Studies on the Deep Basin Site Effects Based on the Observed Strong Ground Motions and Microtremors

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The remaining issues of ESG on GMP

1) What is the best method to quantify the S-wave amplification factor of earthquake at a site ?
2) What is the minimum depth sufficient to get quantitative value of S-wave amplification ?
3) Why don't we have significant reduction of variation even after the site correction on GMPE ?
4) What is the best single index (e.g. Vs30) as a representative of S-wave amplification ?
5) What is the best strategy for easy yet precise evaluation of ESG on GMP ?

Do we have answers ? Yes, of course!

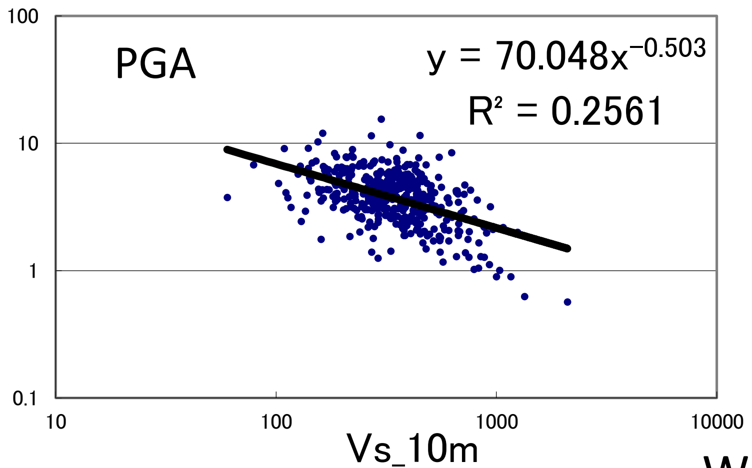
1) Best method: 1D (for most cases) or 3D (for long period basin effects) S-wave velocity modelling is needed and sufficient.
2) Minimum Depth: Down to the bedrock with Vs~3km/s.
3) Why no reduction: Because we use a single index in GMPEs with ergodic assumption.
4) Best index: There is no single index effectively represent ESG on GMP.
5) Observe GM at a site ➔ Create a velocity model (preferably 3D) ➔ Calculate basin response theoretically ➔ Use source and site specific GMP methodology ➔ Realistic GM!

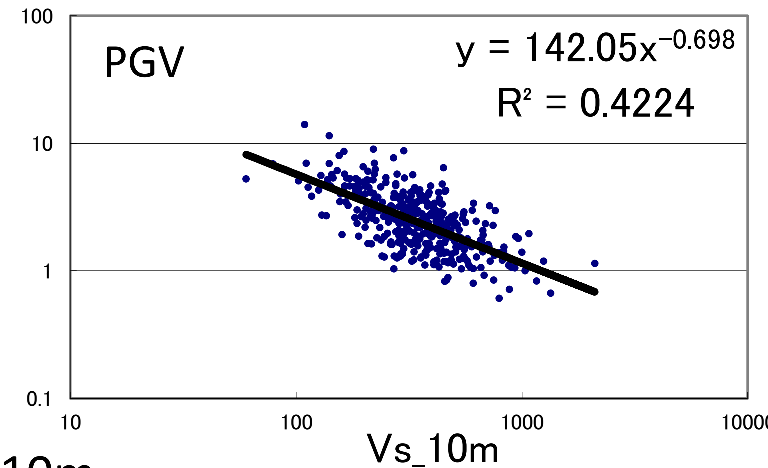
Why any single site index would fail ?

Simply because it is not physical.

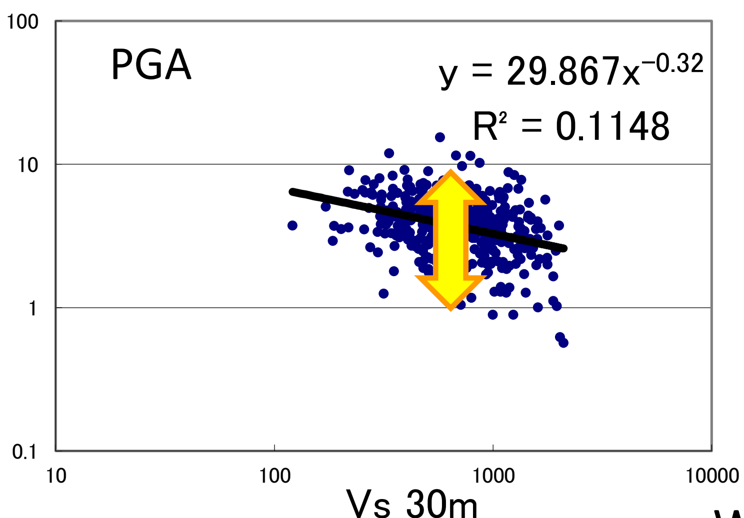
1) PGA, PGV, and Sa or Sv (response spectra) are all "strength index", as a function of broad-band spectra of GM (See Bora et al. 2016, BSSA).
2) Relative amplitude of a site is the final results of complex interaction of medium around it.
3) On the contrary, Fourier spectra are the physical quantity, representing site amplification from the bedrock to the surface (or from the surrounding rock to the basin center).

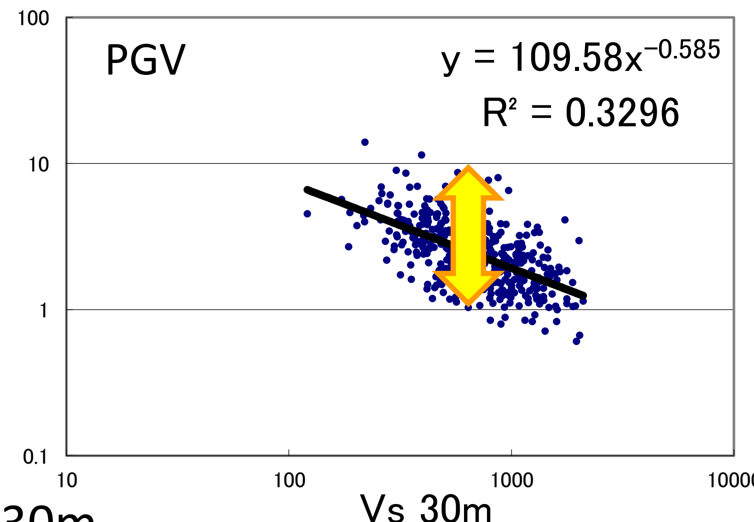
PGA and PGV Site factors separated from K-NET, KiK-net, and JMA-net with Vs_10m or Vs_30m





W.R.T. Vs_10m

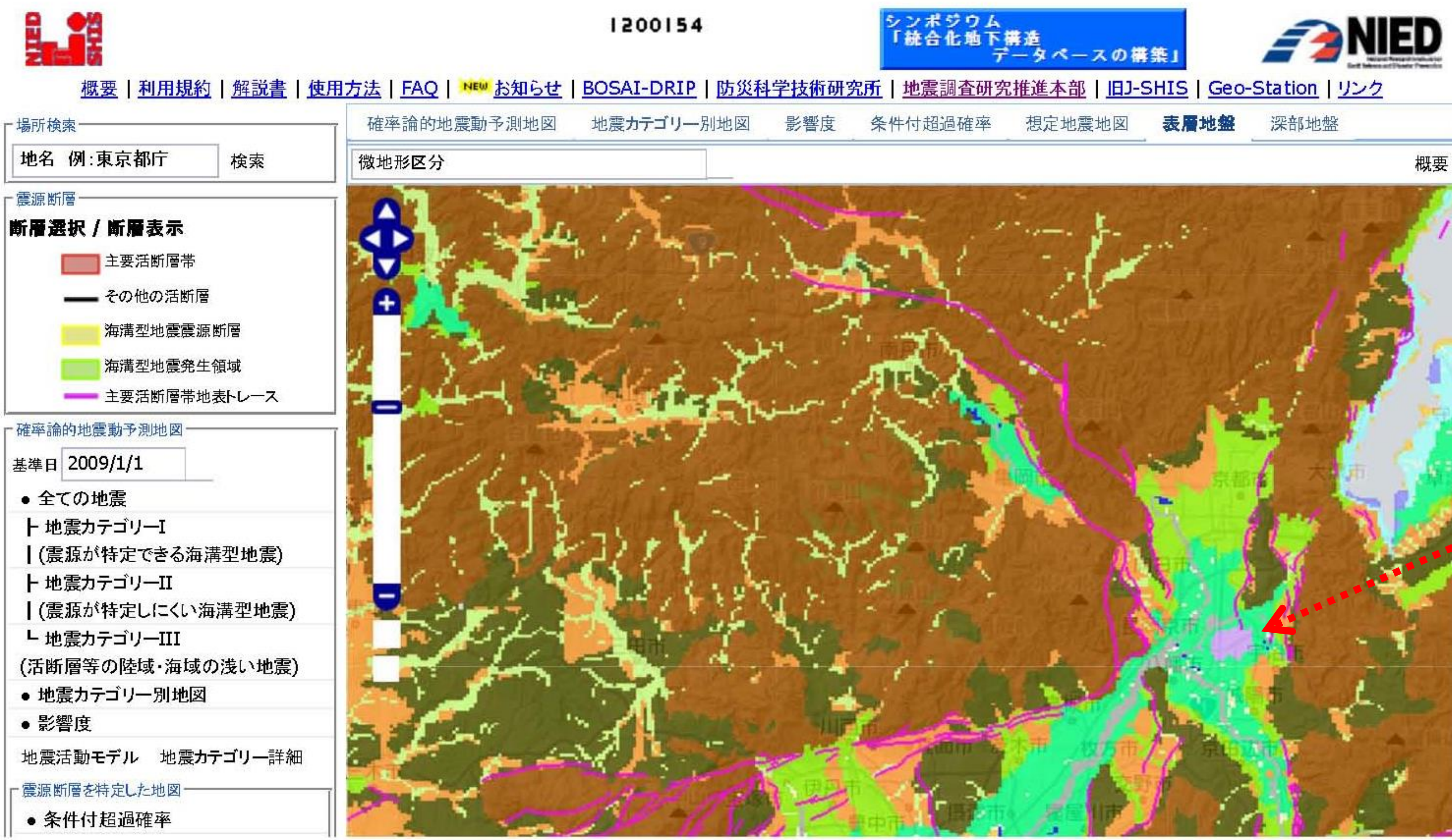




W.R.T. Vs_30m

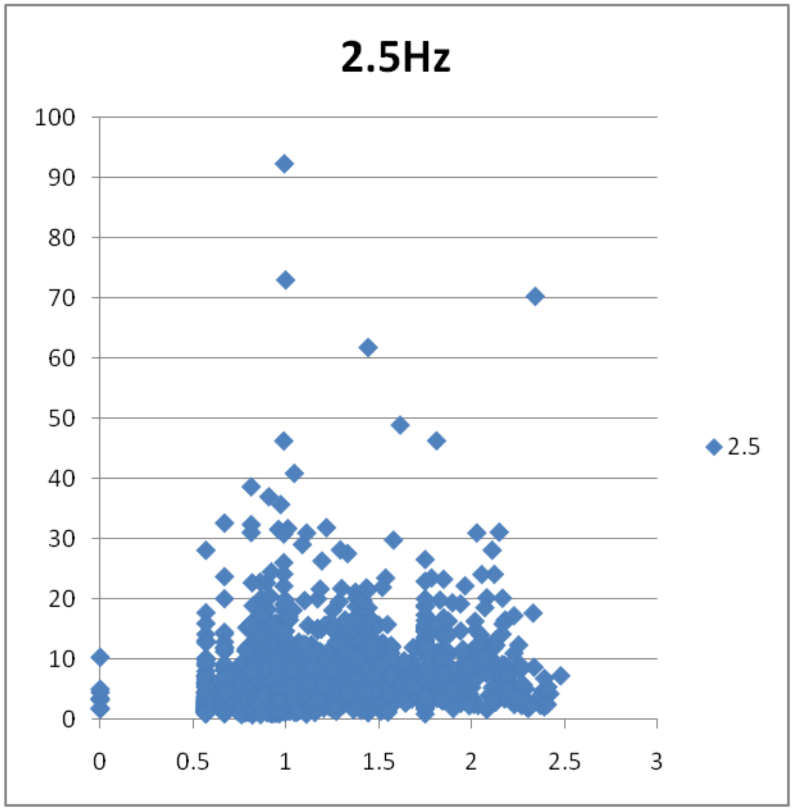
（Kawase & Mastuo, 2004)

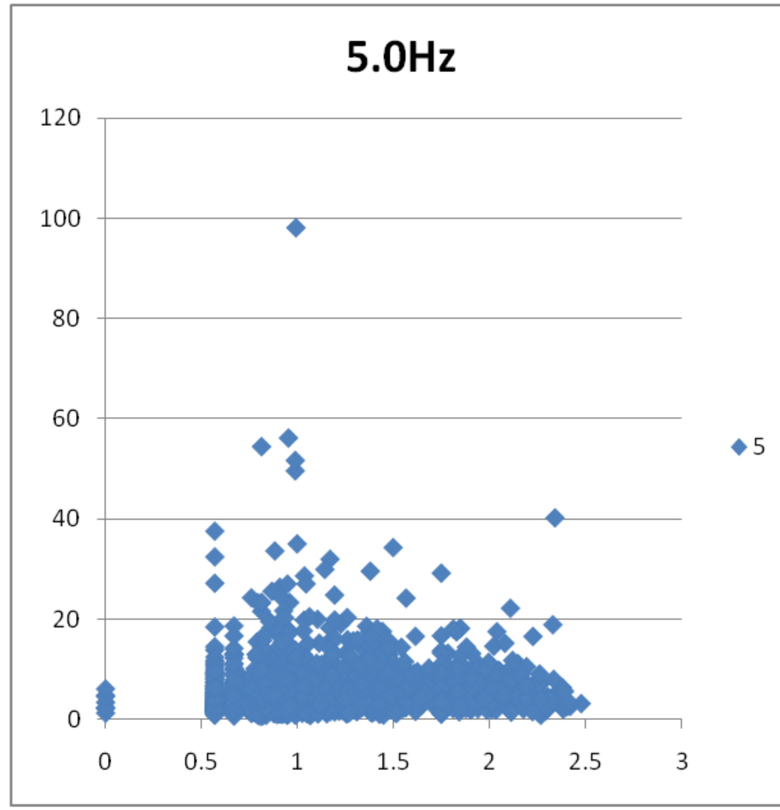
GIS data from land-use maps (NIED)



DPRI is here!

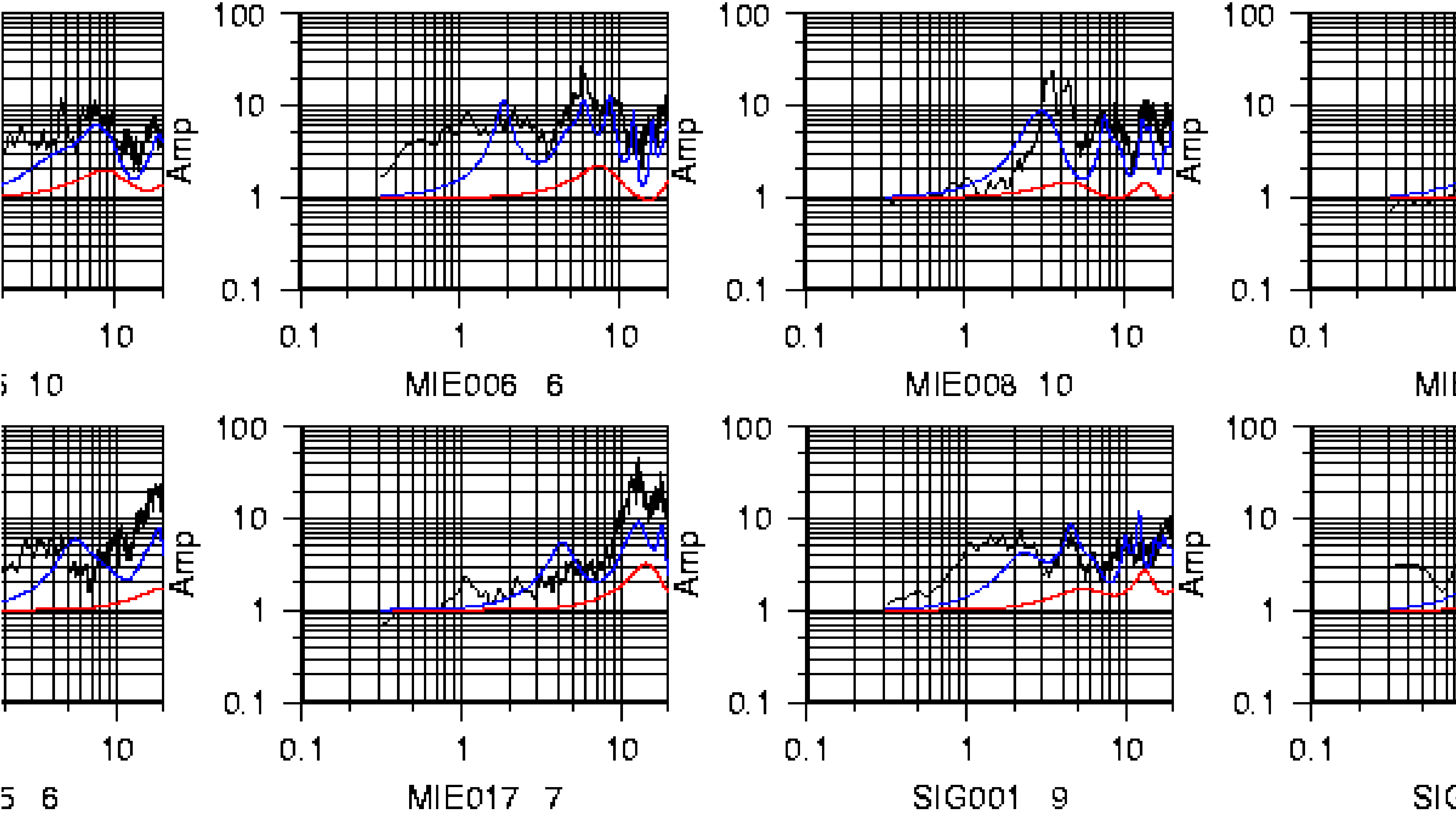
Correlation of site factors from observed spectra (1/3 octave band average) and those estimated from GIS-based Vs30





Almost no correlation!

Reproduction of Site Effects by 1D model Response (Red: 20m boring only, Blue: Inverted 1D, Black: Obs.)



What is the best method to get velocities down to the bedrock, then?

- Since the target of ESG simulation is GM characteristics to predict, it would be better to use earthquake data.
- However, it is costly to collect certain amount of records, especially in seismically less active areas where we need years of observation.
- Microtremor is much easier and much less costly, since we can place an instrument only 30 min at a site.

➔ But, can we really get reliable velocity ?

Problems associated with HVRs

1) Does earthquake HVR correspond to the site amplification factor of S-wave (of earthquake) ?
2) Does HVR of microtremors correspond to the Rayleigh (or surface) wave ellipticity ?
3) Is HVR of earthquake (EHVR) the same as HVR of microtremors (MHVR) or different ?

Q: What is the proper theoretical expressions for EHVR and MHVR, after all ?

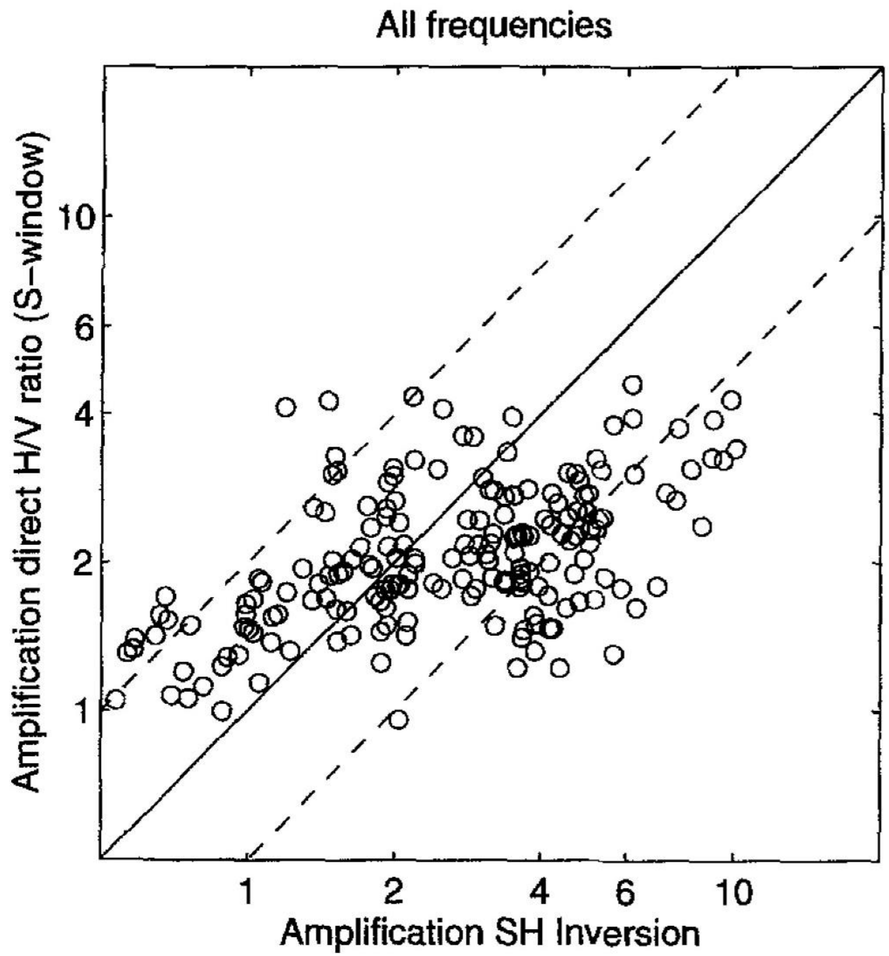
Does EHVR correspond to the site amplification factor of S-wave?

1) Nakamura (1980) said “yes” based on two dogmatic assumptions: no vertical component amplification from the bottom to the surface and unit HVR (=1.0) at the bedrock. There are many papers who support the idea but there are also more papers who does not, e.g.,

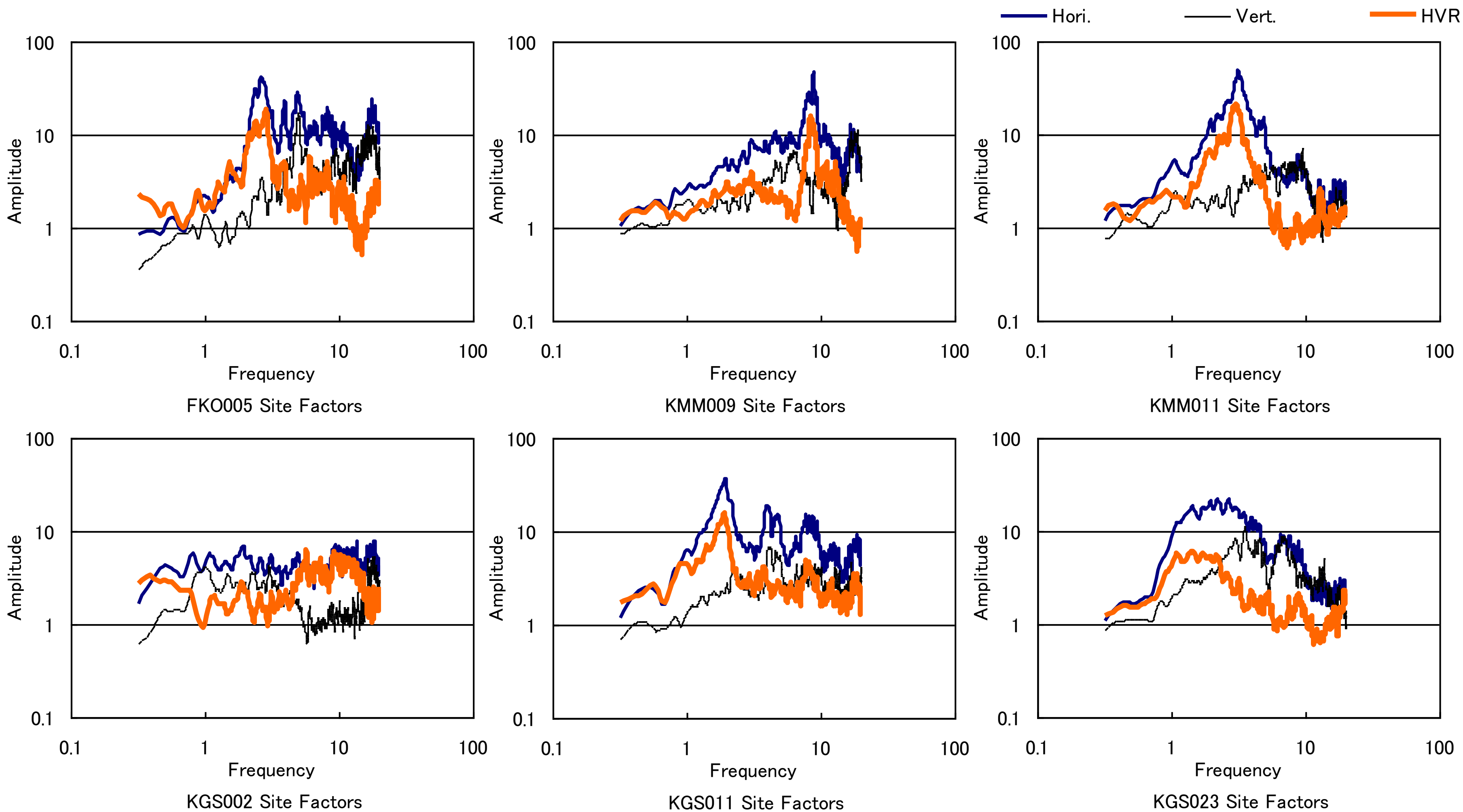
- Bonilla et al. (1997) showed that when compared frequency-by-frequency the amplitude of EHVR does not correspond to that of S-wave.
- Satoh et al. (2001) showed that when we have high impedance contrast, the observed HVR peak frequency corresponds to that of S-wave, but not the amplitude.
- Kawase and Matsuo (2004) show significant amplification in the vertical component.

➔DFA suggests that the answer is “No, it doesn’t.”

Bonilla et al. (1997); comparison of amplitudes by EHVR and S-wave, frequency-by-frequency



EHVR (Orange), HHR of Horizontal component (Blue), and VVR of vertical component (Black thin line)



Peak frequency is corresponding because VVR shows different frequency from HHR. However, VVR makes peak EHVR amplitude lower.

Does MHVR correspond to the Rayleigh (surface) wave ellipticity?

1) Aki (1957) showed statistically vertical component of microtremors must consist mainly of Rayleigh waves.
2) Nogoshi and Igarashi (1971) showed MHVRs in longer period range corresponds to the Rayleigh wave ellipticity.
3) There are many papers who used dispersion characteristics derived from array measurement of microtremors such as Horike (1985), Okada (1990), or Tokimatsu and Arai (1998).
4) Arai and Tokimatsu (2004) showed mixture of Rayleigh and Love wave gives similar HVR to observed MHVR.

➔ But we need mode participation factors to get proper amplitude!

➔DFA solves these problems.

What is the proper theoretical expressions for HVRs?

1) EHVR looks similar to S-wave amplification but not exactly the same.
2) MHVR looks similar to HVR of surface waves but we do not know relative contributions of S, P, Love and Rayleigh waves.

➔DFA provides complete yet compact solutions.

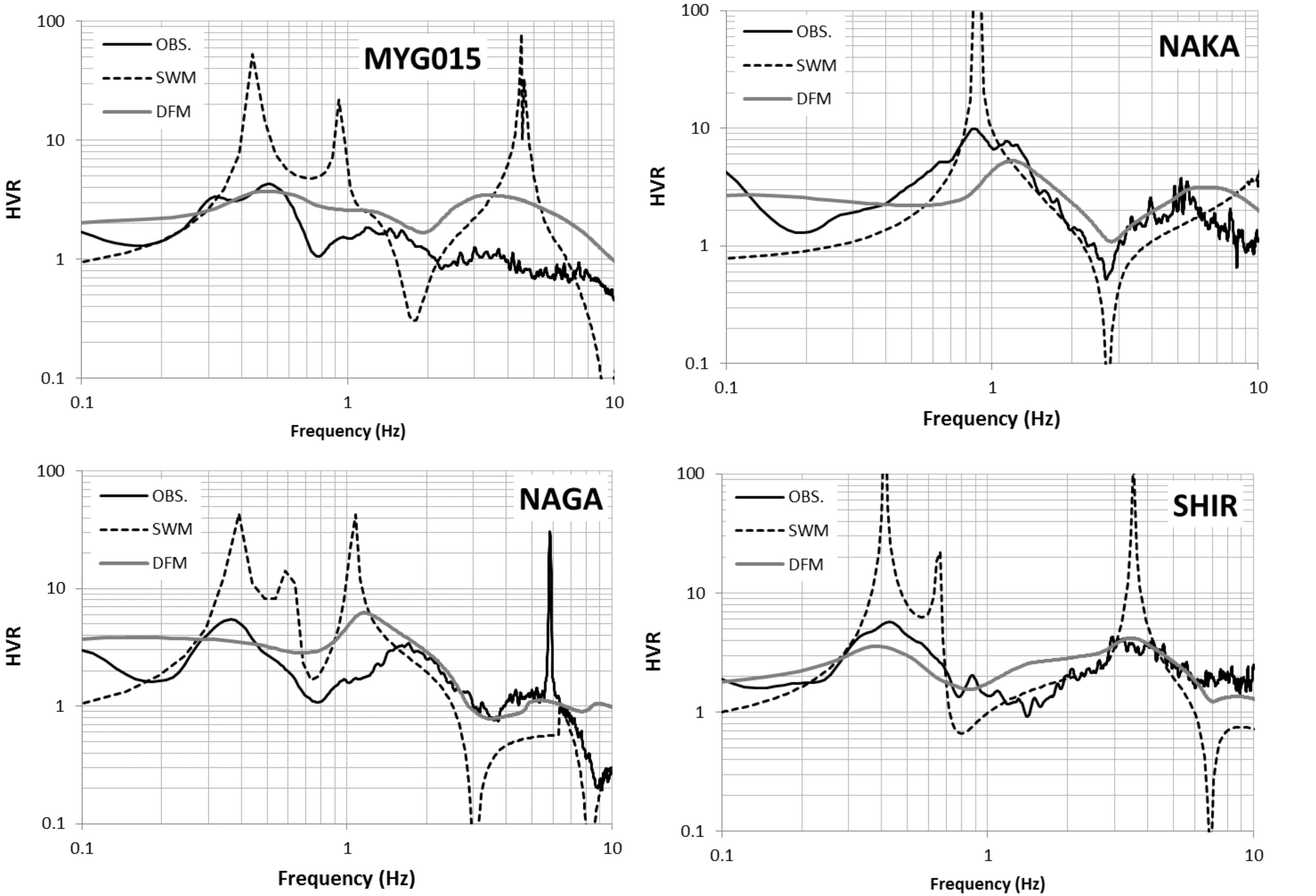
●Based on the diffuse field assumption, MHVR can be interpreted as **ratios of the imaginary part of horizontal Green's function w.r.t. vertical one**.

●Based on the diffuse field assumption, EHVR can be interpreted **as ratios of the S-wave amplification factor w.r.t. the P-wave one of vertical incidence**.

(Please come and see the lecture by Sanchez-Sesma!)

Validity of the DFA for MHVR

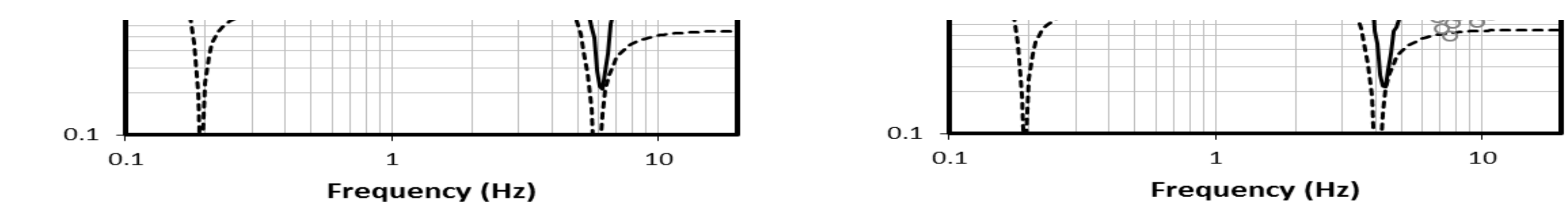
Kawase et al. (2015) compares to Satoh et al. (2001)



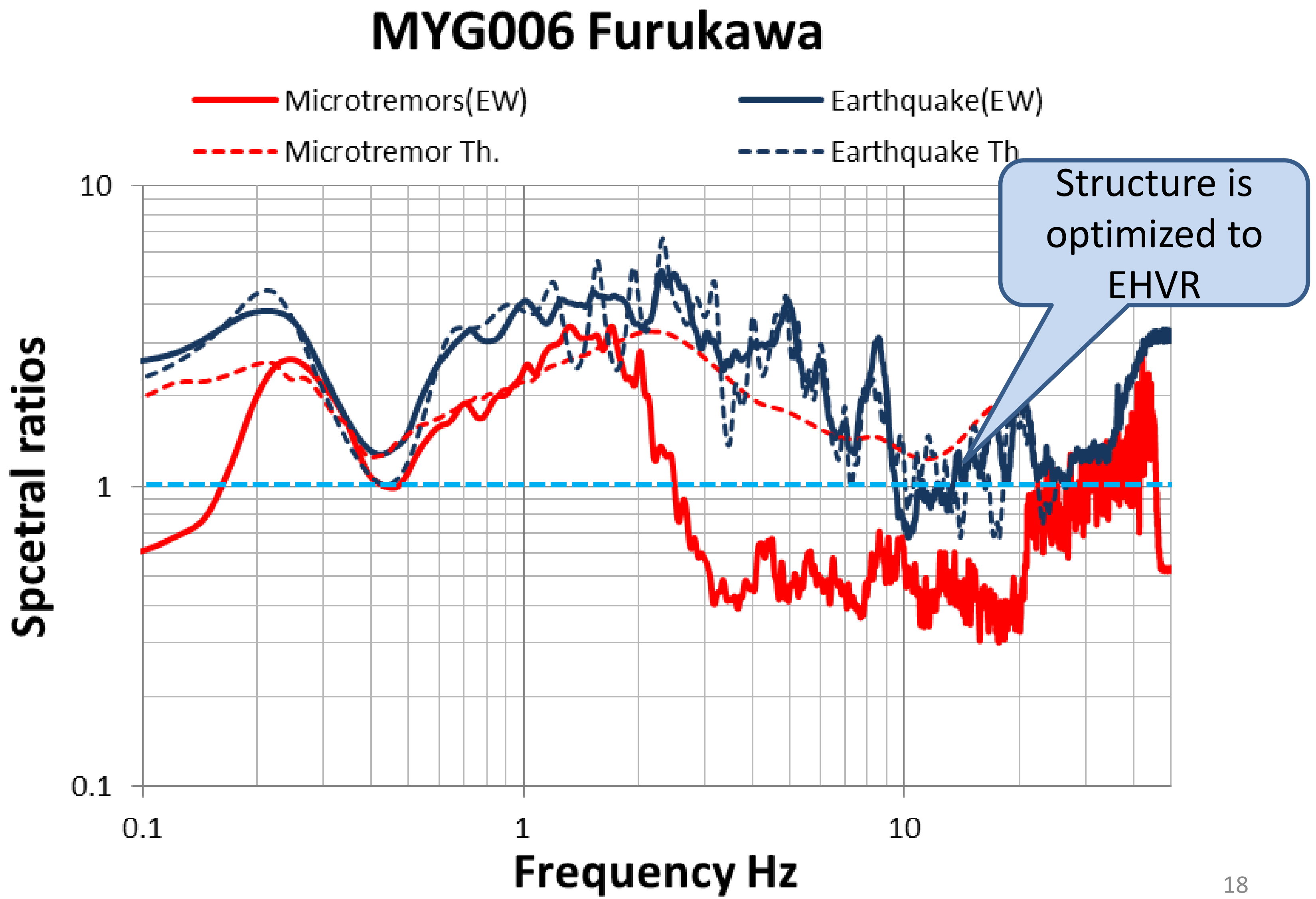
Validity of the DFA for MHVR

Kawase et al. (2015) compares to Arai and Tokimatsu (2004)

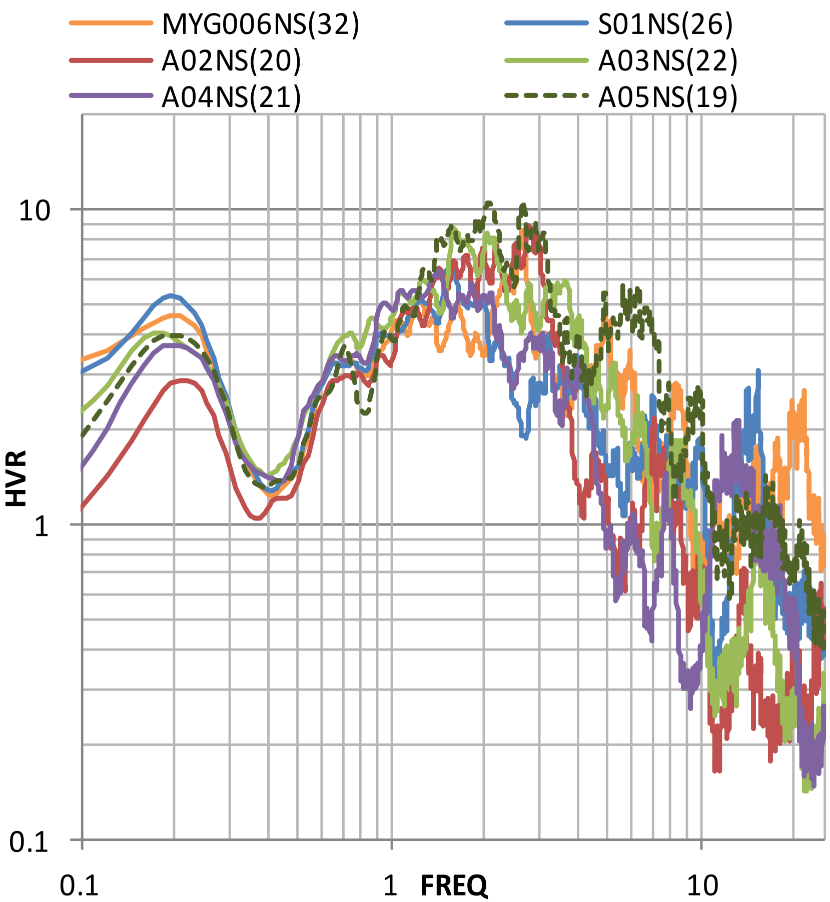
Here the relative amplitude ratio between Rayleigh and Love is assumed to be 0.4 by Arai & Tokimatsu (2004). These theoretical MHVRs are calculated for the inverted structures for the theory of Arai & Tokimatsu (2004). Note that sharp dips associated with zero horizontal amplitude in Rayleigh wave contribution in Arai & Tokimatsu (2004) are not filled up, while DFA theory in Kawase et al. (2015) can follow the data even at such dip frequencies.

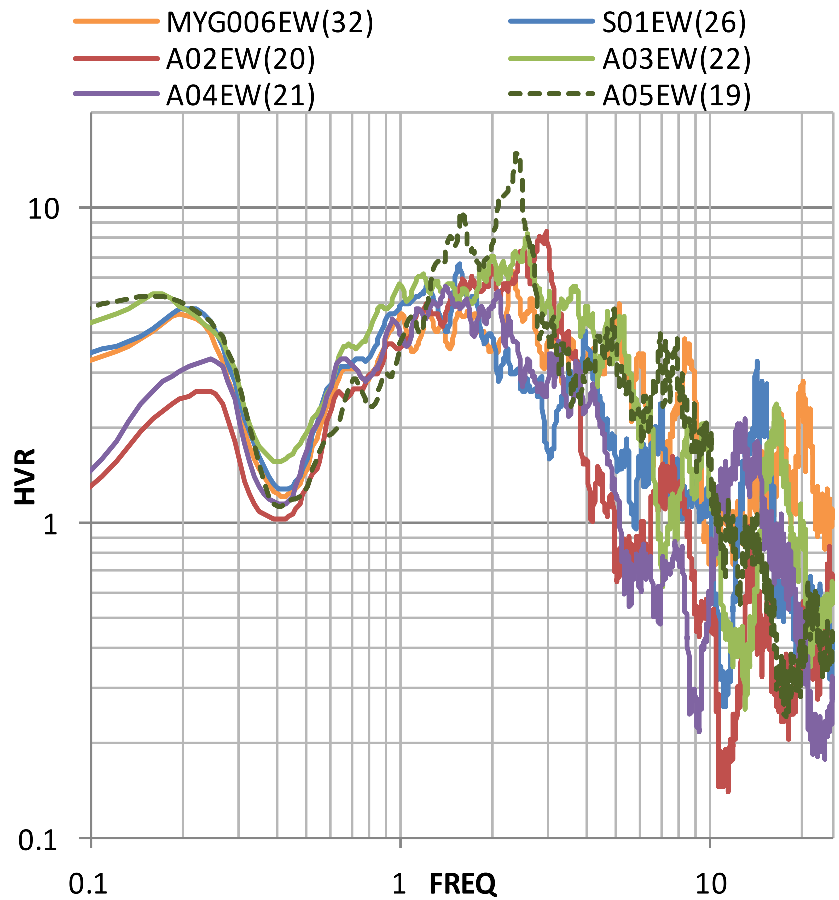


EHVR & MHVR @ K-NET MYG006

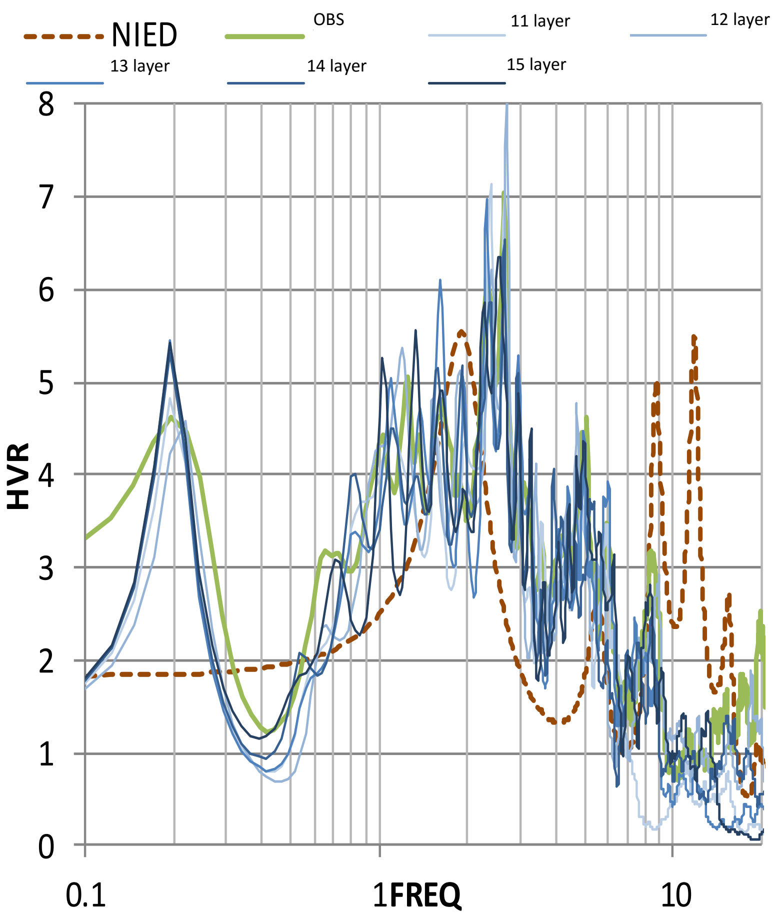


Low-freq. EHVR ← common; deep
High-freq. EHVR ← site dependent

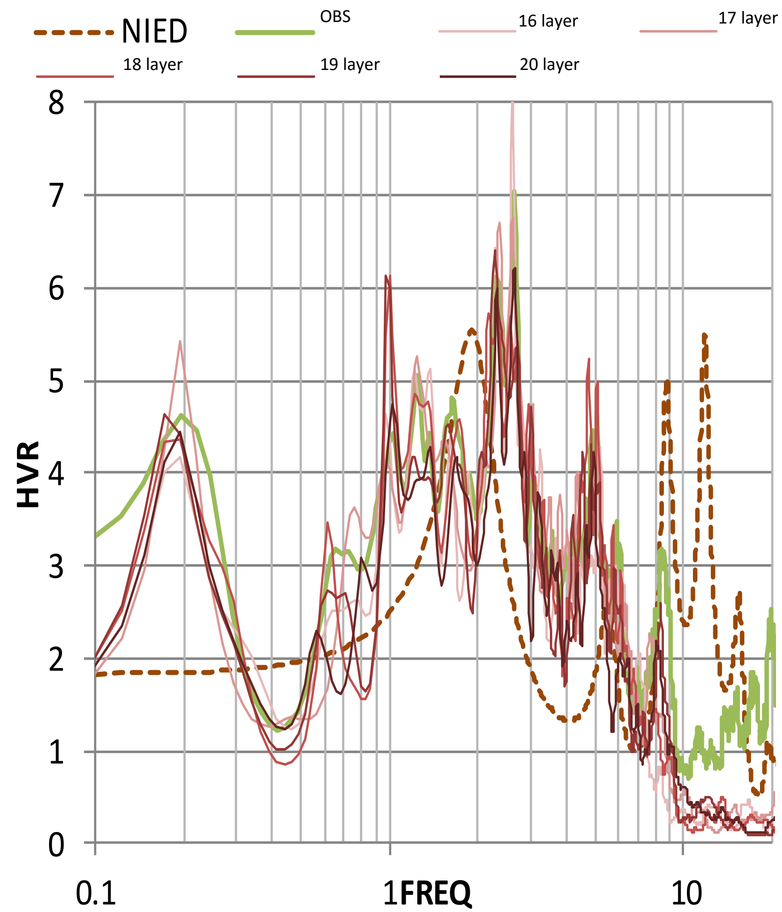




No. of layers that can be constrained by data (with the same depth)

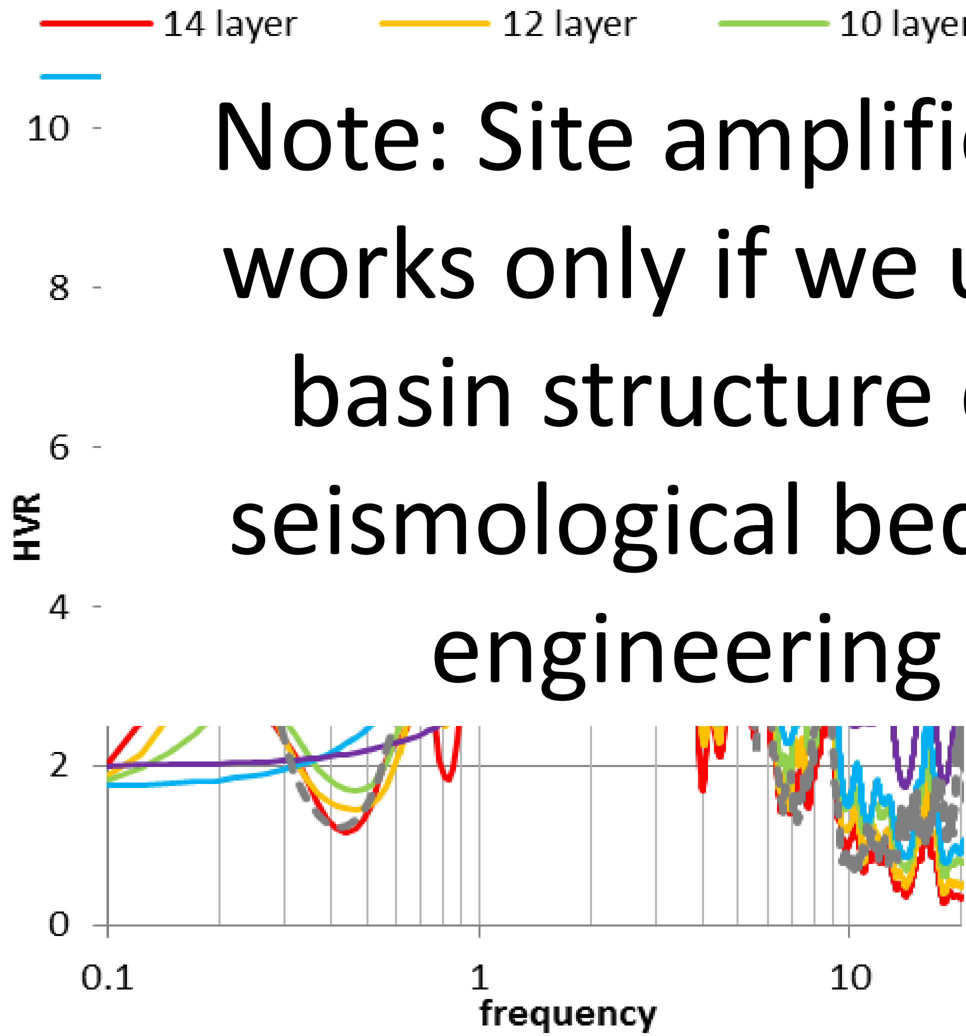


No. of layer = 11 to 15 layers



No. of layer = 16 to 20 layers

We should note that "the whole basin structure contributes to high-freq. EHVR"



Note: Site amplification by GRA works only if we use the whole basin structure down to the seismological bedrock, not the engineering bedrock.

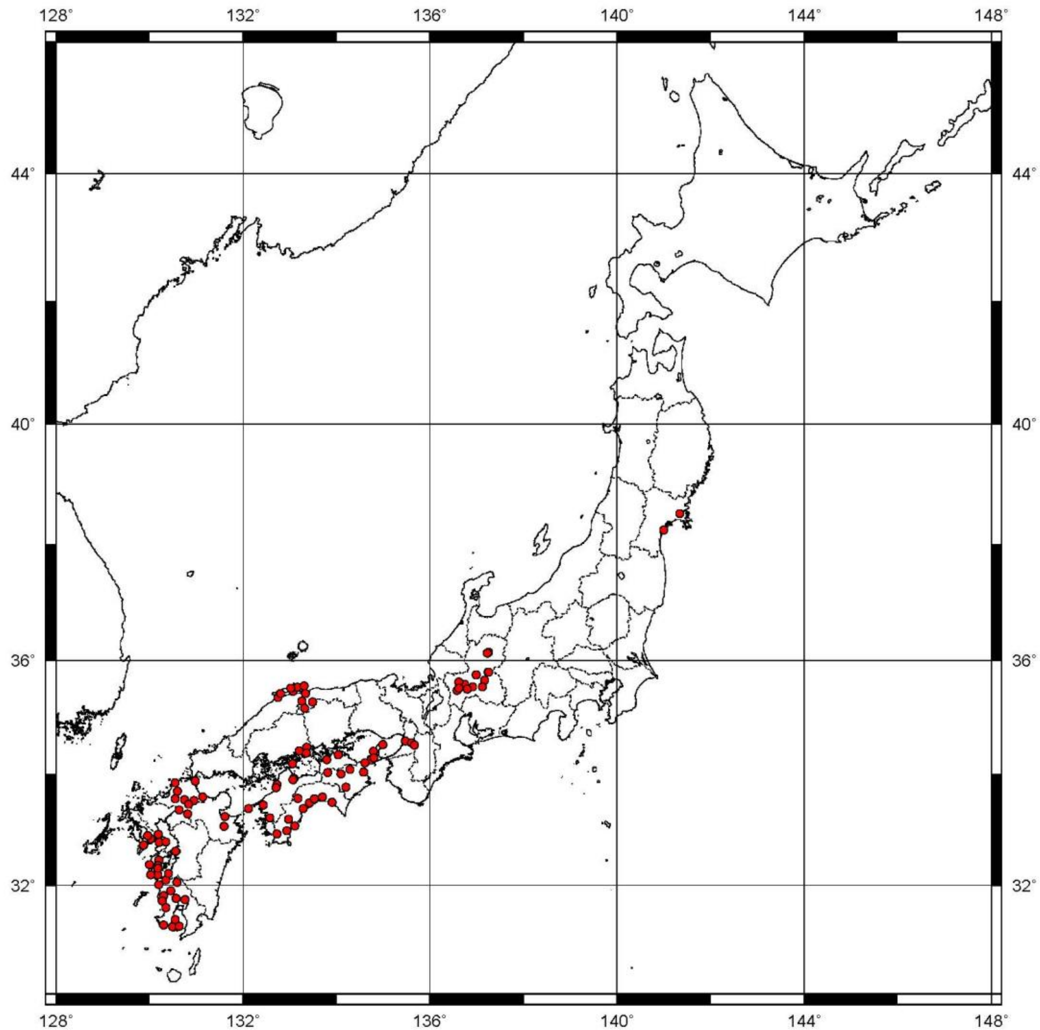
					sity m3]
					1.54
					1.57
					1.63
					1.64
					1.74
					1.78
					1.86
					1.94
					2.03
					2.11
11	1593	3564	662	1497	2.25
12	2006	4171	238	1735	2.35
13	2404	4695	1245	2980	2.44
14	3400	5744	0	2980	2.64

Background of the proposed EMR method

- The theory for MHVR was proposed by Sánchez-Sesma et al. (2011), but it needs a lot of computational time since we need **wavenumber summation**.
- Velocity-structure inversion **using EHVR is very easy** and already proved to be very effective as shown in Ducellier et al. (2013) and Nagashima et al. (2014).
- We know that MHVR and EHVR are similar but not the same, especially in the high frequency range.

If there is a meaningful relationship between MHVR and EHVR, we can transform MHVR into pseudo EHVR to estimate velocity structures using theoretical EHVR.

We conducted a systematic study (Mori et al., 2016)

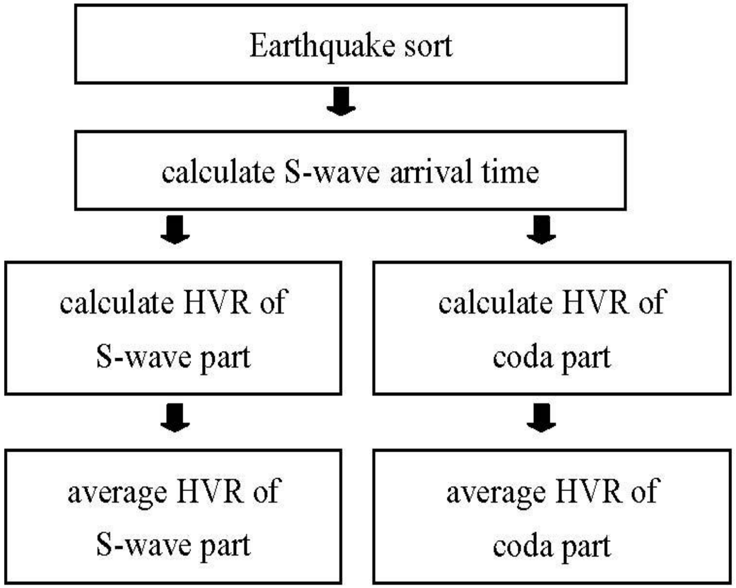


- Target point

  K-NET and KiK-net
- At these sites records are available for earthquakes by NIED and microtremors by ourselves
- total 100 points

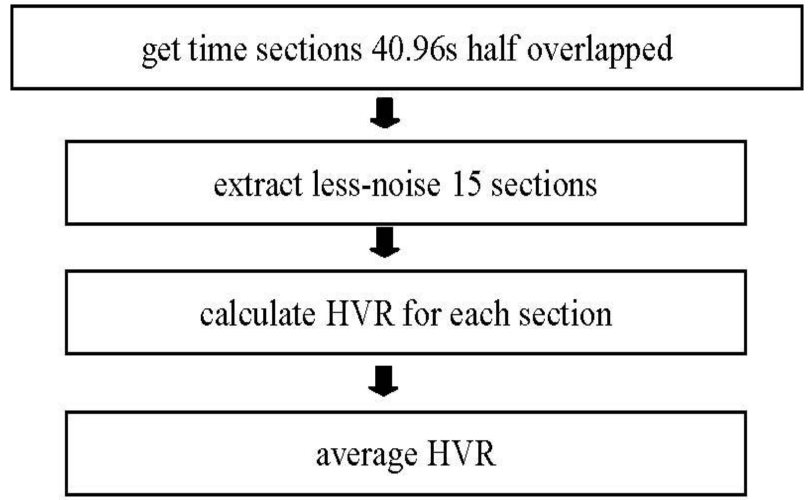
Spectral Analysis

Earthquakes



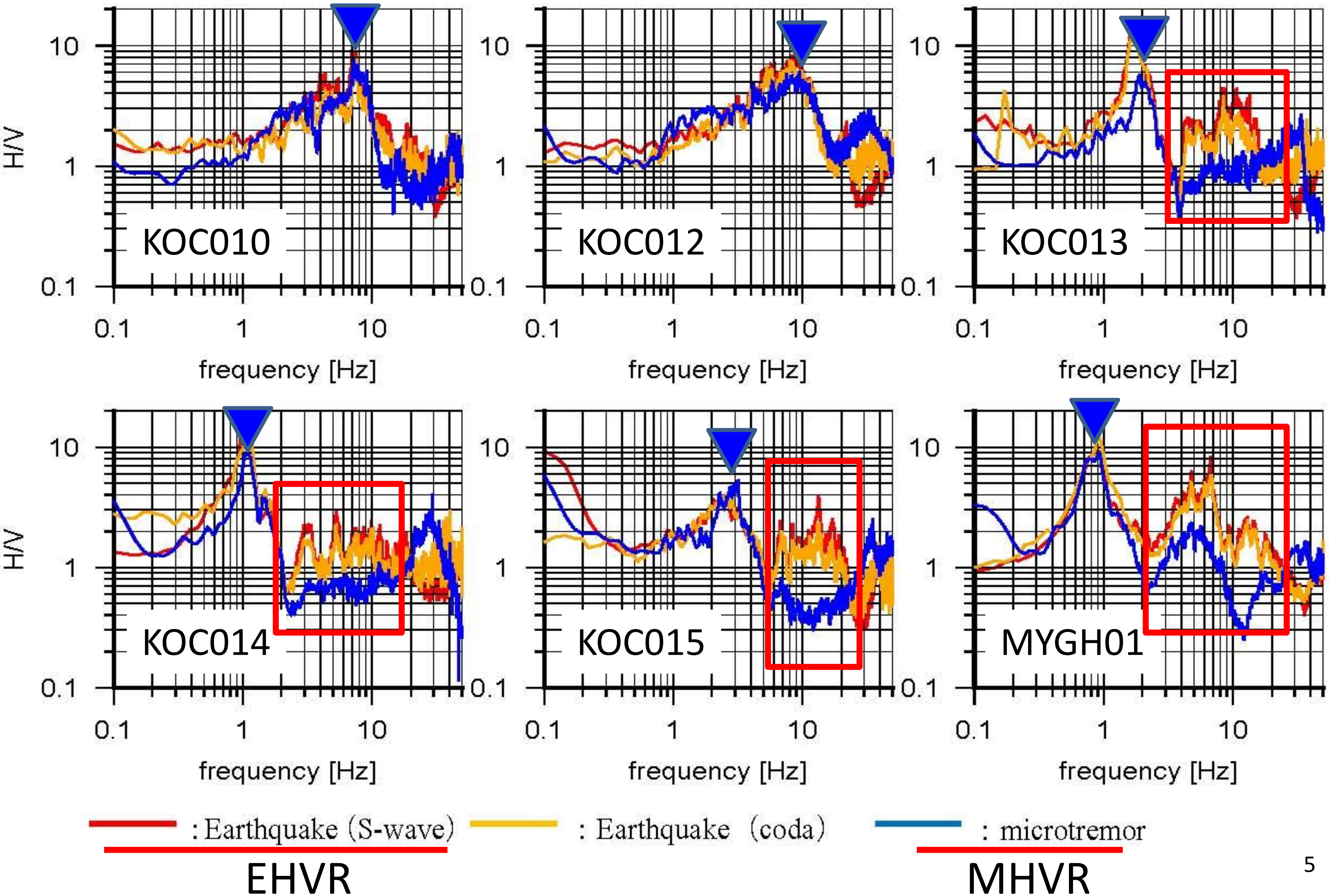
- 1.0 gal ≦ Peak Acc. ≦ 50.0 gal
- M_{jma} ≦ 6.5
- record section 40.96 s
- using cosine function at both ends
- Parzen window 0.1 Hz
- SNR≧2.0

Microtremors

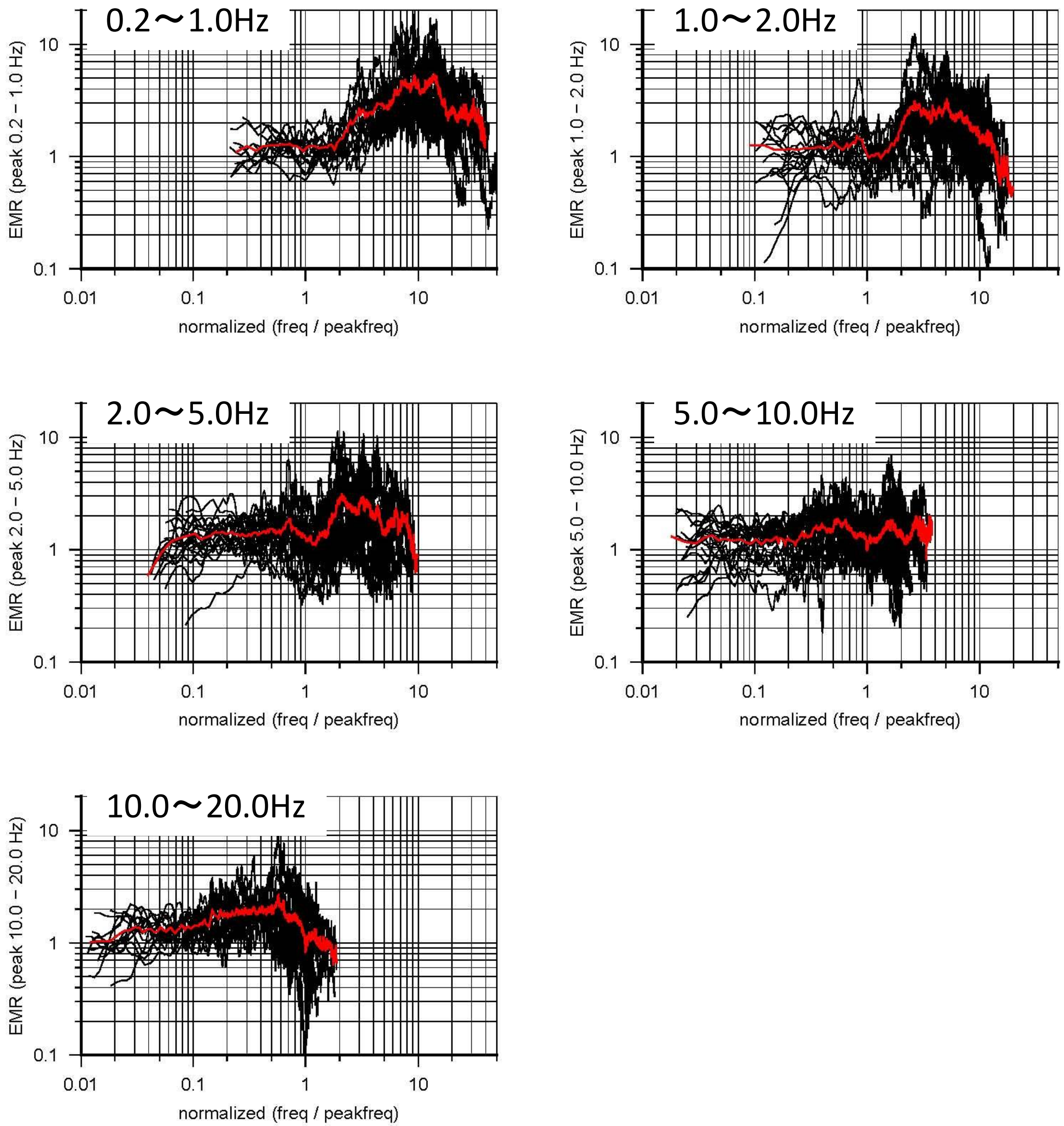


- record section 40.96 s
- using cosine function at both ends
- Parzen window 0.1 Hz

Observed results



Calculating EMR



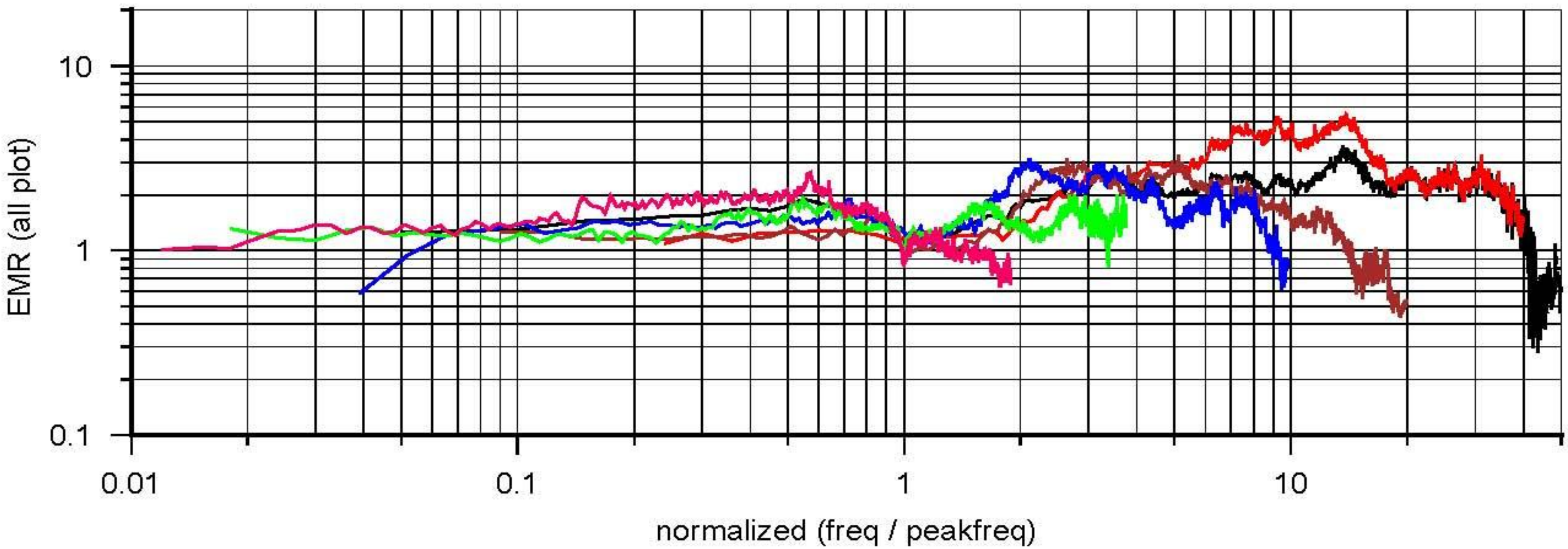
- Horizontal axis

  frequency normalized by peak frequency of MHVR
- Selection of points

  when having clear 1st peak at 0.2～20.0 Hz in MHVR
- Categorize with peak frequency of MHVR
- In total we have 87 points, 14 to 20 in each category.

Comparison of each category's EMR

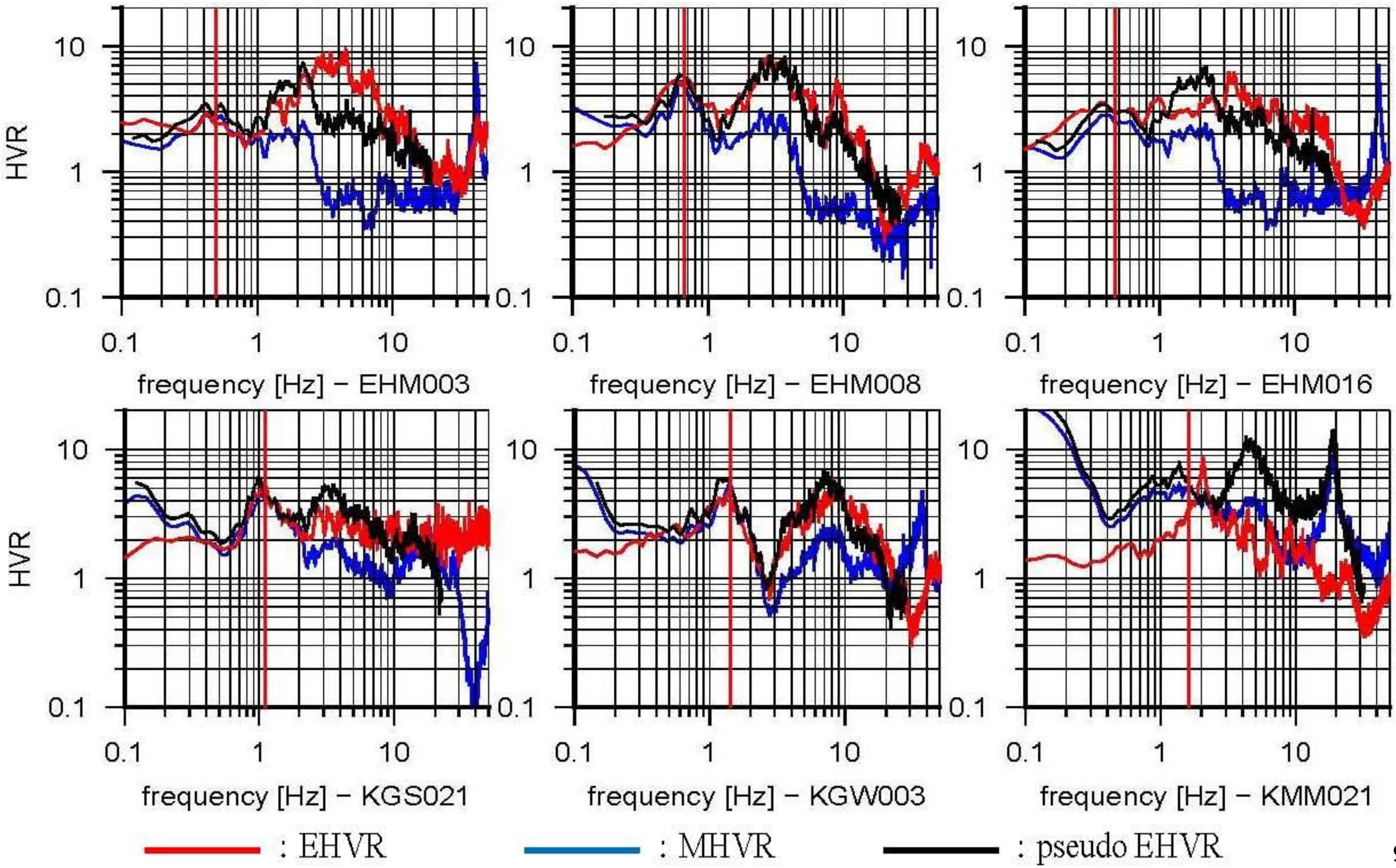
category	Category-1	Category-2	Category-3	Category-4	Category-5
peak freq	0.2 – 1.0 Hz	1.0 – 2.0 Hz	2.0 – 5.0 Hz	5.0 – 10.0 Hz	10.0 – 20.0 Hz
station	15	17	21	20	14
pitch ⊿	0.06	0.03	0.013	0.006	0.003



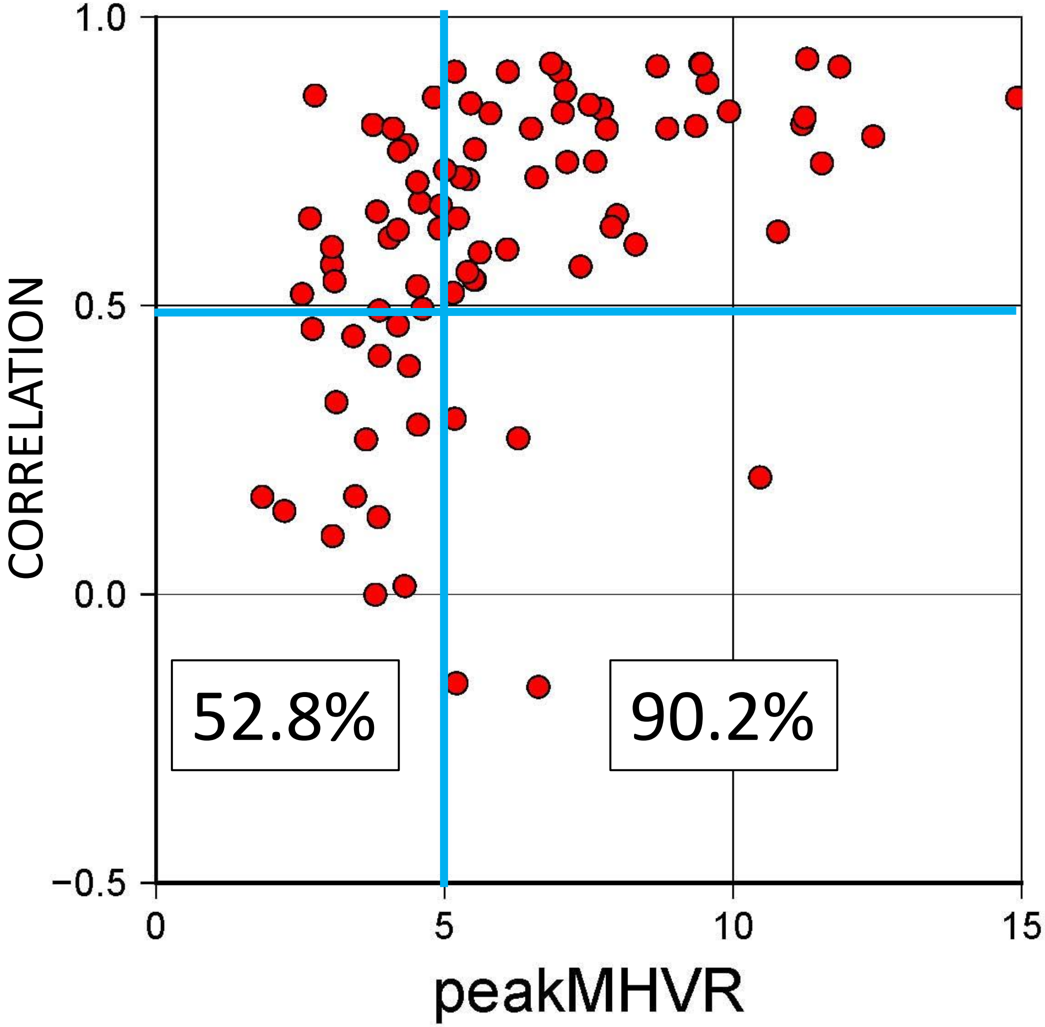
Since they are similar to each other if it is adjacent but they are different if it is not, we use each category's EMR.

Calculated pseudo EHVR

$$\text{Pseudo EHVR}(f) = \text{MHVR}(f) \times \text{EMR}(f)$$



Pseudo EHVR effectiveness



$$\text{CORRELATION} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}}$$

X: EHVR, Y: pseudo EHVR

Large peak in MHVR

≈

Large contrast in velocity structure

There is high correlation between EHVR and pseudo EHVR

Inversion method & its parameter

Target： EHVR, pseudo EHVR, and MHVR

No.	Vs [m/s]	Vp [m/s]	Ro [g/cm3]	H [m]
1	350	1600	1.85	sum of layers （ 350≤Vs＜600） at J-SHIS
2	650	2000	1.95	sum of layers （ 600≤Vs＜900） at J-SHIS
3	1200	2600	2.15	sum of layers （ 900≤Vs＜1500） at J-SHIS
4	1800	3600	2.35	sum of layers （1500≤Vs＜2100） at J-SHIS
5	2400	4500	2.45	sum of layers （2100≤Vs＜2700） at J-SHIS
6	3000	5500	2.60	sum of layers （2700≤Vs＜3300） at J-SHIS
7	3300	5700	2.70	semi-infinite ground

borehole data

No.	Vs [m/s]	H [m]
1	290	5
2	590	5

J-SHIS data

No.	Vs [m/s]	H [m]
1	350	4
2	650	6
3	1200	10
4	1800	20
5	2400	60
6	3000	1915
7	3300	0

: adding layer

No.	Vs [m/s]	H [m]
1	290	5
2	590	5
3	790	1
4	990	1
5	1190	1
6	1200	7
7	1800	20
8	2400	60
9	3000	1915
10	3300	0

Genetic algorithm
+
Simulated annealing

Yamanaka et al.(2007)

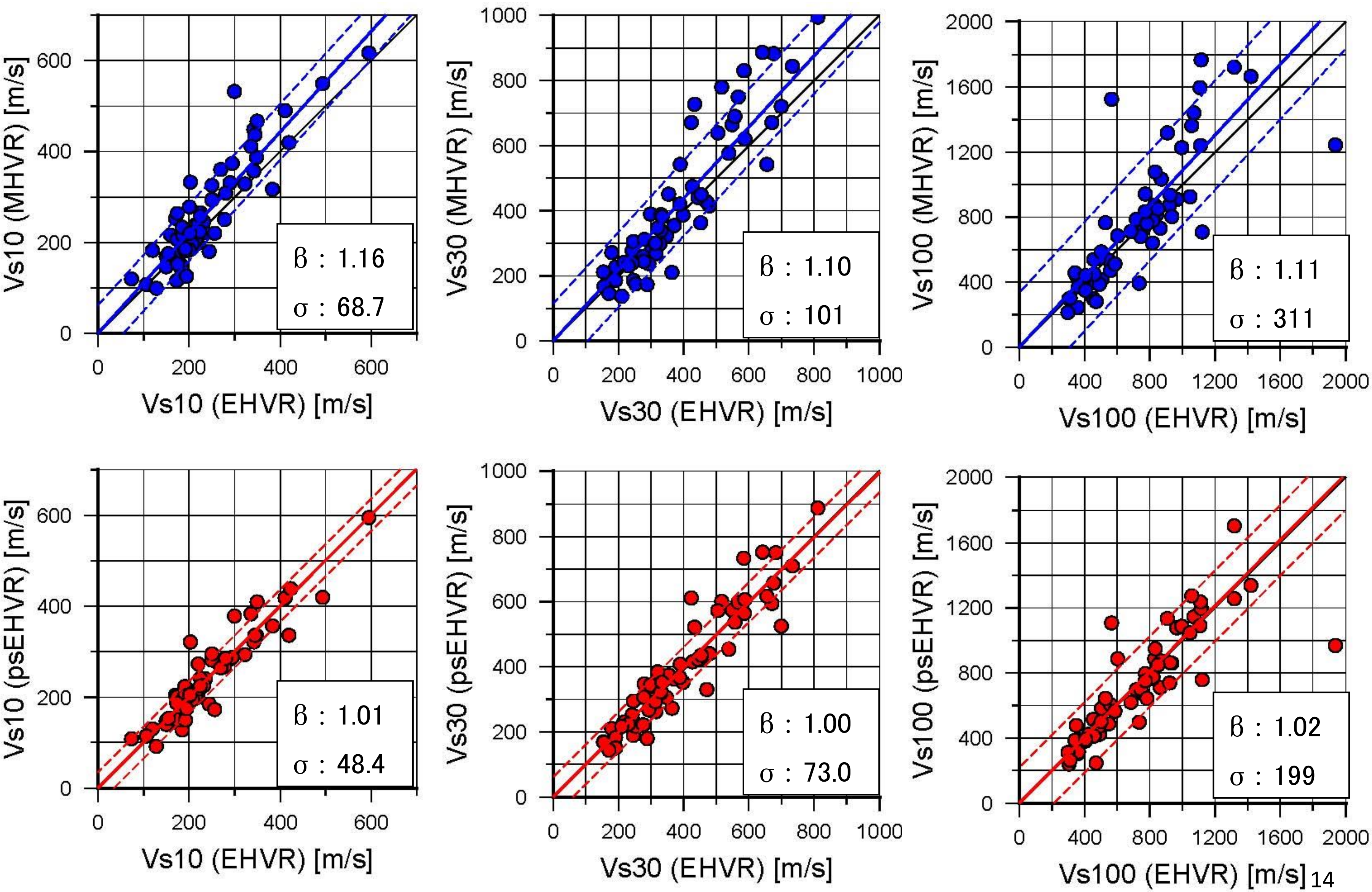
- population: 200 gen: 200
- cross: 0.7 mutation: 0.1
- attenuation: 1.1%
- searching range:

  Vs:30% H:0%（borehole）

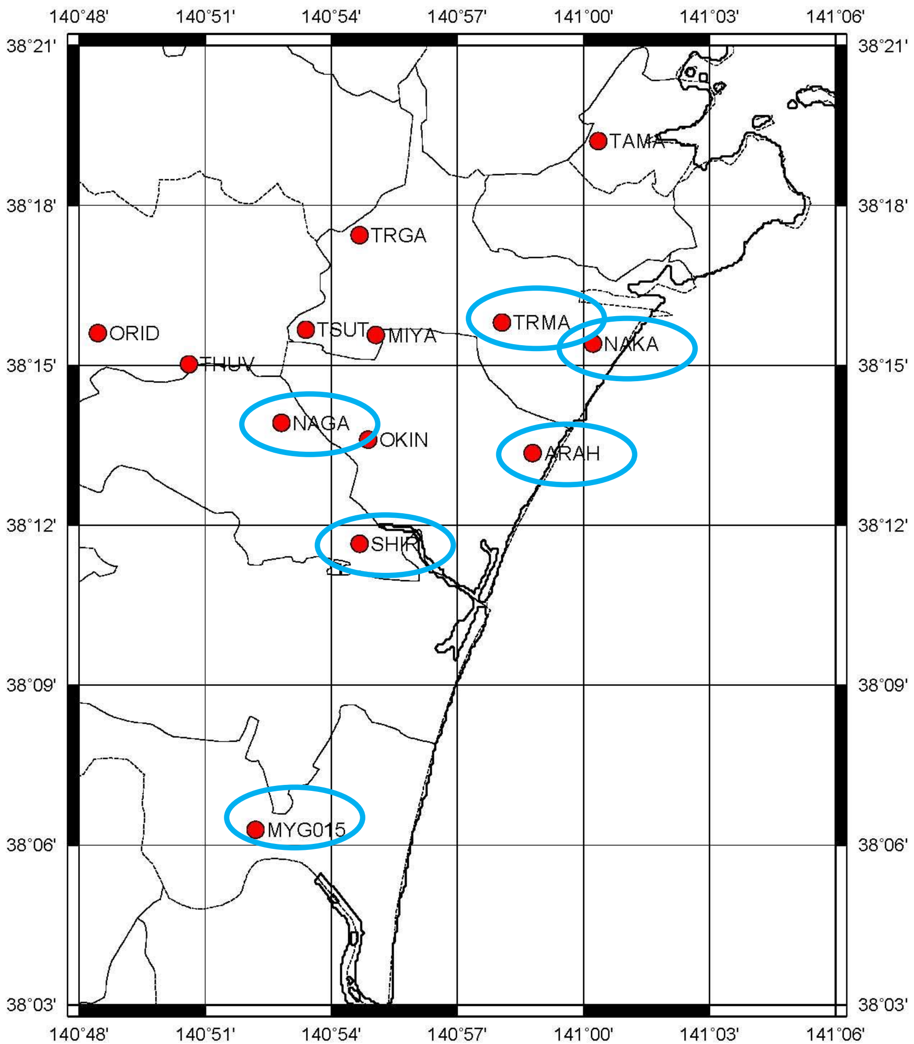
  Vs:fixed H:free（J-SHIS）

Referring to Nagashima et al.(2014)

Comparison of average Vs



Verification



- Independent target points:

  Targets are where we can get MHVR & EHVR and already estimate velocity structure by Satoh et al. (2001).

- In total we have 6 sites:

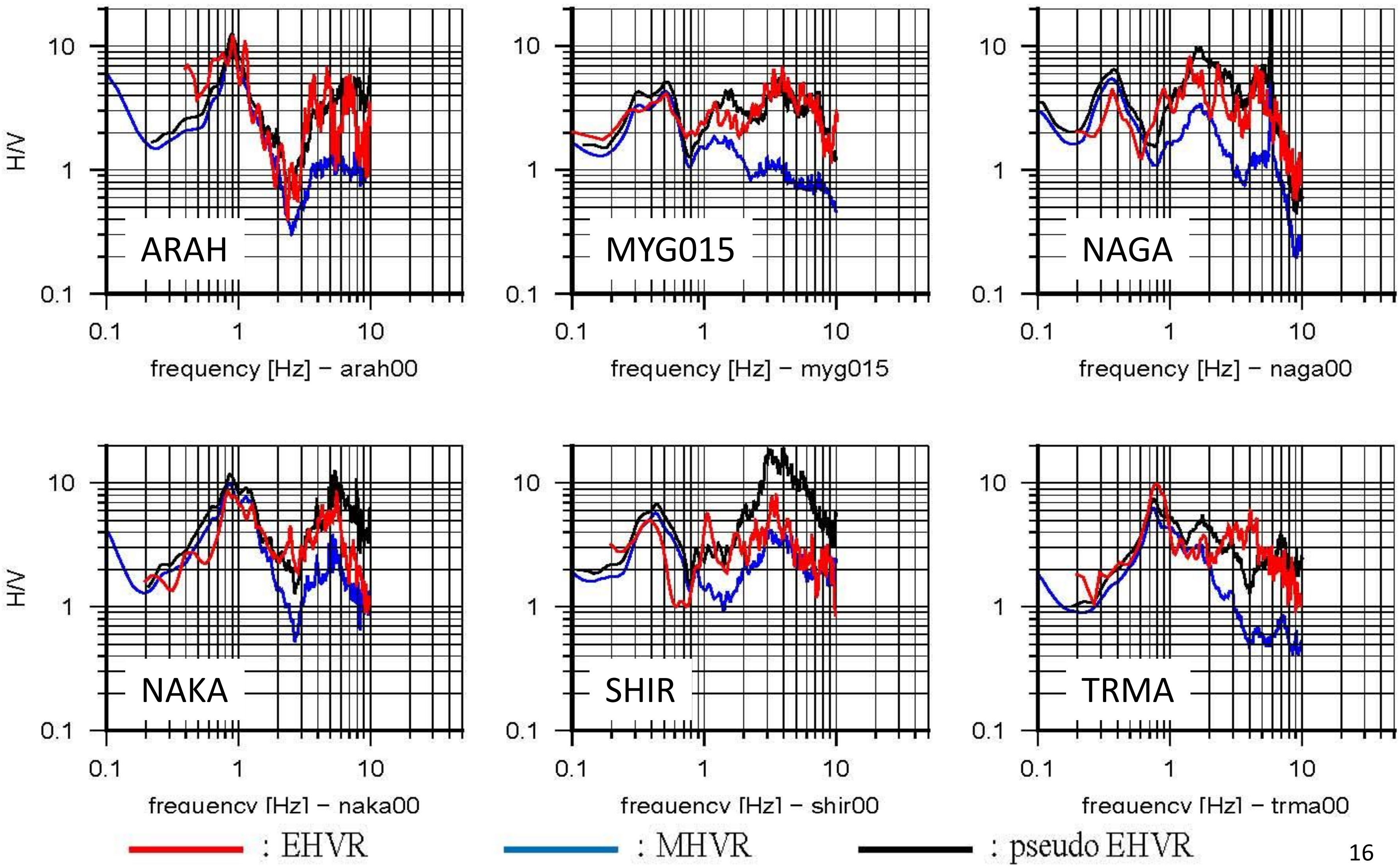
  ARAH, MYG015,

  NAGA, NAKA, SHIR,

  TRMA.

Calculated pseudo EHVR

Pseudo EHVR（f）＝ MHVR（f） × EMR（f）



Soil model（using a-priori information）

MYG015

No.	Thickness (m)	Depth (m)	Vp (m/s)	Vs (m/s)	density (g/cm3)
1	2.0	2.0	370.0	100.0	1.56
2	2.0	4.0	1600.0	100.0	1.62
3	4.0	8.0	1600.0	180.0	1.74
4	9.0	17.0	1600.0	250.0	1.85
5	79.1	96.1	1600.0	410.0	1.97
6	266.0	362.1	2000.0	850.0	2.10
7	565.9	927.0	3300.0	1700.0	2.34
8	∞	∞	6100.0	3500.0	2.70

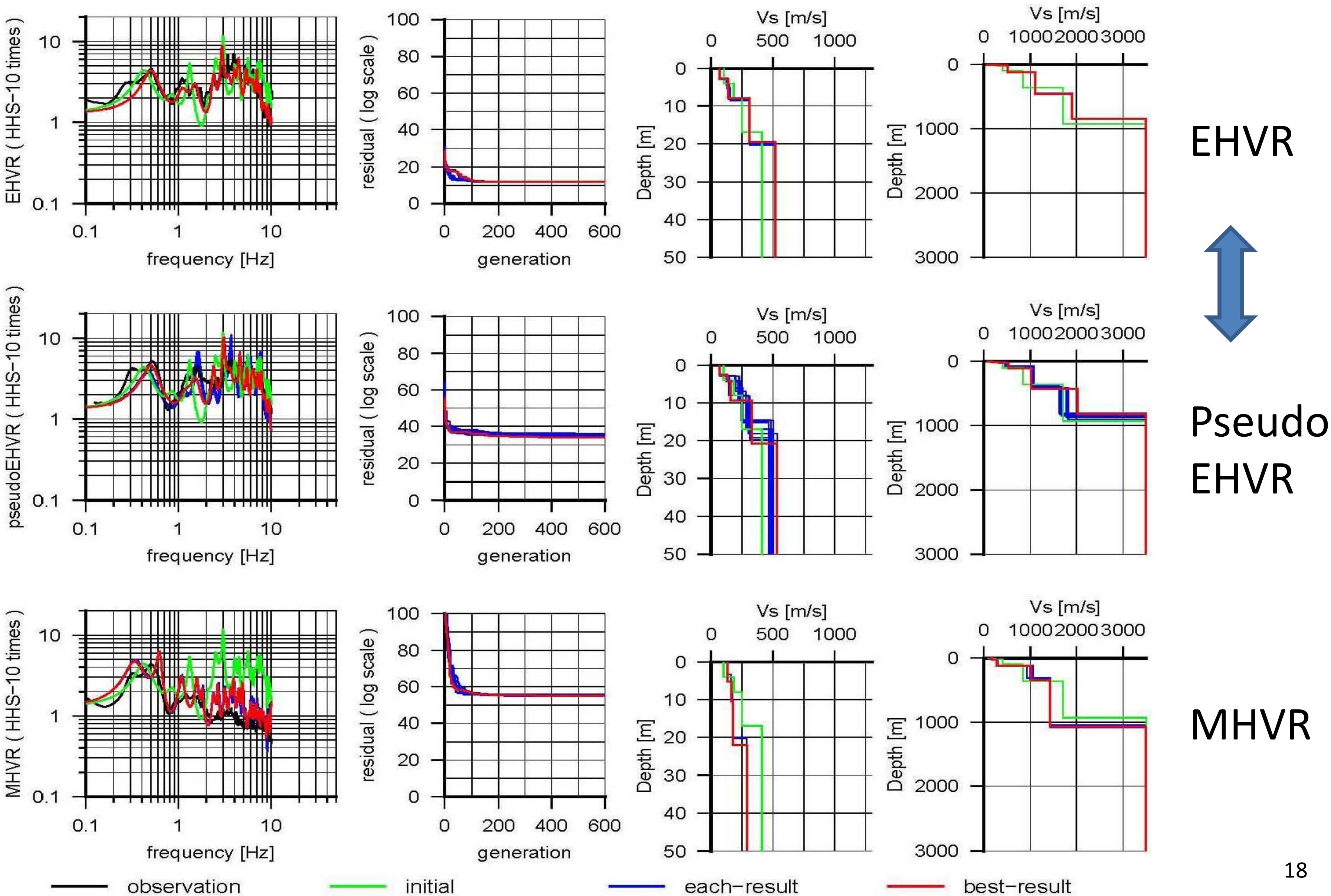
$$\mathrm{misfit} = \sum \frac{\left(\log(\mathrm{HV_{obs}}) - \log(\mathrm{HV_{the}})\right)^2}{\mathrm{f}}$$

We set initial models based on the inversion results by Satoh et al. (2001), although we do not need initial models.

- searching range
  Vs: ±30%　H: ±30%
- attenuation: 1.1%
- population: 200　gen: 600
- cross: 0.7　mutation: 0.1
- calculate 10 times and choose the result whose misfit is minimum.

Result（using a-priori info.）

MYG015



HVR residuals

	ARAH	MYG015	NAGA	NAKA	SHIR	TRMA
Satoh et al.(2001) (EHVR)	61.9	57.9	231.9	72.2	93.9	78.0
prior-model result (EHVR)	0.0	0.0	0.0	0.0	0.0	0.0
prior-model result (pseudo EHVR)	21.5	9.0	23.4	31.3	48.7	24.0
prior-model result (MHVR)	57.5	75.1	81.3	33.7	49.4	121.6

If this is true

When we did inversion for MHVR (EMR=1), we can still get the results satisfied with MHVR using EHVR theory, but the obtained velocity structures are different.

Conclusions

- We need a velocity structure down to the seismological bedrock for quantitative evaluation of site amplification.
- In order to use single-station microtremor records for the whole velocity structure inversion, we proposed to use empirical ratios between EHVR and MHVR (=EMR) to compensate difference in EHVR and MHVR.
- Using EMR we can get "pseudo EHVR" which has higher correlation with EHVR than MHVR.
- We inverted velocity structures by using EHVR, MHVR, and pseudo EHVR through DFA theory on EHVR, and found that velocities obtained from pseudo EHVR were closer to those obtained from EHVR than MHVR.

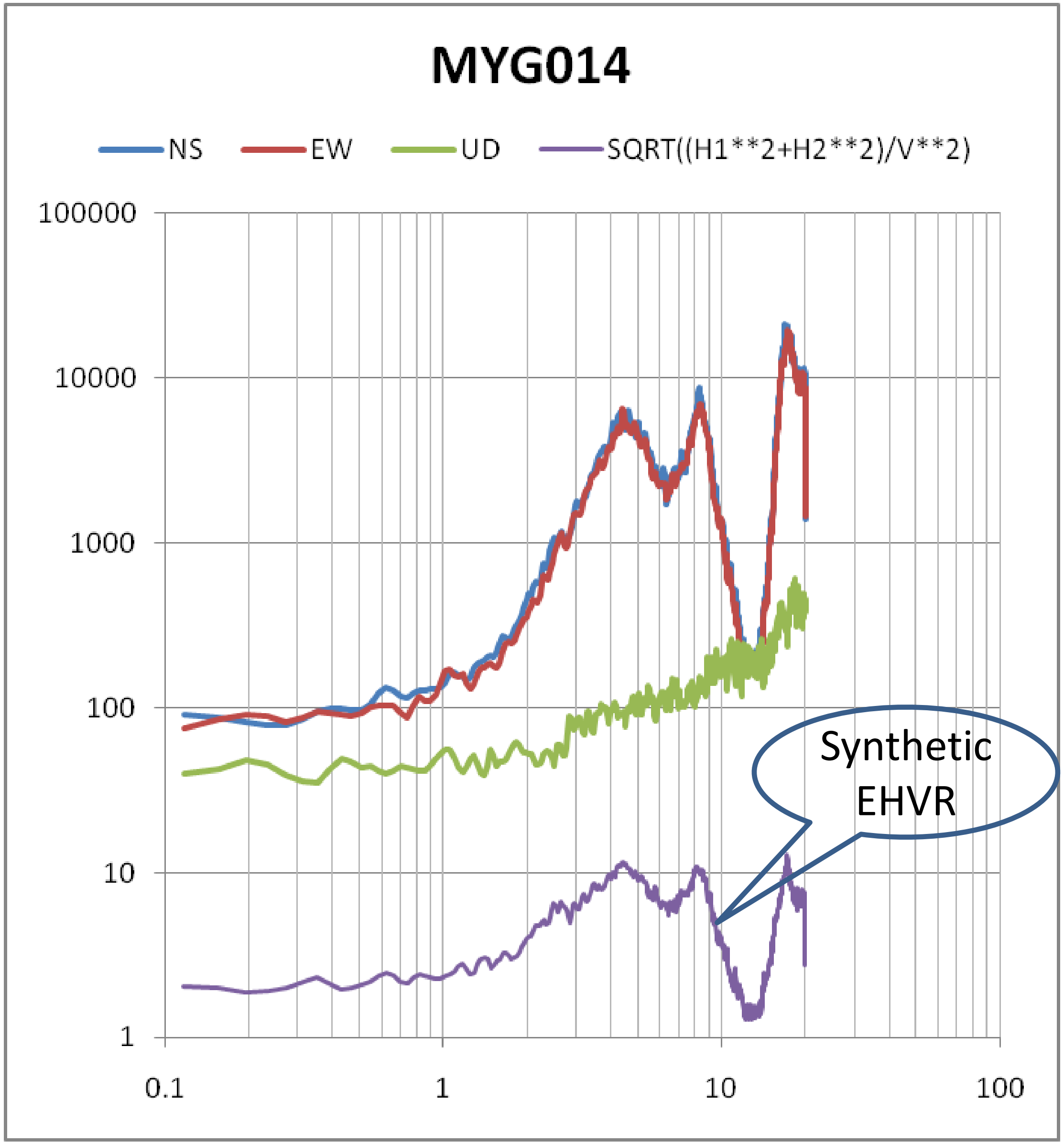
Future works

- We need to establish standardized way to make initial models with proper searching ranges based on observed microtremors w/wo a priori geological information.
- We need to do joint-inversion for MHVR and EHVR to better reproduce both characteristics simultaneously.
- Empirically we can obtain S-wave amplification directly from pseudo EHVRs, assuming the average Vertical-to-Vertical amplification.

Thank you for your attention.

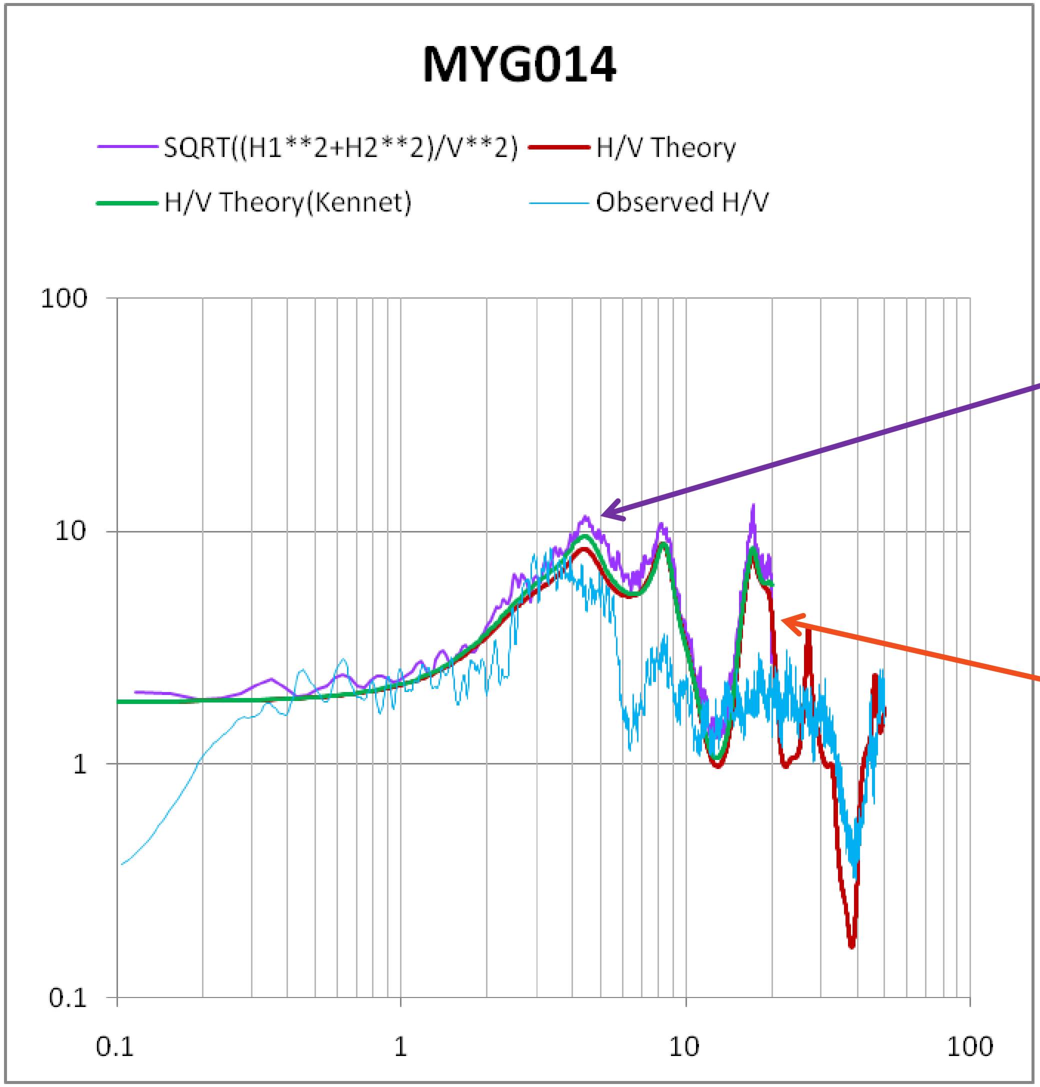
Acknowledgement:
KiK-net and K-NET data are provided by NIED and Sendai array data are provided by T. Satoh.

Simple synthetics test



300 S-wave and 60 P-wave are generated as synthetics of plane waves with random incidence angles from 5 to 25 degrees.

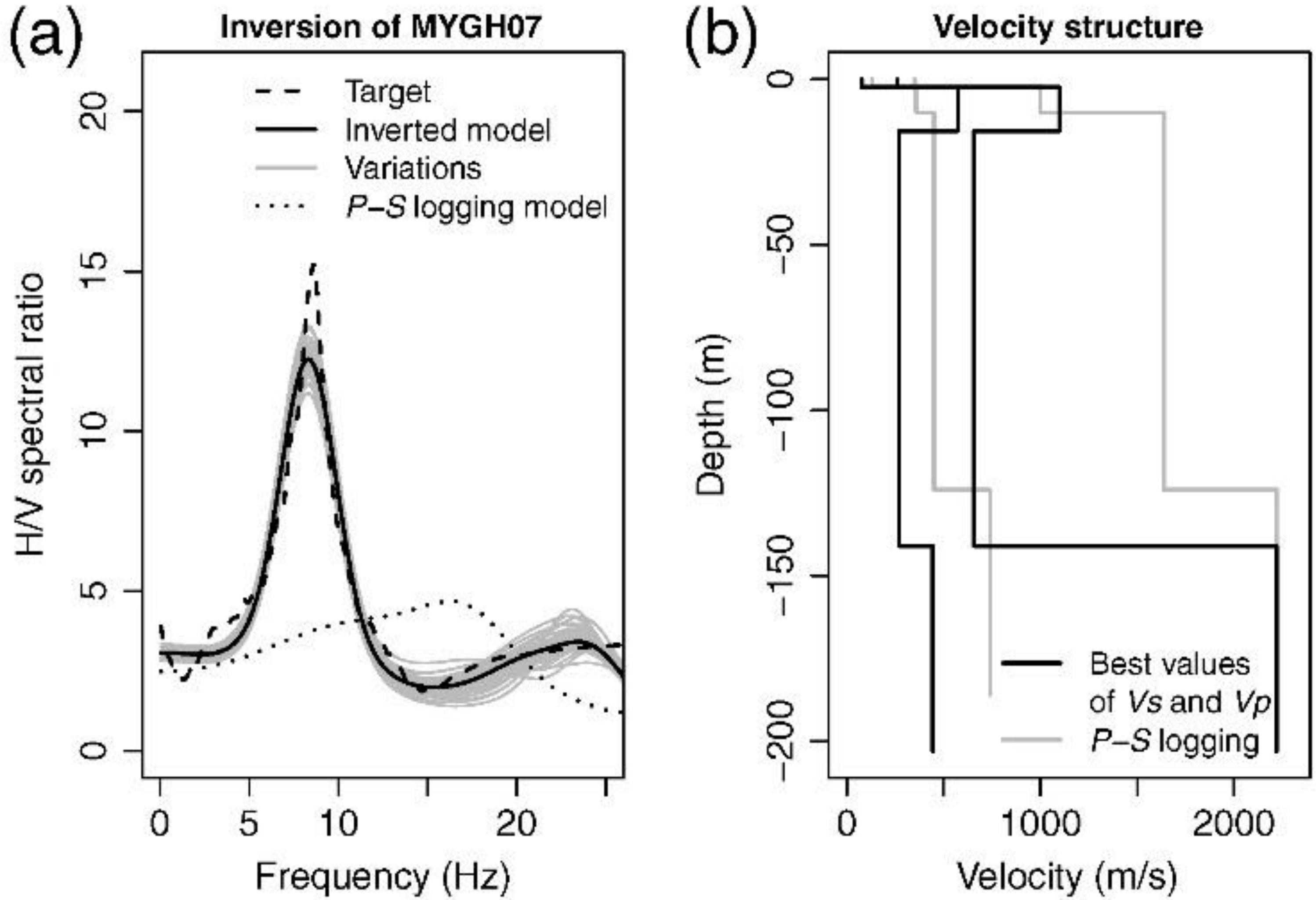
Theoretical EHVR and EHVR from synthetics: exact match



Spectral ratios ((H1**2+H2**2)/V**2) of "summed up" power spectral density of generated synthetics give exactly the ratios of S-wave amplification divided by P-wave amplification with vertical incidence from the bedrock.

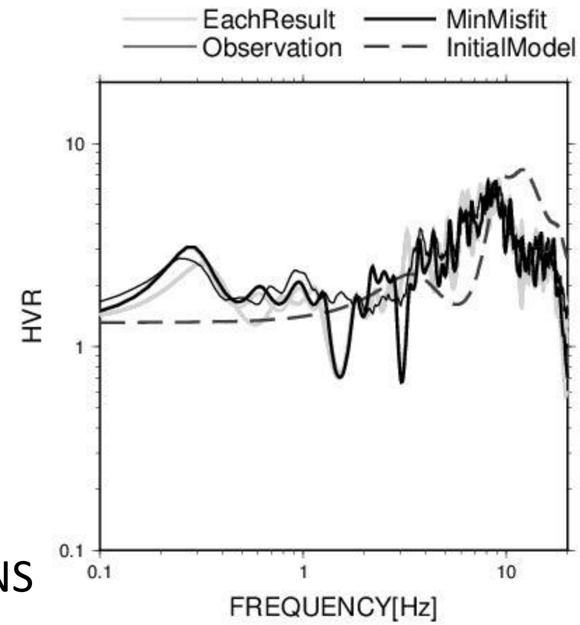
Validity of the DFM for EHVR by Inversion

Ducellier et al. (2013) inverted velocity structures



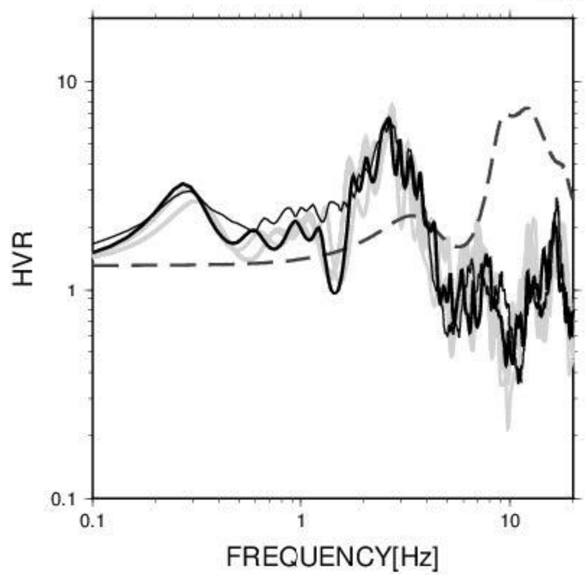
Validity of the DFM for EHVR by Inversion

Nagashima et al. (2014) inverted velocity structures

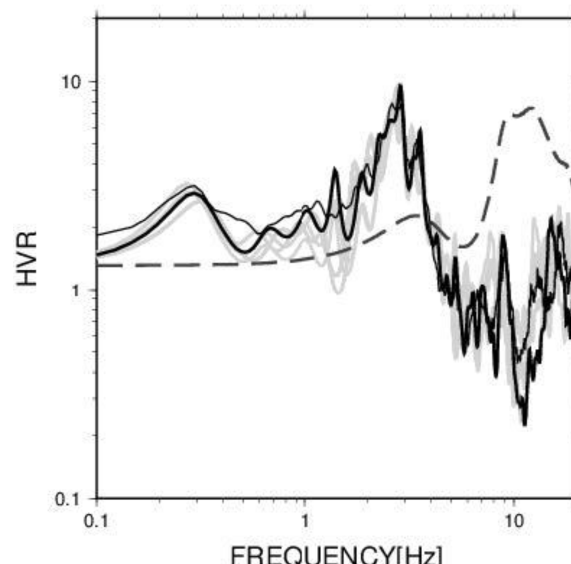


MYG004 Tsukidate EW

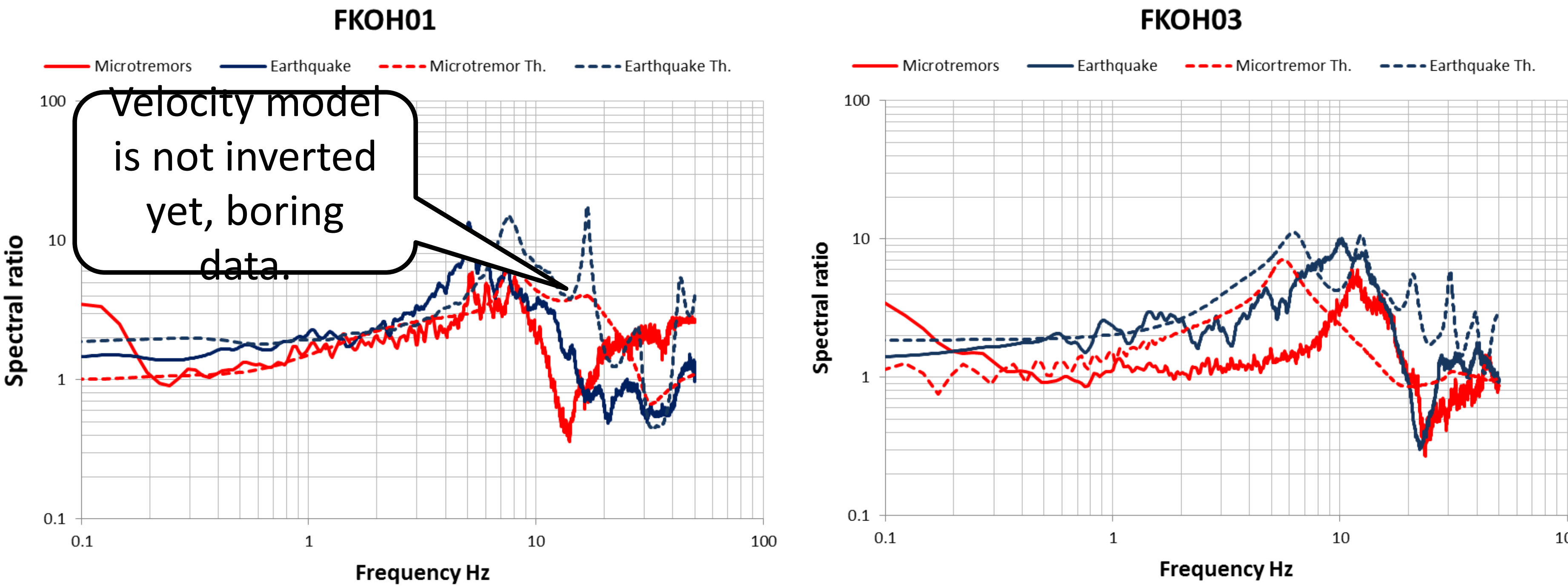
Z04 Aftershock st. NS



Z04 Aftershock st. EW



EHVR and MHVR at KiK-net stations



General tendency:

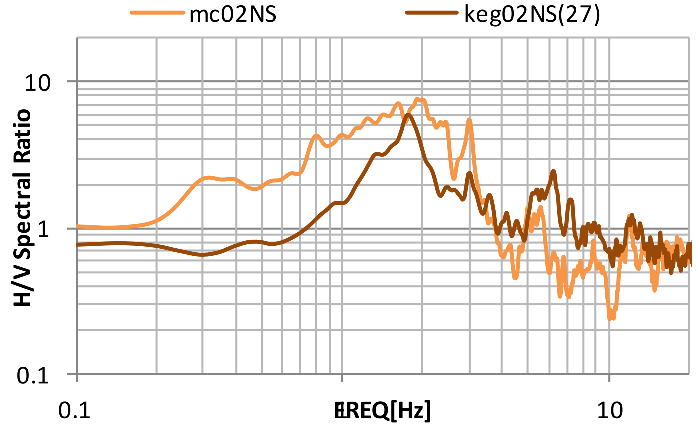
1) Observed MHVR ≦ Observed EHVR.
2) Peak and dip frequencies are similar (but not always the same) to each other.
3) Theoretical results show the same tendency.

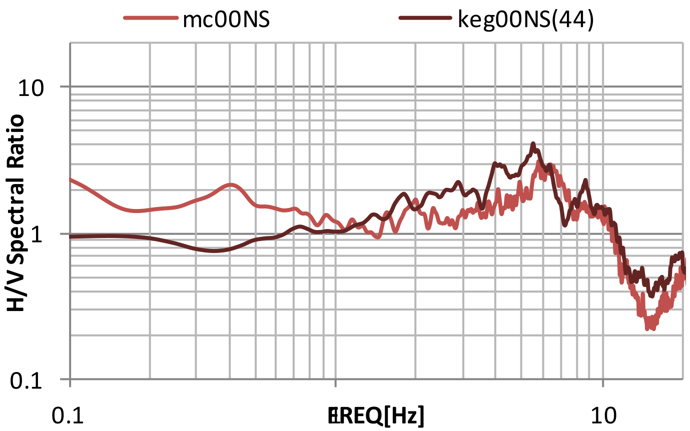
Fukuoka project

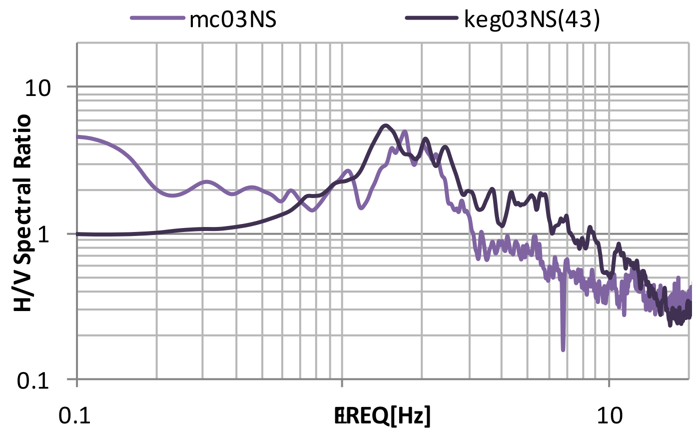
Kego Fault

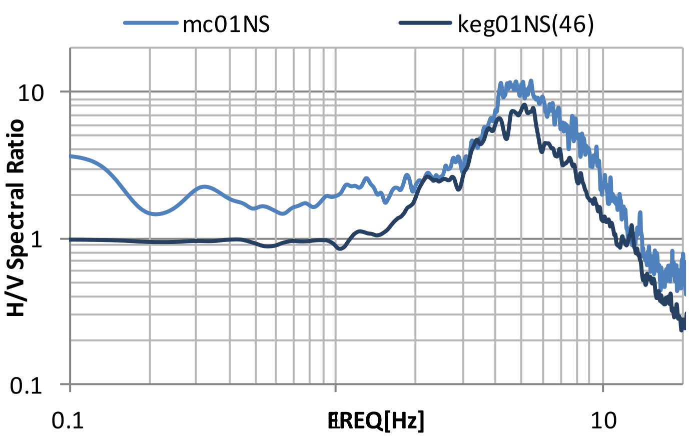
EHVR and MHVR

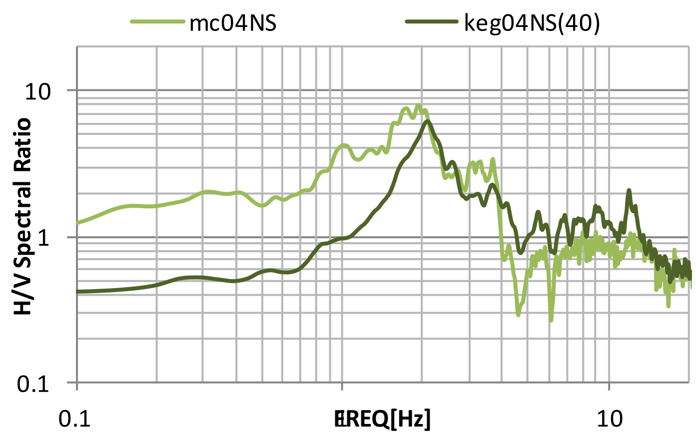
Dark:EHVR, Light:MHVR







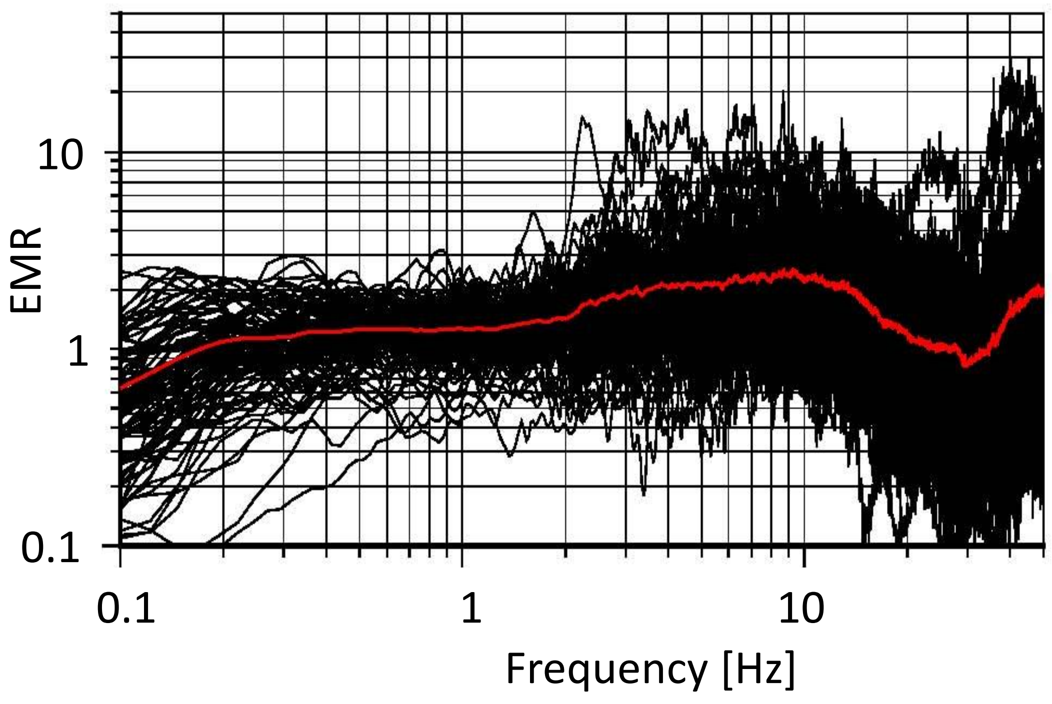




Calculating EMR

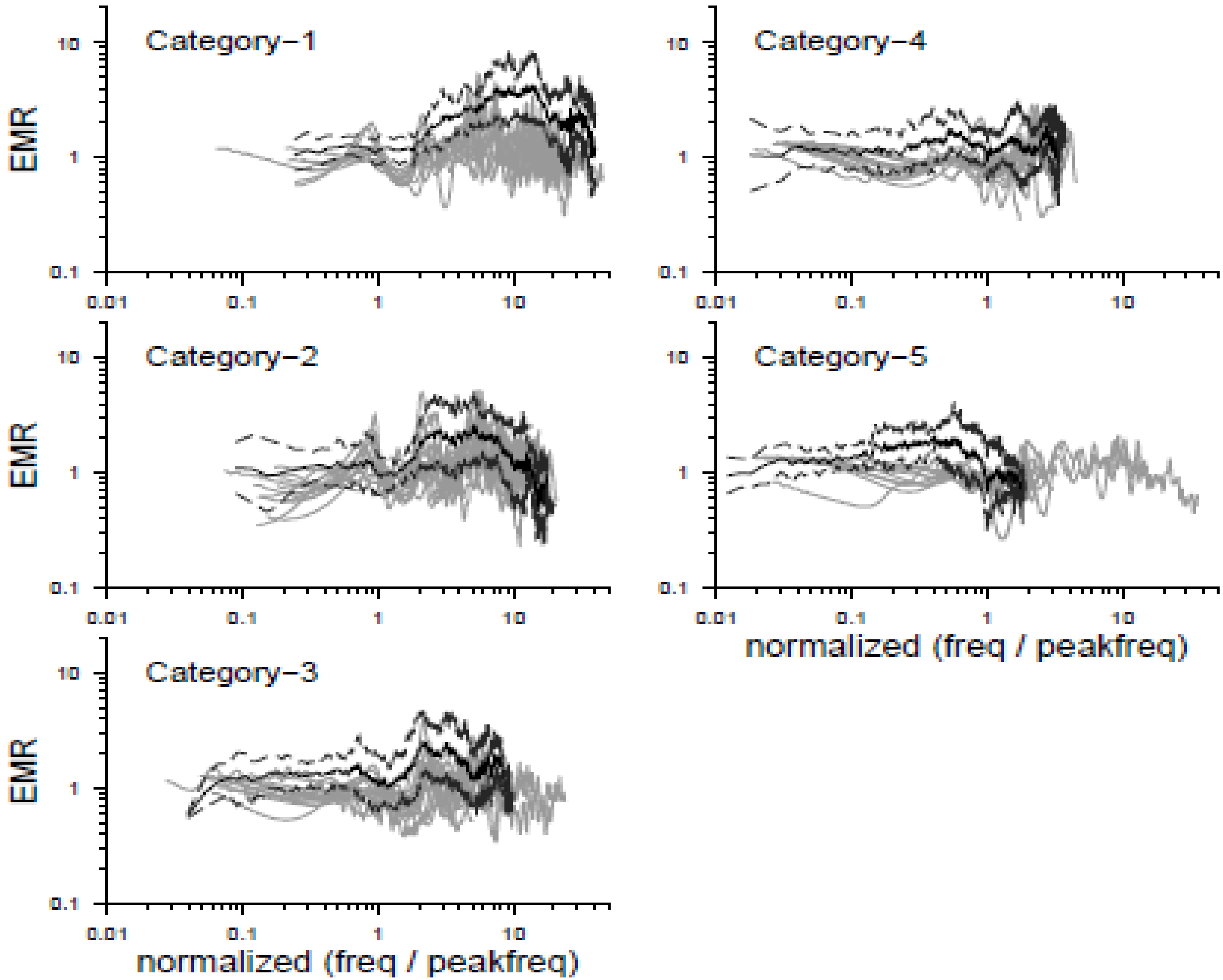
EMR : earthquake-to-microtremor ratio of HVR

$$\mathrm{EMR}(f) = \frac{\mathrm{EHVR}(f)}{\mathrm{MHVR}(f)}$$



- horizontal axis
  frequency [Hz]
- objective points
  all
- total 100 points

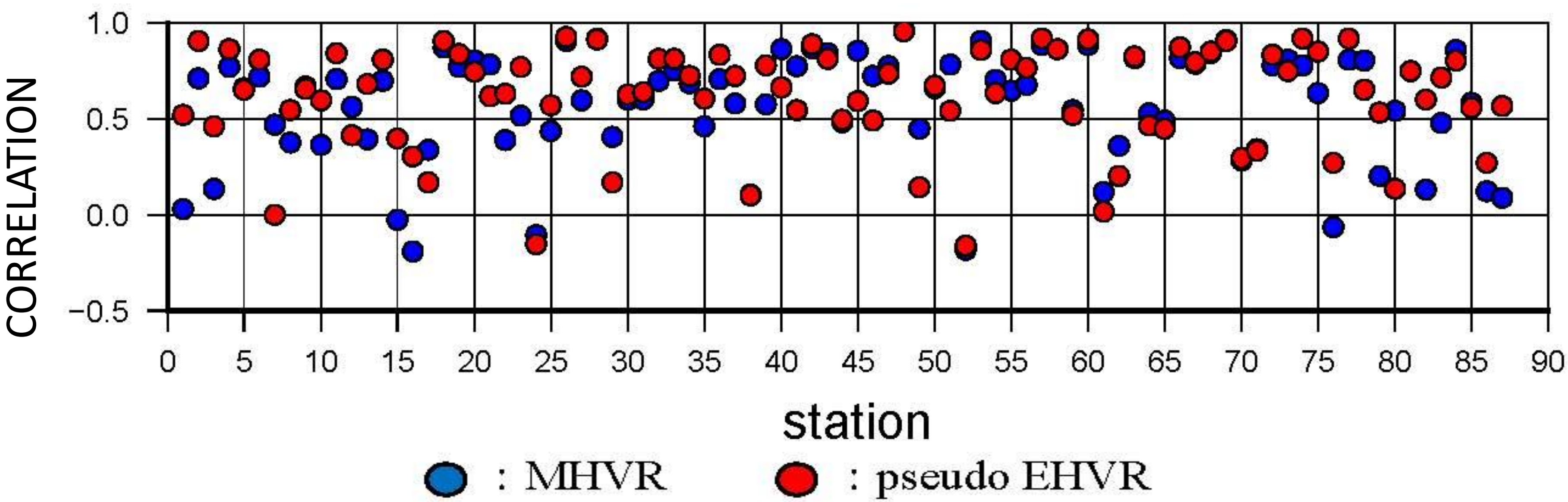
Theoretical proof: Overestimate in Category 1



Pseudo EHVR: effectiveness

Correlation with EHVR

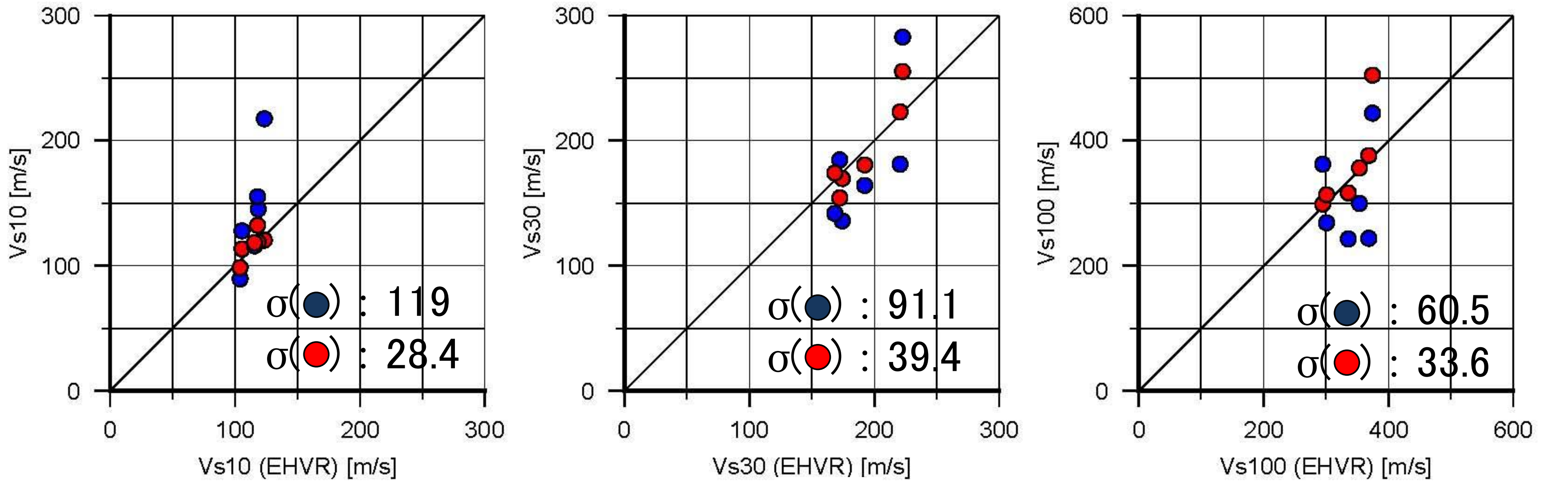
$$\text{CORRELATION} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$$



average of correlation : 0.575 → 0.617

Correlation of pseudo EHVR is higher than that of MHVR

Comparison of average Vs（using a-priori info.）



Vs10 Vs30 Vs100

● : inversion result using pseudo EHVR

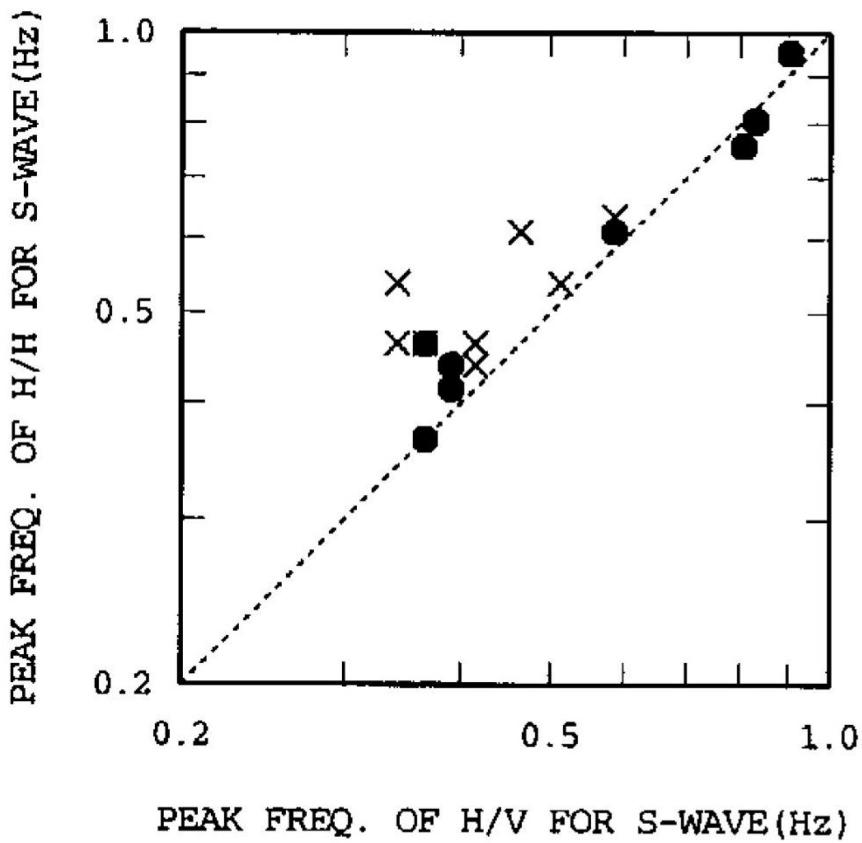
● : inversion result using MHVR directly

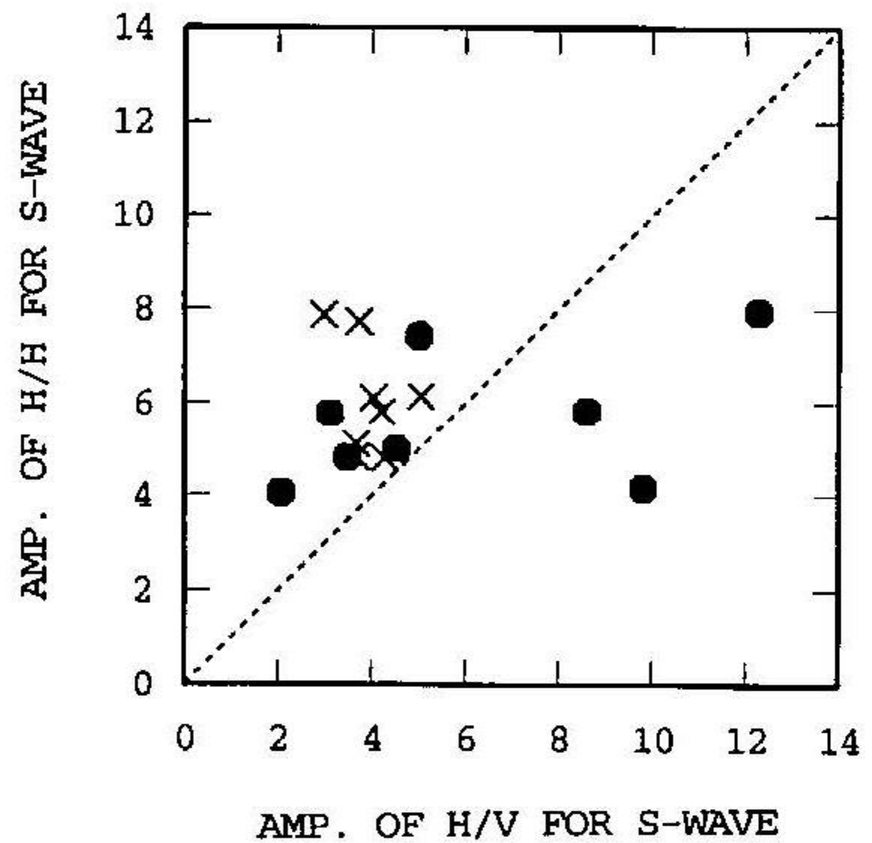
Can we treat HVR amplitude as a representative value of S-wave amplification (or site effect) ?

1) Since there is always a possibility to have amplification in the vertical component between the bedrock and the surface, peak amplitude in HVR is always equal to or less than the corresponding HHR, as shown in Satoh et al. (2001) and Kawase and Tsuzuki, (2002).
2) However, usually the first predominant frequency in the vertical component is much higher than that of the horizontal component, so that we have similar amplitude in the lowest predominant frequency.
3) We also observed that the higher the impedance contrast, the higher the peak amplitude in HVR as well as HHR, as a natural consequence.

➔DFA suggests that the answer is “Only special cases”.

Satoh et al. (2001); the observed EHVR and HHR of S-waves





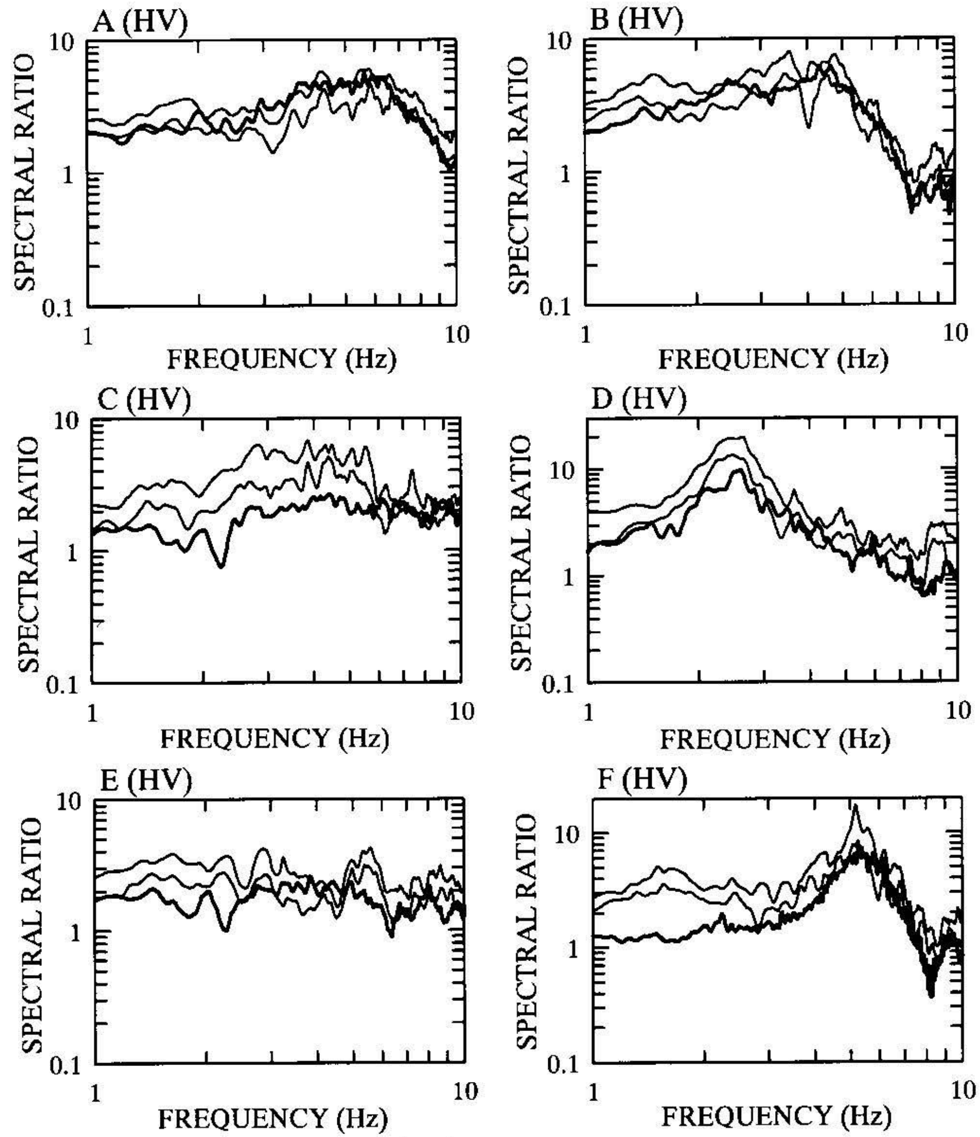
If we see any peak frequencies, we cannot see good correlation but if we restrict sites with H/V higher than 3 and peak frequency less than 1 Hz (●), we can see correlation. Even for that case we cannot see good correlation for amplitudes.

Is HVR of earthquake (EHVR) the same as HVR of microtremors (MHVR)?

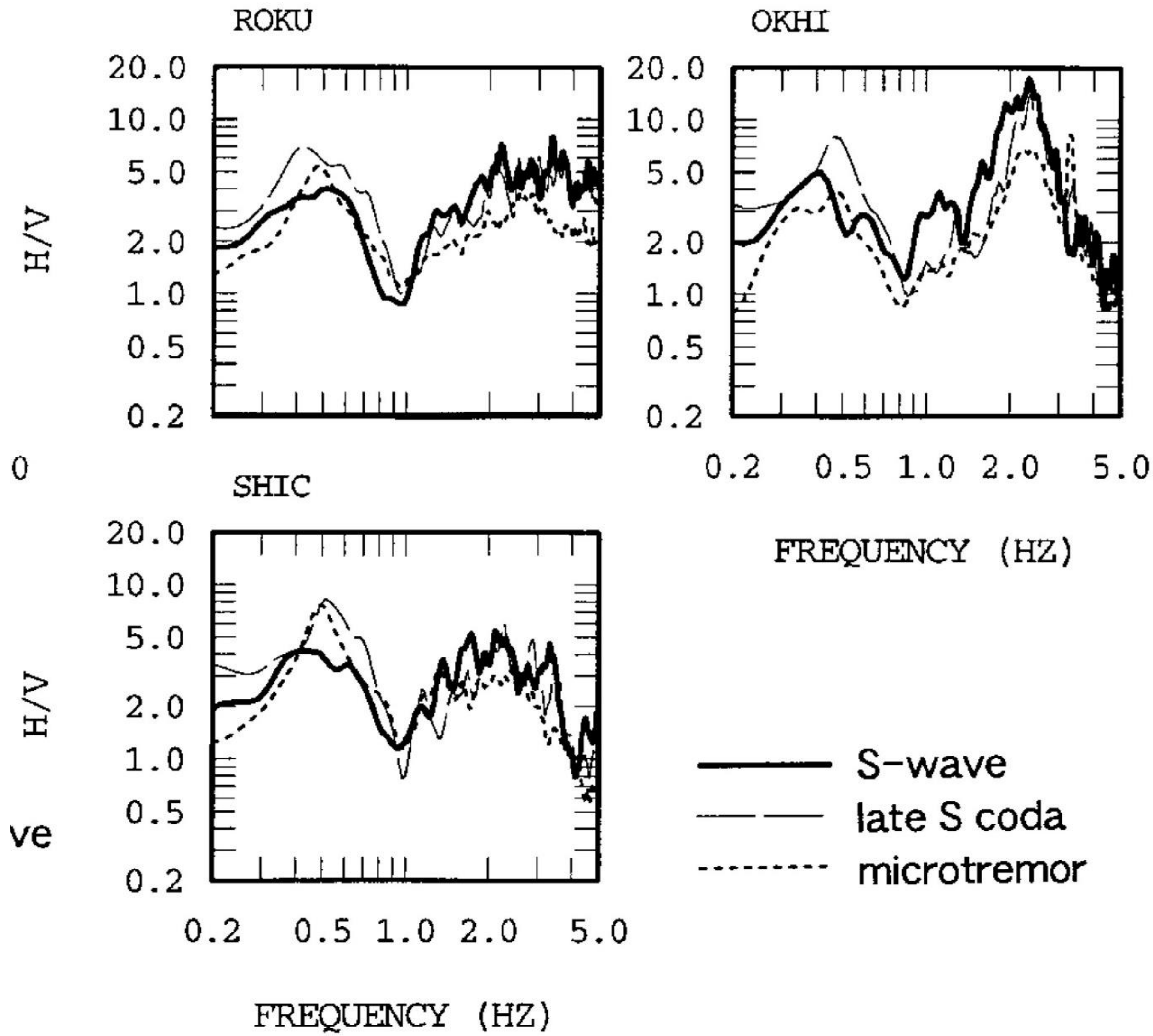
1) After HVR proposal of Nakamura (1980), there are many confusing usage of HVRs, either microtremors or earthquakes.
2) In Horike et al. (2001) we can see half of the sites showed difference between earthquake HVRs (EHVR) and those of microtremors (MHVR).
3) In Satoh et al. (2001) we can see similarity between EHVR and MHVR, yet the amplitudes were not the same.

→DFA solves all these problems.

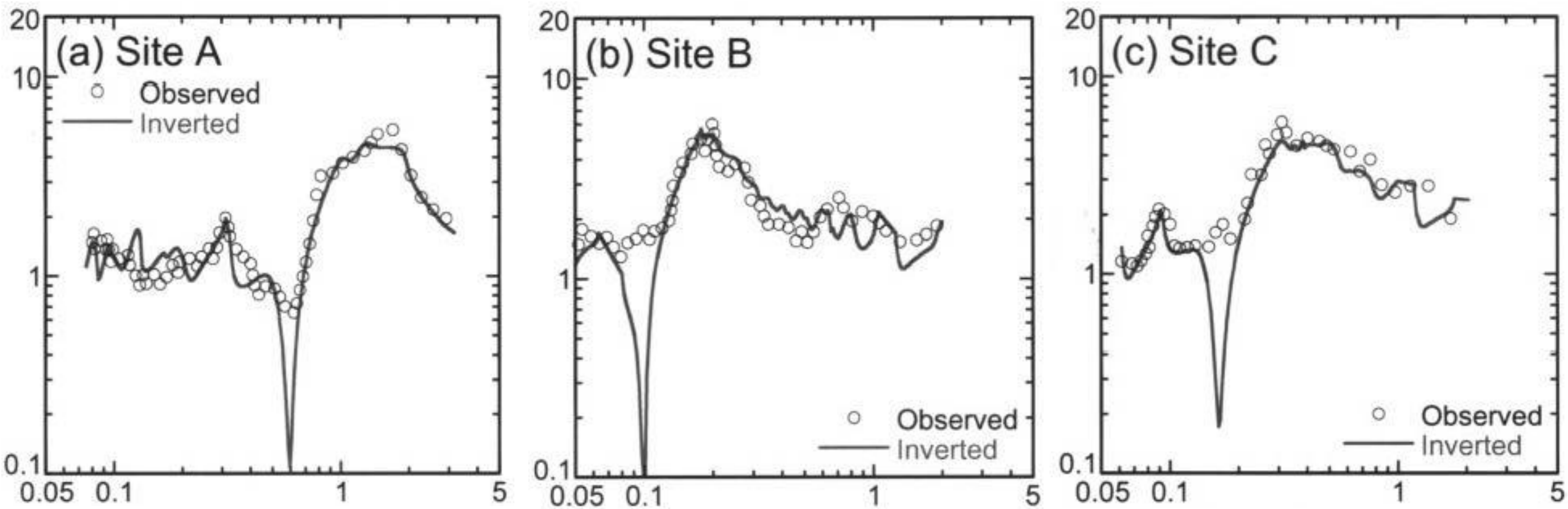
Horike et al. (2001); the observed EHVR and MHVR (thick: EHVR)



Satoh et al. (2001); the observed EHVR and MHVR at stations in Sendai City

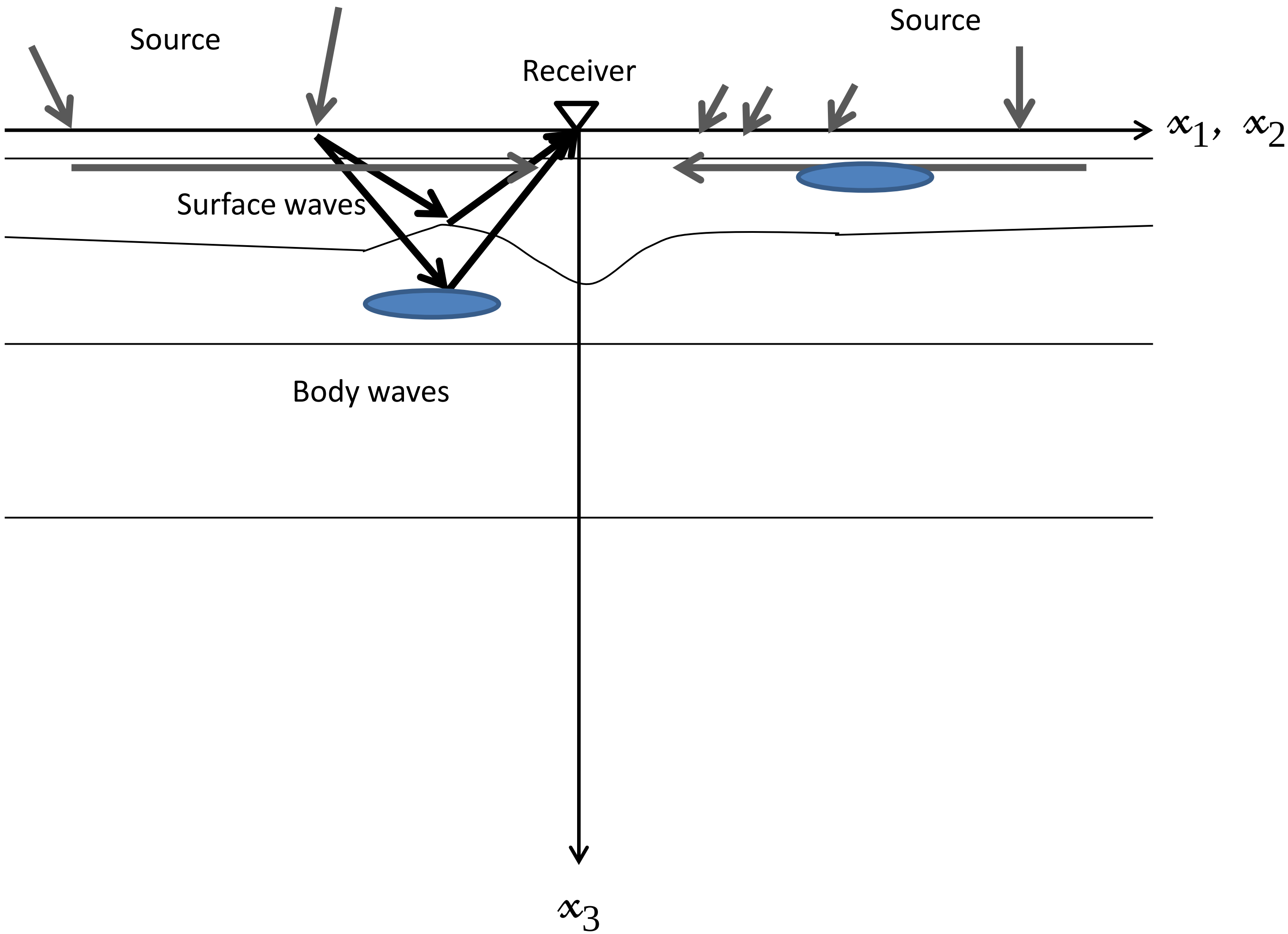


Arai & Tokimatsu (2004); the observed HVR and mufti-mode Love- and Rayleigh-wave summation method



Assuming the relative amplitude ratio between Rayleigh and Love to be 0.4, Arai & Tokimatsu calculated theoretical MHVR and used it for inversion. Note that sharp dip associated with zero horizontal amplitude in Rayleigh wave contribution is not filled up.

Assumed wavefield for microtremors



For MHVRs the relationship of Energy Density and the imaginary part of Green function at the source is derived in Sánchez-Sesma et al. (GJI, 2011). The DFM starts from the fact that the cross correlation corresponds to the imaginary part of the Green's function at one location to the other;

$$\langle u_i(\mathbf{x}_\mathrm{A},\omega)u^*_j(\mathbf{x}_\mathrm{B},\omega)\rangle = -2\pi E_S k^{-3}\mathrm{Im}\left[G_{ij}(\mathbf{x}_\mathrm{A},\mathbf{x}_\mathrm{B},\omega)\right]$$

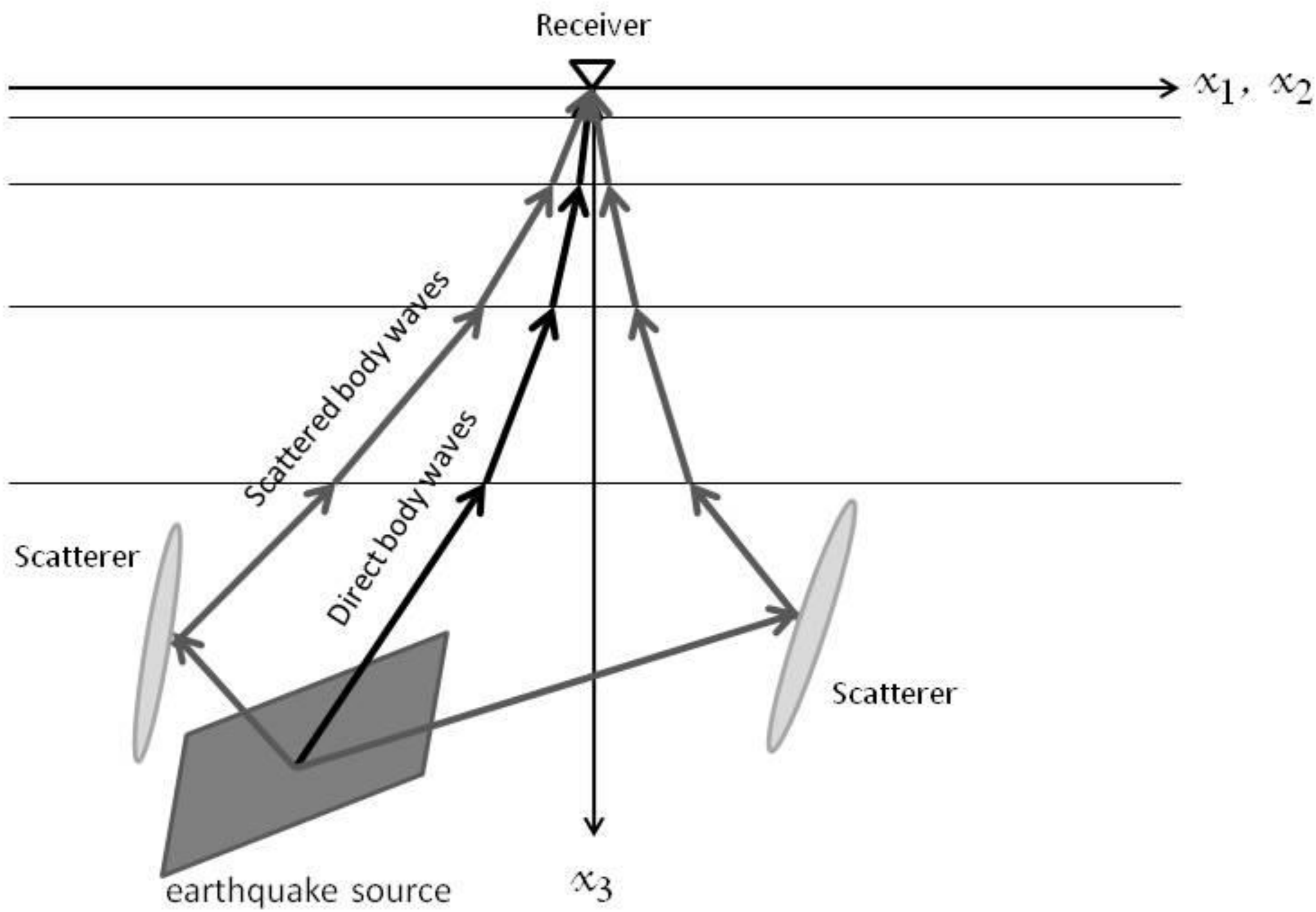
If two locations are the same, then the auto-correlation gives;

$$E(\mathbf{x}_\mathrm{A}) = \rho\omega^2\langle u_m(\mathbf{x}_\mathrm{A})u^*_m(\mathbf{x}_\mathrm{A})\rangle = -2\pi\mu E_S k^{-1}\mathrm{Im}[G_{mm}(\mathbf{x}_\mathrm{A},\mathbf{x}_\mathrm{A})]$$

Then

$$\frac{H^2}{V^2}(\omega) = \frac{E_1(\mathbf{x},\omega)+E_2(\mathbf{x},\omega)}{E_3(\mathbf{x},\omega)} \qquad \frac{H}{V}(\omega) = \sqrt{\frac{\mathrm{Im}[G_{11}(\mathbf{x},\mathbf{x};\omega)]+\mathrm{Im}[G_{22}(\mathbf{x},\mathbf{x};\omega)]}{\mathrm{Im}[G_{33}(\mathbf{x},\mathbf{x};\omega)]}}$$

Assumed wavefield for earthquakes



For EHVRs the relationship of Energy Density and the imaginary part of Green function at the source is:

$$E(P,\omega) \propto \left\langle \frac{\left|u(P,\omega)\right|^2}{\int \left|u(P,\varpi)\right|^2 d\varpi} \right\rangle \propto \mathrm{Im}\big(G(P,P,\omega)\big)$$

For a layered medium we can write Claerbout (1968) result:

$$\left\langle \frac{\left|u(P,\omega)\right|^2}{\int \left|u(P,\varpi)\right|^2 d\varpi} \right\rangle = K \times \left|TF(\omega)\right|^2 = -K \times \rho_{HS} c_{HS} \omega \,\mathrm{Im}[G^{1D}(P,P,\omega)]$$

or : $$\omega \times \mathrm{Im}\big(G^{1D}(P,P,\omega)\big) = \frac{\left|TF(\omega)\right|^2}{-\rho_{HS} c_{HS}}$$

$\left|TF(\omega)\right| =$ 1D transfer function amplitude for incoming plane waves of vertical incidence

EHVRs in diffuse field assumption

Since the autocorrelation corresponds to the imaginary part of the Green's function, if the body waves from the relatively deep source are diffused

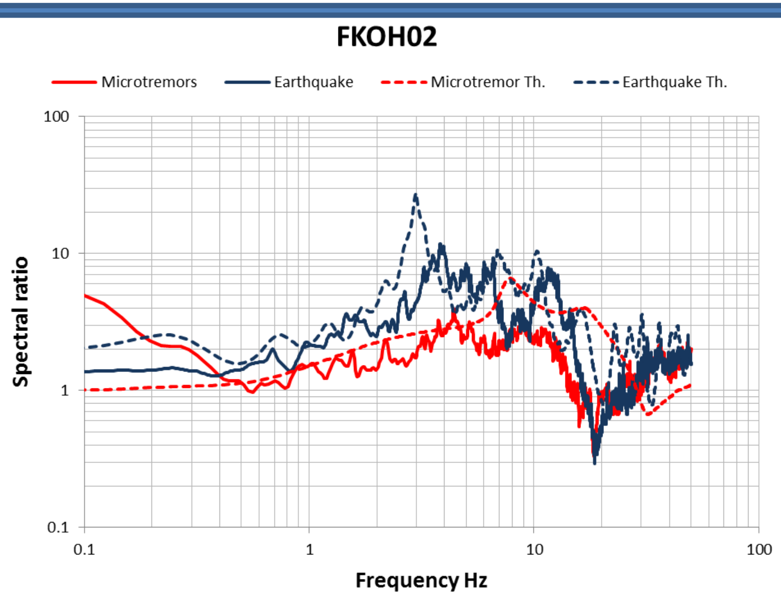
$$\frac{H(\omega)}{V(\omega)} = \sqrt{\frac{2\,\mathrm{Im}[G_{11}^{1\mathrm{D}}(\mathbf{x},\mathbf{x};\omega)]}{\mathrm{Im}[G_{33}^{1\mathrm{D}}(\mathbf{x},\mathbf{x};\omega)]}}$$

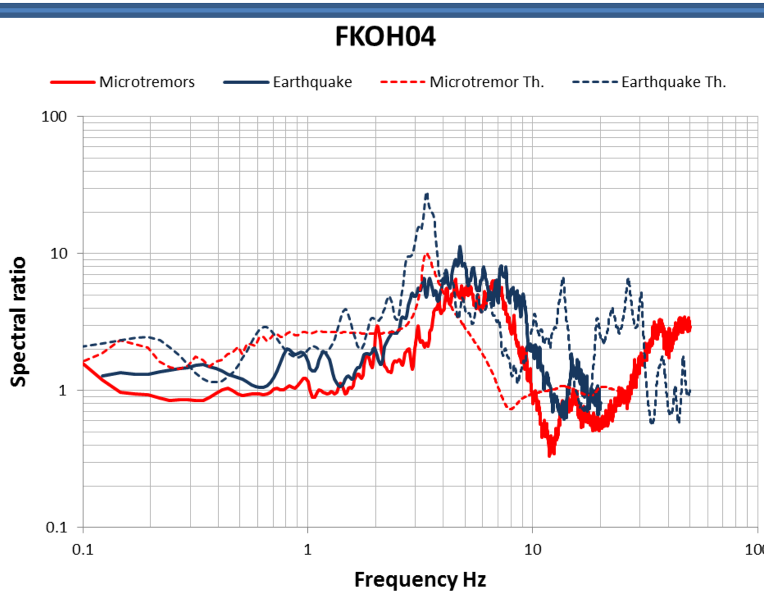
Then using Claerbout's (1968) relationship, we get

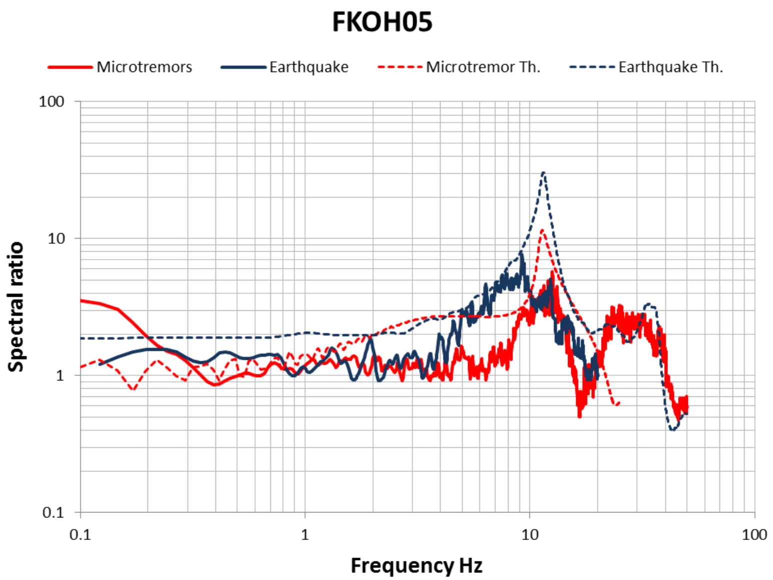
$$\frac{H(0,\omega)}{V(0,\omega)} = \sqrt{\frac{2\alpha_H}{\beta_H}\frac{|TF_1(0,\omega)|}{|TF_3(0,\omega)|}}$$

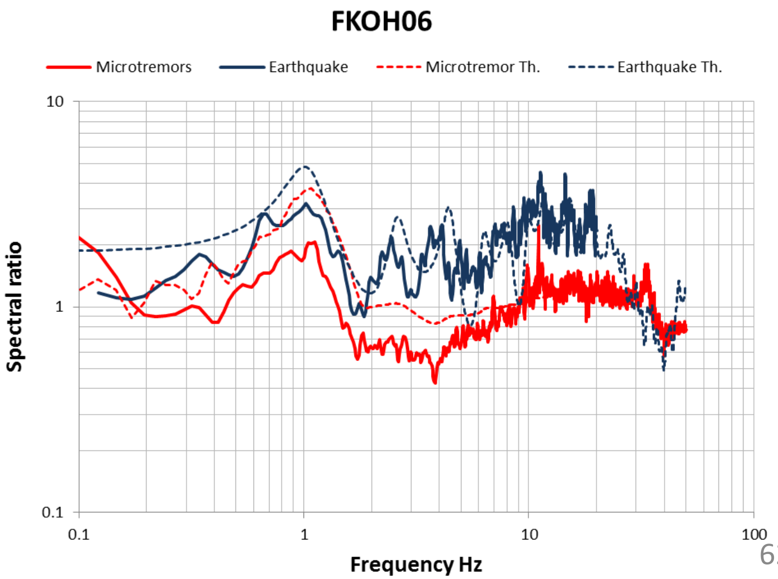
for surface components. Here α_H and β_H are the bedrock velocities of P- and S-waves, respectively.

EHVR and MHVR at KiK-net stations

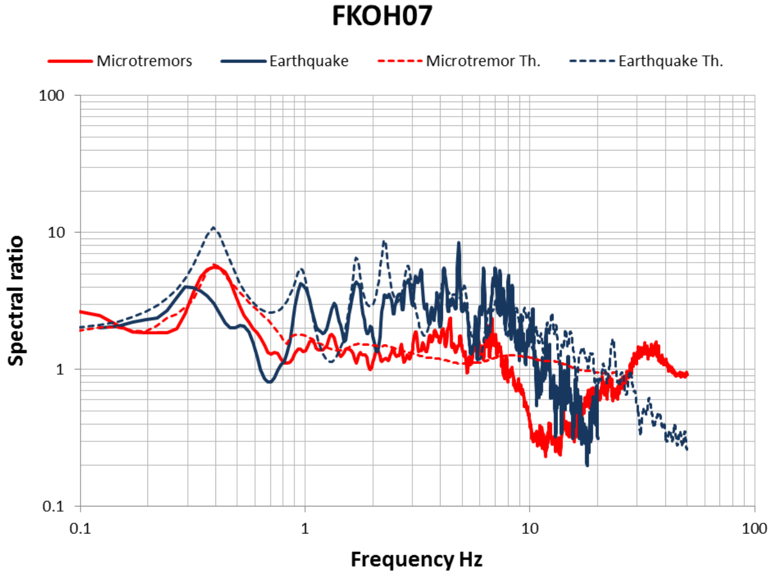


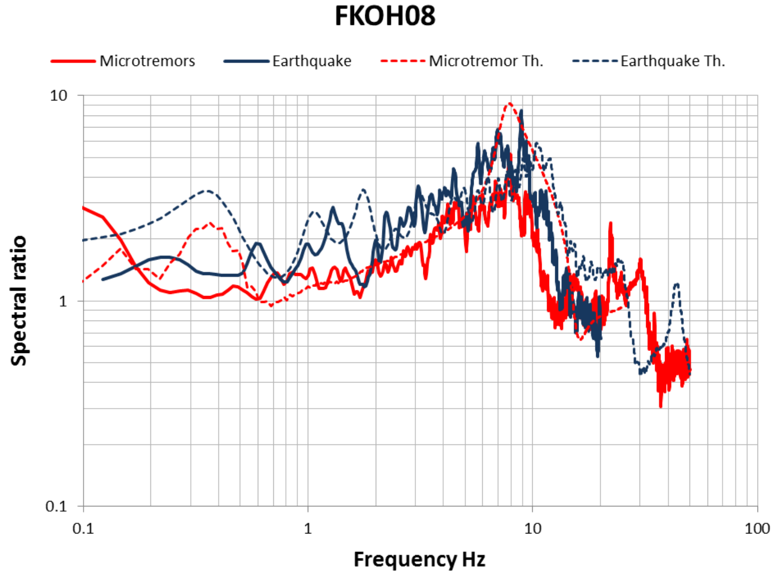


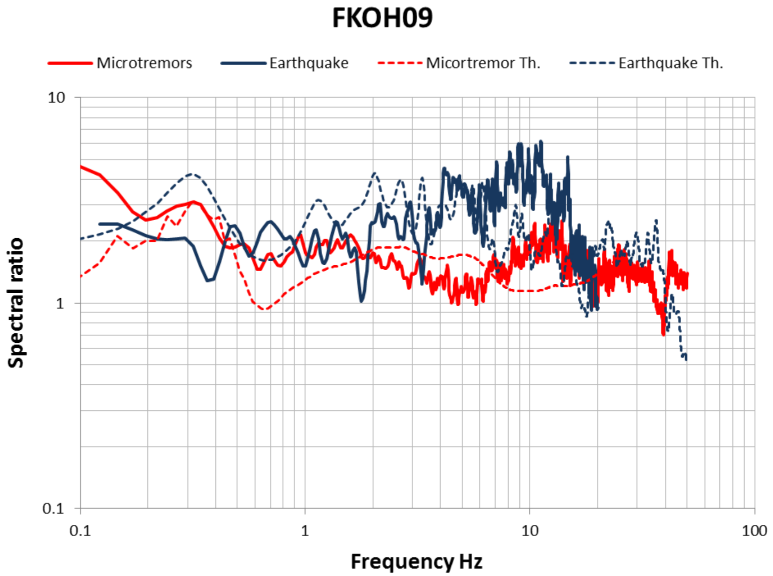


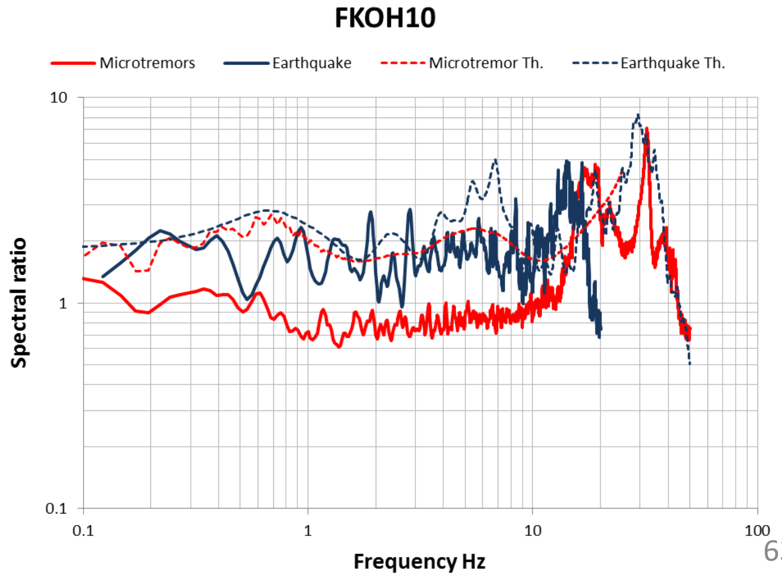


EHVR and MHVR at KiK-net stations

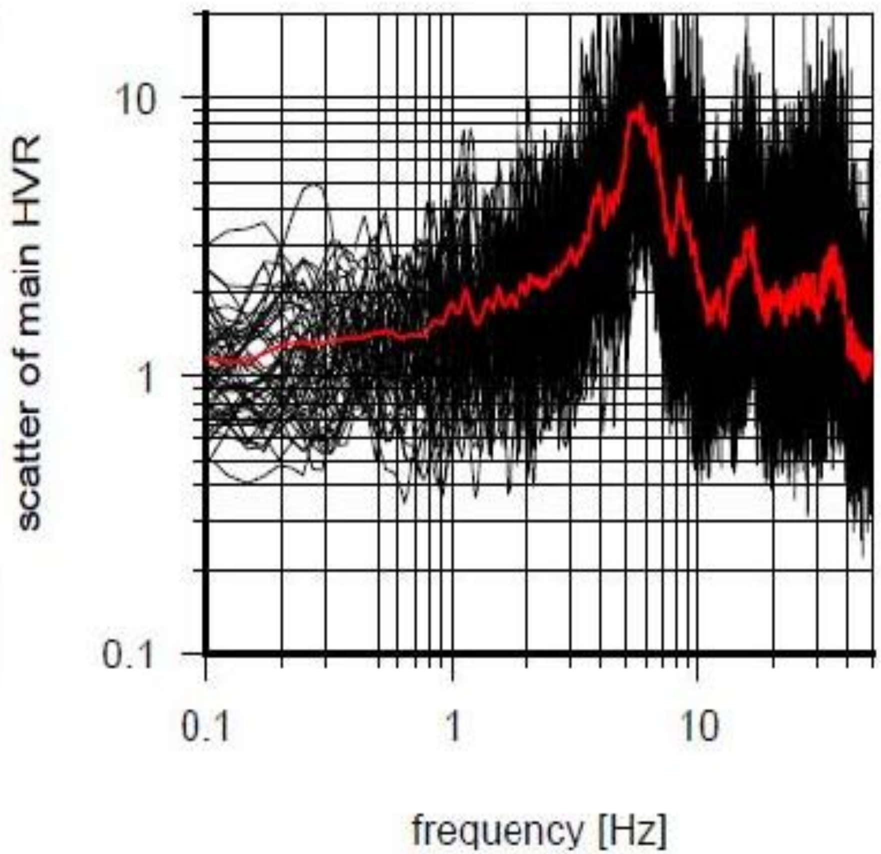




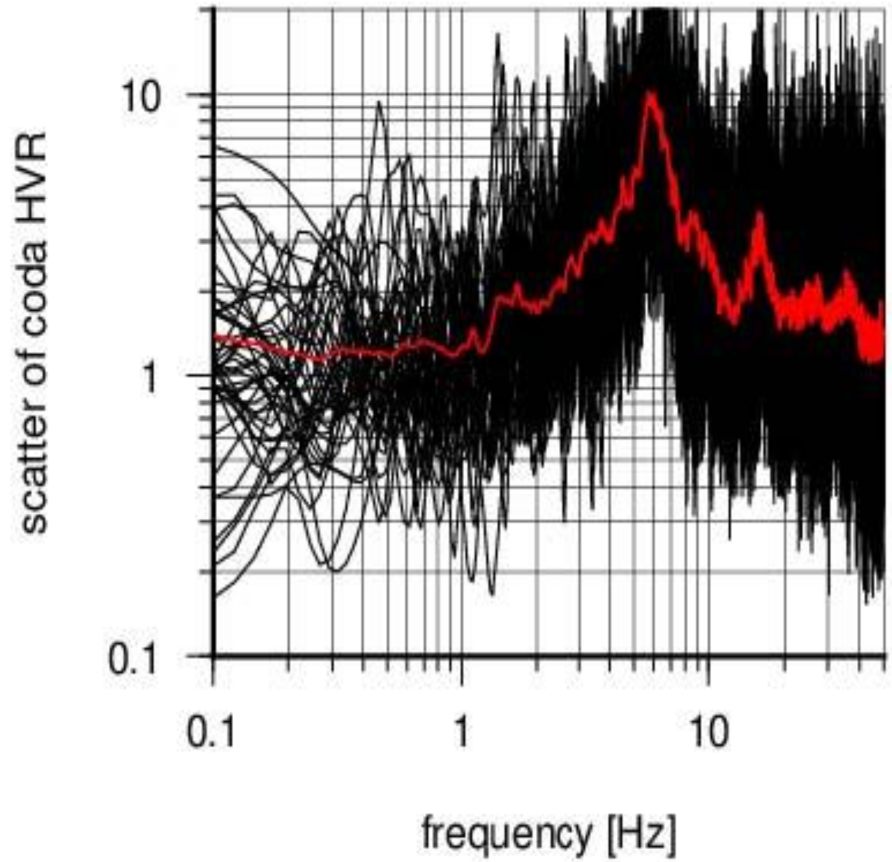




S-wave part and Coda part issue
➔Basically the same



S-wave part



Coda part