



ON REVISION OF AIJ RECOMMENDATIONS OF SEISMIC LOADS ON BUILDINGS

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SUMMARY

Architectural Institute of Japan (AIJ) has recently publicized the draft of seismic load s on buildings for 2004 revision of AIJ Recommendations for Loads on Buildings [1]. The draft has the following features: 1) more detailed inclusion of ground conditions, 2) adaptability to the performance-based design concept, 3) basis on the probabilistic seismic hazard assessment results, and 4) inclusion of design earthquake ground motions for dynamic response analyses. In the present paper, AIJ revision is reported briefly and an equivalent static force proposed in the recommendations is intensively discussed, and some future studies are mentioned.

BACKGROUND OF AIJ LOAD RECOMMENDATIONS

AIJ started to issue the first recommendations in 1975. The original role of the recommendations were expected to publicize the-state-of-art research results which are useful for structural design of buildings, while the design loads specified in Japanese Building Standard Law have not frequently been revised so far. The first AIJ recommendations did not include sections on seismic loads simply because many

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relevant activities had been going on elsewhere then. After the past three times revisions: 1981, 1986 and 1993, the year of 2004 is the year for the current revision of the recommendations.

The major role of the AIJ recommendations is to describe "appropriate design loads" while the current code of practice stating only the minimum level of design loads, and the recommendations have been used not only as design criteria for various decision-making but also as useful materials for structural design so far. At the revision in 1993 [2, 3], the previous recommendations were extensively reviewed and drastically revised, i.e., such as 1) first inclusion of seismic loads, 2) adoption of basic values of loads, 3) Applicability to various design methods such as allowable stress design (ASD), ultimate strength design (USD) and limit state design (LSD), and 4) to provide scientific knowledge on mean tendency as well as on variability of various loads. At the last revision in 1993, all loads applied to buildings were taken and treated statistically within the same framework so that the recommendations can be effectively utilized even if a different design method is adopted. Basic values of loads which correspond to characteristic values of loads, equivalently, 100-year return period values for time-varying loads, and 99 percent-fractile values for non-time-varying loads, have been introduced first in the recommendations. Then the design loads used for actual design are expressed in terms of the product of the basic value and corresponding load factors. The load factors are determined in such a way that they depend upon both target (required) structural performance level and variability of the loads. Parts of the AIJ recommendations issued in 1993 indeed provided the basis for the 1998 revision of the Building Standard Law in Japan.

BASIC REQUIREMENTS FOR 2004 REVISION

General

The current revision of the seismic load in the recommendations particularly focuses the following subjects: 1) more detailed reflection of ground conditions, 2) adaptability to the performance-based design concept, 3) basis on the probabilistic seismic hazard assessment results, and 4) inclusion of design earthquake ground motions for dynamic response analyses.

As for 1), the previous recommendations just categorize ground soil conditions into only three: firm ground, soft diluvial soil and soft soil, to estimate response spectra to a building. Viewing that the ground soil conditions can indeed affect not only the input ground motion characteristics but also the vibration behavior of a building, these effects of ground soil conditions on the structural response must be treated properly. To do so, site-specific analyses have to be done if the information on the ground characteristics is given. The recommendations suggest to collect the information as much as possible to reflect them on the calculation of seismic load. One-dimensional wave propagation theory is placed on as a recommended method to reflect the shear wave amplification effect within the ground soil although more advanced methodology has been developed [4]. Theoretical solutions for a two-layer ground media is also suggested in case that sufficient information required by the 1D wave propagation theory is not available. Soil-structure interaction effect is roughly taken into account.

As for 2), the concept of the R factor is fully utilized, but the critical inter-story drift can be explicitly given toward a displacement-based seismic design rather than force-based in the concept of the current performance-based seismic engineering, which must be taken care of nowadays. LSD is one of the targeted design methods which will be understood as the most promising method to achieve the performance-based design. The R factor in the US, equivalently, the structural characteristic factor D_s in Japan and the behavior factor Q in the European countries, have the same origin to approximately take account of inelastic behavior of a building. These factors is, however, not sufficient toward the future performance-based design since they are not directly related to clearly defined performance of a building.

The recommendations suggest to use the same factor, but to estimate structural performance in terms of story drift which is considered a good indicator to represent the damage state of a building.

Performance-based design (PBD) has been attracting practitioners as well as researchers for the last decade [5]. The most important objective for building design is to clearly define various class of required performance under multi-levels of seismic loads. LSD is one of the most promising structural design method in which two kinds of design limit states, i.e., ultimate limit state (ULS) and serviceability limit state (SLS) are often taken as targeted structural performance [6-8]. In Japan, a reparability limit state (RLS), which much more focuses on functional failure of buildings and their contents inside as private property has been seriously discussed after the Kobe earthquake 1995, viewing the fact that buildings slightly damaged from the viewpoint of structural safety were not functional anymore. After in-depth discussion on whether or not the RLS should be included, eventually the revised recommendation does not cover the RLS simply because the RLS cannot clearly be defined in the present time. This issue will need further discussion and study.

As for 3), the probabilistic seismic hazard map covering the whole Japan has been achieved to specify the 100-year peak ground acceleration (PGA) on the engineering bedrock considering historical earthquake data as well as available information on active faults. The previous version defined the hazard map of PGA at the ground surface and was based on the historical earthquake data only. Since various ample information has been available nowadays such as information on active faults throughout Japan, more precise attenuation formulae proposed recently, these precious information must be reflected for the evaluation of seismic ground motions. To incorporate them in the hazard evaluation, the probabilistic seismic hazard analysis based on the Cornell's approach [9] is the most appropriate. It then follows that the hazard map associated with the PGA on the bedrock surface has been built in the current revision.

As for 4), dynamic response analysis, which is nowadays popular in Japan, requires time histories and a dynamic building model. The revised AIJ recommendations describe two ways to define the seismic design load: an equivalent static force and design earthquake motions. In order to specify the earthquake motions, there are two methods suggested: the earthquake motions compatible to the response spectra on which the equivalent static force is based, and the earthquake motions based on fault models which have recently been developed and become available.

FRAMEWORK OF REVISED SEISMIC LOAD

Contents of revised recommendations

The revised recommendations describe both seismic load which is, as the external force, applied to equivalent static analyses of buildings, and a basic procedure setting design earthquake ground motions required in the dynamic response analyses. The external force is specified in terms of a story shear force at each story of a building, which is expected to be used for the LSD, ASD and USD of the building. As was done in the previous version, the external force is computed by means of the response spectrum method in which modal decomposition of the structural model is needed. It is suggested in the recommendations that a structural model should be based on a Sway-Rocking (SR) model with multiple lumped mass and stiffness which can take account of the soil-structure interaction effect (inertial interaction) properly [4].

The structural response of the SR model which results in the seismic load effect is a function of many factors from earthquake ground motions characteristics as well as building vibration characteristics, as is shown in Figure 1.



Figure 1 Factors determining seismic load to a building

More specifically, from the response spectrum defined at the engineering bedrock surface, the modified response spectrum to the SR building model has to be taken considering not only the wave amplification effect within ground soil media but also the soil-structure interaction effect between the ground and the building.

The seismic load effect to an inelastic building subjected to strong shaking must be the one that takes account of such inelastic behavior of the building. The concept that is the same of the R factor used in the US is adopted in the recommendations.

Table 1 Chapter 7 of revised AIJ load recommendations [1]

7. Seismic Loads
7.1 Estimation of Seismic Loads
7.1.1 Seismic load and design earthquake ground motion
7.1.2 Idealization of buildings and location of input ground motion
7.2 Calculation of Seismic Loads
7.2.1 Methods for calculating seismic load
(1) Procedure with modal analysis
(2) Procedure without modal analysis
(3) Consideration of soil-structure interaction
7.2.2 Acceleration response spectrum
(1) Acceleration power spectrum at engineering bedrock
(2) Soil amplification factor
(3) Adjustment factor for soil-structure interaction
(4) Basic peak acceleration
(5) Conversion factor for return period
7.2.3 Reduction factor related to ductility and response deformation
7.2.4 Amplification factor related to irregularities of building
7.3 Design Earthquake Motions
7.3.1 Fundamental concept for generating design earthquake motions
7.3.2 Design earthquake motions compatible with response spectrum
7.3.3 Design earthquake motions based on scenario earthquakes
(1) Scenario earthquakes
(2) Evaluation of earthquake motions
(3) Generation of design earthquake motions
(4) Earthquake response analysis of buildings

The revised recommendations also include the basic procedure for generating earthquake ground motions to be used for dynamic response analyses, which was not covered in the previous version. The background of this inclusion is simply due to the fact that dynamic response analyses have now often been used, and much advancement of generation technique of ground motion time histories. The

Table 1 shows the contents of chapter 7 describing the revised seismic load in the AIJ recommendations in order to demonstrate the overall framework of seismic loads.

Table 2 Comparison of revised and previous recommendations

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Response characteristics of building	Modal analysis	not done	done	done
	Soil-structure interaction (kinematic interaction)	Modification of T_1 and ζ_1	Sway-Rocking model	T_j and ζ_j are evaluated properly.
	Distribution of story shear force	Empirical distribution of story shear force k_{Vi}	Superposition of mode (SRSS, CQC)	Superposition of mode (SRSS)
	Effect of inelastic response	Reduction factor for external force k_{Di}		Structural characteristic factor D_s

The equivalent static force is defined as a story shear force of each story of a building V_{Ei} as in the following equation, based on the rule of square root of the sum of square (SRSS). Therefore, the seismic force must basically be computed from the results of the modal analysis of a SR lumped mass system. The recommendations also state a procedure without carrying out the modal analysis in case that contributions from the second and higher modes can be neglected or included approximately because of significance of the first mode.

$$V_{Ei} = k_{Di} k_{Fi} \sqrt{\sum_{j=1}^{j_c} V_{ij}^2} \quad (1)$$

where k_{Di} and k_{Fi} are, respectively, a factor representing building plastic deformability and a penalty factor representing irregularity of a building, j_c is a maximum number of vibration mode under consideration and V_{ij} is an i -th story shear force response due to j -th vibration mode, which takes the following form.

$$V_{ij} = \frac{S_a(T_j, \zeta_j)}{g} \sum_{k=1}^n (w_k \beta_j \phi_{kj}) \quad (2)$$

where $S_a(T_j, \zeta_j)$ is an acceleration response spectrum with natural period T_j and a damping ratio ζ_j , g : acceleration gravity, n : the total number of story, w_k : the weight of the k -th story mass, β_j : j -th participation factor and ϕ_{kj} : k -th story value of j -th modal shape.

The response spectrum $S_a(T_j, \zeta_j)$ is now computed based on the spectral transformation technique between the response spectrum and the corresponding power spectrum which is based on the assumption of the stationary random process and the first excursion probability theory [10-12]. The recommendations suggest the following simple rule to determine the maximum response value $S_a(T_j, \zeta_j)$ using a mean peak factor of a linear single-degree-of-freedom (SDOF) system with a natural period T_j and a damping ratio ζ_j $k_p(T_j, \zeta_j)$.

$$S_a(T_j, \zeta_j) = k_p(T_j, \zeta_j) \sigma_a(T_j, \zeta_j) \quad (3)$$

where, $\sigma_a(T_j, \zeta_j)$ is a root mean square of an acceleration response process of the SDOF system which is given below, and a peak factor of 3.0 can be used from experience even though $k_p(T_j, \zeta_j)$ is a function of the natural period and damping of the system. The root mean square of the acceleration response of the system subjected to the input random process with its one-sided power spectrum denoted by $G_a(\omega)$ can be computed based on its original physical meaning,

$$\sigma_a^2(T_j, \zeta_j) = \int_0^{\infty} |H_j(\omega)|^2 G_a(\omega) d\omega \quad (4)$$

where $H_j(\omega)$ is an acceleration transfer function of the system to the input acceleration process described by

$$|H_j(\omega)|^2 = \frac{(\omega_j^2)^2 + (2\zeta_j \omega_j \omega)^2}{(\omega_j^2 - \omega^2)^2 + (2\zeta_j \omega_j \omega)^2} \quad (5)$$

where $\omega_j = 2\pi/T_j$.

$G_a(\omega)$ is a one-sided power spectrum of the input earthquake ground motion to be applied to the SR lumped mass system of a building and is determined from the following equation so as to take account of the soil-structure interaction and wave amplification effects within the ground surface, as is computed from the following form in a frequency domain.

$$G_a(\omega) = |H_{GS}(\omega)|^2 |H_{SSI}(\omega)|^2 G_{a0}(\omega) \quad (6)$$

where $H_{GS}(\omega)$: a function representing wave amplification effect of the ground surface which must be evaluated by means of a one-dimensional wave propagation theory, $H_{SSI}(\omega)$: the SSI adjustment function which is needed for the case for deeply embedded foundation or rigid foundation of a building, and $G_{a0}(\omega)$: a one-sided power spectrum of the acceleration time history at the bedrock. Approximate functions for $H_{GS}(\omega)$ and $G_{a0}(\omega)$ are also provided in the recommendations if sufficient information on the ground conditions cannot be obtained. In such cases, $H_{GS}(\omega)$ can take the following simple function which is based on a theoretical solution of two-layered media.

$$|H_{GS}(\omega)|^2 = \left| \frac{1}{\cos A + i\alpha_G \sin A} \right|^2 : A = \frac{\omega T_G}{4\sqrt{1 + 2i\zeta_G}} \quad (7)$$

where α_G is an impedance ratio of the ground surface motion to that of the engineering bedrock, T_G and ζ_G are, respectively, a dominant period and a damping ratio of the ground lying on the bedrock. $H_{GS}(\omega)$ for typical ground conditions are plotted in Fig. 3.

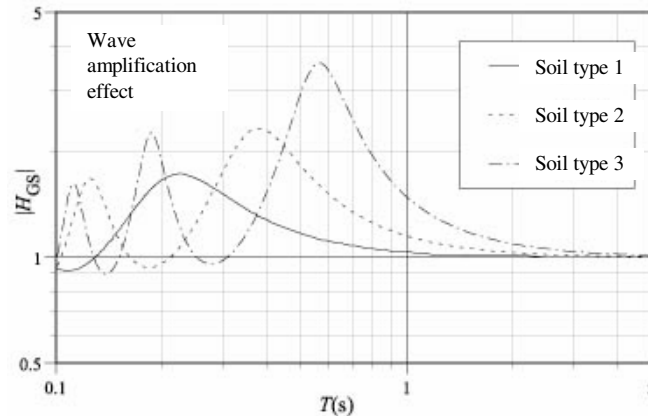


Figure 3 A function representing wave amplification effect for typical ground conditions

Regarding $H_{SSI}(\omega)$, an alternative function which can be used easily is proposed. The effect of soil-structure interaction is associated with change of input ground motions due primary to embedment of

building foundation, which is so called "kinematic interaction" and can be approximated in terms of the following simple form.

$$|H_{SSI}(\omega)|^2 = \begin{cases} \frac{1}{1+2\eta\delta_d^2} & : \delta_d \leq 1 \\ \frac{1}{1+2\eta} & : \delta_d > 1 \end{cases} \quad (8)$$

where δ_d is a non-dimensional frequency and η is a ratio of embedment depth to the building foundation size. $H_{SSI}(\omega)$ in the above equation is plotted for different ratios of embedment depth as is given in Fig. 4 [13].

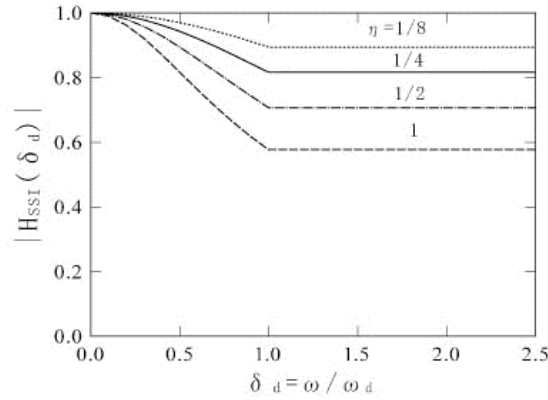


Figure 4 An SSI adjustment function $H_{SSI}(\omega)$ for different embedment ratios [13]

Now $G_{a0}(\omega)$ can be transformed from the response spectrum evaluated at the engineering bedrock since the intensity of the power spectrum is not given there, in other words, no ground motion attenuation equations available have been proposed to estimate the power spectrum. Therefore, the recommendations show the response spectral shape normalized by the basic PGA at the engineering bedrock a_0 , as is plotted in Fig. 5 and is given as follows,

$$S_a(T, 0.05) = k_{rE} a_0 S_0(T, 0.05) = \begin{cases} k_{rE} a_0 (1 + (k_{R0} - 1)T/T'_C) & : (T < T'_C) \\ k_{rE} a_0 k_{R0} & : (T'_C \leq T < T_C) \\ k_{rE} a_0 k_{R0} T_C / T & : (T \geq T_C) \end{cases} \quad (9)$$

where k_{rE} : a return period conversion factor if PGA values except for a 100-year return period value are needed, a_0 : a basic PGA at the engineering bedrock which can be read from the seismic hazard map shown in Fig. 5, $S_0(T, 0.05)$: a normalized acceleration response spectrum, T'_C and T_C : periods controlling the spectrum shape as are indicated in Fig. 5, and k_{R0} : a response amplification factor in the range from 2 to 3.

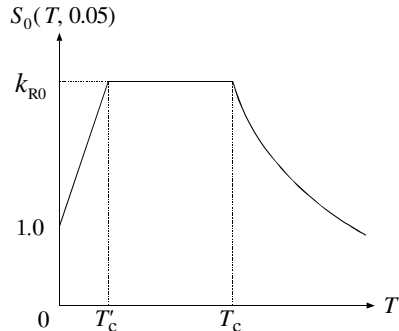


Figure 5 A normalized acceleration spectrum at engineering bedrock

Transformation between power and response spectra [12]

Since frequency dependency of the wave amplification within the ground layers as well as of the soil-structure interaction effect between a building and surrounding ground must be taken into consideration for calculation of seismic loads, representation of the wave form in terms of the corresponding power spectra is considered useful and easy to treat. These frequency-dependent effects can recently be taken care of with several levels of sophistications such as 2-dimensional finite element methods and more advanced techniques [4]. In this regard, the representation in terms of the response spectra, which have been used so long in most seismic design, is not adequate for this purpose. Once the frequency dependency of each effect can be evaluated properly, then it can be multiplied with the input power spectrum to take account of each effect in a frequency domain.

Since the seismic load to be applied to a building model, however, can be computed from the response spectrum, as has been done so far, the evaluated power spectrum should be converted into the form of the response spectrum. This can be conveniently done based on the random process theory and the first excursion probability. The past literatures proposed the practical method for mutual transformation of the two spectra [12] based on the first excursion theory [10,11]. This recommendation adopts the proposed method. The method is based on the assumption that the maximum response of a linear SDOF subjected to a filtered stationary random process of the input motion can be probabilistically estimated. This assumption is now verified comparing the maximum response of a SDOF based on the step-by-step time integration method with the method used. Figures 6 show the comparison of results from the two methods [14]. Solid lines indicate the used method based on the first excursion theory and dotted lines are from the direct time history analyses. Relatively good agreement of the results can be observed within the natural period range of ordinary buildings except for the cases that the damping ratio of the SDOF system is small, say, 0.01, the natural period of the system is relatively long, and the duration time of the response is short. It can easily be understood that assumption of stationarity of the SDOF system response may fail in such cases: the short duration, a lower damping and relatively longer natural periods.

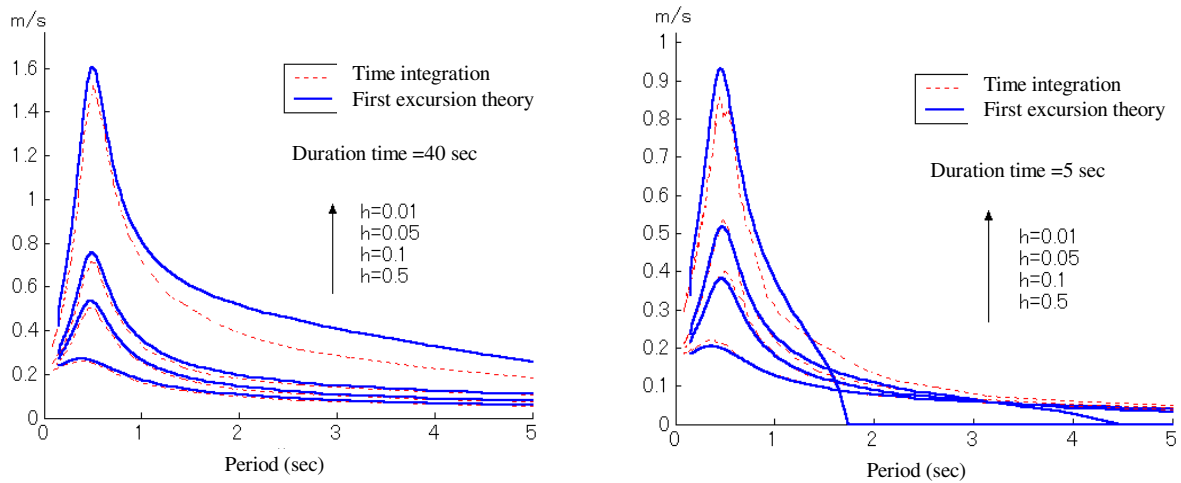


Figure 6 Accuracy of transformation of spectra [14]

Probabilistic Seismic Hazard Map

Probabilistic seismic hazard analysis has been conducted for all of Japan, which is based on the Cornell type approach. The hazard analysis is based on two types of source modeling, i.e., 28 earthquake regions based on historical earthquakes and 117 regions based on characteristic earthquakes all over Japan. The PGA attenuation equation from Annaka & Yashiro [15] is used since the equation provides peak ground acceleration at engineering bedrock in Japan. The equation takes the following form,

$$\begin{aligned}
\log A &= 0.606M + 0.000459H_c - 2.136 \log d + 1.730 \\
d &= R + 0.334 \exp(0.653M) \\
H_c &= \begin{cases} H & : H \leq 100\text{km} \\ 100 & : 100 < H < 200\text{km} \end{cases}
\end{aligned} \tag{10}$$

where M : an earthquake magnitude, R : a closest distance to the fault plane, H : a depth of the fault. The uncertainty of the above mean attenuation equation is taken 0.5 in a logarithmic scale.

Seismic hazard curves at every grid point by 15 degree in longitude and 15 degree in latitude have been computed and two levels of PGA, i.e., 100- and 500-year return period values at the bedrock are given in a form of hazard map. Figure 7 shows the hazard map of 100-year return period PGA value at the engineering bedrock, which gives the basic value of seismic load. Once two points on the hazard curve at a specified location are given, more accurate estimation of seismic load intensity can be achieved.

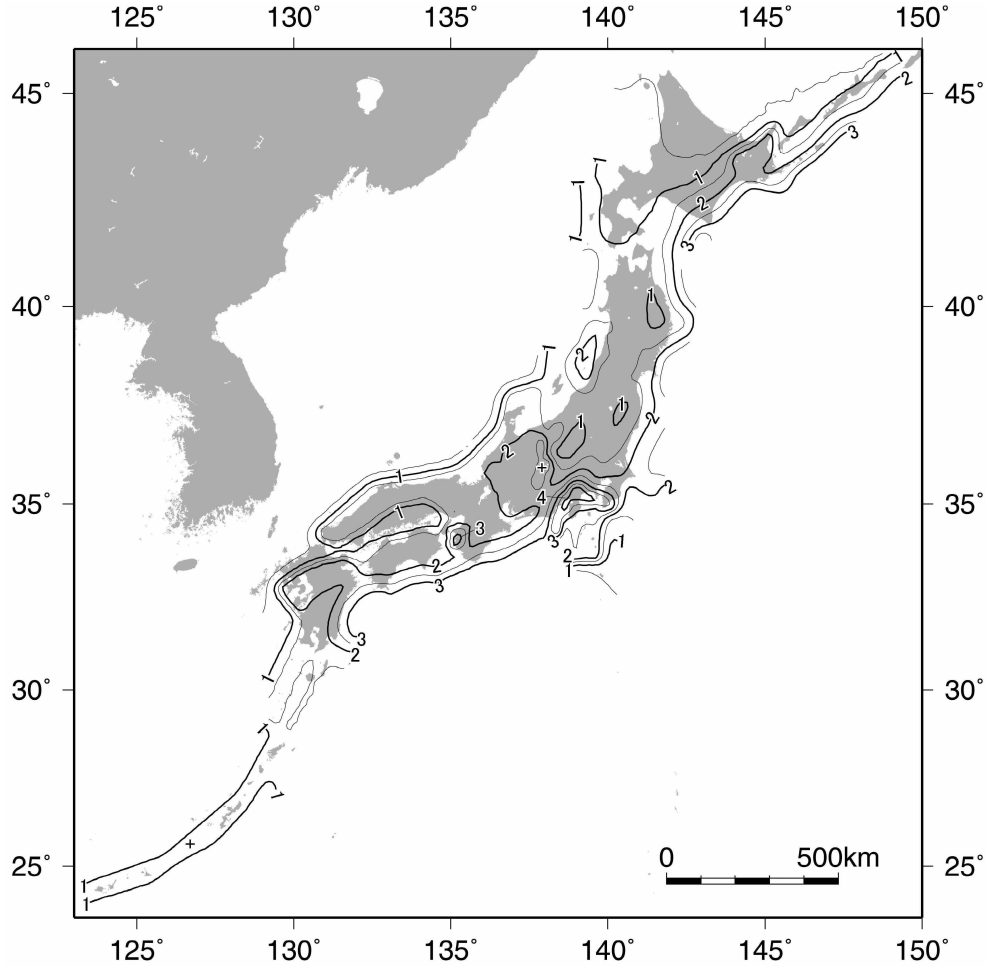


Figure 7 A standard hazard map for a basic PGA at bedrock (in m/s²) [1]

DISCUSSION AND FUTURE REQUIRED ISSUES

The revised AIJ recommendations for seismic loads requires slightly tedious calculations such as transformation of the response and power spectra, power spectrum representation as is seen in Eq. (6),

both of which have to be done in a frequency domain, computation of $H_{GS}(\omega)$ including complex numbers. These are handled by providing a spread-sheet computation downloaded from an AIJ web page. In addition, the analysis conditions, intermediate and final results on the probabilistic seismic hazard computation are also publicized through the web page. These can facilitate the tedious computation involved.

As future research subjects, the seismic loads which can meet the framework of the performance-based seismic design have to be explored more in a future. Regarding the above, the concept of the R factor has to be replaced by more accurate treatment of inelastic response behavior of buildings such as appropriate determination of the seismic external force to be used for the static pushover analyses of buildings. As was mentioned in a preceding section, various types of design limit states including reparability limit state have to be clarified and appropriate loading criteria corresponding to the limit states of interest have to be provided in a future.

CONCLUSIONS

The revised AIJ recommendations were described briefly and future research subjects are mentioned in the present paper. This revision has been conducted by a special revision committee on seismic loads in AIJ recommendations chaired by the first author of this paper.

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