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Paper No. 1806. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DESIGN EARTHQUAKE GROUND MOTION FOR DYNAMIC ANALYSIS OF BUILDING

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ABSTRACT

Japan is characteristically subjected to seismic activity, therefore, it is a matter of concern how building structures behave under earthquake conditions. In actuality, however, there are no standardized earthquake ground motions used for seismic design. Therefore, thorough investigation should be conducted during the design phase of the structure to determine what types of earthquake ground motion are to be used for the design of building structures constructed on various ground types. On this premise, this paper presents an outline for composing design earthquake ground motion for dynamic analysis of buildings.

KEYWORDS

Design Response Spectra ; Horizontal and Vertical Component ; Engineering-oriented Base Layer ; Seismicity ; Amplification of Upper Soil Layer ; Liquefaction Effect ; Topographical Condition ; Longer-period Characteristic ; Synthesized Time History.

INTRODUCTION

Since the seismic design method for building structures in Japan was amended in 1981, research focus has been changed from static analysis to dynamic analysis. Dynamic analysis, as a technology aided by the recent rapid progress in both theory and computers, appears to be the most precise design method for the dynamic phenomenon of an earthquake. Most seismic behavior of various structures can be elucidated by structural experiments. However, despite advances in theoretical modeling, earthquake motions have been collectively treated on the safe side due to difficulties with recurrence and with scarce opportunities for actual proof.

To address the demand for dynamic analysis, the Research Committee for Design Earthquake Ground Motion (chaired by Prof. B. Kato) was organized in the Building Center of Japan (BCJ) to carry out a cooperative research program between the Building Research Institute (BRI) and BCJ. As a final outcome of this 4-year research program that began in 1989, a guideline was proposed for composing design earthquake ground motion for buildings incorporating the latest research results on ground motion (Committee, 1992, Kitagawa *et al.*, 1994). This paper discusses the technical aspects of composing design earthquake ground motion for building structures.

DESIGN EARTHQUAKE GROUND MOTION

Earthquake motion on the ground surface is characterized by the fault slip behavior, route of wave transmission through bed-rock and the amplification in the soil layer. It is possible to determine design

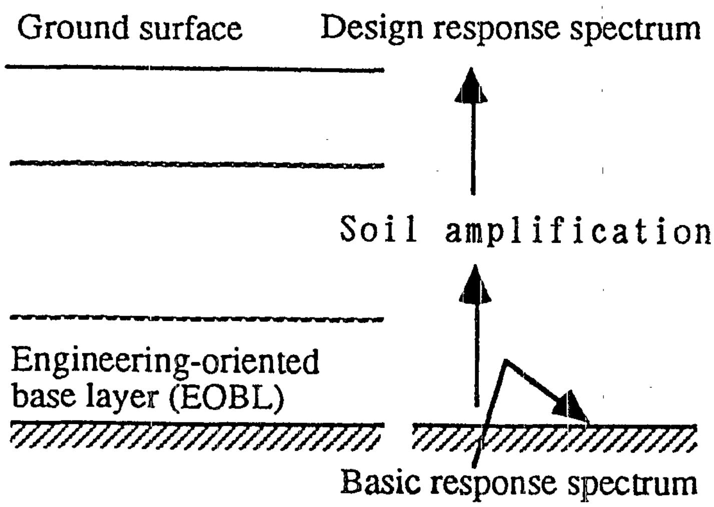


Fig. 1. Design response spectrum

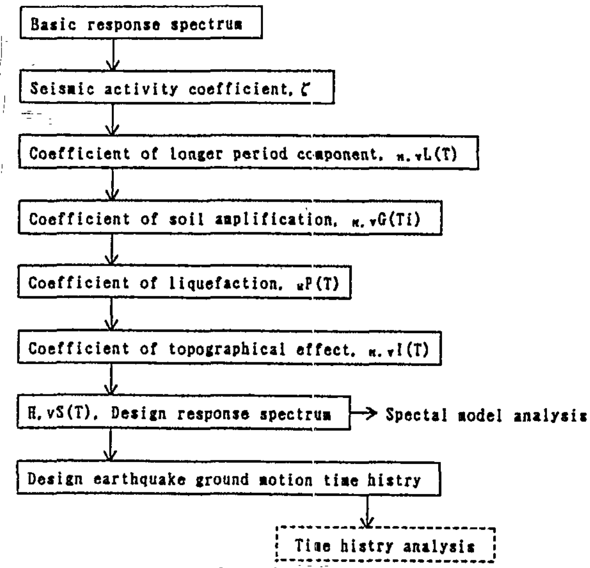


Fig. 2. Flowchart for composing design earthquake ground motion

earthquake motion properly if these characteristics are evaluated rationally.

At present, observed and/or synthetic earthquake motions are used for the dynamic analysis of highrise buildings or base-isolated structures to check the earthquake resistant capability of those structures; e.g. (1) strong earthquake records observed in the past, (2) observed records modified with respect to their amplitudes and frequency characteristics, and (3) synthetic earthquake motions compatible to the specified response spectra or synthesized taking fault mechanisms and wave transmission into account. However, these input earthquake motions are sometimes not representing the characteristics of the site of construction, or need elaborate work to be generated according to the variety of respective site condition.

The proposed method herein is intended to simplify the calculation process of the input earthquake motion site by site. Several modification coefficients are multiplied to the basic response spectra specified at the engineering-oriented base layer to obtain the design response spectra on the ground surface. Those coefficients represent seismicity, longer-period characteristics of the site, amplification in the upper soil layer, liquefaction effect and topographical condition. Modal analysis can be done using these design response spectra, or response analysis can be done using synthesized time histories compatible to the design response spectra.

GUIDELINE FOR COMPOSING DESIGN EARTHQUAKE GROUND MOTION

The guideline presented here includes methodologies to construct the design response spectrum, and, consequently, the time history of design earthquake ground motion. It also includes both usage of the generated motion for analysis as a design procedure and examples of applying design spectra to cases of design. These methodologies are mainly for high-rise buildings and base-isolated buildings that require dynamic analysis in the seismic design phase. They can, however, be applied to other classes of buildings. Portions of this guideline may be excluded during implementation when appropriate extra investigation and / or research undertaken.

The design earthquake ground motion is composed using the following procedure : (1) evaluate the basic response spectrum ; (2) compute the dynamic characteristics of the surface soil ; (3) set up the design response spectrum ; (4) generate the design earthquake ground motion time history, if necessary. The concept of the design response spectrum is shown in Fig. 1.

The design response spectra determined must be those of the horizontal and/or vertical components for two design levels. Each design response spectrum must be computed with a seismic activity coefficient, a standard response spectrum, and coefficients of both the longer-period component and soil amplification. Furthermore, coefficients of both liquefaction and topographical effect must be taken into account when those effects can not be ignored. A flowchart for this composition of design earthquake ground motion is shown in Fig. 2.

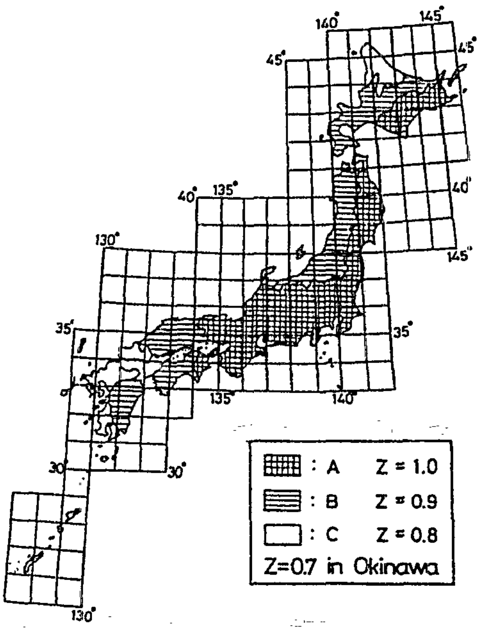


Fig. 3. Seismic zoning factor, Z (use as ξ)

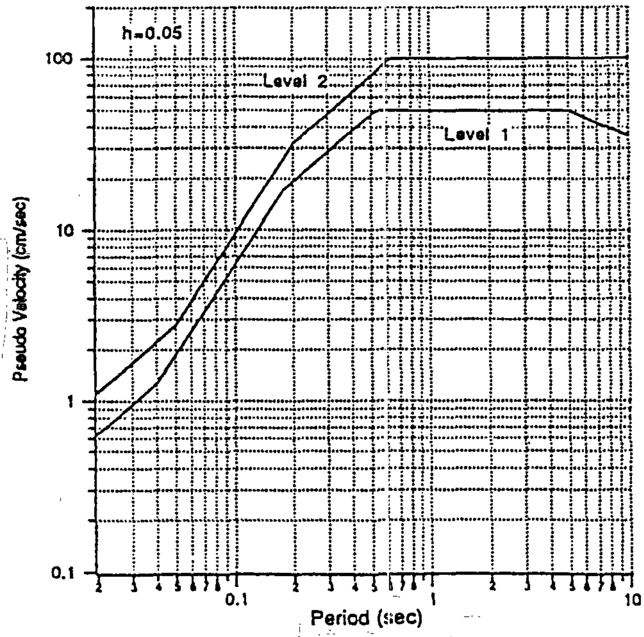


Fig. 4. Basic response spectrum for horizontal motion, ${}_{H}B(T)$

This composition is prescribed as follows.

(1) Design earthquake ground motion must be determined considering the seismic activity around the construction site, the properties of ground motion at the engineering-oriented base layer (EOBL), the longer-period components of the earthquake ground motion, and the amplification characteristics of the surface soil.

(2) Design earthquake ground motion must be determined for the following two design levels.
  Level 1 - the level of earthquake ground motion that is expected to occur more than once during the service period of the building
  Level 2 - the level of the maximum ground motion that has been experienced in the past or is expected to occur in the future around the site

(3) Design earthquake ground motion must be set up for both horizontal and vertical motions.

(4) Design earthquake ground motion must be first set up as design response spectrum in the following form: acceleration response spectrum or pseudo relative velocity response spectrum with 5% damping ; valid for the period range between 0.02 and 10 sec.

(5) Design earthquake ground motion time history is subsequently generated based on the design response spectrum.

Design Response Spectrum for Horizontal Motion, ${}_{H}S(T)$

The design response spectrum for horizontal motion is computed using the following expression.

$$ {}_{H}S(T) = \xi \cdot {}_{H}B(T) \cdot {}_{H}L(T) \cdot {}_{H}G(T_i) \tag{1} $$

where ξ is the seismic activity coefficient (Fig. 3), ${}_{H}B(T)$ is the basic response spectrum for horizontal motion (Fig. 4), ${}_{H}L(T)$ is the coefficient of the longer-period component for horizontal motion (Fig. 5), ${}_{H}G(T_i)$ is the coefficient of soil amplification for horizontal motion (Fig. 6), T is the period, Ti is the i-th period that defines the amplification property of soil layers.

The computed spectrum is further modified by incorporating the coefficients of both liquefaction and topographical effect, when the possibility of liquefaction in sandy soil is high, and/or when the effect of surface land form can not be ignored. The expression is then

$$ {}_{H}S'(T) = {}_{H}S(T) \cdot {}_{H}P(T) \cdot {}_{H}I(T) \tag{2} $$

where ${}_{H}P(T)$ is the coefficient of liquefaction for horizontal motion, ${}_{H}I(T)$ is the coefficient of topographical effect for horizontal motion.

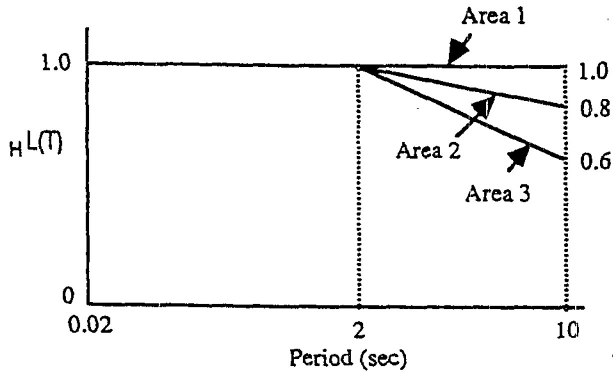


Fig. 5. Coefficient of longer-period component for horizontal motion, $_HL(T)$

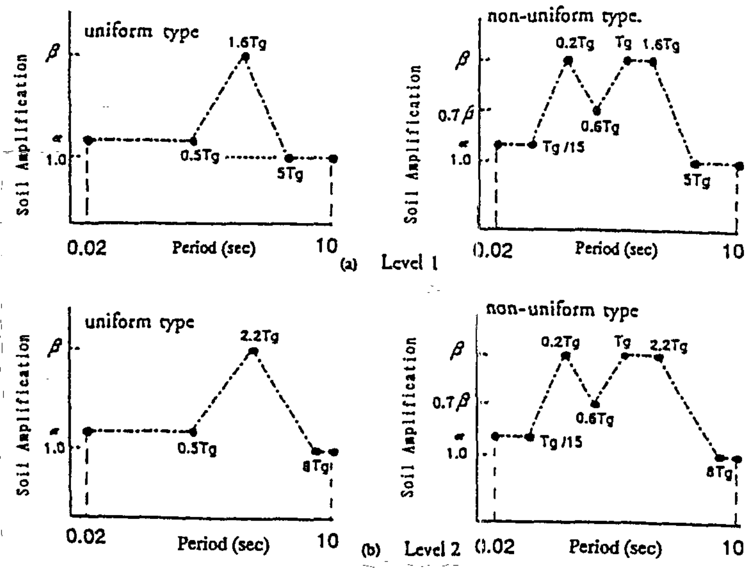


Fig. 6. Coefficient of soil amplification for horizontal motion, $_HG(T_i)$

When the design response spectrum is required at the EOBL, the following expression is used.

$$_HS(T) = \xi \cdot {_HB(T)} \cdot {_HL(T)} \tag{3}$$

The magnification in acceleration response spectra must not exceed 4 for design response spectra. The basic response spectrum for horizontal motion, $_HB(T)$, is defined as the response spectrum at the EOBL and is provided in Fig. 4.

Seismic Activity Coefficient, ξ

The seismic activity coefficient introduces regional information about the seismic activity. The seismic zoning factor (as shown in Fig. 3) that is used in the current seismic design code may be used for this coefficient.

Coefficient of the Longer-period Component for Horizontal Motion, $_HL(T)$

The coefficient of the longer-period component for horizontal motion introduces the regional gap into the amplitude of the longer-period components. In terms of this coefficient, Japan is divided into the three regions. The coefficients for those three areas are shown in Fig.5.

Coefficient of Soil Amplification for Horizontal Motion, $_HG(T_i)$

The coefficient of soil amplification for horizontal motion introduces the amplification characteristics of the soil deposit above the EOBL and is prescribed for different classes of surface soils and for two design levels. The surface soils are classified into two categories : uniform type and non-uniform type. The non-uniform type is assigned when $\Delta V/Ve$ is larger than or equal to 0.2, where ΔV is the variation of shear wave velocities of surface soil deposits and Ve is the average shear wave velocity of surface soils, and when Ve/Vb is larger than or equal to 0.25, where Vb is the shear wave velocity at the base layer. Otherwise, the uniform type is assigned. ΔV and Ve are defined as follows.

$$Ve = \sum_i Vi \cdot hi / \sum_i hi, \qquad \Delta V = \sum_i (|Vi - Ve| \cdot hi) / \sum_i hi \tag{4}$$

where hi is the thickness of the i-th layer and Vi is the shear wave velocity of the i-th layer.

The coefficients of soil amplification for horizontal motion, $_HG(T_i)$, are given in Fig. 6. The fundamental period of surface soils Tg, the coefficient of soil amplification in short period α, and the maximum coefficient of soil amplification β are given as follows.

Table 1. Liquefaction category

Category	Influence	F_L	Correct
A	ignorable	$1.5<F_L$	No
B	exists	$1.0<F_L\leqq 1.5_L$	Yes
C	liquefaction	$F_L\leqq 1.0$	detail*

* individual study in detail

Table 2. Coefficient of liquefaction for horizontal motion

Design Level	Coefficient of liquefaction				
1	T(s)	0.02	1.6Tg	5Tg	8Tg
	$_HP(T)$	1.0	1.0	1.2	1.0
2	T(s)	0.02	2.2Tg	5Tg	8Tg
	$_HP(T)$	1.0	1.0	1.2	1.0

$$Tg=4\sum_{i} hi / Ve \tag{5}$$

For Level 1

For the uniform type,

$\alpha=1.5-0.5Tg$, and $Tg\geqq 0.5$

$\beta=2.6-1.6\,(Ve/Vb)$

For the non-uniform type,

$\alpha=1.9-0.9Tg$, and $Tg\geqq 0.5$

$\beta=3.2-2.2\,(Ve/Vb)$

For Level 2

For the uniform type,

$\alpha=1.0-0.4Tg$, and $Tg\geqq 0.5$

$\beta=2.4-1.4\,(Ve/Vb)$

For the non-uniform type,

$\alpha=1.6-Tg$, and $Tg\geqq 0.5$

$\beta=2.9-1.9\,(Ve/Vb)$

The coefficient of topographical effect for horizontal motion introduces the influence of the land forms at the site on the ground motion. The coefficient of soil amplification assumes that a soil deposit consists of horizontally layered soils.

Coefficient of Topographical Effect for Horizontal Motion, $_HI(T)$

However, in most cases, the underground structure has geological irregularities in the layering or surface land forms. When the influence of such irregularities cannot be ignored, the effect of soil amplification should be considered according to the soil properties. The soil conditions with geological irregularities include those for surface irregularity, such as cliffs, slopes, hills (or ridges), embankments, and valleys and that for the irregularity of layer interfaces.

Coefficient of Liquefaction for Horizontal Motion, $_HP(T)$

The coefficient of liquefaction for horizontal motion introduces the influence of the earthquake-induced excess pore pressure on the ground motion and is prescribed according to the stages of liquefaction. When the soil deposit includes saturated sand with high liquefaction potential, another non-linearity due to an increase in the pore pressure, which causes a decrease in the effective confining pressure, should be considered. This is in addition to the non-linearity of soil due to an increase in the strain that is already taken into account in this guideline by discriminating the amplification property according to the level of the earthquake motion at the EOBL. The influence is classified into categories according to the liquefaction potential described by a parameter, such as the liquefaction resistance ratio, F_L, which is commonly used in Japan. The liquefaction category and the coefficient of liquefaction for horizontal motion are shown in Tables 1 and 2, respectively.

Design Response Spectrum for Vertical Motion, $_VS(T)$

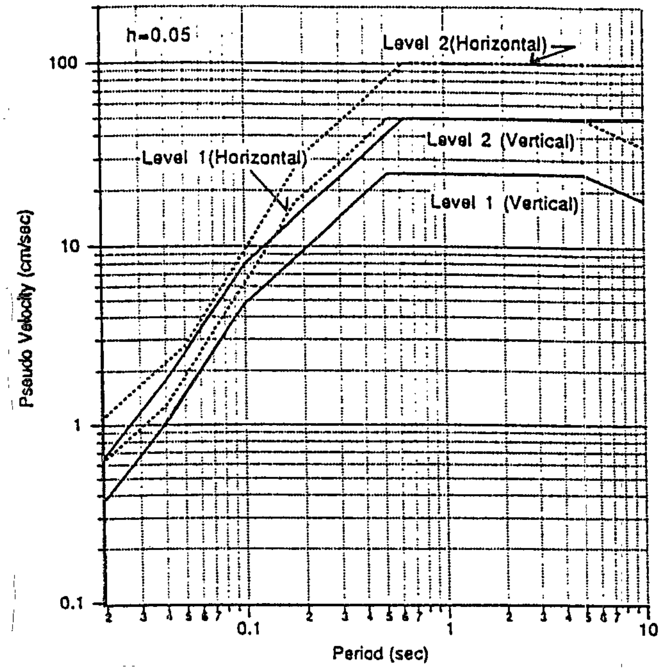


Fig. 7. Basic response spectrum for vertical motion, $_{V}B(T)$

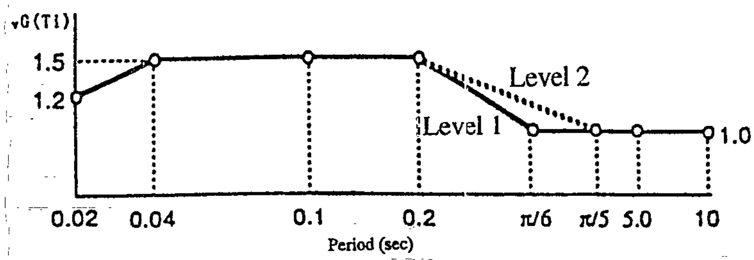


Fig. 8. Coefficient of soil amplification for vertical motion, $_{V}G(T_i)$

The description for vertical motion is essentially identical to that for the horizontal motion. Compared with the research activity for horizontal motion, however, that for vertical motion is inadequate in providing sufficient data. Therefore, the basic response spectrum and the coefficient of soil amplification are explicitly prescribed. The coefficients of longer-period, liquefaction, and topographical effect are added only to maintain consistency with the horizontal motion. The basic response spectrum for vertical motion, $_{V}B(T)$, is defined as the response spectrum at the exposed EOBL and is provided in Fig. 7. The coefficient of soil amplification for vertical motion, $_{V}G(T_i)$, introduces the amplification property of the soil deposit above the base layer for vertical motion and is prescribed for the different classifications of surface soils and for two design levels, as shown in Fig. 8.

Generation of Design Earthquake Ground Motion Time History

The design earthquake ground motion time history must be generated for two design levels considering the frequency content and time varying property of the amplitude. This time history must be generated so that the response spectrum is compatible with the design response spectrum. The time-varying property of ground motion is prescribed by both the duration and by the envelope function. There are many schemes to define wave forms. Here, the acceleration wave form is expressed as a superposition of many components. In most cases, the phase angle of the i-th component is assumed to be uniformly distributed between 0 and 2π. There is a method in which phase angles of a recorded accelerogram are used instead of random phase angles. In such a case, it is preferable to avoid a record that has a small magnitude and a short duration. The generated accelerogram should be qualified using criteria such as good compatibility with the design spectrum, sufficient number of frequency components, and proper values of peak velocity and peak displacement. As check points in determining the compatibility of the resulting wave form with the design response spectrum, three items, such as minimum spectral ratio between the calculated response spectrum and the design response spectrum, coefficient of variation of spectral ratio, and deviation of average spectral ratio from 1, can be considered.

It is generally recognized that the duration and the envelope function of earthquake ground motion reflect the process of fault rupture. Earthquakes of magnitudes 7 and 8 are assumed for design Levels 1 and 2, respectively. Because the design earthquake ground motion for design Level 1 is used mainly in the allowable stress design method, the duration of time history may be long enough to give peak response values. For design Level 2, the coda portion of the wave should be taken into account to consider the non-linear response of a structure.

Example of Generated Design Earthquake Ground Motion

We show the composition of the design response spectra, $_{H}S(T)$, for two sites, (Site 1) and (Site 2), with the

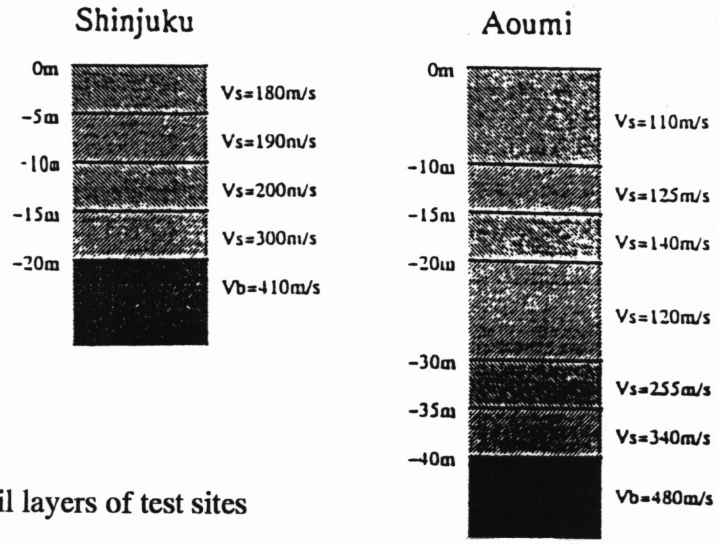


Fig. 9. Soil layers of test sites

Table 3. Parameters for determining ${}_{H}G(T_i)$ for two test sites

	Site 1	Site 2
Ve(m/sec)	217.5	165
Tg(sec)	0.368	0.970
Ve/Vb	0.544	0.413
ΔV(m-sec)	41.25	66.25
ΔV/VE	0.190	0.402
Soil Classification	Uniform	Non-unioform
α (Level 1)	1.32	1.03
α (Level 2)	0.85	0.63
β (Level 1)	1.73	2.29
β (Level 2)	1.64	2.12

seismic activity coefficient of 1.0 and with the coefficient of the longer period component, ${}_{L}(T)$, of 1 for the period longer than 2 sec. The configurations of the soil layers at each site are shown in Fig. 9. The parameters used for composing ${}_{H}G(T_i)$ are summarized in Table 3. The design response spectra composed for Sites 1 and 2 are shown in Fig. 10 for two design levels. The time histories corresponding to the given spectra were generated for the basic design response spectra. The time histories are shown in Fig. 11. It seems that good compatibility is obtained among the design spectra and those of observed strong motions in both cases.

Usage of the Design Earthquake Ground Motion

When the spectral modal analysis method is used in the dynamic analysis of structures, the design response spectrum may be corrected in accordance with each modal damping factor. When input motion is required at ground levels other than the base layer or ground surface, design earthquake ground motion may be determined using the response analysis of the soil deposits.

CONCLUDING REMARKS

In this paper a brief outline was described to determine the design earthquake motion in a simplified manner taking the site condition into consideration. This method is believed to be the alternative way to the conventional ones such as using observed strong motion records at different sites or synthesizing input motions through complicated and detailed calculation.

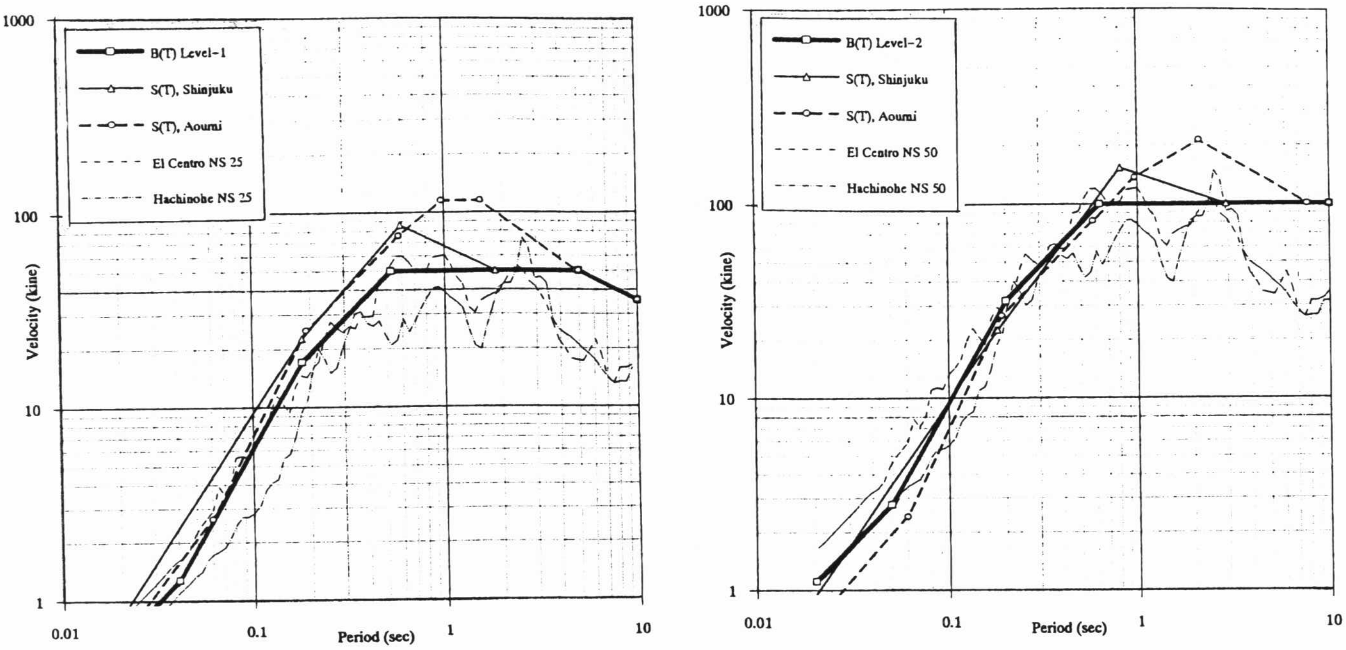
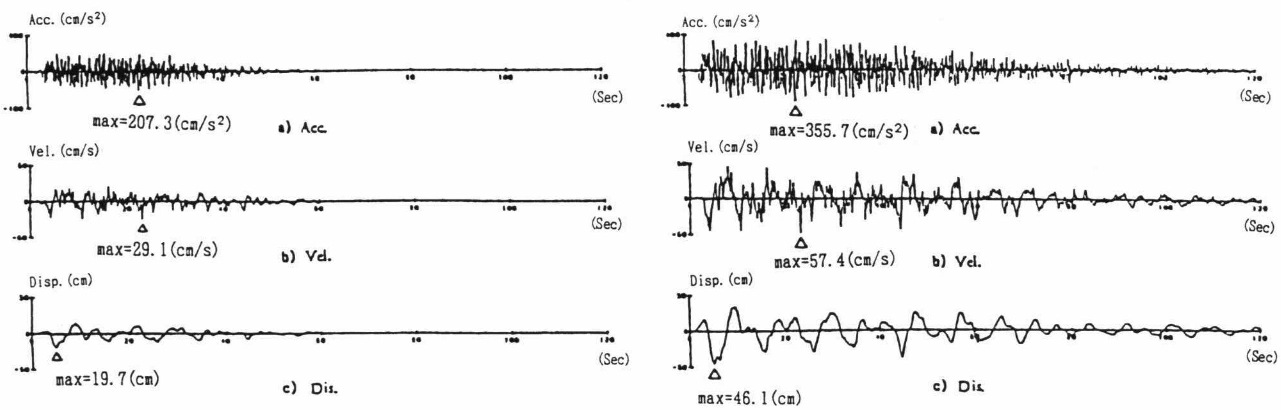


Fig. 10. Design response spectra for test sites



(a) for Level 1 (b) for Lavel 2

Fig. 11. Generated time histories

It is recommended to use the proposed method in addition to the conventional ones to check and confirm the effectiveness of this method. Further investigation is also required to be done on the subjects with in sufficient information, such as topographical condition and liquefaction effect. Compilation of strong earthquake motion records is necessary to ensure or improve the validity of this method. Data exchange program among related institutions worldwide will be effective to promote the data-compilation and relevant research.

ACKNOWLEDGEMENTS

Many researchers have contributed greatly to the completion of this guideline proposal. We express our sincere thanks to Dr. I.Okawa and Mr.T.Kashima, members of BRI, and the Research Committee members for their collaboration.

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