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ENGINEERING SEISMIC BASE LAYER FOR DEFINING DESIGN EARTHQUAKE MOTION

Nozomu YOSHIDA [1], Sumio SAWADA[2] and Susumu NAKAMURA[3]

ABSTRACT

Engineer's common sense that incident wave is common in a widespread area at the engineering seismic base layer is shown not to be correct. An exhibiting example is first shown, which indicates that earthquake motion at the ground surface evaluated by the analysis considering the ground from a seismic bedrock to a ground surface simultaneously (continuous analysis) is different from the one by the analysis in which the ground is separated at the engineering seismic base layer and analyzed separately (separate analysis). The reason is investigated by several approaches. Investigation based on eigen value problem indicates that the first predominant period in the continuous analysis cannot be found in the separate analysis, and predominant period at higher order does not match in the upper and lower ground in the separate analysis, which disagreement result in different amplification characteristics. The earthquake response analysis indicates that reflected wave at the engineering seismic base layer is not zero, which indicates that conventional engineering seismic base layer does not work as the term "base". All these results indicate that wave that goes down to the deep depths after reflecting in the surface layer and again reflects at the seismic bedrock cannot be neglected in evaluating the response at the ground surface. In other words, interaction between the surface layer and below it cannot be neglected.

INTRODUCTION

Earthquake motion spreads from a fault to the site where an engineer is going to evaluate seismic motion. Ideally, an analysis considering the fault mechanism and path characteristics simultaneously is to be carried out in order to evaluate the earthquake motion at the ground surface. It is, however, very difficult and complicated, and far from the engineering practice. An alternate method is, then, usually employed. One of the frequently used methods is that they are separated into several parts and evaluate wave-traveling characteristics in each part individually. The earthquake motion at the interested site is obtained by a chain method, i.e., response of the ground surface is evaluated by the product of fault mechanism, attenuation characteristics from a fault to the seismic bedrock, and amplification characteristics from the seismic bedrock to the ground surface. Here, seismic bedrock is defined to be a layer whose shear wave velocity is greater than about 3km/s.

The last path, from the seismic bedrock to the ground surface is usually separated into two parts: a

[1] Professor, Department of Civil and Environmental Engineering, Tohoku Gakuin University, Japan, Email: yoshidan@tjcc.tohoku-gakuin.ac.jp
[2] Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
[3] Professor, Department of Civil Engineering, Nihon University of California, Fukushima, Japan

path from the seismic bedrock to the engineering seismic base layer and a path in a surface ground, i.e., from the engineering seismic base layer to the ground surface. In this method, the outcrop motion at the engineering seismic base layer is first computed and a half of the outcrop motion is applied to the base of the surface ground as incident wave to the surface ground. The engineering seismic base layer is physically or mechanically defined to be a layer whose impedance is sufficiently larger than that of the surface layer and it spreads in wide area, but the definition of the shear wave velocity is not uniquely defined. The largest shear wave velocity, 700 m/s, is used in the design of the nuclear power plant (Electric Technical Guideline Committee, 1987), but many design specifications in Japan use value between 350 m/s and 400 m/s, which corresponds to the layer with SPT-*N* value of 50.

This separation of the amplification characteristics indicates that it is sufficient to specify the incident wave at the engineering seismic base layer in order to evaluate the behavior of the surface ground during earthquake. This concept is widely accepted. For example, when an engineer want to evaluate the seismic motion by an earthquake by using an earthquake motion obtained a little apart from the site, he first evaluates the incident wave at the engineering seismic base layer of the site where earthquake motion was obtained by a deconvolution analysis, and treats it as an incident wave at the engineering seismic base layer of the interested site. Moreover, many design specifications specify design earthquake motion at the engineering seismic base layer when it outcrops (e.g., Japan Road Association, 2002; Architectural Institute of Japan, 2001; Railway Technical Research Institute, 1999). In the North American practice, rock or hard deposit outcrop is used instead of engineering seismic base layer, but both are same meaning.

This kind of separation of the ground is valid when there is no interaction between parts; mechanical definition of the engineering seismic base layer described in the preceding explains it well. However, there are several researches that seem to indicate that this concept is not correct. Kaneko (1993), for example, examined the reason why blind test results (IASPI/IAEE Joint Working Group on ESG, 1992) by equivalent linear analyses scatters significantly, although difference caused by different engineer has been believed to be small in the equivalent linear analysis. Observed rock outcrop motions at a nearby site are given and ground motions at the top and the bottom of the soft surface layer are requested to output in this blind test. He found that assumption of the depth of the base layer at which incident wave to be applied in the interested site is evaluated by a deconvolution analysis makes different evaluation of the earthquake motion at the ground surface. One of the author investigated effect of nonlinear behavior of the seismic base layer on the response of the surface deposit, and earthquake motion is affected by the definition of seismic base layer (Yoshida, 2001). In these analyses, however, interaction between the surface layer and below it is not clearly interested in.

In this paper, we will show that conventional method to separate the ground at the engineering seismic base layer may lead incorrect evaluation of earthquake motion at the ground surface through the analysis.

EXIBITING EXAMPLE

A site in Hachinohe-city, Japan, is investigated. Soil profiles at this site up to the seismic bedrock ware evaluated by Midorikawa and Kobayashi (1978), which is shown in Table 1. Here, h denotes depth from the ground surface, V_s denotes shear wave velocity, ρ denotes mass density and Q denotes a quality factor by which damping ratio D is evaluated as D=1/(2Q). The engineering seismic base layer is set at two depths. The one is the layer below GL-180 m; the shear wave velocity is 690 m/s, which corresponds to the definition in design specification of nuclear power plant (Electric Technical Guideline Committee, 1987). The other is the layer below GL-50m, whose shear wave velocity is 378 m/s and corresponds to the definition of engineering seismic base layer in many design specifications (e.g., Japan Road Association, 2002; Architectural Institute of Japan, 2001; Railway Technical Research Institute, 1999). These two engineering seismic base layers are distinguished by the name EB1 and EB2 as shown in Table 1. The shear wave velocity structure is also shown at the right of Table 1 in natural scale so that locations can be easily recognized.

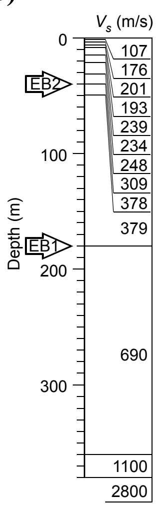
Two one-dimensional models are used in analyzing the ground in Table 1. The one is a continuous analysis in which the ground from the seismic bedrock to the ground surface is solved simultaneously, and will be referred as continuous analysis. The other is a separate analysis in which the whole ground is analyzed by dividing into two parts, i.e., from the seismic bedrock to the engineering seismic base layer and a surface layer. The analysis is carried out in two steps in the latter model. The outcrop motion at the engineering seismic base layer is first computed, and a half of the outcrop motion is applied at the bottom of the surface layer as an incident wave. This analysis is called as separate analysis, and the lower part and upper part of the model will be referred as lower and upper grounds, respectively, in this paper. The upper ground is the same meaning of the surface ground.

A multi-reflection theory, which solves equation of motion in frequency domain, is employed in the following analyses in order to distinguish incident and reflected waves. In the case to analyze nonlinear behavior, improved equivalent linear method (Yoshida et al., 2002) is used, which overcomes shortages that conventional equivalent linear method such as SHAKE (Schnabel et al., 1972) have.

Figure 1 shows amplification factor from the seismic bedrock to the ground surface. Here, E and F denote incident and reflected waves, respectively, and subscripts S, E and G indicate the seismic bedrock, the engineering seismic base layer and the ground surface, respectively. For example, E_E/E_S is ratios of Fourier amplitudes at the engineering base layer to those at the seismic bedrock. The amplification in the separate analysis is computed by multiplying the amplification factor in the lower

Table 1 Soil profiles (modified from Midorikawa and Kobayashi, 1978)

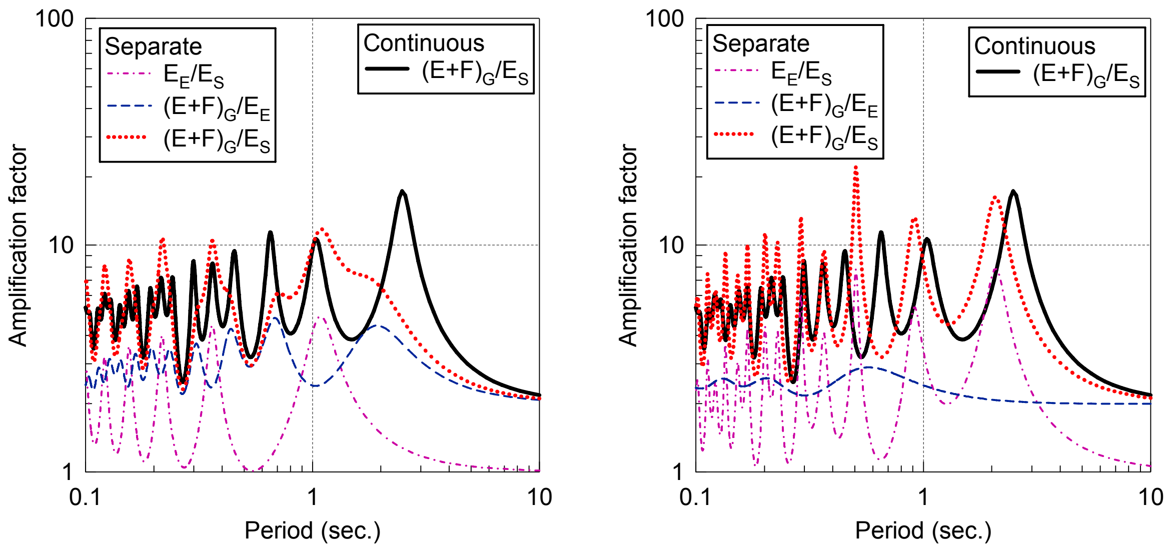
Layer No.	h (m)	V_s (m/s)	ρ (t/m^3)	Q	Comment
1	2.0	107	1.80	14	
2	4.0	176	1.80	13	
3	6.5	201	1.90	12	
4	9.0	193	1.90	12	
5	15.5	239	1.70	12	
6	22.0	234	1.70	9	
7	32.0	248	1.80	7	
8	40.0	309	1.80	7	
9	50.0	378	1.80	7	EB2
10	180.0	379	1.70	100	
11	360.0	690	2.00	100	EB1
12	380.0	1100	2.10	100	
13		2800	2.50	200	SB



h: Depth at lower boundary, V_s: Shear wave velocity, ρ: Mass density ground (E_E/E_S) and that in the upper ground ($(E+F)_G/E_E$). If $(E+F)_G/E_S$ by both continuous and separate methods coincides to each other, the separate analysis is justified.

Separate analysis by the EB1 model, Figure 1(a), does not have the peak amplification at around 2.5 seconds and 0.65 second that the continuous analysis has. Since these two periods are important periods in many structures, design based on the separate analysis may cause significant error. Disagreement is also seen in short period, too. The reason why predominant period of 2.5 seconds does not appear seems clear; there is no peak amplification in the separate analysis in this period. Since amplification ratio at the ground surface is product of two amplifications in the separate analyses, it is impossible to produce large amplification without peak response in one or both amplification characteristics. The same discussion can be made for another peak. For example, since there is peak amplification at about 1 second in the lower ground, and amplification ratio of the surface layer is greater than two, amplification around 1 second is produced. On the other hand, amplification at about 0.65 second is almost minimal in both the upper and lower grounds and it is the season why peak of amplification does not appear in the separate analysis.

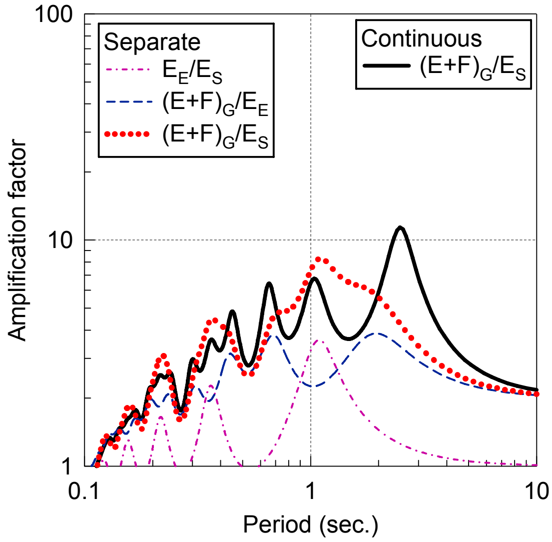
In the case of the EB2 model, amplification is nearly reproduced at periods of 2.5 and 1 seconds although periods are a little shorter. However, there is no peak around 0.65 second, and there are significant differences in peak amplification at periods shorter than 0.65 second. As can be seen in Table 1, since thickness of he lower ground is very large compared with the surface layer in the EB2 model, peak of amplification at 2.5 and 1 seconds are predominantly controlled by the lower ground. This explains the reason why these peaks are reproduced in the separate analysis, and why the peak period is a little shorter than that of the continuous analysis. Actually, amplification ratio of the surface ground is nearly identical (about 2.0) and it is the reason why agreement between continuous and separate analyses is better than that of the EB1 model. However, amplification of the ground surface is larger than that of the continuous analysis at periods where the surface ground shows maximal amplification. It indicates that the separate analysis show error at the predominant periods of the surface ground.



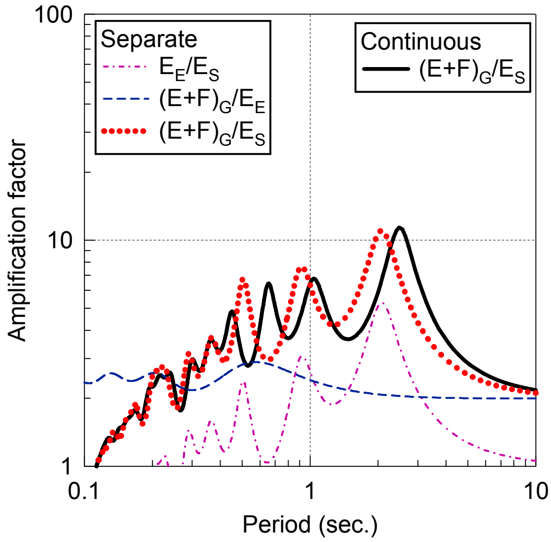
(a) EB1 model (b) EB2 model

Figure 1 Comparison of amplification characteristics

The Q value of 100 below GL-180 meter may be small from present common sense, so the same analyses are carried out by revising the Q value from 100 to 10 below GL-50 m. The results are shown in Figure 2. The same discussion can be made for amplifications at 2.5, 1 and 0.65 seconds. Disagreements at shorter periods become much smaller than that in the previous analysis because amplification characteristics are predominantly controlled by the behavior in the lower ground in both cases.



(a) Case 1 (EB1)



(b) Case 2 (EB2)

Figure 2 Comparison of amplification characteristics

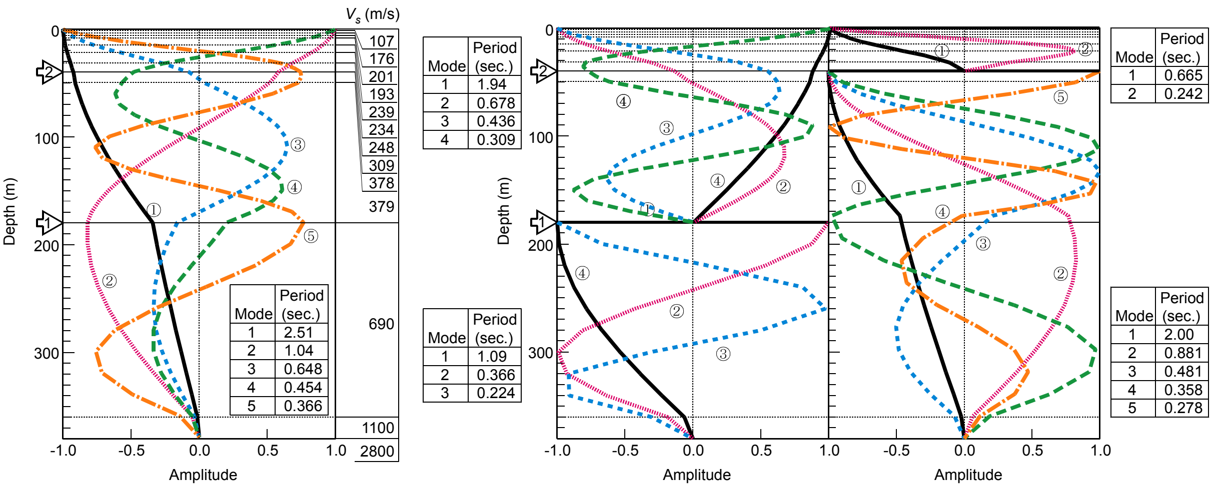
INVESTIGATION THROUGH EIGEN VALUE PROBLEM

Typical eigen values (predominant periods) and eigen vectors are summarized in Figure 3. In the figure, circled number is the order of mode. Figure 3 (a) is a result of the continuous analysis; eigen mode up to 5th order is shown in the figure. On the other hand, Figure 3 (b) shows results of the separate analyses. Left side figure is the case of the EB1 model and right side figure is the case of the EB2 model. Eigen vectors are shown in each model. Eigen modes are shown up to the mode whose shortest predominant period is less than that of fifth mode of the continuous analysis. Periods shown in the figure are same with the ones derived from the periods with peak amplification in Figure 1.

The overall ground from the seismic base layer to the ground surface vibrates without reflection point in the first mode. Since there is no such vibration mode in two separate analyses, it is natural that the separate analysis cannot produce this mode. On the other hand, in the case of the EB2 model, since the upper ground is shallow, its contribution of overall behavior is small. In addition, since the period at first mode of the surface ground is 0.665 second, which period is shorter than the first mode period of the continuous analysis, 2.5 seconds; it hardly affects the behavior in longer periods. This is the reason why, in Figure 1 (b), amplification characteristics in the EB2 model are similar to the ones in the continuous analysis around the first mode period of the whole ground, although periods at maximal amplification is a little short. Actually, the first mode shape on the continuous analysis is quite similar to the ones in the lower ground.

The second mode period is 1.04 seconds in the continuous analysis. On the other hand, the first mode period of the lower ground in the EB1 model is 1.09 seconds. They are close to each other and this agreement is the reason why period at maximal amplification about 1 second appears in both continuous and separate analyses. In this sense, this agreement can be said to be accidental.

As can be seen in the discussion in this section, agreement and disagreement of the natural periods between the upper and lower layers determine the ground vibration characteristics of the overall ground by the separate analysis, and predominant periods are determined individually without interaction to each other, there is no guarantee that predominant period of the continuous analysis agrees with the ones by the separate analysis.



(a) Continuous analysis (b) Separate analysis (EB1 at left and EB2 at left)

Figure 3 Eigen vectors and predominant periods

WAVE PROPAGATION: INCIDENT AND REFLECTED WAVES

If interaction between the lower ground and the surface ground does not occur, the separate analysis is justified. This will occur in two cases. The one is that all the energy by incident wave is absorbed in the surface ground such as by the nonlinear effect, and the other is that all reflected wave does not pass the engineering seismic base layer. The former case will be discussed in the subsequent section. In the latter case, incident waves at the engineering seismic base layer in the continuous analysis and the separate analysis are identical and downward wave does not travel from the surface ground into the engineering seismic base layer.

The earthquake motion at Furofushi site obtained during the 1983 Nihonkai-Chubu earthquake, shown in Figure 4, is used in the investigation. The waveforms at the engineering seismic base layer are shown in Figure 5 for the EB1 model. Here, response between 35 and 45 seconds are enlarged in order to sea the differences easily.

Reflected wave is compared with incident wave in Figure 5 (a). Magnitude of the reflected wave is smaller than that of the incident wave in general, but it is sufficiently large compared with zero or they are the same order. In other words, all wave traveled downward is not completely reflected at the engineering seismic base layer.

Incident and reflected waves by the separate analysis are compared with those by the continuous analysis in Figure 5 (b) and (c). It is clear that differences of incident wave caused difference of seismic motion at the ground surface by two analyses.

NONLINEAR ANALYSIS

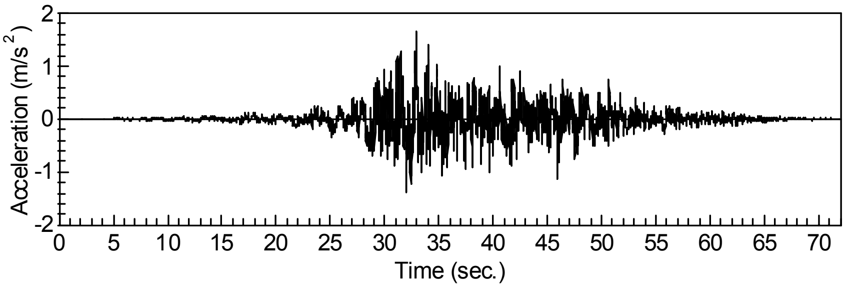
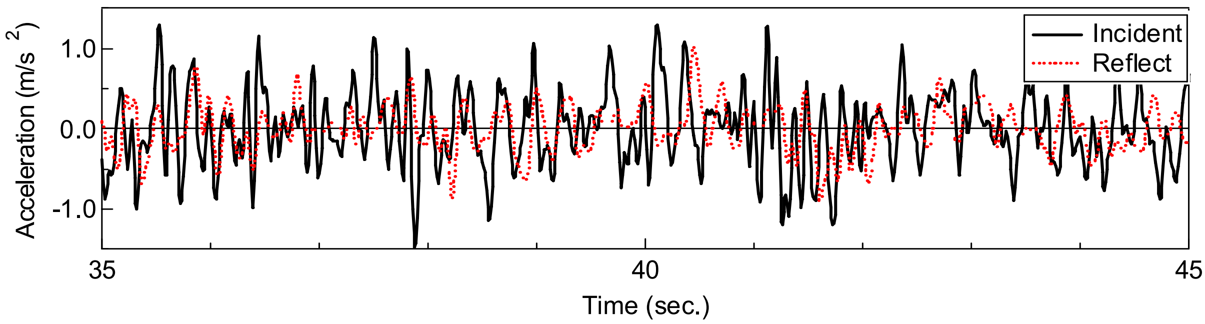
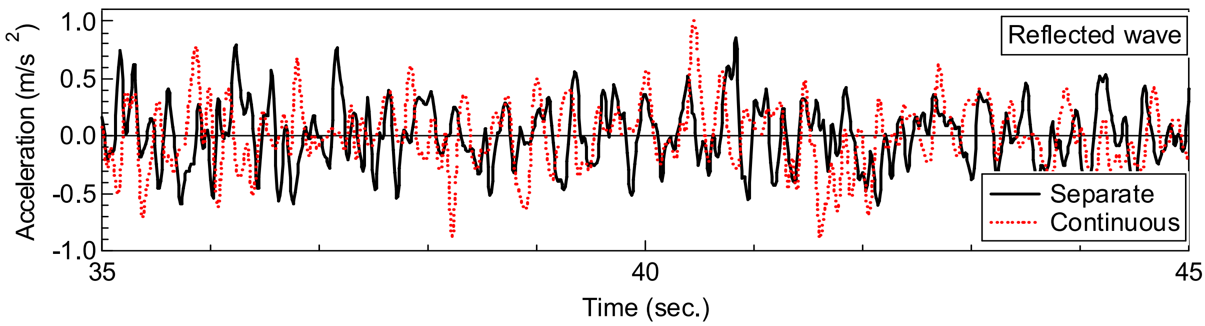


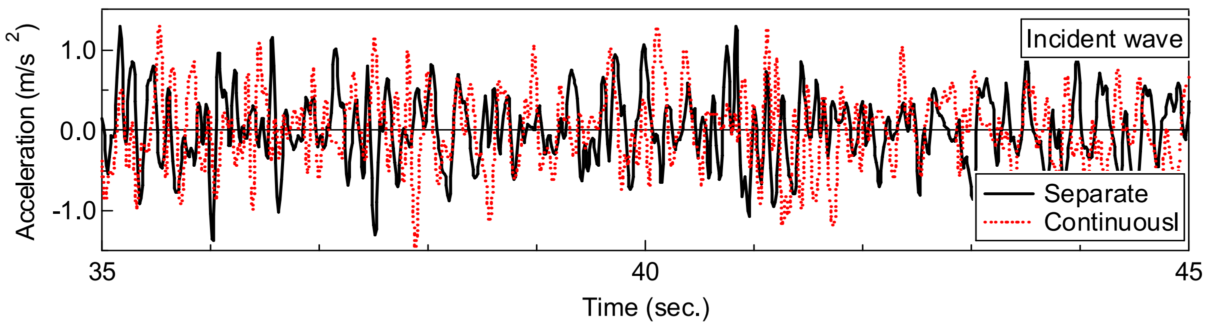
Figure 4 Outcrop waveform at seismic bedrock



(a) Comparison between upward and downward waves (continuous analysis)



(b) Comparison of reflected waveforms between separate and continuous analyses



(c) Comparison of incident waveforms between separate and continuous analyses

Figure 5 Ground shaking at engineering seismic base layer

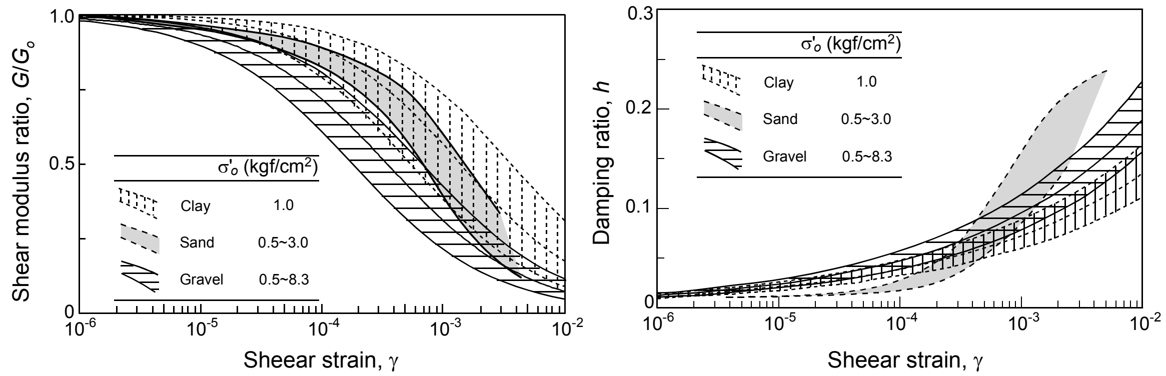


Figure 6 Dynamic deformation characteristics (compiled by Imazu and Fukutake, 1986, revised by Japanese Geotechnical Society, 1992)

Finally, the effect of the separate analysis is investigated by the nonlinear analysis; the separate analysis may be justified if all the energy is absorbed by the hysteretic nonlinear behavior. Nonlinear behavior is taken into account in the layers up to GL-50m. The ground below GL-50m is treated as elastic media with Q value of 10. Average of dynamic deformation characteristics compiled by Imazu and Fukutake (1986), shown in Figure 6, are used as dynamic deformation characteristics of soil. Accelerations at the ground surface by the continuous and separate analyses are compared in Figure 7. They cannot be said to be identical or similar. Amplification characteristics and acceleration response spectrum with 5% damping ratio are compared in Figure 9. Difference of amplification characteristics has the same tendency with Figure 2(a); peaks of amplification at period of 2.5 and 0.65 seconds are not reproduced in the separate analysis. Acceleration response is underestimated at periods longer than about 0.3 second and that is overestimated at shorter periods. Differences are especially large at period longer than about 1 second.

CONCLUDING REMARKS

The earthquake motion at the ground surface is usually evaluated by the analysis of the surface ground by assuming that incident wave at the engieering seismic base layer (or hard deposit outcrop) is uniquely defined in widespread area. If incident wave at the seismic bedrock is specified, the incidet wave at the engineering seismic base layer is first evaluated by assuming outcrop engineering seismic base layer, and the surface ground is analysized separately under the incident wave obtained in the previous analysis. Validity of this separate analysis is examined be comparing the continuous analysis in which ground from the seismic bedrock to the ground surface is analysized simultaneously. The following conclusions are obatined.

1) Vibration characteristics of overall ground cannot be obtained by the separate analysis because vibration characteristics of each ground are different from those of total ground.
2) Behavior at period longer than the predominat period of each separated ground is not reproduced by the separate analysis.
3) If one of the separated ground is much smaller than the other, effect of separation is not large.
4) All these result indicates that engineering seismic base layer does not work as base, even if shear wave velocity is about 700 m/s which is the largest shear wave velocity used in desigh specificaitons.
5) The wave that goes down through the engineering seismic base layer and reflect at the seismic bedrock or before it cannot be neglected in evaluating the earthquake motion at the ground surface. In other words, interactive behavior of the grounds above and below the engineering

seismic base layer cannot be negrected.

6) Difference appears in the important period range in the geotechnical engineering.

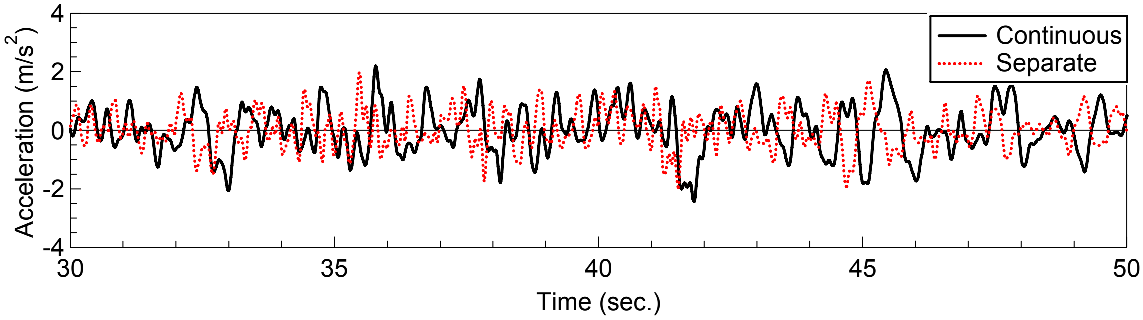


Figure 7 Waveforms at the ground surface by nonlinear analysis

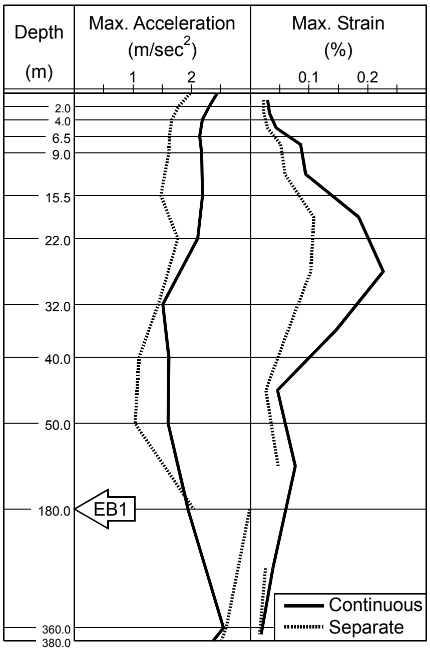
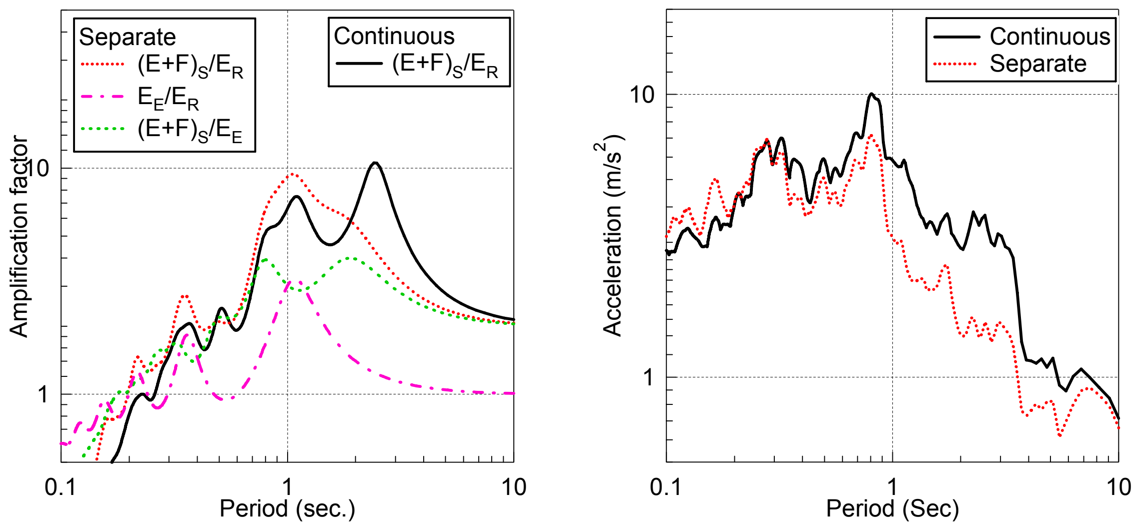


Figure 8 Maximum acceleration and strain by nonlinear analysis



(a) Amplification factor (b) Acceleration response spectrum

Figure 9. Comparison of response in nonlinear analysis (EB1 model)

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