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EVALUATION OF AMPLIFICATION CHARACTERISTICS OF SUBSURFACE GROUND FOR SETTING DESIGN INPUT GROUND MOTION

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SUMMARY

Seismic ground motions at the surface greatly depend on the amplification characteristics of the subsurface ground, and so when a design seismic ground motion is set, evaluation of the amplification characteristics of the subsurface ground is as important as evaluation of the earthquake source faults. In implementing seismic micro-zoning or in setting a design seismic ground motion for an extensive area, it is impractical to conduct laboratory experiments and detailed ground surveys at many sites. Amplification characteristics of subsurface ground need to be evaluated, with a given accuracy, on the basis of simple indices. This paper focuses on a method proposed by Midorikawa and Matsuoka[1)] to evaluate amplification characteristics of subsurface ground by means of geographic classification obtained from digital national land information. This method was applied to ground information of the Kushiro area for evaluation of the local amplification characteristics. To examine the practical applicability of the method, the results were compared with the amplification characteristics obtained from seismic ground motion records for the same area at the time of the 1994 Hokkaido Toho-oki Earthquake. The amplification factors estimated by the method were 0.8 - 1.6 times those obtained from the seismic motion records. This suggests that although the method when applied to a wide area can guarantee a certain level of accuracy, the accuracy varies greatly by site location.

INTRODUCTION

Because seismic ground motions at the surface greatly depend on the amplification characteristics of the subsurface ground, evaluation of the amplification characteristics is as important as evaluation of earthquake source faults in the setting of design seismic ground motion. The amplification characteristics of subsurface ground are greatly influenced by liquefaction and non-linearity of ground as well as by ground structure; thus, ground surveys and soil tests are necessary to obtain detailed ground information. However, in implementing seismic micro-zoning and setting a design seismic ground motion for a wide area, ground surveys and soil tests need to be done at numerous sites because amplification

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characteristics differ greatly, even at neighboring sites[2]. In many cases, these surveys and tests are unfeasible. It is necessary to find a method that evaluates amplification characteristics of subsurface ground with a given accuracy, based on simple indices.

One method uses simple indices for evaluating amplification characteristics of subsurface ground (Midorikawa and Matsuoka[1]). It makes use of digital national land information. In this method[1], the time-weighted average shear-wave velocity (AVS) in the 30-m-deep surface layer is determined on the basis of geographic classification contained in digital national land information[3,4], and an amplification factor for maximum ground velocity (ARV)[5] is obtained from AVS by using an empirical expression. The empirical expression for the relationship between AVS and ARV was derived from strong motion records obtained in the Kanto region at the time of the Chiba-ken Toho-oki Earthquake (M 6.7) of December 17, 1987. Therefore, in applying the method by Midorikawa and Matsuoka, strong motion records should satisfy the following conditions: (1) The records should be of earthquakes whose intensities are comparable to that of the Chiba-ken Toho-oki Earthquake; and (2) the records should have been taken for both the ground surface and the engineering base layer.

At the time of the Kushiro-oki Earthquake (M 7.9) of January 15, 1993, strong-motion records were taken at five sites in the city of Kushiro. Even though these five observation sites were located almost in the same direction from the hypocenter, and the path of the seismic wave propagation and the hypocentral distance were nearly the same, the maximum acceleration of the strong motion records differed, with the greatest of these exceeding the smallest by a factor of three. The ESG Research Committee of the Association for Earthquake Disaster Prevention attributed the differences in seismic ground motion in such a small area to variations in ground structure at the observation sites, and the Committee conducted joint observation in the city of Kushiro towards qualitatively evaluating the effects of subsurface ground structures on the seismic ground motions. At the time of the Hokkaido Toho-oki Earthquake of October 4, 1994, valuable records of strong motions were obtained at 17 stations, although they were records of ground surface[6]. During this earthquake, at a observation site in Kushiro Port included in the Port and Harbor Strong Earthquake Motion Observation Network, strong motion records were taken at the ground surface and at G.L. −77.45 m, a depth considered to be the engineering base layer. These strong motion records are suitable for examining amplifications of seismic ground motions in various subsurface ground structures in a relatively small area.

This paper focuses on ground in the city of Kushiro where many strong motion records were measured during the Hokkaido Toho-oki Earthquake (M 8.1) of October 4, 1994, toward examining the applicability of the method proposed by Midorikawa and Matsuoka. Subterranean strong motion records measured by the Port and Harbor Strong Earthquake Motion Seismograph Network were regarded as strong motion records on the engineering base layer, and an amplification factor for maximum ground velocity from the engineering base layer to each seismograph station was obtained for comparison with the amplification factors determined by the method of Midorikawa and Matsuoka.

EVALUATION OF AMPLIFICATION CHARACTERISTICS BASED ON STRONG MOTION RECORDS

Observation Site

Figure 1 shows the observation site where strong motion records of the Hokkaido Toho-oki Earthquake were available, together with the geological features of Kushiro and an east-west cross-section of the ground structure. Of the 23 stations covered by ESG joint observation, strong motion records were obtained at 17 sites. The strong motion records at three sites (KAI, KRK and NSM) are excluded

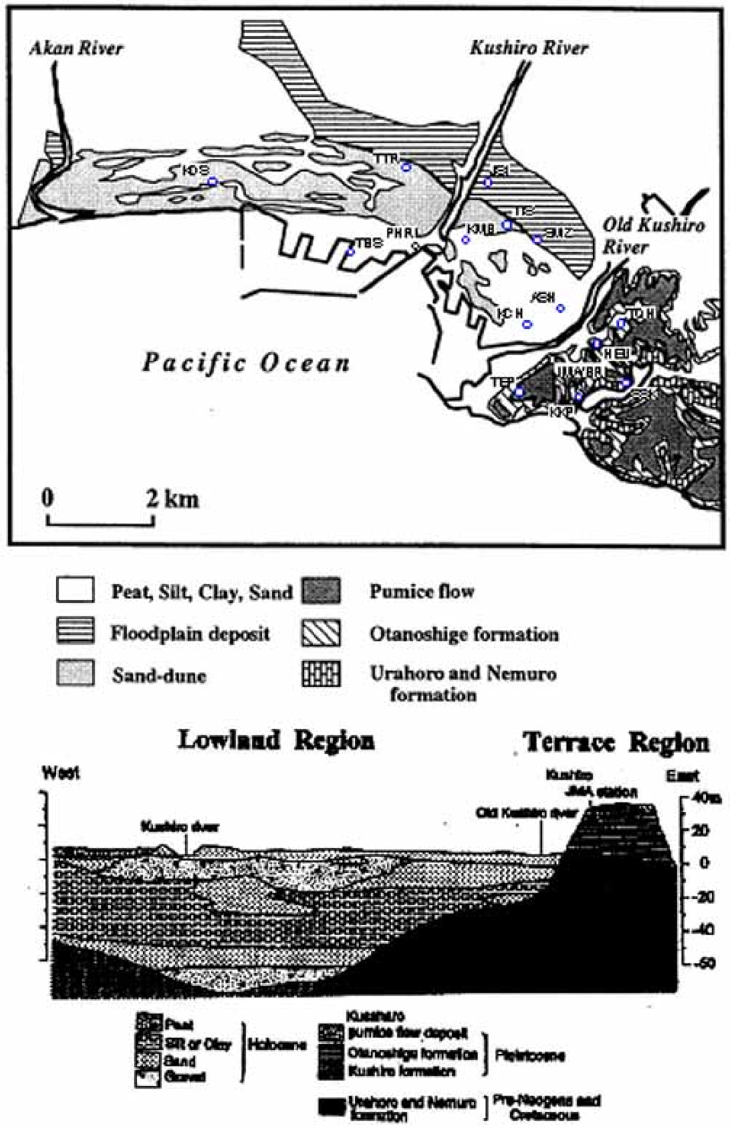


Figure 1. Observation sites and surface geology of Kushiro city
(Observation sites were added on figure after Jwg of ESG[6].)

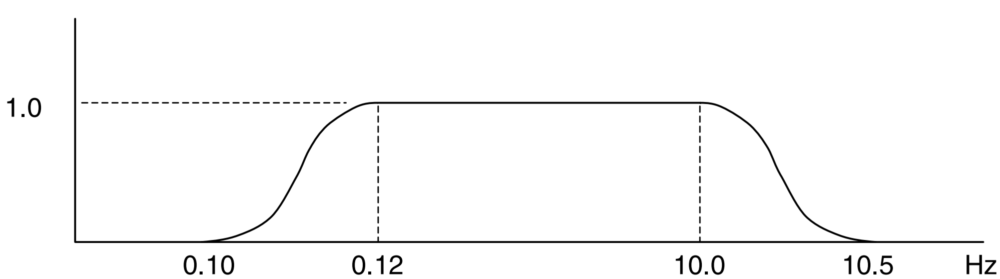
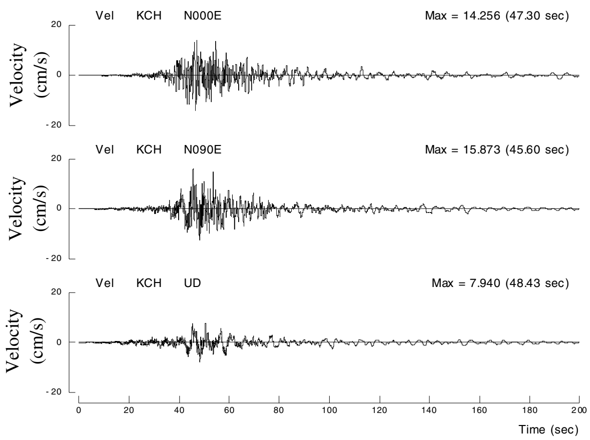
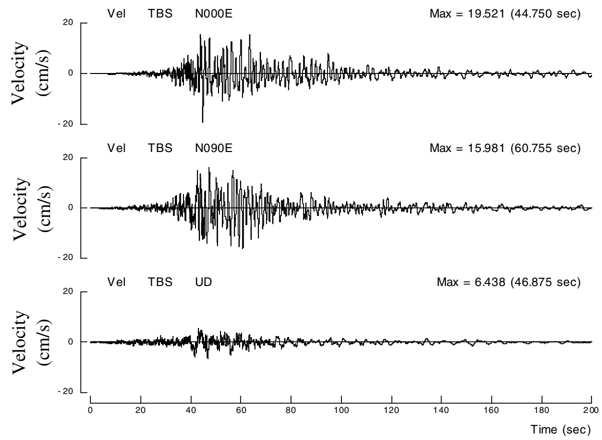


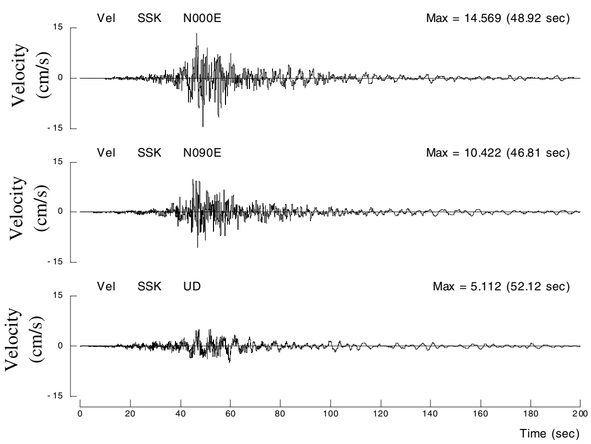
Figure 2. Filter for fourier integration of acceleration records



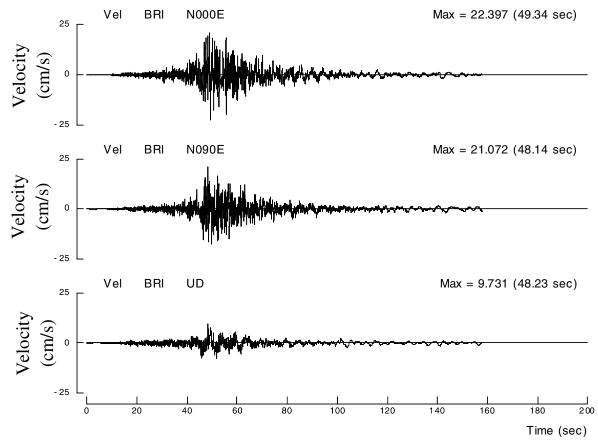
a) KCH



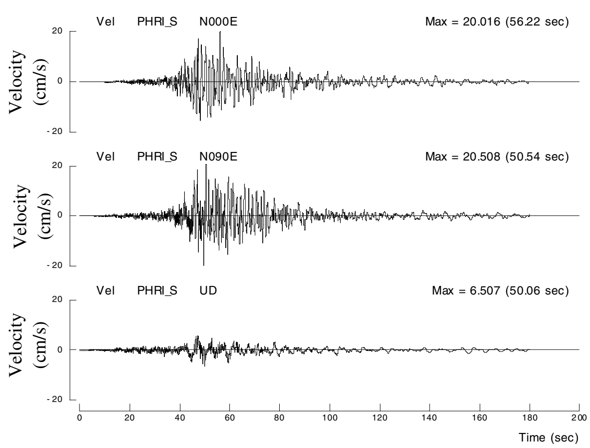
b) TBS



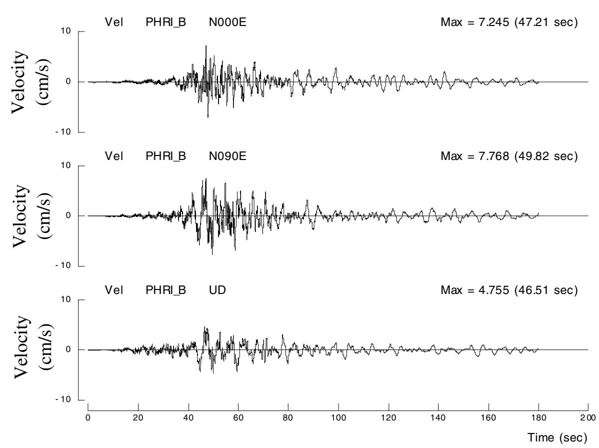
c) SSK



d) BRI



e) PHRI-S



f) PHRI-B

Figure 3. Time histories of velocity observed during the Hokkaido Toho-oki Earthquake of 1999, by site

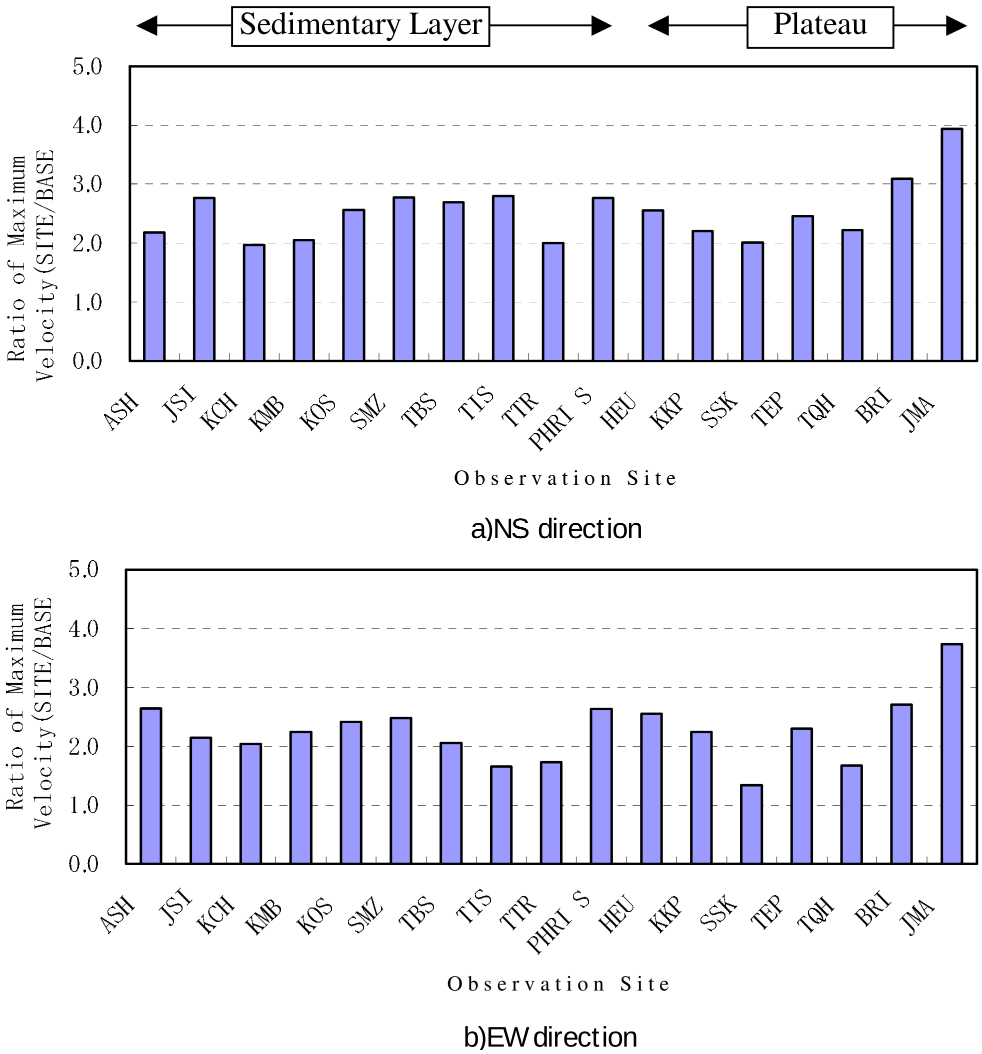


Figure 4. Amplification of maximum velocity based on strong motion records

because of inaccurate recording. Strong motion records at the remaining 14 observation sites are used in this study. In addition to these sites, strong motion records were measured in Kushiro at the sites of the Port and Harbor Strong Earthquake Motion Observation Network (currently the Port and Airport Research Institute (PHRI)), the Building Research Institute of the Ministry of Construction (currently the Building Research Institute (BRI)[8)]), and Japan Meteorological Agency (JMA)[9)], and their records are included in this study. Altogether, 17 observation sites are referred to in this study.

To the east of the Old Kushiro River in Kushiro lies a Pleistocene plateau. To the west of the plateau are relatively soft Holocene sedimentary layers of peat and sand. The Holocene layers have a maximum combined thickness of about 80 m. The observation sites are distributed on the plateau (TEP, KKP, JMA, BRI, HEU, TQH and SSK) and on the sedimentary layers (KOS, TBS, TTR, PHRI, JSI, KMB, TIS, SMZ, KCH and ASH). The underground observation site of PHRI is presumed to be on the bottom sand layer or on the Pleistocene Kushiro layer. The ground surface and underground observation sites of PHRI are represented as PHRI-S and PHRI-B respectively.

Ratios of velocities of strong motion record vs. the maximum velocities from the engineering base layer to the ground surface

Of the 17 observation sites, velocities were measured at TIS sites and accelerations were measured at the other sites. The orientations of seismometers were not uniform. Thus, an average of velocities for the whole time period was used as a baseline deviation for correcting the baseline for each time history waveform. Then, the azimuth of strong motion records of N000E and N090E were corrected. Regarding acceleration time histories, a filter (Fig. 2) was applied to strong motion records that had been corrected in terms of its baseline, and Fourier integration was performed to obtain velocity time histories.

Figure 3 shows waveforms of the velocity time histories on several observation sites and of the velocity time histories on the engineering base layer of the PHRI observation sites. Figure 4 shows the ratios of maximum ground velocity on G.L. -77.45 m of PHRI sites obtained from the strong motion records these sites.

AMPLIFICATION CHARACTERISTICS DETERMINED USING THE EVALUATION METHOD OF MIDORIKAWA AND MATSUOKA BASED ON DIGITAL NATIONAL LAND INFORMATION

The method of Midorikawa and Matsuoka

For the purpose of identifying amplification characteristics of subsurface ground, Midorikawa and Matsuoka proposed a method that estimates an amplification factor of maximum ground velocity on the basis of geographic classification derived from digital national land information[2]. In this method, data such as those of microtopography, altitude and distance from a river are used to estimate a time-weighted average shear-wave velocity in the ground according to Equation (1)[3),4)].

$$\log AVS = a + b \log H + c \log D \pm \sigma \qquad (1)$$

AVS: time-weighted average shear-wave velocity (m/s) to a depth of 30 m
H: altitude (m)
D: shortest distance from a river (km)
σ: standard deviation
a,b,c: coefficient of regression from Table1

Next, based on the strong motion records obtained during the Chiba-ken Toho-oki Earthquake of December 17, 1987, ARV is calculated from AVS obtained by Equation (1), by using an empirical expression (2) that gives the relationship between amplification factor for maximum ground velocity (ARV) and a time-weighted average shear-wave velocity (AVS) in the 30-m-deep surface layer5).

$$\log AVS = 1.83 - 0.66 \log AVS \pm 0.16 \qquad (2)$$

ARV: amplification factor for maximum ground velocity with respect to tertiary ground that corresponds to stiff soil with the AVS of 600 m/s

Classification into geomorphologic units using digital national land information

Geographical classification by digital national land information is based on a land classification map with a scale of 1 to 100,000 - 200,000, in which the unit mesh size is 30 seconds latitudinally and 45 seconds longitudinally (approximately 1 × 1 km.) Because the unit of this geographical classification is not fine enough for estimation of the amplification factors for the maximum ground velocity shown in Table 1,

Table 1. Coefficient of regression

Geomorphologic unit or Geology	a	b	c	σ
(1) Reclaimed Land	2.23	0	0	0.14
(2) Artificial Transformed Land	2.26	0	0	0.09
(3) Delta, Back Marsh (D ≤ 0.5)	2.19	0	0	0.12
(4) Delta, Back Marsh (D > 0.5)	2.26	0	0.25	0.13
(5) Natural Levee	1.94	0.32	0	0.13
(6) Valley Plain	2.07	0.15	0	0.12
(7) Sand Bar, Dune	2.29	0	0	0.13
(8) Fan	1.83	0.36	0	0.15
(9) Loam Plateau	2.00	0.28	0	0.11
(10) Gravel Plateau	1.76	0.36	0	0.12
(11) Hill	2.64	0	0	0.17
(12) Other Geom. Unit	2.25	0.13	0	0.16
(13) Pre-Tertiary	2.87	0	0	0.23

Table 2. Amplification factors for PGV using Midorikawa and Matsuoka's method

Obs. site	a*	H	D	b*	AVS (m/s)			ARV								
								−0.16			±0			+0.16		
					−σ	± 0	+σ	−σ	± 0	+σ	−σ	± 0	+σ	−σ	± 0	+σ
ASH	21	4	0.38	(3)	117.5	154.9	204.2	2.01	1.68	1.40	2.91	2.42	2.02	4.21	3.50	2.92
JSI	21	3	0.26	(3)	117.5	154.9	204.2	2.01	1.68	1.40	2.91	2.42	2.02	4.21	3.50	2.92
KCH	21	3	0.38	(3)	117.5	154.9	204.2	2.01	1.68	1.40	2.91	2.42	2.02	4.21	3.50	2.92
KMB	21	3	0.33	(3)	117.5	154.9	204.2	2.01	1.68	1.40	2.91	2.42	2.02	4.21	3.50	2.92
KOS	22	3	0.55	(7)	144.5	195.0	263.0	1.76	1.44	1.18	2.54	2.08	1.71	3.67	3.01	2.47
SMZ	21	3	1.35	(4)	145.4	196.1	264.6	1.75	1.44	1.18	2.53	2.07	1.70	3.65	3.00	2.46
TBS	22	1	0.03	(5)	64.6	87.1	117.5	2.99	2.45	2.01	4.32	3.54	2.91	6.24	5.12	4.21
TIS	21	4	0.96	(3)	133.5	180.1	243.0	1.85	1.52	1.25	2.67	2.19	1.80	3.86	3.17	2.60
TTR	21	4	1.16	(4)	140.0	188.8	254.8	1.79	1.47	1.21	2.59	2.13	1.75	3.75	3.07	2.52
PHRI	22	1	0.05	(5)	64.6	87.1	117.5	2.99	2.45	2.01	4.32	3.54	2.91	6.24	5.12	4.21
HEU	33	10	0.49	(9)	147.9	190.5	245.5	1.73	1.46	1.24	2.50	2.11	1.79	3.61	3.06	2.59
KKP	33	5	0.10	(9)	121.8	156.9	202.2	1.97	1.66	1.41	2.84	2.40	2.03	4.11	3.47	2.94
SSK	21	20	0.09	(3)	117.5	154.9	204.2	2.01	1.68	1.40	2.91	2.42	2.02	4.21	3.50	2.92
TEP	33	20	0.49	(9)	179.6	231.4	298.0	1.52	1.29	1.09	2.20	1.86	1.57	3.18	2.69	2.27
TQH	33	5	0.76	(9)	121.8	156.9	202.2	1.97	1.66	1.41	2.84	2.40	2.03	4.11	3.47	2.94
BRI	21	20	0.17	(3)	117.5	154.9	204.2	2.01	1.68	1.40	2.91	2.42	2.02	4.21	3.50	2.92
JMA	21	20	0.17	(3)	117.5	154.9	204.2	2.01	1.68	1.40	2.91	2.42	2.02	4.21	3.50	2.92

a*: Microtopography unit No. by digital national land information

b*: Detailed Microtopography unit after Table 1

data including distance from a river were used for fine sorting[10]. Based on the literature10), the results (Table 2) were obtained after fine-sorting the seismograph stations into geomorphologic units required for the estimation of the amplification factors for maximum ground velocity.

HEU, KKP, TEP and TQH are classified as loam plateau (9). Sites shown as lowland floodplains are classified as delta and back marsh, and are further divided into (3) delta, back marsh (D ≤ 0.5) and (4) delta, back marsh (D > 0.5) depending on distance from the river. Sites JMA and BRI are in this group, although they are on the plateau to the east of the Old Kushiro River. Additionally, SSK is classified as delta and back marsh because it is on the shore of Lake Harutori, whereas this site is actually on the plateau.

Although geomorphologic units of KOS, TBS and PHRI sites are classified as natural levee and sandbar, TBS and PHRI should be included in the category of natural levee because they are within 5 km of the coast and within 1 km of a major river (the Kushiro River). In fact, TBS is on reclaimed land, and KOS is classified as sandbar because it is less than 7 m above sea level.

Amplification factor for maximum ground velocity estimated using the method of Midorikawa and Matsuoka

Table 2 shows the amplification factors for maximum ground velocity (ARV) evaluated using the method of Midorikawa and Matsuoka. The time-weighted average shear-wave velocity to a depth of 30 m (AVS) is used for calculating ARV. Because AVS has variations in the range of $-\sigma$ to $+\sigma$ and ARV also has variations, nine different values are obtained.

Figures 5(a) and 5(b) show the relationships between ARVs obtained from strong motion records and the ARVs obtained using the method of Midorikawa and Matsuoka. For the latter ARVs, the average values (i.e., average ARVs based on average AVSs) and the range covered by the maximum and the minimum values are presented. Figure 5(c) shows the ratios of amplification factors for maximum ground velocity, which are obtained by dividing the average ARVs obtained using the method of Midorikawa and Matsuoka by the ARVs of the strong motion records.

In general, ARVs estimated using the method of Midorikawa and Matsuoka are greater than the observed ARVs. The reason for this difference seems to be that the ARVs obtained by the method of Midorikawa and Matsuoka are those on the engineering base layer where Vs = 650 m/s, which is greater than the shear wave velocity on the engineering base layer of PHRI, 337 m/s.

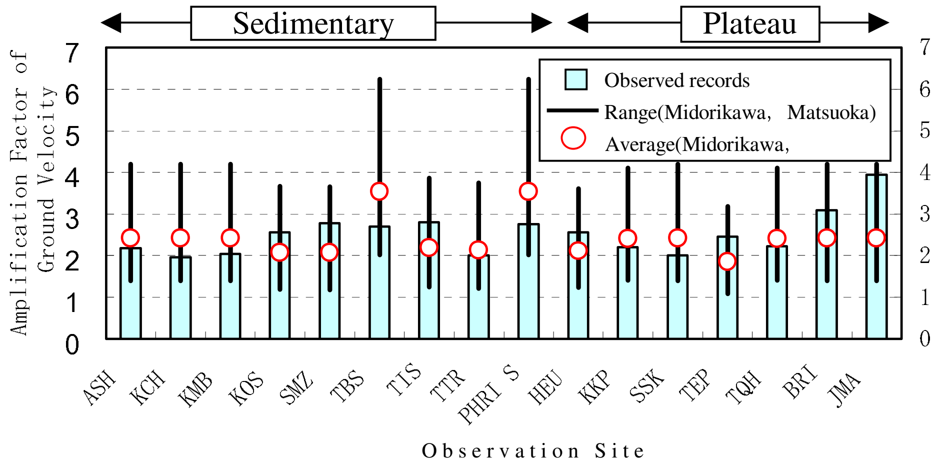
As for the individual observation sites, ARVs at the three sites of TBS, PHRI and SSK are larger and those at the two sites of JMA and BRI, where large-scale strong motion records were observed, are smaller than the observed ARVs.

Estimation of the amplification factor for maximum ground velocity after microtopographical correction

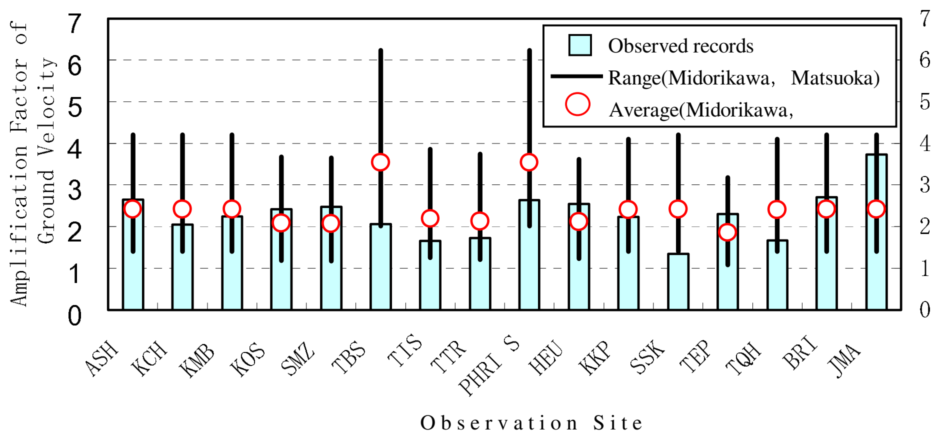
Microtopographical categories of sites TBS, PHRI, JMA, BRI and SSK do not conform to the actual geographical features. Because the ARVs estimated using the method of Midorikawa and Matsuoka at these five observation sites did not agree well with the observed ARVs, it is possible that the microtopographical classification has some flaws. Thus, the microtopographical classification was modified to reflect the actual topographic features, and ARVs were recalculated.

TBS is in reclaimed land. PHRI is near the river mouth, and so it is considered reasonable to classify it as (2) graded land. JMA, BRI and SSK are on the plateau and are included in (9) loam plateau. Table 3 shows the sites reclassified in terms of microtopography, together with AVSs, and ARVs. In Figure 6, the relation between ARVs from the strong motion records and the ARVs using the method of Midorikawa and Matsuoka. The results for the sites other than the five microtopographically reclassified sites are the same as those shown in Figure 5.

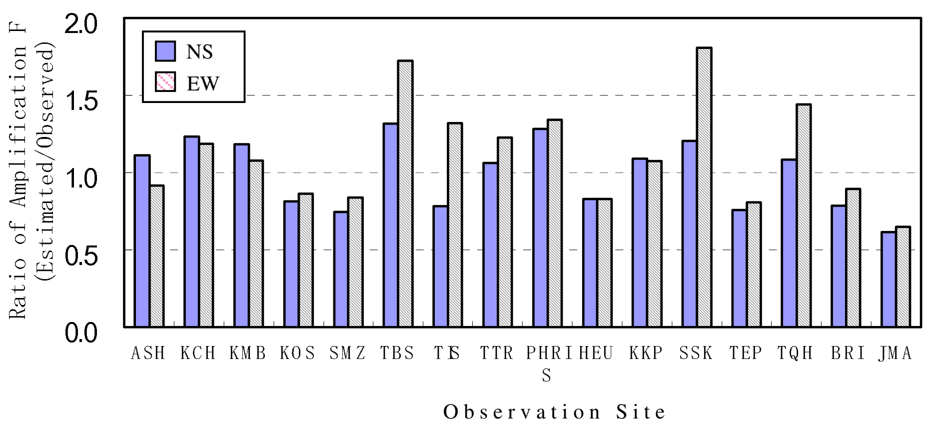
As a result of the above-mentioned modification, the amplification factors of TBS, PHRI and SSK were improved, and greater conformity between the microtopographical classification and the actual geographical features was achieved. However, the ARVs at JMA and BRI estimated using the method of



a)NS

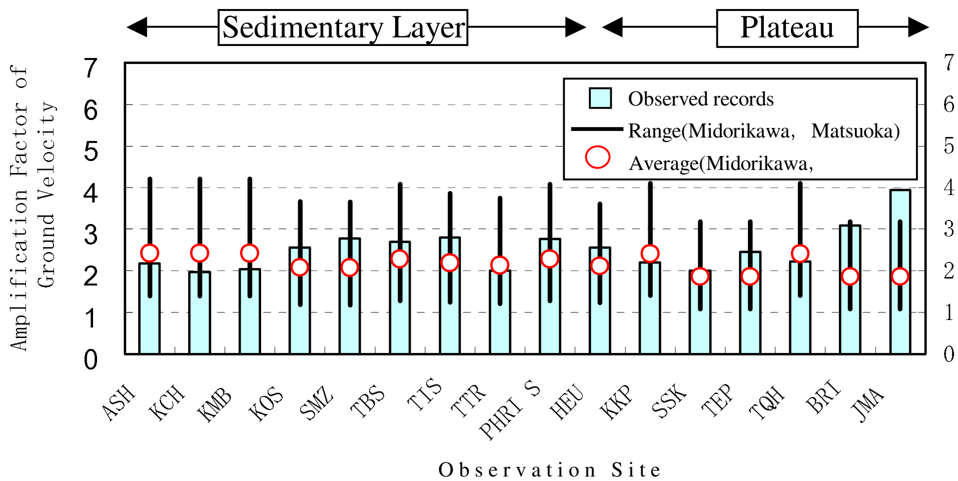


b)EW

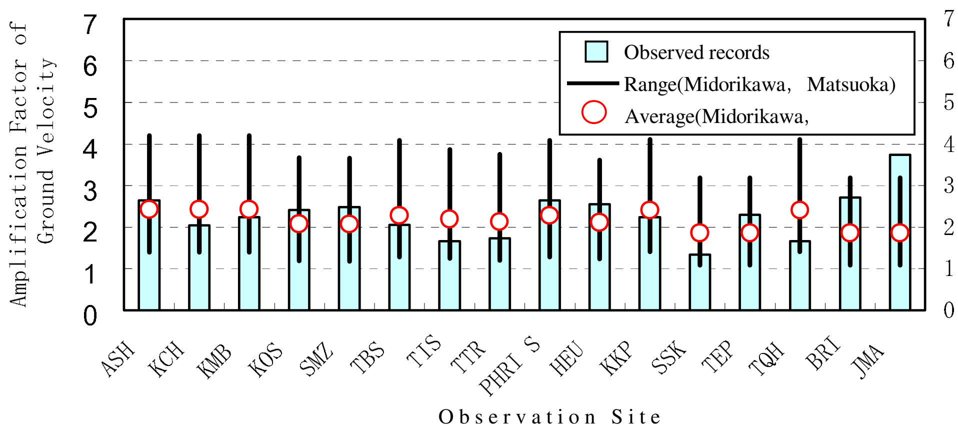


c)Ratio of Amplification Factor (Estimated/ Observed)

Figure 5. Comparison of amplification factor for PGV obtained from strong morion records and by using Midorikawa and Matsuoka's method



a)NS



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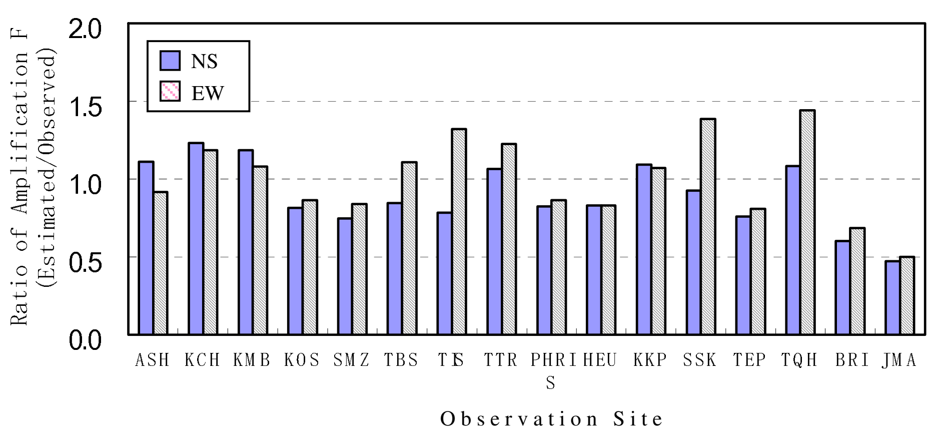

c)Ratio of Amplification Factor (Estimated/ Observed)

Figure 6. Comparison of amplification factor for PGV obtained from strong motion records and using Midorikawa and Matsuoka's method (geomorphological units of five sites were revised according to actual geomorphology.)

Table 3. Amplification factors for PGV using Midorikawa and Matsuoka's method

Obs. site	a*	H	D	b*	AVS (m/s)			ARV								
								−0.16			±0			+0.16		
					−σ	± 0	+σ	−σ	± 0	+σ	−σ	± 0	+σ	−σ	± 0	+σ
TBS	22	1	0.03	(1)	123.0	169.8	234.4	1.95	1.58	1.28	2.82	2.28	1.84	4.08	3.30	2.67
PHRI	22	1	0.05	(1)	123.0	169.8	234.4	1.95	1.58	1.28	2.82	2.28	1.84	4.08	3.30	2.67
SSK	21	20	0.09	(9)	179.6	231.4	298.0	1.52	1.29	1.09	2.20	1.86	1.57	3.18	2.69	2.27
BRI	21	20	0.17	(9)	179.6	231.4	298.0	1.52	1.29	1.09	2.20	1.86	1.57	3.18	2.69	2.27
JMA	21	20	0.17	(9)	179.6	231.4	298.0	1.52	1.29	1.09	2.20	1.86	1.57	3.18	2.69	2.27

a*: Microtopography unit No. by digital national land information
b*: Detailed Microtopography unit after Table 1

Midorikawa and Matsuoka become smaller; thus, the accuracy of reproduction of the strong motion record-based ARVs decreased. Yahata and Sasaki[11)] concluded that the strong motion records at JMA and BRI had been remarkably affected by the geographical irregularity because these two observation sites are on a cliff that has a vertical drop of 30 m. It is probable that ARVs differed by site, because the method by Midorikawa and Matsuoka does not take into account local features of amplification characteristics.

EXAMINATION OF THE ACCURACY OF AVS ESTIMATION AND THE RELATIONAL EXPRESSION COMPARING AVS AND ARV

The time-weighted average shear-wave velocity (AVS) from the ground surface to the depth of 30 m at PHRI

Estimation of AVS is critical for adequate estimation of ARV. To examine the accuracy of AVS estimation, the AVSs derived from the shear wave velocities in the ground of the PHRI observation site and the ARVs based on the AVSs are compared with the AVSs and ARVs obtained according to the microtopographical classification. Equation (3) is used for calculating the time-weighted average shear-wave velocity to the depth of 30 m.

$$AVS_{obs} = \frac{30}{\sum_{i=1}^{30} \frac{1}{Vs_i}} \qquad (3)$$

AVSobs: time-weighted average shear-wave velocity (m/s) to the depth of 30 m, which is obtained from a ground survey
Vsi: shear wave velocity (m/s) in each 1-m-thick stratum

The time-weighted average shear-wave velocity to the depth of 30 m at PHRI is calculated by Equation (3) to be AVSobs = 279.2 m/s. Assuming that the microtopographical category is natural levee or reclaimed land, the AVS (i.e., the center of dispersion) is 87.1 m/s or 169.8 m/s, respectively. The upper limit of the dispersion is 117.5 m/s and 234.4 m/s, respectively, which is about 1.2 times as fast as the AVSobs obtained through a ground survey. Therefore, it is difficult to adequately estimate the AVSs at PHRI solely on the basis of the microtopographical classification of the digital national land information.

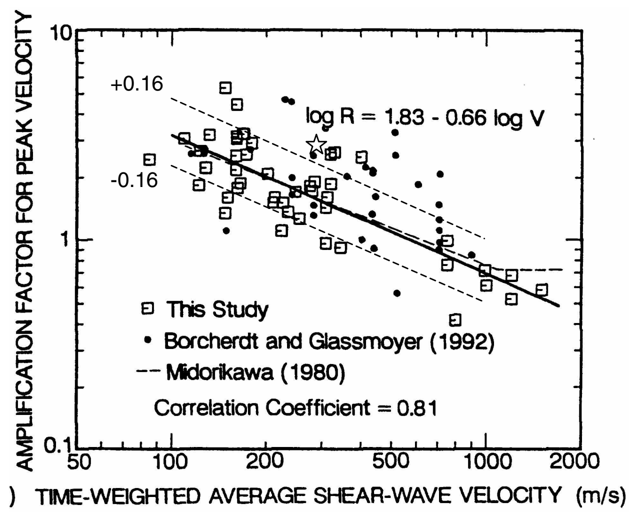

Figure 7. Correlation of average shear wave velocity with amplification factors for max. ground velocity (after Midorikawa [5])

Relationship between AVS and ARV

Figure 7 shows the relationship between ARV and AVS according to Midorikawa et al. It is clear that the relationship between ARV and AVS varies widely. ARVs calculated using AVSobs are 1.14, 1.64 and 2.38 (–0.16, 0, +0.16) when the regression coefficient of reclaimed land is applied. ARVs based on the strong motion records are 2.76 and 2.64. Not only are these ARVs underestimated, but so are the values of upper limit of dispersion. In Figure 7, a star indicates the correlation between the AVSobs at PHRI and the ARV according to the strong motion records. This correlation is marked above the upper limit (+0.16) derived from the relational expression of Midorikawa et al., which suggests that estimation of AVSs by the proposed method is difficult at PHRI.

The ground amplification factor is greatly influenced by the structure and the dynamic characteristics of the ground as well as by the strong motion characteristics. Amplification factors determined using the method of Midorikawa and Matsuoka are representative values statistically worked out from strong motion records at many sites, and they should be used only after the possible data dispersion is thoroughly understood.

CONCLUSIONS

Toward evaluating wide-area seismic ground motions, a method proposed by Midorikawa and Matsuoka was used for estimating amplification characteristics of subsurface ground. The amplification characteristics determined by this method were compared with those obtained from the strong motion records to examine the applicability of the method. The results are sumarized below:

1. The amplification factors obtained using the method of Midorikawa and Matsuoka are dispersed 0.6 - 1.8 times as much as the amplification factors derived from strong motion records. The amplification factors obtained using the proposed method are greater than those obtained by strong motion records at many sites, presumably because the shear wave velocity at the engineering base layer, which is used as the basis for amplifications of strong motion records, is smaller than that estimated using the method of Midorikawa and Matsuoka.

2. The microtopographical classification based on the digital national land information was tailored to actual geographic features. This brought the estimated ARVs into closer agreement with the observed ARVs, and the estimated ARVs were found to be 0.8 - 1.4 times the ARVs based on strong motion records, except for some sites. Adequate microtopographical classification is indispensable for the improvement of estimation accuracy.

3. For the purpose of understanding possible seismic ground motions and extent of damage in an extensive area, for example, estimating damage by earthquake for regional disaster prevention planning, the method proposed by Midorikawa and Matsuoka is useful in evaluating local amplification characteristics.

4. ARRs calculated using the method of Midorikawa and Matsuoka are 0.8 - 1.4 times the strong motion record-based ARVs: Such deviations are too large for detailed response analysis of structures and seismic ground motion estimation at specific sites. The amplification factors obtained using the method of Midorikawa and Matsuoka are representative values that were statistically worked out from strong motion records at many sites. Thus, the method should be applied on the basis of a thorough recognition that estimation of amplification factors may vary by individual sites.

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