ON SEISMIC DAMAGE PREDICTION OF WOODEN HOUSE USING AVERAGE SHEAR WAVE VELOCITY, AVS30

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ABSTRACT

In this paper, a relationship between average shear wave velocity*AVS*30 in the upper layer of 30mand seismic response of wooden house is investigated in order to apply the information of subsurface structure to a seismic damage prediction for wooden house. Shear wave velocity of subsurface layer and surface ground acceleration are numerically examined by the seismic ground response analysis based on the equivalent linear method at a site of borehole in Maizuru city, Kyoto Prefecture. A relationship between the surface ground acceleration response evaluated by the seismic ground response analysis and the maximum drift angler of wooden house is investigated. Seismic acceleration response in short period range strongly affects *R* when a base shear coefficient *Cy* of wooden house becomes large. Finally, it is clarified that *AVS*30 correlates to *R* for *Cy*=0.1 and 0.3.

Keywords:*AVS30*, Maximum Drift Angle, Seismic Damage Prediction of Wooden House.

1. INTRODUCTION

Recently, a detailed information on surface soil layer structure, which plays an important role in the prediction of seismic ground motion, has been prepared and maintained to be ready for use in Japan. Both the average shear wave velocity *AVS30* (Midorikawa et al. 1992) at the upper layer of 30m of surface ground and the boring data have been classified and opened to the public on its websites (J-SHIS; Geo-Station). *AVS30*may be a significant index on a seismic damage prediction of wooden house within a large area against the strongest assumed earthquake for a target region, because *AVS30* has a high correlation[4)] with an amplification spectrum with the frequency range affecting seismic damage of wooden house. Although *AVS30* has been used in only the evaluation of ground amplification characteristics, it has not been used in the seismic damage prediction of wooden house. It is more effective that *AVS30* can be used in the seismic wooden house damage in wider region against a strongest assumed earthquake, because an information on *AVS30* throughout Japan

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is ready for use in evaluating the ground amplification characteristics. A relationship between *AVS30* and the seismic response of wooden house against a strongest assumed earthquake is investigated to obtain a fundamental knowledge in the seismic damage prediction of wooden house within a wider area using a surface ground layer information.

In this paper, the shear wave velocity structure at each estimating location based on the boring data collected in Maizuru city, which were picked out more suitable data for the ground surface response analysis. *AVS30* can be calculated from the shear wave velocity strata, and the ground surface motion at each estimating location is numerically evaluated by seismic ground motion analysis. In this paper,*AVS30* calculated from boring data with higher accuracy is employed in seismic ground motion analysis.

In order to investigate the effect of the ground surface layer on the seismic surface ground motion, an input earthquake motion into bed rock is assumed to be the same at all estimating points in this paper. Amplification spectrum and its first natural period are evaluated from the ratio of acceleration response spectrum of the bed rock motion to that of the surface ground motion. Moreover, the maximum drift angle *R* of wooden house model on each estimation point is evaluated from both the acceleration response spectrum and the equivalent-performance acceleration response spectrum[6)], and a correlation between *AVS30* and *R* is investigated in this paper.

2. GROUND BORING DATA

2.1. Ground Boring Data

In this paper, 131 boring data are employed in the seismic damage prediction of wooden house. These data are picked out from a lot of boring data not only in Maizuru city office but on Geo-station website, and each boring data has an over 50 N-value (Standard Penetration Test) on sandstone or mudstone. Based on information of boring data including N-value, soil classification at each depth, shear wave velocity in the depth direction can be evaluated by the following empirical equation (Ohta and Goto 1978).

$$V_S = 62.48 N^{0.218} \cdot H^{0.228} \cdot F \tag{1}$$

where, V_s is shear wave velocity(m/s), N is N-value and H is depth(m). F is a coefficient on soil classification, and F value is 1.073 for sand, F is 1.0 for clay soil, and F is 1.199 for gravel. Shear wave velocity of bed rock is assumed to be 600m/s.

2.2. Average Shear wave velocity

In Japan, an average shear wave velocity *AVS30*at the upper 30m of surface ground layer has been employed as an index of surface ground characteristics.

$$AVS30 = 30 / \sum d / V_S \tag{2}$$

where, d is a thickness of each soil layer.

Figure 1 indicates a distribution of *AVS30*. Ground boring data were classified into 5 types shown in Table 1 by referring to Uchiyama and Midorikawa (2003). There are many locations with small *AVS30* value in the central region in Maizuru city.

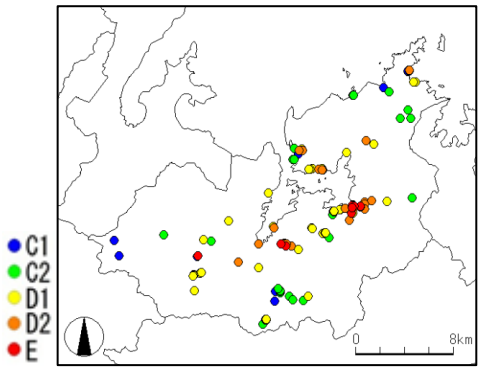

Figure 1: Boring data and *AVS30*.

3. GROUND RESPONSE ANALYSIS

3.1. Surface Ground Seismic Motion

Using each ground boring data previously mentioned, seismic surface ground motion is numerically evaluated by an advanced ground response analysis (Yoshida and Suetomi 1996) based on the equivalent linear method. Because the density of each soil layer at an estimating point is needed for the ground response analysis, the density ρ(t/m^3) can be obtained from the following equation (Kobayashi et al. 1995)

Table 1: Classification by *AVS30*.

Type	*AVS30* (m/s)	Data Number
C1	$460 < AVS30 \leq 760$	13
C2	$360 < AVS30 \leq 460$	30
D1	$250 < AVS30 \leq 360$	46
D2	$180 < AVS30 \leq 250$	30
E	$AVS30 \leq 180$	12

$$\rho = 0.67\sqrt{V_S / 1000} + 1.4 \tag{3}$$

Non-linear characteristics (a relationship between strain, damping factor, and shear modulus ratio) in soil classification type is evaluated based on Imazu and Fukutake (1986). In this soil response analysis, a seismic wave motion (referred as a notice motion) defined by the notice No. 1461(2000) of the Ministry of Land, Infrastructure, Transport and Tourism, 2002, was employed as an input earthquake motion into engineering bed rock. As a target of the response spectrum expressed by Equation (4), which is indicated in Figure 2, the notice motion was obtained from multiplying by Jennings envelop function (Jennings et al. 1968) to an artificial wave with random phase. Jennings envelop function can be given by Equation (5). Because shear wave velocity at the engineering bed rock in this paper is different from that in the notice wave, the seismic surface ground motion in this paper can be obtained by multiplying by the revision coefficient of amplification due to an impedance ratio to the spectrum of the notice motion.

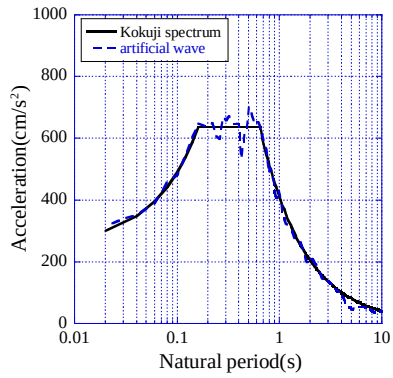

Figure 2: Spectrum of Notice Motion.

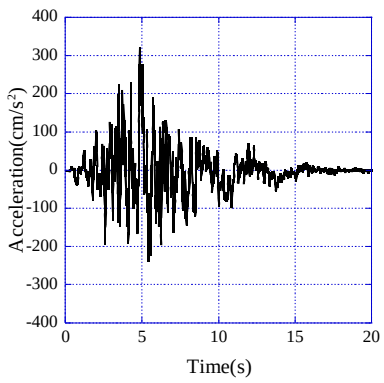

Figure 3: Notice Motion.

$$S_a(T)=\begin{cases}320+3{,}000T & T<0.16\\ 800 & 0.16\le T<0.64\\ 512/T & 0.64\le T\end{cases} \tag{4}$$

$$E(t)=\begin{cases}0 & (0\leqq t\leqq t_a)\\ ((t-t_a)/(t_b-t_a))^2 & (t_a\leqq t\leqq t_b)\\ 1 & (t_b\leqq t\leqq t_c)\\ \exp(-B(t-t_c)) & (t_c\leqq t\leqq t_d)\end{cases} \tag{5}$$

$S_a(T)$ in Equation (4) is an acceleration response spectrum with damping factor h=5%, and $T$is a natural period. $E(t)$ in Equation (5) is an envelope function, and t is time. t_b is duration until a main motion part in the envelope function, t_c-t_b is duration of a main motion part, and t_d is duration of seismic ground motion. B is $-\ln(0.1)/(t_d-t_c)$. t_c-t_a and t_d-t_c can be obtained from the following empirical equation with the Japan Meteorological Agency Magnitude M_{JMA} and the hypocentral distance X. In this paper, the main motion duration (t_c-t_b) is assumed to be three times (t_b-t_a), M_{JMA}=7 and X=10km.

Figure 3 shows an artificial seismic motion whose maximum acceleration is over 300cm/s^2, which is made as a target of the notice motion spectrum shown in Figure 2. As can be seen from Figure 3, the spectrum of the artificial seismic motion in Figure 2 is corresponded well to the notice motion spectrum.

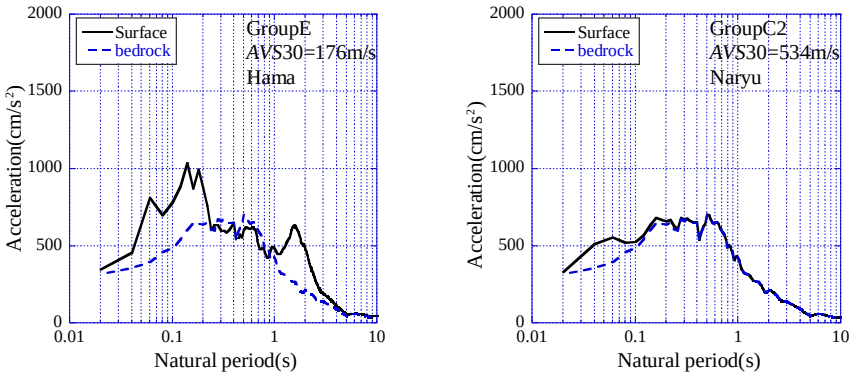

Figure 4: Acceleration Response Spectra (Maizuru city).

Figure 4 indicates an example of acceleration response spectrum of the surface ground seismic motion obtained from the equivalent linear method using the notice motion shown in Figure 3 as an input earthquake motion into the engineering bed rock. Surface ground response spectrum greatly depends on *AVS30*.

3.2. Amplification Spectrum

The amplification spectrum $G(T)$, which is a ratio of acceleration response spectra obtained from the bed rock and the surface ground, is numerically evaluated in order to investigate the amplification of acceleration response

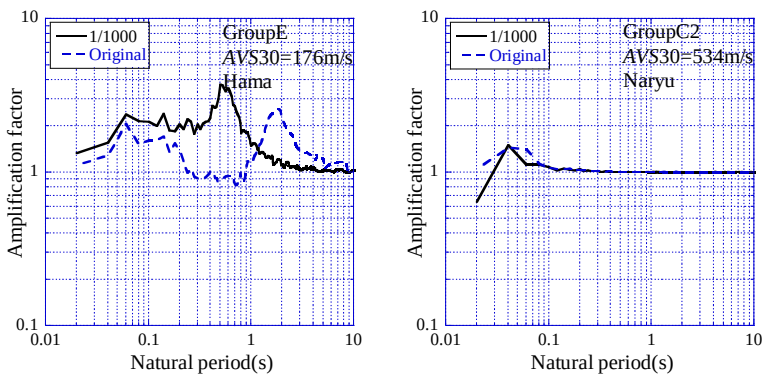

Figure 5: Amplification Spectra (Maizuru city).

between the engineering bed rock and the surface ground. In the calculation of amplification spectrum, seismic ground response was carried out using an input earthquake motion adjusted to 1 in 1,000 of the amplification of the notice motion in order to examine the surface ground response due to the difference of input earthquake motion.

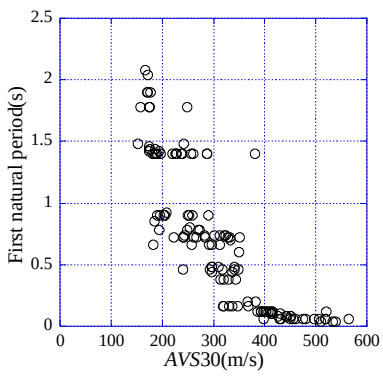

Figure 6: Relationship between*AVS30* and first natural period.

Figure 5 shows the amplification spectra at each estimating location in Figure 4. In soil classification E, the whole amplification spectrum with the amplitude of 1.0 shifts to a long period range in comparison with the spectrum with the amplitude of 1.0 in 1,000.The first natural period of soil classification E moves from 0.5s to 1.78s. On the other hand, the difference due to the amplitude of input earthquake motion in the soil classification C2 is small, and the effect of non-linearity strongly depends on the soil classification. It is found from Figures 4 and 5 that the soil classification due to *AVS30* corresponds to the first natural period. Figure 6 indicates a correlation between *AVS30* and the first natural period in amplification spectrum at all estimating locations. The first natural period in amplification spectrum approaches the period of 1s to 2s with the decrease of *AVS30*. This amplitude of 1s to 2s (Sakai et al. 2004) in amplification spectrum has a high correlation with the severe damage of wooden house due to seismic motion.

4. RELATIONSHIP BETWEEN WOODEN HOUSE RESPONSE AND AVS30

4.1. Evaluation of Maximum Drift angle in Wooden House

Maximum drift angle R of wooden house is evaluated by the performance-equivalent acceleration response spectrum, which was proposed by Saratani et al.(2006) and Hayashi et al.(2008).By a contraction method, a two-story wooden house is assumed to be a single degree of freedom with an equivalent height, H_e, and equivalent mass, M_e. The equivalent-performance acceleration response spectrum means an equivalent response spectrum with a seismic performance capacity of wooden house and can be given by the following equation.

$$S_{ae} = (2\pi H_e R / T_e)^2 / F_h \tag{6}$$

where, S_{ae} is an equivalent-performance acceleration response spectrum (cm/s^2), H_e is an equivalent height (m) in the contraction system from a two-story wooden house to a single degree of freedom, R is a maximum drift angle, T_e is an equivalent period (s), F_h is a reduction rate function of acceleration response spectrum. The hysteresis characteristics of wooden house model are assumed to be a bi-linear type, and the yielding shear force can be given by $M_a g C_y$ for the maximum drift angle R_y (=1/100) at yielding stage. T_e corresponding to the maximum drift angle R_y at yielding stage is given by the following equation.

$$T_e = 2\pi\sqrt{\mu R H_e / C_y g} \qquad (R > R_y) \qquad T_e = \sqrt{\{(1+9(R/R_y)^{0.7})/10\}\mu R_y H_e / C_y g} \qquad (R \le R_y) \tag{7}$$

where, μ is a ratio of an equivalent mass to actual mass, and C_y is a yielding shear force coefficient. The reduction rate function F_h and the damping factor h are given by the following equations.

$$F_h = 1.5/(1+10h) \tag{8}$$

$$h = 0.05 + 0.2(1-(1/\sqrt{R/R_y})) \tag{9}$$

In this paper, μ and H_e are assumed to be 0.9 and 4.5m, respectively, based on the research paper by Saratani et al.[6] C_y are assumed to be 0.1, 0.3, 0.5, and S_{ae} can be calculated for these C_y values.

Figure 7 shows a relationship between acceleration response spectrum $S_a(T)$ in Figure 4 and S_{ae} at surface ground. A point of intersection between $S_a(T)$ and S_{ae} is the maximum drift angle R for an intended seismic motion. S_{ae} gradually increases and shifts to the short period side as Cy increases. Although there is not a large difference in R in the case of C_y=0.1, R in the soil classification E with large acceleration in natural period of 1s to 2s is much larger than that in the soil classification C2 in the case of C_y=0.3. It is found that the natural period of $S_a(T)$ having an effect of C_y on R changes. Accordingly, it should be noted that the characteristics of amplification spectrum having an influence on R can be different by the change of the period characteristics of $S_a(T)$ affecting on R by C_y. Figure 8 indicates a relationship between the first natural period of amplification spectrum and R. In the case of C_y=0.1, R increase with the first natural period of amplification spectrum. R for C_y=0.3 is the same as for C_y=0.1, and there are some small values R in natural period range of 1s to 2s. In

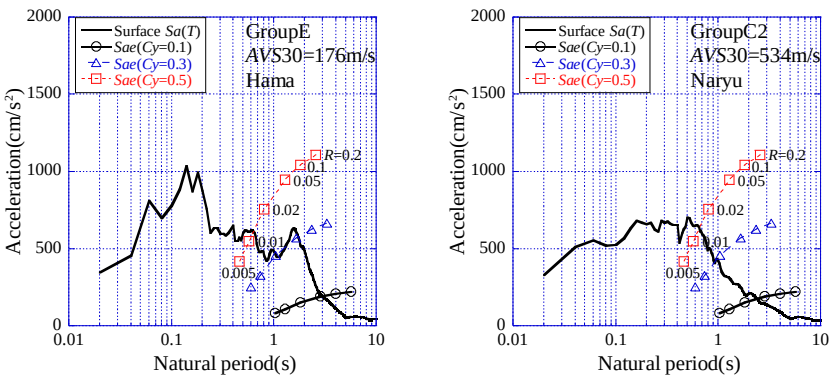

Figure 7: Acceleration response spectrum and equivalent-performance acceleration spectrum.

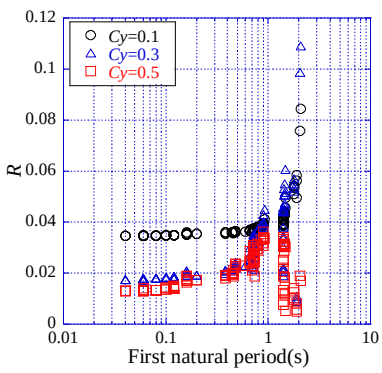

Figure 8: Relationship between first natural period and R.

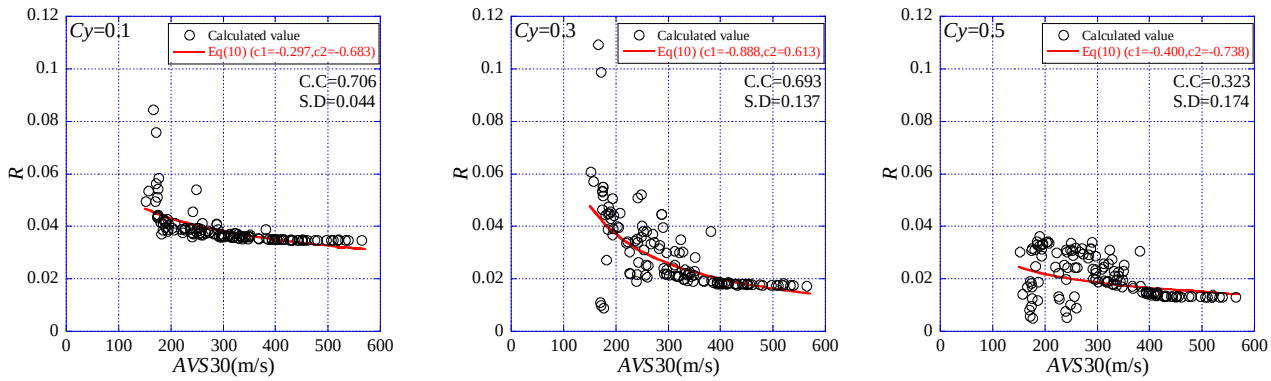

Figure 9: Relationship between *AVS30* and maximum drift angle R.

the case of C_y=0.5, *R* is the largest at the natural period of 0.9s, and *R* trends to be smaller beyond this natural period of 0.9s. Consequently, it should be found that the first natural period of amplification spectrum becomes smaller with the increase of C_y.

4.2. Relationship Between*AVS30* and Maximum Drift angle

A relationship between *AVS30* and the maximum drift angle *R* of wooden house is investigated in this paper. Figure 9 illustrates a relationship between *AVS30* and *R*. In order to investigate a correlation between *AVS30* and *R*, a relational line given by the following equation is shown in Figure 9.

$$\log_{10} R = c_1 \log_{10} AVS30 + c_2 \tag{10}$$

where, "C.C" and "S.D" in Figure 9 mean a correlation coefficient and a standard deviation, respectively.

In the case of *Cy*=0.1, *R* gently changes when *AVS30* is more than 200m/s, while *R* is rapidly large when *AVS30* is less than 200m/s. In the case of *Cy*=0.3, *R* is larger when *AVS30* is less than 400m/s. There is a correlation between *AVS30*and *R*on the whole range of *AVS30*.In the case of *Cy*=0.5, *R* varies widely and is hardly correlated with *AVS30*when *AVS30* is less than 400m/s.

The first natural period of amplification spectrum trends to be longer with the decrease of *AVS30* as shown in Figure 6. The longer the first natural period of amplification spectrum is, the larger *R* becomes in the cases of *Cy*=0.1 and 0.3 as indicated in Figure 8. Because *R* is larger with the decrease of *AVS30*, *R* is correlated to *AVS30* as illustrated in Figure 9. However, the correlation between *AVS30* and *R* trends to smaller in *Cy*=0.5, because *R* is small when the first natural period of amplification spectrum becomes more than 1.0s.

5. CONCLUSIONS

In this paper, a relationship between *AVS30* easily available on Website and seismic response of wooden house during a strong earthquake was investigated for Maizuru city in order to get a fundamental knowledge in applying the surface ground information to the seismic damage estimation of wooden house.

In summary, the following conclusions can be made based on the results presented in this paper.

(1) *AVS30* was evaluated from the shear wave velocity structure at the measuring location from 131 selected boring data in Maizuru city, and seismic ground response analysis was carried out based on *AVS30*.The non-linearity characteristics of surface ground layer greatly depends on the soil classification.

(2) There seems to be a significant correlation between *AVS30* and the first natural period of amplification spectrum obtained by seismic ground response analysis.

(3) The maximum drift angle *R* of wooden house depends on the short period component in the response spectrum with the increase of the yielding shear force coefficient of wooden house.

(4) Because there may be a significant correlation(Correlation coefficient=0.7) between *AVS30* and

R in the cases of *Cy*=0.1 and 0.3, a correlation between *AVS30* and *R* in the case of *Cy*=0.5 is likely to be small. *AVS30* seems to be an effective index in the seismic damage prediction of wooden house with *Cy*=0.1 and 0.3.

6. ACKNOWLEDGMENTS

The authors would like to thank Dr. Kato at Maizuru National College of Technology and Professor Miyajima at Kanazawa University for their valuable opinions and comments. The authors would also like to thank Maizuru city and Geo-Station office for their boring data and soil information, and also thank the Japan Meteorological Agency and the National Research Institute for Earth Science and Disaster Prevention in Japan for their PS logging data in K-NET and KiK-net systems.

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