A New Seismic Design Method for Railway Structures Considering Total Cost

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SUMMARY:
In general, designing a structure that minimizes a total cost, including not only construction but also repairing costs after severe earthquake, requires considerable number of calculations in a trial-and-error basis. In this research, a new design nomograph that gives combinations of demanding natural period, ductility and yielding coefficient in view of minimizing a total cost of structure is proposed by means of nonlinear numerical simulations. It is clarified through comparison of the nomograph and current design spectra based on past earthquake records that the structures comply with current design code meet the demands of preventing severe damage and minimizing the total cost simultaneously.

Keywords: performance based design, seismic design, principle of minimum total cost

1. INTRODUCTION

In the Japanese seismic design standards for highway or railway facilities, two types of design earthquake ground motions are considered; an earthquake to secure the serviceability of structures (the Level-1 earthquake motion), and an earthquake to secure the safety (the Level-2 earthquake motion) [Japan Road Association, 2002] [RTRI, 1999]. The Level 1 earthquake is defined so that its expected occurrence frequency is a few times during the service life of the structures. It is required that structures should be intact against the Level 1 earthquake. However, the legitimacy of the required performance in the engineering point of view has not been clarified [JSCE, 2000]. For example, when the level 1 earthquake with occurrence possibility of a once in 50 years is used, structures, which have exceedance probability for elastic limit of 37 % in 50 years, are designed. However, such design cannot give any information about damage degree of the structures. That is to say, the designed structure will exceed the elastic range against Level 1 earthquake whose probability is 37%. It follows that the structure, designed to be intact against the Level 1 earthquake, still have a potential to be suffering from unexpected damage.
In order to overcome such a problem, the new seismic design method has been proposed as an alternative to such a conventional method [JSCE, 2003]. This new design method is to secure the restorability from the cost-benefit point of view instead of response analysis. The total cost is calculated for each structure as a sum of initial construction, repair, and loss costs. The structural parameters minimizing the total cost is then determined. Figure 1 shows a basic concept of this procedure. Structures can satisfy the economic efficiency by using this method. This economic efficiency means structural function maintains economically after the earthquake. This method is regarded as one of possible seismic design procedures in the ISO standard [ISO TC98/SC3/WG10, 2005] In recent years, some studies considering the total cost are conducted [Ichii, 2002], [Abe et al, 2007]. In addition, this method is adopted to the design of water facility considering the economic efficiency [JWWA, 2009].
However, the structural design by considering the total cost needs complex procedure and advanced knowledge. In this research, a new design nomograph that gives combinations of demanding natural period, ductility and yielding coefficient in view of minimizing a total cost of structure is proposed based on nonlinear numerical simulations. The nomograph makes it possible to design a structure assuring the restorability performance without complicated cost-benefit calculations.

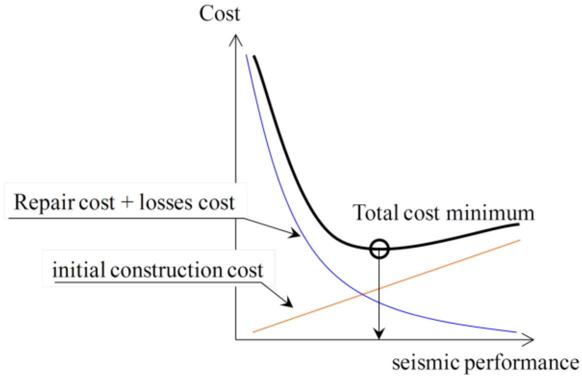


Figure 1. Concept of checking restorability by using total cost

2. RESTORABILITY VERIFICATION METHOD BY USING TOTAL COST

2.1. Attitude of the restorability verification method

Seismic restorability performance of structures is deemed to the performance to restore structural function in adequate time and cost after an earthquake. The performance is expressed as: "minimizing a total cost (a sum of initial construction, repair, and loss costs)." In this research, a total cost (*TC*) is defined as,

$$TC = C_I + \sum P_f \cdot C_f \tag{1}$$

Where C_I is an initial construction cost including material and construction cost, P_f is damage probability of structure, C_f is a loss due to earthquake (C_f = C_{RE} + C_{TD}), C_{RE} is a repair cost (C_{RE} = $b \times C_{RE0}$), C_{RE0} is a repair cost under the ideal condition, *b* is a coefficient representing the condition of construction and C_{TD} is an operating loss due to suspension of operation.
A loss cost due to earthquake does not contain the effect of loss of life, because structural safety against the level2 earthquake is verified prior to a verification of the restorability.

2.2. A new design nomograph for verification of restorability

Advanced knowledge is required about structural engineering and earthquake engineering for architect, when the restorability verification method is conducted by using total cost. Much dynamic analyses must be carried out, too. Now, it is difficult to design economical structure, when designer complies strictly with basic procedure as mentioned above.
In this study, a new method is proposed to design economical structures without complicated and enormous number of calculations. Namely, expected ground motions together with their probability of occurrence are prepared, and the structure's demanding natural period, ductility and yielding coefficient are selected so that the total cost is minimized against the bunch of motions. This structural performance is expressed as restorability nomograph. Figure 2 shows the procedure of composing a nomograph.
Firstly, the seismic hazard analysis is conducted for the selected site. By using this result, ground motions together with their probability of occurrence are calculated. The dynamic analyses of structures are then conducted, variating yielding seismic coefficient while keeping natural period and ductility demands constant. The relationship between yielding coefficient and damage probability is then obtained. Given the result, initial construction cost, repair cost and loss due to earthquake are evaluated for each structure. The total cost is obtained as a sum of these costs and loss accordingly. Consequently, a yielding seismic coefficient minimizing the total cost is determined. The same procedure is repeatedly conducted by varying the natural period and ductility of structure. The results are summarized as nomograph. In this study, the ductility μ_M is a ratio of maximum displacement δ_M to yielding displacement δ_y.

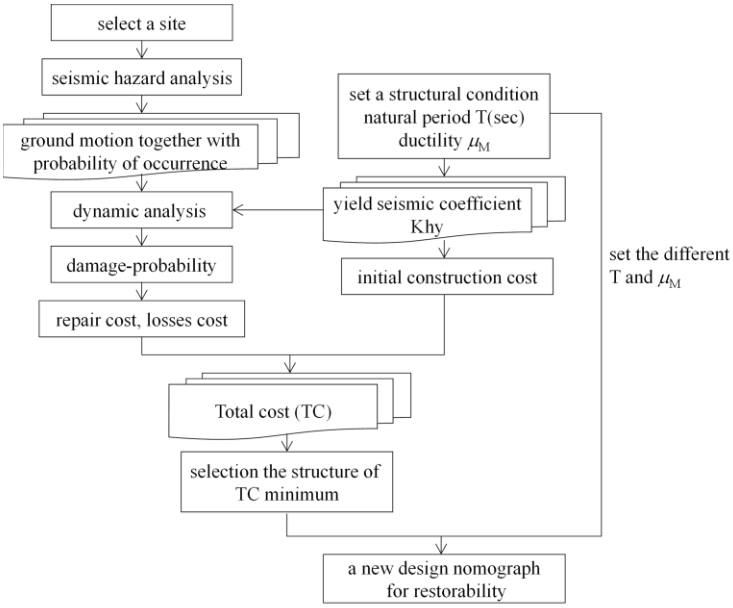


Figure 2. Flowchart of composing nomograph of checking restorability

2.3. Design procedure by using nomograph of restorability check

Figure 3 shows the design procedure by using nomograph of restorability check. At first, the structural safety against the Level2 earthquake is assessed. After that, the structural performance (natural period T_{eq}, ductility μ_M and yielding coefficient K_{hy}) is calculated by nonlinear static push-over analysis. Then the structural ductility response is calculated by non-linear response method using the proposed nomograph. Restorability of structure is checked by verifying that he response μ is less than the ductility μ_M. If the response μ exceeds maximum ductility μ_M, structural conditions are changed and the aforementioned procedure is carried out.

3. CALCULATION FOR THE NOMOGRAPH OF RESTORABILITY CHECK

In this section, the nomograph of restorability check is calculated for wall type RC pier. The value of the nomograph depends not only on the types of structure but also on seismicity at target area. Then, the nomograph at two different sites (Tokyo and Hiroshima) are calculated, whose seismicities are quite different each other.

3.1. Synthesizing of earthquake ground motion with probability of occurrence

We calculate the earthquake ground motion together with probability of occurrence. This ground motion is used for input earthquake motion to calculate structural damage probability. The occurrence probability of earthquake depends on location of site or assuming service life of the structure. The design period is assumed as 100 years which is the endurance o period of the standard railway facility.

3.1.1. Calculation of earthquake occurrence probability

Considering all possible fault models based on the active fault surveys and past seismic records, the occurrence probability of earthquake is given by seismic hazard analysis [Cornell, 1968]. Figure 4 shows the result of the seismic hazard analysis at Tokyo site. It is observed from the figure that exceedance probability become smaller as the intensity of the acceleration becomes larger.

3.1.2. Calculation of earthquake ground motion together with probability of occurrence

Earthquake ground motion is simulated based on the seismic hazard analysis. Firstly, a contribution factor from each fault to the given acceleration *a*(gal) is calculated [Kameda et al, 1997]. The focal

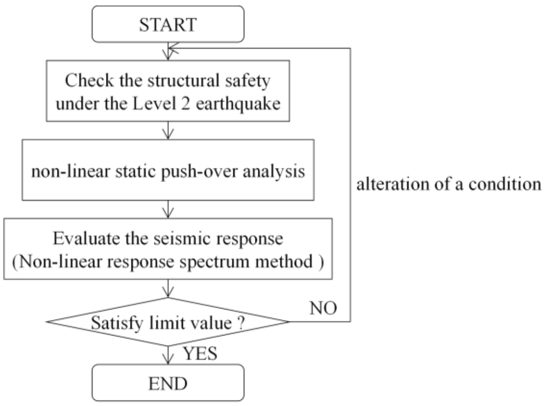


Figure 3. Flowchart of the checking restorability by using a proposed design nomograph

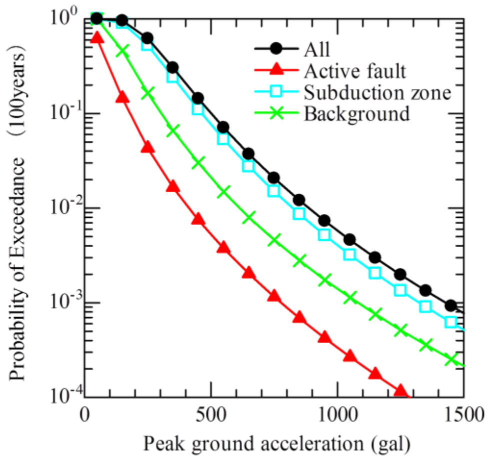


Figure 4. Result of the seismic hazard analysis (Tokyo site)

area causing the supposed earthquake is determined according to the contribution factor of each fault [Annnaka et al, 2005]. For example, suppose that 100 earthquakes in total are needed to be simulated at a specific location and that focal area A has a contribution factor of 20%. According to the proposed method, 20 sub-earthquakes in the area A are needed to synthesize the resulting earthquakes. Each of the 20 acceleration categories between 100 to 1500 gal at 100 gal intervals, i.e. 300 waves in total, are set as earthquake motions together with their occurrence probability in this study.

Firstly, the outline of the acceleration response spectrum with damping of 5% is constructed by using the attenuation relationship for the response spectrum [Annnaka et al, 1997]. The following attenuation relationships with regard to the average and the standard deviation of group delay time are used to determine the phase characteristics [Sato et al, 2000].

$$\mu_{tgr}^{(j)} = \alpha_1^{(j)} \times 10^{\beta_1^{(j)} M} \times R^{\gamma_1^{(j)}}$$
$$\sigma_{tgr}^{(j)} = \alpha_2^{(j)} \times 10^{\beta_2^{(j)} M} \times R^{\gamma_2^{(j)}} \qquad (2)$$

Given the target spectrum as well as initial Fourier amplitude and its phase spectra, the Fourier amplitude of the resulting waveform is iteratively modified to fit the target response spectrum. The time history can be simulated by the inverse Fourier transform. Finally, synthesized time histories together with the occurrence probability are calculated, the maximum acceleration of which is adjusted to the estimated level.

Figure 5 shows examples of simulated earthquake ground motions together with their probability of occurrence at Tokyo site. This figure clearly shows that earthquakes with the same PGA have different frequency properties or duration times, depending on the magnitude and the focal distance of the fault.

The ground surface motion is evaluated by dynamic analysis considering surface soil conditions at target site, since this earthquake is assumed on the engineered bedrock (*Vs*=400m/s). In this study, 0.40 second is assumed for a natural period of sedimentary layer. This surface soil is classified as good soil (G3) condition according to the Japanese seismic design standard for railway structures.

3.2. Calculation of the initial construction cost C_I

The target structure in this study is the wall type RC pier (span *L*=29m, height *H*=8m). Four yielding seismic coefficients (K_{hy}=0.3, 0.4, 0.6, 1.0) are prepared as design property, and three different ductilities are assigned to each case. Namely, total 12 structures are designed. In addition, all these structures are designed so that the first yielding member is a superstructure, not a foundation. Figure 6 illustrates the geometry of the designed structure in case K_{hy}=0.4. After designed these structures, their initial construction costs C_I are calculated. Furthermore, the regression equation of C_I are composed as functions of natural period T_{eq}, ductility μ_M and yielding coefficient K_{hy}, which is

$$C_I = \left(44929 \times K_{hy}{}^2 + 16843 \times K_{hy} + 5319\right) \times T_{eq}{}^{\frac{1}{1.5}} \times \left(1 + \frac{\mu - 2.5}{2.5} \times 0.12\right) \times 1000 \qquad (3)$$

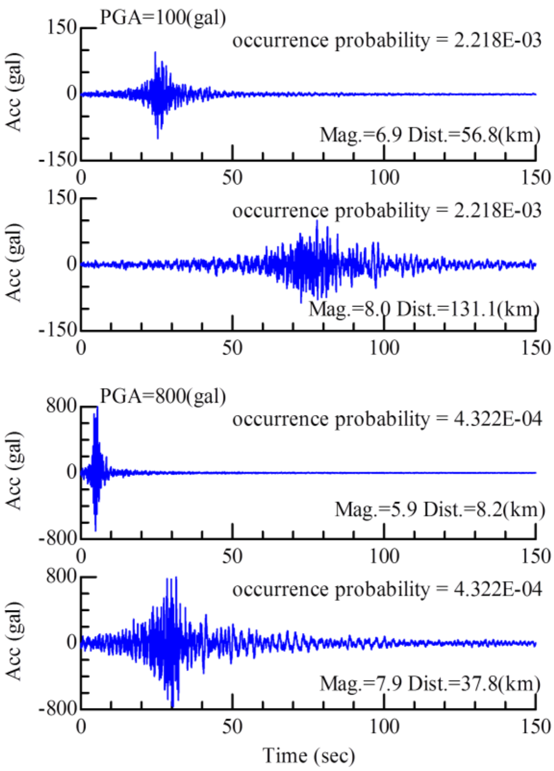


Figure 5. Ground motions together with probabilities of occurrence (Tokyo site)

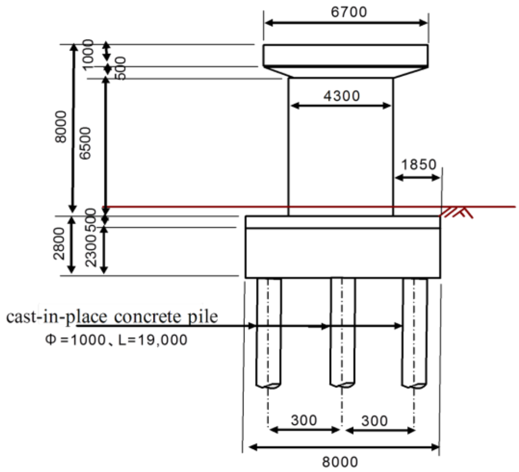


Figure 6. Designed RC pier ($K_{hy} = 0.4$)

3.3. Calculation of the repair cost C_{RE}

Repair cost C_{RE} expressed in equation (1) is given by adjusting the standard repair cost C_{RE0} using coefficient *b*. In calculating C_{RE0}, structural damages are classified as four damage levels, and corresponding repair works are assumed as shown in Table 1. The required costs for those repair works are then estimated. Those costs are expressed as shown in Equation (4) as a function of yielding coefficient, by which the structural property is related to the repair cost. Here, the structures will be reconstructed if its damage exceeds level 3. The corresponding cost is assumed as ten times of initial construction cost C_I, which is derived by the survey of the reconstruction works during 1995 Hyogo-ken Nanbu earthquake.

Damage level 1 : $C_{RE0} = 0$ (4-1)

Damage level 2 : $C_{RE0} = \left(2024 \times k_{hy}^2 + 509 \times k_{hy} + 167\right) \times 1000$ (4-2)

Table 1. Method of repair with every damage level

Damage member	Damage Level			
	Level 1	Level 2	Level 3	Level 4
transverse beam	no repair	set up scaffolding, crack injection	set up scaffolding, crack injection, repair cover concrete	reconstruction
Post, frame	no repair	set up scaffolding, crack injection	set up scaffolding, crack injection, repair cover concrete, back filling	reconstruction

Damage level 3 : $C_{RE0} = \left(5215 \times k_{hy}^2 + 1561 \times k_{hy} + 462\right) \times 1000$ (4-3)

Damage level 4 : $C_{RE0} = 10 \times C_I$ (4-4)

Here, C_{RE0} is a standard value of a repair cost (under the ideal condition). So the actual repair cost is higher than C_{RE0}, due to supplemental costs such as for preparing approach roads or for gaining construction materials.

3.4. Calculation of the operating losses cost C_{TD}

Apart from the repair cost C_{RE}, another loss C_{TD} is considered, including the decline of transportation fee due to suspension of train operation. C_{TD} can be estimated from the daily operating income and suspension duration. However, only a few data is available to estimate these cost in a good accuracy. Then, in this research, it is assumed that C_{TD} correlates with the repair cost C_{RE} ($C_{TD} = k \times C_{RE}$). The correlation coefficient k is set to 2.0 from the survey of repair cost and operation loss during 1995 Hyogo-ken Nanbu earthquake.

3.5. Making the nomograph for restorability

3.5.1. Calculation of total cost

Now that earthquake ground motion together with probability of occurrence, the initial construction cost C_I and the restoration cost (the repair cost C_{RE} and the operating losses cost C_{TD}) are obtained, the total cost of each structure are evaluated to conduct dynamic analysis.

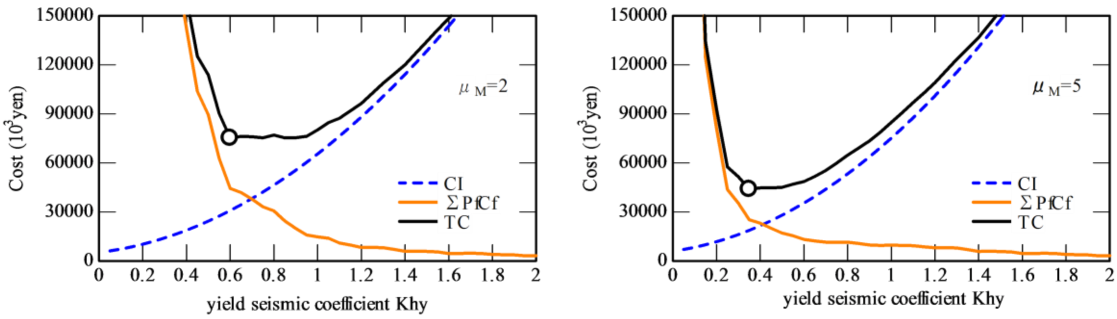
Figure 7 shows representative result of the calculated total costs of structures constructed at Tokyo and Hiroshima site. Natural period of the structure is 1.0second, and ductility is 2.0 and 5.0. As illustrated in this figure, the optimal yielding coefficient of structure under given natural period and ductility are obtained. Circle point in each figure is an optimal yielding coefficient, at which total cost takes its minimum. The optimal yielding coefficient at Tokyo site is higher than that at Hiroshima site, because of the seismicity at Tokyo site is more active.

3.5.2. Calculation of the nomograph for restorability

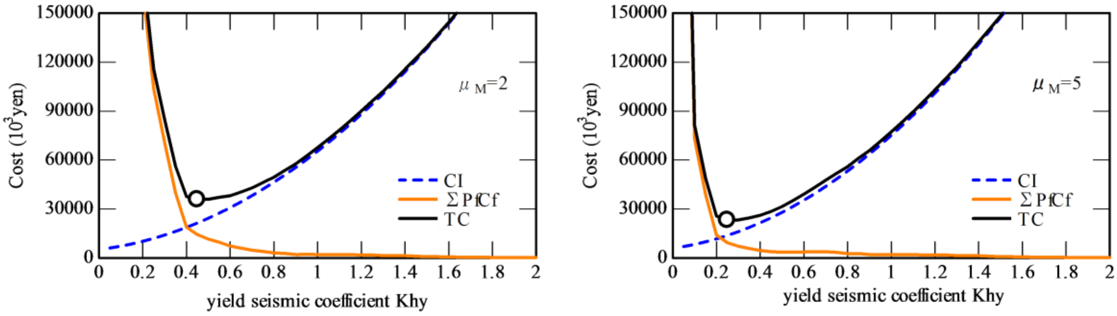
It is cleared that the optimal yielding coefficient is obtained under given natural period and ductility. In this section, the optimal yielding coefficients under various natural periods and ductilities are summarized as a nomograph. That is to say, procedures 3.1 to 3.4 are repeatedly carried out while giving natural period and ductility of structure. Figure 8 shows the proposed nomograph at ductilities μ_M =1, 2, 4, 8.

The design spectrum assuming Level-2 earthquake designated in the seismic design code for Japanese railway facilities are also depicted in the same figure. It should be noted that the restorability nomograph is almost identical to the design spectrum for Level 2 earthquake at Tokyo site, where its seismicity is frequent. It consequently follows that the structure whose restorability is assured by complying with the design standard is actually minimizing the total cost simultaneously.

On the other hand, at Hiroshima site where the activity of seismicity is relatively low, the proposed nomograph for restorability is below the Level 2 earthquake. This discrepancy depends on frequency

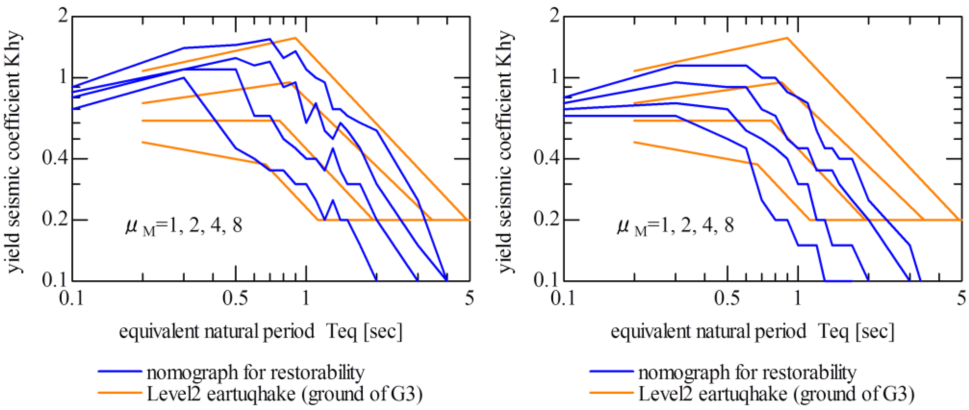


(a) Tokyo site



(b) Hiroshima site

Figure 7. Total cost of the assumed structure (Teq=1.0(sec))



(a) Tokyo site (b) Hiroshima site

Figure 8. Comparison of restorability nomograph and design spectra for L2 motion

of earthquake. The difference of the seismicity, however, is taken into consideration in the design standard by means of the seismic zone factor (see Figure 9). Although the seismic zone factor has been empirically determined, the Level 2 earthquakewith the seismic zone factor (*k*=0.85) are more similar to the nomograph at Hiroshima site (see Figure 10).

4. CONCLUSION

In this research, a new design nomograph that gives combinations of demanding natural period, ductility and yielding coefficient in view of minimizing a total cost of structure is proposed by means of nonlinear numerical simulations. It is clarified through comparison of the nomograph and current design spectra based on past earthquake records that the structures comply with current design code meet the demands of preventing severe damage and minimizing the total cost simultaneously. This

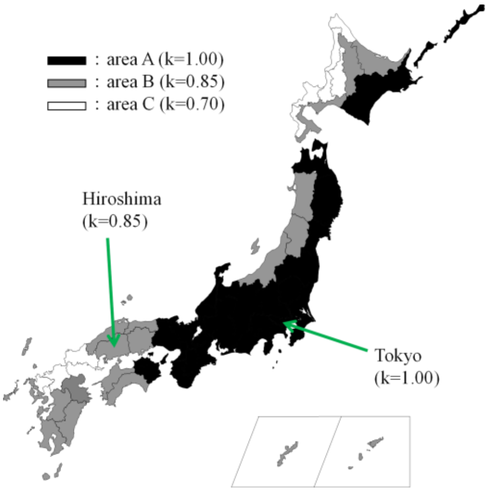


Figure 9. The seismic zone factor

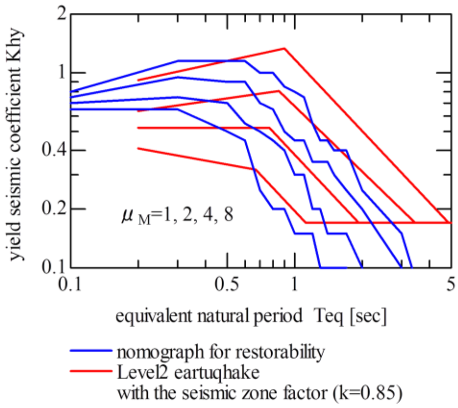


Figure 10. Comparison of restorability nomograph at Hiroshima and design spectra for L2 motion with the seismic zone factor *k*

result gives clearer meaning to current design approach that is developed empirically from past seismic damage.

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