The *H/V* Technique and Example of its Application for L'Aquila and Rome Areas

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Abstract

The *H/V* technique is an estimation tool for the local site effect as not only the predominant frequency but also the amplification factor. Both microtremor and strong motion consist of various kinds of waves as P-wave, S-wave, Rayleigh wave, Love wave and so on, so the spectrum derived from microtremor or strong motion shows many peaks corresponding to these wave components. From the viewpoint of the seismic disaster mitigation, it is important to pick out S-wave from microtremor and investigate its characteristics because the severe damage is mainly caused by S-wave. Although it is fine way to estimate the S-wave structure of the surface ground layers from the characteristics of Rayleigh wave, this technique requires not only a precise setup of the measurement points but also complex analysis. On the other hand, the *H/V* technique is established as a direct approach for the site amplification estimation, so it is easy to apply for the various ground condition. This paper shows the scheme of the *H/V* technique and its application for L'Aquila and Rome areas.

1. Introduction

The *H/V* technique is an estimation tool for the local site effect as not only the predominant frequency but also the amplification factor. Both microtremor and strong motion consist of various kinds of waves as P-wave, S-wave, Rayleigh wave, Love wave and so on, so the spectrum derived from microtremor or strong motion shows many peaks

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corresponding to these wave components. From the viewpoint of the seismic disaster mitigation, it is important to pick out S-wave from microtremor and investigate its characteristics because the severe damage is mainly caused by S-wave. Although it is fine way to estimate the S-wave structure of the surface ground layers from the characteristics of Rayleigh wave, this technique requires not only a precise setup of the measurement points but also complex analysis. On the other hand, the *H/V* technique is established as a direct approach for the site amplification, so it is easy to apply for the various ground condition.

2. Brief story of the *H/V* technique

Originally, the *H/V* spectral ratio was found from strong motion records at various sites in Japan. Although the horizontal motion shows larger value than the vertical motion on the soft ground, the horizontal and the vertical motion are similar in both the maximum value and the shape of the waveform on the hard ground. At first, the horizontal to vertical ratio for the maximum value was derived and compared with the softness and the amplification factor of ground. As a result, the horizontal to vertical ratio of the maximum value highly corresponds to the ground characteristic on the same site [1]. Then the horizontal to vertical spectral ratio (*H/V* spectral ratio) of microtremor was established to estimate the predominant frequency and the amplification factor and confirmed that the estimation result is stable not depended on the measured time and season [2].

3. Outline of the *H/V* technique

There is no reason to be amplified the amplitude of a particular frequency range or direction at the hard and uniform ground. It is natural that the vibration in the hard ground is uniform for wide frequency range or each direction. The measured results of both microtremor and earthquake suggest it. On the other hand, it is important for a soft ground deposition over the hard basement to grasp the amplification characteristics of the horizontal motion. At the frequency range the horizontal motion is amplified, it seems that the vertical motion is not amplified. And at a ground with that kind of the amplification characteristics, it is important to consider the Rayleigh wave propagation on the ground surface. Earthquake disaster is caused mainly by the body wave and if the Rayleigh wave causes any damage, the damage must be a minor damage. That is to say, it is important to understand the phenomenon of the trapped energy of the body wave inside the soft surface layer. The phenomenon shows the amplification characteristics of earthquake motion by so called the multiple reflections.

From this viewpoint, the Rayleigh wave exists as a noise and it is necessary to reject the effect of the Rayleigh wave. The effect of the Rayleigh wave for the amplification characteristics R (= A_{hs}/A_{hb}, the surface (A_{hs}) to the basement (A_{hb}) of the horizontal motion) of the surface ground is estimated by the surface (A_{vs}) to the basement (A_{vb}) ratio of the vertical motion E (= A_{vs}/A_{vb}). Then the corrected amplification characteristic A_m is shown as follows;

$$A_m = R/E = (A_{hs}/A_{hb})/(A_{vs}/A_{vb}) = (A_{hs}/A_{vs})/(A_{hb}/A_{vb}) \approx A_{hs}/A_{vs}$$

This is the *H/V* spectral ratio [2]. **Figure 1** shows the concept of the *H/V* technique. The *H/V* spectral ratio shows the amplification characteristics by the multiple reflections of the SH wave at least around the predominant frequency F_0, and also shows the characteristics contaminated by the Rayleigh wave around $2F_0$. In case of smaller effect of the Rayleigh wave, it is possible to estimate not only the preliminary peak but also the secondary peak of the amplification characteristics caused by the multiple reflections from the *H/V* spectral ratio. Please see [3] or [4] in detail.

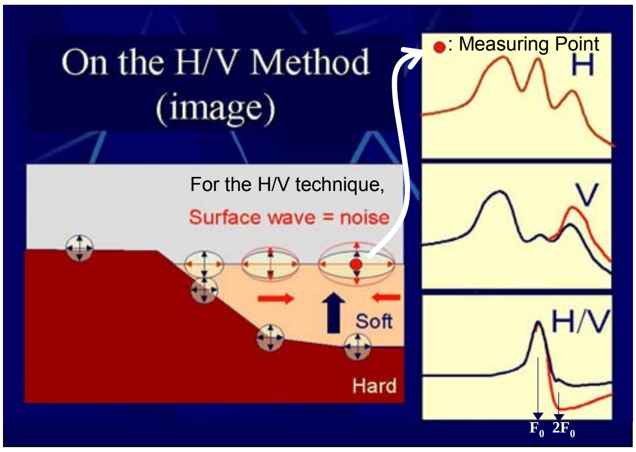

Figure 1. *Concept of the H/V technique*

4. Average velocity, thickness and vulnerability index of surface layer

The *H/V* spectral ratio of both microtremor and strong motion can provide at least fundamental frequency and its amplification factor. Based on the predominant frequency F_g in Hz and the amplification factor A_g derived from the *H/V* spectral ratio, the average velocity AVS in m/s, the thickness h in m for the surface ground are defined as follows,

$$AVS = V_b/A_g,$$
$$h = AVS/(4F_g) = V_b/(4A_gF_g),$$

where V_b is velocity in basement ground.

On the other hand, earthquake damage of members of structures occurs at the time of exceeding the destruct limit of the strain caused by deformation, and it may cause a collapse if the stability of the structure is lacked. Then the vulnerability index was defined focusing on the strain [5]. K value in 10^{-6}/cm/s^2 is defined to estimate the strain in the unit of 10^{-6} at particular parts of the structures, multiplying the possible maximum acceleration at the engineering basement (see **Figure 2**). These K values are defined individually for ground and various structures, as K_g value for ground, K_j value for embankment, K_s value for rigid frame structure, K_b value for building and K_d value for derailment. For example K_g value is defined as follows (see **Figure 3**).

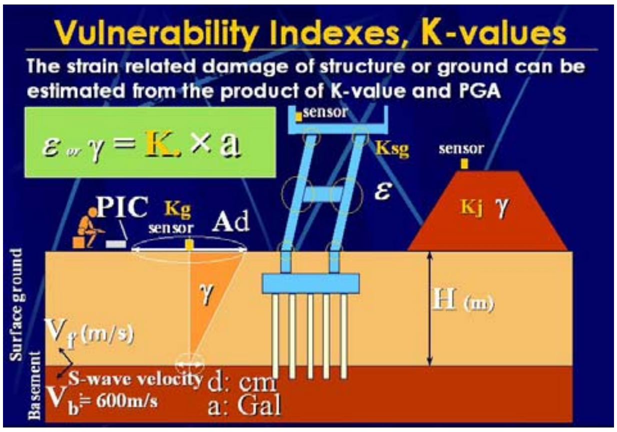

Figure 2. *Vulnerability indexes K values*

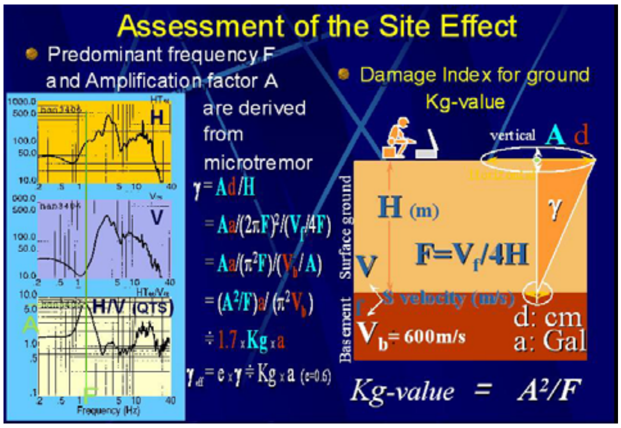

Figure 3. *Vulnerability index K_g value for surface ground*

$$K_g = A_g^2/F_g$$

If maximum acceleration is *100* cm/s^2 at the basement and K_g value is *20*, the average strain at the surface ground layer is estimated *2000* (x10^{-6}) and this strain may cause some damage to this ground. **Figure 4** shows an example of the K_g value distribution at Marina district in San Francisco after the 1989 Loma Prieta earthquake. Large K_g (K_g > *20*) were observed at the severe liquefied area.

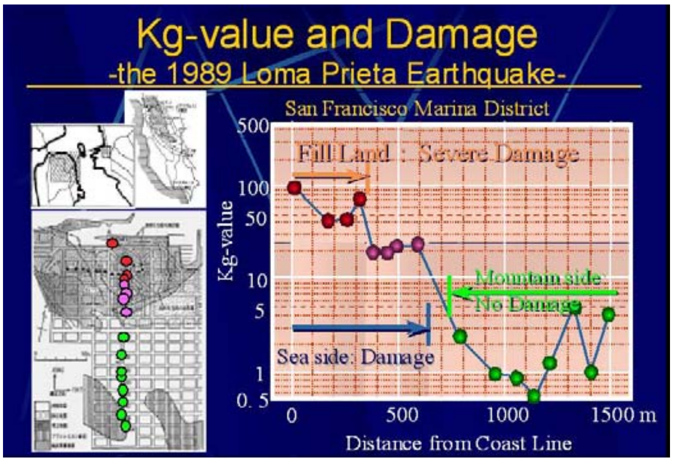

Figure 4. *An example of comparison between K_g value and damage*

5. Microtremor measurements in L'Aquila and Rome

5.1. Location and method

Figure 5 shows the measurement area and locations in L'Aquila and Rome area. L'Aquila area was measured before the workshop with its participants. Rome area was measured after the workshop. Measurement locations around the Colosseum were set as extensions of measurement on 1998.

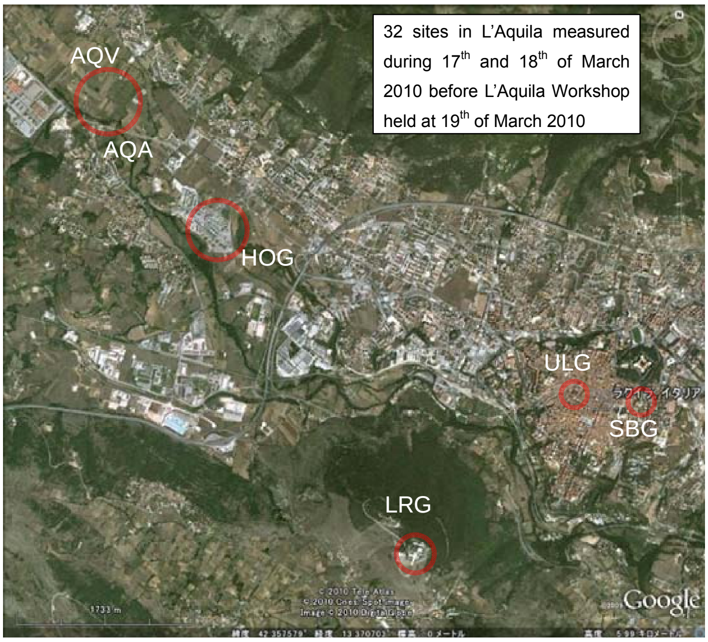

Figure 5(a). *Overview of the measurement in L'Aquila*

Microtremor was measured at each site three times and its length was *40.96* seconds in *100* Hz sampling using NewPIC^{+} of *SDR* (see the detail on http://www.sdr.co.jp).

Fourier Spectrum and *H/V* spectral ratio were calculated for each *40.96* seconds data with twenty times Hanning window and then averaged the three data at each site.

Peak frequency F_g and peak value A_g were read from the averaged spectral ratio *H/V*, and K_g value were calculated with these values.

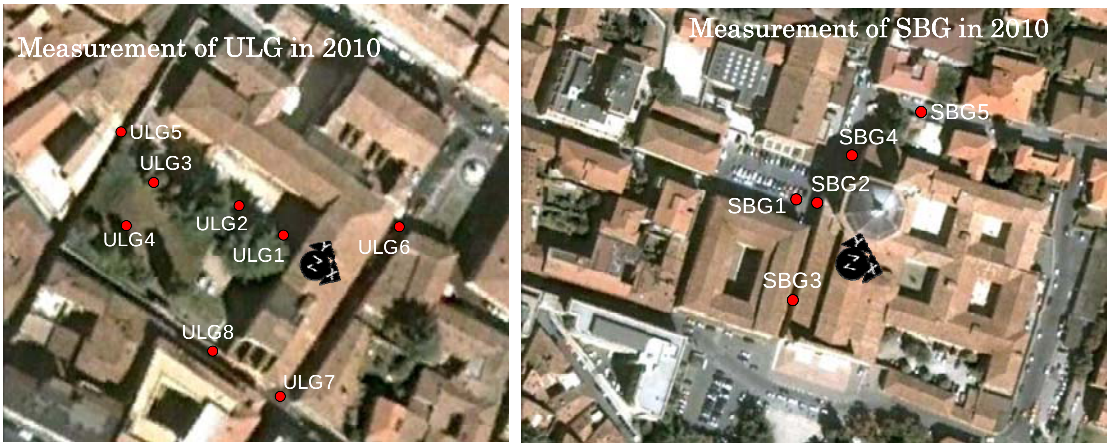

Figure 5(b). *Measured sites in ULG and SBG*

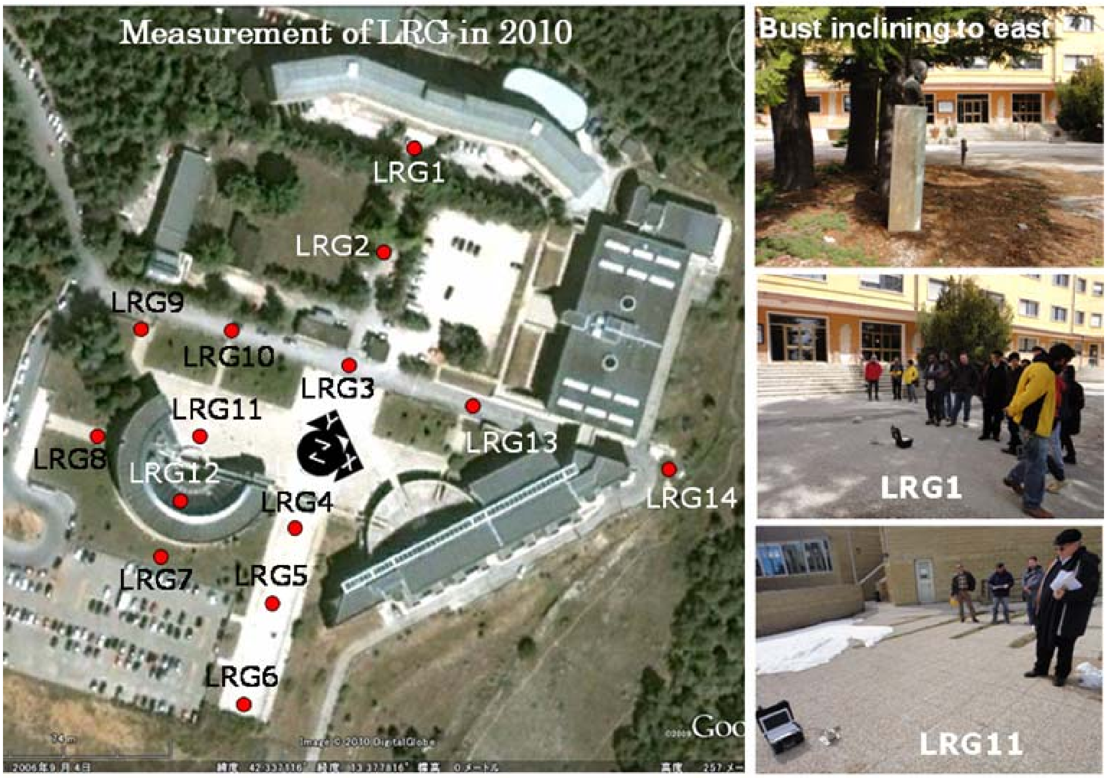

Figure 5(c). *Measured sites in LRG*

Figure 5(d). *Measured sites in HOG, AQV and AQA*

Figure 5(e). *Measured sites in Rome*

5.2. Results

Figure 6 shows the averaged spectral ratio *H/V* for each sites. Please note that the point LRG7 shows abnormal result because of a strong wind, so this data was omitted from the discussions following.

Table 1 summarizes the measurement result for F_g, A_g, K_g, h and AVS. According to this table the predominant frequencies in L'Aquila area distributes totally wide range as *1-9* Hz, and distributes in *2-3* Hz in the mountain area (LRG). And that of Rome area distributes in *1-2* Hz. *AVS* assuming Vs = *600* m/s shows large value in Rome and less than *100* m/s for many sites in L'Aquila, and this suggests that there may exists a soft ground in L'Aquila. The K_g value shows almost small amount in Rome and most part of L'Aquila except the mountain area (LRG), and that in the mountain area shows obviously large value.

Figure 7 shows the distribution of the K_g value. In this figure, the diameter of the circle for each point corresponds to the amount of its K_g value. It is found that the K_g value differs widely from each other. The campus of L'Aquila University in the old town (ULG) was suffered se-

***Table 1.** Summary of measurements*

site	Fg Hz	Ag	Kg μ/Gal	h m	AVS m/s
SBG1	4.32	3.38	2.6	10	178
SBG2	3.86	3.33	2.9	12	180
SBG3	2.49	3.03	3.7	20	198
SBG4	4.05	5.29	6.9	7	113
SBG5	2.78	3.05	3.3	18	197
ULG1	5.71	11.70	**24.0**	2	51
ULG2	6.35	10.80	**18.4**	2	56
ULG3	6.57	14.30	**31.1**	2	42
ULG4	8.72	14.50	**24.1**	1	41
ULG5	6.47	3.78	2.2	6	159
ULG6	9.20	6.37	4.4	3	94
ULG7	6.13	2.54	1.1	10	236
ULG8	5.62	3.16	1.8	8	190
LRG1	2.59	7.40	**21.1**	8	81
LRG2	3.30	7.70	**18.0**	6	78
LRG3	2.12	7.10	**23.8**	10	85
LRG4	3.15	6.18	**12.1**	8	97
LRG5	1.56	3.79	9.2	25	158
LRG6	2.15	5.49	**14.0**	13	109
LRG7	N/A	N/A			
LRG8	2.61	5.93	**13.5**	10	101
LRG9	2.61	4.61	8.1	12	130
LRG10	2.95	4.58	7.1	11	131
LRG11	3.03	5.71	**10.8**	9	105
LRG12	2.93	5.16	9.1	10	116
LRG13	3.10	7.27	**17.0**	7	83
LRG14	2.08	3.74	6.7	19	160
HOG1	1.54	3.20	6.6	30	188
HOG2	4.17	4.25	4.3	8	141
HOG3	7.69	4.71	2.9	4	127
AQV	2.93	5.44	**10.1**	9	110
AQA	8.67	7.04	5.7	2	85
CMGW	1.37	2.76	5.6	40	217
RHG	2.59	4.19	6.8	14	143
ARG1	2.51	2.99	3.6	20	201
ARG2	2.15	3.13	4.6	22	192
ARG3	1.54	2.60	4.4	37	231
ARG4	1.59	1.97	2.4	48	305
ARG5	2.12	1.81	1.5	39	331
ARG6	3.69	1.82	0.9	22	330
ARG7	1.68	3.57	7.6	25	168
ARG8	1.15	2.79	6.8	47	215
98G1	1.37	2.30	3.9	48	261
98G2	1.12	2.39	5.1	56	251
98G3	1.42	2.20	3.4	48	273
98G4	1.44	3.23	7.2	32	186
98G5	2.25	2.69	3.2	25	223
98G6	0.49	2.86	**16.7**	107	210

N/A: affected by strong wind

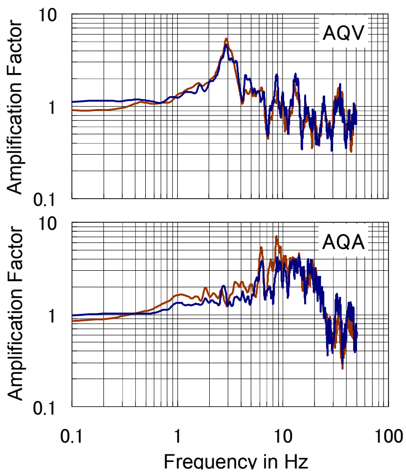

***Figure 6(a).** Spectral ratios H/V for AQV and AQA* vere damage. Especially in the courtyard filled by the ancient debris, the embankment higher than surrounding roads liquefied severely and flew out to the surrounding roads. Hence K_g values are still over *20* even after reconstruction of the embankment, K_g values can be estimated in the same range before the reconstruction and the shear strain in the surface ground seems to be over *1/200* caused by the several hundreds Gals strong motion in the basement ground and the severe liquefaction may be occurred.

There were also subsided road may caused by the liquefaction, so the K_g value seems to be large, too. Thus, advance calculation of K_g value with the microtremor measurement can help taking the proper countermeasure previously with choosing the possible damage area of

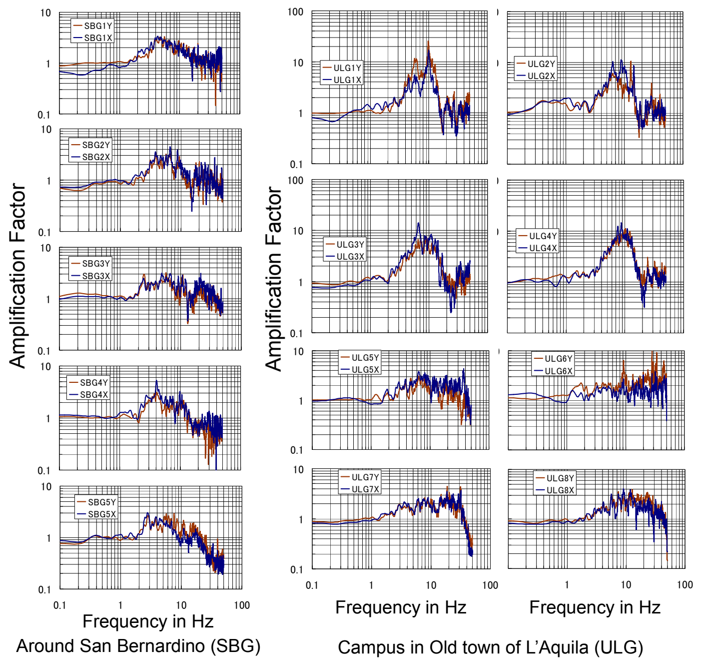

***Figure 6(b).** The H/V for SBG and ULG*

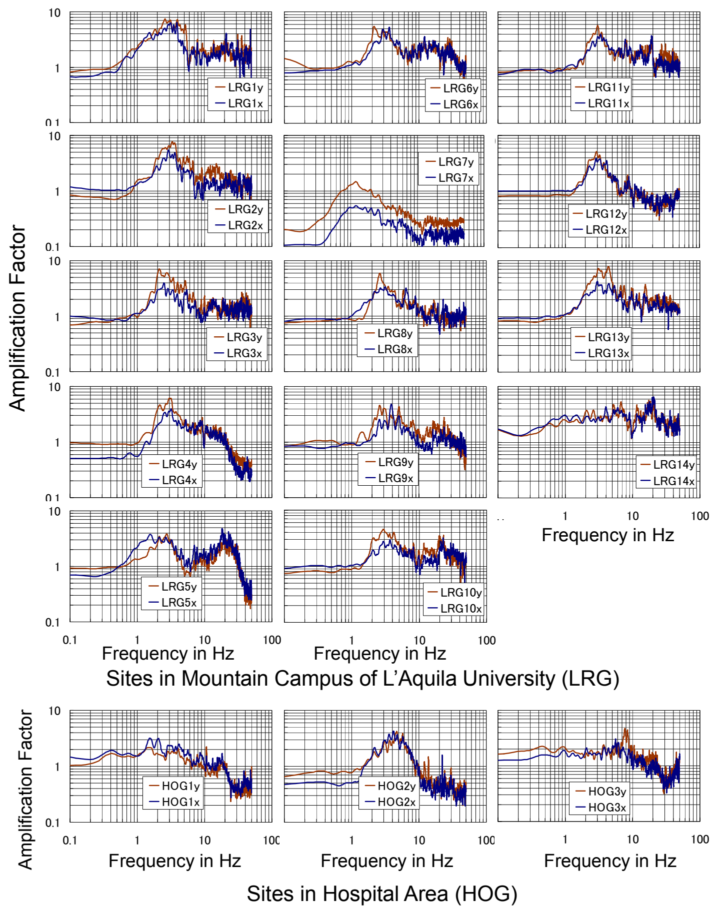

***Figure 6(c).** The H/V for LRG and HOG* the ground fluidization or subsidence.

The K_g values on the mountain area (LRG) are larger than that of other area, especially in the northern side. A leaning bust near the point LRG1 might be suffered by damaged ground. Totally in the L'Aquila area the surface ground damage would be caused in the area with $K_g > 10$.

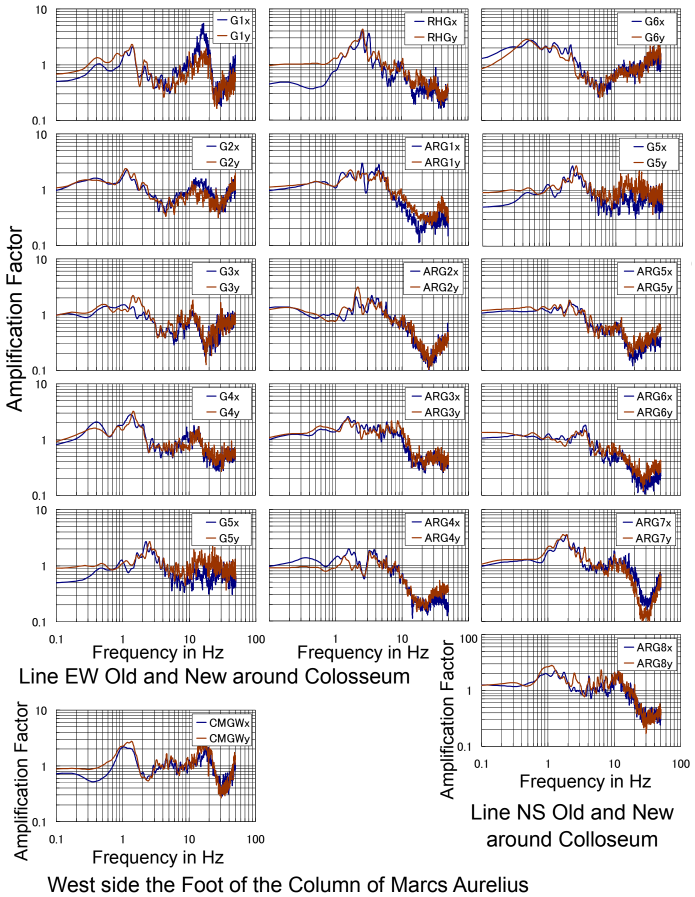

Figure 6(d). *The H/V for sites in Rome*

6. Discussion

Figure 8 shows a comparison between the spectral ratio *H/V* of the strong motion records (*PGA* was around *650* Gal) and that of the microtremor at the observatory AQV. Obviously, both the predominant frequency and the amplification factor of the strong motion are sifted lower and larger, respectively. It seems that this caused by non-linearity of the surface ground.

According to the results of surface layer investigation shown in **Figure 9** [6], the surface ground is estimated as the sediment of silty soil of around *50*m depth on limestone. However the amplitude of strong motion displacement is around *5*cm derived from the double integration of the acceleration records, and the shear strain will be assessed as *1/1000* approximately, then a non-linearity shown in **Figure 8** may not be occurred.

Assuming the shear wave velocity (*Vs*) of the basement ground as *600* m/s regarding to the layer investigation, *AVS* = *110* m/s and h = *9* m for the surface ground are estimated from the *H/V* spectrum of the microtremor. Although the layer with the comparable depth can be seen in **Figure 9**, *Vs* is around *400* m/s and is not similar to this.

Assuming that the estimation result from the microtremor measurement is correct, if the depth of the surface layer is *9* m and the displacement at the ground surface is around *5* cm, the shear strain is estimated as *6/1000* (= *5* cm / *900* cm). On the other hand, because the K_g value at this site is *10*, the shear strain at the ground surface can be estimated at most *6/1000* (= *10* x *600* Gal x 10^{-6}) with assuming that the maximum acceleration at the basement ground is *600* Gal. Both result of the shear strain estimation are similar to each other.

Figure 7. *Distributions of* K_g *value: outside diameter of concentric circles correspond to 20 of* K_g *value*

According to the *G-γ* curve for the clay arranged by Ishihara [7] shown in **Figure 10**, the rigidity of the soil will be reduced to *1/3* with such shear strain. This corresponds to the *0.58* times of the frequency shift and it is agreeable to the observed frequency change from *2.9* Hz to *1.7* Hz.

Namely, the frequency sift shown in the strong motion is attributed to the surface ground *9* m thick and *110* m/s *AVS*.

The K_g value related to the earthquake damage to the surface ground is often more than *10* and it corresponds to the sedimentary layers less than *200* m/s of *AVS*. In Japan the ground of *AVS 500-600* m/s is stiff enough to the basement ground. It is important to extract accurately the sedimentary ground with large K_g value and then to grasp the dynamic characteristics of that site.

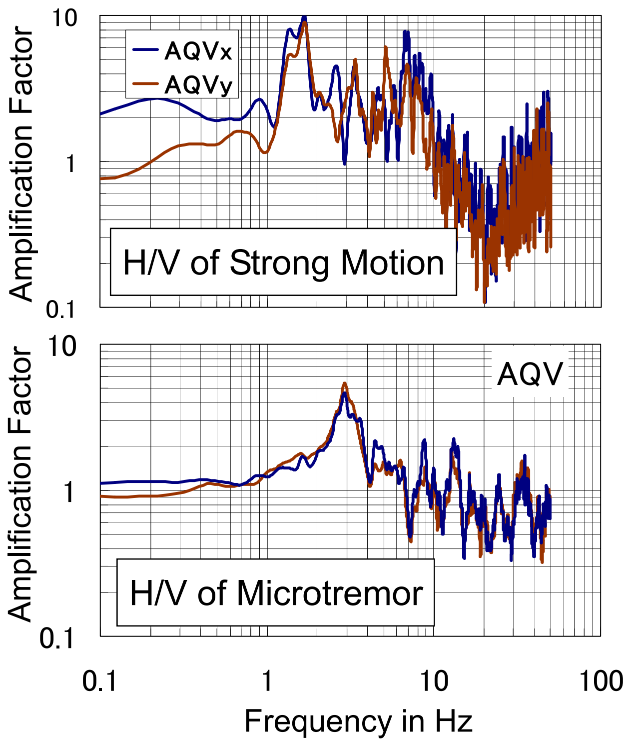

Figure 8. *Comparison between spectral ratio H/V of strong motion and that of microtremor at the site AQV*

7. Conclusion

This paper describes the outline of the *H/V* technique developed by focusing on the multi-reflection phenomena in surface ground and shows its application with the data of the microtremor measurement at the workshop. This time the measurement was done only on the ground. Next time I would like to measure microtremor not only on the ground but also on structures or on buildings. The microtremor includes various valid information. I would like to keep challenging to create proper analysis methods for various purposes

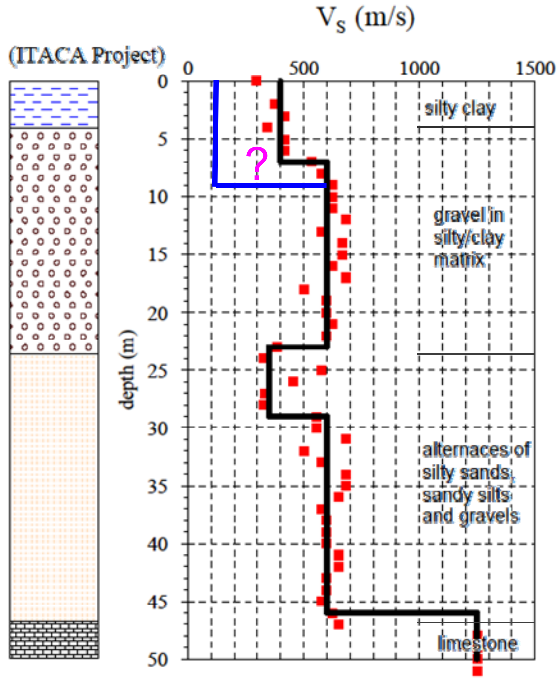

Figure 9. *Geological profile of the site AQV (modified from [6])*

to expand the possibility of microtremor application. I am happy if the proposed *K* value method for vulnerability assessment widely spreads and contributes the improvement of the earthquake resistance ability of cities.

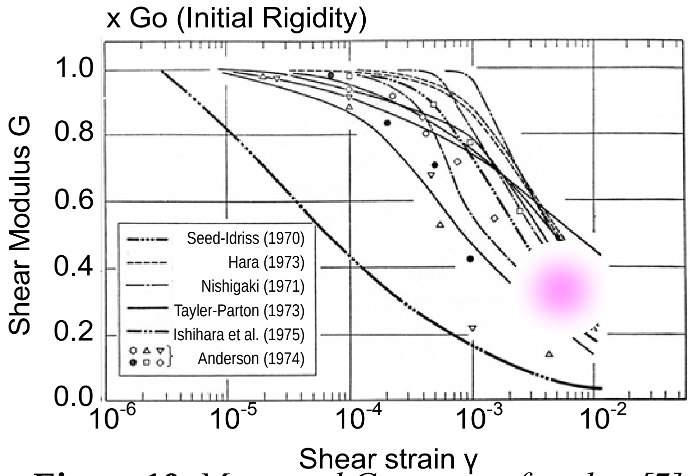

Figure 10. *Measured G-γ curves for clay [7]*

Acknowledgments

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