

TWO-LAYER MODELING OF GROUND BASED ON MICROTREMOR OBSERVATIONS AND ITS APPLICATION TO AREAS DEVASTATED BY RECENT MAJOR EARTHQUAKES IN JAPAN

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ABSTRACT :

We developed an empirical method of modeling surficial soil deposit based on microtremor measurements observed on a ground surface. The method, replacing a layered soil with an equivalent two layer soil model based on horizontal-to-vertical spectral ratio of microtremors, enables evaluation of site amplification factors near/below the predominant frequency of the site. The method is then applied to areas devastated by two recent major earthquakes which occurred consecutively in the Hokuriku area, Japan in 2007. The first one occurred in March at northern Noto Peninsula. Severe damage to houses was concentrated at the Tohge area, Monzen. The second one occurred in Kashiwazaki, Niigata. Severe damage to wooden houses occurred in downtown areas developed on a sand dune. Microtremor measurements were made at approximately 20 locations for each area so as to cover the most severely damaged areas. Obvious relationships between damage to houses and estimated soil characteristics are recognized in Monzen. Contrary, we could not find a clear relationship between damage to houses and site amplification in Kashiwazaki.

KEYWORDS:

microtremor measurement, H/V spectrum, site amplification, multiple reflection theory, Ishikawa-ken Noto peninsula Earthquake, Niigataken Chuetsu-oki Earthquake

1. INTRODUCTION

Microtremor observation is a simple and convenient method to estimate dynamic characteristics of the ground during earthquakes. Horizontal-to-vertical spectrum of microtremors (H/V spectrum) is widely utilized to investigate the ground; its peak frequency (the frequency that corresponds to the peak value of H/V spectrum) provides predominant frequency at the observation site. The predominant frequency usually corresponds to the natural frequency of soil that has a thickness of a quarter-wavelength. The physical meaning of the peak value of H/V spectrum is still not clear.

Two major earthquakes occurred in Japan in 2007; the first one (2007 Noto Peninsula Earthquake, M_{JMA} =6.9) was most severe in Monzen (approximate population of 8,000), in the Noto-area, , and the second one (2007 Niigataken Chuetsu-oki Earthquake, M_{JMA} =6.8) was most severe in Kashiwazaki city (approximate population of 94,000). Localization of damage to wooden houses was noticed in both events. Application of microtremors to these areas may be useful to gain insight into the damage.

Microtremor measurements were conducted on a ground surface at approximately 20 locations in both areas to study local site effects. This study first develops a method of evaluating site amplification by using microtremor measurements of a ground surface. The peak value and peak frequency of horizontal-to-vertical spectrum are utilized to empirically model the ground surface. Then, layered soil deposits are simply modeled by a two layer soil model (soil overlying bedrock) in this approach. The model is, then, applied to the aforementioned

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damaged sites (Monzen and Kashiwazaki) and site effects on the localization of damage to wooden houses at these sites is discussed.

2. EVALUATION OF LOCAL SITE EFFECT USING MICROTREMOR MEASUREMENTS

2.1. Physical Significance of H/V Spectrum

After Nakamura's study in 1986, various studies and discussions have addressed the physical meanings of the H/V spectrum of microtremors at a site. It seems that the only consensus reached is that peak frequency of the H/V spectrum corresponds to the predominant frequency of the site. However, physical meaning of the peak value is still unclear. In addition, the definition of the bed rock that corresponds to the predominant frequency is also unclear.

2.2. Two Layer Modeling Using H/V Peak

First, attempts to replace a multi-layer ground with a single uniform layer overlying on engineering bedrock is shown in Figure 1. Peak values of H/V spectra of microtremor measurements (as shown in Figure 2) are utilized for the regression analysis in which the relationship between the peak value, and Vs_1 , Vs_2 and H_1 are modeled by the least square function. Table 1 shows sites where microtremor measurements were carried out. The sites are mainly from K-NET and KiK-net sites in which PS loggings are available. Vs_1 and Vs_2 are calculated from PS logging. Figure 3 shows the relationship between the H/V peak and T_0Vs_2/Vs_1 . The peak values here are normalized by the averaged value of H/V spectrum over a frequency range of 0 to 10 Hz. The least square model is then estimated as:

$$(\text{peak}/\text{average}) = 0.716 + 2.178 (T_0 Vs_2 / Vs_1)$$
 (2.1)

in which the left-hand side term represents the peak value of H/V spectrum normalized by the H/V average over the frequency range of 0 to 10 Hz, T_0 = predominant period estimated from the H/V spectrum of microtremor, correlation coefficient($|\mathbf{R}|$) is 0.884. As for the predominant period, we use the following relationship:

$$T_0 = 4H_1 / Vs_1$$
 (2.2)

Since there are two equations and three unknowns, one of the three parameters needs to be assumed. The remaining parameters can then be identified from the equations. If H_1 is known from boring-log at a site, the



No.	Borehole site	T_0 (sec)	$\overline{V}s_1$ (m/sec)	Vs ₂ (m/sec)
1	KiK-net Tanbara (Ehime Pref.)	0.24	130	390
2	K-NET Kure (Hiroshima Pref)	0.50	154	400
3	The Univ. of Tokushima (Medical Campus, Tokushima Pref.)	0.38	170	360
4	K-NET Yuki (Tokushima Pref.)	0.29	190	450
5	KiK-net Takara (Tokushima Pref.)	0.20	286	1130
6	The Univ. of Tokushima (Engineering Campus, Tokushima Pref.)	0.63	185	430
7	Tohoku Institute of Technology (Miyagi Pref.)	0.34	244	470
8	Oroshimachi park (Miyagi Pref.)	0.21	266	460
9	KiK-net Mino (Kagawa Pref.)	0.56	205	390
10	KiK-net Ochi (Kagawa Pref.)	0.21	227	680
11	K-NET Marugame (Kagawa Pref.)	0.11	210	450
12	Institute of Industrial Science, The Univ. of Tokyo (Chiba Pref.)	0.14	140	320
13	Institute of Technology, Shimizu Co. (Tokyo)	1.00	154	440
14	K-NET Shingu (Wakayama Pref.)	0.31	128	340

Table 1 List of sites used for regression analysis



value as known is used to attempt to identify Vs_1 and Vs_2 . The identified Vs_2 is then considered to be the common value over the target area. Vs_1 and H_1 are then estimated over the target area.

2.3. Evaluation of Transfer Function By the Simple Soil Model

The replaced soil model is a uniform, damped soil on elastic rock. It is questionable whether the simple model can represent the site amplification characteristics of the multi-layered ground, since the simplified model only reflects characteristics near the predominant frequency (usually first mode). Hence, transfer function amplitudes are compared between surface and base rock for various soil models. The computed transfer functions illustrated a good fit with each other in the relatively low frequency range as shown in Figure 4 as an example. Thus, the simplified model is able to express the site amplification characteristics of multi-layered ground.



3. APPLICATION OF THE MODEL TO AREAS DEVASTATED BY TWO RECENT MAJOR EARTHQUAKES

In 2007, two major earthquakes occurred in Japan. Researchers and engineers noted that damage hardly happened to modern buildings and bridges, but was concentrated on traditional Japanese wooden houses, which were constructed using wooden posts and lintels in Noto and Kashiwazaki. One common perception is that localization of damage might be due to decay of wooden members. One factor may be the site amplification effect. In this study, the simple soil model identified by microtremors to those areas is applied, and whether the soil model can explain the localization of damage is discussed.

Microtremor measurements were conducted under calm conditions (with no wind and rain) for three minutes at each site using a portable ambient vibration monitoring system (SPC-35N) and servo velocity meter (VSE-15D). The ground motion velocities of one vertical and two horizontal directions were recorded at 100Hz. The overall frequency characteristics of the apparatus are reported to be flat over 0.2 Hz.

3.1. 2007 Noto Peninsula Earthquake

The Noto Peninsula Earthquake occurred on March 25, 2007, with a magnitude of M_{JMA} 6.9 (M_W 6.7) and top intensity upper 6(JMA) recorded in Wajima City as well as some other places. The hypocenter was about 11 km deep, at N37.281 E136.602, approximately 12 km offshore from the Noto Peninsula. As of Dec. 28, 2007, statistics by the Fire and Disaster Management Agency show the damage includes 265 injuries, 91 serious injuries, 1 fatality, 684 buildings totally destroyed, 1,733 partly destroyed and 26,935 other buildings damaged to a lesser degree.

The second author made the first field investigation in the Tohge area. The distribution of damage to wooden houses in the area was investigated by referring to red tag (unsafe) and yellow tag (limited entry), that were posted on damaged houses as objective damage indices, which represents about 34% of the houses totally damaged and 32% houses partly damaged. The result is shown in Figure 5. Green circles indicate no damage or slight damage. Evidently, severe damages to houses were distributed unevenly in the area: a lesser degree of damage can be recognized near the hill side. The damage is suspected to be related to soil conditions. The



Figure 5 Distribution of damage to wooden houses in Tohge Distrct, Monzen Town (original map from Geographical Survey Institute)

Figure 6 Distribution of predominant frequency (Hz)



geological condition of the central area is an alluvial plain developed by the Hakka River, which is surrounded by hills. This results in different geographic features between the central and edge area. The red dotted line in Figure 5 indicates the former route of the Hakka River (1980). Thus, the severely damaged area retains weak stratum along the former route of the Hakka River.

The second investigation studies the relationship between damage to houses and soil condition. Microtremor observations have been conducted at 19 locations covering the Tohge area during May 19 – May21, 2007. Figure 6 shows the distribution of predominant ground frequencies estimated by using microtremor recordings. From the alluvial plain, the location of severe damage to houses can be recognized, and that the predominant frequencies are around 1.0-2.0 Hz while the region along the hills has higher frequency values. Fundamental frequencies of the local wooden houses in Monzen were reported to be approximately 3-5 Hz by Arai et al (2008).

The proposed method of estimating two-layer soil model is applied. Among the three parameters that prescribe that soil model, one of them needs to be fixed (since there are two known and three unknown parameters). There is a location in which test result by the standard penetration test (SPT) is available. The surface soil thickness H_1 is determined to be approximately 35.0 m at the location (A). Given H_1 , other parameters (Vs₁ and Vs₂) are identified as 202 m/sec and 373 m/sec at the location. Thus, the identified Vs₂ are used for other locations in this area (Vs₂ is assumed to be the shear wave velocity of the widespread common baserock in the area). Figure 7 shows distribution of identified H_1 . The alluvial plain shows the recognizable severe damage to houses, that H_1 are around 35-55 m. However, H_1 of the location (S) is fixed as 12 m which is investigated by SPT.

Soil profiles of each location were identified to evaluate site amplification effects by calculating the transfer function of the estimated two layer ground model. As mentioned above, fundamental frequencies of wooden houses are 3-5 Hz, hence, the calculated transfer function amplitude is at 4 Hz by considering weighted average around 4 Hz. Results are shown in Figure 8. Distribution of transfer function amplitude at 4 Hz does not correlate with the damage distribution. Taking into account the effect of soil degradation due to the strong ground shaking, the transfer function was calculated at 2 Hz. As shown in Figure 9, distribution of transfer function amplitude at 2 Hz correlates with the distribution of damage to houses.



Figure 7 Distribution of estimated H_1 (m)

Figure 8 Distribution of transfer function amplitude at 4 Hz





Figure 9 Distribution of transfer function amplitude at 2 Hz

3.2. 2007 Niigataken Chuetsu-Oki Earthquake

The Niigataken Chuetsu-Oki Earthquake occurred on July 16, 2007, with a magnitude of M_{JMA} 6.8, maximum acceleration 667 gal, and top intensity upper 6 (JMA) recorded in Kashiwazaki city and other places. The hypocenter was approximately 17 km deep, at N37.557 E138.608, around 60 km offshore from Niigata. As of Dec. 28, 2007 statistics by the Fire and Disaster Management Agency show the damage includes 1,992 injuries, 323 serious injuries, 15 fatalities, 1,319 buildings totally destroyed, 5,612 partly destroyed and 35,070 other buildings damaged to a lesser degree.

Figure 10 is a map of downtown Kashiwazaki showing the distribution of damage to houses quoted from an investigation report by Niigata University. According to the report, the surface soil condition in downtown Kashiwazaki can be split up into three sections as divided by the dotted line in Figure 10. The severely damaged area is located on the sand dune slope. Microtremor observations were conducted at 21 locations in downtown Kashiwazaki from July 19 – July 21 and September 13 – September 16, 2007. Distribution of predominant frequencies is illustrated in Figure 11. The predominant frequencies are around 0.6-1.0 Hz in the area. The method of modeling the soil with a two layer model was applied. At the location (T), shown in the map, H₁ is evaluated as 48.0 m from the available soil profile (1981). Given the surface soil thickness H₁, shear wave velocities Vs₁ and Vs₂ are identified as 121 and 326 m/sec, respectively, at the location (T). Figure 12 shows the distribution of the identified H₁. The transfer function amplitude was also calculated at 2 Hz in the same way as that of the Noto Peninsula (Figure 13). Figure 13 does not correlate with the severely damaged zone.

4. CONCLUSIONS

We developed an empirical method of representing surficial soil deposit based on microtremor measurements observed on a ground surface. The method, replacing, the multi-layer ground with an equivalent two layer soil model based on horizontal-to-vertical spectral ratio of microtremors enables us to evaluate site amplification factors near/below the predominant frequency of the site. Localization of damage to wooden houses at Noto Peninsula was recognized at areas where the estimated depth of surface soil deposit is thick. However, a close correlation could not be found between the area of the damage to the wooden houses and the soil model estimated by the developed method. The reason for this could be that the severely damaged area in downtown Kashiwazaki is located on soil with special characteristics, having developed on a sand dune.





Figure 10 Distribution of damage to wooden houses in Kashiwazaki City



Figure 12 Distribution of estimated H_1 (m)



Figure 11 Distribution of predominant frequency (Hz)



Figure 13 Distribution of transfer function amplitude at 2 Hz

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REFERENCES

Nakamura, Y. and Ueno, M. (1986). A simple estimation method of dynamic characteristics of subsoil. *Proc. The 7th Japan Earthq. Eng. Symp.* 265-270 (in Japanese). Japan Meteorological Agency: 2007 Noto Peninsula Earthquake. (http://www.seisvol.kishou.go.jp/eq/2007_03_25_noto/index.html).



Fire and Disaster Management Agency. 2007 Noto Peninsula Earthquake. (http://www.fdma.go.jp/detail/710.html).

Keiichiro Yamaguchi (1980). "Nihon-Zushi-Taikei Chubu II". 312-313. Asakura Publishing co., Lid

Arai et al. (2008). Peak Ground Velocity and Cause of Damage to Wooden Houses Estimated in Near-Source Area During The 2007 Noto Hanto Earthquake. *J Struct. Constr. Eng.*, *AIJ*. **73:624**, 227-234 (in Japanese).

Japan Meteorological Agency: 2007 Niigataken Chuetsu-oki Earthquake.

 $(http://www.seisvol.kishou.go.jp/eq/2007_07_16_chuetu-oki/index.html).$

Fire and Disaster Management Agency. 2007 Niigataken Chuetsu-oki Earthquake.

(http://www.fdma.go.jp/detail/751.html).

Niigata Univ., Research center for Natural Hazard and disaster Recovery (2007). Structure of subsurface ground and Damage to building in downtown Kashiwazaki-city. (http://geo.sc.niigata-u.ac.jp/~070716/).

Ministry of Construction (1981). Geotechnical map of the part of the Niigata plain 1-5. Hokuriku Construction Association.