentary basin model used in the project of Osaka Prefecture (2007)

4.2.3.4 Examples of strong ground motion estimation

In this section, strong ground motion estimation conducted for earthquake disaster prevention (Osaka Prefecture, 2007; Osaka City, 2007) is shown as an example.

In the Osaka sedimentary basin where Osaka Prefecture and City locate, a lot of geophysical explorations have been conducted for obtaining active fault and sedimentary structure information after the 1995 Hyogo-ken Nanbu (Kobe) earthquake. The Osaka sedimentary basin is the one of world most minutely surveyed area about deep sedimentary structure. Additionally, almost 50,000 high quality borehole data are arranged as a database (Kansai Geo-informatics Network, 2008). Using the basic information, deep and shallow sedimentary structure models are constructed. And the model was verified with ground motion records observed by high quality local network (KAGAWA et al., 2004). It is one of the most suitable areas for applying strong ground motion estimation technique. (631A)

Osaka Prefecture evaluate earthquake hazard in 3 steps (Osaka Prefecture, 2007; Osaka City, 2007). For first step, empirical method, attenuation formula and site amplification from soil classification, is applied for 12 active fault systems in and around Osaka Prefecture. Six fault systems are selected as large impact earthquake sources. Exposure population of high seismic intensity, summation of simulation meshes where JMA intensity is 6 high and larger multiplied by population in the mesh, is considered to choose the target earthquakes. As second step, 73 cases of fault rupture scenario are assumed for the six fault systems. Simulations by stochastic Green's function method are applied for the scenarios. The scenarios are set from engineering request without probability of them that there is no area where estimated ground motion is smaller enough not to consider earthquake disaster prevention. Hybrid simulation technique is applied for step 3. Long period components of five major scenarios of crustal earthquake and one subduction zone earthquake are calculated by 3-D finite difference method. Through the three-step evaluation, earthquake hazards due to the worst scenarios for Osaka Prefecture are estimated and used for disaster evaluation and following disaster mitigation plan. The ground motion waveforms are also used for presuming standard ground motion level for seismic design of public buildings.

The ground motion estimation above is a pioneering approach that provides shake maps and waveforms at where minute sedimentary structure model has been constructed, applying hybrid simulation method and recipe for strong ground motion that are considered to have the highest precision at present stage,.

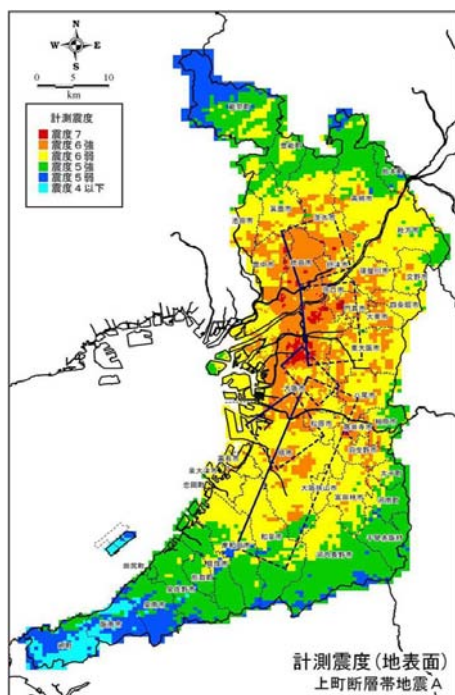


Figure 28 — Distribution of JMA seismic intensity caused by a scenario earthquake, the Uemachi fault A (Osaka Prefecture, 2007)

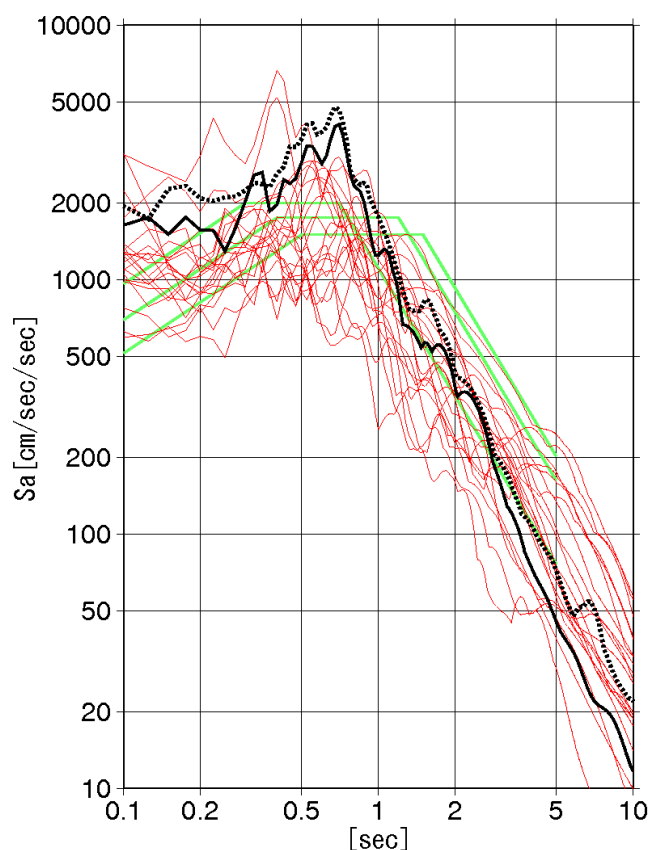


Figure 29 — Example of calculated grand motions in diluvium zones due to the scenario earthquake (Osaka Prefecture, 2007) with observed ground motion at Ojiya site due to the 2004 Chuetsu earthquake.

4.2.4 Deterministic approach - Ground motion estimation based on semi empirical approach

4.2.4.1 Outline

Generally speaking, strong ground motions are determined by three effects, namely, the source effect, the path effect and the site effect as shown in Figure 30 in Subclause 4.2.1. Among these, the site effect can be defined as the influence of sediments on strong ground motions and it includes amplification of body waves, propagation of basin-induced surface waves and so on. The existence of sediments below the site has significant effects on the amplitude, the frequency content and the duration of strong ground motions. Recent development of the nation-wide strong motion networks in Japan has greatly contributed to our understanding of the importance of the site effect. Figure 30 shows a typical example. The left panel of Figure 30 shows the topography around the Port of Sakai, western Japan. Two seismometers, namely, Sakaiminato-G (Strong Motion Earthquake Observation in Japanese Ports) and JMA (the Japan Meteorological Agency) are located in the plains of Yumigahama Peninsula. Other two seismometers, namely, SMN001 of K-NET (Kinoshita, 1998) and SMNH10 of KiK-net (Aoi *et al.*, 2000) are located in mountainous Shimane Peninsula. Observed peak ground velocities during the 2000 Tottori-ken Seibu earthquake ($M_j 7.3$) were approximately four times larger for the plains of Yumigahama Peninsula than for mountainous Shimane Peninsula (Figure 30). Thus, evaluation of the site effect is fundamentally important to predict strong ground motions from future large earthquakes and to determine design ground motions.



Figure 30 — The topography around the Port of Sakai, western Japan (left) and the velocity waveforms for the fault-normal component recorded around the port during the 2000 Tottori-ken Seibu earthquake (M_J7.3). The peak ground velocities observed in the plains of Yumigahama Peninsula were approximately four times larger than those observed in mountainous Shimane Peninsula (Nozu et al., 2008).

Figure 31 shows an example of the effect of the sediments on the frequency content of strong ground motions. At Hachinohe Port, both of the Fourier spectra from the 1968 Tokachi-oki earthquake (M_J=7.9) and the 1994 Sanriku Haruka-oki earthquake (M_J=7.5) are characterized by a peak at 2.5 seconds. On the other hand, at Kansai International Airport, both of the Fourier spectra from the 1995 Hyogo-ken Nanbu earthquake (M_J=7.3) and the 2000 Tottori-ken Seibu earthquake (M_J=7.3) are characterized by a peak at 5 seconds. The difference of predominant periods can be attributed to the thickness of sediments down to the bedrock at each observation station.

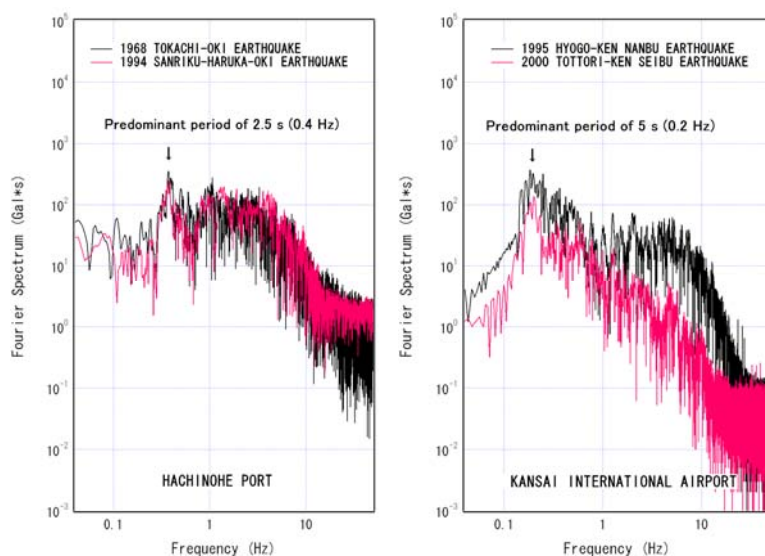


Figure 31 — Fourier spectra of past major strong motion records obtained at Hachinohe Port (NS component) and Kansai International Airport (Runway-normal component)

In principle, there are two ways to evaluate the site effect for the prediction of strong ground motions: one is the numerical evaluation based on the information on subsurface structures and the other is the empirical evaluation based on earthquake observation at the site of interest. The former type of evaluation is suitable for the areas with relatively dense information on subsurface structures, while the latter type of evaluation is

suitable for the areas with relatively high seismicity but relatively sparse information on subsurface structures. The semi-empirical approach to strong motion prediction described in this section is based on the latter type of evaluation of the site effect. Descriptions on the former type of evaluation can be found in Subclause 4.2.3.2. (622A)

The present semi empirical approach begins with the evaluation of the site amplification factors (defined here as the amplification of Fourier amplitude spectrum caused by the sediment) based on the seismograms obtained at the construction site. The approach may include temporary earthquake observations at the construction site. Because the site for the construction of important geotechnical works is often fixed years before its design procedure begins, well-organized design program will allow us to conduct temporary (typically 1-3 years in Japanese practice) observations of earthquake ground motions at the site before the design of geotechnical works. The method for the evaluation of the site amplification factors will be described in Subclause 4.2.4.2. The strong ground motions from future large earthquakes are synthesized, taking into account the rupture process of the earthquakes, together with the effect of sediments both on the Fourier amplitude and the Fourier phase of strong ground motions. The method for the synthesis will be described in Subclause 4.2.4.3. Examples of the application of the synthesis method are presented in Subclause 4.2.4.4., both for a shallow crustal earthquake and a huge subduction earthquake. (622A)

4.2.4.2 Evaluation of site amplification factor

To evaluate site amplification factors from earthquake records, an earthquake observation station sufficiently close to the construction site should be selected. In addition, it is preferable to conduct microtremor observations to make sure that the characteristics of ground motions do not differ significantly between the site of construction and the observation station. If there is no appropriate permanent earthquake observation station, it is recommended to conduct a temporary earthquake observation at the site of construction to evaluate the site amplification factor. The site amplification factor evaluated from a seismogram usually represents the amplification factor from the bedrock to the ground surface because the seismometer is located at the ground surface in many cases. The site amplification factor (from the bedrock to the outcrop of the firm ground) can be obtained by dividing the site amplification factor (from the bedrock to the ground surface) by the transfer function (from the outcrop of the firm ground to the ground surface), which is typically evaluated by the linear multiple reflection theory.

(1) Spectral inversion

The spectral inversion (Iwata and Irikura, 1986) is one of the methods to evaluate the site amplification factor at earthquake observation stations. Let us assume that the ground motions from M earthquakes have been observed at N stations. Then the Fourier spectra of the observed ground motions can be represented as the product of the source effect, the path effect and the site effect as follows.

$$O_{ij}(f) = S_i(f)P_{ij}(f)G_j(f) \quad (15)$$

Where

$O_{ij}(f)$: Fourier spectrum of the record from the i^{th} earthquake at the j^{th} station,

$S_i(f)$: Source effect (source spectrum) for the i^{th} earthquake,

$P_{ij}(f)$: Path effect from the i^{th} earthquake to the j^{th} station,

$G_j(f)$: Site effect for the j^{th} station.

The path effect can be represented as follows, taking into account the geometrical spreading and the inelastic damping.

$$P_{ij}(f) = \frac{1}{r_{ij}} \exp(-\pi f r_{ij} / QV_S) \quad (16)$$

Where

r : distance from the i^{th} earthquake to the j^{th} station,

Q : Q value along the propagation path.

By substituting the equation (2) into the equation (1) and taking the natural logarithm, one obtains

$$\log O_{ij} = -\log r_{ij} + \log S_i + \log G_j - (\log e) \pi f r_{ij} / QV_s \quad (17)$$

In general, the numbers of the unknowns included in the equation (17) is smaller than the number of the equations, i.e., the number of the records. Thus one can solve the equation (17) by using the least square method. It should be noted, however, that the least square solutions of the equation (17) are not unique. For instance, if S_i and G_j are the least square solutions, $S_i/2$ and $2 G_j$ will also be the least square solutions. Thus, in this analysis, an additional constraint is required. One of the recommended way to give the constraint is to select a frequency-dependent reference site for which the site amplification factor is smallest among all the sites (excluding soft soil sites) and to assume that the site amplification factor is unity for this reference site (Nozu and Nagao, 2005). It is also recommended to make sure that the seismic moments estimated from the solutions of the equation (17) are in agreement with those of Centroid Moment Tensor (CMT) solutions on the average. Other recommendations on the spectral inversion can be summarized as follows.

- It is preferable to avoid records with epicentral distances larger than 150 - 200 km because the equation (16) is not applicable to long-distance records.
- It is preferable to avoid records from large earthquakes ($M \geq 6$ for example) because it is not appropriate to assume a azimuth-independent source effect S_i for large earthquakes.
- It is preferable to avoid records from small earthquakes ($M < 4$ for example) because, for small earthquakes, the signal-to-noise ratio at low frequencies tends to be insufficient.
- It is preferable to avoid records with large amplitude to avoid the effects of soil nonlinearity.

Nozu and Nagao (2005) and Nozu *et al.* (2006) used the method to evaluate site amplification factors for strong-motion sites all over Japan including K-NET sites, KiK-net sites and sites at major ports. Medium-sized earthquakes were used, whose JMA magnitude is in the range from 4.5 to 6.0. To avoid the effects of soil nonlinearity, records with PGAs exceeding 100 cm/s^2 were excluded from the analysis. As for the path effect, geometrical spreading and nonelastic attenuation were considered. The analysis was conducted in two steps: In the first step, O_{ij} is calculated from portions of the records with duration of 40 seconds including S waves. Then, based on the equation (3), S_i is estimated. In this step, G_j is assumed to be unity for the reference site. In the second step, O_{ij} is calculated from portions of the records with duration of 160 seconds including not only S waves but also later phases. Then, based on the equation (3) and using the S_i previously determined, G_j is estimated. G_j thus estimated reflects the lengthening of ground motion duration due to local geology (e.g., Beauval *et al.*, 2003) and suitable for strong motion simulation technique described in 3). Figure 32 (left) shows the location of strong motion sites and hypocenters of the earthquakes used in the spectral inversion analysis for Kanto region. In Figure 32 (right) the seismic moments estimated from the analysis for Kanto region is compared with those of the F-net CMT solutions. F-net CMT solutions are based on very long period (0.01-0.1 Hz) surface waves. The agreement between the two seismic moments indicates that the reference site is adequately chosen and there is no serious overestimation or underestimation of the source effect. Figure 33 shows examples of site amplification factors in Kanto region. The digital data of the site amplification factors in Japan evaluated in this way are available on a CD-ROM (Nozu and Nagao, 2005).

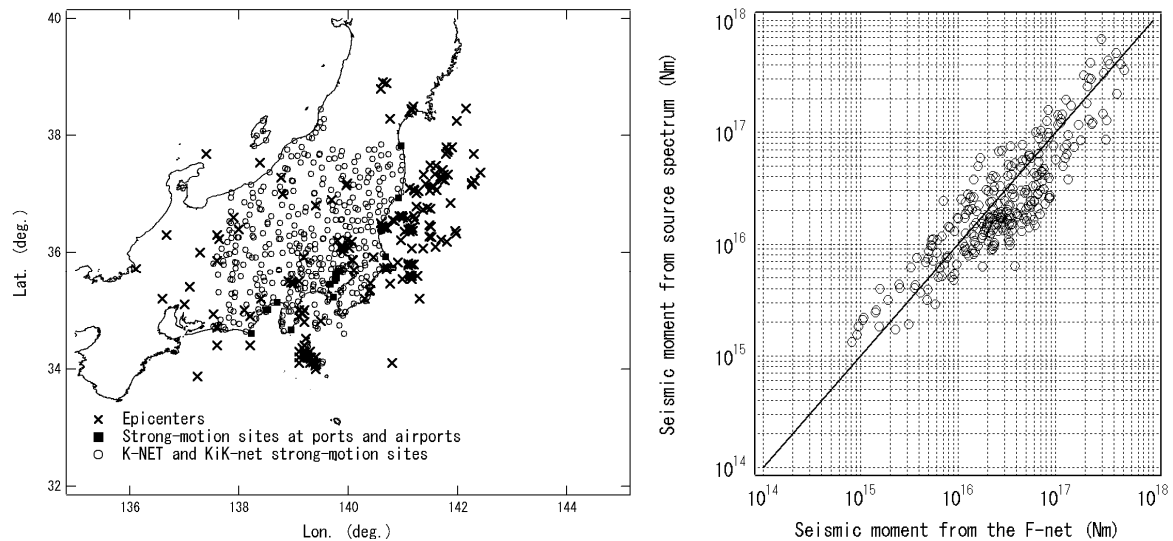


Figure 32 — (left) Location of strong motion sites and hypocenters of the earthquakes used in the spectral inversion analysis for Kanto region. (right) Comparison between the seismic moments estimated from the analysis for Kanto region and those of the F-net CMT solutions.

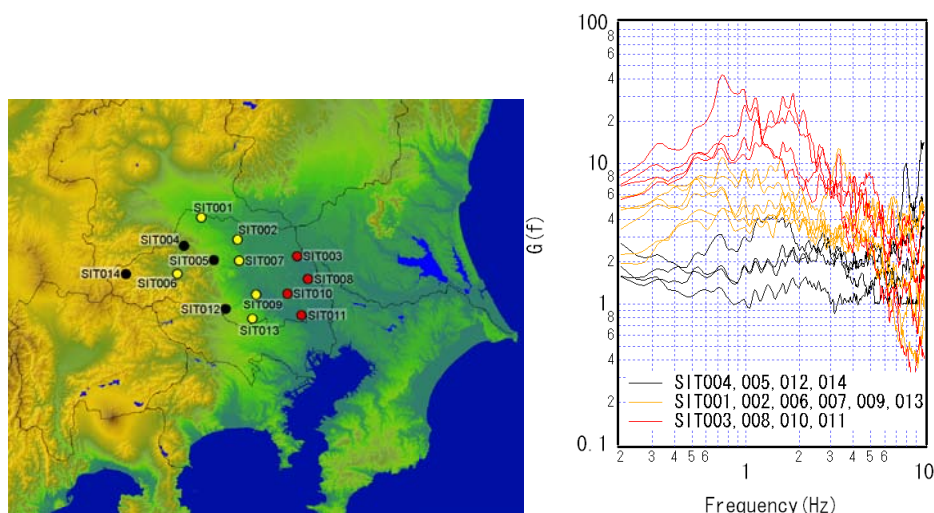


Figure 33 — Examples of site amplification factors in Kanto region. Large site amplification factors are estimated at sites located in plains (SIT003, 008, 010, 011), whereas small site amplification factors are estimated at sites located in mountains (SIT004, 005, 012, 014). Medium site amplification factor is estimated for Chichibu (SIT006), which is in a small basin surrounded by mountains (after Nozu and Nagao, 2005).

(2) Temporary earthquake observation

The term for the temporary observation should be determined taking into account the seismicity of the area. Typically, in Japan's case, a term of 1-3 years would be required. The seismometers used for the observation should cover all the frequency range for which strong ground motions should be predicted. If the predicted ground motion is intended to be used for the design of geotechnical works, the predicted ground motion should be preferable reliable down to 0.2 Hz. The trigger level should be chosen carefully. In general, a very small trigger level should be chosen to obtain as many records as possible in a limited term. It might be useful to adopt a mechanism in which the seismometer is triggered when the velocity, instead of the acceleration, exceeds certain value. The location of the observation should also be determined carefully. When it is difficult to install the seismometer just at the construction site, then microtremor observation should be conducted in and around the construction site and the seismometer should be installed within an area in which the

characteristics of microtremor can be regarded uniform. As can be seen from Figure 34 in Subclause 4.2.1, the effect of earthquake magnitude on the Fourier amplitude is especially significant for low frequencies. Fourier spectra calculated from the records of small earthquakes are often not reliable at low frequencies. To evaluate reliable site amplification factors down to low frequencies, it is important to obtain the records of relatively large ($M \geq 4$ for example) earthquakes.

(3) Evaluation of site amplification factors at a temporary station

Based on the known site amplification factors at permanent stations, the site amplification factor at a temporary station can be evaluated as follows. The first step is to find earthquakes, which are recorded both at the temporary station and the surrounding permanent stations. Then, for these earthquakes, the source spectra should be determined so that the equation (15) is satisfied for the permanent stations. It is a common practice to assume that the source spectra follow the ω^{-2} model (Aki, 1967):

$$S(f) = C \frac{M_0}{4\pi\rho V_s^3} \frac{(2\pi f)^2}{1 + (f/f_c)^2} \quad (18)$$

Where

M_0 : seismic moment,

f_c : corner frequency,

ρ : density in the bedrock,

V_s : shear wave velocity in the bedrock,

C: constant.

Finally, using the source spectra thus obtained and the observed spectra at the temporary station, the site amplification factor at the temporary station can be determined from the equation (15).

A simplified version of this analysis can be applied if the temporary station is very close to a permanent station for which the site amplification factor is known. In this case, these stations share the same source effect and the same path effect. Therefore, the Fourier spectral ratio of the records from the same earthquake at these stations represents the ratio of the site amplification factors. Thus, the site amplification factor for the temporary station can be easily obtained from the spectral ratios.

4.2.4.3 Evaluation of strong ground motion

To evaluate strong ground motions, the rupture process of the target earthquake should be specified. It has been revealed that the slip on the fault of a large earthquake is not uniform and there is a relatively small region called “asperities” in which the slip (and the slip velocity) is especially large. It is necessary to take into account the existence of asperities for the reliable evaluation of strong ground motions. To characterise the rupture process of a large earthquake, the “characteristic source model” is often employed. The “characteristic source models” is defined as a source model composed of rectangular asperities, within which the slip and the slip velocity is uniform. In the characteristic source model, the source parameters to be specified fall into three categories: the macroscopic parameters, the microscopic parameters and the other parameters. The macroscopic source parameters include the location of the fault, the strike of the fault, the dip of the fault, the area of the fault and the seismic moment of the fault. The microscopic parameters include the number of the asperities, the area of the asperities, the seismic moment of the asperities, the rise time of the asperities and the location of the asperities. The other parameters include the rupture starting point and the rupture velocity. The meaning of the source parameters are shown in Figure 34.

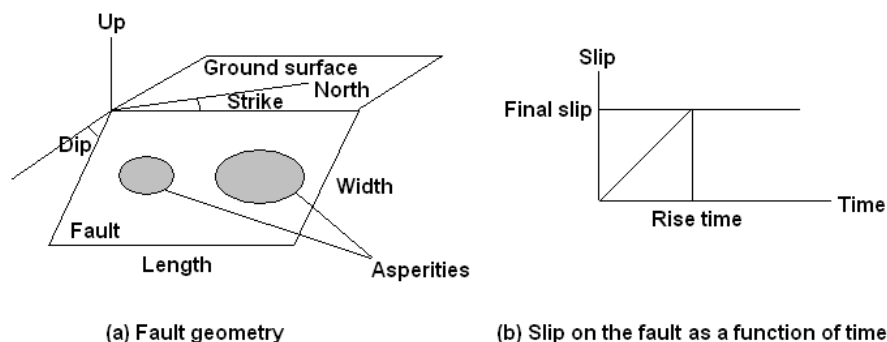


Figure 34 — Meaning of the source parameters

To calculate ground motions for a past earthquake, a source model optimized for the particular earthquake will be useful. To calculate ground motions for a future hypothetical earthquake, the source parameters should be determined based on empirical relations. In the examples shown in Subclause 4.2.3.1.4, optimized source models for individual earthquakes are used.

There are several reliable methods for the synthesis of earthquake ground motions for a prescribed source model. In this section, the Kowada's method (Kowada, 1998; Nozu and Sugano, 2008; Nozu *et al.*, 2008) is described.

First, a small earthquake should be hypothesized, whose area is equal to the area of the target asperity divided by N^2 and whose seismic moment is equal to the seismic moment of the target asperity divided by N^3 . The ground motion from the small earthquake is called the "Green's function". The Fourier amplitude of the Green's function is evaluated as a product of the source effect $S(f)$, the path effect $P(f)$ and the site amplification factor $G(f)$. The source effect and the path effect can be specified as follows.

$$S(f) = R_{\theta\phi} FS \cdot PRTITN \cdot \frac{M_{0e}}{4\pi\rho V_s^3} \frac{(2\pi f)^2}{1 + (f/f_c)^2} \quad (19)$$

$$P(f) = \frac{1}{r} \exp(-\pi f r / QV_s) \quad (20)$$

Where

M_{0e} : seismic moment of the small event

f_c : corner frequency of the small event

$\tilde{\rho}$: density in the bedrock

V_s : shear wave velocity in the bedrock

$R_{\theta\phi}$: radiation coefficient

FS : amplification due to free surface (=2)

$PRTITN$: coefficient representing the partition of seismic energy into two horizontal components

r : hypocentral distance for the small earthquake

Q : Q value along the propagation path.

The corner frequency of the small earthquake can be obtained from the area of the small earthquake S_e as follows (Brune, 1970; Brune, 1971).

$$f_c = 0.66 V_s / \sqrt{S_e} \quad (21)$$

As for the Fourier phase, the Fourier phase of a record at the earthquake observation station can be used. If the site amplification factor from the bedrock to the ground surface is used, the Fourier phase at the ground surface should be used. If the site amplification factor from the bedrock to the outcrop of a firm ground is used, the Fourier phase at the outcrop of the firm ground should be used. If several records are available at the site, it is recommended to choose an event, which has a similar incident angle and a similar back-azimuth with the target asperity. The Green's function in the frequency domain can be written as follows.

$$|S(f)| |P(f)| |G(f)| |O_s(f)| / |O_s(f)|_p, \quad (22)$$

Where $O_s(f)$ is the Fourier transform of a record at the site and $|O_s(f)|_p$ is its Parzen-windowed amplitude (typically the band width of 0.05 Hz is used). The time domain Green's function can be obtained as the inverse Fourier transforms of the equation (8). Finally, the time domain Green's function can be superposed as follows (e.g., Miyake *et al.*, 1997).

$$U(t) = \sum_{i=1}^N \sum_{j=1}^N (r/r_{ij}) f(t) * u(t - t_{ij}) \quad (23)$$

$$f(t) = \delta(t) + \left\{ 1/n' / (1 - e^{-1}) \right\} \sum_{k=1}^{(N-1)n'} \left[e^{-(k-1)/(N-1)/n'} \delta\{t - (k-1)\tau/(N-1)/n'\} \right]$$

$$t_{ij} = (r_{ij} - r_0)/V_s + \xi_{ij}/V_r$$

Where

$U(t)$: Ground motion from the asperity (designated as "large event" in Figure 35)

$u(t)$: Green's function

$f(t)$: Function to correct for the difference of slip velocity time functions for the asperity and those for the small earthquake

r : hypocentral distance for the small earthquake

r_{ij} : distance from the subfault ij to the site

$\hat{o}$: Rise time of the asperity

n' : integer used to remove artificial periodicity

r_0 : distance from the rupture starting point to the site

$\hat{r}_{ij}$: distance from the rupture starting point to the subfault ij .

V_s : shear wave velocity in the bedrock

V_r : Rupture velocity

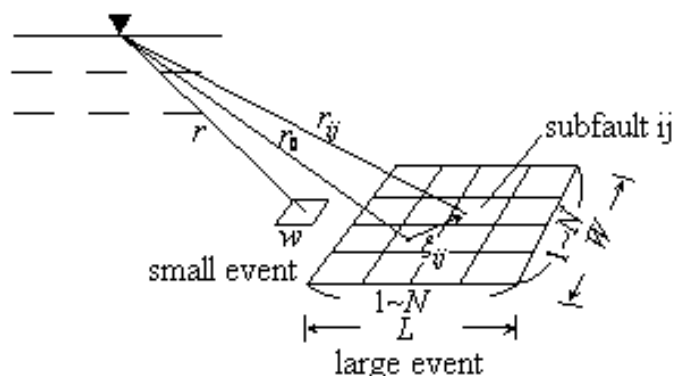


Figure 35 — Division of target fault to be superimposed by using Green's functions from divided sub-faults

The ground motion thus obtained is either at the ground surface or at the outcrop of the firm ground, depending on the site amplification factor used in the equation (8). To obtain the ground motion at the outcrop of the firm ground from the ground motion at the ground surface, the linear multiple reflection theory can be used. A computer program to synthesize strong ground motions based on the method described above is open to public from the Port and Airport Research Institute (Nozu and Sugano, 2008).

Finally, a recommended procedure to incorporate soil nonlinearity is introduced. Figure 36 shows seismic rays connecting the source and the site on a sedimentary basin. In general, the seismic rays cross the soft soil deposit somewhere in the basin before its incidence to the local soft soil deposit at the site except for the direct S wave. Therefore, when the soft soil deposit exhibit a nonlinear behaviour during a large event, the seismic waves will be affected by the soil nonlinearity more than once along the rays, except for the direct S wave. The phenomenon is referred to as the “multiple nonlinear effects” (Nozu and Morikawa, 2003; Nozu and Morikawa, 2004).

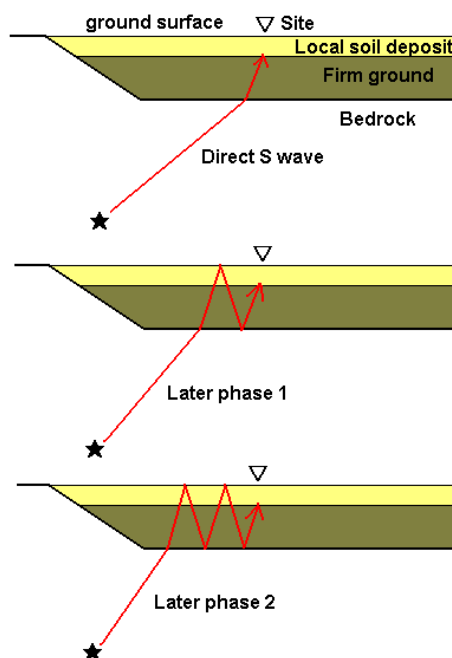


Figure 36 — Multiple nonlinear effects

In the present approach, the nonlinear effect on the seismic wave after its incidence to the local soft soil deposit is evaluated by an effective stress analysis, while the nonlinear effect on the seismic wave before its

incidence to the local soft soil deposit is evaluated by a simplified scheme using the “nonlinear parameters” (Nozu and Morikawa, 2003; Nozu and Morikawa, 2004). The latter procedure can be described as follows.

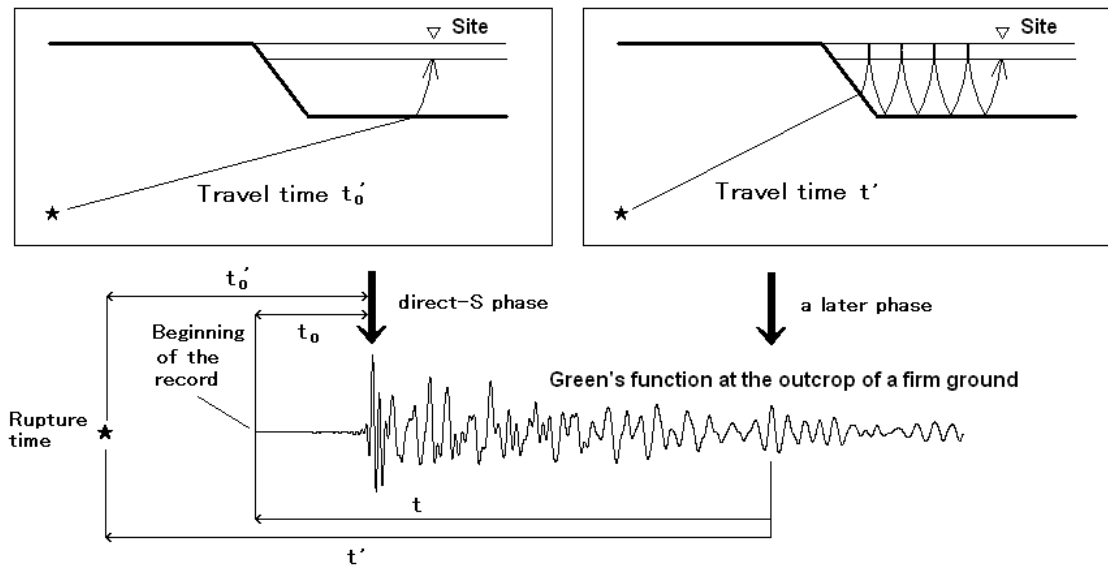


Figure 37 — Introduction of “nonlinear parameters”

A key assumption in the present method is that the delay of an arbitrary later phase found on the Green's function is caused by the trapping of the seismic ray within the sedimentary basin as schematically illustrated in Figure 37. Thus the difference of the arrival times of the direct-S phase and the later phase on the Green's function $t-t_0$ is approximately equal to the time for which the seismic ray corresponding to the later phase is trapped within the sedimentary basin. During a large event, the materials within the sedimentary basin can exhibit nonlinear behaviour including the reduction in shear wave velocity and the increase in damping (Beresnev and Wen, 1996). The nonlinear behavior is typically most prominent near the surface of the basin. Due to the nonlinear behaviour, the arrival time of the later phase will be delayed and its amplitude will be reduced. Two parameters, $\hat{I}_1$ and $\hat{I}_2$, are introduced to represent the deviation of the material properties of the sediments from the linear status due to the soil nonlinearity. The parameter $\hat{I}_1$ is defined as the averaged reduction in shear wave velocity along the ray in the sediments, that is, $\hat{I}_1 = V_s/V_{s0}$, where V_s is the shear wave velocity for a strong motion and V_{s0} is the shear wave velocity for a weak motion. The parameter $\hat{I}_2$ is defined as the averaged increase in damping factor along the ray in the sediments, that is, $\hat{I}_2 = h-h_0$, where h is the damping factor for a strong motion and h_0 is the damping factor for a weak motion. Then, during a large event, the seismic ray corresponding to the later phase will be trapped within the sedimentary basin $1/\hat{I}_1$ times longer than the linear case. At the same time, the amplitude of the later phase will be reduced by a factor of $\exp[-\hat{I}_2 \hat{u}(t-t_0)]$, because $t-t_0$ is approximately equal to the time for which the seismic ray corresponding to the later phase is trapped within the sedimentary basin as discussed above. As a result, the Green's function is modified as follows:

$$g_n(t) = g(t) \quad \text{for } t < t_0 \quad \text{and}$$

$$g_n(t_0 + (t-t_0)/\hat{I}_1) = g(t) \exp[-\hat{I}_2 \hat{u}(t-t_0)] \quad \text{for } t > t_0, \quad (24)$$

Where $g(t)$ is the original Green's function at the outcrop of the firm ground and $g_n(t)$ is the Green's function after modification. The parameters $\hat{I}_1$ and $\hat{I}_2$ are referred to as “the nonlinear parameters”. In practice, if the Green's function is narrow-band, the corresponding angular frequency can be used in equation (10). If the Green's function is broad-band, it is decomposed into components having different frequencies and then each component is modified in the same manner as in the narrow-band case. Finally, the modified components are summed up.

4.2.4.4 Example of application

(1) Application to the 1995 Hyogo-ken Nanbu, Japan, earthquake ($M_J 7.3$)

First, the method is applied to the 1995 Hyogo-ken Nanbu, Japan, earthquake, which is a shallow crustal earthquake. Using the characteristic source model by Yamada *et al.* (1999) (Figure 38), ground motions at two CEORKA (The Committee of Earthquake Observation and Research in the Kansai Area) sites in Kobe, KBU and MOT, are simulated. Site amplification factors at these sites (Nozu and Nagao, 2005) are shown in Figure 39. Based on the simulation of aftershock ground motions, the seismic moments of the asperities are re-evaluated as 3.4×10^{17} Nm, 1.3×10^{18} Nm and 2.3×10^{18} Nm for asperities 1, 2 and 4, respectively. Rise times of the asperities are 0.4s, 0.5s and 0.6s for the asperities 1, 2 and 4, respectively. The westernmost asperity was neglected in the simulation because it has little effects on the ground motions in Kobe. To determine the phase characteristics of the Green's functions, the records from an aftershock (1995/2/2 16:19) were used, whose hypocenter is shown in Figure 38. The synthetic velocity waveforms and the velocity Fourier spectra are compared with the observed ones in Figure 40 and 12, respectively. It can be clearly seen that the damaging velocity pulses generated by the asperities can be reproduced with high accuracy with the present method. The results also indicate the validity of the characteristic source model for a shallow crustal earthquake.

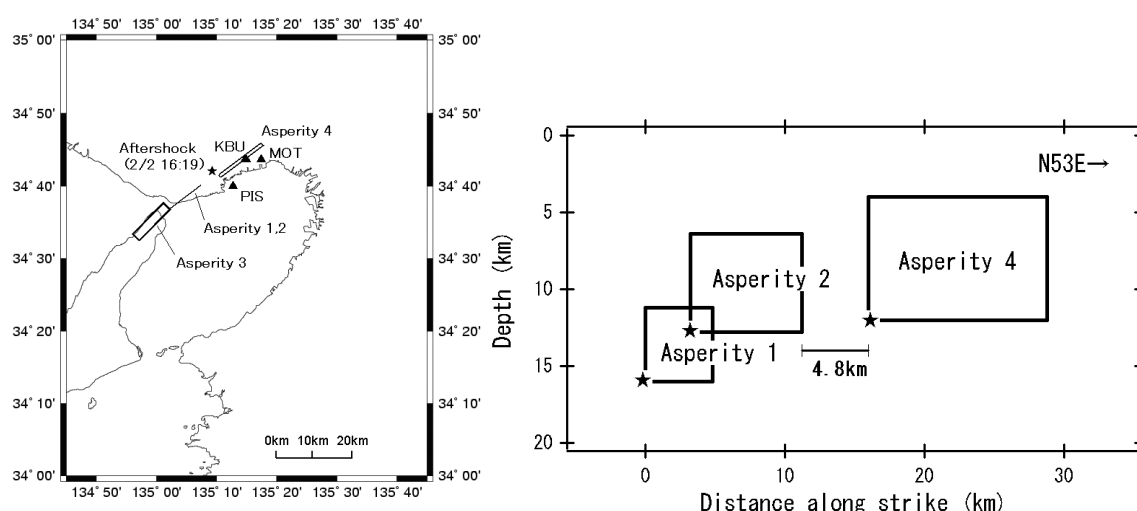


Figure 38 — Characteristic source model by Yamada *et al.* (1999) for the 1995 Hyogo-ken Nanbu earthquake, epicenter of the aftershock used and location of CEORKA sites KBU and MOT. Cross section shows only the Kobe side of the model.

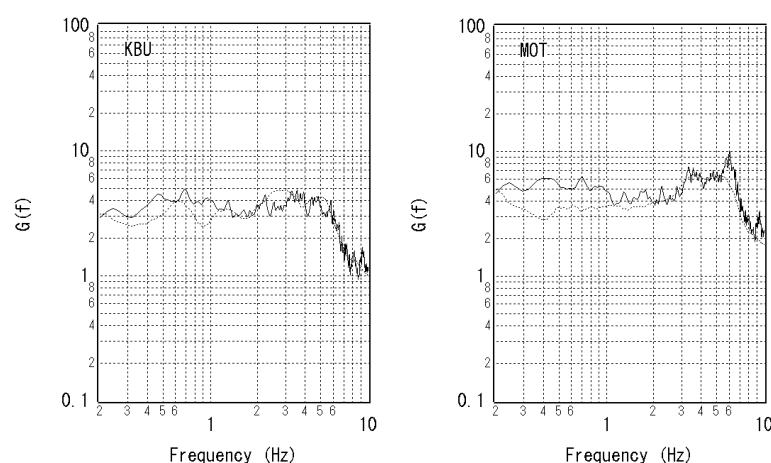


Figure 39 — Site amplification factors for CEORKA strong motions sites KBU and MOT at the ground surface estimated by Nozu and Nagao (2005) (thick lines) and those estimated by Tsurugi *et al.* (2002) (dotted lines).

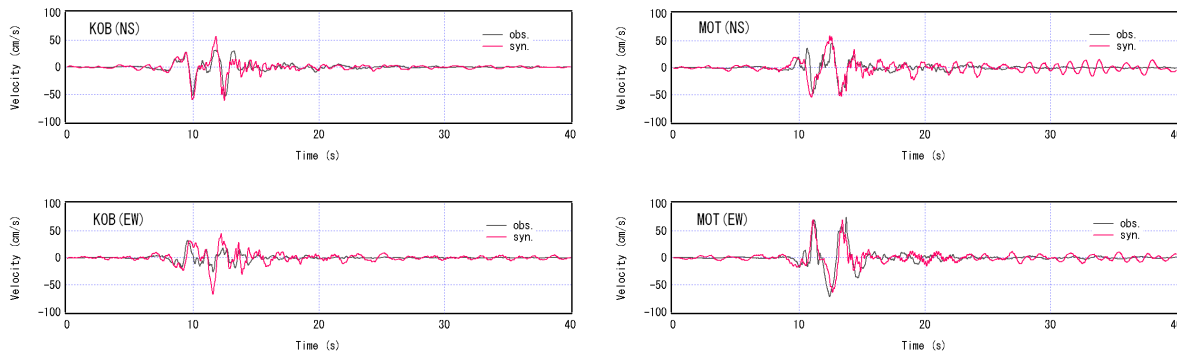


Figure 40 — Recorded (black) and simulated (red) velocity waveforms at KBU and MOT for the 1995 Hyogo-ken Nanbu earthquake.

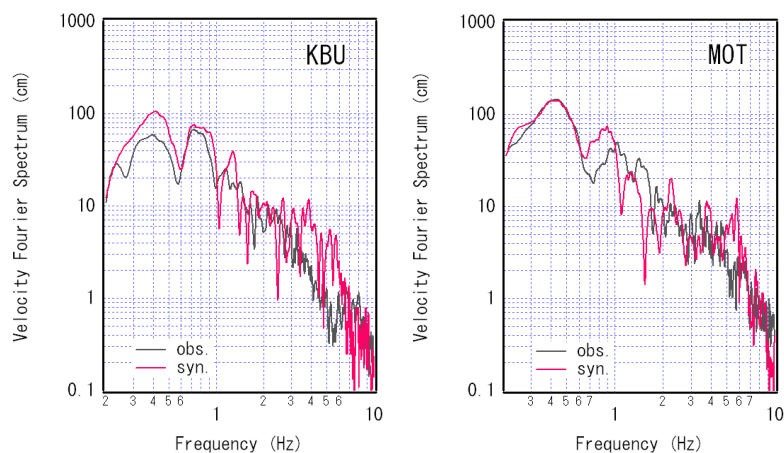


Figure 41 — Recorded (black) and simulated (red) velocity waveforms at KBU and MOT for the 1995 Hyogo-ken Nanbu earthquake.

The same source model and the same method were applied to the PIS vertical array station, where the nonlinear behaviour of the soft soil deposit was significant. Figure 42 shows the site amplification factor for PIS at the outcrop of the firm ground. To determine the phase characteristics of the Green's functions, the records from an aftershock (1995/2/18 21:37) were used. The Green's functions were modified based on the equation (10). The nonlinear parameters $\dot{\epsilon}_1 = 0.91$ and $\dot{\epsilon}_2 = 0.06$ were used. Then, the equation (9) was applied to the modified Green's functions to estimate the ground motion at the outcrop of the firm ground during the large event. Finally, an effective stress analysis (Iai *et al.*, 1992) was conducted to evaluate the nonlinear behaviour of the local soft soil layers. The parameters listed in Table 2 were used for this analysis. In this table, initial shear modulus (G_{ma}) which depends on initial mean effective stress (σ_{ma}') and internal friction angle ϕ_f' for each layer are shown as well as other parameters. Excess pore water pressure was considered for the 2nd and the 3rd layers. The synthetic velocity waveforms (0.2-2 Hz) at four depths are compared with the observed ones in Figure 43. The synthetic waveforms are consistent with the observed ones.

Table 2 — Parameters used for the effective stress analysis

Layer No.	Thickness of layer (m)	Material	Density (Mg/m^3)	initial shear modulus, G_{ma} (kPa)	initial mean effective stress, σ_{ma}' (kPa)	internal friction angle, ϕ_f'
1	3.4	Masado	1.8	79,380	63	36
2	4.6	Masado	1.8	79,380	63	36
3	1.0	Silt	1.7	74,970	143	30
4	8.0	Masado	1.8	79,380	63	36
5	13.0	Clay	1.7	74,970	143	30
6	30.0	Sand	1.8	79,380	63	36
7	23.0	Clay	1.7	74,970	143	30

Note:

- Excess pore water pressure generation is considered for Layers 2 and 3.
Iai's model parameters for the two layers: $\phi_p=28$ deg, $W1=6.0$, $P1=0.5$, $P2=0.8$, $C1=2.43$, $S1=0.005$
- Coefficient of Rayleigh damping, $b=0.002$
- Masado is the Japanese name of weathered Granite soil.

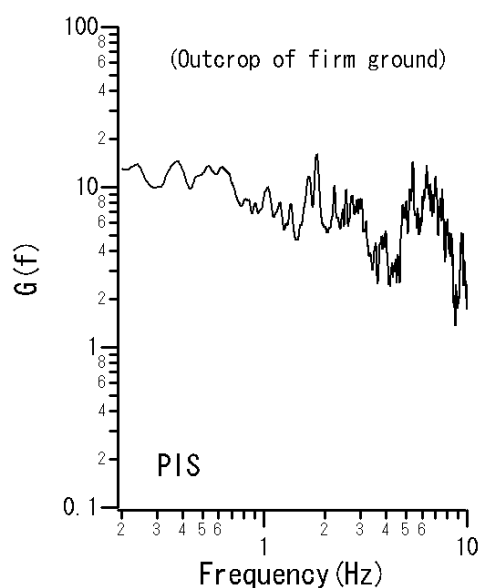


Figure 42 — Site amplification factor for PIS at the outcrop of the firm ground

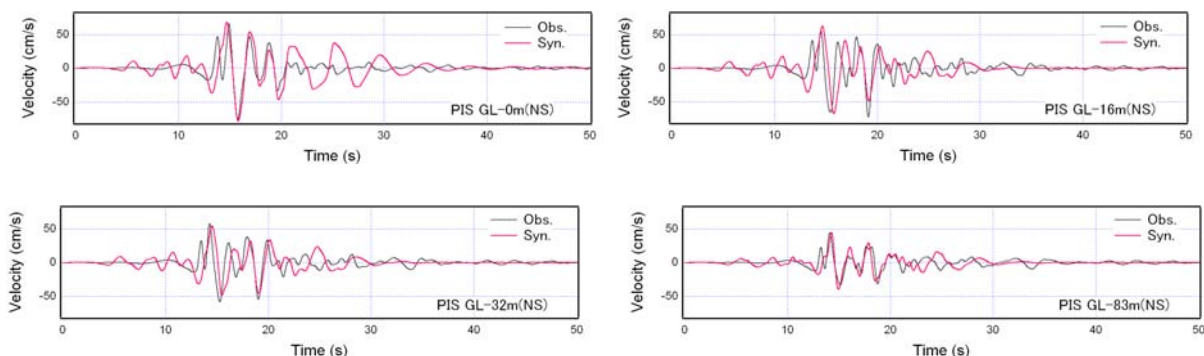
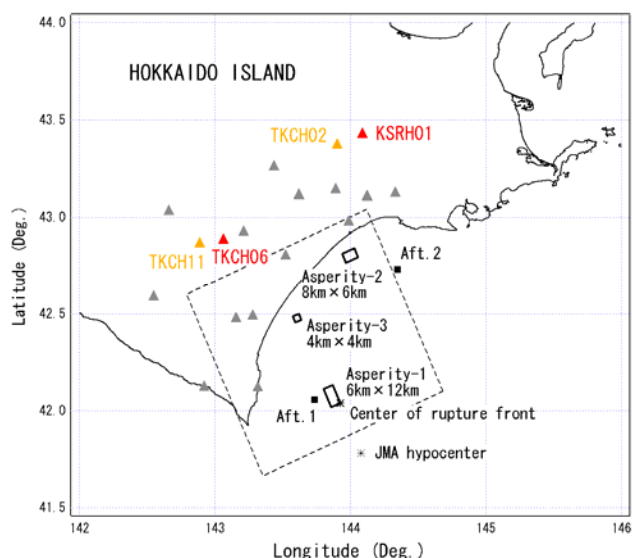


Figure 43 — Observed and synthetic velocity waveforms (0.2-2 Hz) at PIS at four depths during the 1995 Hyogo-ken Nanbu, Japan, earthquake.

(2) Application to the 2003 Tokachi-oki, Japan, earthquake ($M_j 8.0$)

Secondly, the method is applied to the 2003 Tokachi-oki, Japan, earthquake, which is a huge subduction earthquake. Figure 44 shows the characteristic source model developed for the earthquake. The model is composed of three asperities. Ground motions at four KiK-net stations, namely, TKCH06, TKCH11, KSRH01 and TKCH02 are simulated. The site amplification factors at these sites (Nozu and Nagao, 2005) are shown in Figure 45. Although the former two stations are located close to each other, their site amplification factors are quite different. Similarly, although the latter two stations are located close to each other, their site amplification factors are quite different. The records from the aftershock 1 (2003/9/26 7:20) were in the equation (8) for the former two stations, because the effect of the asperity 1 is dominant for these stations and the aftershock 1 is close to the asperity 1. The records from the aftershock 2 (2003/9/27 17:06) were used in the equation (8) for the latter two stations, because the effect of the asperity 2 is dominant for these stations and the aftershock 2 is close to the asperity 2. The hypocenters of these aftershocks are shown in Figure 44. The synthetic velocity waveforms (0.2-1Hz) are compared with the observed ones in Figure 46. Note the significant difference of the amplitude and the duration of the observed velocity waveforms. The difference can be attributed to the site effects. The synthetic velocities are consistent with the observed ones in terms of the amplitude and duration. Thus, it is quite important to take into account the effect of sediments both on the Fourier amplitude and the Fourier phase of strong ground motions. The results also indicate the validity of the characteristic source model for a huge subduction earthquake.



[Macroscopic parameters] Density: 3.1g/cm³, Shear wave velocity: 3.9km/s, Strike: 246, Dip: 18, Rupture starting point: (143.925E, 42.039N, d=30.1km), Rupture velocity: 2.7km/s

[Microscopic parameters]

[Asperity-1] Area: 6×12km², Seismic moment: 4.2E+26 dyne-cm, Rise time: 0.6s, Discretization: 5×5×5

[Asperity-2] Area: 8×6km², Seismic moment: 2.1E+26 dyne-cm, Rise time: 0.6s, Discretization: 3×3×3

Figure 44 — Characteristic source model developed for the 2003 Tokachi-oki, Japan, earthquake composed of three asperities (open rectangles). Triangles indicate strong-motion sites. Closed rectangles indicate small events whose records were used in equation (8).