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STUDY ON APPLICABILITY OF RESPONSE AND LIMIT STRENGTH CALCULATION FOR SUBSURFACE SOIL LAYERS

Shin Koyama [1] and Masanori Iiba [2]

SUMMARY

The applicability of Response and Limit Strength Calculation (RLSC) for subsurface soil layers is studied. The building code of Japan stand on performance-based type had been adopted since 2000. The recommended calculation procedure, RLSC, is applying response spectrum method. The applicability of RLSC is studied using simple subsurface soil model, up to three layers including engineering bedrock, considering several parameters such as thickness, soil types and shear wave velocity. The effectiveness of RLSC is examined comparing first natural period, T_1, and its amplification factor, $G_S(T_1)$, derived from RLSC with those from Equivalent Linear Analytical (ELA) method. When subsurface soil models are rather simple and be able to be replaced using equivalent one layer, T_1 and $G_S(T_1)$ results from RLSC are coincident with those from ELA within +/- 20% difference. Even though, T_1 and $G_S(T_1)$ by RLSC show first natural period dependent trends, they are qualitatively explained considering conversion equation that connects amplitude in frequency and time domain.

INTRODUCTION

The building code of Japan stand on performance-based type had been adopted since 2000. The basic concept for seismic design spectra consists of 1) basic design acceleration response spectra defined at the exposed engineering bedrock, and 2) evaluation of site response from geotechnical data of surface soil layers. In the procedure, iterative calculation is required in order to consider the strain-dependant soil deposit characteristics (nonlinear effect) of subsurface soil layer. The recommended calculation procedure, RLSC, is proposed in order to provide rather simple but can deal with nonlinear effect of subsurface soil layer semi-theoretically. RLSC is applying response spectrum method and replaces the subsurface soil layers to a uniform stratum with an equivalent shear wave velocity [V_{se}], equivalent mass density [ρ_e] and equivalent damping coefficient [h_e], then evaluates amplification factor.

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[1] Senior Researcher, National Institute for Land and Infrastructure Management (NILIM), Ministry of Land, Infrastructure and Transport (MLIT), Tsukuba, Japan, Email: skoyama@nilim.go.jp
[2] Research Coordinator for Advanced Building Technology, NILIM, MLIT, Tsukuba, Japan, Email: iiba-m92hx@nilim.go.jp

In this paper, first, we explain the procedures to evaluate acceleration response spectrum on ground surface by RLSC. Next, the applicability of RLSC is investigated. The subsurface soil layer models up to three layers including engineering bedrock with several parameters such as thickness, soil types and shear wave velocity are applied in analysis. The limits of these parameters are decided to satisfy actual ground condition. Finally, the applicability is examined comparing first natural period, T_1, and its amplification factor, $G_S(T_1)$, derived from RLSC with those from ELA (Schnabel, et al. [1]) using same subsurface soil models.

ACCELERATION RESPONSE SPECTRUM AT GRAOUND SURFACE

Basic Response Spectrum at Engineering Bedrock

In RLSC, the earthquake load for evaluation is specified with earthquake ground motion. The evaluation earthquake ground motion is represented with the acceleration response spectrum in the following formula.

$$S_A(T) = ZG_S(T)S_0(T) \qquad (1)$$

where, $S_A(T)$ is acceleration response spectrum for evaluation, Z is seismic zoning factor, $G_S(T)$ is soil amplification factor, $S_0(T)$ is the basic acceleration response spectrum at exposed (outcropping) engineering bedrock, and T is period in second. The engineering bedrock is defined as the layer with shear wave velocity larger than 400 m/s and certain thickness. The basic response spectrum has S_A uniform and S_V uniform parts as shown in Figure 1. The basic response spectra consist of different two levels, i.e., for life safety and damage limitation.

The level for life safety is based on the design force for the intermediate soil class specified in the prescriptive type of the provisions in Building Standard Law of Japan.

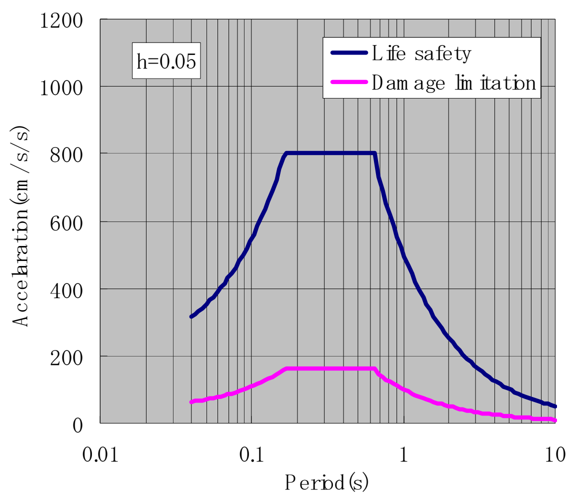

Figure 1 The basic response spectra for life safety and damage limitation

Evaluation Procedures of Acceleration Response Spectrum at Ground Surface

In order to evaluate the acceleration response spectrum on the ground surface at objective site, the amplification factor cause by subsurface soil deposits on the engineering bedrock is considered. The initial subsurface soil mode, i.e., the geotechnical data should be mostly obtained in the investigations conducted within the area. The recommended evaluation procedure RLSC is considering nonlinear soil properties as shown in Figure 2. The simplified analytical method, RLSC, is in accordance with the referring response spectrum method (Miura, et al. [2]) with some modification, i.e., the Poisson's ratio is fixed 0.4 and Stodola method is adopted to calculate mode shape.

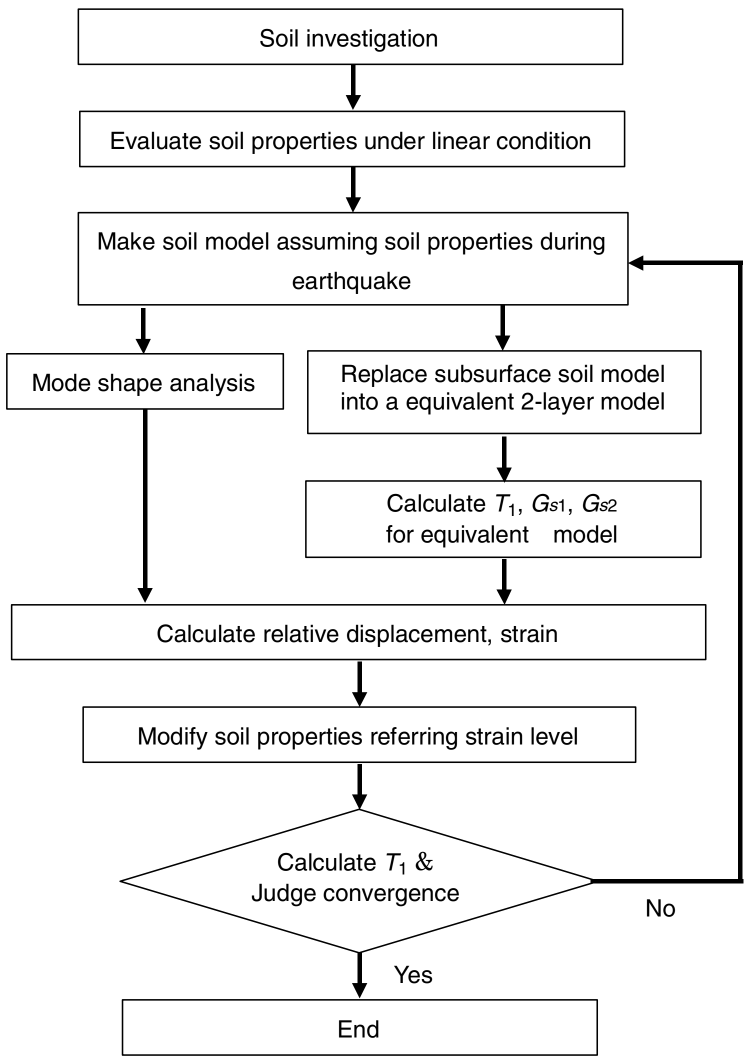

Figure 2 Procedures of iterative calculation

Transformation of response spectrum defined at outcropping engineering bedrock

The earthquake ground motion defined on the outcropping engineering bedrock is given as an acceleration response spectrum with 5% damping ratio $S_A(T, h = 0.05)$. A $S_A(T, h = 0)$, a velocity response spectrum $S_V(T, h = 0)$, and a Fourier spectrum of acceleration $F_A(T)$, have the approximate relations as

$$F_A(T) \approx S_V(T, h = 0) = (T/2\pi) S_A(T, h = 0) \quad (2)$$

Mode shape analysis of soil profile

Subdividing the soil profile, a shear model of n-degrees of freedom is formed. The first mode shape vibration, U_i (normalized by the value at the surface) is obtained through the Stodola method. This mode shape is used to distribute displacement at surface to each subsurface soil layer.

Equivalent shear wave velocity and impedance

The subsurface soil layers at objective site are replaced to a uniform stratum with an equivalent shear wave velocity, V_{se}, an equivalent mass density, ρ_e, and an equivalent damping ratio, h_e, which are calculated using the properties of each soil layer.

$$V_{se} = \sum_{\mathrm{i=1}}^{\mathrm{n-1}} V_{si} H_i \Big/ \sum_{\mathrm{i=1}}^{\mathrm{n-1}} H_i \tag{3}$$

$$\rho_e = \sum_{\mathrm{i=1}}^{\mathrm{n-1}} \rho_i H_i \Big/ \sum_{\mathrm{i=1}}^{\mathrm{n-1}} H_i \tag{4}$$

where, V_{si}, H_i and ρ_i are shear wave velocity, layer height and mass density at the i-th layer from the surface, respectively. The shear wave velocity is defined $V_{si} = \sqrt{(G_i / \rho_i)}$ where G_i is shear modulus. These G_i reflect the nonlinear characteristics of the surface soil layers considering the $G-\gamma$ relationship of soil properties. The impedance of a wave motion, α, between the equivalent surface soil layer and the engineering bedrock is expressed as

$$\alpha = (\rho_i V_{se})/(\rho_B V_{sB}) \tag{5}$$

where, V_{sB} and ρ_B are shear wave velocity and mass density at the engineering bedrock, respectively.

Amplification factor of subsurface soil layers

The amplification factor of the uniform subsurface soil layer to the outcropping engineering bedrock could be obtained by using the one-dimensional wave propagation in frequency domain. The amplification factor of the subsurface soil layers and the engineering bedrock to the outcropping one at first and second natural period are expressed as

$$G_S(T_1) = 1/(1.57 h_e + \alpha) \tag{6}$$

$$G_S(T_2) = 1/(4.71 h_e + \alpha) \tag{7}$$

for surface over outcropping engineering bedrock,

$$G_B(T_1) = 1.57 h_e/(1.57 h_e + \alpha) \tag{8}$$

for engineering bedrock over outcropping engineering bedrock.

The equivalent damping ratio, h_e, of each soil layer should reflect the nonlinear characteristics of the subsurface soil layers considering the $h-\gamma$ relationship.

Response acceleration and displacement of subsurface layers at the first natural period T_1

Applying Eq. (2), the Fourier spectrum on the ground surface, $F_{SA}(T)$, is defined as

$$F_{SA}(T) = F_{0A}(T) G_S(T, h_e, \alpha_e) \approx (T/2\pi) S_{0A}(T, h=0) G_S(T, h_e, \alpha_e) \tag{9}$$

where, $G_S(T, h_e, \alpha_e)$ is amplification factor with equivalent h_e and α_e, $S_{0A}(T, h=0)$ is converted basic response spectrum with $h=0$. In RLSC, the response displacement at the first natural period on the ground surface, $Ds(T_1)$, and those at the lower boundary, $Db(T_1)$, are defined as

$$Ds(T_1) = (T_1/2\pi)^2 As(T_1) = (T_1/2\pi)^2 (1/T_1) F_{SA}(T) = (T_1/2\pi)^2 (1/T_1) F_{0A}(T) G_S(T, h_e, \alpha_e)$$

$$\approx (T_1/2\pi)^3 (1/T_1) S_{0A}(T_1, h=0) G_S(T, h_e, \alpha_e) = \frac{T_1^2}{(2\pi)^3} \frac{1}{1.57 h_e + \alpha_e} S_{0A}(T_1, h=0) \tag{10}$$

$$Db(T_1) \approx \frac{T_1^2}{(2\pi)^3} \frac{1.57 h_e}{1.57 h_e + \alpha_e} S_{0A}(T_1, h=0) \tag{11}$$

ANALYTICAL METHOD

Considered models

The subsurface soil models considered in this study are simplified ones with several parameters, i.e., thickness, number, shear wave velocities, soil types of subsurface layers are selected as shown in Figure 3. Soil types are simply classified into clay or sand whose mass densities are 1.6, 1.8t/m^3, respectively. As the models that have 4 times bigger $V1$ than $V2$ are not realistic and not applied. The models composed of these parameters get up to 252 models. The initial damping coefficient of subsurface layers is fixed as 0.03. For engineering bedrock, shear wave velocity and the damping coefficient are also fixed as 400m/s and 0.02, respectively. In the analysis, subsurface layers are divided into 20 layers independent of whole thickness of subsurface layer.

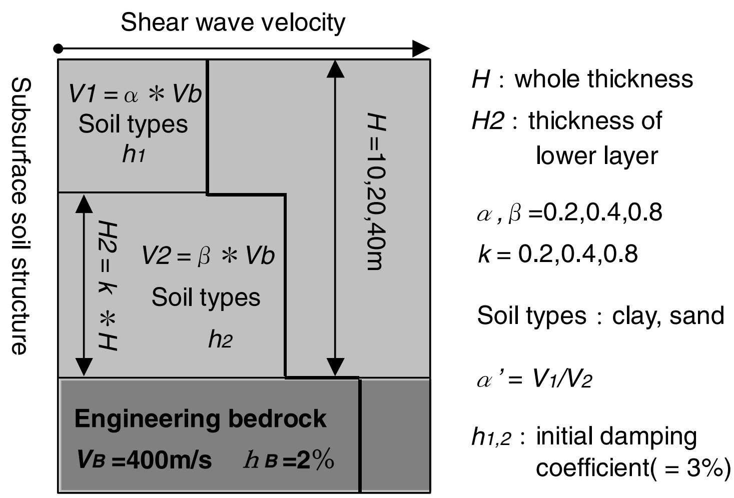

Figure 3 Considered parameters for soil models

Calculation methods

RLSC considers the strain-dependant soil deposit characteristics (nonlinear effect) of subsurface soil layers adopting iterative calculation in accordance with the former response spectrum method, Miura, et al. [2]. The judgment of convergence is satisfied if the variation of T_1 is less than 0.01. In order to examine the accuracy of RLSC, the sample subsurface models, as shown in Figure 4, were made in accordance with reference. The values were read from the referring models and mass densities for clay, sand and engineering bedrock were fixed 1.6, 1.8 and 2.0 m/s3, respectively. The first natural period T_1 got by RLSC and references are expressed in Table 1. Referring homogeneous/inhomogeneous classification by “A Guideline for Composing Design Earthquake Ground Motion for Dynamic Analysis of Buildings” (BRI and BCJ [3]), the sample model “Site-2” is classified homogeneous and others are classified inhomogeneous. Particularly “Site-3” & “Site-5” have low homogeneity. When subsurface soil condition is homogeneous, Site-2, or homogeneity is high enough, Site-1 & 4, the evaluated first natural period by RLSC showed good agreement with those from Miura, et al.

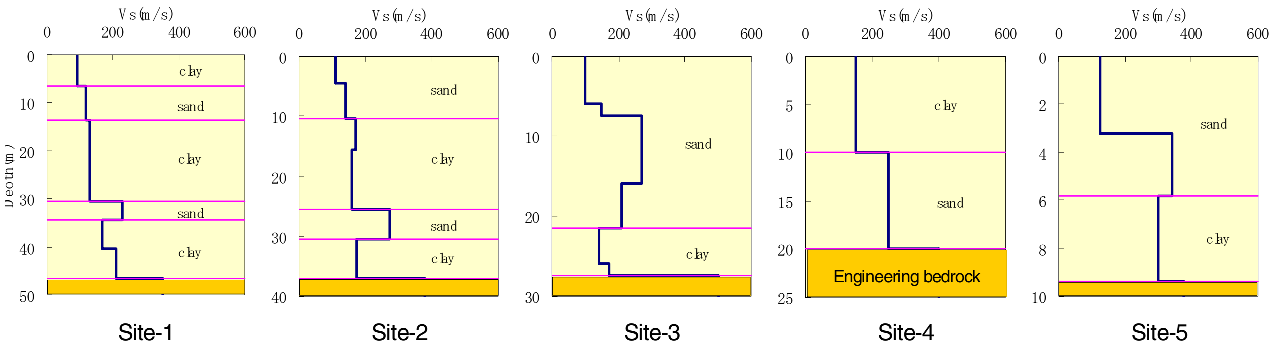

Figure 4 Applied soil models for examination (after Miura, et al. [2])

Table 1 Comparison of first natural period

	Miura, et al.*1 (A)	This method (B)	(A)/(B)	ELA *1
Site-1	2.19	2.17	1.009	2.38
Site-2	1.53	1.53	1.000	1.55
Site-3	1.40	0.94	1.484	1.32
Site-4	0.66	0.78	0.848	0.68
Site-5	0.23	0.17	1.386	0.21

*1 is referred Miura, et al. [2]

In ELA, the 10 input seismic motions fitted basic response spectrum following "A Guideline for Composing Design Earthquake Ground Motion for Dynamic Analysis of Buildings" (BRI and BCJ [3]) were used.

Comparison

In RLSC, the amplification characteristic of subsurface layer, $G_S(T)$, is defined with first and second natural periods and two amplification factors, $G_S(T_1)$ and $G_S(T_2)$, at those natural periods. In ELA, the amplification characteristic is evaluated by the mean response spectral ratio with respect to 10 input motions. Each of the response spectrum ratios was calculated dividing response spectrum from surface motion by one from input motion. Making a comparison, two types of values are examined, i.e., 1) first natural period and its amplification factor got from the spectral ratio, as comparison "type-A", and 2) T_1 and $G_S(T_1)$ got following Notification No. 1457, the Ministry of Construction (2000), as comparison "type-B".

RESULTS OF ANALYSIS

Figures 5 and 6 show amplification factor, $G_S(T)$, under damage limitation from RLSC and ELA, respectively. They are classified with homogeneity, α', explained in Figure 3. In Figure 5, lower limit of amplification factor following Notification No. 1457, the Ministry of Construction (2000) was applied. The predominance in 0.1 to 0.2 sec period range recognized in the figure of $\alpha' = 0.25, 0.50$ for ELA does not appear in RLSC. The amplification factors, $G_S(T)$, in RLSC are always equal or bigger than those of ELA. Figure 7 shows distribution of T_1 and $G_S(T_1)$ ratio taken with respect to those by ELA, RLSC over ELA, under both of "damage limitation" and "life safety" for comparison "type-A". The X-axis shows T_1 calculated by ELA. If T_1 and $G_S(T_1)$ by RLSC and ELA are coincident, T_1 and $G_S(T_1)$ ratios will be 1.0.

In Figure 7, the lines correspond to +/- 20% differences against 1.0 are also depicted. Both of the situation under "damage limitation" and “life safety", the T_1 ratios decrease when T_1 get longer. The T_1 ratio under "damage limitation" result within 0.8 to 1.2 levels if α' is 0.5, 1.0 and homogeneous. Under “life safety", the T_1 ratios get smaller than under "damage limitation" and lower than 1.0 except partial case for α' is 0.5. In case of the $G_S(T_1)$ ratios, they increase when T_1 get longer. The most of $G_S(T_1)$ ratios under "damage limitation" are distributed within 0.8 to 1.2 levels. If α' is 0.25 and T_1 is rather short, $G_S(T_1)$ can’t be correctly evaluated because $G_S(T_1)$ ratios show about 0.6. Under “life safety", $G_S(T_1)$ ratios show same tendency as under "damage limitation" with rather big values.

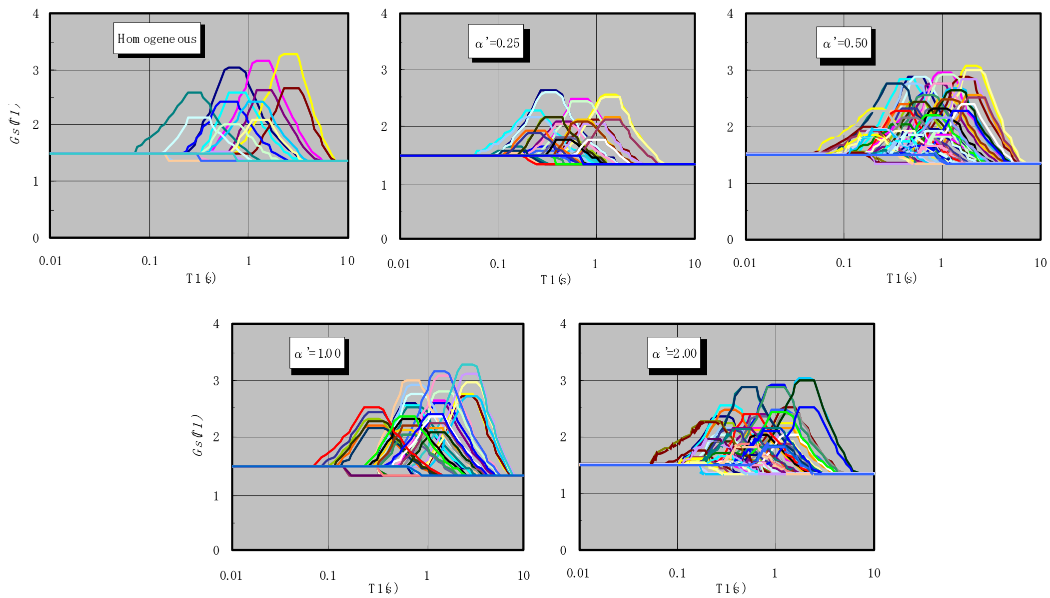

Figure 5 Amplification factor $G_S(T)$ derived from RLSC for damage limitation

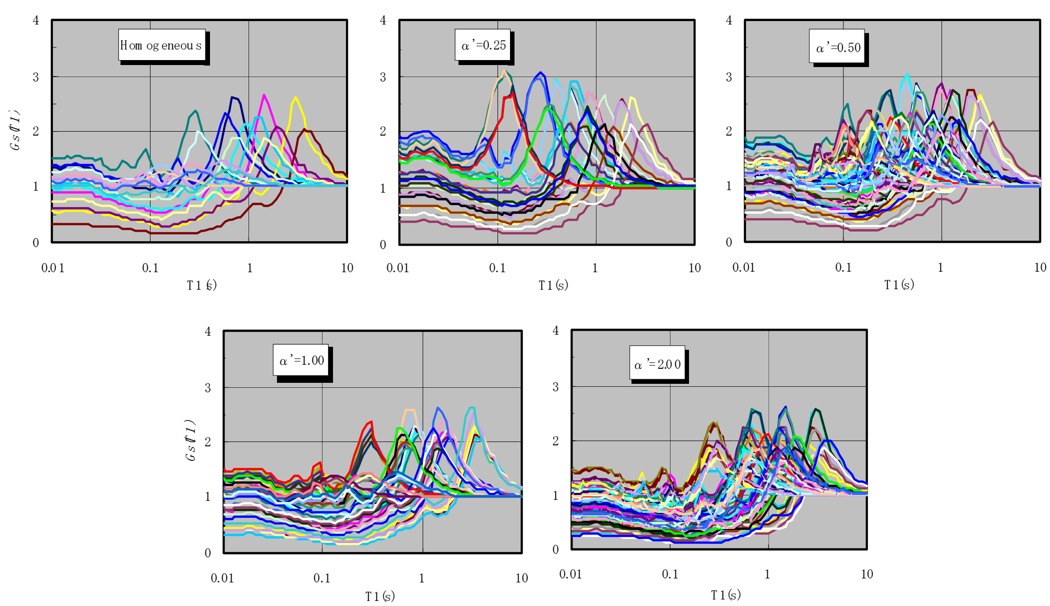

Figure 6 Amplification factor $G_S(T)$ derived from ELA for damage limitation

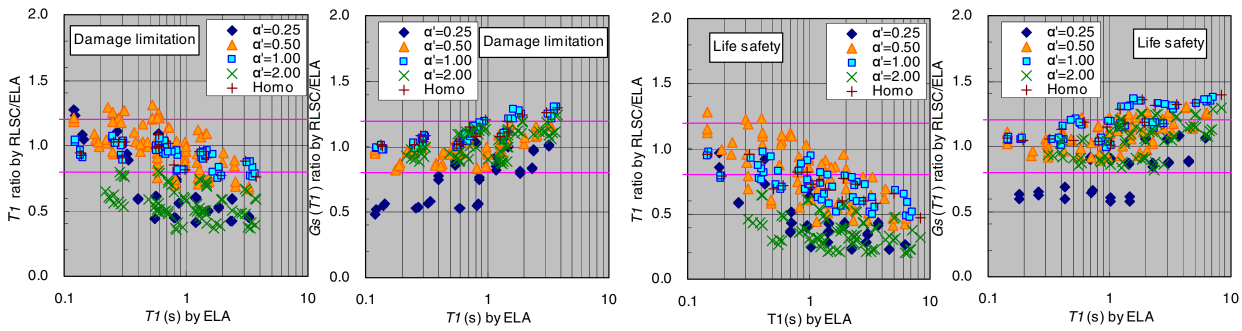

Figure 7 Distribution of T_1 and $G_S(T_1)$ ratio taken with respect to those by ELA for comparison “type-A”

The correlation coefficient was examined depending on α' value in order to indicate relation of T_1 calculated by RLSC and ELA with values. As shown in Table 2, about T_1, they get bad under “life safety” than under "damage limitation" in all cases. The correlation coefficients for $G_S(T_1)$ show the almost same values under both of damage limitation and life safety except in case that α' is 0.25.

Table 2 Cross correlation coefficient with α' for “type-A”

	α'	Homogeneous	0.25	0.50	1.00	2.00
Damage limitation	*T1*	0.993	0.955	0.967	0.995	0.935
	Gs(T1)	0.974	-0.069	0.901	0.972	0.937
Life safety	*T1*	0.978	0.918	0.928	0.977	0.890
	Gs(T1)	0.962	-0.194	0.805	0.976	0.934

Figure 8 shows distribution of T_1 and $G_S(T_1)$ ratio following comparison “type-B” evaluation explained at “Comparison”. In this evaluation type, the distribution of T_1 and $G_S(T_1)$ show the same but not so strong tendency as “type-A”. The T_1 and $G_S(T_1)$ ratios result within 0.73 to 1.28 and 0.88 to 1.21 levels, respectively for all analytical cases. In Table 3, the correlation coefficient was examined depending on α' value in order to indicate relation of T_1 as same as in “type-A”. All of the correlation coefficients are improved than in “type-A” and over 0.948. And that they show the same values in “damage limitation” and “life safety” independent of α', T_1 and $G_S(T_1)$.

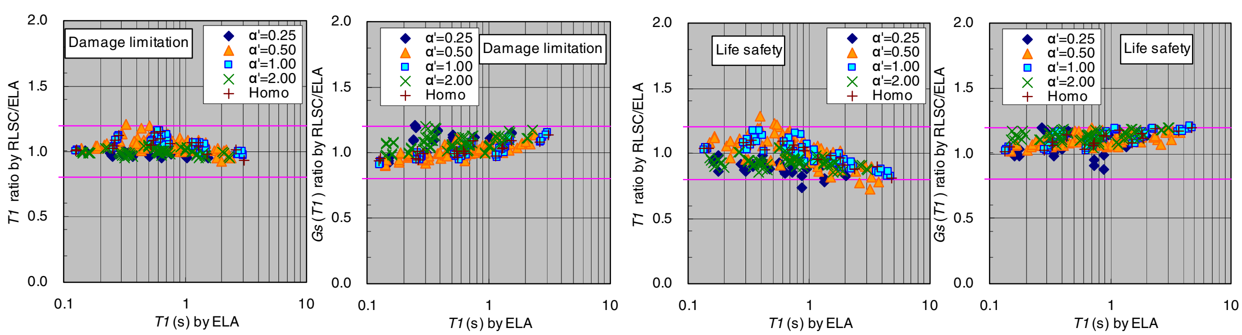

Figure 8 Distribution of T_1 and $G_S(T_1)$ ratio taken with respect to those by ELA for comparison “type-B”

Table 3 Cross correlation coefficient with α' for “type-B”

	α'	Homogeneous	0.25	0.50	1.00	2.00
Damage limitation	*T1*	0.997	1.000	0.997	0.999	0.999
	Gs(T1)	0.981	0.948	0.966	0.979	0.972
Life safety	*T1*	0.997	0.995	0.988	0.997	0.998
	Gs(T1)	0.988	0.953	0.978	0.993	0.991

In summarize, the first natural period, T_1, gets good results when α' is 0.50, 1.0 and homogeneous under "damage limitation". About $G_S(T_1)$, the correlation coefficient doesn't depend on input motion level, i.e., "damage limitation" and "life safety", shows good relation when α' is 1.00, 2.00 and homogeneous. The correlation coefficients from “type-B” values are higher than those from “type-A”. As the amplification factor was set uniform from T_1-20% to T_1+20% period range with $G_S(T_1)$ level by Notification No. 1457, the Ministry of Construction (2000) relate to RLSC, the 20% difference against ELA was considered to some extent.

Even though, first natural period dependant trends could be seen. Then, the equivalent shear wave velocities, V_{se}, and the equivalent damping ratios, h_e, that characterizes calculated T_1 and $G_S(T_1)$, by RLSC and ELA under converged state were compared. As shown in Figure 9, both V_{se} and h_e ratio also have first natural period dependent trend, i.e., V_{se} ratio increase and h_e decrease together with T_1. In Eq.10, Fourier amplitude was divided by first natural period, T_1, to get time domain amplitude about T_1 component. This operation decreases time domain amplitude in accordance with increase of period. For instance, assuming that the amplitude about two arbitrary periods T_X and $2T_X$ in frequency domain are equal, i.e. $F_{SA}(T_0)$ is equal to $F_{SA}(2T_0)$, the converted amplitude into time domain will be $(1/T_X)F_{SA}(T_X)$ and $(1/2T_X)F_{SA}(2T_X)$, without considering amplification factor $G_S(T_1)$. When the amplitude in time domain decreases, the strain-dependant characteristics of soil does not progress, and then V_{se} doesn’t decrease and h_e doesn’t increase. The trend appeared in Figure 9 could be explained qualitatively.

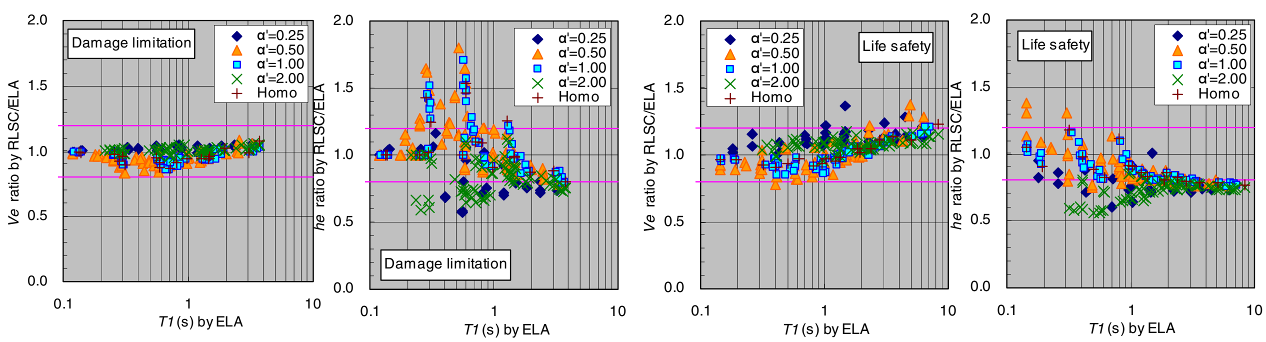

Figure 9 Distribution of V_{se} and h_e ratio with respect to those by ELA under “damage limitation” and “life safety”

CONCLUSIONS

The applicability of Response and Limit Strength Calculation (RLSC) for subsurface soil layers was studied. One layer subsurface models and simple two layers models similar to homogeneous layer showed that both of T_1 and $G_S(T_1)$ derived from RLSC and ELA were usually coincident each other. In case that the subsurface models consisted of complicated two layers and hard to be replaced by an equivalent uniform stratum model, T_1 and/or $G_S(T_1)$ from RLSC were different from those of from ELA with more than 20% difference, in some cases over 100% difference. As the amplification factor was set uniform from T_1-20% to T_1+20% period range with $G_S(T_1)$ level by Notification No. 1457, the Ministry of Construction (2000) relate to RLSC, the 20% difference against ELA was considered to some extent. While, T_1 and $G_S(T_1)$ by RLSC showed first natural period dependent trends. They were also recognized in the equivalent shear wave velocities, V_{se}, and the equivalent damping ratios, h_e, that characterizes calculated T_1 and $G_S(T_1)$. Considering conversion equation that connects amplitude in frequency and time domain, they are qualitatively explained.

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REFERENCES

1. Schnabel, P. B., Lysmer, J. and Seed, H. B., "SHAKE - A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites", Report No. EERC 72-12, EERC, 1972.
2. Miura, K., Koyamada, K. and Iiba, M. "Response spectrum method for evaluating nonlinear amplification of surface strata", Journal of Structural and Construction Engineering, Transaction of Architectural Institute of Japan, No.539, 57-62, AIJ, 2001.
3. BRI and BCJ "A Guideline for Composing Design Earthquake Ground Motion for Dynamic Analysis of Buildings", Appendix of Annual Report of the Committee on Technical Guideline for Design Earthquake Ground Motion, 1992 (in Japanese).