Relationship between Geomorphological Land Classification and Soil Amplification Ratio Based on JMA Strong Motion Records

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ABSTRACT

The relationship between the soil amplification ratio and ground conditions was examined using strong motion records measured at 77 Japan Meteorological Agency (JMA) stations over a period of more than 8 years. The amplification ratios for the instrumental JMA intensity, as well as for the peak ground acceleration and velocity, were obtained from the station coefficients of the attenuation relationships. A combined use of geomorphological land classification and subsurface geology was found to yield the best estimate of the amplification ratio. This result suggests that the Digital National Land Information may be conveniently used for the estimation of strong motion distribution over large areas in Japan.

Key Words: strong motion records, soil amplification ratio, geomorphological land classification, Digital National Land Information, PGA, PGV.

INTRODUCTION

The estimation of strong motion distribution is important in the seismic design and retrofit of structures, damage assessment and emergency response of urban areas, and analysis of earthquake damage data. In particular, considering the use of estimated strong motion distribution in damage assessment systems [1,2], it is desirable to have a handy method applicable to a large area based on generally available data.

The major factors that affect the strong ground motion are the source characteristics typically represented by the magnitude, the wave propagation path effect represented by the source-to-site distance and the subsurface soil condition, which governs the amplification ratio. Attenuation relations provide a convenient tool to estimate the strong motion distribution using the magnitude and depth, source-to-site distance and in some cases, the soil conditions. The attenuation relations are often used in earthquake damage assessments and seismic hazard analyses. Molas and Yamazaki [3, 4] and Shabestari and Yamazaki [5] have recently developed attenuation relationships for the peak ground acceleration (*PGA*), peak ground velocity (*PGV*), JMA (the Japan Meteorological Agency) instrumental seismic intensity and response spectrum using records from the JMA-87-type accelerometers. In this study, the station coefficients, which represent the relative amplification of observation stations in the attenuation relationships, are employed to characterize the soil condition.

Several recent studies have used geomorphological and geological information included in the Digital National Land Information (DNLI), which covers entire Japan with a 1 km x 1 km mesh, as a method to estimate soil amplification characteristics.

Matsuoka and Midorikawa [6] compared the average S-wave velocity (V_s) of a recording site, or $AVS(d)$, to a certain depth d (in meters) from the surface, and the amplification ratios for *PGA* and

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PGV at 47 locations where strong motion records were obtained in the 1987 Chibaken-Toho-Oki Earthquake. As a result, they proposed the formulas that predict the *PGA* and *PGV* amplification ratios with respect to hills of the Tertiary Period or earlier, in terms of *AVS* (10) and *AVS* (30), respectively. They also proposed an empirical method to estimate *AVS* (30) from the subsurface geology, geomorphology and elevation based on S-wave velocity data from 459 sites in the Kanto region and geomorphological data in the DNLI. Using these two relations, the amplification ratio for *PGV* can be estimated from the DNLI through *AVS* (30).

Fukuwa et al. [7] also proposed a method to predict soil amplification ratios based on the DNLI using the results of earthquake damage assessment studies in Aichi Prefecture and Nagoya City. They determined the amplification ratios for *PGA* and *PGV* between the surface and the rock outcrop (corresponding to V_s=3 km) from the regression analysis using the elevation, geomorphology, subsurface geology from the DNLI. The strain-dependent non-linear effects are considered in this proposed method.

It should be noted that the two methods described above were developed based on soil and geomorphological data from specific regions in Japan (the Kanto and Nobi regions, respectively). Although the applicability of these methods to those respective regions has been demonstrated, a further study may be necessary for their applicability to the other parts of Japan. Therefore, there is a need for methods that can be applicable to entire Japan to estimate strong motion distribution in damage assessment and emergency management. At present, the method by Matsuoka and Midorikawa [6] is being used in the earthquake damage assessment systems of the National Land Agency [8] and the Fire Defense Agency.

The instrumental seismic intensity, which replaces the conventional seismic intensity scale based on human perception, came into use as the official measure by the JMA from October 1996. Many seismometers, which monitor the instrumental seismic intensity, have been deployed all over Japan [2]. Hence, the JMA instrumental seismic intensity will be used more than other indices in the near future. Thus a research on the amplification ratio of the JMA intensity may be necessary.

Under these circumstances, the present study aims to propose an estimation method of the amplification ratio that is applicable to the entire Japan. Comparing the relationship between geomorphological and geological conditions of the JMA stations nationwide and the soil amplification ratios determined from the attenuation equations based on the JMA strong motion records, the Digital National Land Information is employed to predict the amplification ratios for *PGA, PGV* and JMA intensity.

METHOD FOR ESTIMATION OF SOIL AMPLIFICATION RATIO

Attenuation relationship and Station Coefficients

Molas and Yamazaki [3, 4] used 2,166 sets of two horizontal component records from 387 earthquakes observed from August 1, 1988 to December 31, 1993 by the JMA-87-type accelerometers at 76 JMA stations in Japan and constructed attenuation relationships for *PGA* and *PGV*. Adding data observed till March 31, 1996 by the same instruments, Shabestari and Yamazaki [5] developed an attenuation equation for the instrumental JMA intensity (*I*) and revised the *PGA* and *PGV* attenuation equations. The records used in the study are 3,990 sets from 1,020 earthquakes at 77 JMA free field stations (Fig. 1).

The following functions were used in the regression analysis.

$$\log_{10} PGA = b^A_0 + b^A_1 M_J + b^A_2 r - \log_{10} r + b^A_4 h + c^A_i \quad (1)$$

$$\log_{10} PGV = b^V_0 + b^V_1 M_J + b^V_2 r - \log_{10} r + b^V_4 h + c^V_i \quad (2)$$

$$I = b^I_0 + b^I_1 M_J + b^I_2 r - 1.89 \log_{10} r + b^I_4 h + c^I_i \quad (3)$$

in which M_J is the JMA magnitude, r is the shortest distance (km) to the fault plane, h is the focal depth in kilometer, b_0, b_1, b_2, and b_4 are coefficients determined by regression. c_i, is the station

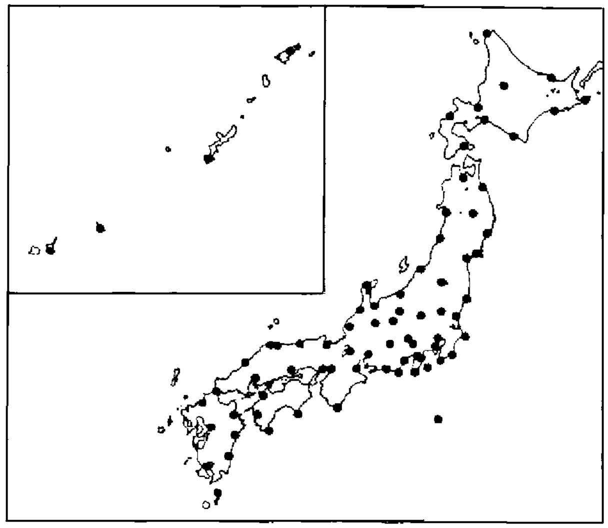


Fig.1 Location of 77 JMA recording stations of the JMA 87-type-accelerometers

coefficient represent the site effect at site i. The suffixes A, V and I indicate the PGA, PGV, and instrumental JMA intensity, respectively.

The two-stage regression procedure proposed by Joyner and Boore [9] was used for the regressive analysis, considering the correlation between the magnitude and distance in the data. In this method, dummy variables are used for each earthquake. The coefficients related to the distance (b_2, b_4) are determined in the first stage, and the coefficients related to the magnitude (b_0, b_1) are determined in the second stage. Fukushima and Tanaka [10] also demonstrated the importance of this method.

Since the station coefficients are different for each station, the same numbers of dummy variables are also required. Thus, determination of the regression coefficients with the standard two-stage regression method would become difficult due to an excessive number of dummy variables, causing the singularity of the matrix. To solve this problem, a three-stage regression method, named the iterative partial regression was developed [3], and the coefficients were determined using this method.

The station coefficient represents the site effect of the recording station as a supplement of the attenuation equation. The station coefficient may be affected by the geological and geomorphological conditions at the recording site and the conditions of the instrument, e.g. response characteristics of the instrument and its foundation. The mean of the station coefficients at all recording stations is zero. Stations with positive station coefficients are supposed to have higher amplification than the average site, while stations with negative station coefficients to have lower amplification.

Table 1 is a list of the station coefficients at the 77 JMA recording sites obtained by the analysis [5]. Figure 2 plots these station coefficients with respect to the station number (Table 1). The station coefficient for PGA and JMA intensity is largest for Kushiro and smallest for Matsushiro. It has been known that large acceleration is always recorded at Kushiro. This analysis proved this fact. Matsushiro is the only site where the instrument is placed in a rock tunnel. This fact explains the reason of the smallest station coefficient at this site. The station coefficients for PGV show similar tendency with those for PGA. The station with the largest coefficient is Sakata, and the smallest coefficient is observed again in Matsushiro.

Conversion of Station Coefficient to Soil Amplification Ratio

If the peak ground acceleration at surface point i and that at the (hypothetical) outcrop beneath point i are represented by PGA_{Si} and PGA_{Bi} respectively, the amplification ratio ARA_i of PGA at point i is given by

$$ARA_i = PGA_{Si} / PGA_{Bi} \tag{4}$$

Table 1 Summaries of station coefficients for 77 JMA recording stations and classification of geology, geomorphology and ground conditions of JMA station

No	Station name	Elevation (m)	Station coefficient *PGA*	Station coefficient *PGV*	Station coefficient JMA Intensity	Age of deposit	Geomorphologic classification	Type of sediment and rock	Subsurface geology	Soil type	No. of group of this study
1	Abashiri	38	-0.374	-0.316	-0.756	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel, Volcanic ash	2	7
2	Ajiro	68	0.209	0.091	0.297	Neogene	Mountain	Talus	Basalt	1	11
3	Akita	2	-0.124	0.114	0.123	Holocene	Delta	Unconsolidated sediment	Mud	4	3
4	Aomori	3	0.140	0.218	0.438	Holocene	Delta	Unconsolidated sediment	Sand	4	4
5	Asahikawa	112	-0.347	-0.082	-0.310	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
6	Ashizuri	32	-0.148	-0.285	-0.587	Unknown	Mountain	Volcanic rock	Syenite	1	11
7	Choshi	28	-0.111	-0.080	-0.156	Pleistocene	Terrace	Unconsolidated sediment	Sand, Loam	2	7
8	Fukui	10	0.064	0.117	0.270	Holocene	Flood plain	Unconsolidated sediment	Mud	4	3
9	Fukuoka	14	0.066	0.132	0.309	Holocene	Delta	Unconsolidated sediment	Sand	3	4
10	Hachijojima	80	0.059	-0.010	0.060	Pleistocene	Volcanic foot	Volcanic rock	Volcaniclastic material	2	10
11	Hachinohe	28	0.282	0.000	0.348	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel, Volcanic ash	2	7
12	Hakodate	35	-0.121	-0.133	-0.163	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel, Volcanic ash	2	7
13	Hamada	21	-0.111	-0.277	-0.619	Neogene	Mountain	Volcanic rock	Andesite	1	11
14	Hamamatsu	33	-0.094	-0.107	-0.244	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel	2	7
15	Hikone	87	0.184	0.310	0.602	Holocene	Delta	Unconsolidated sediment	Mud	4	3
16	Hiroshima	-4	0.041	0.103	0.239	Holocene	Delta	Unconsolidated sediment	Sand, Clay	4	4
17	Iida	484	0.013	-0.109	-0.175	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel	2	7
18	Irozaki	55	-0.162	-0.239	-0.564	Neogene	Hills	Volcanic rock	Volcanic rock	1	9
19	Ishigakijima	6	-0.160	-0.122	-0.287	Pleistocene	Terrace	Unconsolidated sediment	Limestone	2	8
20	Ishinomaki	44	0.206	-0.089	-0.037	Neogene	Hills	Consolidated sediment	Conglomerate	1	9
21	Kagoshima	6	0.008	0.164	0.258	Holocene	Delta	Unconsolidated sediment	Sand	4	4
22	Kanazawa	0	-0.005	0.171	0.233	Holocene	Delta	Unconsolidated sediment	Mud	4	3
23	Katsuura	10	-0.013	-0.141	-0.170	Holocene	Sand dune	Unconsolidated sediment	Sand	3	2
24	Kawaguchiko	860	0.315	0.067	0.241	Pleistocene	Volcanic foot	Volcanic rock	Lava	1	10
25	Kobe	59	-0.005	0.017	0.057	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel, Sand, Clay	2	7
26	Kofu	274	0.086	0.095	0.266	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
27	Kumamoto	39	-0.028	0.040	0.133	Pleistocene	Terrace	Volcanic rock	Volcanic ash, Lava	2	6
28	Kushiro	33	0.562	0.339	0.924	Pleistocene	Terrace	Volcanic rock	Volcanic ash, Sand	2	6
29	Maebashi	112	-0.255	-0.205	-0.518	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
30	Maizuru	3	-0.009	-0.045	0.012	Holocene	Reclaimed land	Unconsolidated sediment	Sand	3	1
31	Matsue	21	0.074	0.065	0.092	Neogene	Hills	Weakly consolidated sediment	Sandstone	1	9
32	Matsumoto	610	-0.308	-0.246	-0.596	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
33	Matsushiro	431	-0.537	-0.690	-1.443	Unknown	Mountain	Consolidated sediment	Mudstone	1	11
34	Matsuyama	34	0.119	0.179	0.385	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
35	Mishima	22	0.015	0.040	0.031	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
36	Mito	30	0.299	0.148	0.394	Pleistocene	Terrace	Volcanic rock	Loam, Sand and gravel	2	6
37	Miyakojima	41	0.020	-0.074	-0.124	Pleistocene	Terrace	Unconsolidated sediment	Limestone	2	8

Table 1 (continued)

38	Miyazaki	7	-0.098	0.057	0.099	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel	2	7
39	Morioka	154	0.343	0.241	0.763	Pleistocene	Terrace	Weakly consolidated sediment	Sand and gravel	2	7
40	Murotomisaki	186	-0.009	-0.058	-0.135	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel, Mud	2	7
41	Nagoya	56	0.068	0.050	0.058	Pleistocene	Hills	Weakly consolidated sediment	Sand and gravel	1	9
42	Naha	28	-0.115	-0.019	-0.142	Neogene	Terrace	Consolidated sediment	Mudstone	1	8
43	Naze	4	0.145	0.244	0.543	Holocene	Delta	Unconsolidated sediment	Clay, Sand and gravel	4	3
44	Nemuro	26	-0.025	-0.189	-0.303	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel, Volcanic ash	2	7
45	Niigata	3	-0.055	0.149	-0.001	Holocene	Reclaimed land	Unconsolidated sediment	Sand	4	1
46	Nobeoka	20	-0.063	-0.223	-0.455	Palaeogene	Mountain	Consolidated sediment	Shale	1	11
47	Ofunato	37	0.275	-0.032	0.198	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel	1	7
48	Oita	5	-0.029	0.131	0.237	Holocene	Delta	Unconsolidated sediment	Sand, Mud	4	4
49	Okayama	17	0.116	0.034	0.165	Holocene	Flood plain	Unconsolidated sediment	Clay	4	3
50	Omaezaki	45	-0.148	-0.168	-0.400	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel	2	7
51	Onahama	5	0.023	0.054	0.065	Holocene	Delta	Unconsolidated sediment	Sand	4	4
52	Osaka	13	-0.313	-0.199	-0.542	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel	2	7
53	Oshima	76	0.069	-0.002	0.102	Holocene	Volcanic foot	Volcanic stone	Lava	2	10
54	Sakata	4	0.135	0.411	0.654	Holocene	Delta	Unconsolidated sediment	Mud	4	3
55	Sapporo	17	-0.284	-0.105	-0.378	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
56	Sendai	37	0.063	0.039	0.130	Pleistocene	Terrace	Weakly consolidated sediment	Sand and gravel	2	7
57	Shimonoseki	18	0.091	0.091	0.277	Holocene	Reclaimed land	Unconsolidated sediment	Sand	3	1
58	Shionomisaki	74	0.040	-0.094	-0.117	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel	2	7
59	Shizuoka	14	-0.161	-0.207	-0.318	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
60	Suttsu	33	-0.029	-0.136	-0.249	Neogen-Holocene	Terrace	Volcanic rock	Andesite, Lava	2	8
61	Takada	15	0.135	0.200	0.302	Pleistocene	Terrace	Unconsolidated sediment	Sand and gravel · Mud, Sand	2	7
62	Takayama	561	-0.217	-0.306	-0.661	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
63	Tanegashima	18	-0.371	-0.317	-0.744	Palaeogene	Terrace	Consolidated sediment	Sandstone	1	8
64	Tateyama	6	0.061	0.148	0.308	Holocene	Lowland between bars	Unconsolidated sediment	Sand, Mud	3	2
65	Tokyo	21	0.198	0.155	0.375	Pleistocene	Terrace	Volcanic rock	Loam	2	6
66	Tomakomai	7	0.277	0.213	0.519	Pleistocene	Terrace	Volcanic rock	Volcanic ash	2	6
67	Tottori	14	0.131	0.227	0.521	Holocene	Delta	Unconsolidated sediment	Mud	4	3
68	Toyama	10	-0.150	-0.179	-0.323	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel · Sand, Mud	3	5
69	Tsu	-1	0.120	0.147	0.273	Holocene	Delta	Unconsolidated sediment	Sand	4	4
70	Urakawa	30	0.216	0.218	0.473	Pleistocene	Terrace	Volcanic stone	Volcanic ash	2	6
71	Utsunomiya	121	0.049	-0.028	-0.062	Pleistocene	Terrace	Semi-Consolidated sediment	Sand and gravel, Loam	2	7
72	Uwajima	94	0.084	0.067	0.106	Mesozonic	Hills	Consolidated sediment	Alternation of sandstone and mudstone	1	9
73	Wajima	7	-0.137	-0.008	-0.093	Holocene	Delta	Unconsolidated sediment	Sand	3	4
74	Wakamatsu	212	-0.324	0.008	-0.725	Holocene	Alluvial fan	Unconsolidated sediment	Sand and gravel	3	5
75	Wakkanai	11	0.061	0.192	0.494	Holocene	Reclaimed land	Unconsolidated sediment	Sand	4	1
76	Yokohama	38	-0.088	-0.154	-0.367	Pleistocene	Terrace	Volcanic rock	Loam, Mud, Sand, Sand and gravel	2	6
77	Yonago	7	0.067	0.189	0.395	Holocene	Sand bar	Unconsolidated sediment	Sand, Sand and gravel	3	2

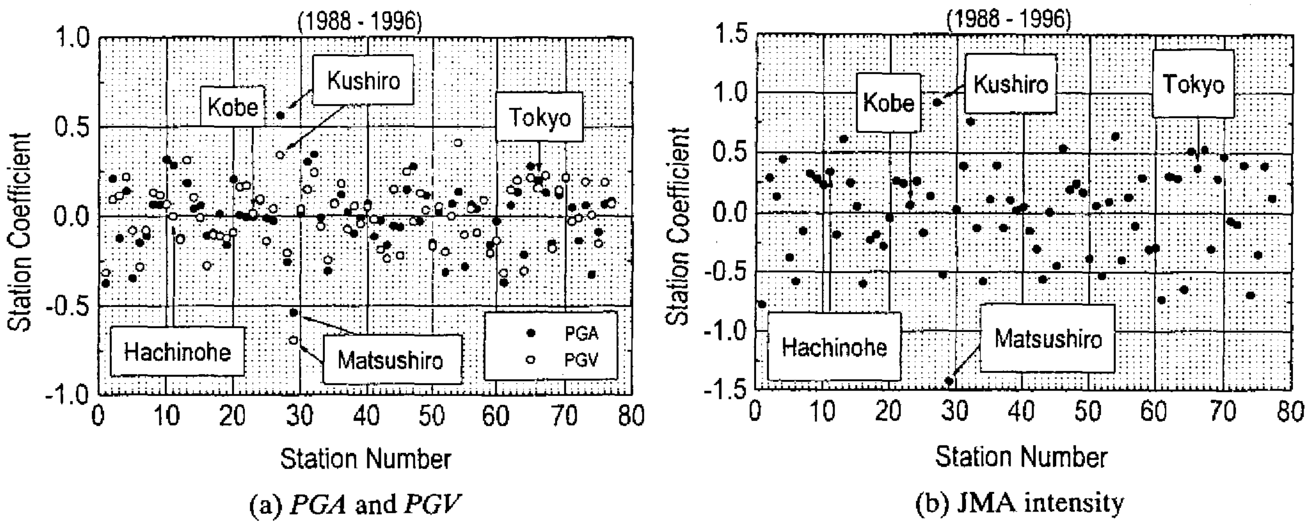


Fig.2 Station coefficients for (a) peak ground acceleration (*PGA*) and peak ground velocity (*PGV*) and (b) JMA intensity for 77 JMA recording stations

The outcrop in this study is assumed as the surface of a stratum having sufficient rigidity (for example, with V_s of at least 400 m/s). Then the supplement term (station coefficient) of the attenuation relation at the outcrop may have a constant value $C^A{}_0$. From equation (1), PGA_{Bi} at the outcrop is written as

$$\log_{10} PGA_{Bi} = b^A{}_0 + b^A{}_1 M_J + b^A{}_2 r - \log_{10} r + b^A{}_4 h + c^A{}_0 \qquad (5)$$

The peak ground acceleration at the ground surface is given by

$$\log_{10} PGA_{Si} = b^A{}_0 + b^A{}_1 M_J + b^A{}_2 r - \log_{10} r + b^A{}_4 h + c^A{}_i \qquad (6)$$

The difference between equations (5) and (6) yields

$$\log_{10} (PGA_{Si} / PGA_{Bi}) = c^A{}_i - c^A{}_0 \qquad (7)$$

From equations (4) and (7), we obtain

$$ARA_i = 10^{c^A{}_i - c^A{}_0} \qquad (8)$$

Similarly, the amplification ratio of the *PGV* is determined by

$$ARV_i = 10^{c^V{}_i - c^V{}_0} \qquad (9)$$

Performing a similar operation on the amplification ratio of the JMA intensity, we get

$$ARI_i = c^I{}_i - c^I{}_0 \qquad (10)$$

From the equations (8), (9) and (10), the amplification ratios for *PGA*, *PGV* and JMA intensity can be determined from their station coefficients. For the range of input motion in which soil non-linearity becomes significant, the soil amplification ratios, especially for *PGA*, depends on the amplitude of ground strain. However, the attenuation relationships in this study were developed using the measured records. Since only few records are considered to be in the non-linear range, it would be difficult to introduce this effect to the amplification ratios.

We must propose a method to estimate the station coefficient of an arbitrary site other than the recording sites. The most influential factor determining the station coefficient may be the subsurface

Table 2 Items of land classification available from the Fundamental Land Classification Survey

Geomorphologic classification	Age of deposit	Type of sediment and rock	Subsurface geology
Mountain Volcanic footslope Hill Terrace Alluvial fan Sand bar Sand dune Lowland between bars Delta Flood plain Reclaimed land Polder	Palaeozonic Mesozonic Palaeogene Neogene Pleistocene Holocene	Metamorphic rock Plutonic rock Volcanic rock Consolidated sediment Weakly consolidated sediment Unconsolidated sediment	Base rocks Gravel Sand and gravel, Sand/Sandy soil Mud/Muddy soil Clay/Clayey soil Volcanic ash Loam Lava Volcaniclastic material

soil condition. Therefore, we will compare the station coefficients with the geological and topographical conditions of the recording sites hereafter.

RELATIONSHIP BETWEEN GROUND CONDITIONS AND STATION COEFFICIENTS

JMA Recording Stations and Ground Conditions

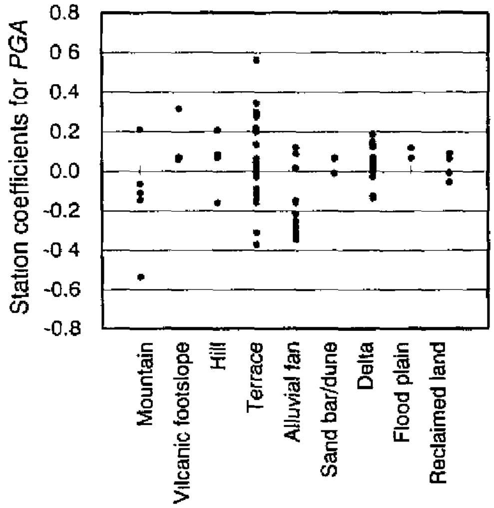
To clarify the relationship between the ground condition and the station coefficient, it is necessary to investigate the ground conditions at the 77 JMA recording sites. To obtain the ground data at the recording stations, which are distributed all over Japan, one feasible way would be the use of geomorphological and geological data compiled in the DNLI. Note that the geomorphological and subsurface geological data in the DNLI were made based on the geomorphological classification maps and subsurface geology maps by region on a scale of 1/200,000 (1/100,000 scale only for Tokyo and Kanagawa Prefecture). This digital information gives the attributes of geomorphological and subsurface geological pixels, which account for the largest area in each pixel of the standard regional mesh (about 1 km x 1 km), established by the Geographical Survey Institute of Japan. Therefore, although it is effective for macroscopic determination of the average geomorphological and geological distribution over a very large area, it is possible that the DNLI could lead to an erroneous conclusion in a case obtaining the geomorphological and geological conditions of a specific point such as an recording station.

Therefore, it was decided that other means would be used to determine the land classification of the recording stations. The geomorphological classification, age of deposit, type of the sediment, and subsurface geology shown in Table 2 were determined using the subsurface geology maps and geomorphological classification maps (published by the Economic Planning Agency and prefectures) from the Fundamental Land Classification Survey. The results are summarized in Table 1.

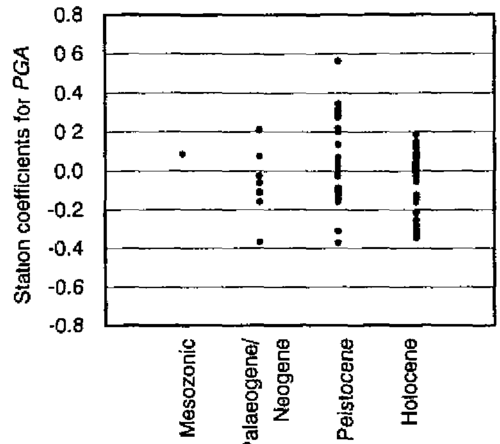
Relationship between Land Classification and Station Coefficients

The relationships between the land classification of JMA stations and the station coefficients for *PGA, PGV*, and JMA intensity are investigated.

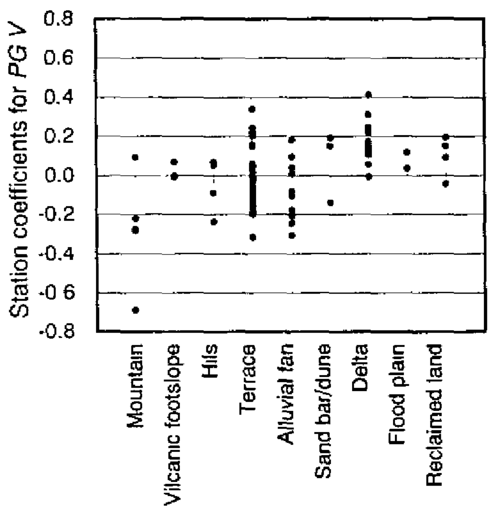
Figure 3 shows the relationship between the geomorphological classification and the station coefficients for *PGA*, *PGV*, and JMA intensity. With regard to *PGV* and JMA intensity, such tendency is observed that the harder the ground corresponding to the geomorphological classification, the smaller the station coefficient becomes. However, there is a great deal of scatter of station coefficients within the same geomorphological classification. Hence, one can conjecture that the geomorphological classification alone is not the controlling factor of the station coefficient. Possible reasons for this scatter include the followings: 1) the influence from other factors, such as the foundation of instruments or the deep ground structure of the site, may be significant; 2) the recording stations classified as a geomorphologic unit do not present the standard ground condition for the unit;



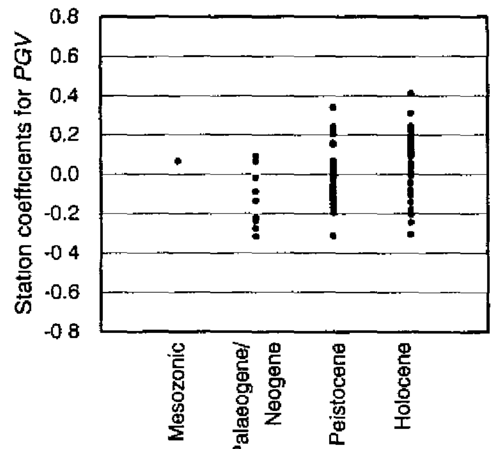
(a) PGA



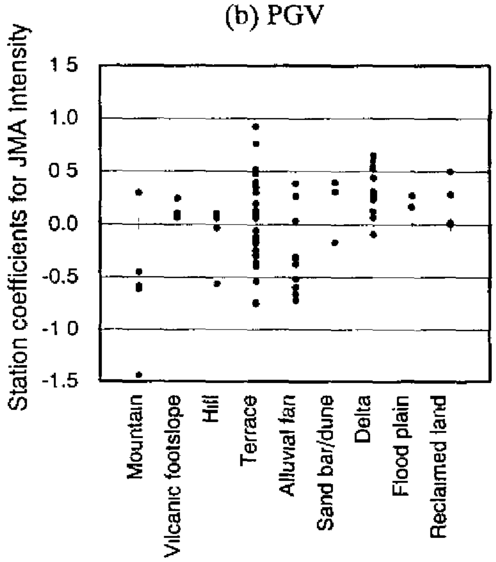
(a) PGA



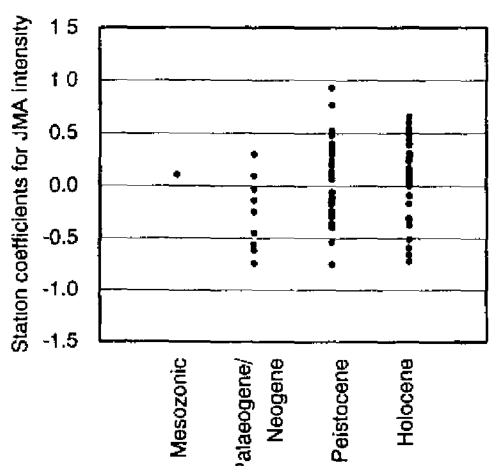
(b) PGV



(b) PGV



(c) JMA Intensity



(c) JMA Intensity

Fig. 3 Station coefficients for (a) *PGA*, (b) *PGV* and (c) JMA intensity with respect to the geomorphologic classification at JMA stations

Fig. 4 Station coefficients for (a) *PGA*, (b) *PGV* and (c) JMA intensity with respect to the age of deposit at JMA stations

Table 3 Correlation coefficient between the mean values of station coefficients in each classification and the station coefficients based on attenuation relationship proposed by Shabestari and Yamazaki [5]

Method of classification	Station coefficient for *PGA*	Station coefficient for *PGV*	Station coefficient for JMA intensity
Geomorphologic classification	0.43	0.61	0.57
Age of deposit	0.22	0.36	0.30
Subsurface geology	0.47	0.64	0.61

and 3) A large difference may be associated in the geological condition even in the same geomorphological classification. A more detailed classification may be necessary for the geomorphologic units with large scatter in the station coefficient, in order to find a classification with a small amount of scatter.

Figure 4 shows the relationship between the geological periods and the station coefficients for three indices. Practically no correlation is seen for any of these indices. Hence, it would be difficult to estimate the station coefficient using only the geological period.

Figure 5 shows the relationship between the subsurface geology and the station coefficients for three indices. In the geologic classification, lava is included under volcaniclastic material since this is a type of volcanic rubble. Loam in Japan, which is a kind of volcanic cohesive soil, is combined with volcanic ash. In the figure, all of the station coefficients exhibit a rising trend in the order of rock, gravelly soil, sandy soil, clayey soil, volcaniclastic material, and volcanic ash (order of smaller particle size); that is, the softer the ground, the larger the amplification ratios.

Table 3 shows the coefficients of correlation between the actual station coefficients and the average values of station coefficients in the same group according to three types of land classification (geomorphological classification, geological period, and subsurface geology) In each of the station coefficients (those for *PGA*, *PGV*, and JMA intensity), the correlation coefficient was largest in the classification by subsurface geology, and second largest in that by geomorphology.

Relationship between Elevation and Station Coefficients

Matsuoka and Midorikawa [6] and Fukuwa et al. [7] considered the elevation as a factor in the estimation of soil amplification ratio. Hence, we also examined the relationship between elevation and the station coefficient. The relationship was studied for each geomorphological classification, in order to minimize the influence of other factors. As an example, Figure 6 shows the relationship between the elevation and the station coefficient at the stations classified as terraces. Practically no correlation can be found between them. Categories other than terraces were also studied in the same way, but correlation was again not found. A possible reason for this may be explained as follows.

As stated before, the previous studies [6,7] were conducted for specific regions of Japan (the Kanto plain and the Nobi plain). If dealing with a single fluvial plain, such as the above regions, the composition of sediment differs upstream to downstream of the river, even with the same geomorphology. In a single alluvial fan, the further downstream you go, the finer the sediment becomes. Matsuoka and Midorikawa [6] considered the effect of change in the characteristics of sediment by elevation. This kind of geomorphological principle cannot be applicable in the case of a nationwide study such as the present one, which covers a large number of river basins.

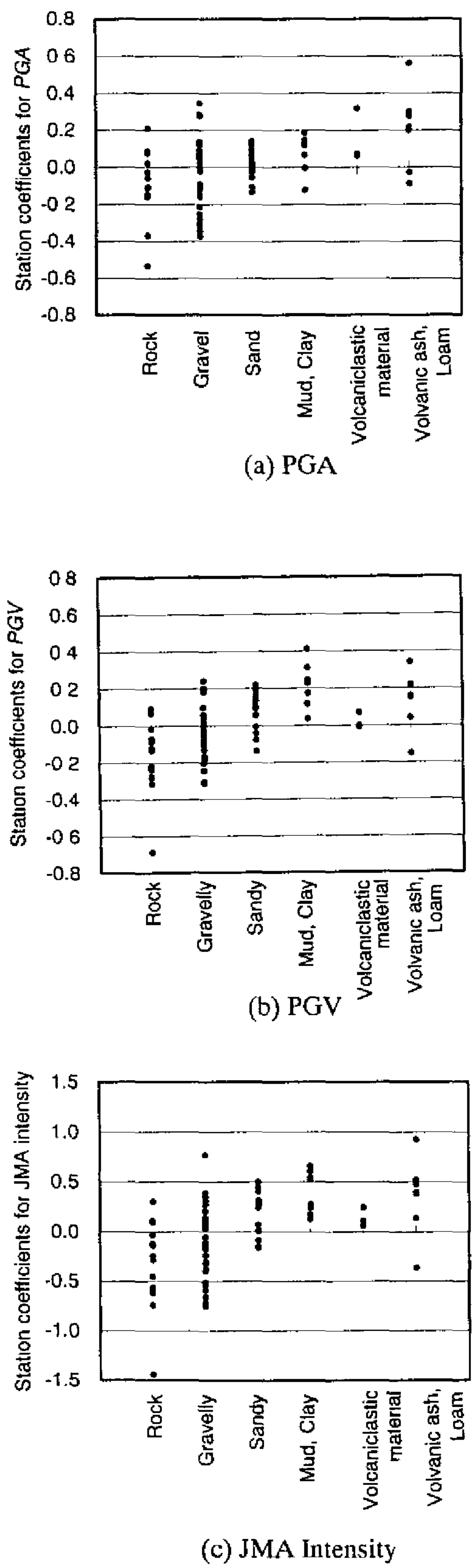


Fig. 5 Station coefficients for (a) *PGA*, (b) *PGV* and (c) JMA intensity with respect to the subsurface geology of JMA stations

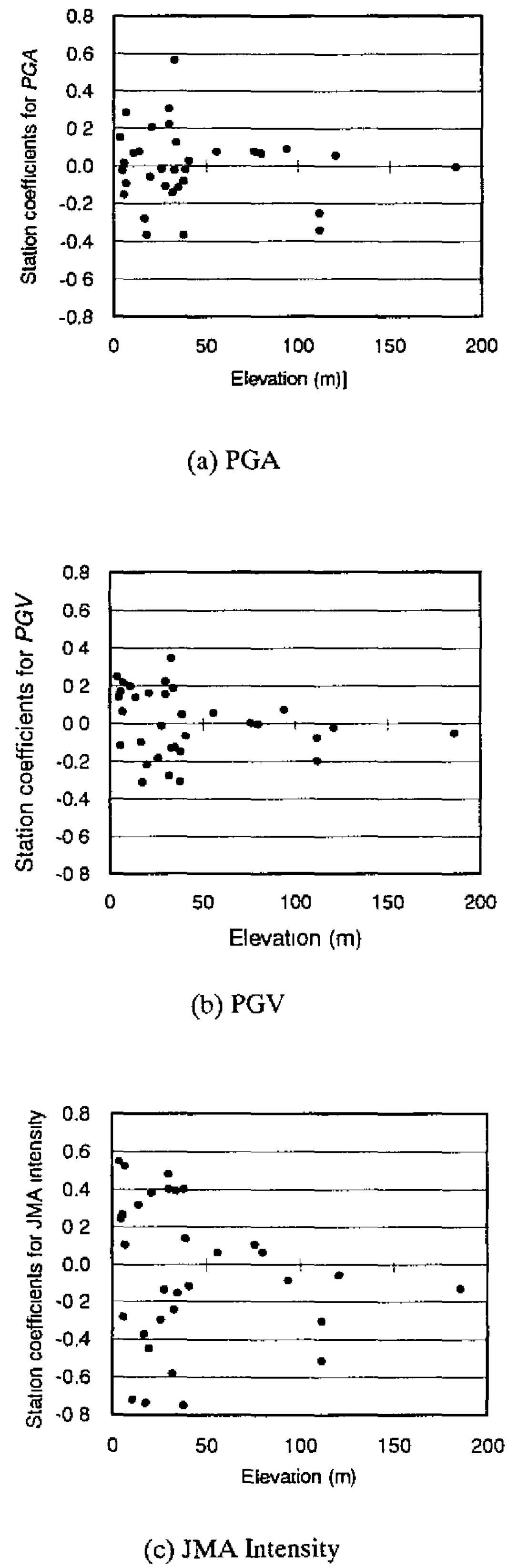


Fig. 6 Station coefficients for (a) *PGA*, (b) *PGV* and (c) JMA intensity with respect to the elevation of JMA stations located on terrace

Table 4 Classification of soil type for JMA stations [11]

Soil type	Geologic definition	Definition by predominant period
Type 1 (rock and hard soil)	Tertiary or older rock (defined as bedrock), of Pleistocene deposit with $H < 10$ m	$T_G < 0.2$ sec
Type 2 (hard soil)	Pleistocene deposit with $H \geq 10$ m or Holocene deposit with < 10 m	$0.2 \leq T_G < 0.4$ sec
Type 3 (medium soil)	Holocene deposit with $H < 25$ m including soft layer with thickness less than 5 m	$0.4 \leq T_G < 0.6$ sec
Type 4 (soft soil)	Other than above, usually soft Holocene deposit or fill	$T_G \geq 0.6$ sec

Relationship between Soil Type and Station Coefficients

Classification of ground by soil type has been used in the field of civil engineering. The relationship between the soil type classification [11] shown in Table 4 and the station coefficient was investigated. The soil types of the 77 JMA stations were primarily determined from their geomorphological classification. Boring data were needed to distinguish between soil types 3 and 4. Thus, if boring data revealed that the thickness of the Holocene deposit was equal or more than 25 m, the station was considered to be soil type 4; and if not, it was considered to be soil type 3.

Figure 7 shows the relationship between the soil type and station coefficient for the three indices of strong ground motion. For each index, a large amount of scatter is observed in the station coefficient within the same soil type. However, the average values of the station coefficients for *PGV* and JMA intensity increase in the order of type 1 to type 4. That is, the softer the ground, the bigger the seismic response. This tendency is remarkable for *PGV*. This fact has already been pointed out in the previous papers [3, 4].

RELATIONSHIP BETWEEN LAND CLASSIFICATION AND SOIL AMPLIFICATION RATIO

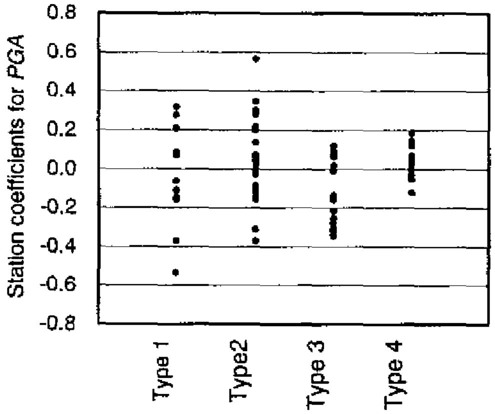
The relationships between various geological, geomorphological and soil conditions and the station coefficients were investigated above. It was found that a great deal of scatter exists in the relationship if each attribute is considered individually. However, considering the use of soil amplification ratios to the estimation of seismic motion distribution over a large area, we will develop a method to predict amplification ratios based on land classification. Land classification can be estimated using the Digital National Land Information (DNLI), without using information difficult to obtain, such as boring data and predominant periods.

Among the land classifications discussed above, the correlation coefficients for subsurface geology and geomorphological classification were relatively high in Table 3. Therefore, we investigated differences in the station coefficients due to the difference in subsurface geology in the same geomorphological classification as shown in Fig. 8.

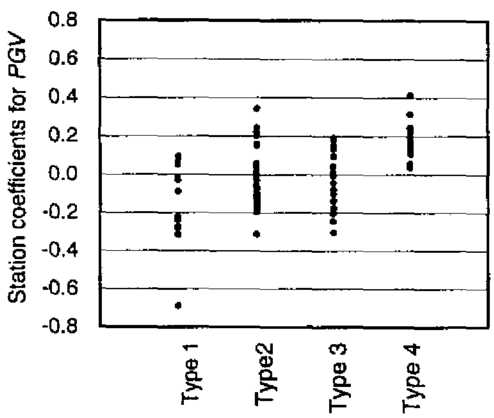
The subsurface geology of terrace was divided into the groups of rock, sand/gravel, and volcanic ash. The average values of the station coefficients for each group are found to increase in the order of rock, sand/gravel and volcanic ash for the three strong motion indices. Thus, the three-group subdivision was adopted for terrace.

The subsurface geology of delta was divided into two groups, sandy soil and clayey soil, as also shown in Fig. 8. The average value of the station coefficients is higher for the clayey soil group than that for the sandy soil group with respect to *PGA*, *PGV*, and JMA intensity. Hence, this subdivision for delta was adopted.

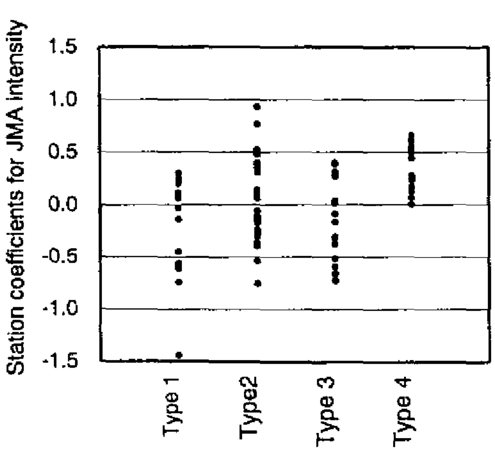
The geomorphological classifications other than delta and terrace, namely mountain, hill, alluvial fan, sand bank/dune, and reclaimed land, could not be subdivided because the subsurface geology was of the same composition in each classification.



(a) PGA



(b) PGV



(c) JMA Intensity

Fig. 7 Station coefficients for (a) *PGA*, (b) *PGV* and (c) JMA intensity with respect to the soil-type classification of JMA sites

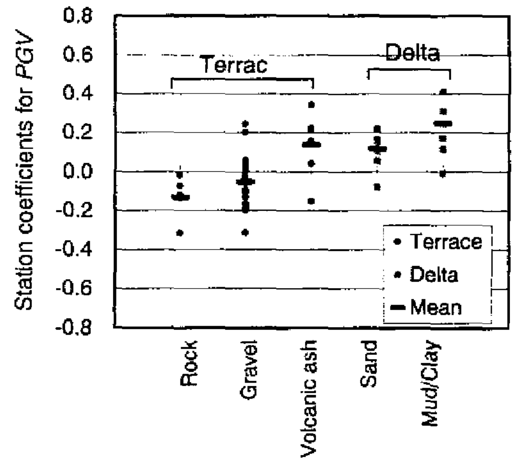


Fig. 8 Effect of subsurface geology in a geomorphologic classification with respect to the station coefficient of *PGV*

Based on these considerations, the geomorphological classifications were used as the major class and then subdivided into groups according to subsurface geology, as shown in Table 5. The smallest units of geomorphological classification were made considering the geomorphological origin, topography, material composition, and time of formation, resulting in the consideration of age of deposit as well in the classification shown. The result of classification of the 77 JMA stations into the eleven groups was listed in Table 1.

Table 5 also shows the average station coefficients in each group, the number of recording stations used to calculate the average values, and the correlation coefficient between the average values and the actual station coefficients. In determining the average values of the station coefficients, three stations were omitted: Matsushiro, Ajiro and Wakkanai. The instrument of Matsushiro (mountain) is placed in a rock tunnel and that of Ajiro (mountain) is located on talus (colluvial deposit) ground. These conditions significantly differ from the conditions for other stations. Therefore, these station coefficients look singular points in Figs. 2 and 3. Wakkanai station (reclaimed land) is located on a small-scale reclaimed land built adjacent to a mountainous area. This condition was judged to be different from that for ordinary reclaimed lands in Japan due to the reason that the bedrock lies in a shallow depth.

Table 5 Mean of station coefficient for eleven geomorphologic and geologic-based classifications in this study

Geomorphologic and geologic classification	*PGA*	*PGV*	JMA intensity	Number of stations
1. Reclaimed land	0.009	0.065	0.096	3
2. Sand bar, sand dune	0.038	0.065	0.178	3
3. Delta (mud, clay)	0.081	0.203	0.389	8
4. Delta (sand)	0.029	0.118	0.216	8
5. Alluvial fan	-0.166	-0.092	-0.286	11
6. Terrace (volcanic ash)	0.205	0.137	0.350	7
7. Terrace (sand and gravel)	-0.005	-0.053	-0.064	18
8. Terrace (rock)	-0.131	-0.134	-0.309	5
9. Hill	0.054	-0.029	-0.069	5
10. Volcanic foot	0.148	0.018	0.134	3
11. Mountain	-0.107	-0.261	-0.554	3
Correlation coefficient	0.602	0.705	0.684	74

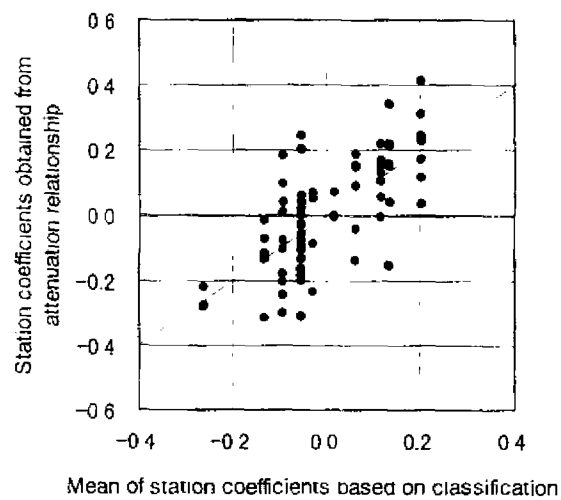


Fig. 9 Mean of station coefficients based on the classification in this study for *PGV* compared with the station coefficients obtained from the attenuation relationship proposed by Shabestari and Yamazaki [5]

The correlation coefficient between the average values of the station coefficients in a group and the actual station coefficients is highest for *PGV* (0.705) and lowest for *PGA* (0.602). This tendency has also been seen in the other classifications described before.

The average values in each of the 11 groups categorized by geomorphology and subsurface geology are proposed as the estimation of the station coefficients. Figure 9 shows the relationship between these values and the actual station coefficients. Even though geomorphology is combined with subsurface geology, considerable variation is still seen in the estimation of station coefficients.

Table 6 shows the amplification ratios, converted from the average values of station coefficients in Table 5. The ground surface in regions geomorphologically classified as mountain is considered to be close to the rock outcrop. Then the conversion is performed so that the amplification ratios of the mountain group is set as 1.0 (for JMA intensity, set as 0.0). Table 6 also shows the names of groups indicating geomorphology and subsurface geology in this study, together with the geomorphological and subsurface geological categories in the DNLI. Using Table 6 and the DNLI, it is possible to estimate the soil amplification ratios throughout Japan by 1 km square pixel.

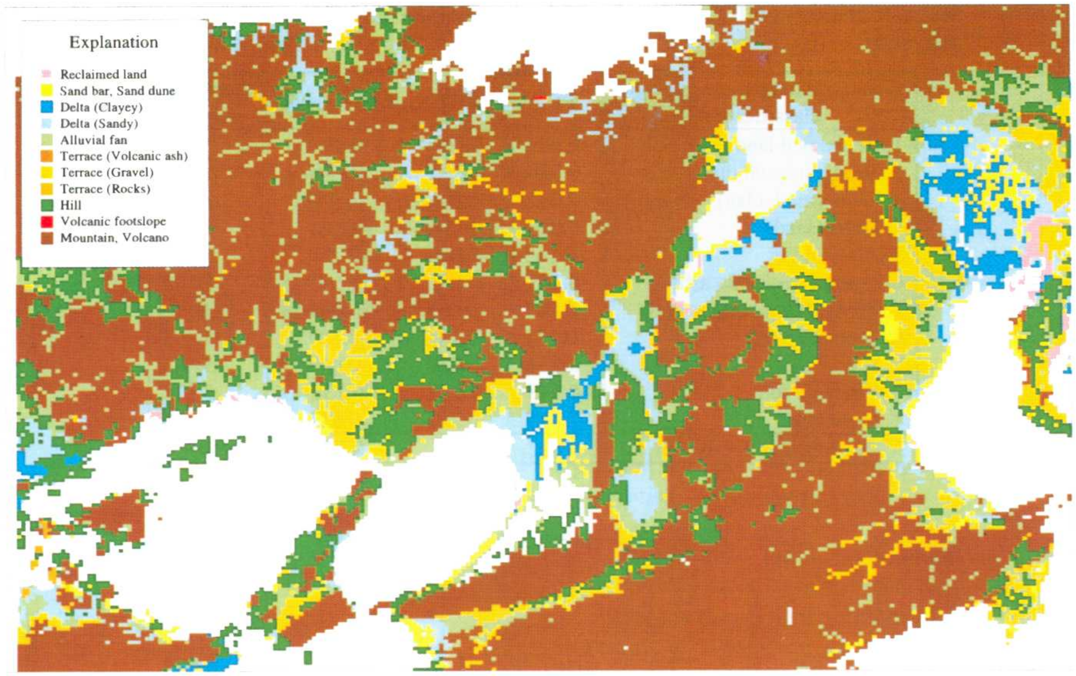


Fig. 10 Distribution of eleven soil groups proposed in this study for Kinki region evaluated from the Digital National Land Information

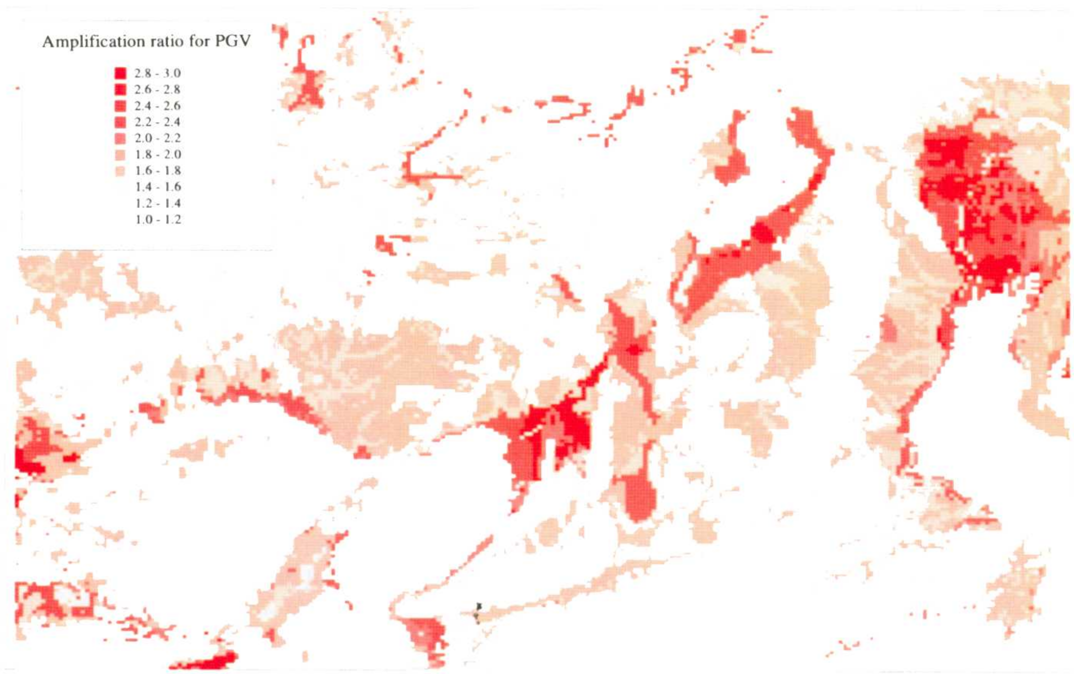


Fig. 11 Distribution of the predicted amplification ratio of *PGV* for Kinki region

Table 6 Amplification ratios for eleven groups proposed in this study, and classification of the Digital National Land Information equivalent of the eleven groups

Digital National Land Information		Group of this study		Amplification ratio		
Geomorphologic classification	Subsurface geology			PGA	PGV	JMA intensity
Reclaimed land, Reclaimed land/polder	Sand, Sandy soil	1.	Reclaimed land	1.31	2.12	0.65
Natural levee, Natural levee/Sand bar, Lowland between sand dune, Sand dune covered with vegetation	Sand, Sandy soil, Dune sand	2.	Sand bar/Sand dune	1.40	2.12	0.73
Reclaimed land, Delta, Flood plain	Mud, Muddy soil, Silt, Clay, Peat	3.	Delta (mud, clay)	1.54	2.92	0.94
	Sand, Sandy soil, Sand and Mud, Alternation of sand and mud	4.	Delta (sandy soil)	1.37	2.39	0.77
Alluvial fan, Volcanic fan	Gravel, Gravelly soil, Sand and gravel	5.	Alluvial fan	0.87	1.48	0.27
Loam terrace(upper, middle, lower), Loam terrace (upper, middle, lower), Shirasu terrace (upper, lower), Volcanic sand terrace	Volcanic ash, Loam, Pumice flow deposit, Shirasu,	6.	Terrace (volcanic ash)	2.05	2.50	0.90
Sand and gravel terrace (upper, middle, lower)	Gravel, Gravelly soil, Sand and gravel	7.	Terrace (sand and gravel)	1.26	1.62	0.49
Rock terrace (upper, middle, lower), Rock terrace (terrace I , terrace II), Limestone terrace (upper, middle, lower)	Rock	8.	Terrace (rock)	0.95	1.34	0.24
High-relief hills, low-relief hills, Volcanic hills	Rock	9.	Hill	1.45	1.71	0.48
Volcanic footslope, Lava flow field, Lava plateau	Volcaniclastic material, Lava, Mud flow deposit	10	Volcanic footslope	1.80	1.91	0.69
High-relief Mountain, Middle-relief Mountain, Low- relief mountain, Foot of mountain, High-relief volcano, Middle-relief volcano, Low-relief volcano	Rock, Volcanic rock	11.	Mountain	1.00	1.00	0.00

* Amplification ratio for JMA intensity is defined as the difference between the intensity at ground surface and that at bedrock.

The distribution of amplification ratio for PGV is provided as an example for a rectangular area of the Kinki region (centered by Osaka and Kobe) with 270 km east-west and 180 km north-south directions (total of 41,266 pixels). The geomorphology and subsurface geology of the area were obtained by the DNLI, and the results were converted to the 11 categories of this study (Fig. 10). Then, the amplification ratio of PGA, PGV, and JMA intensity were determined on the basis of those 11 categories as shown in Fig. 11 for PGV.

COMPARISON OF THE RESULTS WITH THE PREVIOUS STUDIES

The soil amplification ratio obtained in this study (Table 6) was compared with the results of two previous studies [6,7]. The amplification ratios for PGV based on these three studies are compared. Both the studies by Matsuoka and Midorikawa [6] and Fukuwa et al. [7] considered the elevation to estimate the soil amplification ratio. For the purpose of comparison, elevation values should be assigned for each of the geomorphological and subsurface geological categories used in this study. Using the elevations at the 77 JMA stations, the average elevations for each geomorphological and subsurface geological category were calculated and they were used in the estimation equations [6, 7]. A unified definition of the bedrock was also needed to compare the amplification ratios from the three studies. Matsuoka and Midorikawa's study proposes an amplification ratio, taking the hill of the Neogene period or earlier as a reference point [6]. We assumed that this reference point is almost equivalent to our reference ground "mountain" and a direct comparison was made. Since Fukuwa's study considered the bedrock with V_s= 3 km/s as a reference point, the amplification ratios proposed by Fukuwa were divided by 1.45, which is the amplification ratio for mountainous ground in their study.

Table 7 and Figure 12 compare the amplification ratios for PGV by the three studies. All the three estimation methods provide basically the same tendencies in the relative amplification in each

Table 7 Amplification ratios for *PGV* proposed in this study compared with those proposed by previous studies

This study		Matsuoka and Midorikawa (1993)			Fukuwa et al. (1998)		
Geomorphologic and geologic classification	Amplification ratio	Geomorphologic classification	Subsurface geology	Amplification ratio	Geomorphologic classification	Subsurface geology	Converted amplification ratio
Reclaimed land	2.12	Artificially changed land		1.55	Polder	Unconsolidated (Sand)	2.18
Sand bar, Sand dune	2.12	Sand bar, Natural levee	Mud	1.98	Natural levee, Sand bar	Unconsolidated (Mud)	2.96
Delta (mud)	2.92	Sand bar, Natural levee	other than mud	1.65	Natural levee, Sand bar	Unconsolidated (Sand)	2.22
Delta (sand)	2.39	Delta	Tokyo lowland	2.58	Delta	Unconsolidated (Sand)	2.02
Alluvial fan	1.48	Reclaimed land		2.19	Reclaimed land, fill	Unconsolidated (Sand)	1.45
Terrace (volcanic ash)	2.50	Loam terrace		1.61	Sand and gravel terrace	Unconsolidated (Sand)	1.32
Terrace (sand and gravel)	1.62	Sand and gravel terrace		1.32	Sand and gravel terrace	Unconsolidated (alternation of strata)	1.04
Terrace (rock)	1.34	Alluvial fan		1.34	Alluvial fan	Unconsolidated (gravel)	0.87
Hill	1.71	Low-relief Hills		1.50	Low-relief hill	Consolidated	1.59
Volcanic footslope, volcanic terrace	1.91	Neogene deposit		1.23	Mountain	Consolidated	1.00
Mountain	1.00	Mesozonic or Palaeozonic deposits		0.71			

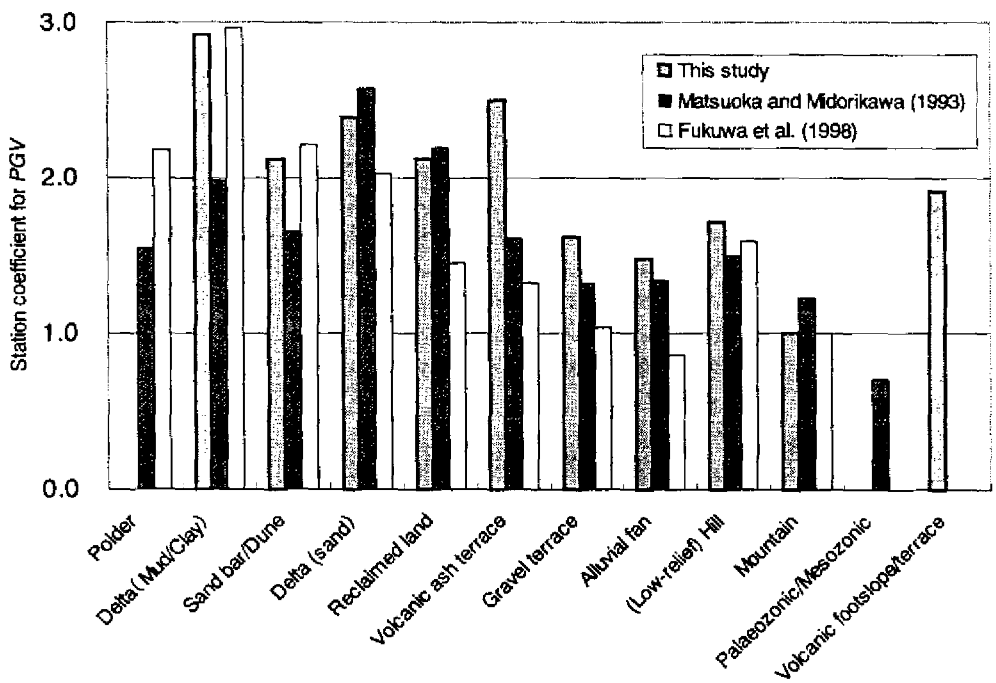


Fig.12 Comparison of amplification ratios for *PGV* proposed in this study and the previous studies

geomorphological and geological category. The absolute values of the converted amplification ratios are also almost equivalent. Although these three studies used completely different seismic records and ground data in deriving amplification ratios, the results are mostly very close. But non-trivial differences are still observed for some soil categories. A further study using more comprehensive data set, e.g. from K-NET with 1,000 recording sites nationwide, is suggested.

As stated before, the estimation of soil amplification ratios from geomorphology and subsurface geology alone may be associated with considerable variability. Thus, the use of the proposed amplification ratios should be limited for the gross estimation of seismic motion over a large area.

CONCLUSION

A method for estimation of the soil amplification characteristics in Japan from generally available data was investigated considering its use in earthquake damage assessment for a large area. The station coefficients in the attenuation equations for *PGA*, *PGV* and JMA instrumental seismic intensity, based on the strong earthquake records measured by the JMA-87-type-accelerometers, were compared with land classifications by the Fundamental Land Classification Survey and others. After several trials, the scatter of station coefficients within each soil group was minimized when the 77 JMA stations are divided into 11 soil groups based on their geomorphological classification and subsurface geology.

From the average values of the station coefficients in each group, the soil amplification ratios for the strong motion indices were obtained taking a mountainous ground in the geomorphological classification as the reference. Thus, the amplification ratios for *PGA*, *PGV*, and JMA intensity can be estimated by 1 km x 1 km pixels throughout Japan using the geomorphological and subsurface geological data in the Digital National Land Information. A comparison with two previous studies showed relatively close results for the *PGV* amplification ratios, irrespective of the differences in method and data used.

A further study using more comprehensive strong motion data sets, for example, from K-NET, may improve the accuracy of the proposed relations between the soil amplification and land classification.

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