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EVALUATION OF SEISMIC RESPONSE OF BUILDING WITH SIMPLIFIED ESTIMATION OF SPRING AND DASHPOT AT BASE

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ABSTRACT

To evaluate predominant frequency of buildings under soil structure interaction (SSI), sway and rocking spring constants need to be calculated easily. A simplified method for incorporating SSI effect and for calculating spring constants based on a cone modeling is introduced. The SSI system is assumed to be a single degree of freedom one. The application of the procedure to a residence building is conducted. The earthquake motion on the ground surface is calculated through the acceleration response spectrum defined at the outcropped engineering bedrock and soil amplification of surface layers. The seismic response of the building is calculated based on the building characteristics with SSI effect and the acceleration response spectrum on the ground surface. A time history analysis of a sway-rocking model is conducted. The seismic responses based on acceleration response have a little underestimation compared with those by the time history analysis.

Keywords: Soil structure interaction, performance-based design, response during earthquake, simplified method, response spectrum

INTRODUCTION

The Building Standard Law in Japan and its related enforcement and notices were revised for the direction to the performance-based design in 1998. The calculation method of response and limit strength was provided for checking structural serviceability and safety of buildings (Midorikawa et al., 2000, Kuramoto et al., 2002). The soil structure interaction (SSI) effects should be considered when the interaction effect would be not negligible. The appropriate method for checking the structural safety of buildings during severe earthquake needs to be proposed.

A simplified method for incorporating SSI effects and for calculating spring constants and damping effects is presented, to evaluate predominant frequency and damping factor of buildings with SSI (Iiba et al., 2002). The method is applied to a residence building with a span in short direction. The earthquake motion, which is given by the acceleration response spectrum (ARS), is defined at the outcropped engineering bedrock. The ARS on the ground surface includes the soil amplification. The seismic response of the building with SSI is calculated based on the ARS, through treating a single degree freedom system with equivalent linear period and damping factor. A time history analysis of a sway-rocking model is also conducted. The results by the spectrum-based method are compared with those by the time history analysis.

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RESPONSE EVALUATION PROCEDURE

The evaluation procedure involves the application of the equivalent linearization technique using an equivalent single-degree-of-freedom (ESDOF) system and the response spectrum analysis (Kuramoto et al. 2000). A variety of linearization techniques has already been studied (e.g. Shibata & Sozen 1976). Several applications of linearization techniques have also been published (AIJ 1989, AIJ 1992, Freeman 1978, ATC-40 1996).

The building is idealized as an ESDOF system as shown in Figure 1 (Kuramoto et al. 2002). This is based on the result of a nonlinear push-over analysis, for horizontal forces at each floor level, of which the distribution should be in proportion to the first mode of the building vibration. The force-displacement relationship of the ESDOF system is given by equations (1) and (2), when the force corresponds to the base shear (${}_1Q_B$), 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 ($\beta_1\{u\}_1 = 1.0$)

$$ {}_1Q_B = {}_1\overline{M}\cdot{}_1S_a \qquad (1)$$

$$ {}_1\Delta = {}_1S_d \qquad (2)$$

Where, ${}_1\overline{M}$ is equivalent mass corresponding to the 1st mode, and ${}_1S_a$ and ${}_1S_d$ are acceleration response and displacement response for the 1st mode, respectively

According to the procedures, the steps to be followed are;

(1) To determine the response spectrum to be used in the evaluation procedure. Acceleration (S_a) and displacement response spectra (S_d) on the ground surface are drawn up (Demand Spectrum).

(2) To determine the equivalent stiffness and equivalent damping ratio of the building.

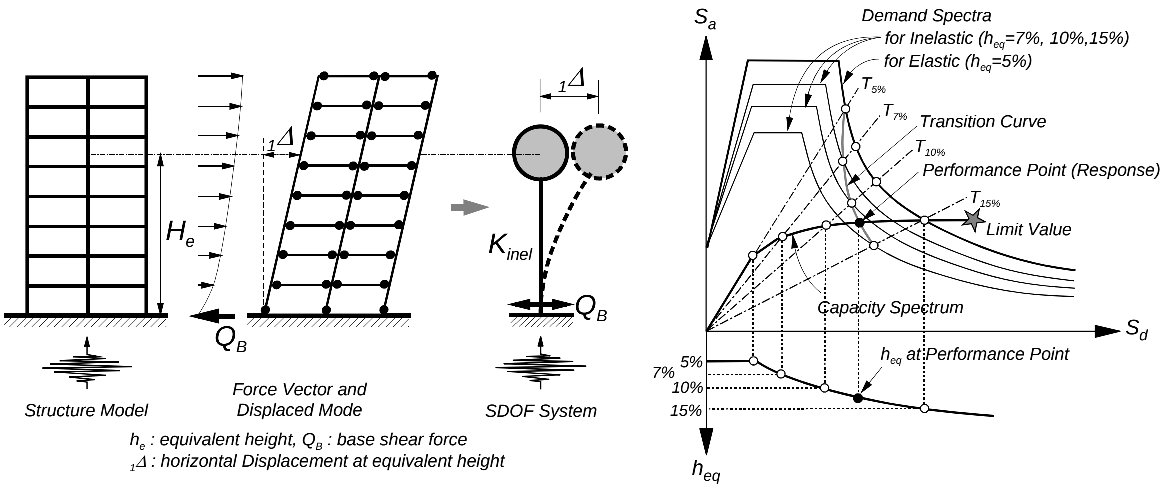
a) To replace to the ESDOF system and establish force-displacement relationship (Capacity Spectrum), through the non-linear push-over analysis.

b) To determine the equivalent damping ratio on the basis of viscous damping ratio, hysteretic dissipation energy and elastic strain energy of the building.

c) To consider the SSI effects on the period and damping factor of building.

(3) To calculate the response values on the basis of the response spectra determined by step (1) and the force-displacement relationship of the ESDOF system of the building given by step (2).

PREDOMINANT PERIOD AND DAMPING FACTOR IN SSI SYSTEM



a) Push-over and ESDOF system of building b) Determination of response points

Figure 1. Illustration of seismic evaluation procedure for major earthquake events

Definition of Spring Constant and Equivalent Damping Factor

When a sinusoidal force is exerted to the massless foundation, a dynamic impedance with a complex becomes as follows;

$$\overline{K} = \frac{\overline{F}}{\overline{u}} = K + iK' \tag{3}$$

Where $\overline{F}$ and $\overline{u}$ are amplitude of dynamic force and responded displacement, and i is imaginary unit. Real and imaginary parts of the impedance are corresponding to the spring constant (K) and damping property (K'). The equivalent damping factor and viscous coefficient are obtained in the following;

$$h = \sin\left(0.5\tan^{-1}\left(\frac{K'}{K}\right)\right) \tag{4a}$$

$$h = \frac{K'}{2K} \quad \text{(when } K'/K \text{ is small)} \tag{4b}$$

$$c = K'/\omega \tag{5}$$

For the sway and rocking motions, subscripts of h and r are added, respectively.

$$\overline{K}_h = K_h + iK_h' = K_h(1 + i2h_h) = K_h + ic_h\omega \tag{6a}$$

$$\overline{K}_r = K_r + iK_r' = K_r(1 + i2h_r) = K_r + ic_r\omega \tag{6b}$$

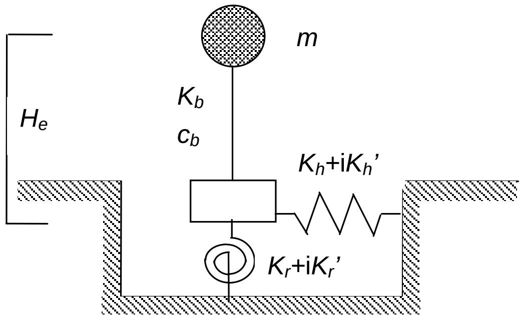
The impedance has a frequency dependency. Considering the convenience to incorporating into design, the frequency dependency is a little complicated. The value at rest (frequency is zero) will be used as to spring constant. As to the damping factor, the value at predominant circular frequency (ω_e) will be applied.

$$\text{Spring constant: } K = K(\omega = 0) \tag{7a}$$

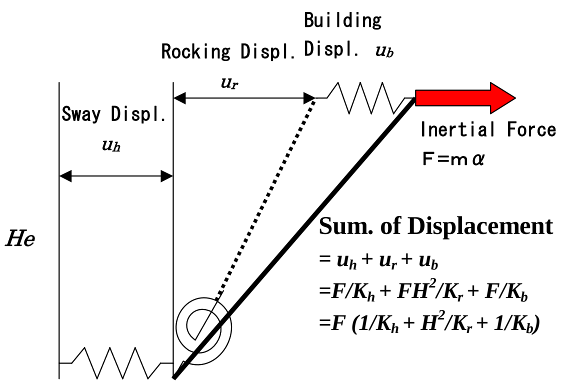
$$\text{Equivalent damping factor: } h = \sin\left(0.5\tan^{-1}\left(\frac{K'(\omega_e)}{K(\omega = 0)}\right)\right) \tag{7b}$$

Calculation of Predominant Period and Damping Factor in SSI System

The SSI model consisting of a superstructure with one mass, a base and sway and rocking springs is illustrated in Figure 2a). Through an assumption that the influence of base mass and moment of inertia at each floor on response in the SSI system is negligible, an external force acting to the superstructure, sway and rocking springs is only the inertial force of superstructure, as shown in Figure 2b) (Bielak,



a) Simplified SSI model



b) Series spring and displacement

Figure 2. Sway-rocking model and relationship between Force and displacement in SSI system

1976). In the case that the springs are arranged in a series, an equivalent spring constant; K_e for the SSI system can be obtained as follows;

$$\frac{1}{K_e} = \frac{1}{K_b} + \frac{1}{K_h} + \frac{H_e^{\,2}}{K_r} \tag{8}$$

Where K_b, K_h, and K_r and H_e are spring constants for superstructure, sway and rocking motions, and the equivalent height from base bottom. Circular frequencies of ω_b, ω_h and ω_r corresponding to each motion are obtained as follows;

$$\omega_b^{\,2} = \frac{K_b}{m},\ \ \omega_h^{\,2} = \frac{K_h}{m},\ \ \omega_r^{\,2} = \frac{K_r}{mH_e^{\,2}} \tag{9}$$

Where m is the equivalent mass of superstructure at first mode (= $_1\overline{M}$). The predominant period of the SSI system is obtained by using $T_e = 2\pi/\omega_e$, $T_b = 2\pi/\omega_b$, $T_h = 2\pi/\omega_h$ and $T_r = 2\pi/\omega_r$.

$$T_e = \sqrt{T_b^{\,2} + T_h^{\,2} + T_r^{\,2}} \tag{10}$$

In the same way, an equivalent damping factor of the SSI system is estimated by follows;

$$h_e = h_b\left(\frac{T_b}{T_e}\right)^3 + h_h\left(\frac{T_h}{T_e}\right)^2 + h_r\left(\frac{T_r}{T_e}\right)^2 \tag{11}$$

Where h_b, h_h and h_r are the equivalent damping factors. The h_h and h_r are calculated by equation (4). The h_b is expressed by c_b which is the viscous damping coefficient of superstructure.

$$h_b = \frac{1}{2\omega_b}\frac{c_b}{m} \tag{12}$$

SIMPLIFIED CALCULATION OF SPRING CONSTANT

Spring Constant of Sway and Rocking at Base for Spread Foundation

Considering the application of solutions for a uniform layer to that for multiple layers, a cone model is applied, as drawn in Figure 3 (Wolf, 1994, Iiba et al., 2002). The spring constants (K_{hb} , K_{rb}) for sway and rocking motions are expressed as follows;

$$K_{hb} = \beta_h K_{1hb} \tag{13}$$

$$K_{rb} = \beta_r K_{1rb} \tag{14}$$

$$\beta_h = \frac{1}{\sum_{i=1}^{n}\frac{1}{\alpha_{hi}}} \tag{15}$$

$$K_{1hb} = \frac{8G_1 r_{h0}}{2-\upsilon_1} \tag{16}$$

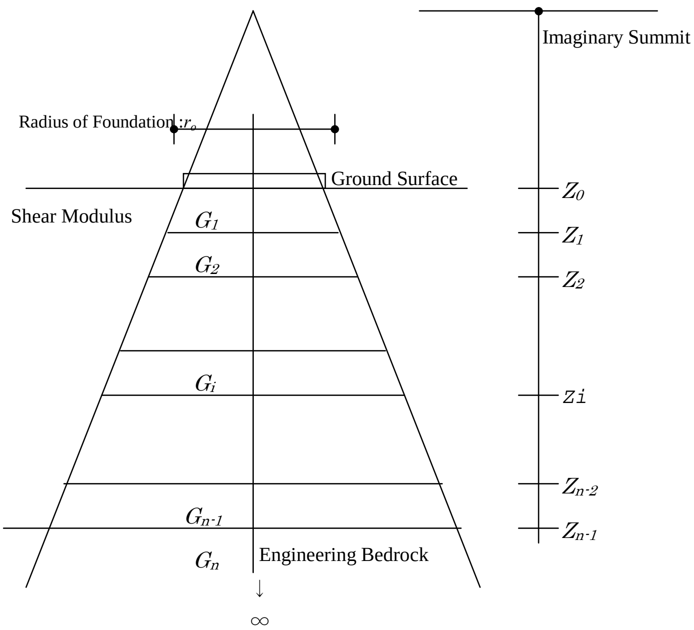


Figure 3. Cone model evaluation of spring constant at base

$$\alpha_{hi} = \left(\frac{G_i}{G_1}\right) \cdot \frac{Z_{hi} Z_{hi-1}}{Z_{h0}\left(Z_{hi} - Z_{hi-1}\right)} \ (i = 1,2,\cdots,n-1), \quad \alpha_{hn} = \left(\frac{G_n}{G_1}\right) \cdot \frac{Z_{hn-1}}{Z_{h0}} \ (i = n) \quad (17)$$

$$\beta_r = \frac{1}{\sum_{i=1}^{n} \frac{1}{\alpha_{ri}}} \quad (18)$$

$$K_{1rb} = \frac{8}{3} \frac{G_1 r_{r0}{}^3}{(1 - \upsilon_1)} \quad (19)$$

$$\alpha_{ri} = \left(\frac{E_i}{E_1}\right)\left(\frac{Z_{ri-1}}{Z_{r0}}\right)^4 \frac{Z_{r0} Z_{ri}{}^3}{Z_{ri-1}\left(Z_{ri}{}^3 - Z_{ri-1}{}^3\right)} \ (i = 1,2,\cdots,n-1), \ \alpha_{rn} = \left(\frac{E_n}{E_1}\right)\left(\frac{Z_{rn-1}}{Z_{r0}}\right)^3 \ (i = n) \quad (20)$$

$$Z_{h0} = \pi r_{h0} \frac{2 - \upsilon_1}{8}, \quad Z_{r0} = \frac{9}{16} \pi \left(1 - \upsilon_1{}^2\right) r_{r0} \quad (21)$$

$$E_i = 2(1 + \upsilon_i) G_i \quad (22)$$

$$r_{h0} = \sqrt{B \cdot D / \pi}, \ r_{r0} = \sqrt[4]{\frac{B^3 D}{3\pi}} \quad (23)$$

Where β_h and K_{1hb} are a sway modification factor and the sway spring constant for rigid foundation on semi-infinite uniform layer with soil property of first layer, respectively. β_r and K_{1rb} are the rocking modification factor and the rocking spring constant for above-mentioned condition, respectively. υ_i, E_i and G_i are the Poisson's ratio, elastic modulus and shear modulus of i-th layer of ground. B and D are a width and depth of foundation. Z_{hi} and Z_{ri} are the distance from the cone summit for sway and rocking motion. r_{h0} and r_{r0} are an equivalent radius for sway and rocking.

The K_{hb}, K_{rb} in equations (13) and (14) are complex when using the complex shear modulus of soils. In the calculation, nonlinearity of the soil property during wave propagation is considered.

Spring Constant of Sway and Rocking for Pile Foundation

As it is conformed that the sway spring constant of a pile foundation is almost the same as that of the spread foundation which has the same dimension of plan configuration (Iiba et al., 2002), the horizontal spring constant at pile head is calculated by equation (13). On the other hand, the rocking spring constant of the pile foundation is remarkably larger than that of the spread foundation.

The vertical spring constant of the pile consists of springs of friction on pile surface and end bearing at the pile tip. The spring constant of friction per unit length (S_v) is estimated by following equation (Randolf and Wroth, 1978).

$$S_v = \frac{2\pi G_e}{\log_e(2r_m / B)} \quad (24)$$

$$r_m = 2.5L(1-\upsilon_e) \quad (25)$$

$$G_e = \frac{1}{L}\sum_{i=1}^{n} G_i d_i \quad \upsilon_e = \frac{1}{L}\sum_{i=1}^{n} \upsilon_i d_i \quad (26)$$

Where L and $B(=2R_o)$ are pile length and diameter, and G_e and υ_e are an averaged shear stiffness and Poisson's ratio along the pile length. The *di* is a height of i-th layer. The spring constant at pile tip (k_b) is estimated by following;

$$k_b = \frac{3\pi}{8} \frac{\pi G_b R_o}{1-\upsilon_b} \quad (27)$$

Where G_b and υ_b are the shear stiffness and Poisson's ratio of the engineering bedrock, respectively. To combine two spring constants, the vertical stiffness of pile is obtained (Masuda et al., 1993).

$$K_v = EA\beta \frac{EA\beta(1-e^{-2\beta L}) + k_b(1+e^{-2\beta L})}{EA\beta(1+e^{-2\beta L}) + k_b(1-e^{-2\beta L})} \quad (28)$$

Where there is $\beta^2 = S_v / EA$, and E and A are an elastic modulus and a cross-sectional area of pile.

The rocking spring constant of a pile group is expressed through the summation of all pile (m). The rocking spring constants for x and y axes are as follows.

$$K_{Rx} = \sum_{i=1}^{m} K_v y_i^2 \text{ , } K_{Ry} = \sum_{i=1}^{m} K_v x_i^2 \quad (29)$$

SIMPLIFIED CALCULATION OF DAMPING FACTOR

Equivalent Viscous Damping Factor for Spread Foundation

The imaginary part of sway impedance is shown in Figure 4. In the range of the predominant frequency of building with SSI (ω_e) is less than the predominant frequency of soil deposit (ω_g), the imaginary part is dependent on the damping characteristics due to soil nonlinearity. It will be changed that it is applicable for ω_e less than 2*ω_g in the rocking spring. The sway and rocking impedances are expressed as follows.

$$\overline{K}_{hb} = K_{hb} + iK_{hb}' = K_{hb}(1+2ih_{hb}) \quad (30)$$

$$\overline{K}_{rb} = K_{rb} + iK_{rb}' = K_{rb}(1+2ih_{rb}) \quad (31)$$

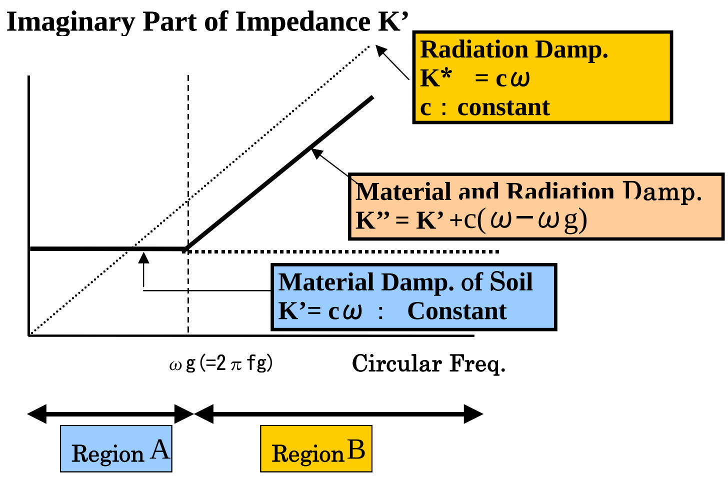


Figure 4. Imaginary part of impedance

Where K_{hb} , K_{hb}' and h_{hb} are the real and imaginary parts of impedance and the damping factor at the bottom for sway motion, respectively. The subscript *r* is corresponding to the rocking motion.

On the other hand, when the ω_e is higher than ω_g, the radiation effect is added to the damping characteristics due to soil nonlinearity. The radiation effect is considered to be proportional to the circular frequency. The following radiation damping effect is proposed.

$$K_{rad}' = c(\omega - \omega_g) \tag{32}$$

In case of $\omega_e > \omega_g$, the imaginary part for sway and rocking modes is expressed as follows. In the case of rocking motion, it will changed that ω_g should be $2*\omega_g$.

(for sway motion)

$$\overline{K}_{hb} = K_{hb} + i(K_{hb}' + K_{hrad}') = K_{hb} + iK_{hb}'' = K_{hb}(1 + 2ih_{hb}') \tag{33a}$$

$$K_{hb}'' = 2K_{hb}h_{hb} + 2\pi^2 r_{h0}{}^2 \sqrt{\rho_e G_{hb}} \left(\frac{1}{T_e} - \frac{1}{T_g} \right) \tag{33b}$$

(for rocking motion)

$$\overline{K}_{rb} = K_{rb} + i(K_{rb}' + K_{rrad}') = K_{rb} + iK_{rb}'' = K_{rb}(1 + 2ih_{rb}') \tag{34a}$$

$$K_{rb}'' = 2K_{rb}h_{rb} + \frac{1.7\pi}{1 - \upsilon_e} r_{r0}{}^4 \sqrt{\rho_e G_{hb}} \left(\frac{1}{T_e} - \frac{2}{T_g} \right) \tag{34b}$$

Where ρ_e and T_g are average density of soil and predominant period soil deposit, respectively.

Equivalent Viscous Damping Effect for Pile Foundation

Damping Effect of Sway for Pile Foundation (K_{hp}')

As the damping effect of the pile foundation for sway motion is almost the same as that of the spread foundation (Iiba et al., 2002), the imaginary part of the impedance for the spread foundation expressed in the equations (31) and (34) is used for that for the pile foundation.

Damping Effect of Rocking for Pile Foundation (K_{rp}')

The damping effect of the pile foundation is calculated based on that of the spread foundation. The damping constant of the pile foundation can be obtained by following equation.

$$\overline{K}_{rp} = K_{rp} + iK_{rp}' = K_{rp}(1 + 2ih_{rp}) \tag{35}$$

$$h_{rp} = \frac{2}{3} h_{rb} \tag{36}$$

RESPONSE EVALUATION BY USING ACCELERATION RESPONSE SPECTRUM

Building Model, Soil Condition and Earthquake Motion

Three buildings with 5, 8 and 14 stories and one soil ground are selected. A transverse direction, which consists of continuous bearing walls through the height, is analyzed, to investigate the sway and rocking effects to the response. The height, mass distribution and other properties are presented in Table 1. The push-over analysis for the buildings with base-fixed condition is conducted (Watanabe et al., 2004). The relationship between story shear force and story drift for the 8-story building as drawn in Figure 5, is replaced to the force-displacement relationship of the ESDOF system, where the force is corresponds to the base shear (${}_IQ_B$), and its displacement (${}_I\Delta$) corresponds to the displacement at the height (H_e), as shown in Figure 1.

Table 1. Dimensions and properties of buildings

	Floor	5-story		8-story		14-story	
		Height(m)	Mass(ton)	Height(m)	Mass(ton)	Height(m)	Mass(ton)
Superstructure	R					39.70	764.1
	14					36.95	673.6
	13					34.20	682.4
	12					31.45	687.0
	11					28.70	702.5
	10					25.95	711.0
	9			22.60	764.8	23.20	727.7
	8			19.85	666.5	20.40	737.0
	7			17.10	679.0	17.60	748.2
	6	14.35	804.6	14.35	682.8	14.80	755.3
	5	11.60	699.0	11.60	695.2	12.00	774.6
	4	8.85	679.1	8.85	705.8	9.15	786.6
	3	6.10	680.2	6.10	707.5	6.30	794.6
	2	3.35	685.9	3.35	714.3	3.45	799.2
	1	0.60	964.0	0.60	1163.8	0.60	1628.3
	Total		3548.8		5615.9		10343.9
Foundation	Effective Value for 1st Mode	7.29 9.49*	3119.0	12.92 15.12*	4628.0	25.08 27.28*	8053.0
	Df	1.60		1.60		1.60	
	Pile Diameter(m)	1.3-1.5		1.6-1.8		2.2	
	Pile Tip:depth(m)	GL-32		GL-32		GL-32	

*Include the depth of embedment

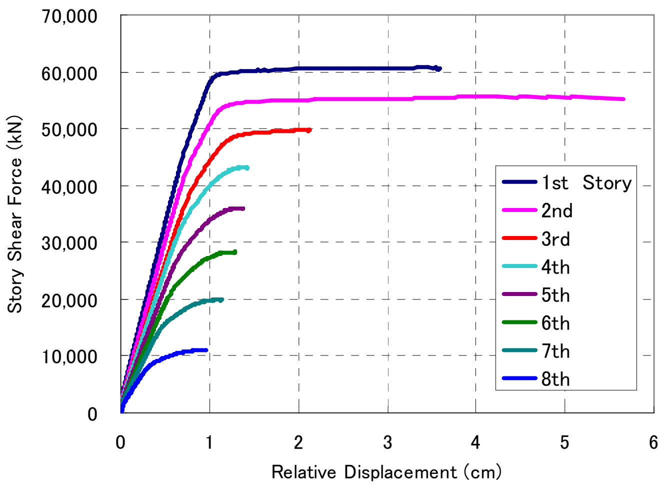


Figure 5. Relationship between story shear force and story drift at each story

The soil condition and properties of ground on the engineering bedrock are shown in Table 2 and Figure 6. The soil deposit has 0.73s in predominant period at the small shear strain of soil.

The earthquake motion is given as the ARS at the outcropped engineering bedrock whose shear wave velocity is around and more than 400 m/s, as drawn in Figure 7. Ten earthquake motions with time history with random phase are made. By using equivalent linear analysis (Program SHAKE), the time history wave forms on the ground surface are calculated, whose average ARS is drawn in Figure 7.

Response of building by Time History analysis

The time history analysis on multi degree of freedom model of 5, 8 and 14-story buildings is conducted. The relationship between restoring force and story drift of superstructures are a tri-linear skeleton curve based on the results by pushover analysis. The hysteretic characteristics are modelled as a standard type and the damping factor is 3% in proportional to the initial stiffness at the story.

Table 2. Soil properties of ground model

Depth (m)	Soil type	Density (t/m^3)	Vp (m/s)	Vs (m/s)
0-14	clay	1.6	500	130
14-20	Fine sand with silt	1.8	450	150
20-28	Fine sand	1.8	575	200
28-	Gravel	2.0	1000	400

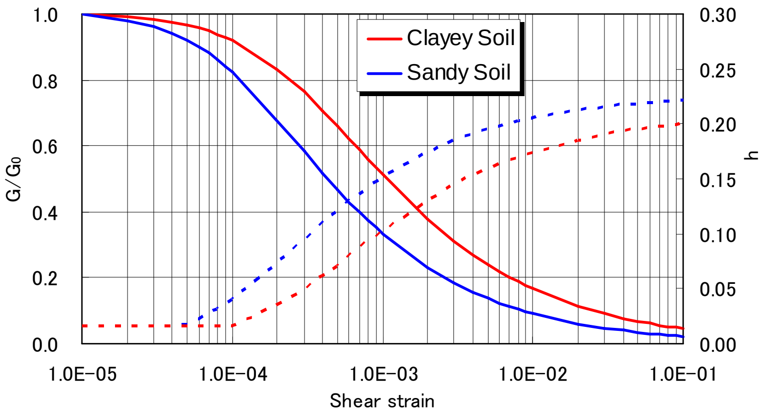


Figure 6. Shear strain dependency of soil

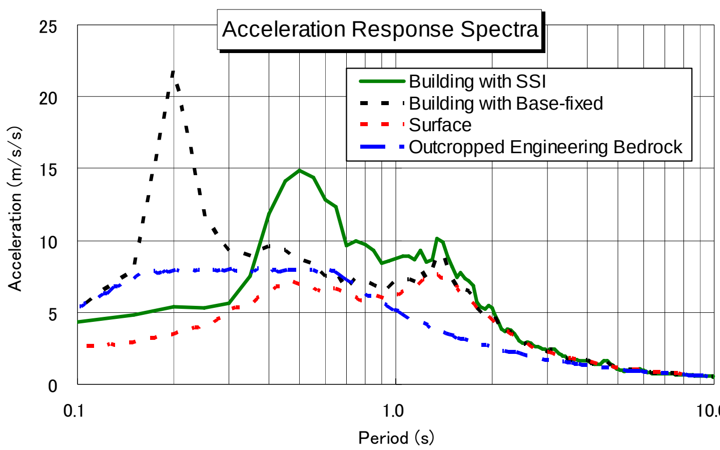
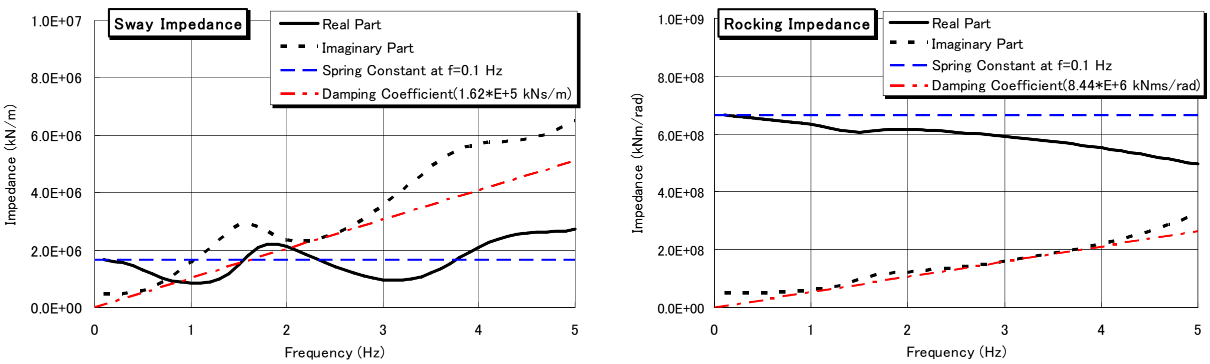


Figure7. Acceleration response spectra of engineering bedrock, ground surface and building

The building models at base-fixed and with SSI are analyzed. In the case of SSI model, dynamic impedances of pile foundations are calculated by the thin layer element (TLE) method. The method is based on the linear approximation through the equivalent linear soil properties are used, which are obtained in the equivalent linear analysis of soil deposit. The impedance functions of the foundation with 8 story building are drawn in Figure 8. As the impedance functions have a frequency dependency, spring constants and dashpot coefficients are constant in the time history analysis to avoid frequency dependent, as shown in Figure 8.

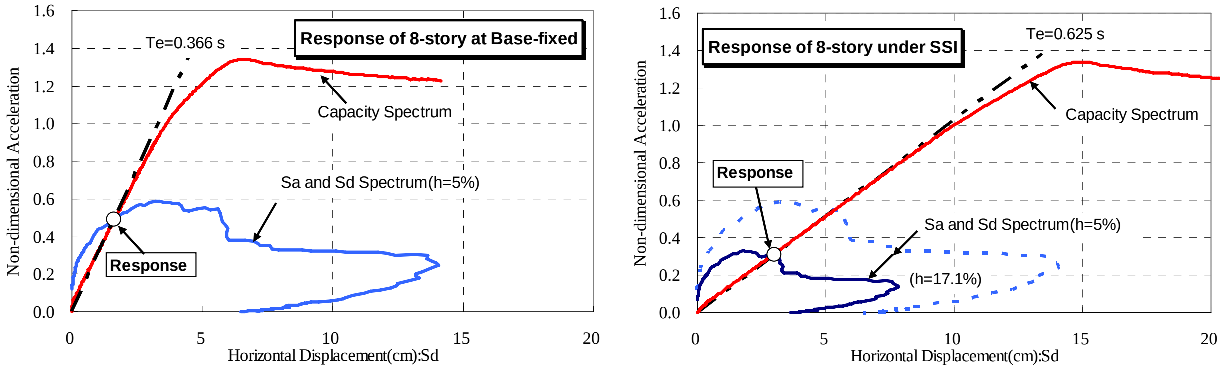
Response of building with base-fixed condition

The response of 8-story building by the response spectrum method is shown in Figure 9a). The response point is the intersection between the capacity spectrum of building and the response spectrum at ground surface considering the corresponding damping effect. The accelerations and base shear forces of three buildings are summarized in Table 3a). The base shear forces are obtained by multiplied by the effective mass at first mode. The responses by the spectrum-based method are a little larger than those by the time history analysis. That shows that the spectrum-based method gives the appropriate results in the case of base fixed condition.



a) Sway Mode b) Rocking Mode

Figure 8. Impedance function on foundation of 8-story building



a) Base-fixed condition b) SSI effect considered

Figure 9. Response of 8-story building

Table 3 Base shear of buildings compared with results by time history analysis

a) Base-fixed condition

No. of Story	Spectrum-based Method Acceleration Response Sa/g*	Spectrum-based Method Base Shear (A) (kN)	Time History Base Shear (B) (kN)	A / B
5	0.323	9.82E+03	9.45E+03	1.04
8	0.485	2.20E+04	1.82E+04	1.21
14	0.540	4.24E+04	3.80E+04	1.12

*g:gravity acceleration

b) SSI effect considered

No. of Story	Spectrum-based Method Acceleration Response Sa/g	Spectrum-based Method Base (A) Shear (kN)	Time History Base Shear (B) (kN)	A / B	Spectrum Base Shear (C)* (kN)	C / B
5	0.233	7.08E+03	1.05E+04	0.67	8.12E+03	0.77
8	0.306	1.39E+04	1.82E+04	0.76	1.68E+04	0.92
14	0.247	1.93E+04	3.16E+04	0.61	2.50E+04	0.79

*All mass of superstructure is used to calculate base shear.

Table 4 Comparison of spring constants and viscous damping coefficients

No. of Story	Sway Spring and Dashpot				Rocking Spring and Dashpot			
	Simplified Method		Thin Layer Element		Simplified Method		Thin Layer Element	
	Spring Constant (kN/m)	Viscous Coefficient (kNs/m)	Spring Constant (kN/m)	Viscous Coefficient (kNs/m)	Spring Constant (kNm/rad)	Viscous Coefficient (kNms/rad)	Spring Constant (kNm/rad)	Viscous Coefficient (kNms/rad)
5	9.56E+05	5.33E+04	1.44E+06	1.25E+05	5.16E+08	1.11E+07	5.30E+08	6.88E+06
8		5.82E+04	1.65E+06	1.62E+05	6.35E+08	1.18E+07	6.65E+08	8.44E+06
14		6.04E+04	1.92E+06	2.05E+05	8.75E+08	1.64E+07	1.03E+09	1.18E+07

Table 5 Equivalent periods and damping factors of buildings

Story	T_b(s)	T_h(s)	T_r(s)	T_e(s)	h_b(%)	h_h(%)	h_r(%)	h_e(%)
5	0.233	0.359	0.147	0.453	0.030	0.387	0.150	0.263
8	0.366	0.437	0.257	0.625	0.030	0.306	0.093	0.171
14	0.560	0.577	0.520	0.958	0.030	0.207	0.062	0.099

Response of building with SSI

Table 4 compares the spring constants and viscous damping coefficients of three buildings. The sway spring constants by the simplified method are about a half to two thirds times those by the TLE method. The rocking spring constants by the simplified method are very comparable to those by the TLE method. The viscous damping coefficients for sway by the simplified method are about one third those by the TLE method. For rocking, coefficients are a little larger than those by the TLE method.

Figure 9b) shows the response of 8 story building under the response acceleration at surface (Figure 7) and the force-displacement relationship of the system with SSI. The equivalent period with SSI (0.625 s) is much longer than the period at base-fixed (0.366 s). The equivalent periods and damping factors of buildings expressed in equations (10) and (11) are summarized in Table 5. The equivalent periods with SSI are about two times periods of buildings at base-fixed. Table 3b) shows the maximum acceleration at equivalent height and the maximum base shear of buildings with SSI. To get the acceleration response according to the damping factor of building, a following reduction factor for the ARS is used.

$$F_h = \frac{1.5}{1+10h_e} \tag{37}$$

The base shears by the spectrum-based method are about two thirds times those by the time history analysis. As the equivalent spring constants are smaller in the spectrum-based method, the longer periods of buildings make the response of acceleration less than those in the time history. And it seems that those make the damping effects overestimated. Another reason is that the responses of higher modes equal to and more second mode are not included in the results by the spectrum-based method. In Table 3b), the results are presented where the total mass of superstructure is used for the base shears. Since the underestimated results are given, the spectrum-based method need be checked and be improved.

CONCLUDING REMARKS

Concluding remarks in the responses of buildings with SSI through the spectrum-based method are summarized as follows.

a) Through modeling a degree of freedom system and neglecting the effect of base mass and moment of inertia at each floor, the equivalent period and damping factor for the SSI system are expressed in the simple equation.

b) The simplified method to calculate the spring constant and damping factor for spread and pile foundation is proposed to neglect the frequency dependency.

c) The sway spring constants and equivalent viscous damping coefficients are about one third to two third times those by the TLE method. For the rocking motion, results by the simplified method are very comparable to those by the TLE method.
d) The base shears of buildings by the spectrum-based method are almost the same as those by time history analysis in the case of base fixed condition.
e) In the case of SSI considered, the base shears by the spectrum-based method are about two thirds times those by the time history analysis. As the equivalent spring constants are smaller in the spectrum-based method, the longer periods and damping effects seem to reduce the response of acceleration.
f) The base shears using the total mass of superstructure are also smaller than those in the time history analysis to investigate the effect of higher modes. Since the underestimated results are given, the spectrum-based method need be checked and be improved.

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