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A STUDY ON NON-LINEAR SOIL CHARACTERISTICS USING STRONG AND WEAK MOTION RECORDS

T. Kagawa[(1)], T. Noguchi[(2)]

[(1)] *Professor, Tottori University, Graduate School of Engineering, kagawa@tottori-u.ac.jp*
[(2)] *Assistant Professor, Tottori University, Graduate School of Engineering, noguchit@tottori-u.ac.jp*

Abstract

A methodology to evaluate non-linear soil characteristics at strong motion observation sites is proposed. Horizontal to vertical spectral ratios (H/V) are estimated for strong motion record with non-linear soil response and weak motion records without non-linear behavior. Usually, the two types of H/V do not match each other because of reduced rigidity and increased damping factor under non-linear soil response. Velocity structures for strong and weak motions are estimated by applying diffuse wavefield theory. Difference between the two models is expected in shallow low velocity layers. The velocity structure under strong ground motion is assumed as an equivalent linear soil structure under high strain level, and the velocity structure estimated from weak motion is an initial one. Input ground motion on engineering bedrock can be estimated from surface strong motion data and velocity structure under strong motion. From the input motion, surface ground motion can be reproduced using equivalent linear soil response based on the velocity structure under weak motions and adequate non-linear soil characteristics. The reproduced waveform is compared with the observed record. Non-linear soil characteristics are tuned up until the divergence between the reproduced and observed waves reaches small enough. Ramberg and Osgood model is applied for the non-linear soil characteristics, and parameters of reference strain γ_{ref} and maximum damping factor h_{max} are estimated for each soil layer. The methodology is applied to the ground motion records observed at Sakaiminato city, Tottori, prefecture, Japan including a strong ground motion due to the 2000 western Tottori prefecture earthquake. Reasonable non-linear soil parameters are estimated for sand and clay layers respectively. Accumulating results by the method, it is expected that non-linear soil parameters for equivalent linear approach would be well modeled and accuracy of surface soil amplification would improve in shake maps simulated from detailed wave propagation theory.

Keywords: non-linear soil characteristics, strong ground motion, weak ground motion, diffuse wavefield theory

1. Introduction

Non-linear soil response of soft alluvial layers under strong ground motions is an important issue for strong ground motion estimation especially at urban areas located in sedimentary basins or flat plains. The phenomenon is caused by strong ground motions that break interparticle bonds of soils, and it progresses over time under high strain. There is an equivalent linear method incorporating this phenomenon. It is a classical method but still widely used in shake map estimation, since the methodology is simple and does not require detailed parameters. However, the required two parameters, i.e. reference strain γ_{ref} and maximum damping factor h_{max}, are not investigated enough, but standard models derived from not much data are generally used. It is because the soil laboratory tests to obtain the parameters are time consuming and expensive. Since the parameters might differ depending on the soil conditions, it is desirable to set them uniquely to the target area.

A new methodology to evaluate non-linear soil characteristics at strong motion observation sites is proposed in this study. Horizontal to vertical spectral ratios, hereafter H/V, are estimated for strong motion record with non-linear soil response and weak motion records without the effect. Velocity structures for strong and weak motions are estimated by applying diffuse wavefield theory. Difference between the two models is caused by non-linear soil response in shallow low velocity layers under strong ground motion. The velocity structure due to the strong ground motion is estimated as equivalent linear soil response under high strain level and the velocity structure at the same site under weak motion is estimated as an initial condition with low strain level. Input ground motion on engineering bedrock can be estimated from surface strong ground motion and velocity structure under strong motion assuming linear soil response. Using the input motion, surface ground motion can be reproduced using equivalent linear methodology with the velocity structure under weak motion as an initial condition and optimal non-linear soil characteristics of each layer. Using the proposed process, non-linear soil characteristics can be estimated from ground motion records without soil laboratory tests.

2. Estimation of equivalent linear soil characteristics using diffuse wavefield theory

2.1 Target site and observed waves

Large ground motion with PGA 299 cm/s^2(NS) and 784 cm/s^2(EW) was observed at Sakaiminato city, Tottori prefecture, Japan due to the 2000 western Tottori prefecture earthquake (M_{JMA} 7.3). The site locates about 30 km north from the epicenter, however, sedimentary structures amplify the ground motion. Fig. 1 shows the horizontal components of the observed ground motion. Duration of large shaking is almost 10 seconds and effects of surface waves are not clearly recognized despite of long epicentral distance.

H/V spectral ratio of the ground motion is estimated as Fig. 2. The left panel shows average of four small earthquakes, i.e. the 2013 Awaji island earthquake (M_{JMA} 6.3), the 2016 central Tottori prefecture earthquake (M_{JMA} 6.6), the 2018 western Shimane prefecture earthquake (M_{JMA} 6.1), the 2018 northern Osaka prefecture earthquake (M_{JMA} 6.1), and two thin lines indicate NS or EW component versus vertical component, and bold line shows geometric mean of horizontal component over vertical component. The right panel shows H/V from mainshock of the 200 western Tottori prefecture earthquake. The shape of H/V spectra are clearly different especially in the period range shorter than 1 second. The main shock ground motion is dominant in EW component, mainly because of source radiation effect from vertical strike slip fault rupture with almost NS direction. However, the geometric mean of horizontal component is used in the later analysis.

2.2 equivalent linear soil characteristics under strong motion and weak motions

Diffuse wavefield theory [1] is employed to estimate sedimentary structure from H/V spectrum of seismic ground motions. Eq. (1) shows theoretical H/V spectra with body wave incidence to horizontal layers derived from the diffuse wavefield theory. Here T_H and T_V indicate transfer function of horizontal and vertical

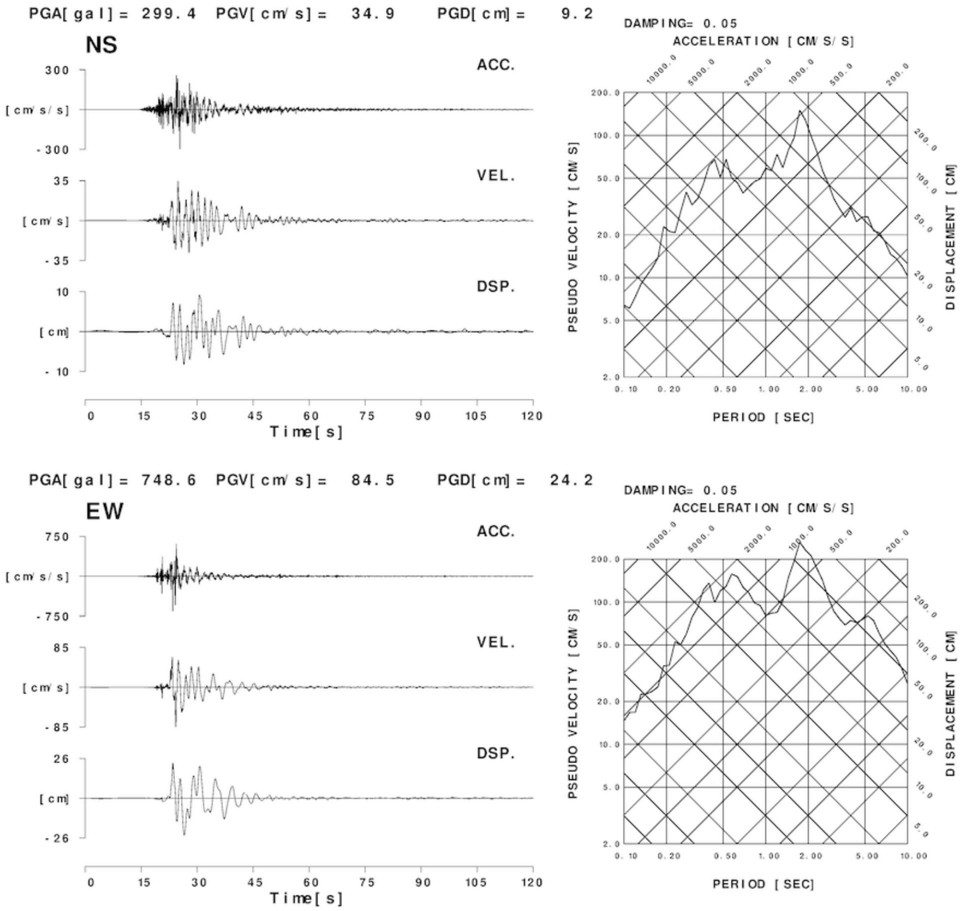

Fig. 1 – Main shock observation record at the JMA Sakaiminato site due to the 2000 western Tottori prefecture earthquake (Acceleration, velocity, displacement waveform of two horizontal components and their tripartite response spectra)

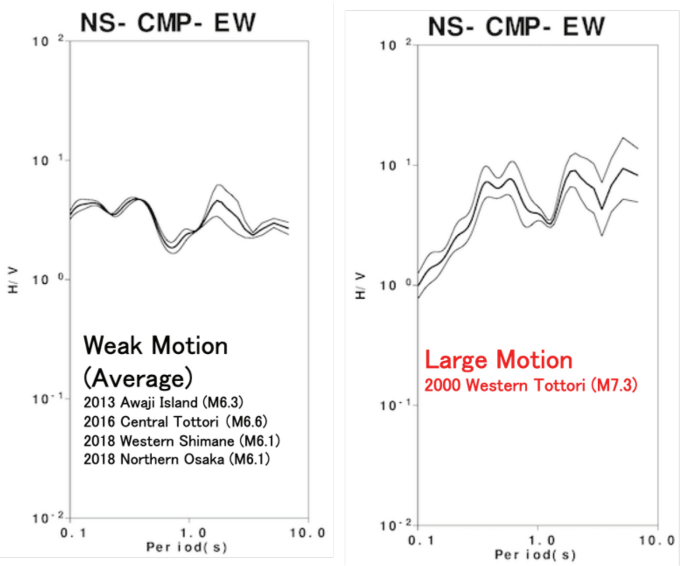

Fig. 2 – H/V spectra of weak motions and large motion at the JMA Sakaiminato site

components respectively from seismic bedrock to surface. V_{P0} and V_{S0} indicate P and S wave velocity of the seismic bedrock.

$$HV(f) = \sqrt{\frac{2V_{P0}}{V_{S0}} \frac{T_H(f)}{T_V(f)}} \tag{1}$$

Applying the theory to the observed H/V spectra, velocity structures from seismic bedrock to surface are estimated to match the theoretical H/V with the observed. Vector sum of horizontal components is used to apply equation (1) instead of geometric mean shown in Fig. 2. The targets of estimation are thickness, S wave velocity and damping of each layer, and other parameters are evaluated from empirical relationships. P wave velocities are estimated from S wave velocities [2]. Densities are evaluated from P wave velocities [3]. Geophysical investigations [4, 5] conducted after the 2000 western Tottori prefecture earthquake are referred to set the velocity structure model.

Fig. 3 shows the result of velocity structure estimations. Simulating annealing technique [6] is used to fit synthesized spectra to the observation. First, weak motion structure model from bedrock to surface is estimated and next shallow structure model is modified to fit the large motion H/V with fixed deep structure model. In large motion case, short period coincidence is good enough, but long period is not, because the deep structure model is fixed as the weak motion case. Long period of large motion, i.e. main shock of the 2000 western Tottori prefecture earthquake, might include some other effect due to irregular deep sedimentary structures. However, only shallow structure affected on short period range is treated in this study.

Fig. 4 indicates S wave velocities and damping factors of shallow layers. In shallow portion, S wave velocities of strong motion model change to smaller and damping factors larger than those of weak motion model. Since the strong motion model could be expressed by changing the shallower part of the weak motion model, the layer with S wave velocity 500 m/s could be used as an engineering bedrock that is safe from nonlinear soil response.

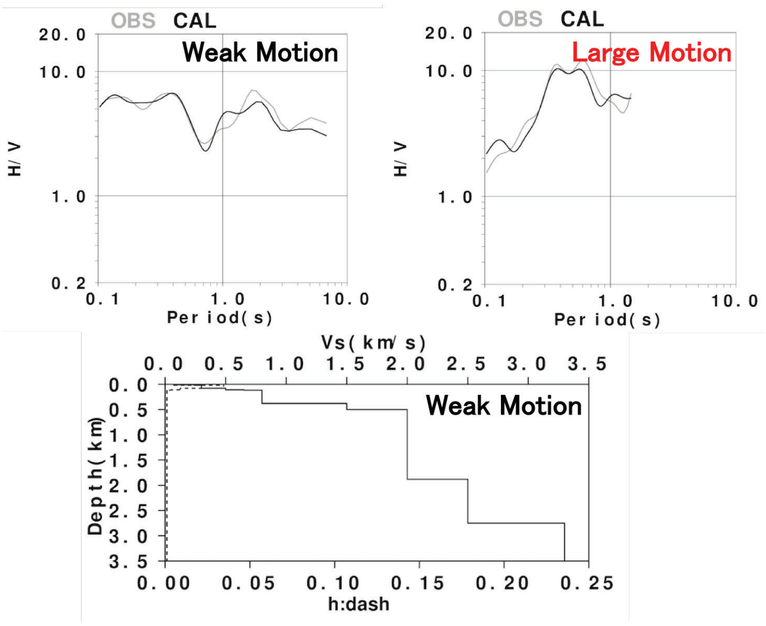

Fig. 3 – Observed and synthesized H/V spectra of weak motion (upper left) and large motion (upper right) with velocity structure model down to the seismic bedrock in case of weak motion.

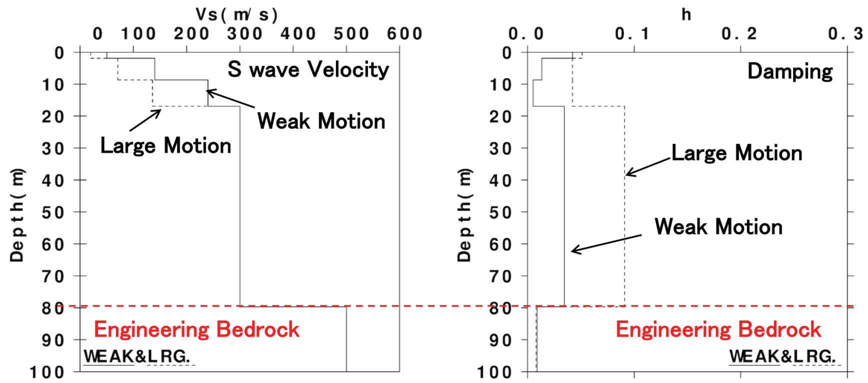

Fig. 4 – Difference of shallow S wave velocity and damping models under weak and large motions.

3. Estimation of non-linear soil characteristics

3.1 Estimation of input ground motion on engineering bedrock

The procedure for estimating non-linear soil characteristics in this study is shown as a schematic diagram in Fig. 5. First, input ground motion of the 2000 western Tottori prefecture earthquake on engineering bedrock is estimated from the observed mainshock record and velocity structure model under large main shock assuming linear soil response. Fig. 6 shows the ground motion on engineering bedrock as free surface. Second, applying the input motion, surface ground motion is reproduced using equivalent linear methodology [7] with optimal non-linear soil characteristics of each layer considering the velocity structure under weak motion as an initial soil model.

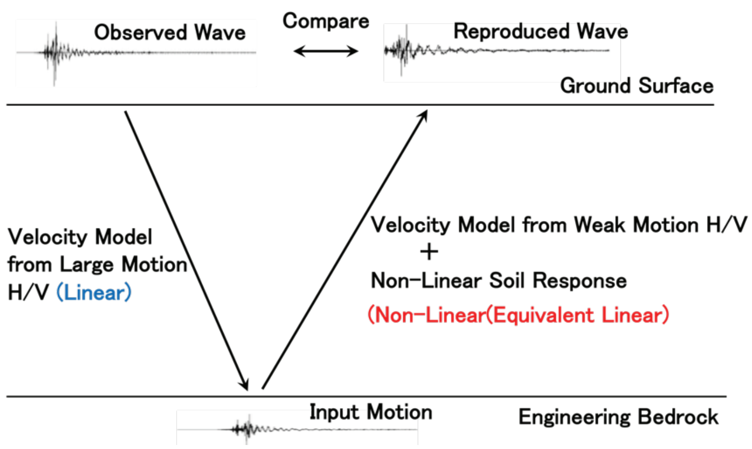

Fig. 5 – Schematic diagram of analysis method in this study

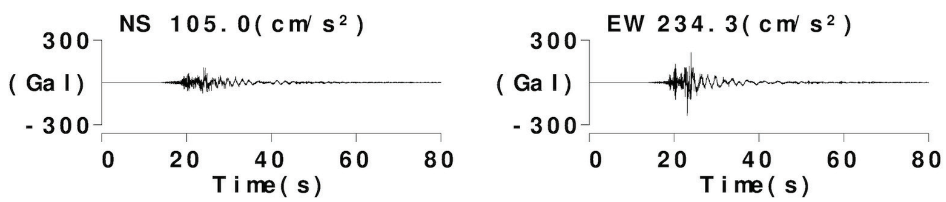

Fig. 6 – Estimated input ground motion of the 2000 western Tottori prefecture earthquake on engineering bedrock at JMA Sakaiminato site (Free surface)

3.2 Estimation of optimal non-linear soil characteristics

As for next step, equivalent linear analysis [7] is conducted to calculate surface ground motion under large strain level. The non-linear characteristics model by the Cabinet Office Japan, Central Disaster Prevention Council [8] was employed as a reference model. Optimal non-linear parameters for each layer, i.e. reference strain γ_{ref} and maximum damping factor h_{max}, are searched in ranges shown in Table 1. Individual non-linear characteristics are given for every 10m thickness. Applying equivalent linear technique, layers structure in Fig. 4, weak motion, is subdivided into thin layers with about 1.5 to 3 m thicknesses according to their S wave velocities. Soil type is set from neighboring borehole data around the observation site. From the data, about 30 m from the surface layer is sand ground, about 30 to 50 m is clayey ground, and 50 to 95 m is sandy ground again.

Table 1 – Search range for nonlinear response parameters

	Sand	Clay
γ_{ref}	2.0×10^{-4}～5.0×10^{-3}	1.0×10^{-3}～2.0×10^{-2}
h_{max}	0.03～0.30	0.02～0.20

Fig. 7 shows resulting horizontal waveforms and response spectra with observed data. Simulating annealing technique [6] is also used to fit synthesized data to the observation. The calculation of two horizontal components is performed at the same time, and non-linear characteristics are set based on the average strain in each layer. The synthetic waveform reproduces the observed data well both in time and frequency domains.

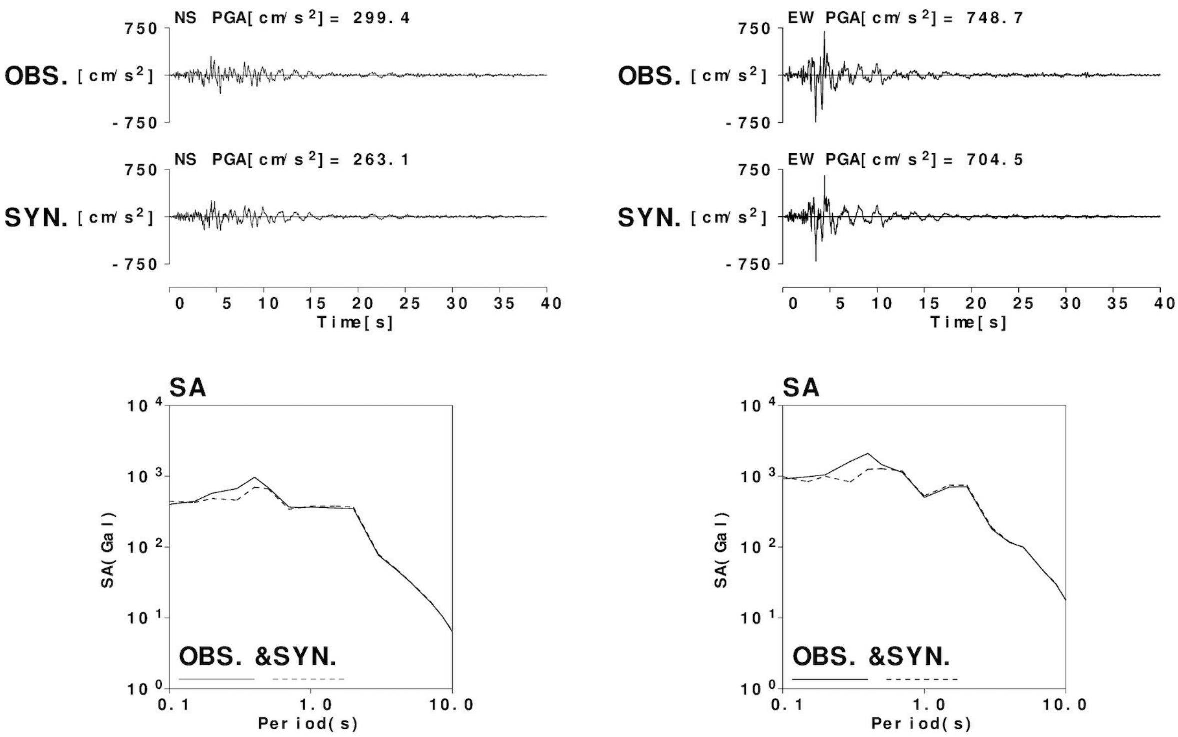

Fig. 7 – Comparison between observed and synthesized waves
(Upper: waveforms, Lower: Response spectra)

Fig. 8 shows estimated non-linear characteristics for each 10 m thickness of sand and clay layers. All parameters were found within the preset search range. Warm colors correspond to sandy ground, and cool colors to clayey ground.

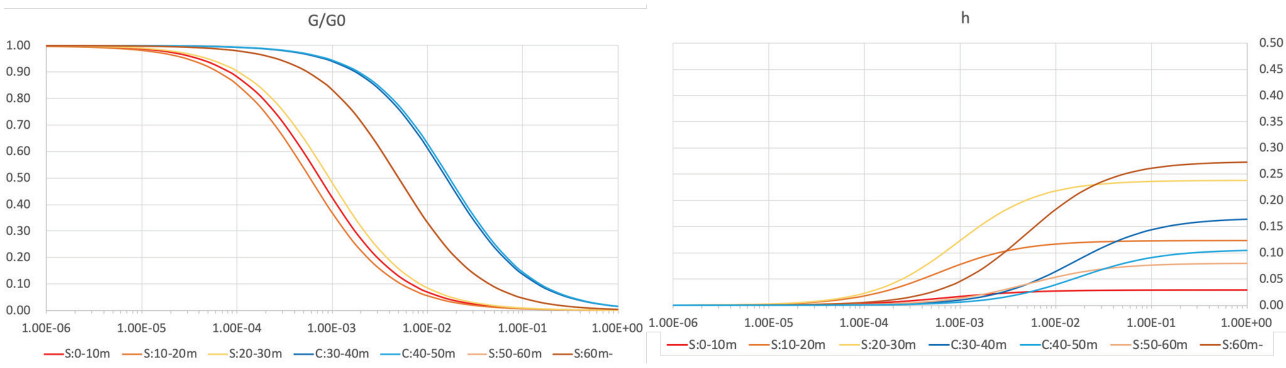

Fig. 8 – Estimated non-linear characteristics for each 10 m thickness

4. Discussions

Concerning the results in Fig.8, detailed characteristics are discussed. Regarding rigidity drop characteristics, there clayey layers seem to have larger reference strain (γ_{ref}) than sandy layers. The deepest sandy layer has larger reference strain than others, however, there is no remarkable depth dependency in other depths. As for damping factor, there is no remarkable difference depending soil type and depth, but clayey layers tend to have smaller maximum damping factor (h_{max}) than sandy laeyers. The search ranges of reference strain and maximum damping factor overlap in sandy and clayey layers, and both are found within the search range, so the difference is considered significant. This result is considered to be natural, and consistent with previous studies [8]. It suggests that non-linear soil characteristics can be derived from strong ground motion data without conducting laboratory soil test using borehole sample.

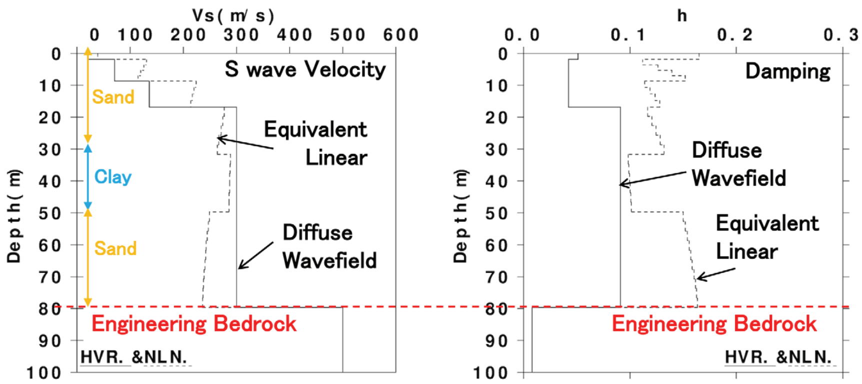

Fig. 9 – Comparison of estimated S wave velocity and damping structured between diffuse wavefield theory (solid line) and equivalent linear analysis (dash line)

Here, it is worthful to compare the results obtained by the equivalent linear analysis with the estimated velocity structure from diffuse wavefield theory that was first performed. Fig. 9 shows the results. The figure also shows the soil types by neighboring borehole. Although the S wave velocity structures generally correspond to each other, the correspondence of the damping structure is not good. The two results are not necessarily to be same because the methodologies of considering non-linear soil response are different. In order to fill this gap, it is necessary to apply more advanced techniques if using equivalent linear methodology, such as giving strain dependency of rigidity and damping independently, not employing same reference strain. Or it might be necessary to introduce a more rational non-linear calculation method when reproducing surface ground motions, because the maximum effective strain close to 10^{-2} is calculated in shallowest layer (Fig. 10).

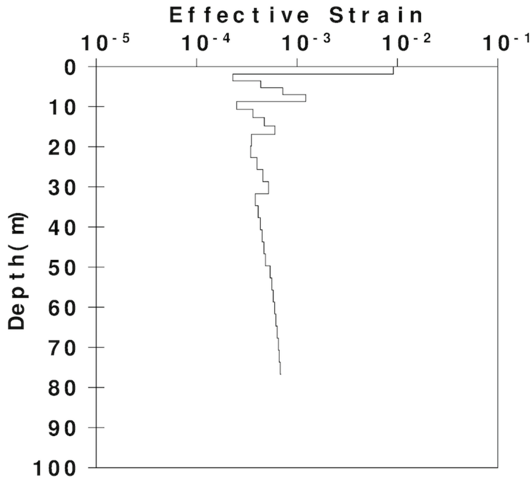

Fig. 10 – Depth distribution of effective strain in calculation of Fig. 7

5. Conclusions

A methodology to evaluate non-linear soil characteristics at strong motion observation sites only from surface recording is proposed. The main shock record of the 2000 western Tottori prefecture earthquake obtained at JMA Sakaiminato site (large motion) and the weak motion records of four other earthquakes at the same site are used to verify the methodology. The procedure is based on the diffuse wavefield theory to estimate velocity structure from observed H/V spectra of ground motion, and (1) estimate input ground motion on engineering bedrock from the equivalent velocity structure under strong motion, (2) calculate the equivalent linear ground response from the input motion with a velocity structure under weak motions, and (3) compare it with the observation to evaluate non-linear characteristics at each depth with individual soil type. The results obtained are consistent with previous findings, and indicate the possibility of the new methodology that can model non-linear characteristics used for equivalent linear calculations that are generally employed for shake map estimation from seismic observation records instead of laboratory soil tests or analysis of vertical array data.

6. Acknowledgements

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