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AMPLIFICATION FACTOR OF PEAK GROUND MOTION USING AVERAGE SHEAR WAVE VELOCITY OF SHALLOW SOIL DEPOSITS

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SUMMARY

A real-time monitoring system has been installed to support disaster emergency activity in the early post disaster environment by many organizations after the 1995 Kobe earthquake in Japan. Amplification characteristics of the shallow soil deposits are very important to evaluate ground motion distribution with seismometry network. In this paper, we propose a new amplification function which has four parameters, 1) amplification factor during weak motion: A_w, 2) its limit input motion: X_1, 3) upper limit: X_L, 4) input motion reaching upper limit: X_2. The upper limit of PGA, JMA seismic intensity scale and SI value are controlled by the shear strength of soil. Earthquake response analyses are carried out with many conditions and 4 parameters are decided. Topography classifications and a predominant period have been often used as ground parameter, but in late years the use of average S-wave velocity increases. Therefore, we connect average S-wave velocity to 20m or 30m deep with four parameters in order to apply to the urban city where borehole data are provided to high density.

INTRODUCTION

We are developing “Integrated Earthquake Disaster Simulation System (IEDSS)” which is a part of the “Special Project for Earthquake Disaster Mitigation in Urban Areas” by the Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government (MEXT). The system to be developed shall utilize rapidly evolved information technology (IT) closely linking with disaster operation fronts, and is aimed at realizing a prototype of drastically improved system, which will be subjected to trial operation by local governments. Details of the project will be reported by Goto et al. [1].

Site effect on earthquake ground motion is very important for a damage estimate to make emergency responses or plan drafting for disaster prevention. Many researches [2], [3], [4], for example, have been carried out and simple amplification factors which are expressed by constant or exponential functions have been proposed. Nonlinear characteristics of soil are not, however, relevantly considered in those models.

Recently, earthquake response analyses are often employed in seismic design. On the other hand, time restrictions, however, prevents use of analyses for a real-time monitoring system. Therefore, amplification

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factors related with soil parameters are still employed. Although a large number of studies have been made on site amplification, lack of accuracy is caused by improper modeling of nonlinear effect of site amplification characteristics.

Modeling methods of amplification functions are classified as, 1) the method based on observed records during strong ground motions, 2) regression analysis of many weak motion records, 3) the method based on earthquake response analysis of surface deposits. An amplification factor during weak motions is nearly constant when shear strain is less than 10^{-4} because shear modulus and damping coefficient of the soil is nearly constant. Therefore, it is untrue in an exponential model that the amplification factor of peak ground acceleration (PGA) at 1 cm/s^2 becomes several times of that at 10 cm/s^2. We can use relations by regression analysis on weak motion records. However, it will not be applicable under large earthquakes directly. Because strong ground motions are rarely observed, then we cannot but check the system with weak motion records. Therefore, amplification functions for real-time monitoring system should be applicable for weak motions and very strong ground motions. At present, observed records near the seismic fault are not enough in order to construct an amplification function, we choose the third method using response analyses in this paper. Input ground motions are estimated by a fault source model for uniformity between weak motions and strong motions.

As seen at Port Island vertical array record during the 1995 Kobe earthquake, the soil deposits have the upper limit of ground motions because the soil layer cannot transfer shear stress larger than its strength towards upper layers [5]. It is, therefore, important to clarify the relation between the shear strength of soil and upper limit of ground motion.

Site parameters are important to estimate a map of the earthquake ground motion. Various site parameters have been used such as predominant period, S_n value [2], the geomorphological classification, average S-wave velocity to the depth of *d*(m): AVS(*d*). As the amplification factor shows strong correlation with the S-wave velocity of ground [3] & [4], average S-wave velocity of the ground is used as a site parameter in this paper.

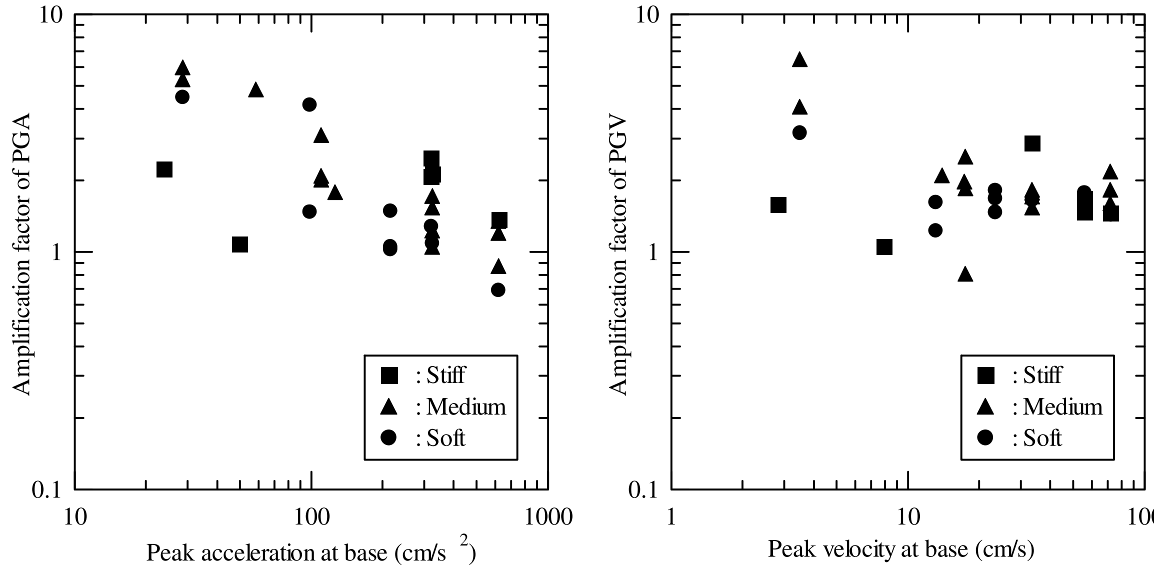
In this paper, firstly, we will inquire into observation records during the 1995 Kobe earthquake in order to show the influence of nonlinear behavior. Secondly, 1-D nonlinear analyses are carried out in order to make the upper limit clear. Thirdly, we propose a new amplification function which can explain nonlinear effect of soil and connect average S-wave velocity with the function in order to apply to the area where borehole data are provided to high density. Finally, case studies are shown in Kawasaki city, Japan.

NONLINEAR EFFECT ON SITE AMPLIFICATION

Nonlinear effect observed at Kobe earthquake

Many strong ground motion records were observed during the 1995 Kobe earthquake. Figure 1 compares amplification factors of peak ground acceleration (PGA) and peak ground velocity (PGV) in the stiff, medium and soft grounds [6]. The ground classification was made based on the Specification of Highway Bridges [7].

The surface geology is shown to affect more on amplification of PGA than on that of PGV. Liquefaction occurred at all soft deposit sites. This indicates that, although the term soft deposit includes both clay and sand layers, there exist surface sand layer at almost all soft deposit sites. On the other hand, evidence of liquefaction was not observed at the medium deposit. As seen in Figure 1, clear difference is seen in the acceleration amplifications between the soft and medium deposit; those at medium deposit is larger than those at soft deposit.



(a) Acceleration (b) Velocity

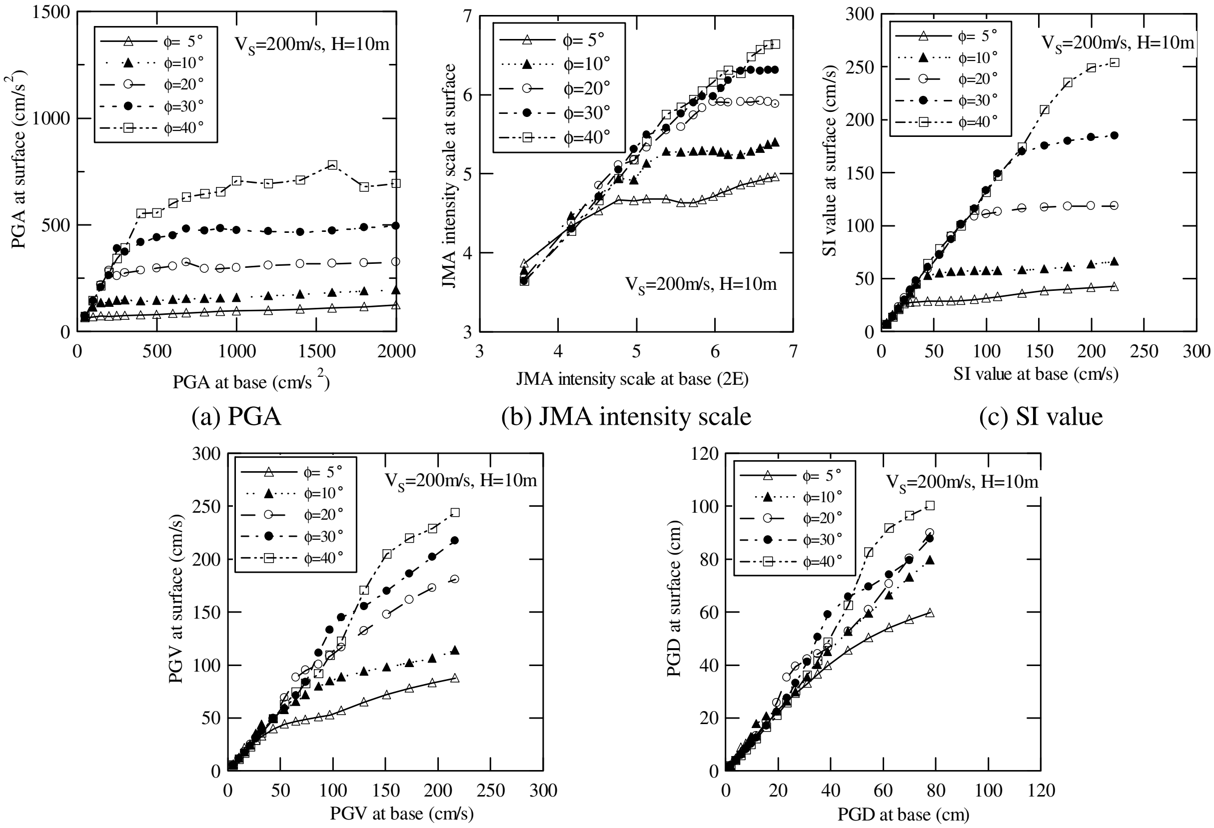
Fig. 1 Relationships between peak responses at the surface and at the base in the observed earthquake records [6]

Same as past researches, amplification ratio of PGA has a tendency to decrease as input motion increases, which suggests importance to consider nonlinear behavior. This tendency is the most clear in the site where liquefaction occurred (soft deposit site); the ratio reaches 1 and sometimes less than 1. This is acceptable because occurrence of liquefaction decrease shear strength. It is noted, however, that decrease of the amplification of PGV hardly occurs even if liquefaction occurs.

The amplifications are fairly large at three soft sites whose peak acceleration at the base is less than 200 cm/s^2. Occurrence of the liquefaction was not confirmed at just points of the earthquake observation, but evidence was observed close by, therefore liquefaction was supposed to occur in these sites as well. This fact may seem against the common knowledge that acceleration is not amplified at the site where liquefaction occurs. This can be, however, explained by the following reason. One of the characteristics of the earthquake motion in this earthquake is that large motion came at first. Therefore, peak response occurred prior to the occurrence of the liquefaction especially at the far site about 30 kilometers away from the fault. Since the number of shaking is more at the far sites, liquefaction can occur even if peak acceleration is small. On the other hand, at the near site, nonlinear behavior as well as liquefaction occurs even during first large motion because of the large amplitude of shaking, resulting in a small amplification ratio.

Upper limit of ground motion

As seen at Port Island vertical array record during the 1995 Kobe earthquake, the soil deposits have the upper limit of ground motions because the soil layer cannot transfer the shear stress larger than its shear strength to upper layers. In order to clarify the relation between the shear strength of soil and upper limit of the ground motion, 1-D nonlinear analyses of sand layers are carried out. Thickness of surface ground (H), shear wave velocity (V_S) and the angle of internal friction (ϕ) are chosen as parameters. A model proposed Hardin and Drnevich [8] expressed as



(a) PGA (b) JMA intensity scale (c) SI value

(d) PGV (e) PGD

Fig. 2 Comparison of amplification characteristics of maximum ground motion indices (*H*= 10m, V_S= 200m/s)

$$\frac{G}{G_{\max}} = \frac{1}{1+\dfrac{G_{\max}\gamma}{\tau_f}}, \quad \frac{h}{h_{\max}} = \left(1-\frac{G}{G_{\max}}\right) \qquad (1)$$

is used in the analysis, where G denotes secant shear modulus, $G_{\max}$ denotes shear modulus at strain levels of 10^{-6}, γ denotes shear strain, τ_f denotes shear strength, h denotes damping ratio, and h_{max} denotes maximum damping ratio. τ_f is expressed as $\tau_f = \sigma_v$' $\tan\phi$ for sand (σ_v': effective mean stress). The stress-strain relation is constructed by [9]. The incident wave at Port Island at a depth of GL-83.4m [6] is used as the incident wave at the base. The peak value of incident wave is changed from 50 cm/s^2 to 2000 cm/s^2 as outcrop condition. Small angles of inertial friction are employed to refer the fall of shear strength caused by the liquefaction phenomenon.

Figure 2 shows the relation between input motion and surface motion of JMA intensity scale, SI value, PGV and PGD when H=10m, V_S=200m/s. JMA intensity scale by Japan Meteorological Agency is calculated with a filter which emphasizes the component of the periods at about 1.2 seconds [10]. As this is expressed with a logarithm, amplification factor becomes a difference. SI value is expressed by

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} S_V(T; h = 20\%)\,dT \qquad (2)$$

where T denotes natural period, S_v denotes velocity response spectrum. It is shown that the upper limits corresponding the angle of inertial friction exist for JMA intensity scale and SI value as well as PGA. In contrast, upper limits are not seen for PGV and PGD. Rather a tendency that amplification factor becomes larger as the predominant period becomes longer is seen for ϕ=30° or 40°. We must note that power of a moment has the upper limit but the energy becomes larger with input motion. Further details for upper limits are reported by Suetomi et al.[11].

NONLINEAR AMPLIFICATION FUNCTION

Earthquake response analyses

An earthquake response analysis is still necessary to evaluate the amplification factor from weak motion to extremely strong ground motion because observation records near the faults are not enough to evaluate it. We can keep consistency from weak motion to extremely strong ground motion by making an input ground motion with fault source models by the statistical Green's function method by Kamae et al. [12]. Asperities for the case of M=7 and M=8 are shown in Figure 3. A point source model are used for the case of M=4, 5, 6. We conduct earthquake response analyses with about 60 site models and construct amplification functions. Soil models such as Port Island which are verified with vertical array observation records are included. The shear wave velocity at the engineering basement is 500m/s. Equivalent linear method improved by Suetomi and Yoshida [13], which overcomes shortage of conventional equivalent linear method by mapping frequency dependent characteristics in time domain into frequency domain, is employed for the response analyses.

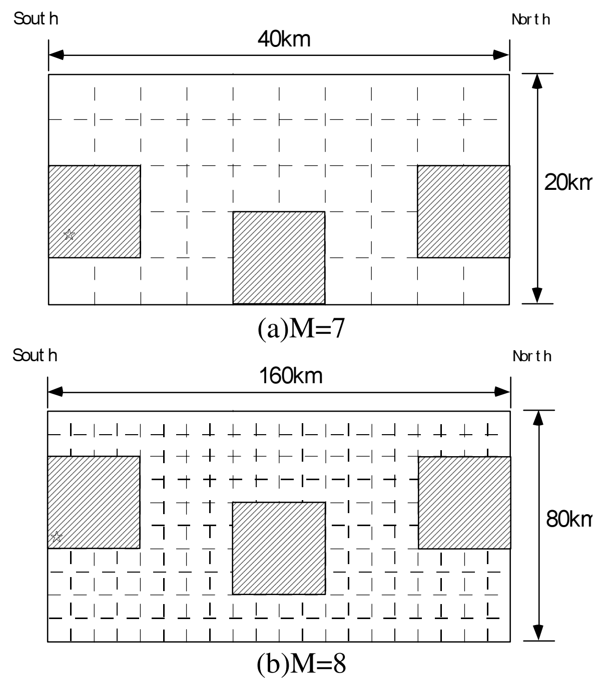
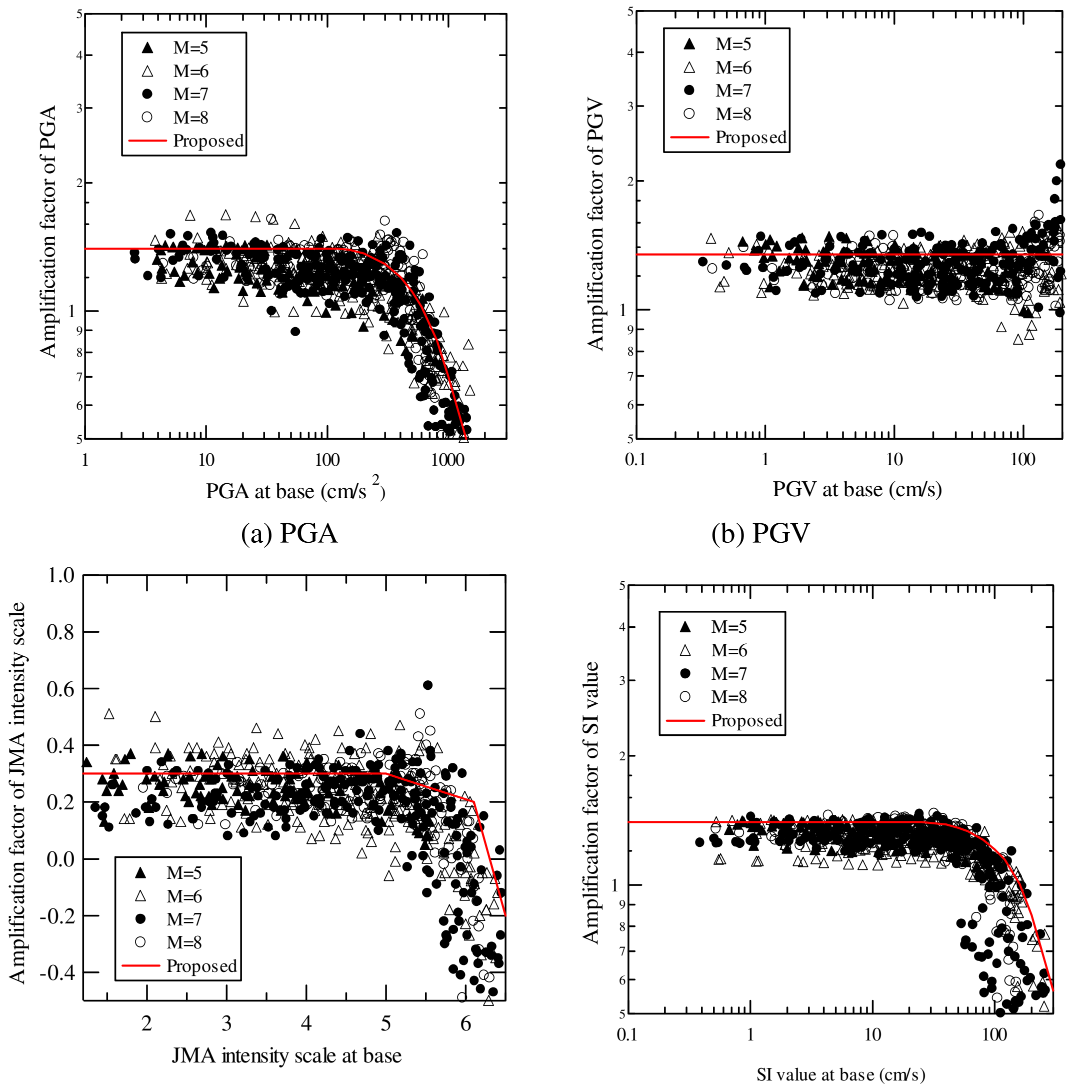


Fig. 3 Fault model with asperity

The relation between the input motion and the amplification factor for the ground model at Technical Research Center of Kansai Electric Power Co. Ltd. (TKE) is shown in Figure 4 as an example. As the influence of nonlinear behavior of the ground is not seen in other ground models in addition to TKE model either, amplification factor of PGV should be constant independent on input motion. Therefore, amplification factor estimated with records of weak motion can be applied to strong ground motion for PGV. It is shown that an amplification factor is constant during weak motion and the surface motion reaches the upper limit during very strong ground motion for other peak parameters. As an input motion becomes larger, an amplification factor becomes smaller rapidly. Nonlinear characteristics above mentioned have not been considered by a conventional model, therefore we propose a new model below.

Nonlinear amplification function model

Damages of urban structures come to be estimated from indices such as PGA or PGV, because they are easiest indices to obtain after the earthquake and because the estimation should be made immediately after the earthquake. Therefore they are generally used instead to conduct dynamic response analyses in order



(a) PGA (b) PGV

(c) JMA intensity scale (d) SI value

Fig. 4 Relation between input motion and amplification factor (TKE model)

to calculate the distribution map of the earthquake ground motion. The amplification factor of the surface soil, λ is expressed as

$$X_S = \lambda(X_b) \cdot X_b \qquad (3)$$

where X_s denotes ground motion index at the ground surface, X_b denotes outcrop base motion. As mentioned above, λ is function with respect to X_b because the soil shows nonlinear behavior during strong motions.

The value of λ becomes smaller monotonously as input motion becomes larger in a conventional model. In fact, a change of rigidity and damping ratio is small when the shear strain is smaller than about 10^{-5}, then a change of amplification factor should be also small. Nevertheless, amplification factor at 1cm/s^2 base motion is different from that at 10cm/s^2 base motion for the conventional monotonous model. This contradicts it in an observation fact. Inspection of precision with weak motion records observed by real-time monitoring system is important in order to improve accuracy of the system. The consideration of upper limits of ground motion parameters is also important. On the basis of such concept, a new model is proposed which consists of three domains as shown in Fig. 5. In the first domain, λ is constant under weak motions. In the second domain, amplification factor is given so that it continues smoothly with the first and the third domains. In the third domain, the ground motion parameter at the ground surface reaches the upper limit.

$$
\begin{aligned}
&X_S = \alpha \cdot X_b && (X_b \le X_1) \\
&X_S = X_L - \beta \cdot (X_2 - X_b)^n && (X_1 < X_b < X_2) \\
&\quad n = \alpha \frac{X_2 - X_1}{X_L - \alpha \cdot X_1} && \\
&\quad \beta = \frac{X_L - \alpha \cdot X_1}{(X_2 - X_1)^n} && \\
&X_S = X_L && (X_b \ge X_2) \qquad (4)
\end{aligned}
$$

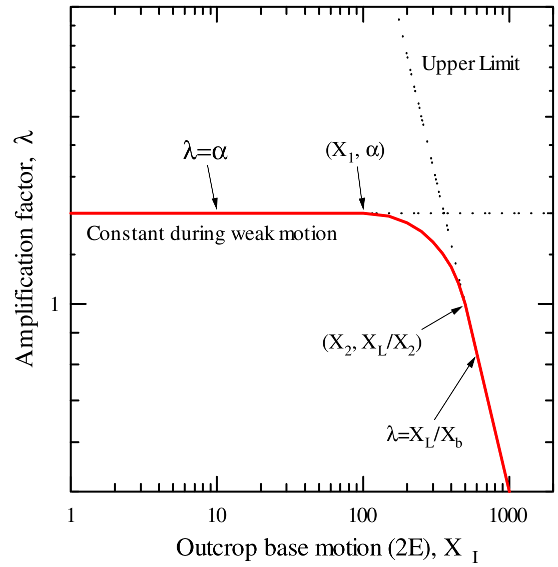


Fig. 5 Nonlinear amplification model

Four parameters in Eq. (4) are decided as shown in Figure 4 by the red line for the TKE model. Parameters of other models are determined likewise.

The proposed model expresses nonlinear characteristics well, but a problem still remains to be resolved. With two points of a neighborhood, a difference of around 3 times is seen to an earthquake ground motion index by a difference of ground condition so as to be able to ignore epicentral distance in a past severe earthquake observation example. By a weak motion record with high density array, a larger difference often appears than it. The amplification factor, however, became only size of around 2 in the weak motion calculated from the earthquake response analysis mentioned above. This seems to be caused that the factor which is not considered in the analysis such as effect of deep structure affects very much. But it is difficult to consider effect of deep structure because information for deep structure and its amplification is not enough. Therefore, we use the amplification factor calculated for statistics with weak motion records. Because it is thought that we can consider influence of nonlinear behavior of soil in the earthquake response analysis of the shallow soil deposits, we do not change other parameters, X_1, X_2 and X_L.

Relation between AVS(20) and parameters of proposed model

There are various ground parameters. We use the average S-wave velocity AVS(*d*) which can be easily utilized detailed ground database here. Tamura et al. [14] estimate relations between the AVS(*d*) and amplification factor obtained by regression analysis of attenuation law of ground motion indices with K-NET by NIED. Basement (α=1.0) of amplification factor is the point of AVS(20) = 500m/s here.

$$\log(\alpha_{PGA}) = -0.436 * \log(AVS(8)) + 1.18 \qquad (5)$$

$$\log(\alpha_{SI}) = -0.785 * \log(AVS(20)) + 2.12 \qquad (6)$$

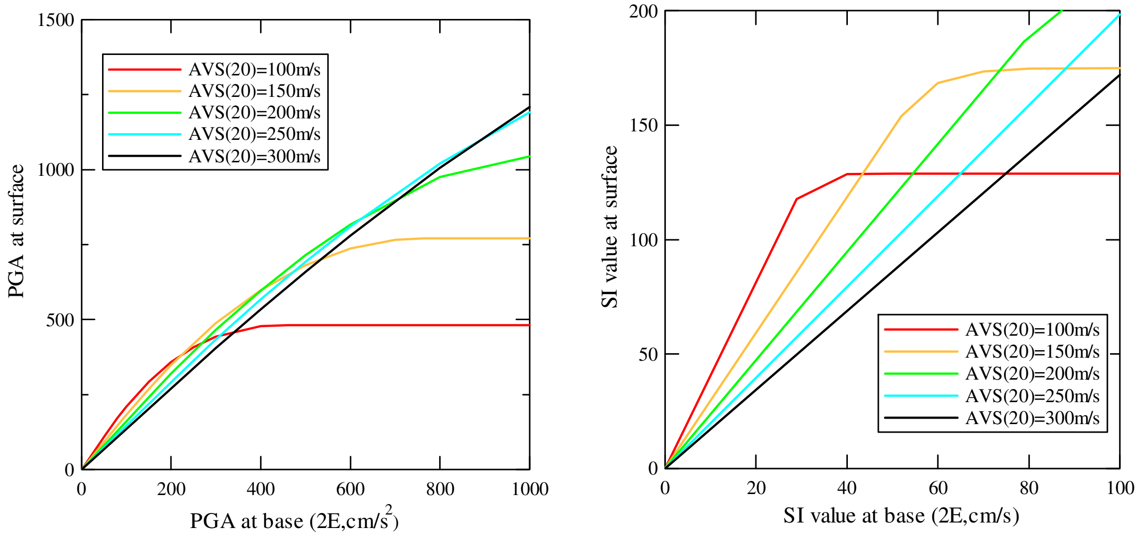
$$\log(\alpha_{PGV}) = -0.734 * \log(AVS(20)) + 1.98 \qquad (7)$$

Table 2 Regression coefficients for PGA

	$AVS(d)$	a_{ACC}	b_{ACC}	R
ACC_1	10m	1.450	-1.087	0.77
	20m	1.355	-0.976	0.79
	30m	1.175	-0.626	0.72
ACC_2	10m	1.031	0.743	0.62
	20m	1.243	0.178	0.82
	30m	1.258	0.074	0.86
ACC_L	10m	0.920	0.986	0.56
	20m	1.159	0.365	0.78
	30m	1.199	0.209	0.84

Table 3 Regression coefficients for SI value

	$AVS(d)$	a_{SI}	b_{SI}	R
SI_1	10m	1.925	-2.545	0.73
	20m	2.123	-3.144	0.89
	30m	2.040	-3.064	0.89
SI_2	10m	0.780	0.626	0.70
	20m	0.851	0.405	0.84
	30m	0.774	0.539	0.80
SI_L	10m	0.773	0.603	0.65
	20m	0.839	0.393	0.78
	30m	0.782	0.482	0.75



(a) PGA (b) SI value

Fig. 6 Amplification function estimated by mean shear wave velocity

On the other hand, 3 parameters for nonlinear characteristics estimated for every 60 models are expressed as relation with AVS(d) shown in Eq. (8) and (9). The coefficients a, b are estimated by a regression analysis. Because it is not necessary to consider influence of nonlinear behavior about PGV, we can apply Eq. (7) until severe earthquake.

$$\log(ACC_X) = a_{ACC} \cdot AVS(d) + b_{ACC} \tag{8}$$

$$\log(SI_X) = a_{SI} \cdot AVS(d) + b_{SI} \tag{9}$$

Regression analyses are carried out for three cases of AVS(d); d=10, 20, 30m. Obtained regression coefficients and correlation coefficients are shown in Table 2 for PGA and Table 3 for SI value. The variable X_1 is affected by shallow parts of the ground and both X_2 and X_l are affected by rather deep parts of the ground, then the correlation coefficient of AVS(10) is large for X_1 and small for X_2 and X_L. However, a clear difference between AVS(20) and AVS(30) does not appear by this analysis. Therefore, it is practical to unify in AVS(20) which shows also good correlation with X_1.

Amplification function of estimated relation with AVS(20) is shown in Fig. 6. The softer the ground is, the larger ground motion indices become during weak motions, but we cannot always say on the soft ground that ground motion indices are large during strong ground motions because of nonlinear behavior. It is estimated by Suetomi and Yoshida [6] that PGA is from 400 to 600 cm/s^2, JMA intensity scale is from 5.6 to 5.8, PGV is about 80 cm/s at the basement during the 1995 Kobe earthquake. In this case, PGA and SI value at the soft ground whose AVS(20) is between 100 and 150 m/s are smaller than the medium ground whose AVS(20) is about 200 m/s. This adjusts it with participation on the damage belt of influence of nonlinear behavior qualitatively. Therefore, it is thought that influence of nonlinear behavior of the ground is considered adequately by the proposed model in this paper.

CASE STUDY

We digitized boring data more than 5,000 sites in Kawasaki city and estimated various soil parameters such as predominant period and AVS(20) in m/s. Figure 7 shows distribution of AVS(20) in 50 meter meshes calculated by the interpolation. AVS(20) at sea-side, especially near the Kawasaki station, is smaller than that at hill-side.

Figure 8 shows distribution of PGA when input motions at base is uniform for 4 cases of 50, 100, 300, 500 cm/s^2. PGA at sea-side is larger when PGA at base is 50 cm/s^2. As PGA at base becomes larger, PGA at sea-side reaches upper limits and the difference between hill-side and sea-side becomes smaller. As an amplification of PGV is constant, PGV at sea-side is always larger than at hill-side. As mentioned above, the proposed model represents nonlinear characteristics very well. We will examine accuracy with observed strong ground motion records by constructing geo-database of the objective area.

We are constructing a simulator of a ground motion distribution as a part of the IDESS. The proposed amplification model in this paper is included in the simulator. The simulator can calculate a ground motion distribution by interpolating observed values at seismic networks considering characteristics of earthquake ground motion. We will check the accuracy of the simulator using many strong motion records observed in Japan.

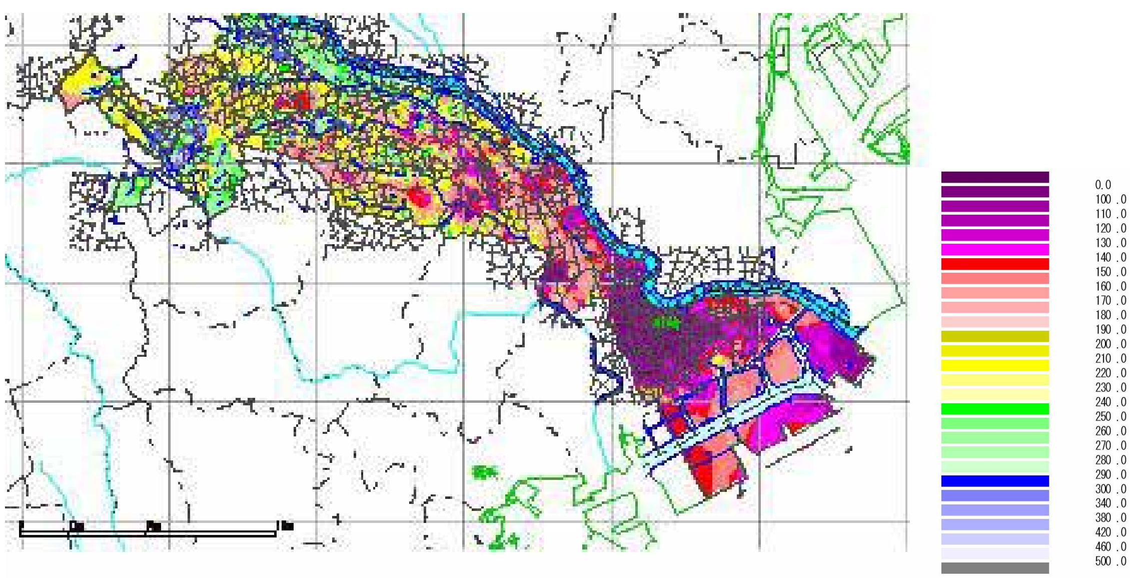
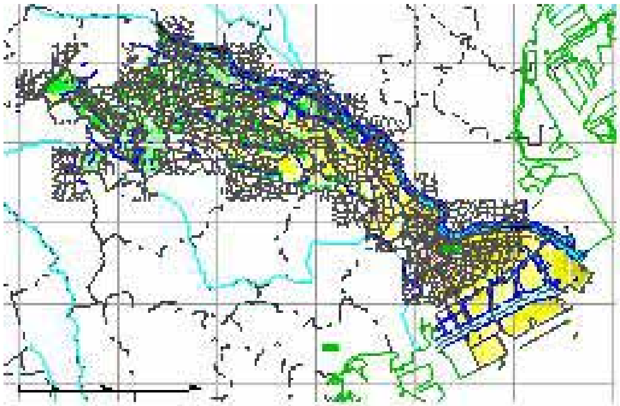
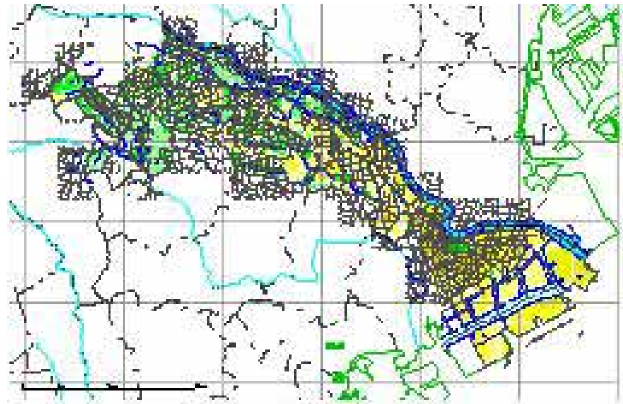


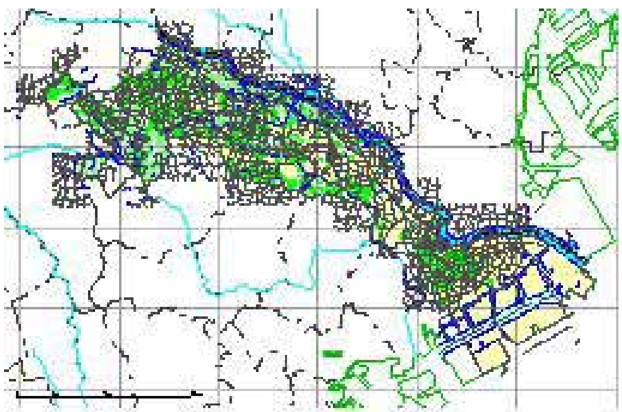
Fig.7 Distribution of AVS(20) in Kawasaki city



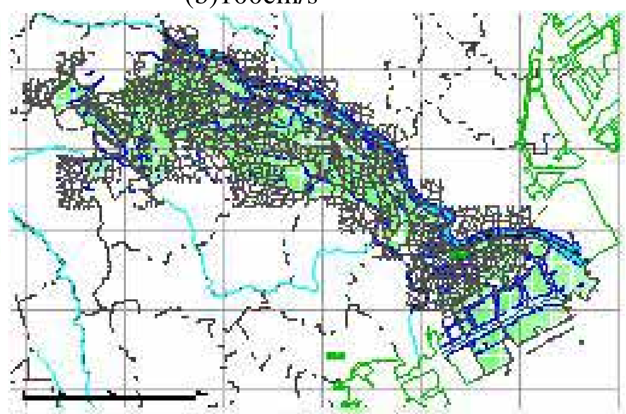
(a)50cm/s^2



(b)100cm/s^2



(c)300cm/s^2



(d)500cm/s^2

Fig. 8 PGA distribution for uniform base motion at Kawasaki city

CONCLUSIONS

Urban cities where borehole data are sufficiently compiles make it possible to evaluate average S wave velocity of the ground in small meshes. Amplification factor evaluation method to use the database is examined by this study, and the following spiritual awakening was provided.

1) Amplification factor is modeled to evaluate influence of nonlinear behavior of the ground adequately.
2) An amplification function parameter is evaluated and is modeled as a function of average S wave velocity to 20m depth through earthquake response analyses at many grounds.
3) It is not necessary to consider influence of nonlinear behavior of the ground when peak ground velocity is employed as the ground motion index.
4) The proposed model enables to estimate a detail ground motion map of the urban city with boring database.

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REFERENCES

1. Goto Y, Kakumoto S, Takeuchi I. "Integrated Earthquake Disaster Simulation System for the Highly-Networked Information Society", Proceedings of the 13th World Conference of Earthquake Engineering, 2004 (in Press).
2. Sugito M, Goto H, Takayama S. "Conversion factor between earthquake motion on soil surface and rock surface with nonlinear soil amplification effect", 7th Japan Earthquake Engineering Symposium, pp.571-576, 1986.
3. Midorikawa S, Matsuoka M, Sakugawa K. "Site effects on strong-motion records observed during the 1987 Chiba-Ken-Toho-Oki, Japan earthquake", 9th Japan Earthquake Engineering Symposium, E-085-090, 1994.
4. Borcherdt RD. "Preliminary amplification estimates inferred from strong ground-motion recordings of the Northridge earthquake of January 17, 1994", Proceedings of the international workshop on site response -subjected to strong earthquake motions-, Vol.2, pp.22-46, 1996.
5. Kazama M, et al., "Stress strain relationship in the ground at Kobe Port island during the 1995 Hyogo-ken Nanbu earthquake inferred from strong motion array records", Journal of Structural Mechanics and Earthquake Engineering, JSCE, No.547/III-36, pp.171-182, 1996. (in Japanese)
6. Suetomi I, Yoshida N. "Nonlinear behavior of surface deposit during the 1995 Hyogoken-Nambu earthquake", Special Issue of Soils and Foundations, pp.11-22, Sept., 1998.
7. Sawada S, Ejiri J, Toki K, Goto Y. "Strong ground motion records," The 1995 Hyogoken-nambu earthquake -investigation into damage to civil engineering structures-, Committee of earthquake engineering, Japan society of civil engineers, pp.7-14, 1996.
8. Hardin BO, Drnevich VP. "Shear modulus and damping in soils: Design equation and curves," J. of SM, ASCE, Vol.98, No.SM7, pp.667-692, 1972.
9. Ishihara K, Yoshida N, Tsujino S. "Modelling of stress-strain relations of soils in cyclic loading", Proc. 5th International Conference for Numerical Method in Geomechanics, Nagoya, Vol.1, pp.373-380, 1985.
10. Web site of Japan Meteorological Agency, http://www.kishou.go.jp/know/shindo/keisoku.html. (in Japanese)
11. Suetomi I, Sawada S, Yoshida N, Ishida E, Goto Y. "Upper limit of amplification factor caused by shear strength in nonlinear response", Proc. of the 11th International Conference on Soil Dynamics & Earthquake Engineering and the 3rd International Conference on Earthquake Geotechnical Engineering, Vol.2, pp.165-172, 2004.
12. Kamae K, Irikura K, Fukuchi Y. "Prediction of strong ground motion based on scaling law of earthquake", Journal of Struct. Constr. Engng, AIJ, No.430, pp.1-9, 1991 (in Japanese).
13. Suetomi I, Yoshida N. "Damping characteristics of soil deposits during strong ground motions", Proceedings of the Second International Symposium on the Effect of Surface Geology on Seismic Motion, Yokohama, pp.765-772, 1998.
14. Tamura I, Yamazaki F, Shabestrai K. "Estimation of the site amplification ratio from the average S-wave velocity using K-NET data", CD-ROM Proceedings of 55th JSCE Annual Meeting, I-B357, 2000. (in Japanese)