DEVELOPMENT OF SEISMIC PERFORMANCE EVALUATION PROCEDURES IN BUILDING CODE OF JAPAN

Mitsumasa MIDORIKAWA[1], Hisahiro HIRAISHI[2], Izuru OKAWA[3], Masanori IIBA[4], Masaomi TESHIGAWARA[5] And Hiroshi ISODA[6]

SUMMARY

The building code of Japan will be changed from current prescriptive into performance-based type by 2000. This paper presents the evaluation procedures of structural seismic performance against major earthquake motions in the performance-based building code of Japan under development at the Building Research Institute (BRI). The basic concept of BRI proposal for seismic design spectra for major earthquake motions is 1) basic design spectra defined at the engineering bedrock, and 2) evaluation of site response from geotechnical data of surface soil layers. The principle of evaluation procedures is that the predicted response values should not exceed the estimated limit values. In case of major earthquakes, the maximum response values of strength and displacement of a structure should be smaller than the ultimate capacity for strength and displacement. The proposed evaluation procedures apply the equivalent single-degree-of-freedom (ESDOF) system and the response spectrum analysis, while the current procedures are based on the estimation of the ultimate capacity for lateral loads. The proposed evaluation procedures make it realistic and simple to predict maximum structural response in case of major earthquakes as well as to confirm whether the predicted response values are smaller than the limit ones.

INTRODUCTION

The building code of Japan will be changed from current prescriptive into performance-based type by 2000 in order to newly compile a highly flexible Building Standard Law of Japan [Hiraishi et al., 2000]. Unlike the in-current-use conventional building code, the performance-based building code prescribes clearly the type and the level of the required performance for a designed building structure. The basic concept of BRI proposal for seismic design spectra for major earthquake motions is 1) basic design spectra defined at the engineering bedrock, and 2) evaluation of site response from geotechnical data of surface soil layers.

This paper presents the evaluation procedures of structural seismic performance against major earthquake motions in the performance-based building code of Japan under development at the Building Research Institute (BRI) [Hiraishi et al., 1999]. The proposed evaluation procedures apply the equivalent linearization technique using an equivalent single-degree-of-freedom (ESDOF) system and the response spectrum analysis, while the current procedures are based on the estimation of the ultimate capacity for lateral loads of a structure. The variety of linearization techniques has already been studied [e.g. Shibata and Sozen, 1976]. Several applications have also been presented in the publications [AIJ, 1989; AIJ, 1992; Freeman, 1978; ATC-40, 1996].

[1] *International Institute of Seismology and Earthquake Engineering, (MOC), Japan. Email: midori@kenken.go.jp*
[2] *Director, Codes and Evaluation Research Center, BRI, MOC*
[3] *Head, Construction Techniques Div., BRI, MOC.*
[4] *Head, Structural Dynamics Div., BRI, MOC.*
[5] *Head, Structure Div., BRI, MOC.*
[6] *Senior Research Engineer, Structure Div., BRI, MOC*

PERFORMANCE-BASED CODE AND SEISMIC PERFORMANCE REQUIREMENTS

Following the principles of structural safety, the evaluation procedures to be used for the estimation of structure's conformity with the required performance level are roughly classified as: a) Proposed evaluation procedures, b) Conventional evaluation procedures, c) Small building evaluation procedures (no structural calculation required), and d) Other alternative evaluation procedures requiring expert judgement. The details of performance-based seismic and structural code proposed by BRI are discussed elsewhere [Hiraishi et al., 2000].

The purposes of seismic performance requirements for building structures are classified in two categories: life safety and damage limitation [Hiraishi et al., 2000].

PROPOSED EVALUATION PROCEDURES FOR MAJOR EARTHQUAKES

Various response and limit values are considered for use in the performance evaluation procedures in accordance with each of the requirements prescribed for building structures. A representative example of this arrangement is shown in Table 1. The principle of evaluation procedures is that the predicted response values due to the action of earthquake motions on building structures should not exceed the estimated limit values. In case of major earthquakes, the maximum response values of strength and displacement of a structure should be smaller than the ultimate capacity for strength and displacement.

Hereafter the focus is put on the proposed evaluation procedures for major earthquakes. The analytical method to be used for predicting the structural response applies the equivalent linearization technique using an ESDOF system and the response spectrum analysis. A flow chart of the procedures is shown in Fig. 1.

According to the procedures, the steps to be followed are:
(1) Confirm the scope of application of the evaluation procedures and the mechanical characteristics of materials and/or members to be used in a structure.
(2) Determine the response spectra to be used in the evaluation procedures.
a) For a given basic design spectrum at the engineering bedrock level, draw up the free-field site-dependent acceleration (S_a) and displacement response spectra (S_d) for different damping levels.
b) In the estimation of free-field site-dependent acceleration and displacement response (step a) above), consider the strain-dependent soil deposit characteristics.
c) In case of need, present graphically the relation of S_a-S_d for different damping levels (see Fig. 1c).
(3) Determine the hysteretic characteristic, equivalent stiffness and equivalent damping ratio of the structure.
a) Model the structure as an ESDOF system and establish its force-displacement relationships (see Fig. 1a).
b) Determine the limit strength and displacement of the structure corresponding to the ESDOF system.
c) The soil-structure interaction effects should basically be considered.
d) In case of need, determine the equivalent stiffness in accordance with the limit values.
e) Determine the equivalent damping ratio on the basis of viscous damping ratio, hysteretic dissipation energy and elastic strain energy of the structure (see Fig. 1b).
f) In case that the torsional vibration effects are predominant in the structure, these effects should be considered when establishing the force-displacement relationship of the ESDOF system.
(4) Examine the safety of the structure. In this final step, it is verified whether the response values predicted on the basis of the response spectra determined according to step 2 satisfy the condition of being smaller than the limit values estimated on the basis of step 3 (see Fig. 1c).

In order to determine the limit strength and displacement of the structure, a specific displaced mode is necessary to be assumed in advance for its inelastic response (see Fig. 1a). Basically, any predominant or possible to be experienced displaced mode of the structure subjected to earthquake motions can be applied. This implies any of the failure modes observed during major earthquakes such as beam failure, story failure or any other definite failure modes.

ACCELERATION RESPONSE SPECTRUM AT GRAOUND SURFACE

Basic Response Spectrum at Engineering Bedrock

In the BRI proposal [Hiraishi et al., 2000], the earthquake load for evaluation is specified with earthquake ground motion not with seismic force given in the current Building Standard Law of Japan. The evaluation earthquake motion is represented with the acceleration response spectrum in the following formula.

$S_A(T) = Z(T)G_s(T)S_0(T)$ (1)

Where, S_A: acceleration response spectrum for evaluation, Z: seismic zoning factor, G_s: soil amplification factor, and S_0: basic acceleration response spectrum at exposed (outcrop) engineering bedrock.

The engineering bedrock is defined as a layer with more than 400 m/s in shear wave velocity. The basic response spectrum for major earthquakes is illustrated in Fig. 2.

Evaluation Procedure of Acceleration Response Spectrum at Ground Surface

To evaluate the acceleration response spectrum at the ground surface, the amplification of surface soil deposits on the engineering bedrock is estimated. An evaluation procedure by using the equivalent linearization technique considering nonlinear soil properties is expressed in the followings. The simplified analytical method in this procedure is proposed and examined in detail elsewhere [Miura et al., 2000].

(1) *Transformation of response spectrum defined at outcrop engineering bedrock*: The earthquake motion defined at the outcrop engineering bedrock is given as an acceleration response spectrum with 5% damping ratio, $S_A(T, \zeta=0.05)$. $S_A(T, \zeta=0)$, a velocity response spectrum, $S_v(T, \zeta=0)$, and a Fourier spectrum of acceleration, $F_A(T)$, have the approximate relations as follows.

$F_A(T) \approx S_v(T, \zeta=0) \approx (T/2\pi)S_A(T, \zeta=0)$ (2)

(2) *Eigen value analysis of soil profile*: Subdividing the soil profile, a shear model of n degrees of freedom is formed. The natural period, T_i, the vibration mode, U_i (normalized by the value at the surface), and the modal damping ratio, ζ_i, are obtained through the eigen value analysis.

(3) *Equivalent shear wave velocity and impedance*: The surface soil layers are replaced to an uniform stratum with an equivalent shear wave velocity, V_{se}, and an equivalent mass density, ρ_e, and an equivalent damping ratio, ζ_1, which are calculated from the properties of each soil layer.

$$V_{se} = \frac{1}{H}\sum_{i=1}^{n-1} V_{si} d_i \quad (3)$$

$$\rho_e = \frac{1}{H}\sum_{i=1}^{n-1} \rho_i d_i \quad (4)$$

Where, $V_{si} = \sqrt{(G_i / \rho_i)}$, H: the total thickness of the surface soil layers, and, G_i, ρ_i and d_i are shear modulus, mass density, layer height, and damping ratio at the i-th layer from the surface, respectively. The impedance of a wave motion, α, between the equivalent surface soil layer and the engineering bedrock is expressed as follows.

$\alpha=(\rho_e V_{se})/(\rho_b V_{sb})$ (5)

Where, V_{sb}: shear wave velocity at the engineering bedrock, and ρ_b: mass density at the engineering bedrock.

(4) *Amplification of surface ground*: The amplification of the uniform surface soil layer to the outcrop engineering bedrock is obtained by using the one-dimensional wave propagation in frequency domain. The transfer function of the surface soil layer and the engineering bedrock to the outcrop one are expressed as follows: a) surface/outcrop engineering bedrock; $G_s(T, \zeta_1, \alpha)$, and b) engineering bedrock /outcrop engineering bedrock; $G_b(T, \zeta_1, \alpha)$. An equivalent shear modulus G_{ei}, and an equivalent damping ratio, h_{ei}, of each soil layer are calculated through the G-γ, h-γ relationships of soil properties considering the nonlinear characteristics of the surface soil layers.

(5) *Acceleration response spectra at ground surface and engineering bedrock*: They are evaluated as follows.

$S_{As}(T, \zeta=0) \approx F_A(T)\ G_s(T, \zeta_1, \alpha)/(T/2\pi)$ (6)

$S_{Ab}(T, \zeta=0) \approx F_A(T)\ G_b(T, \zeta_1, \alpha)/(T/2\pi)$ (7)

(6) *Modification of acceleration response spectrum at ground surface*: To estimate the acceleration response spectrum conservatively at the ground surface, the spectrum is modified by connecting the two peak points, by a straight line, of the acceleration response spectrum corresponding to the first and second modes of the surface soil layer, in order to avoid excessive reduction between these peaks.

Examples of Evaluation of Acceleration Response Spectrum at Ground Surface

Figure 3 shows shear wave velocities, V_s, in several soil deposits to be evaluated. The shear wave velocities are measured by the PS logging method. The soil layer of V_s of more than 400 m/s is selected as the engineering bedrock. The nonlinear characteristics of the surface soil layers are modeled according to the other publication [Ohsaki et al., 1978]. The mass density of the soils is around 1.6 to 2.0.

The amplification factors (transfer functions) of the ground surface to the outcrop engineering bedrock are shown in Fig. 4. The figure includes the results from three analytical methods in the following.

1) Transfer functions in case of multi-layers with V_s by the linear analysis (indicated by "Linear"),

2) Ratios of acceleration response spectrum at the ground surface to that at the outcrop engineering bedrock, that are calculated by the computer program Shake [Schnabel et al., 1972] (indicated by "Equivalent"), and
3) Transfer functions obtained by the proposed method (indicated by "Proposed").
The predominant periods of the surface soil layers subjected to severe earthquake motions are longer by 1.3 to 2.0 times than those to moderate earthquake motions because of the nonlinear behavior of soils. There are some differences between the predominant periods of the proposed method and Shake at Sites 3 and 4. The amplification factors at Sites 3 and 4 by the proposed method are a little less than those by Shake. Figure 5 shows the acceleration response spectra at the surface, which are obtained by the proposed method and Shake. "Modified C_0•R_t" also indicates the acceleration response spectrum converted from the base shear coefficient of buildings for medium soil deposits prescribed in the Building Standard Law of Japan. The response spectra by the proposed method have good agreement with those by Shake.

HYSTERETIC CHARACTERISTICS AND EQUIVALENT DAMPING RATIO OF STRUCTURES

A multi-story building structure is reduced to an ESDOF system as shown in Fig. 6. The reduction to ESDOF system is based on the result of a push-over static analysis by applying horizontal forces at each floor level. The force-displacement relationship of the ESDOF system is given when the force corresponds to the base shear (Q_b), and its displacement (${}_1\Delta$) corresponds to the displacement at the height (h_e) where the natural modal participation function is equal to 1.0 ($\beta_1\{u\}_1$=1.0). The details of this procedure is discussed elsewhere [Kuramoto et al., 2000].

The equivalent damping ratio is defined by the viscous damping ratio, hysteretic dissipation energy, elastic strain energy of structure, and the radiation effects of the ground. The effects of the soil-structure interaction are considered if necessary. The equivalent damping ratio of a SDOF system, h_{eq}, is given by the following equation (see Fig. 6).

$$h_{eq} = (1/4\pi)(\Delta W/W) \tag{8}$$

where, ΔW = Dissipation energy of SDOF system, and W = Potential energy of SDOF system (=Q_b•${}_1\Delta$/2).
Here, the dissipation energy of a stationary hysteretic loop at the assumed maximum response of a structure can be obtained by calculating the area of the enclosed cyclic loop of the structure in a static push-over analysis, or based on the total damping ratios of all the members and joints considered.

PREDICTION OF MAXIMUM RESPONSE

One of typical analysis methods for predicting the maximum earthquake response of an inelastic system is the response spectrum analysis using equivalent linearization techniques. In this procedure, as shown in Fig. 1(c), the intersection of the force-displacement curve of ESDOF system and the required seismic performance spectrum is the maximum response point. In general, the maximum response obtained by using the equivalent damping ratio, h_{eq}, of Eq. (8) is theoretically valid in stationary vibration. In non-stationary vibration caused by earthquakes, h_{eq} based on the assumed maximum response has to be reduced appropriately for appropriately predicting the maximum response. The factor for reducing h_{eq} can be estimated through examination using recorded and synthesized earthquake motions, and some hysteresis curves consisting of bi-linear or tri-linear skeleton curves such as normal bi-linear model and Takeda model [Takeda et al., 1970]. Figure 8 illustrates an example of the results on bi-linear skeleton curves shown in Fig. 7(a). The four input earthquake motions consist of a synthesized earthquake motion by the Building Center of Japan (BCJ) and three recorded earthquake motions; 1995 Kobe NS, 1968 Hachinohe EW and 1940 El Centro NS. Analytical parameters include the natural period, yield stiffness and yield strength. The damping ratio of 2% except for the hysteretic energy dissipation is included. The estimated equivalent damping ratio is reduced to 70 percent of h_{eq}. The responses obtained from the equivalent linearization analysis compare well with the time history responses, although differences are observed to a certain extent as the ductility becomes larger.

Takeda model is used to simulate the response of reinforced concrete structures. The equivalent damping ratio for Takeda model is expressed in the following equation.

$$h_{eq} = \frac{1}{\pi}\left\{1 - \frac{1+d_c/d_y}{1+p_c/p_y}\mu^{\gamma}\frac{1-\alpha+\alpha\mu}{\mu}\right\} \tag{9}$$

Where, d_c = displacement at crack point, d_y = yield displacement, p_c = strength at crack point, p_y = yield strength,
μ = maximum displacement divided by yield displacement, γ = decrease factor of stiffness on unloading, and
α = stiffness after yielding divided by initial stiffness.

By arranging the parameters given in Fig. 7(b), Equation (9) can be expressed as follows.

$$h_{eq} = 0.32\{1-(0.82+0.01\mu)/\sqrt{\mu}\} \tag{10}$$

The comparison of the results between the equivalent linearization and time history analyses is shown in Fig. 9. Here, the natural period, T, calculated using the initial stiffness, is equal to 0.3 s. The yield shear coefficient, $Q_y/(m\mathrm{g})$ (Q_y: yield strength, m: mass, g: acceleration of gravity), is changed from 0.2 to 0.5 by an increment of 0.1. The figure shows that the equivalent damping ratio reduced to 70 percent of h_{eq} is suitable for the design purpose.

CONCLUSIONS

In this paper, presented are the evaluation procedures of structural seismic performance against major earthquake motions in the performance-based building code of Japan under development. The evaluation procedures presented are in essence a blend of ESDOF modeling of building structures with the site-dependent response spectrum concept, which make possible the prediction of maximum structural response for major earthquakes without using time history analyses.

The validity of the proposed evaluation procedures is examined in the paper, focusing on the following items:
1) Simplified analytical method of site-dependant response from surface geotechnical data with the equivalent single surface soil layer considering the nonlinear behavior of soft soils.
2) Estimation of equivalent damping ratios for various hysteretic characteristics such as bi-linear and degrading tri-linear hysteresis models.
3) Applicability of the equivalent linearization technique.

The results show that the proposed evaluation procedures are appropriate to practical seismic design. The proposed evaluation procedures make it realistic and simple to predict the maximum structural response for major earthquakes as well as to confirm whether the predicted response values are smaller than the limit ones.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance with Dr. S. Koyama at BRI in calculating the site-dependant responses. This manuscript was stimulated by the authors' participation as members of the "Task Committee to Draft Performance-based Building Provisions" established at BRI, where they have shared their opinions with other members. They would like to express their gratitude towards all of them.

REFERENCES

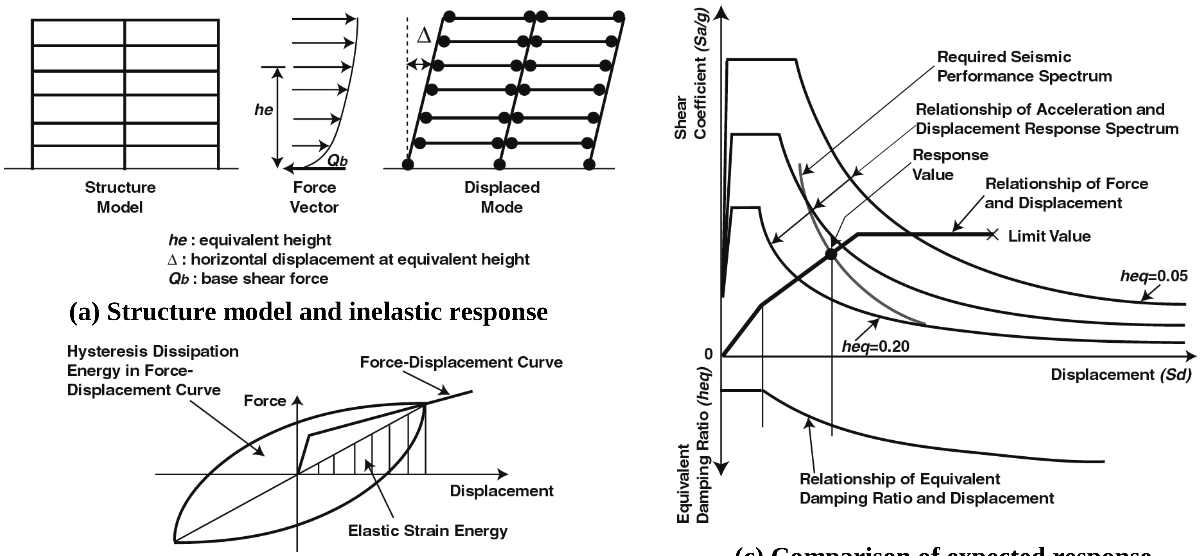
AIJ (1989), *Recommendation for the Design of Base Isolated Buildings*, Architectural Institute of Japan (in Japanese).
AIJ (1992), *Seismic Loading - Strong Motion Prediction and Building Response*, Architectural Institute of Japan, Tokyo (in Japanese).
ATC-40 (1996), *Seismic Evaluation and Retrofit of Concrete Buildings*, Report No. SSC 96-01, Applied Technology Council.
Freeman, S. A. (1978), "Prediction of response of concrete buildings to severe earthquake motion", *Douglas McHenry International Symposium on Concrete and Concrete Structures*, SP-55, ACI, pp. 589-605.
Hiraishi, H. and et al. (1999), "Seismic evaluation of buildings by acceleration spectrum at engineering bedrock (Part 1-Part 13)", Structures II, *Summaries of Technical Papers of Annual Meeting*, AIJ (in Japanese).
Hiraishi, H., Midorikawa, M., Teshigawara, M., Gojo, W. and Okawa, I. (2000), "Development of performance-based building code of Japan -framework of seismic and structural provisions-", *Proceedings 12th World Conference on Earthquake Engineering*.
Kuramoto, H., Teshigawara, M., Okuzono, T., Koshika, N., Takayama, M. and Hori, T. (2000), "Predicting the earthquake response of buildings using equivalent single degree of freedom system", *Proceedings 12th World Conference on Earthquake Engineering*.
Miura, K., Koyamada, K. and Iiba, M. (2000), "Response spectrum method for evaluating nonlinear amplification of surface strata", *Proceedings 12th World Conference on Earthquake Engineering*.
Ohsaki, Y., Hara, A. and Kiyota, Y. (1978), "Stress-strain model of soils for seismic analysis", *Proceedings 5th Japanese Earthquake Engineering Symposium*, pp. 679-704 (in Japanese).

Shibata, A. and Sozen, M. A. (1976), "Substitute structure method for seismic design in R/C", *Journal of the Structural Div.*, ASCE, 102, ST1, pp. 1-18.
Schnabel, P. B., Lysmer, J. and Seed, H. B. (1972), "SHAKE: A computer program for earthquake response analysis of horizontally layered sites", *Report No. UCB/EERC-72/12*, Univ. of California, Berkeley, Calif.
Takeda, T., Sozen, M. A. and Nielsen, N. N. (1970), "Reinforced concrete response to simulated earthquakes", *Journal of the Structural Division*, ASCE, 96, 12, pp. 2557-2573.

Table 1: Seismic performance requirements for building structures and earthquake motion levels illustrating representative response/limit values

Requirement	Earthquake		
(a) Life Safety (to prevent failure of stories in structural frames)	Maximum Earthquake to be considered (earthq. records, seismic and geologic tectonic structures, active faults, etc.)	Response Value	Maximum Internal Force/Displacement
		Limit Value	Limit Strength/Displacement*1
(b) Damage Limitation (to prevent damage to structural frames, members, interior and exterior finishing materials in order to avoid the conditions not satisfying the requirement (a) and others)	Once-in-a-lifetime Event (return period: 30-50 years)	Response Value	Internal Force/Displacement taking place at each structural element
		Limit Value	Limit Strength/Displacement*2

Notes:
*1 - Repeating cycles effect at plastic region of response to be taken into account.
*2 - The whole building structure behaves roughly within elastic range.
1) The limit values corresponding to Maximum Event Level are determined based on the condition that equilibrium of forces and displacement compatibility in the structural system are guaranteed.
2) Displacement and acceleration related limit values, determined on the basis of the requirements for architectural, mechanical and electrical elements permanently attached to building structures, are thought to be considered in certain cases.
3) The deterioration of materials during the lifetime of a structure should be considered.

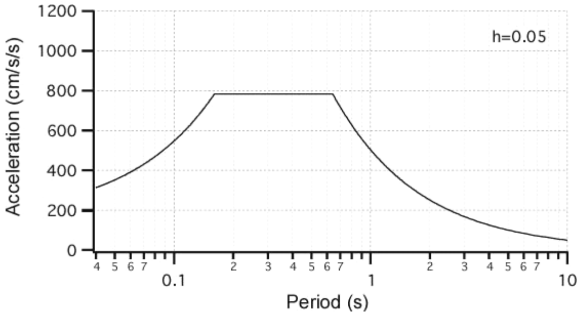


(a) Structure model and inelastic response

(b) Energy for equivalent damping ratio

(c) Comparison of expected response

Figure 1: Illustration of proposed evaluation procedures for major seismic events



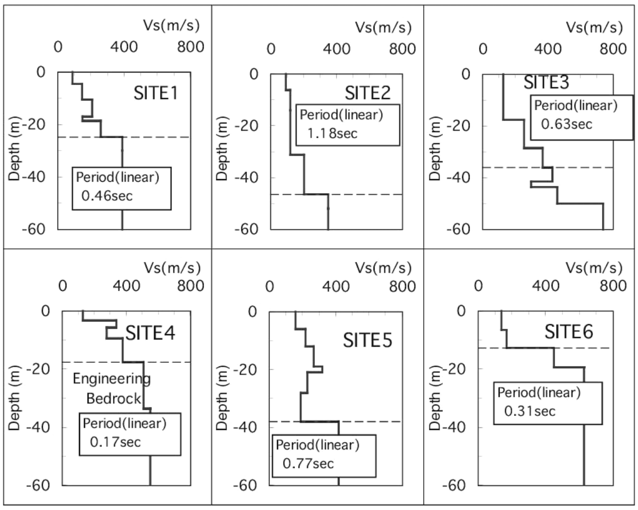


Fig. 2: Basic response spectrum at engineering bedrock   **Fig. 3: Shear wave velocity distribution at sites**

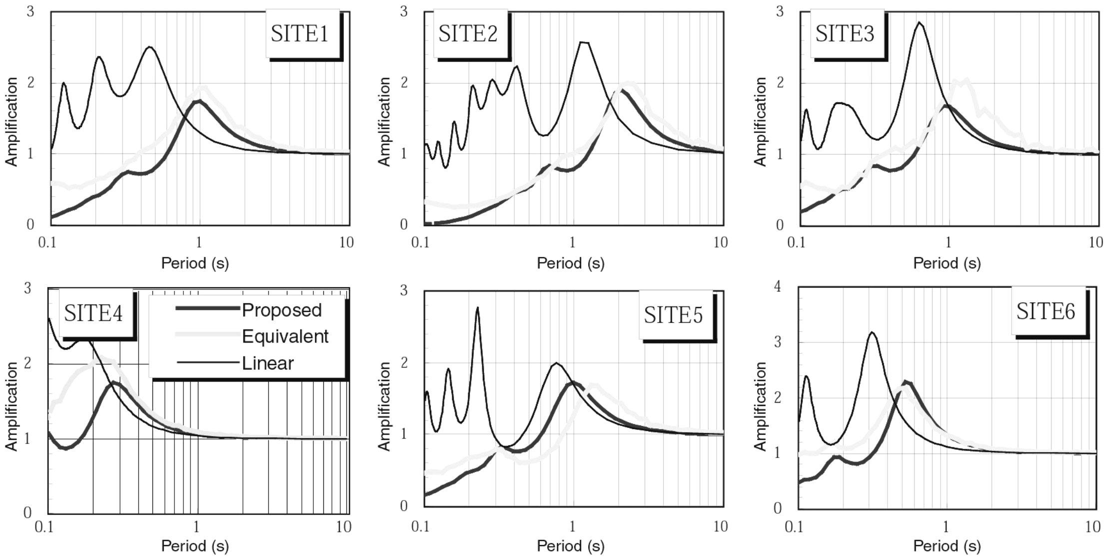


Figure 4: Transfer functions of ground surface to engineering bedrock

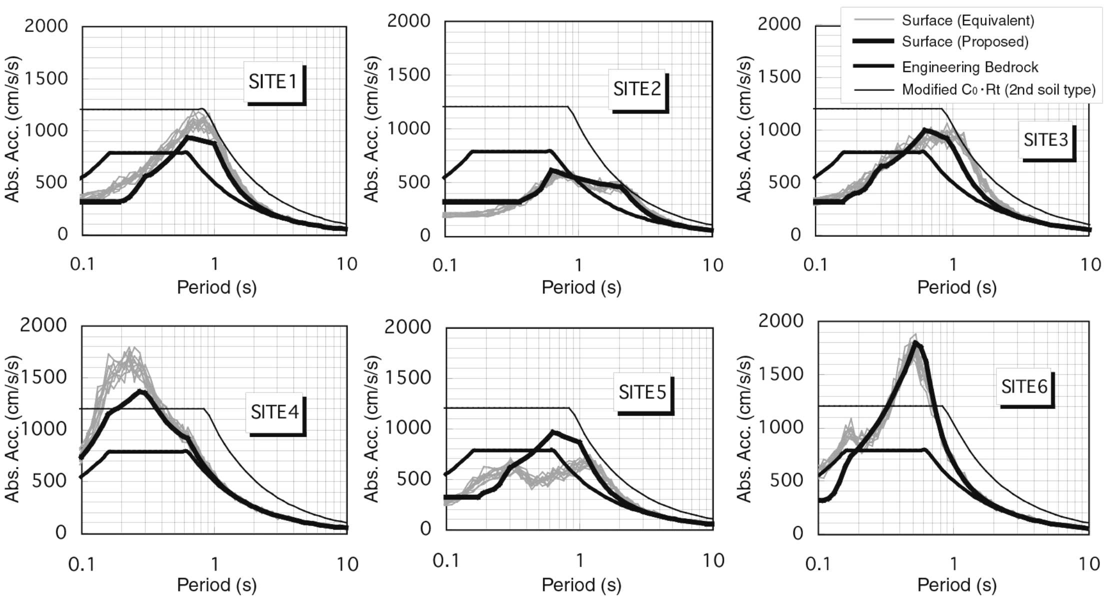


Figure 5: Acceleration response spectra at ground surface (h = 5%)

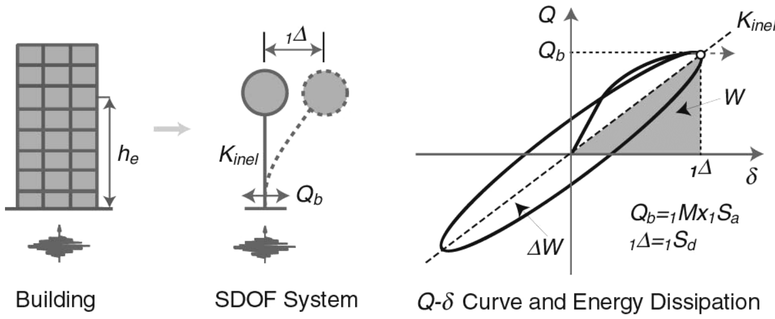
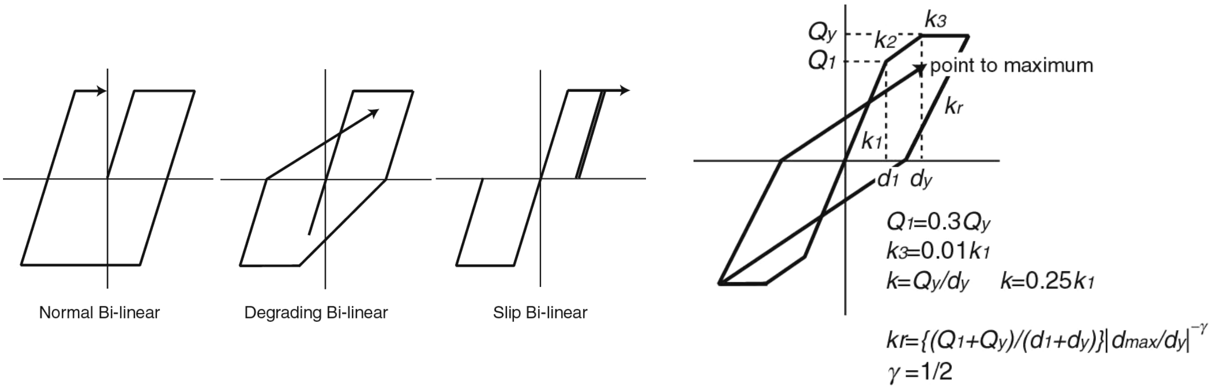


Figure 6: Reduction to single-degree-of-freedom system



(a) Bi-linear hysteresis models **(b) Parameters of Takeda model**

Figure 7: Analytical hysteresis models

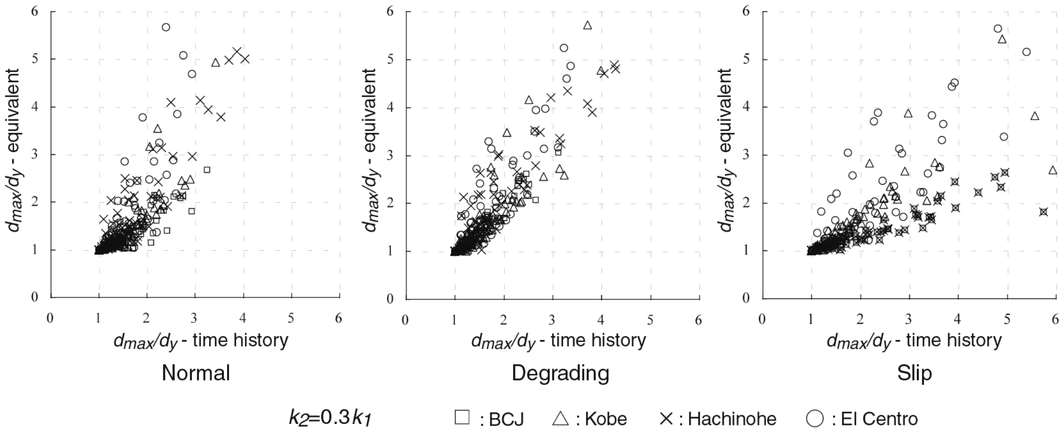


Figure 8: Comparison of maximum response displacements between equivalent linearization and time history analyses

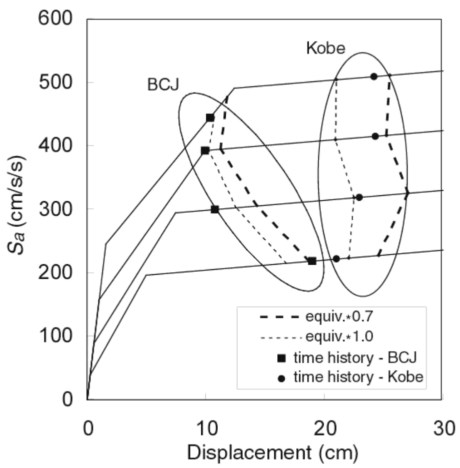


Figure 9: Comparison of equivalent linearization and time history analyses in Takeda model