A Simple Approach for Estimating the First Resonance Peak of Layered Soil Profiles

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1. Introduction

It has long been recognized that the effects of the local site on ground motion should be considered in the seismic design of structures. In most seismic codes throughout the world, the site effects are generally considered according to several site classes. For example, in Eurocode 8 [1] and the International Building Code [2], site effects are reflected in terms of site factors or site coefficients for several site classes. In the Chinese Seismic Code [3] and the 1993 Japanese Loads Recommendation [4], the free-field response spectrum is defined to directly correspond to several site classes, and site effects are implicitly considered by the site classification.

However, in some regions, such as Japan, geological feature is known to vary significantly through the country, the site effects can hardly be described in detail by several classes of sites. In reality, many important site-specific characteristics can be masked by the site classifications. For example, for a site consisting of soft soil on stiffer rock, soil resonance caused by multiple reflections within the soil medium can cause significant amplification of seismic motion with a frequency near the site's fundamental frequency; however, the resonance effect of a specific site is 'averaged' by the site classification and typically cannot be accurately accounted for by a specific site class.

Hence, a site-specific method for estimation of the site effects is incorporated into the 2000 Japanese Seismic Code [5]. In this method, estimation of the first resonance peak, Gs_1, is a very important step. Currently, Gs_1 and fundamental period T_1 are evaluated by approximating a multi-layer soil profile as an equivalent single-layer profile by weighted averaging the soil shear wave velocity and density.

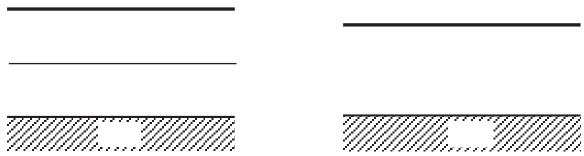
$$Gs_1 = \frac{1}{1.57h + a_G} \tag{1}$$

$$T_1 = \frac{4H}{V} \tag{2}$$

where, h is the soil damping ratio, and a_G is the impedance ratio, H is the soil thickness, V is the soil shear wave velocity. However, this method may underestimate Gs_1, when the impedance contrast of the soil layers is large. In this paper, a new simple procedure for determining the Gs_1 of layered soil profiles is proposed.

2. Development of The TTS Procedure

To overcome the shortcomings of the current method, we introduce a method to equate the fundamental period and Gs_1 of a multi-layer soil profile with those of an equivalent single-layer soil profile; that is, the method replaces a multi-layer soil profile by an equivalent single-layer soil profile with same fundamental period and Gs_1. Therefore, the Gs_1 of the multi-layer soil profile can be simply calculated from that of the equivalent single-layer soil profile. For this purpose, we firstly develop a procedure to replace a two-layer soil profile on bedrock with an equivalent single-layer soil profile with the same fundamental period and Gs_1. This method is called two-to-single (TTS) procedure.



(a) (b)

Fig. 1. Illustration of the concept of replacing a two-layer soil profile on bedrock with an equivalent single-layer soil profile.

Figure 1 schematically shows the procedure developed to replace a two-layer soil profile on bedrock (a) with an equivalent single-layer soil profile (b) with the same fundamental period and Gs_1. To develop this procedure, the fundamental parameters including shear wave velocity V_{eq}, thickness H_{eq}, density ρ_{eq} and damping ratio h_{eq} of the equivalent single-layer soil profile should be expressed in terms of those of the two-layer soil profile based on the following two equivalence equations:

$$T_{1-2L} = T_{1-eq} \tag{3}$$

$$Gs_{1-2L} = Gs_{1-eq} \tag{4}$$

where $T_{1\text{-}2L}$ and $Gs_{1\text{-}2L}$ represent the fundamental period and first resonance peak of the two-layer soil profile, respectively; $T_{1\text{-}eq}$ and $Gs_{1\text{-}eq}$ represent the fundamental period and first resonance peak of the equivalent single-layer soil profile, respectively.

To obtain the equations for the fundamental parameters of the equivalent single-layer soil profile according to Eqs. (3) and (4), the equations for $T_{1\text{-}eq}$, $Gs_{1\text{-}eq}$, $T_{1\text{-}2L}$ and $Gs_{1\text{-}2L}$ expressed in terms of the fundamental parameters of soil profiles must be known. Approximate expressions for $Gs_{1\text{-}eq}$ and $T_{1\text{-}eq}$ are given by Eqs. (1) and (2), respectively. The expression for $T_{1\text{-}2L}$ was derived by Madera [6], and an approximate expression was subsequently developed by Hadjian [7]. The expression for $Gs_{1\text{-}2L}$ was derived by Zhang et al. [8].

Substituting Eqs. (1) and for $Gs_{1\text{-}2L}$ [8] into Eq. (4), the shear wave velocity V_{eq} of the equivalent single layer can be obtained by:

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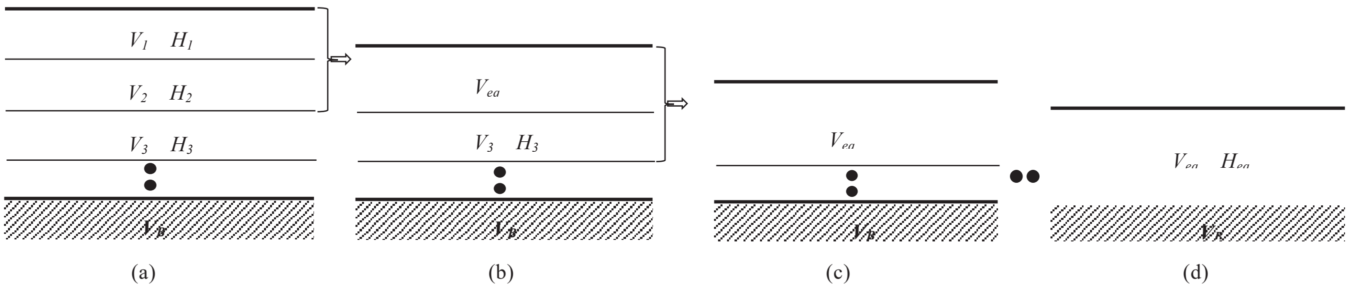


Fig. 2. Illustration of the concept of replacing a multi-layer soil profile on bedrock with an equivalent single-layer soil

$$V_{eq} = \left| \frac{V_1\rho_1}{\rho_{eq}} \sin\frac{\pi T_1}{2T_{1-2L}} \cos\frac{\pi T_2}{2T_{1-2L}} + \frac{V_2\rho_2}{\rho_{eq}} \cos\frac{\pi T_1}{2T_{1-2L}} \sin\frac{\pi T_2}{2T_{1-2L}} \right| \quad (5)$$

and the thickness H_{eq} of the equivalent single-layer soil can be given by:

$$H_{eq} = \frac{T_{1-2L}V_{eq}}{4} \quad (6)$$

where, m is the layer number (m = 1, 2); ρ_m, V_m, and T_m are the density, shear wave velocity, period of mth soil layer, respectively. ρ_{eq} is the destiny of the equivalent layer. $T_{1\text{-}2L}$ is the fundamental period of the two-layer soil profile and can be estimated by the equation by Hadjian [7].

3. Gs_1 of Multi-layer Soil Profiles on Bedrock

This section presents a simple procedure for determining the Gs_1 of multi-layer soil profiles on bedrock by successively applying the TTS procedure developed in Section 2. Specifically, for a multi-layer soil on bedrock [Fig. 2(a)], the top two layers are assumed to overlie bedrock and are replaced by an equivalent single layer using the TTS procedure. Subsequently, the equivalent single layer and the third layer can be treated as a new top two-layer soil and can also be replaced by an equivalent single layer. By applying the TTS procedure successively to the remaining lower layers of the soil profile, the multiple soil layers can finally be replaced by an equivalent single layer, and the fundamental period and Gs_1 of the total soil profile can be obtained. The concept of this procedure is illustrated in Fig. 2 and involves the following steps:

(a) For a multi-layer soil on bedrock [Fig. 2(a)], the top two soil layers are assumed to overlie bedrock and can be replaced with an equivalent soil layer using the TTS procedure [i.e., Eqs. (5), (6)]. Next, a new multi-layer soil [Fig. 2(b)] is formed.

(b) For the new multi-layer soil shown in Fig. 2(b), the top two layers are again assumed to overlie bedrock and are replaced by another equivalent single layer using the TTS procedure. Another new multi-layer soil [Fig. 2(c)] is then formed.

(c) By successively applying the TTS procedure until the last soil layer is considered, a final equivalent single-layer soil is obtained, as shown in Fig. 2(d).

(d) Finally, the Gs_1 for the final single-layer soil can be readily obtained using Eq. (1).

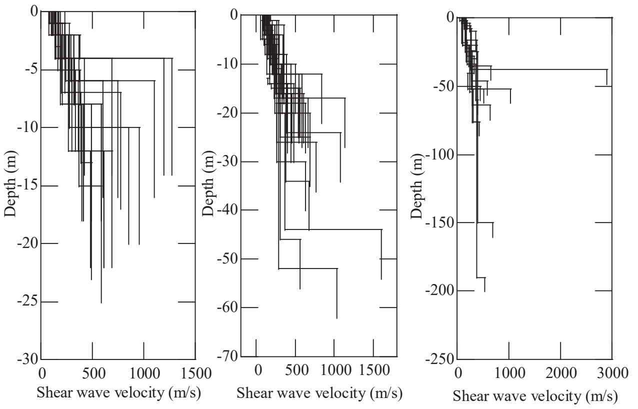
It should be noted that, the developed procedure for Gs_1 is applicable for not only linear analysis but also the equivalent-linear analysis considering soil nonlinearity. For the equivalent-linear analysis, the proposed procedure is applied just using the final strain-compatible shear modulus and damping ratios after the iteration. Many simple equivalent-linear methods have been developed for estimation of soil nonlinearity (i.e. strain-compatible shear modulus and damping ratio) using bedrock response spectrum directly [9, 10]. The method by Miura et al. [9] has been introduced in the Japanese seismic code. Here, any one of these simple methods can be used to consider soil nonlinear in estimation of Gs_1.

4. Numerical Examples Using the Proposed Procedure

In order to investigate the accuracy of the proposed method, 67 representative soil profiles selected from Strong-motion Seismograph Networks (K-NET, KIK-net) are used. According to Japan Road Association [11], these soil profiles are divided into three site classes, and the shear wave velocity profiles above the engineering bedrock of each site classification are presented in Fig. 3. According to Japanese Seismic Code, engineering bedrock is defined as the layer where the shear wave velocity is greater than approximately 400 m/s. The unit weights are not given for some sites; these weights are empirically determined according to Sakai et al. [12] as 15.68 KN/m^3 for clay, 18.62 KN/m^3 for sand, 19.60 KN/m^3 for engineering bedrock with shear wave velocity in the range of 400~800 m/s, and 21.56 KN/m^3 for engineering bedrock with shear wave velocity greater than 800 m/s. The initial fundamental periods of the selected soil profiles are calculated by the SHAKE program, and the results vary widely from 0.05 to 1.72 s.

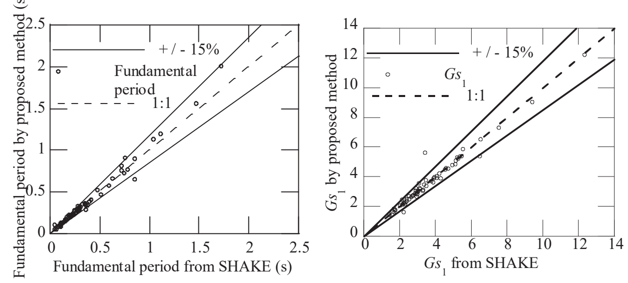
Both linear and equivalent-linear analysis are conducted for the accuracy investigation. For linear analysis, damping ratios of all soil layers are simply considered to be 2%. For the equivalent-linear analysis, the simple method by Inoue et al. [10] is adopted to estimate the strain-compatible soil damping ratios and shear modulus. Here, the modulus reduction and damping curves in Japanese seismic code is used for the analysis. Both the Level 1 and Level 2 response spectra defined on bedrock in Japanese seismic code are used as input motions. For the SHAKE analysis, 10 spectrum-compatible time histories are generated for each of the two load levels. The durations of the Level 1 and Level 2 motions are set to be 60s and 120s, respectively. Peak ground accelerations of the ground motions generated using the Level 2 response spectrum vary from 0.34 to 0.4g.

The fundamental periods and Gs_1 of the 67 soil profiles are estimated by the proposed procedure and compared with those obtained using the



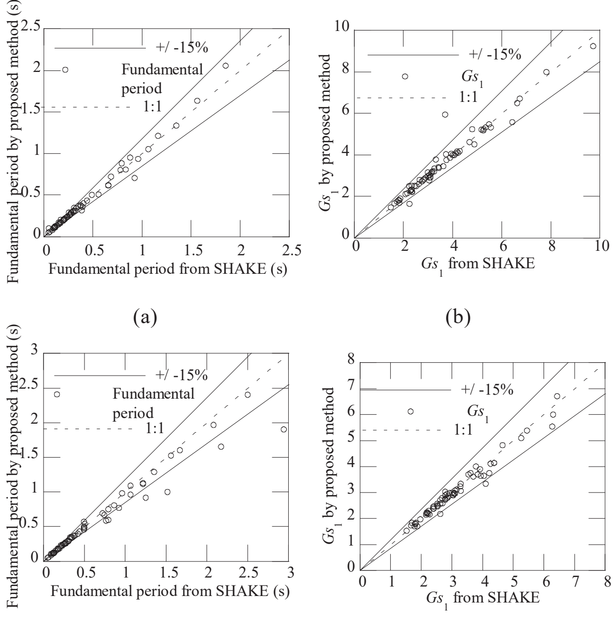
(a) (b) (c)

Fig. 3. Shear wave velocity profiles above engineering bedrock used for analyses: (a) first site class, (b) second site class, and (c) third site class.



(a) (b)

Fig. 4. Comparisons of fundamental period and Gs_1 calculated using the proposed method and SHAKE program for linear analysis.



(c) (d)

Fig. 5. Comparisons of T_1 and Gs_1 calculated using the proposed method and SHAKE program for equivalent-linear analysis: (a) T_1 corresponding to the Level 1; (b) Gs_1 corresponding to the Level 1; (c) T_1 corresponding to the Level 2; (d) Gs_1 corresponding to the Level 2.

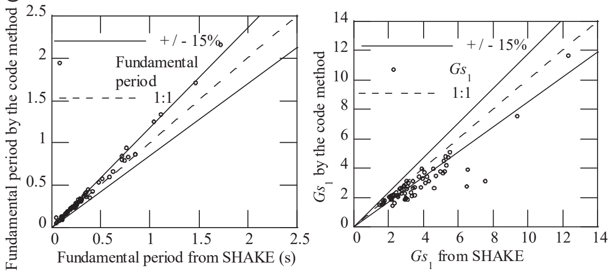
SHAKE program. Figs. 4 and 5, respectively, show the linear and equivalent-linear results. The Gs_1 obtained by the proposed method are remarkably accurate. For the linear analysis, the average error is only 4.6%, and 94% of estimated values are within 15% of the SHAKE results. For equivalent-linear analysis, the average errors corresponding to the Level 1 and Level 2 motions are, respectively, 4.0% and 3.7%; and for both the two levels, 97% of estimates are within 15% of the SHAKE results. The accuracy in fundamental period is also remarkably good. For the linear analysis, 85% of the estimates are within 15% of SHAKE results. For the equivalent-linear analysis, 94% of estimates corresponding to the Level 1 and 88% of estimates corresponding to the Level 2 are within 15% of SHAKE results. The accuracy of the proposed method is considered sufficient for engineering calculation.

In addition, the fundamental periods and Gs_1 are also estimated using the method in the Japanese Seismic Code and compared with those obtained using the proposed method and the SHAKE program. Figs. 6 and 7, respectively, show the linear and equivalent-linear results. The errors in Gs_1 obtained by the code method are significant. For linear analysis, the average error is as large as 17.2%. For equivalent-linear analysis, the average errors corresponding to the Level 1 and Level 2 motions are, respectively, 25% and 24%, which are much greater than that for the proposed method. For both the linear and equivalent-linear analyses, most of the Gs_1 estimated by the code method are underestimated by over 15% compared to the SHAKE results, which is consistent with previous studies [8-10, 12]. The errors in the fundamental period obtained by the code method are also significant. For linear analysis, 37% of the estimates have errors greater than 15%. For equivalent-linear analysis, 73% of the Level 1 estimates and 67% of the Level 2 estimates have errors greater than 15%.

Generally speaking, the proposed procedure produces accurate estimates of both fundamental period and Gs_1 and is much more accurate than the method used in the Japanese Seismic Code.

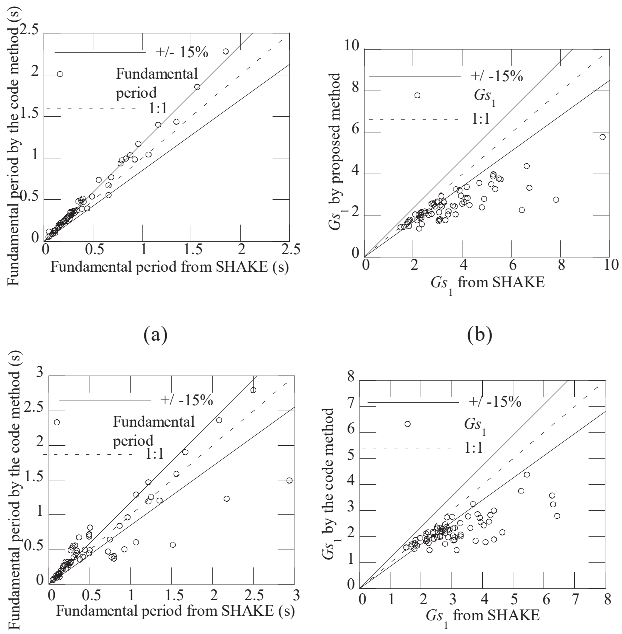
The results of Gs_1 by the proposed method shown in Fig.4 (b) are also compared with those by our methods developed previously shown in Figs.6 (a) of both the earlier two papers [8, 13]. It is found that the results obtained by the method proposed in this paper are more accurate than those by the previous methods.

It should be noted that the equivalent linear method (SHAKE) used for calibration above is an approximate method. The method is generally applicable for the cases when the computed shear strain is less than about 1% [9]. In this section, the computed maximum shear strains of most soil profiles using even the Level 2 motions are less than 1%, thus the findings above are valid. However, when the computed shear strains are larger, errors by the equivalent linear method may be significant [14], and hence the equivalent linear method may be not appropriate for calibration. Validity of the proposed method for larger ground motions than those considered in this paper needs be investigated in the further study.



(a) (b)

Fig. 6. Comparisons of fundamental period and Gs_1calculated by the code method and SHAKE program for linear analysis.



(c) (d)

Fig. 7. Comparisons of fundamental period and Gs_1calculated by the code method and SHAKE program for equivalent-linear analysis: (a) T_1 corresponding to the Level 1; (b) Gs_1 corresponding to the Level 1; (c) T_1 corresponding to the Level 2; (d) Gs_1 corresponding to the Level 2.

5． Conclusions

The content of this paper and the main conclusions are summarized as follows:

(a) A procedure to replace a two-layer soil profile on bedrock with an equivalent single-layer soil profile with the same Gs_1 and fundamental period is developed. The accuracy of the developed procedure is verified using a series of two-layer soil profiles on bedrock.

(b) Based on the developed TTS procedure, a simple procedure for estimating the Gs_1 of a multi-layer soil profile is proposed. The proposed procedure is applied in an example calculation. It is found that the procedure can be easily implemented in a spreadsheet, and the estimated results are highly accurate.

(c) To investigate the validity of the proposed method, the Gs_1 and fundamental periods of 67 representative soil profiles are estimated. The proposed method shows remarkably good accuracy in estimating both the Gs_1 and fundamental period and is clearly more accurate than the current code method.

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