IN SITU SOIL PROPERTIES FOR SEISMIC SITE RESPONSE

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Major References for presentation(1/2):

Aoyagi, T. (2000): Inversion analysis for soil properties based on vertical array record using the extended Bayesian method, Master's thesis, Graduate school of Chuo University.

Fukushima, Y. and Midorikawa, S.(1994): Evaluation of site amplification factors based on average characteristics of frequency dependent Q-1 of sedimentary strata, *J. Struct. Constr.* Eng. Architectural Institute of Japan, No.460, 37-46, 1994.

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Kokusho, T. (1980): Cyclic triaxial test of dynamic soil properties for wide strain range. *Soils and Foundations*: Vol.20, No.2, 45-60.

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Kokusho,T., Yoshida,Y. and Esashi,Y. (1982): Dynamic soil properties of soft clay for wide strain range. *Soils and Foundations:* Vol.22, No.4, 1-18.

Kokusho,T. and Tanaka,Y. (1994): Dynamic properties of gravel layers investigated by in-situ freezing sampling. *Geotechnical Special Publication No44 -Ground Failures under Seismic Conditions*, ASCE Convention (Atlanta), 121-140.

Major References for presentation(2/2):

Kokusho, T. Sato, K. and Matsumoto, M. (1996): Nonlinear dynamic soil properties back-calculated from strong motions during Hyogoken-Nambu Earthquake. Proc. 11th World Conference on Earthquake Engineering, Acapulco, CD publication.

Kokusho, T. & Matsumoto, M. (1998): Nonlinearity in site amplification and soil properties during the 1995 Hyogoken-Nambu earthquake. Special Issue on Geotechnical Aspects of the January 17, 1995 Hyogoken-Nambu Earthquake, No.2; *Soils and Foundations*: 1-10.

Kokusho, T. and Aoyagi, T. (2001): Insitu nonlinear soil properties back-calculated from vertical array records of 1995 Kobe earthquake, Proc. International Conference on In Situ Measurement of Soil Properties and Case Histories, Indonesian Geotechnical Society, Bali, 473-480.

Kokusho, T. and Mantani, (2002):. Seismic amplification evaluation in a very deep down hole array site, *12th European Conference on Earthquake Engineering*, Paper Reference 797.

Nuclear Power Engineering Corporation(2001): Study of Evaluation Methods for Seismic Wave Propagation Characteristics, Report of Siting Reliability Studies relating to seismic design for nuclear power plants (in Japanese).

Seed, H. B., Wong, R. T., Idriss, I. M. and Tokimatsu, K. (1986): Moduli and damping factors for dynamic analyses of cohesionless soils, Journal of Geotechnical Engineering, Vol.112, No.11, 1016-1032.

Suetomi, I. (1997): A Program manual for optimization of soil structure by Bayes Method. Central Research Institute of Sato Kogyo Com. Ltd, (in Japanese).

UNSOLVED PROBLEMS FOR SEISMIC SITE RESPONSE

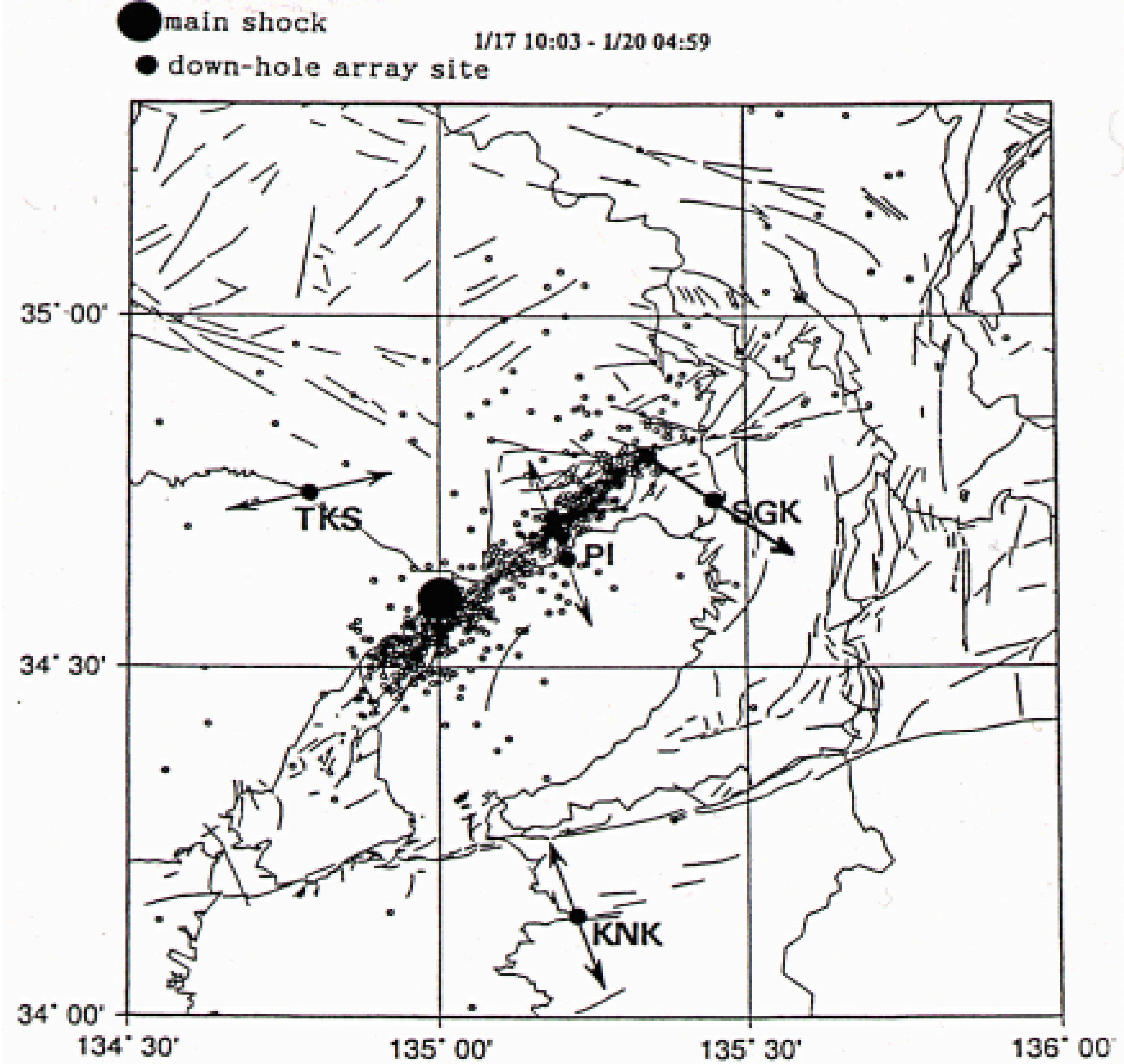
1. In situ modulus degradation compared with laboratory tests.
2. In situ damping compared with laboratory tests.
3. Combination of strain-dependency effect and pore pressure-buildup effect on degradation for larger strains.
4. Amplification in vertical motions and related soil properties.
5. Amplification in deep ground and related soil properties; Effect of confining stress-dependency and frequency dependency of damping.

Topics of the presentation:

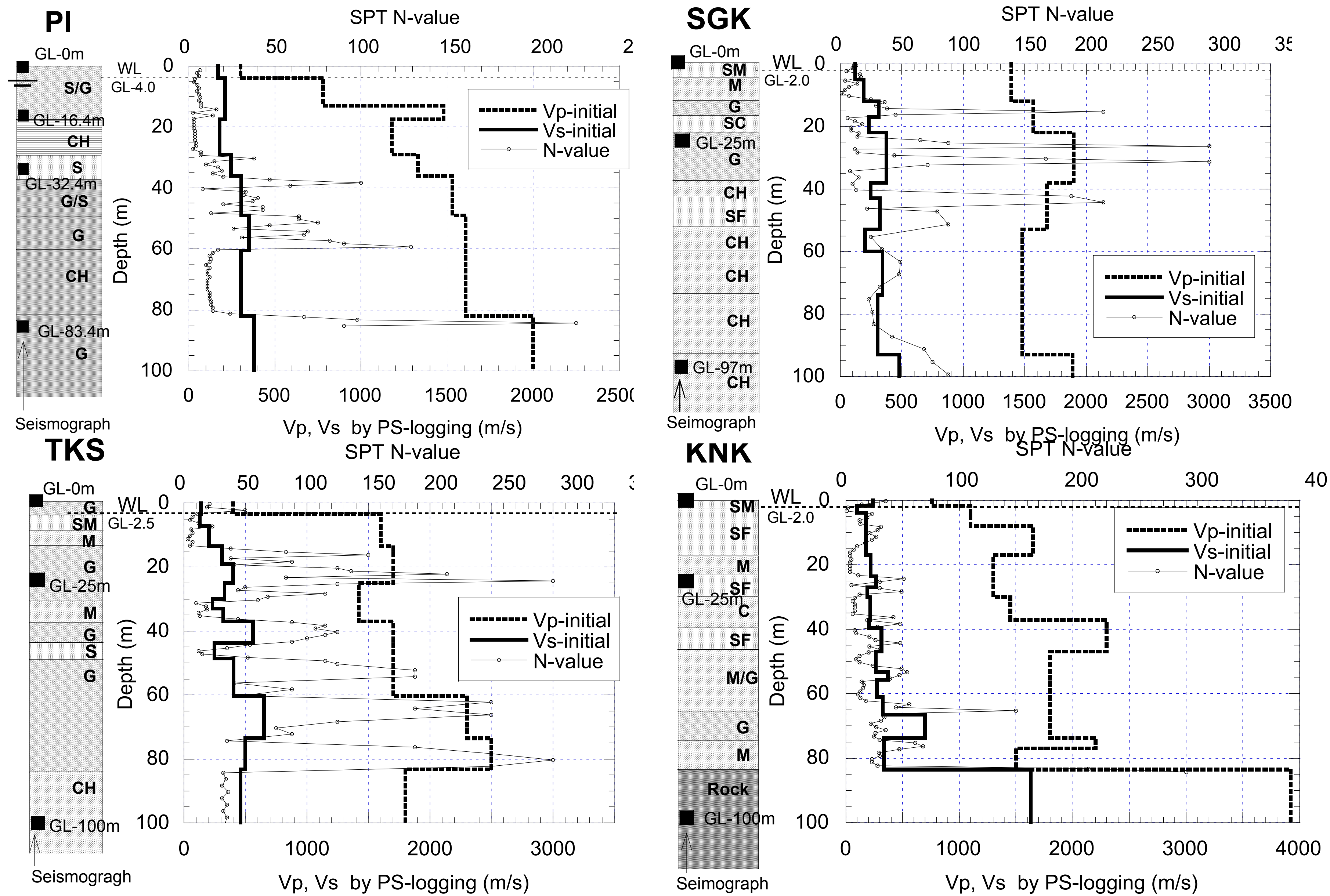
Seismic site amplification during strong earthquakes based on vertical array records

Back-calculated in situ soil properties versus lab data

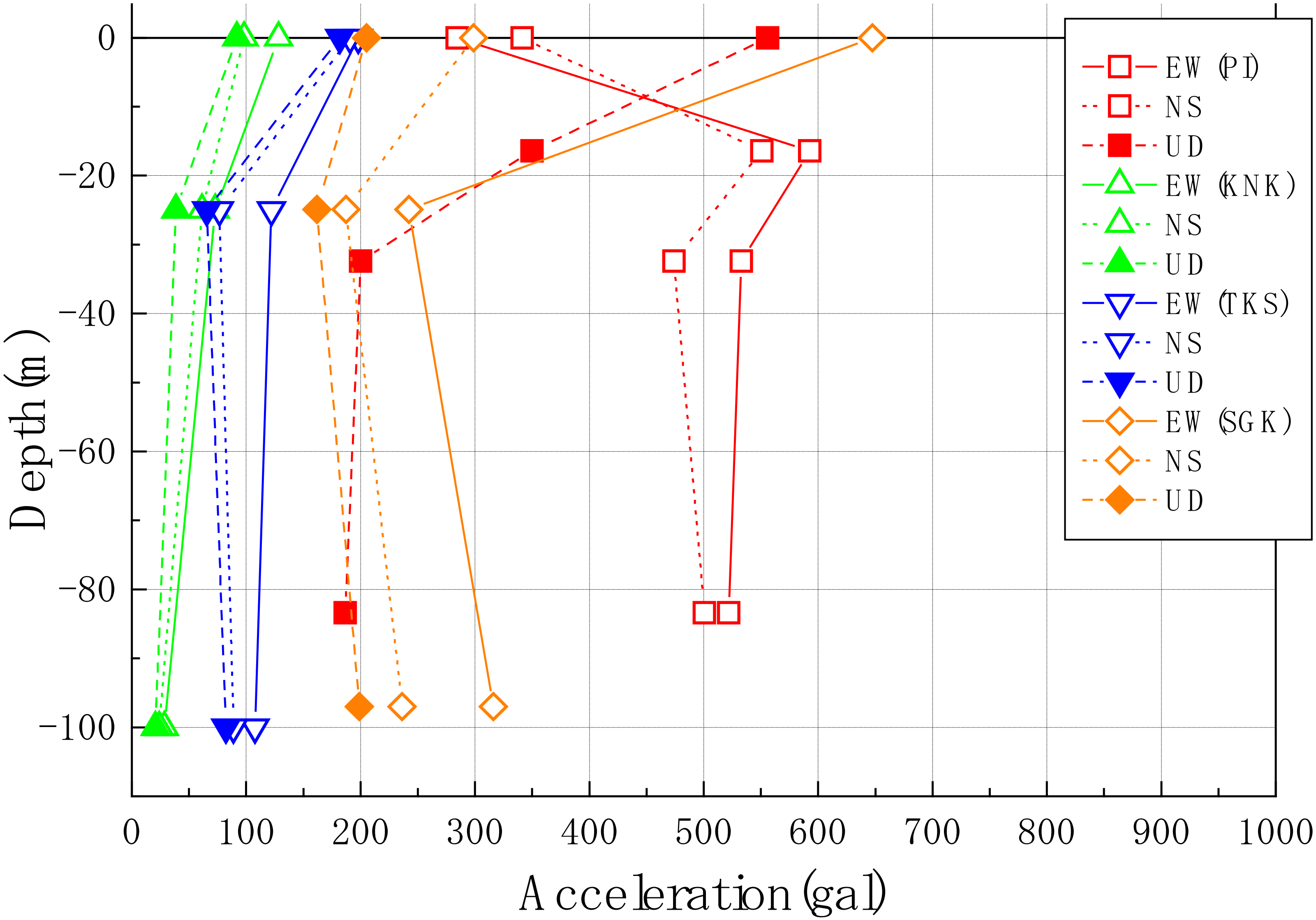
Soil properties for deep soil response



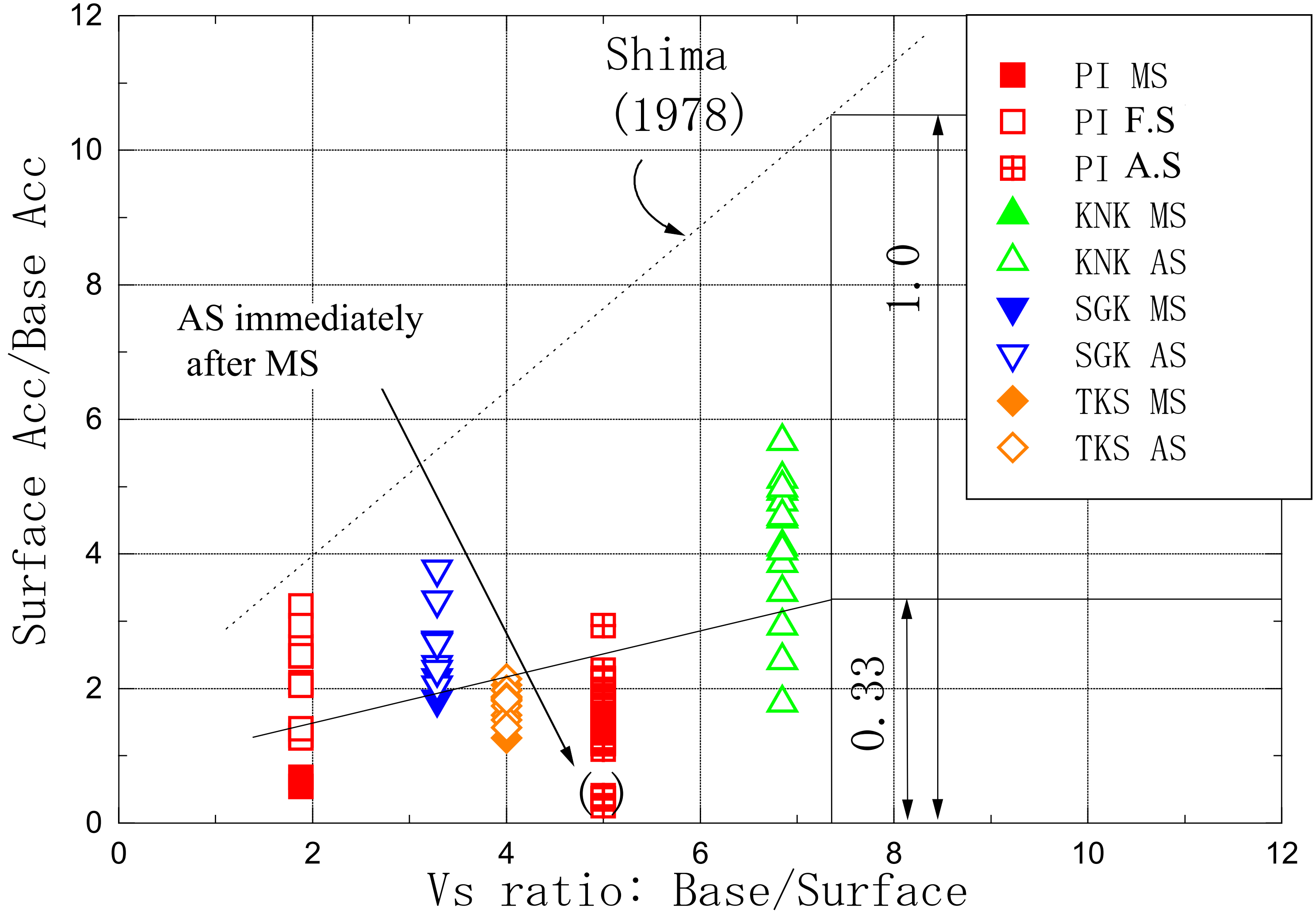
Locations of 4 vertical array sites around Kobe City



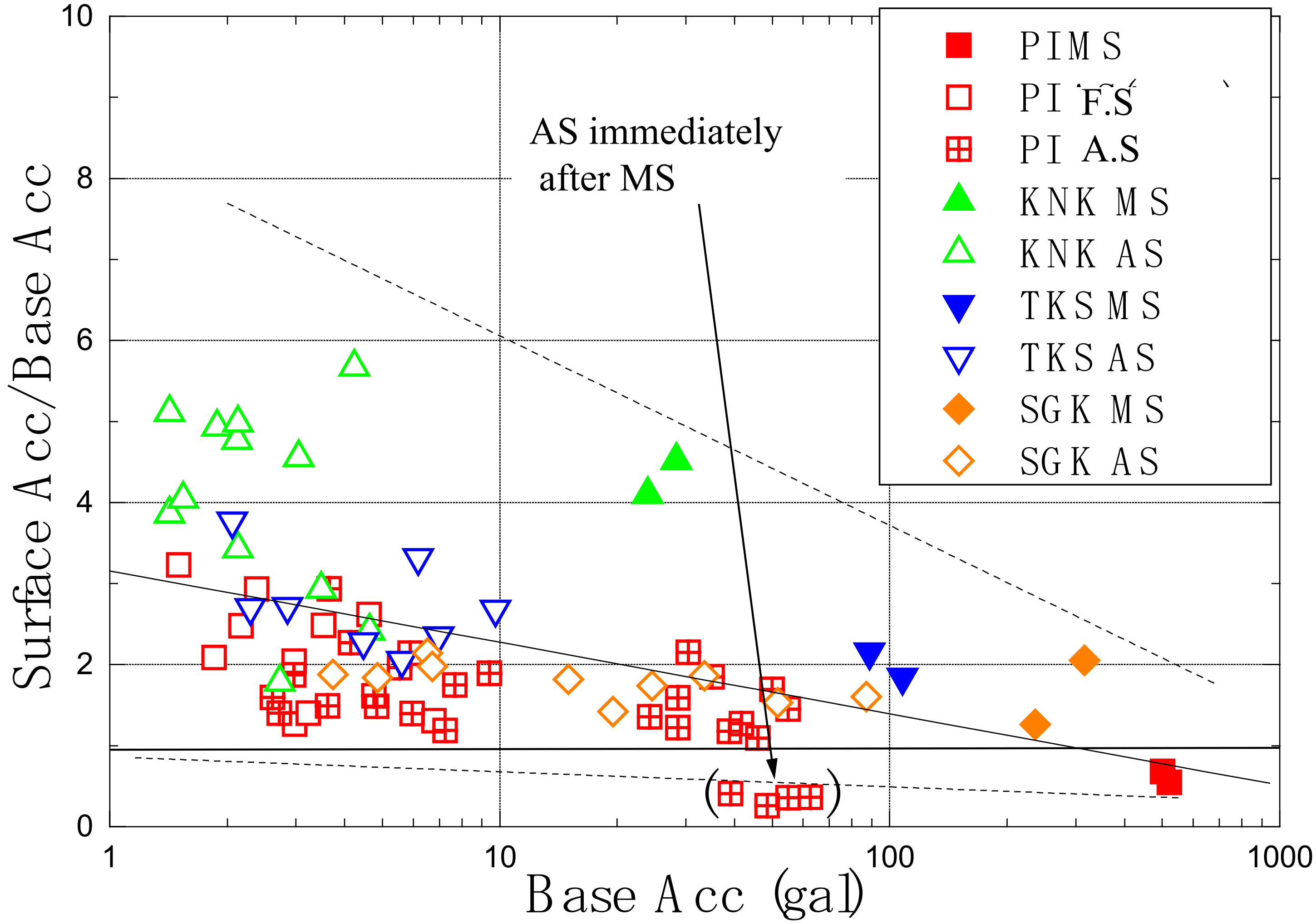
Soil profiles, Vp, Vs, SPT-N & Seismometer installation levels in 4 vertical array sites



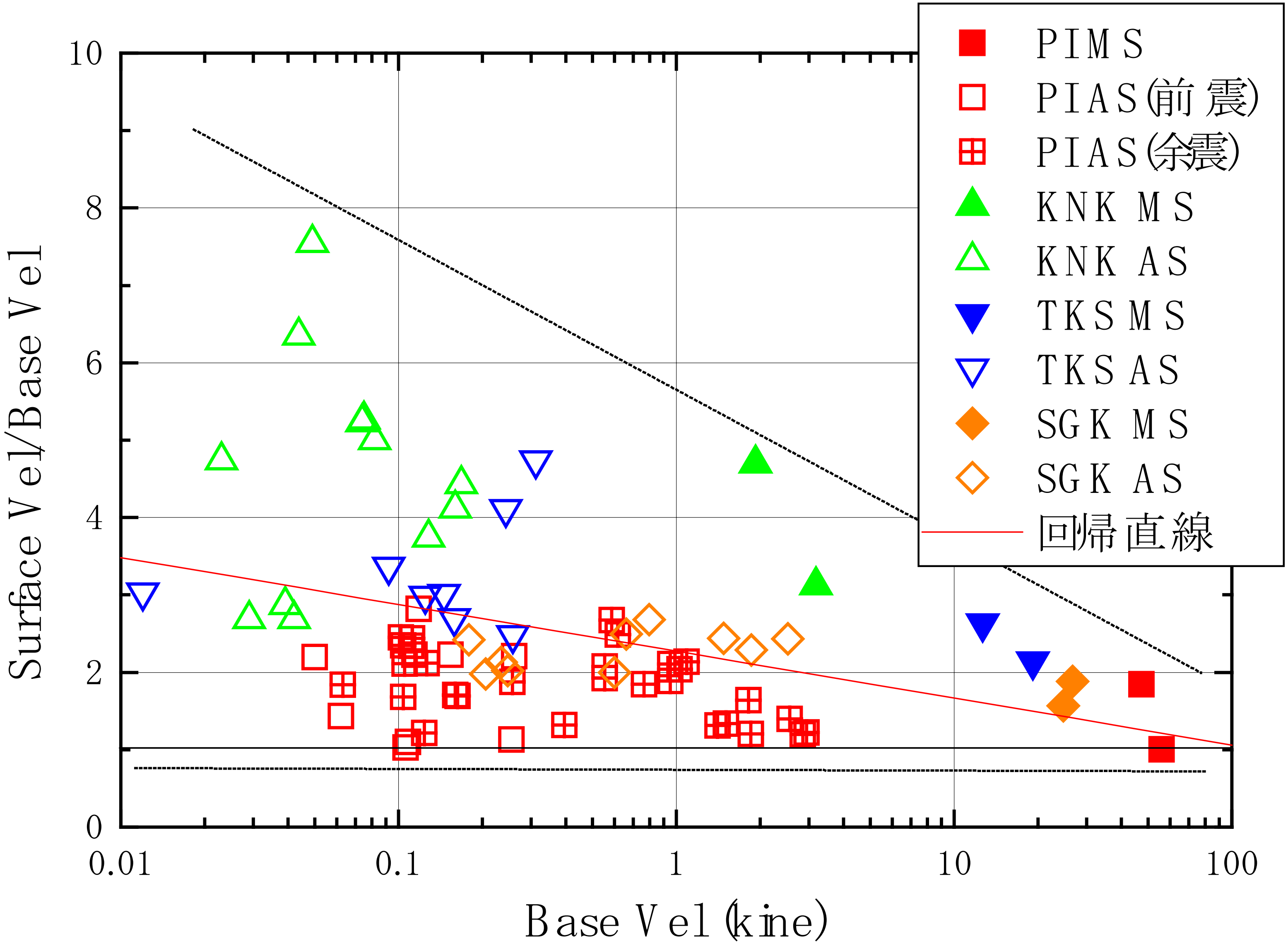
Max. Acc. in 4 vertical array sites during Kobe EQ



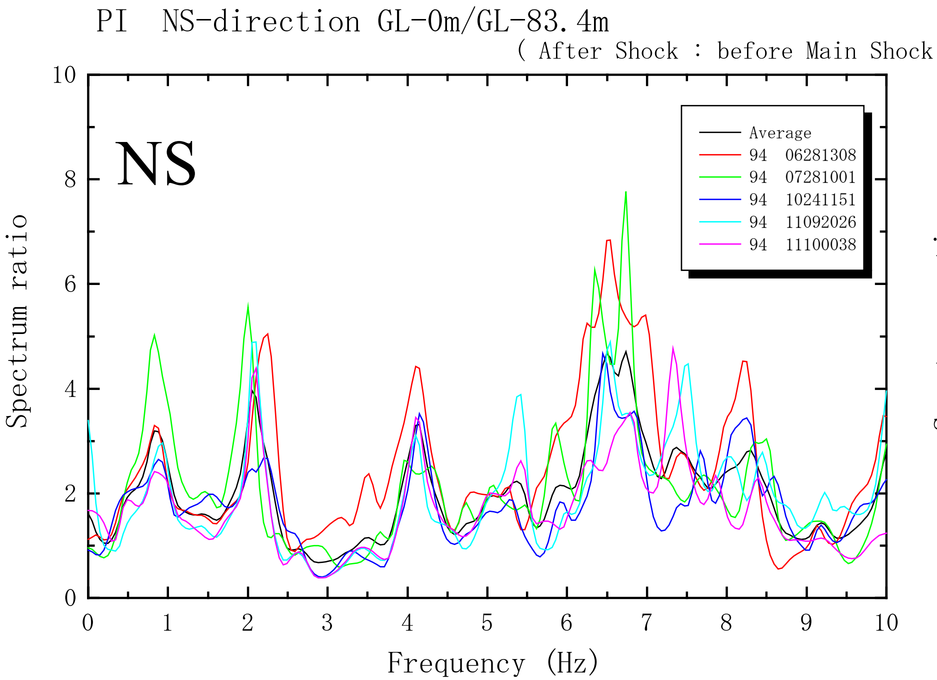
Vs-ratio (base to surface) versus amplification ratio of maximum acceleration

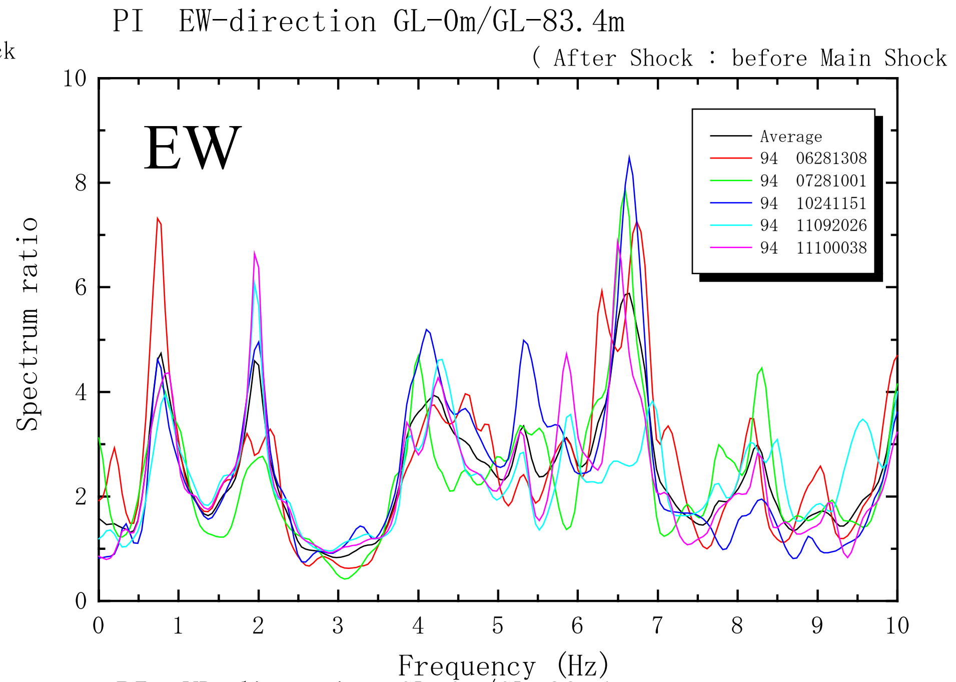


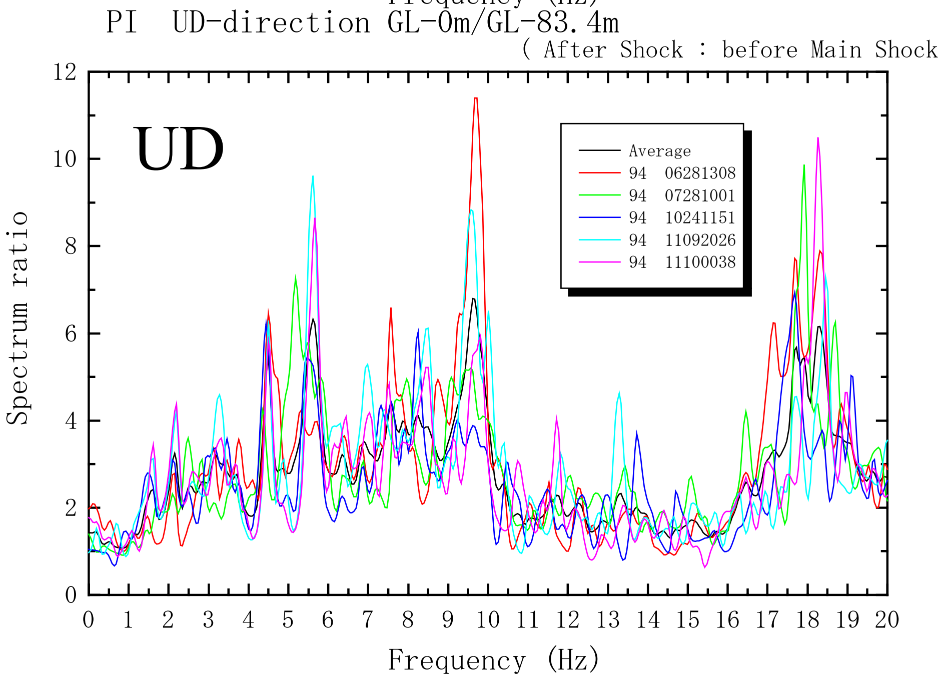
Max. Base Acc. versus Acc. amplification (Surf./Base)



Max. Base Vel. versus Max. Vel. Amplification (Surf./Base)

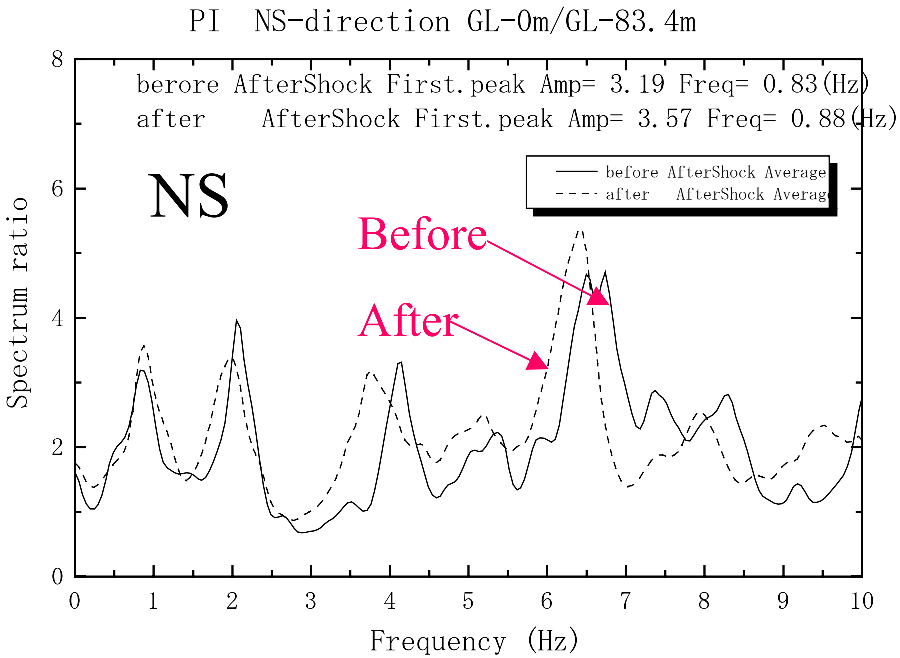


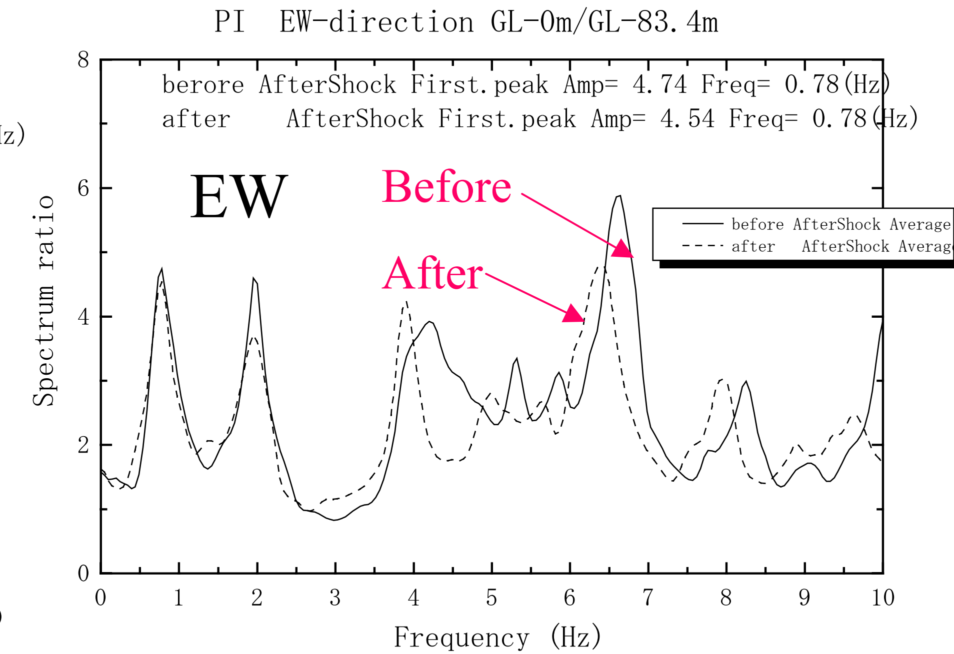




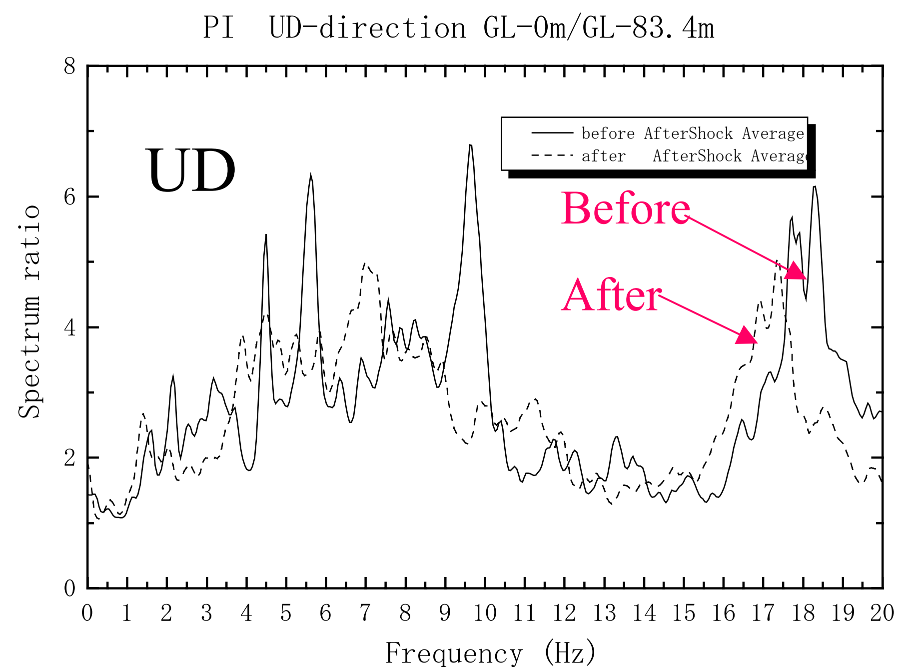
Spectrum ratio

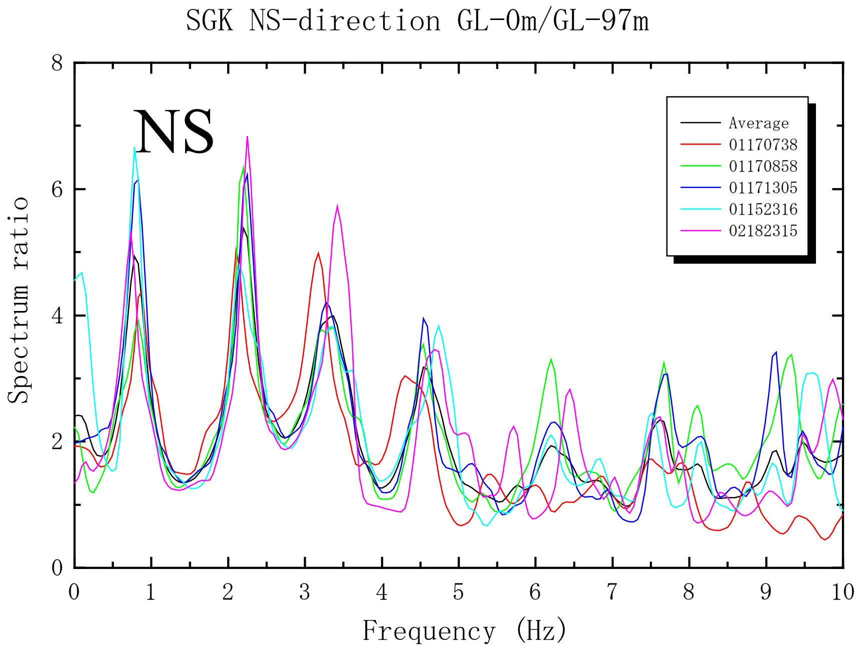
(PI: small shocks before main shock)

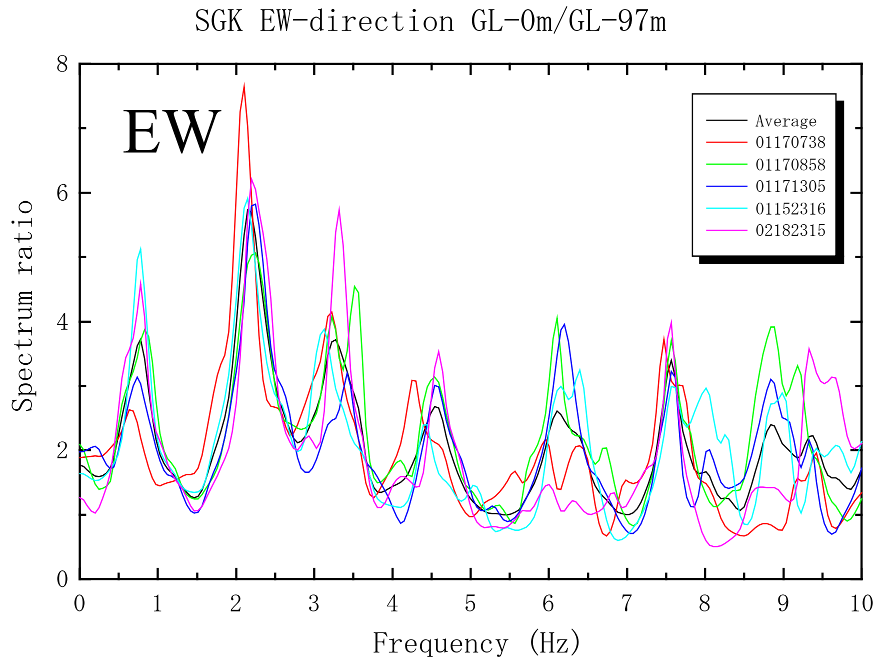




Comparison of averaged spectrum ratios of small shocks before & after main shock (PI)

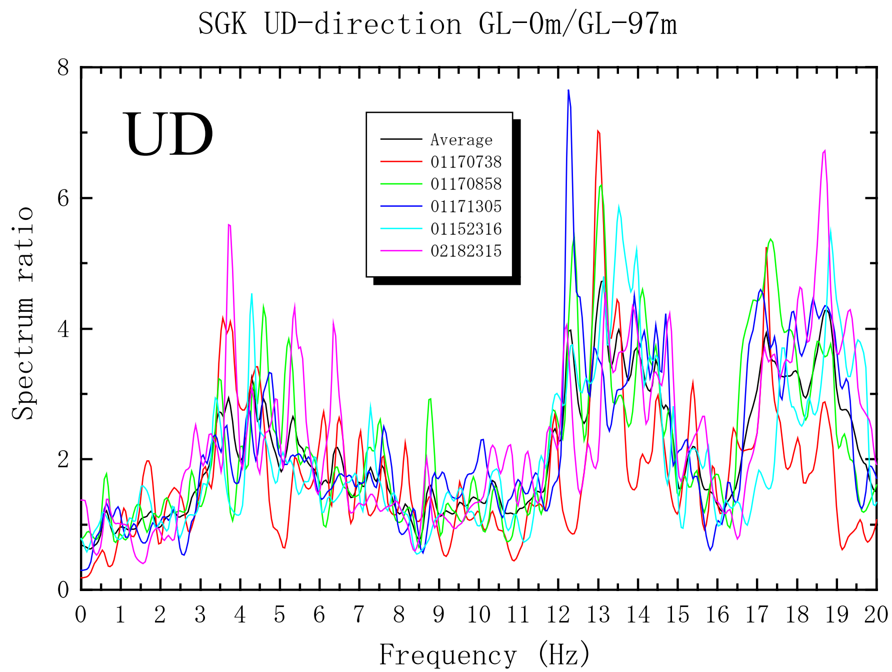


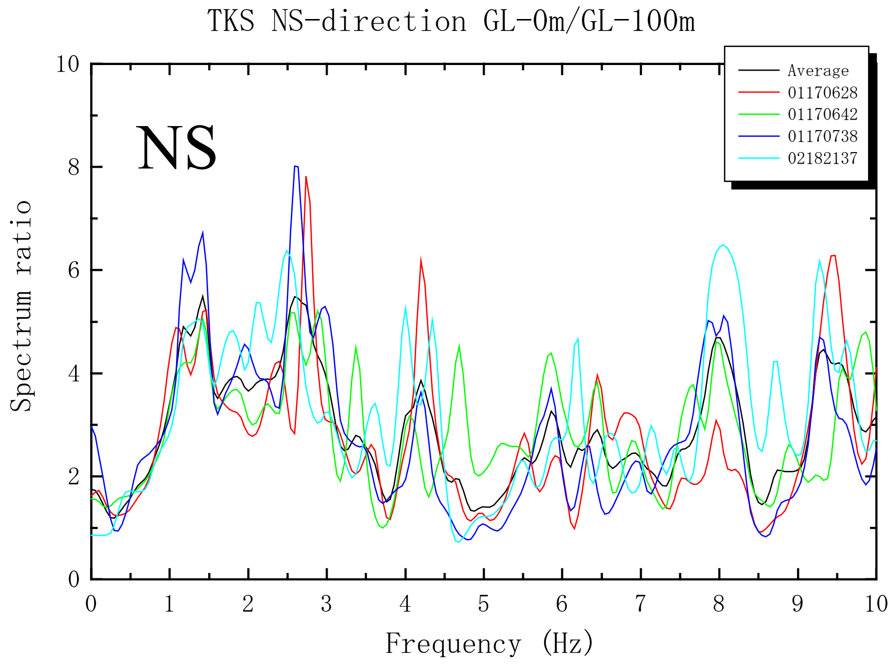


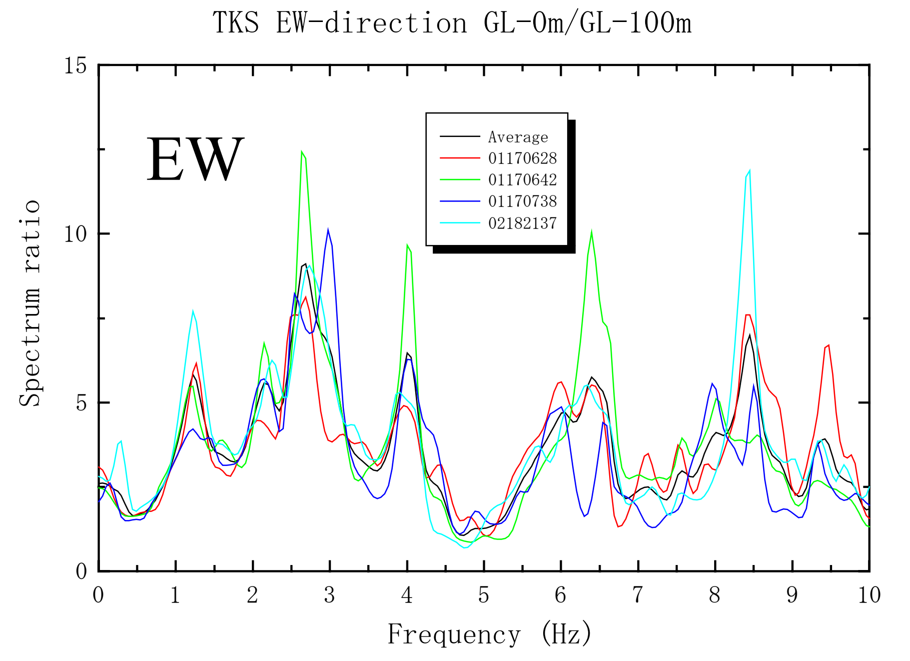


Spectrum ratio

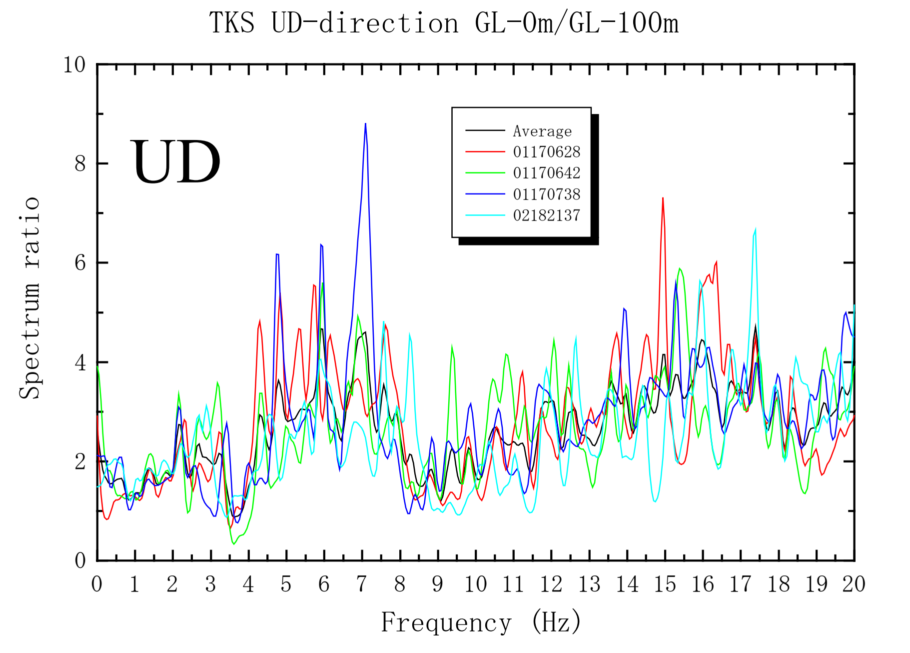
(SGK: aftershocks)

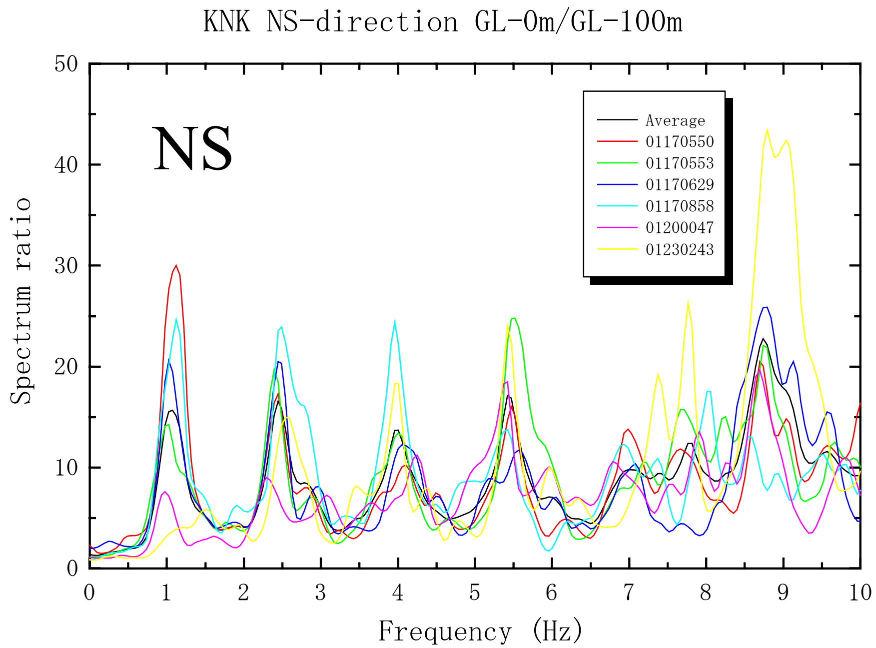


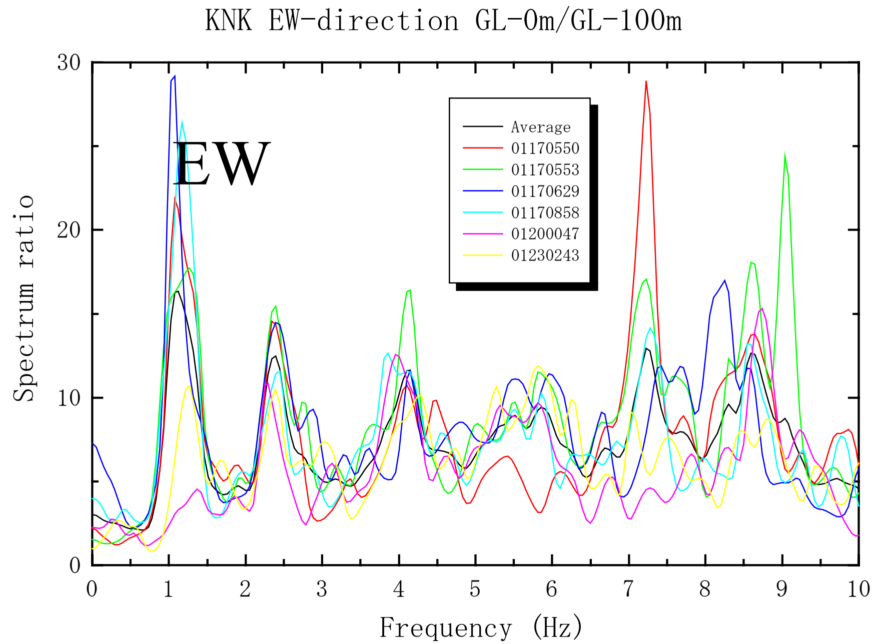


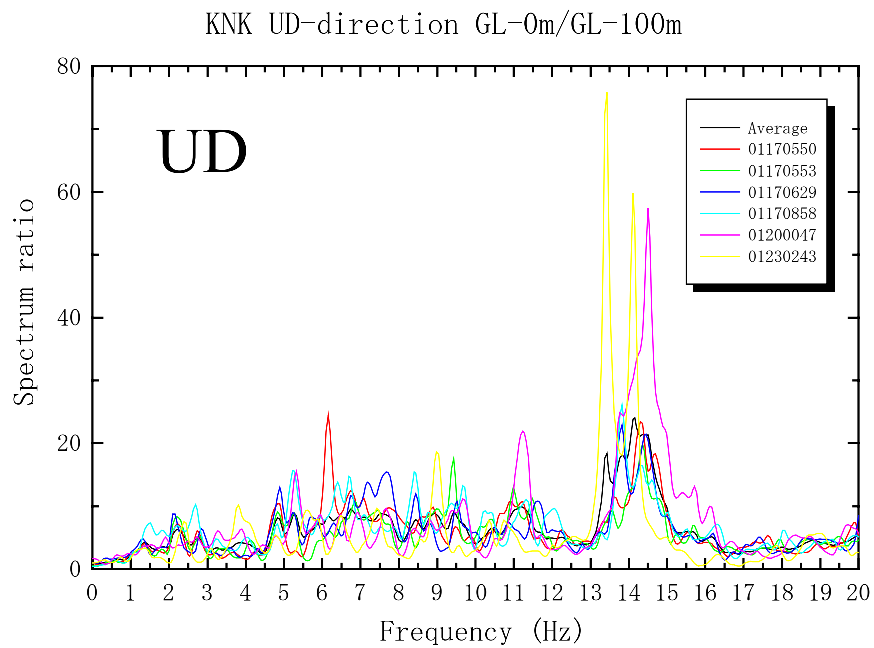


Spectrum ratio (TKS: aftershocks)



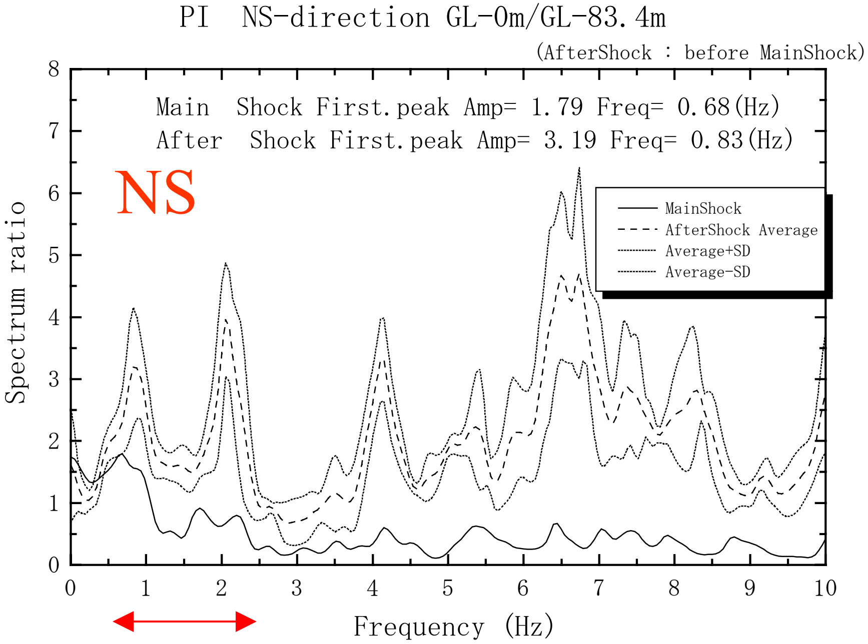


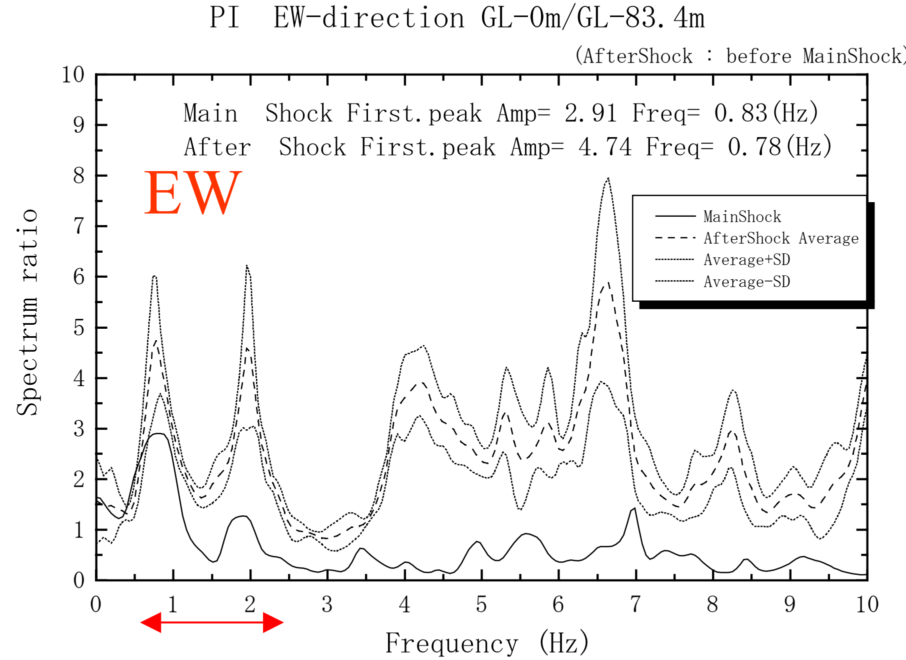




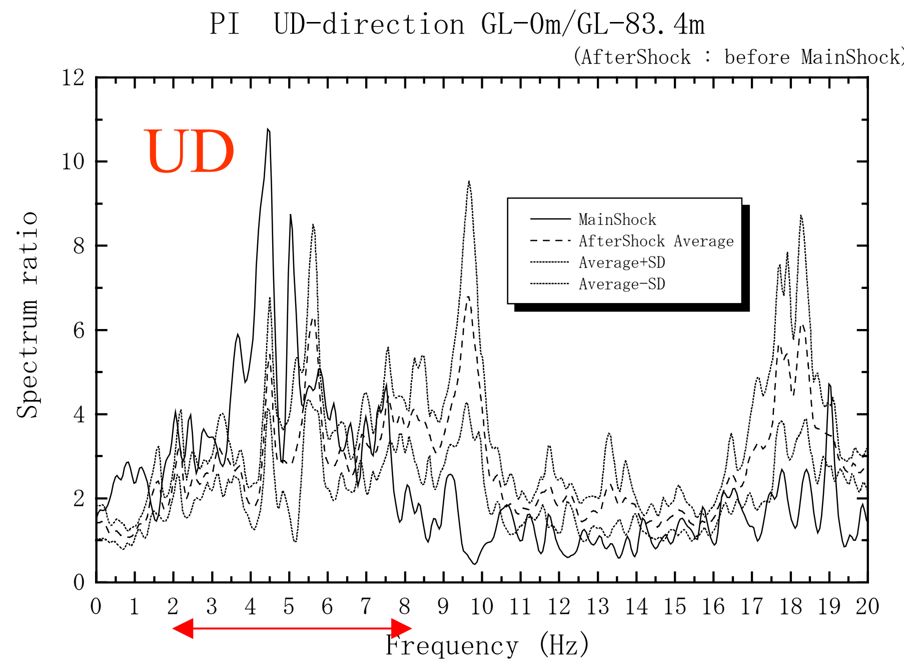
Spectrum ratio

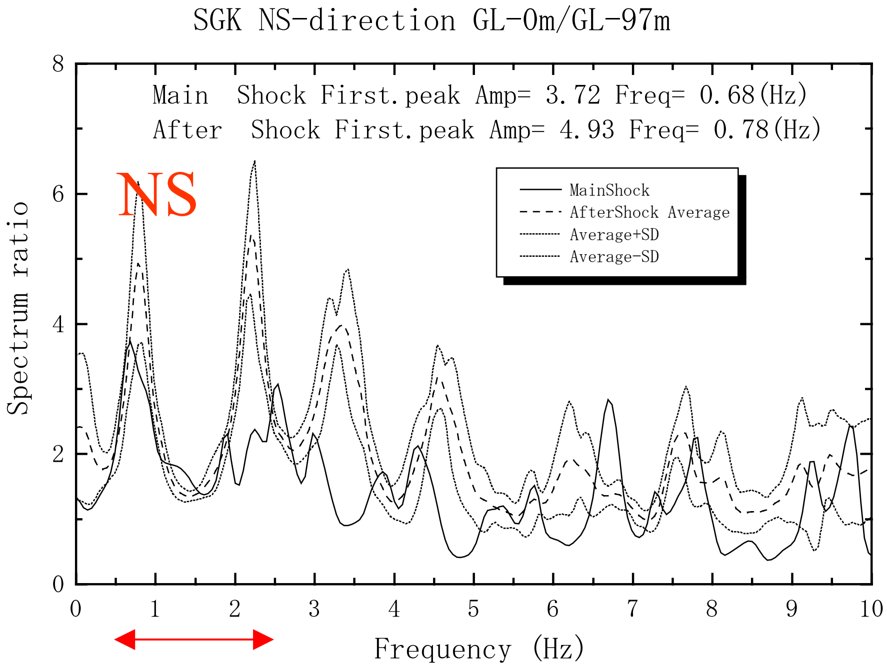
(KNK: aftershocks)

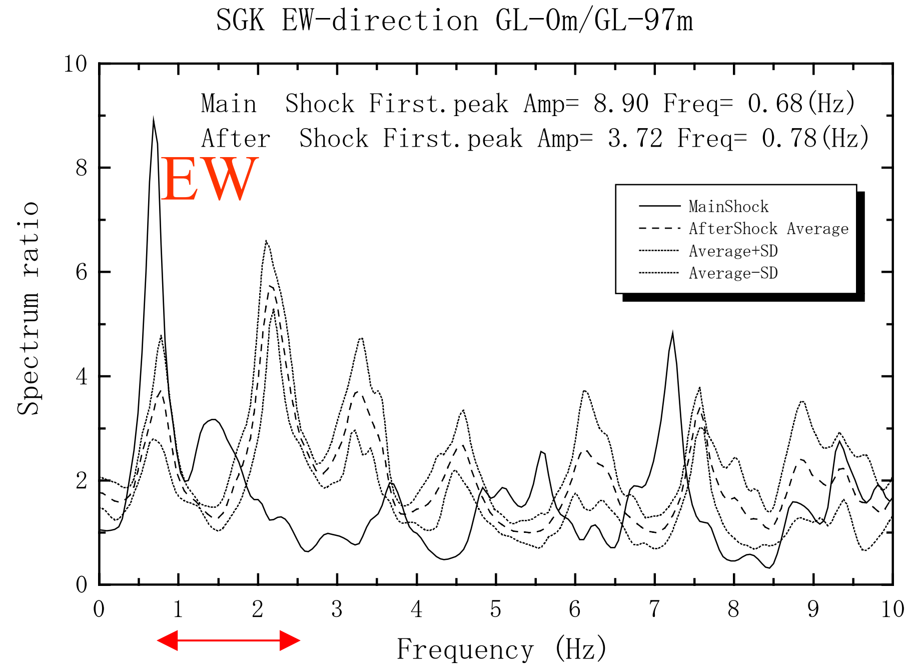




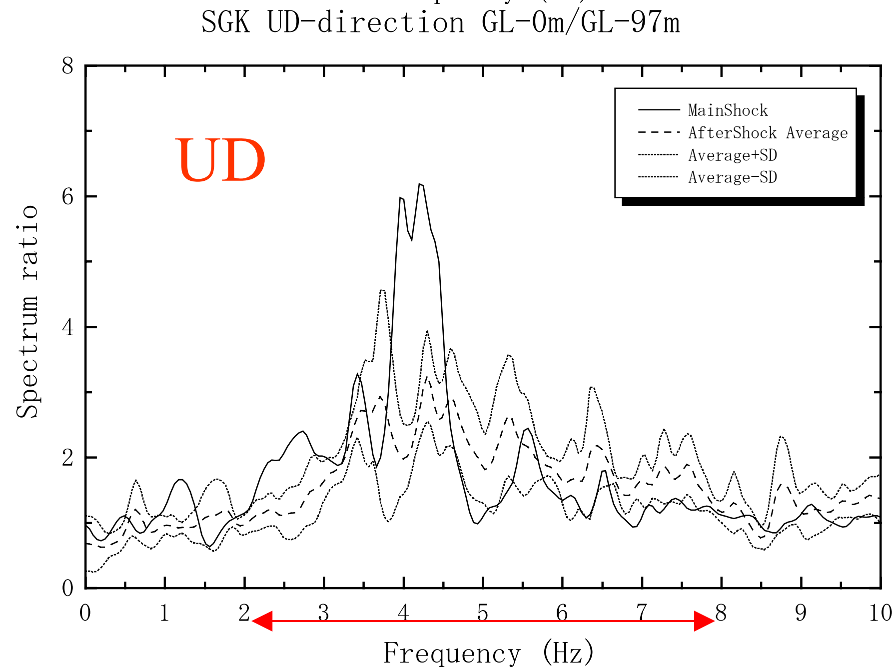
Comparison of spectrum ratio of small shocks and main shock (PI)

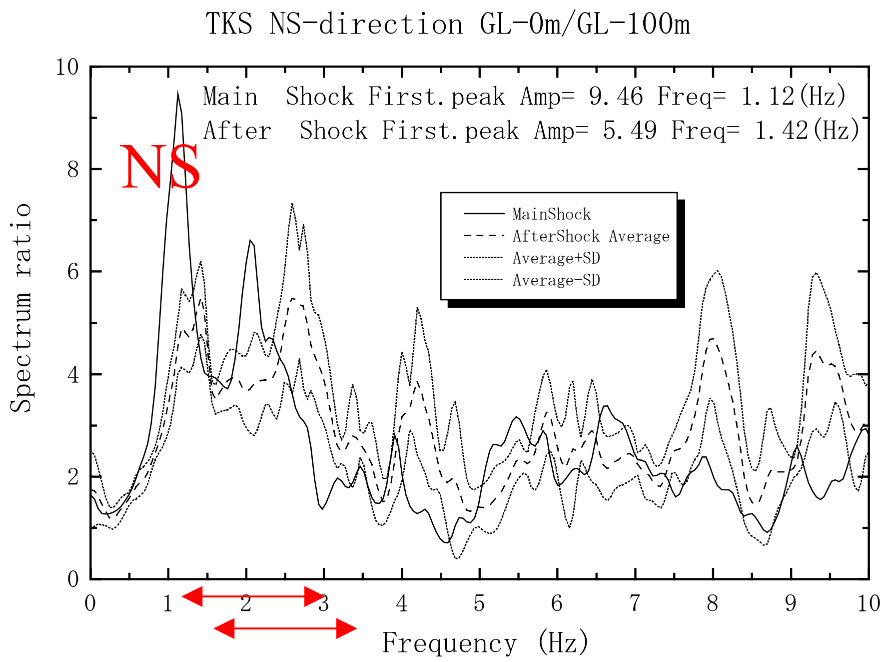


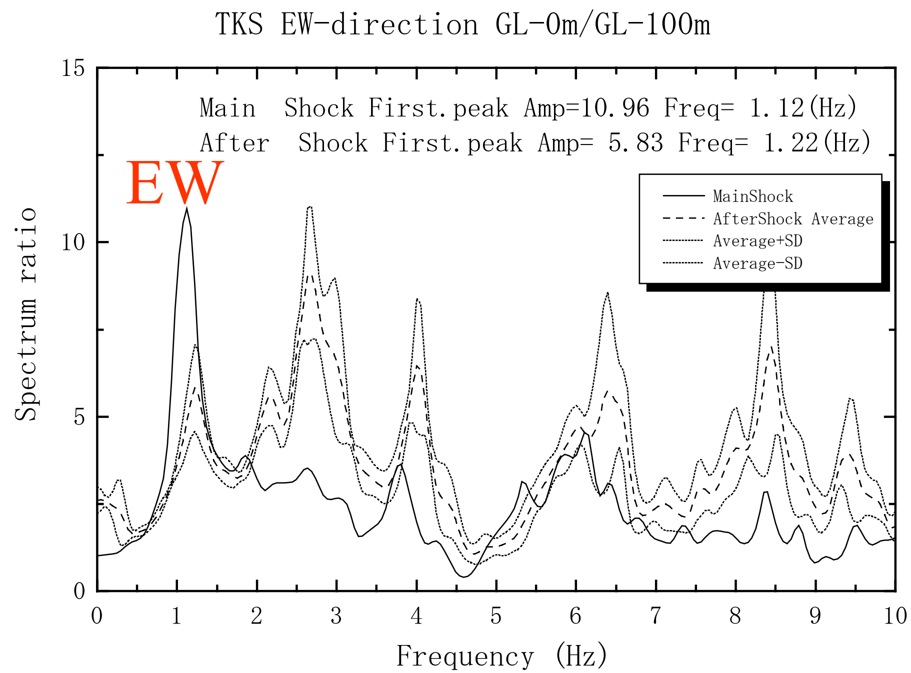




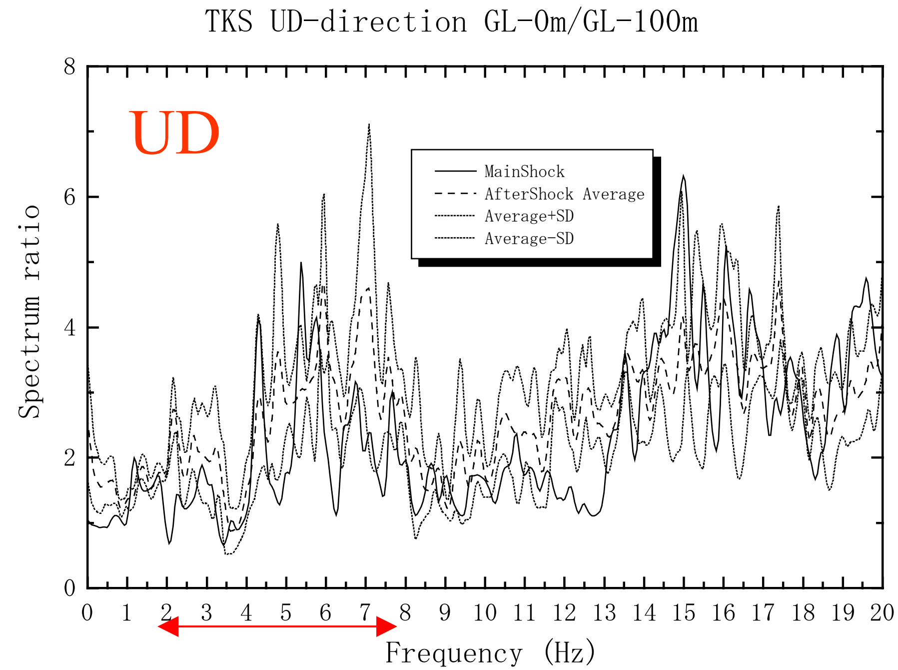
Comparison of averaged spectrum ratio of aftershocks and main shock (SGK)

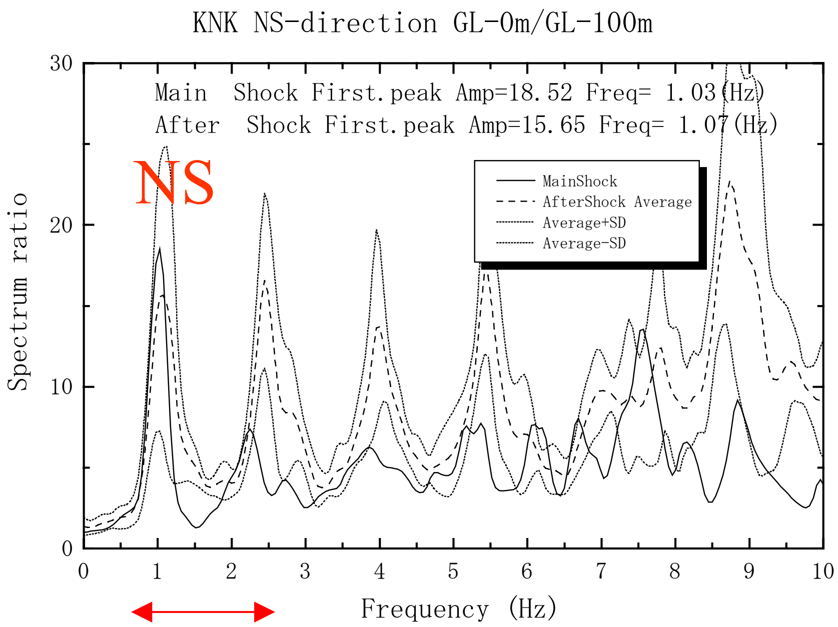


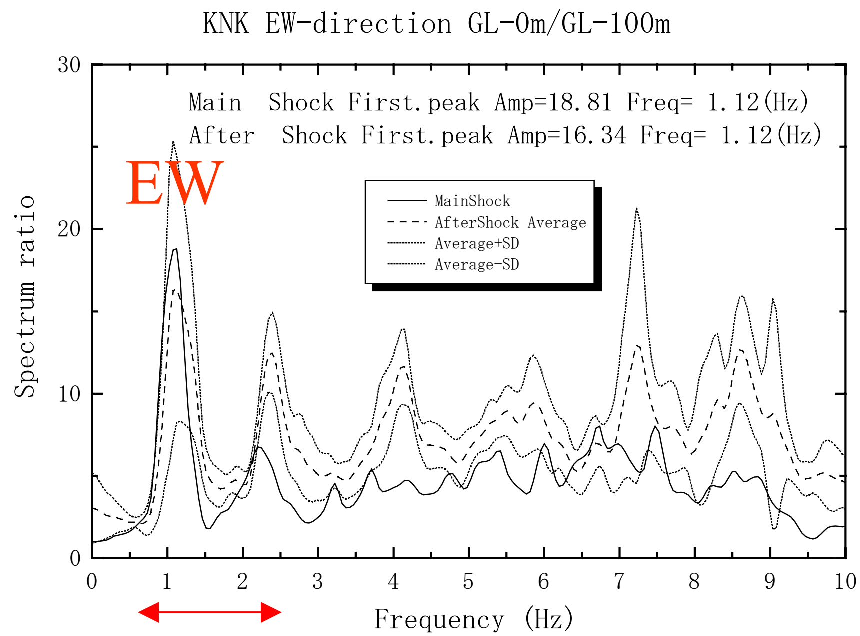




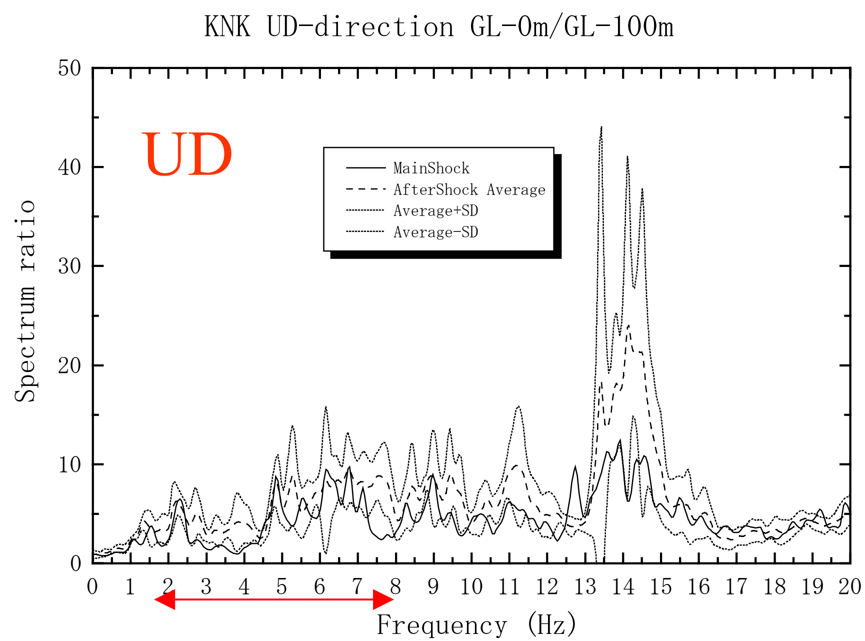
Comparison of averaged spectrum ratio of aftershocks and main shock (TKS)

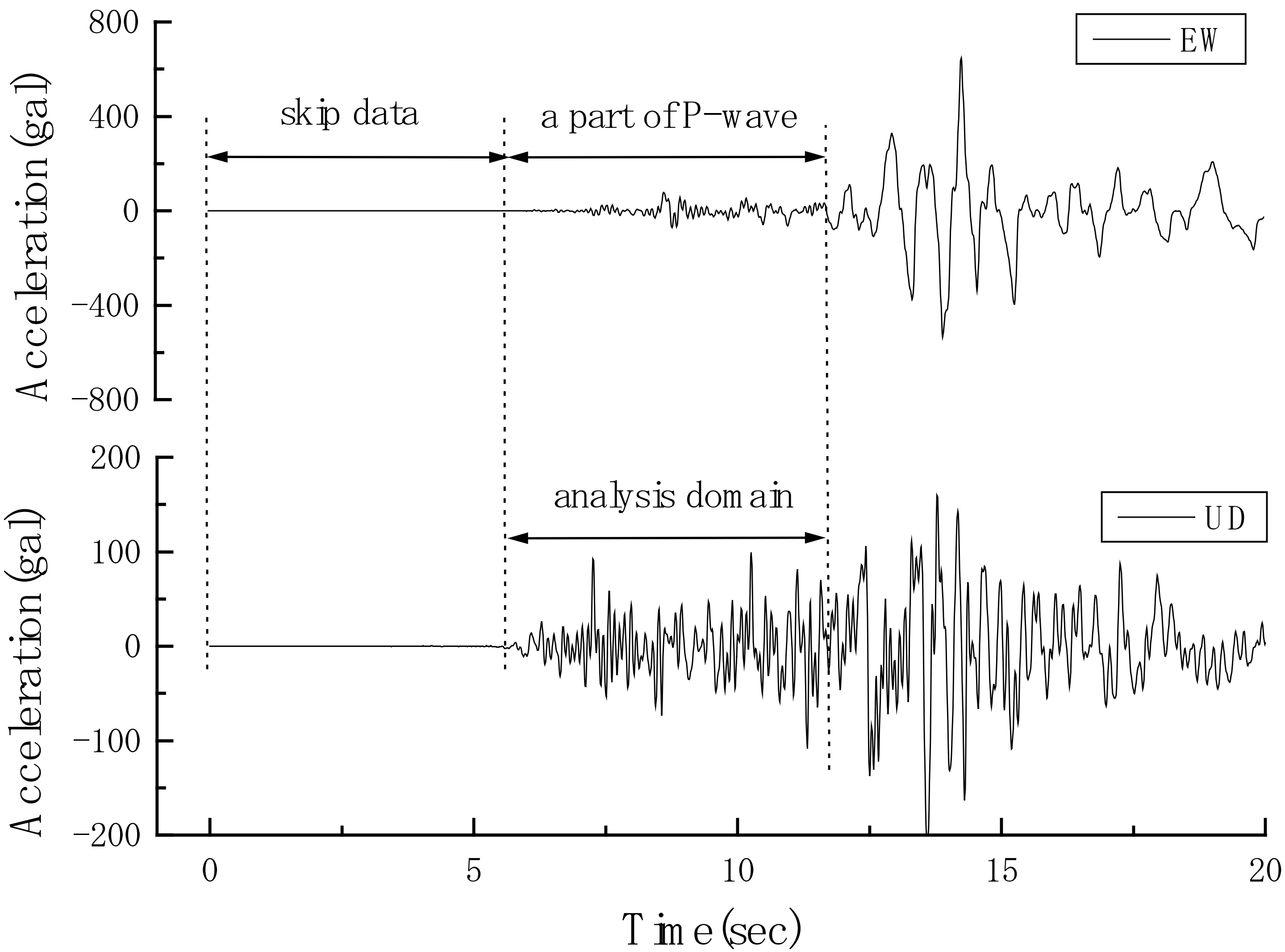




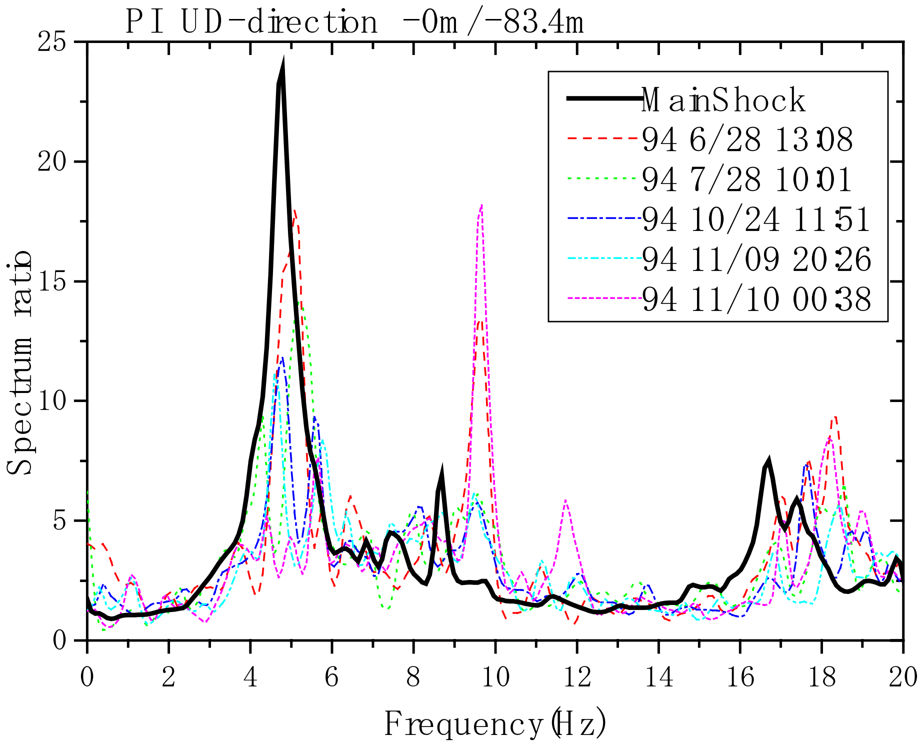


Comparison of averaged spectrum ratio of aftershocks and main shock (KNK)

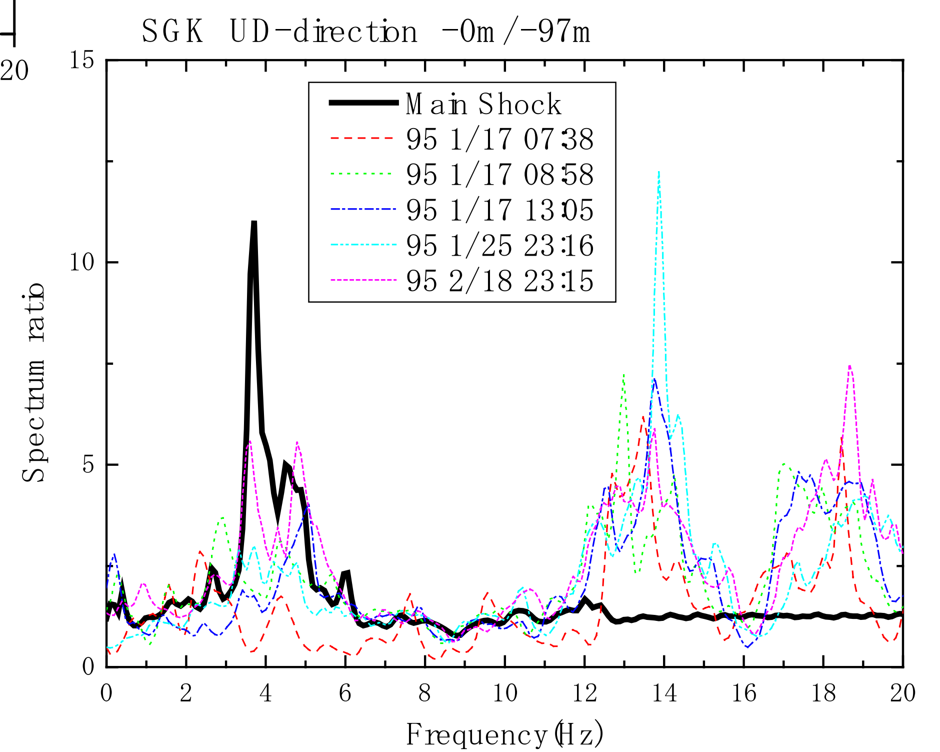


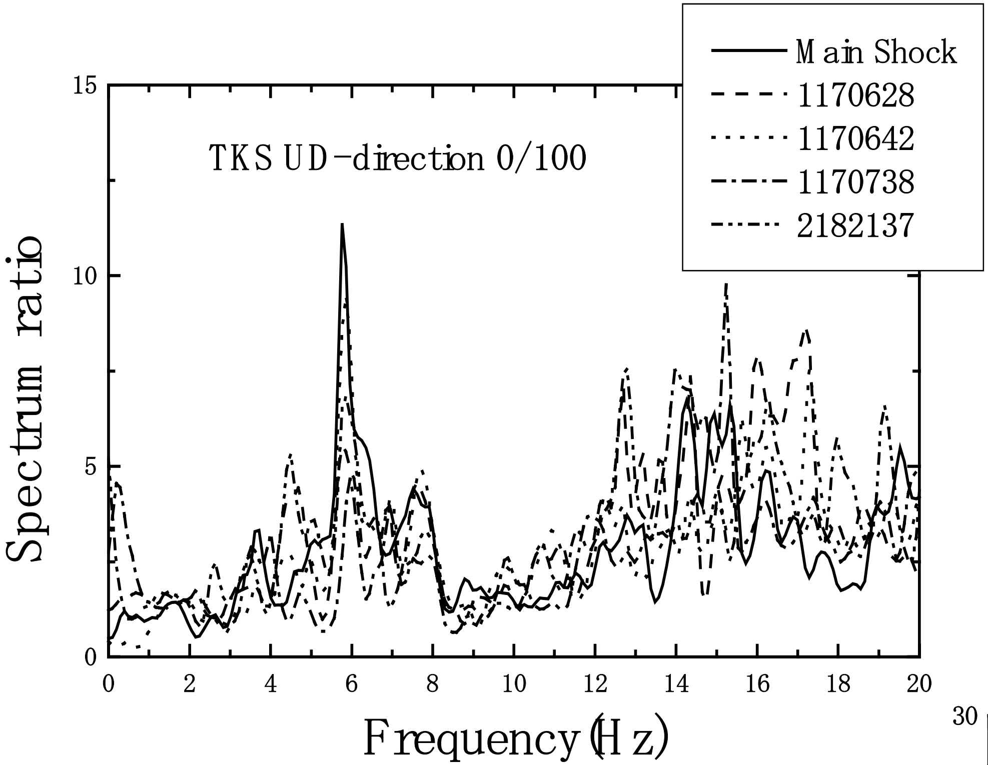


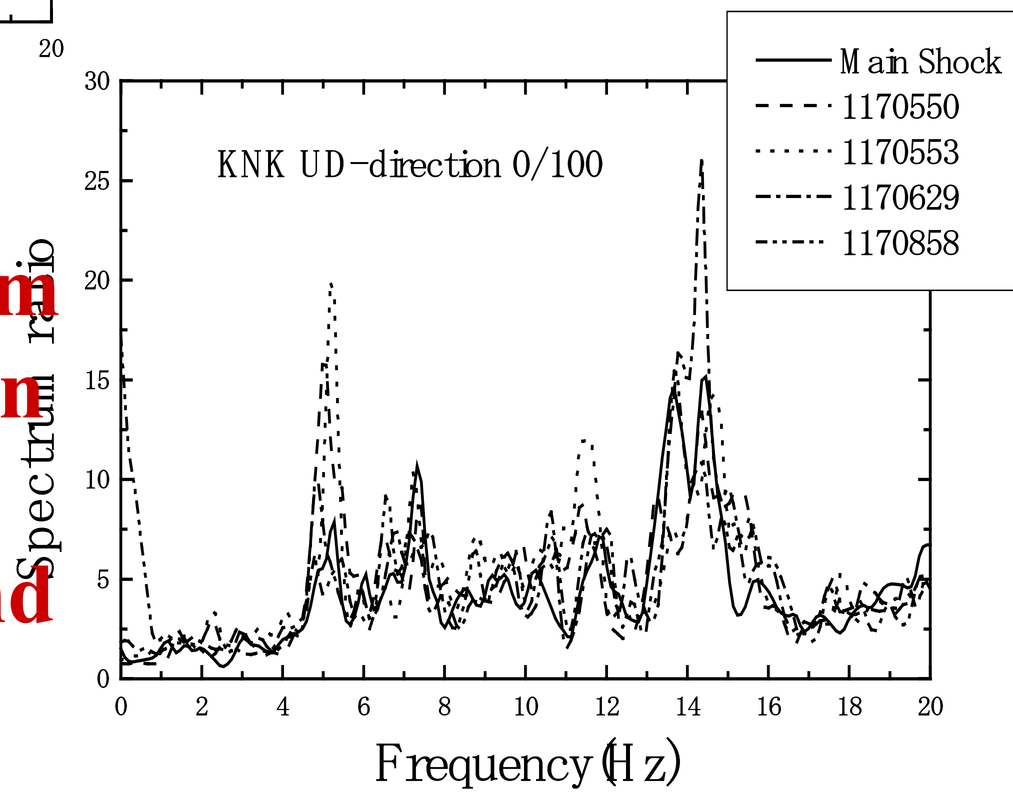
Analysis of vertical motion for initial P-wave



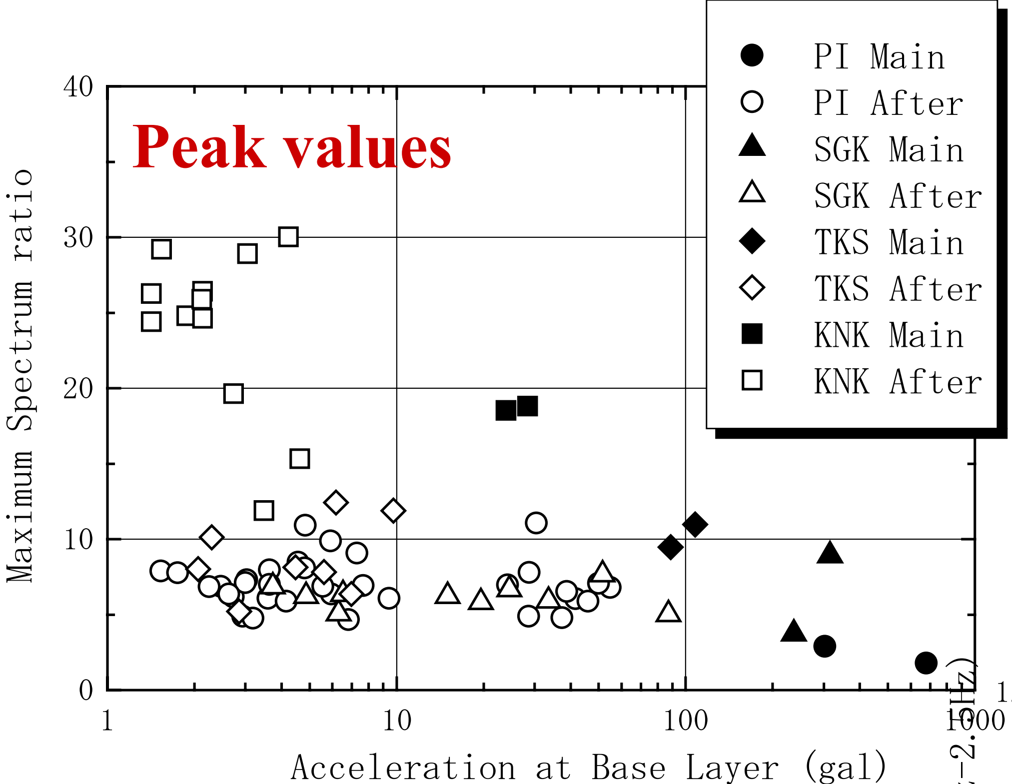
Comparison of spectrum ratios of vertical motion for initial P-wave between main shock and aftershocks

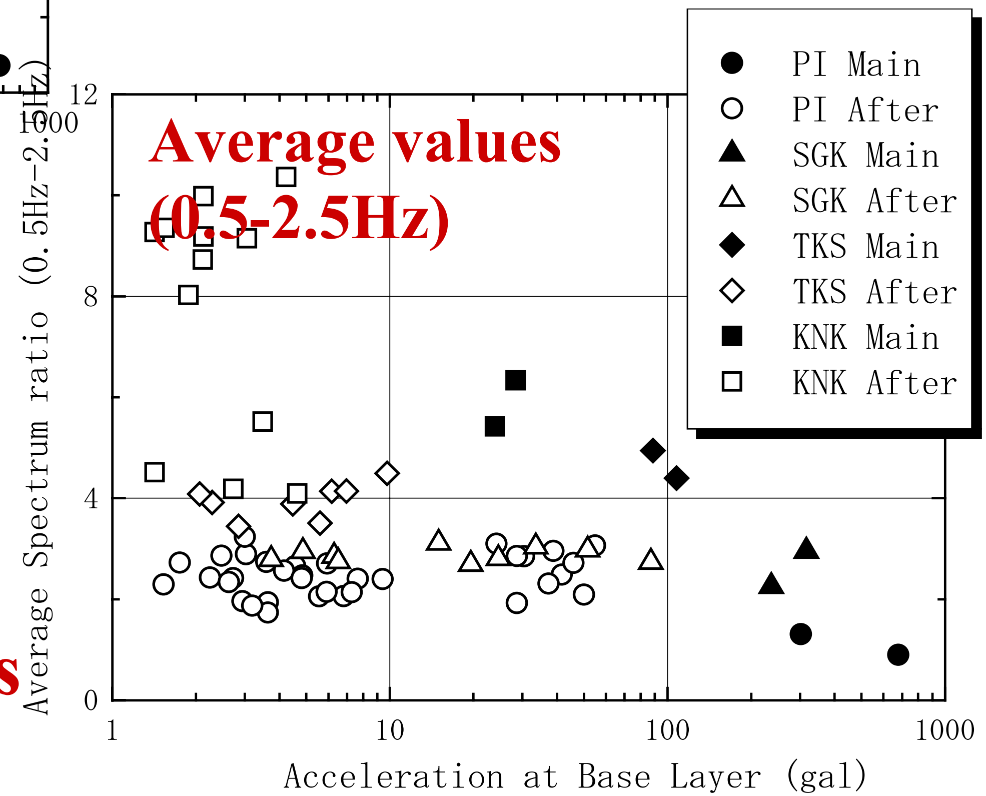




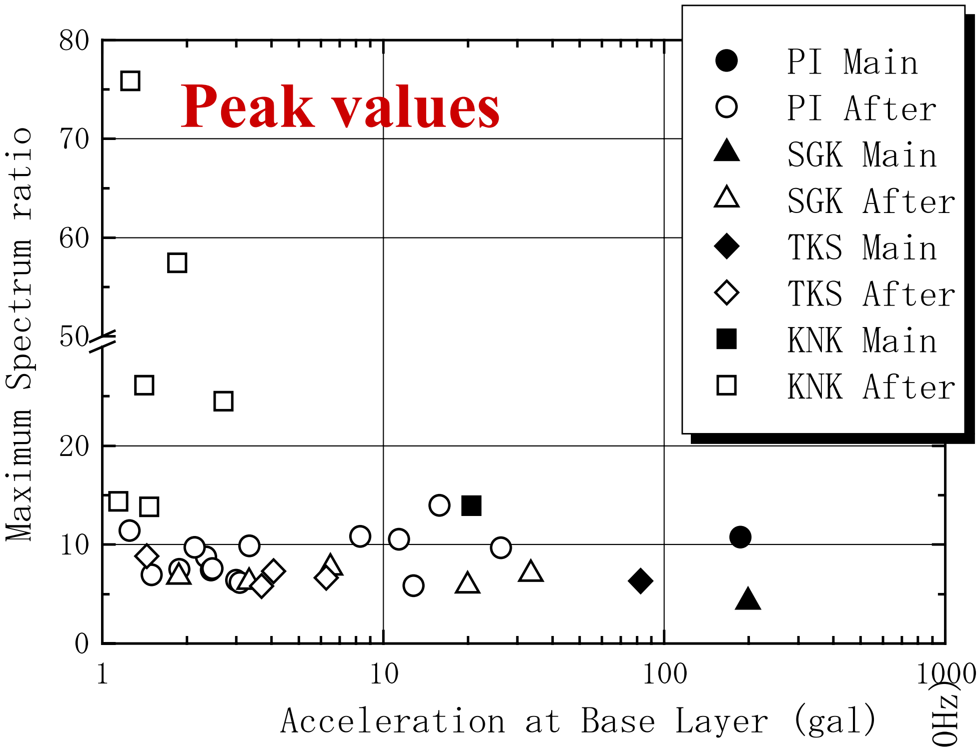


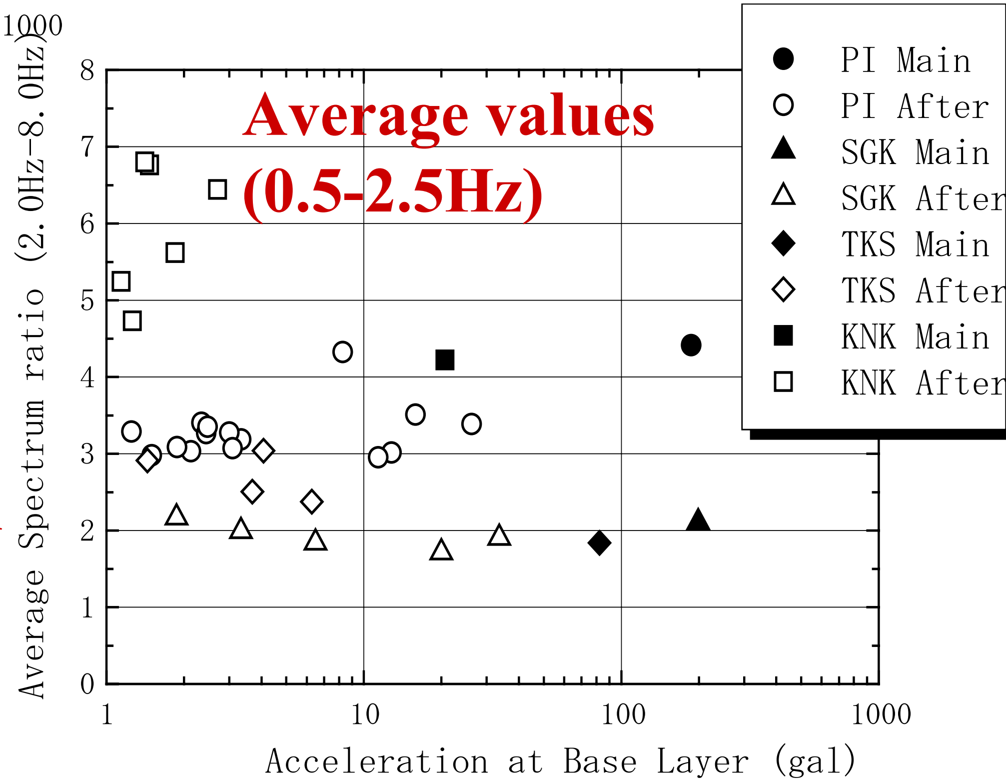
Comparison of spectrum ratios of vertical motion for initial P-wave between main shock and aftershocks





Base Acc. versus Spectrum Ratios of horizontal motions (Peak & Average values)





Base Acc. versus Spectrum Ratios of vertical motions (Peak & Average values)

SUMMARY ON SITE AMPLIFICATION BASED ON VERTICAL ARRAY RECORDS

- Clear Acc. amplification reduction for increasing base Acc. The same trend for Vel. though milder.
- Steady spectral response for small shocks.
- Reduction in peak frequencies and magnitudes of spectrum ratios between main shocks and small shocks particularly in liquefaction sites.
- Increase in amplification with increasing Vs ratio between base and surface.
- In vertical motions, no difference in peak frequencies between main shocks and small shocks

Topics of the presentation:

Seismic site amplification during strong earthquakes based on vertical array records

Back-calculated in situ soil properties versus lab data

Soil properties for deep soil response

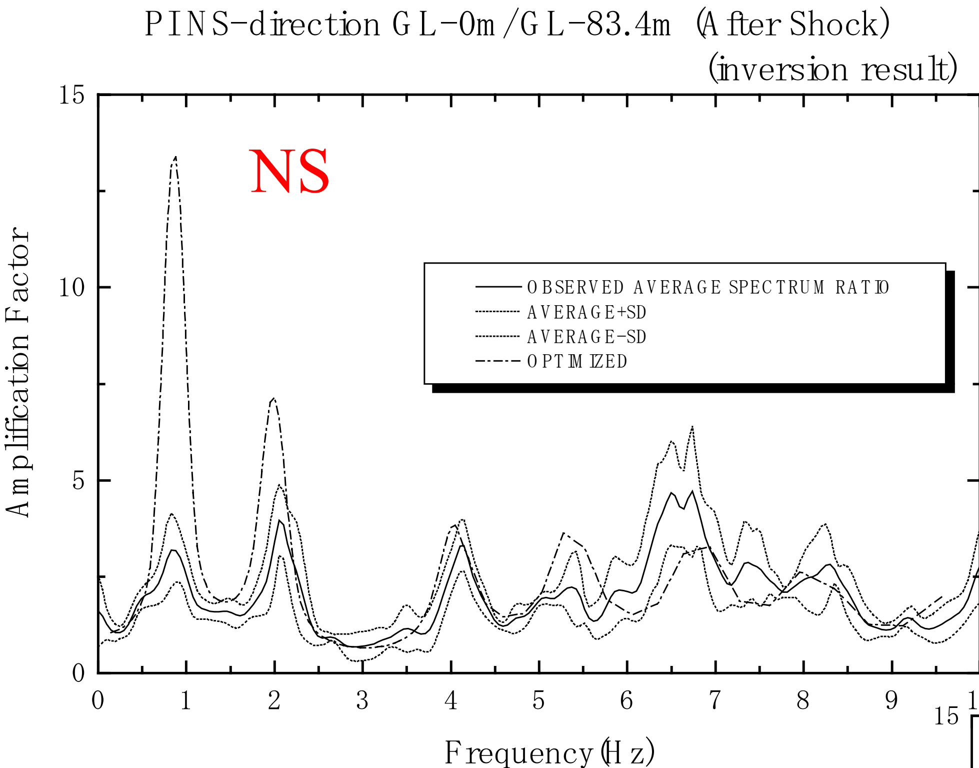
How to back-calculate in situ properties from vertical array records

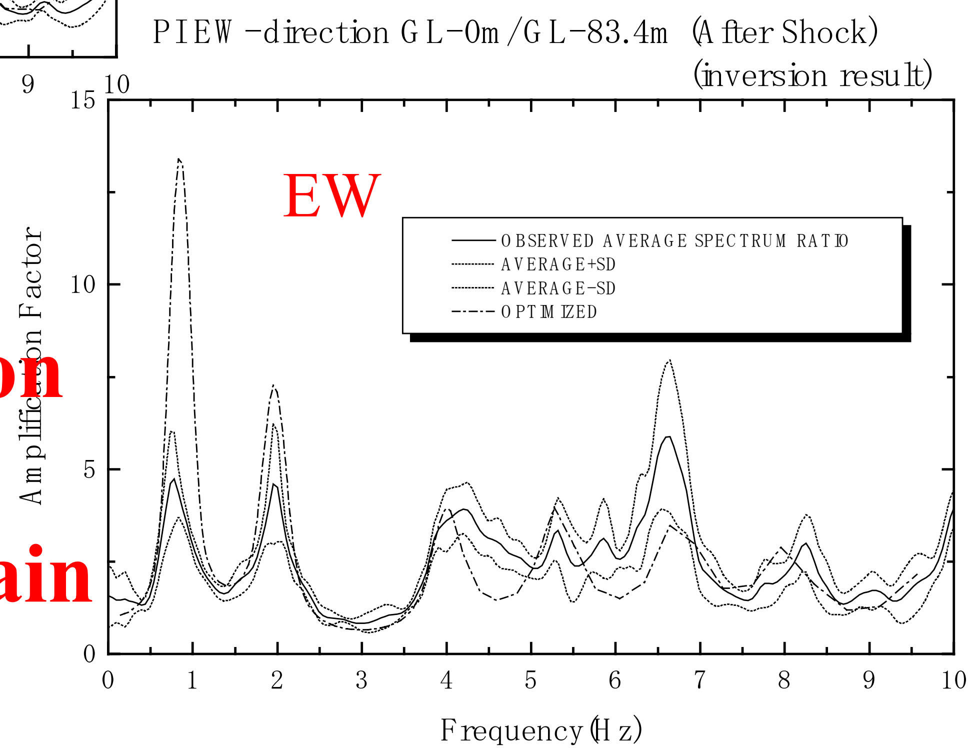
Optimize Vs (S-wave velocity) and D (damping ratio) based on 1D Multiple Reflection Theory of SH-wave.

Minimize residuals by EBM between observed and computed spectrum ratios.

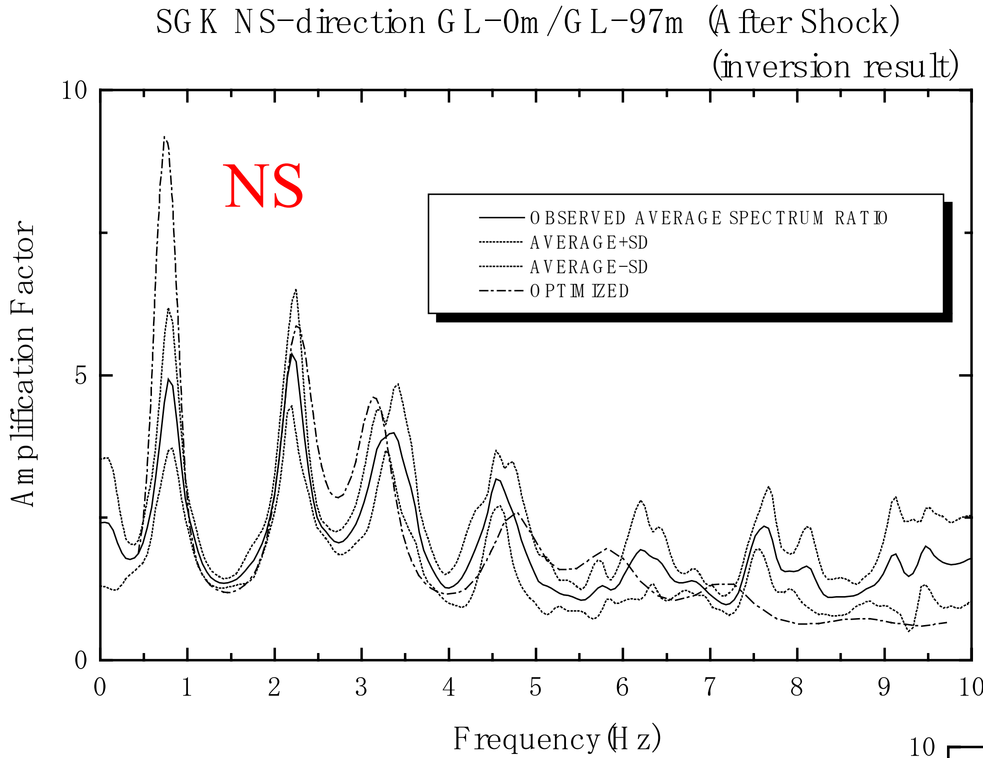
Main shock properties compared with small shock linear properties for in situ degradation curves.

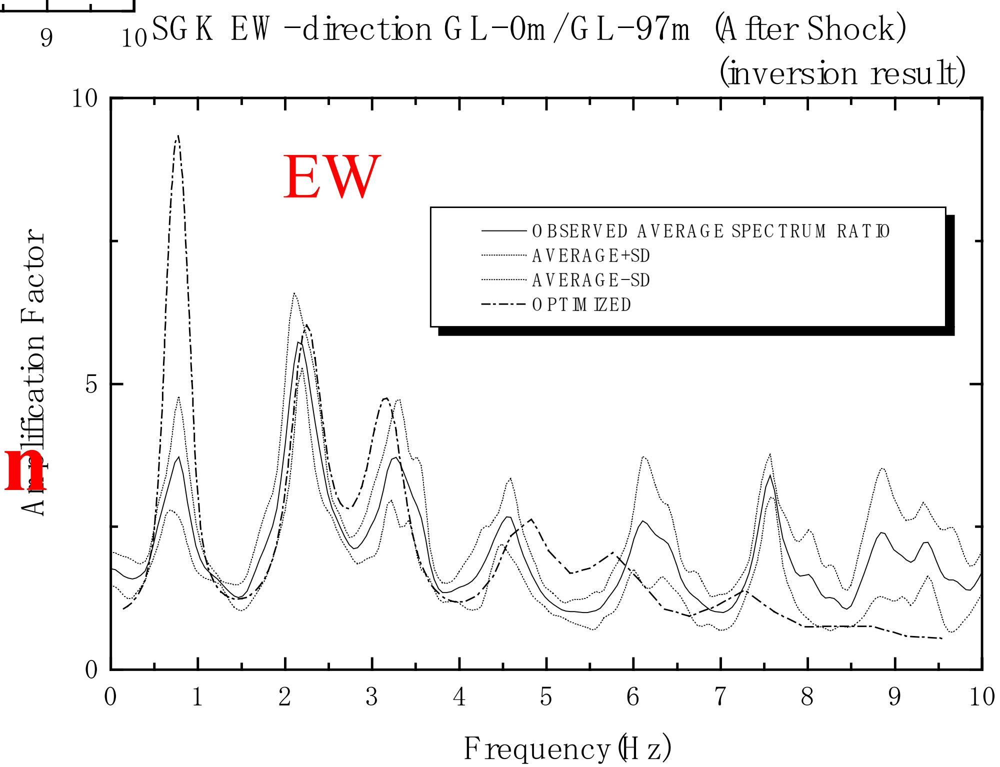
Identify in situ soil-specific properties.



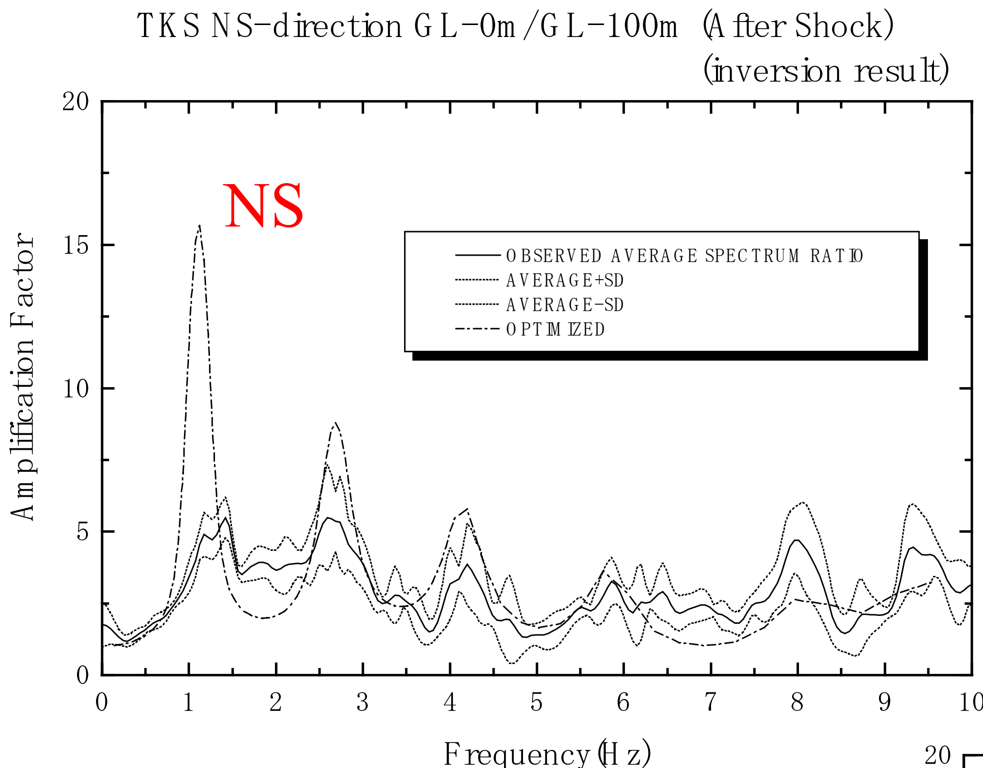


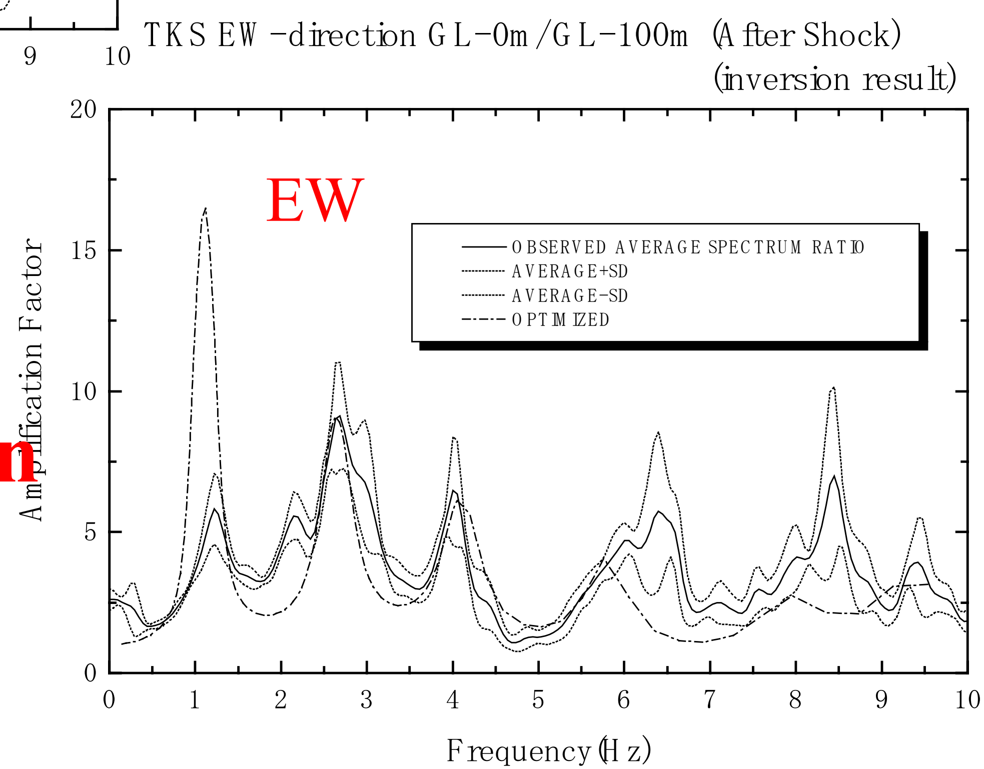
Comparison of inversion and observation (Small shocks before main shock: PI)



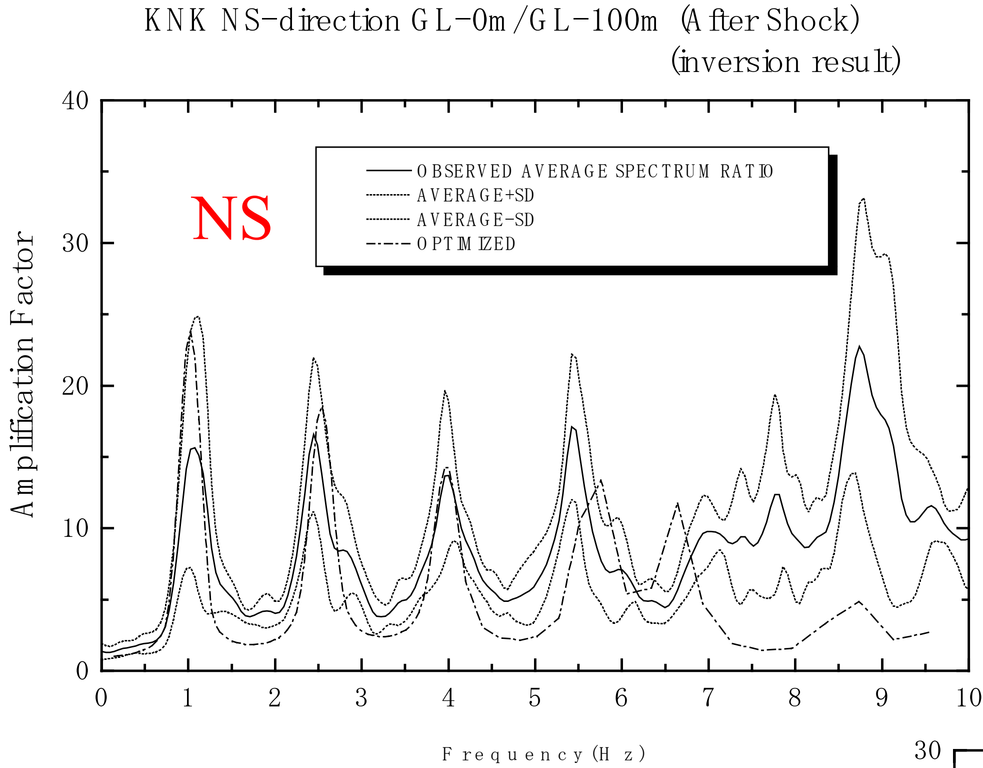


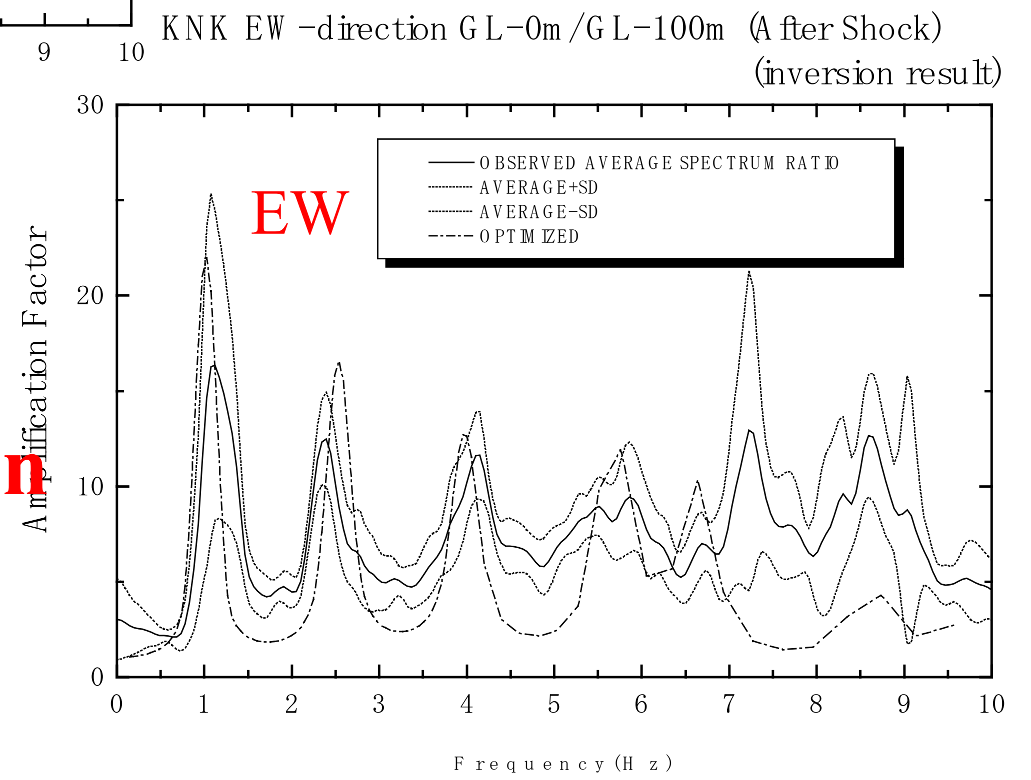
Comparison of inversion and observation (Aftershocks:SGK)



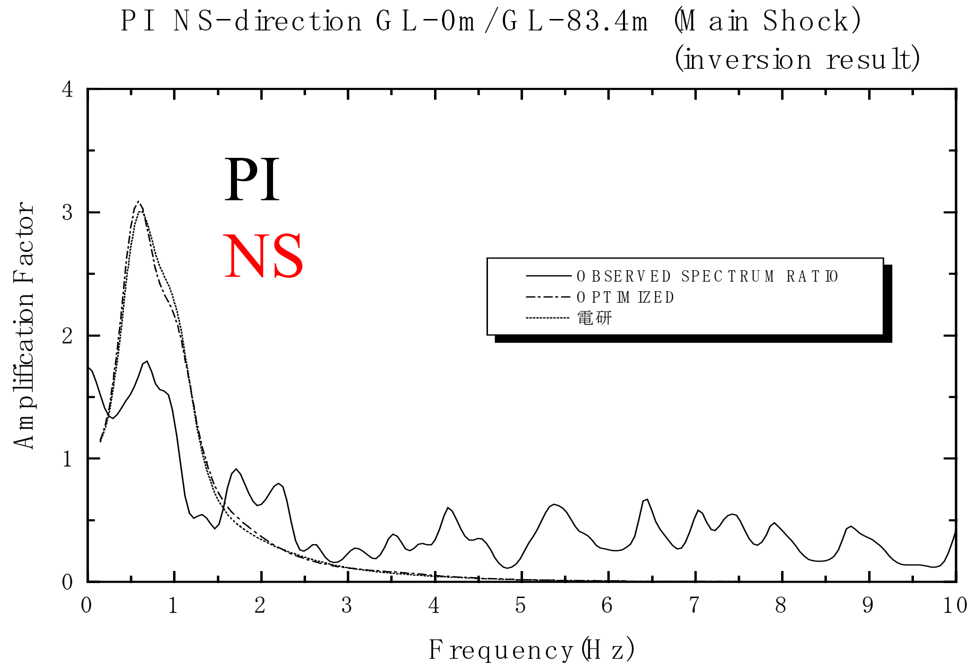


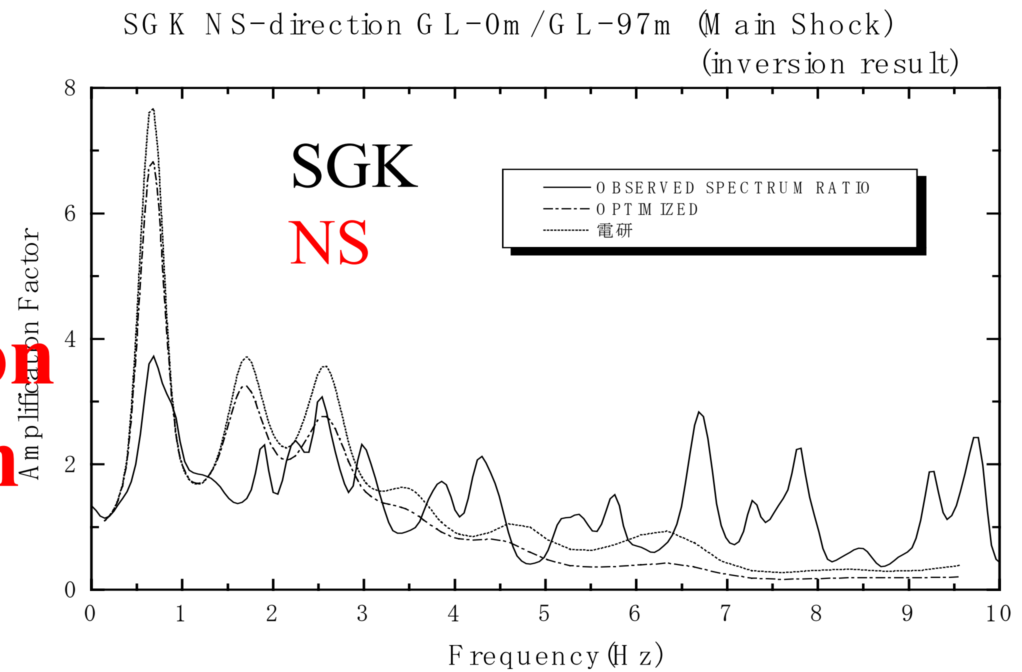
Comparison of inversion and observation (Aftershocks:TKS)





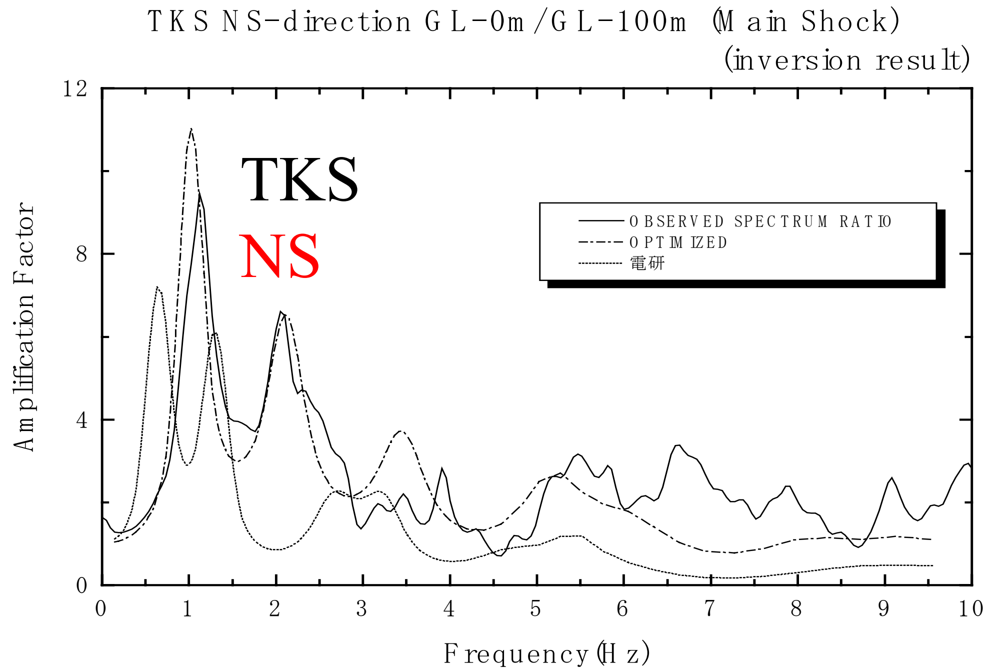
Comparison of inversion and observation (Aftershocks:KNK)

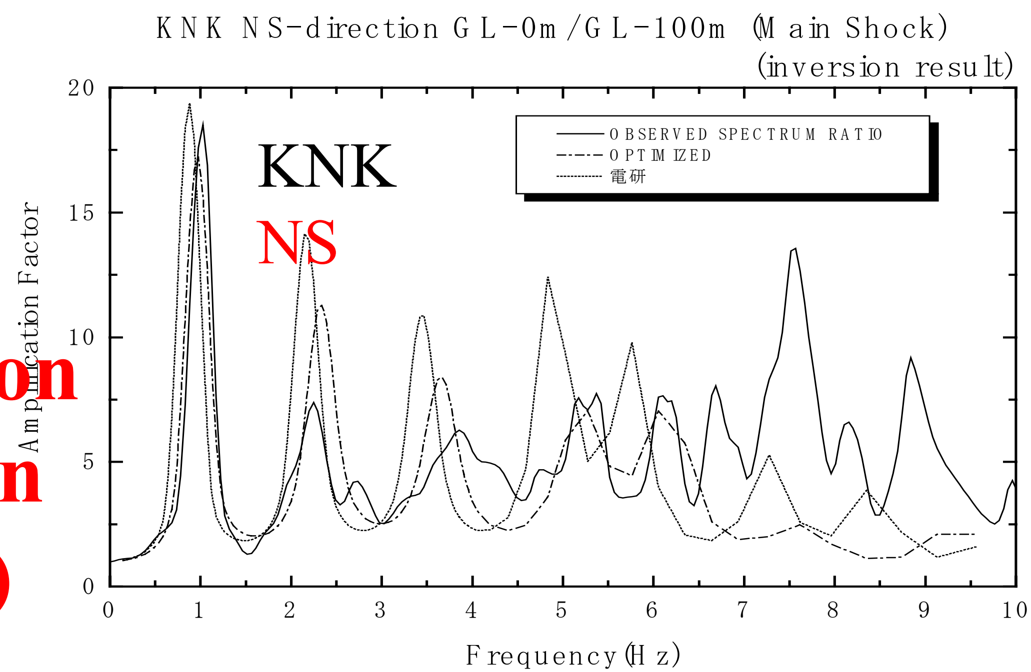




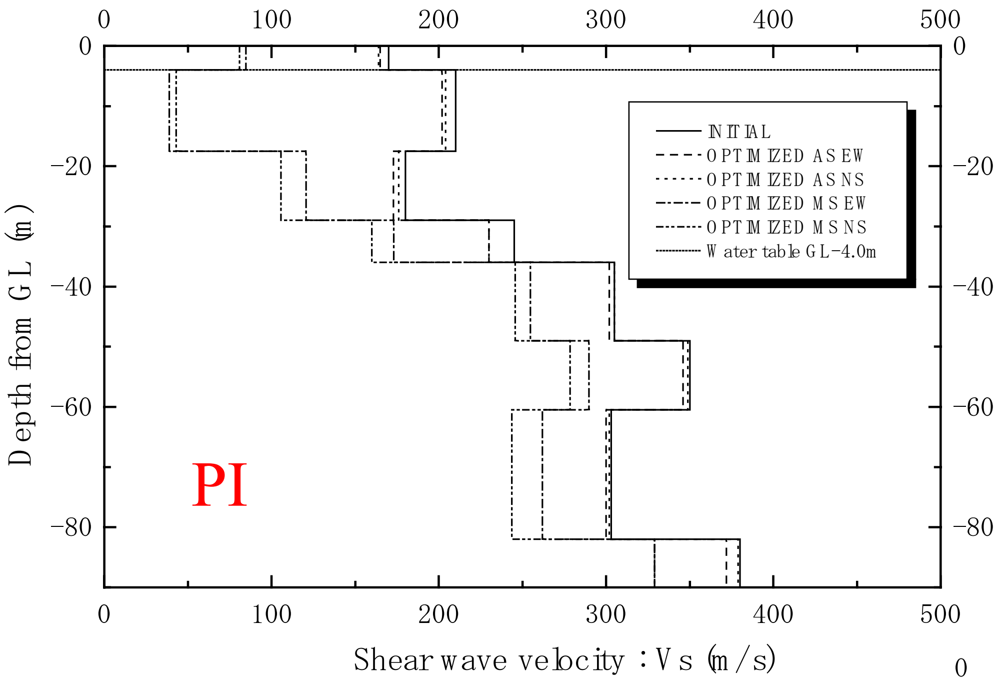
Comparison of inversion and observation (Main shock: PI & SGK)

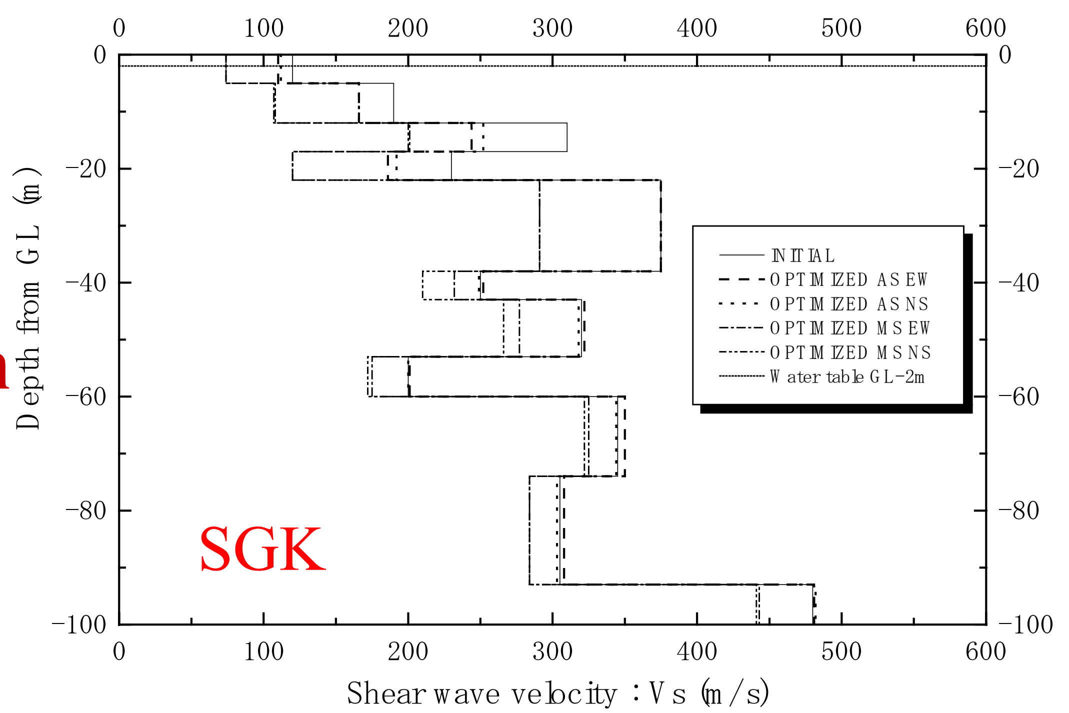
Horizontal



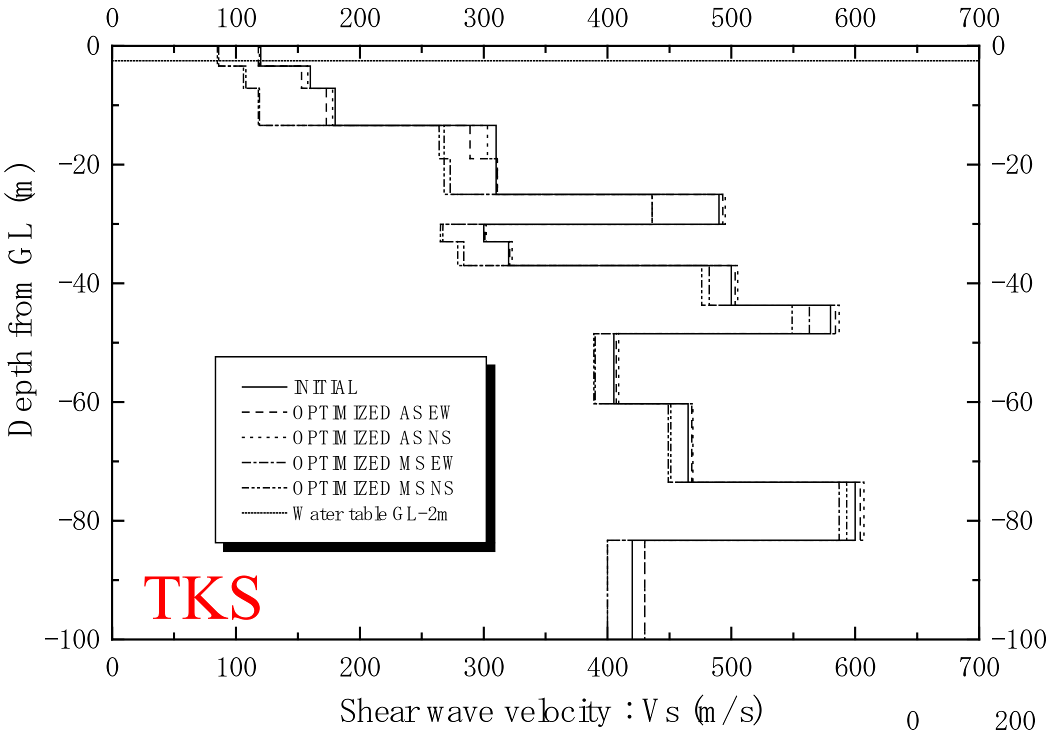


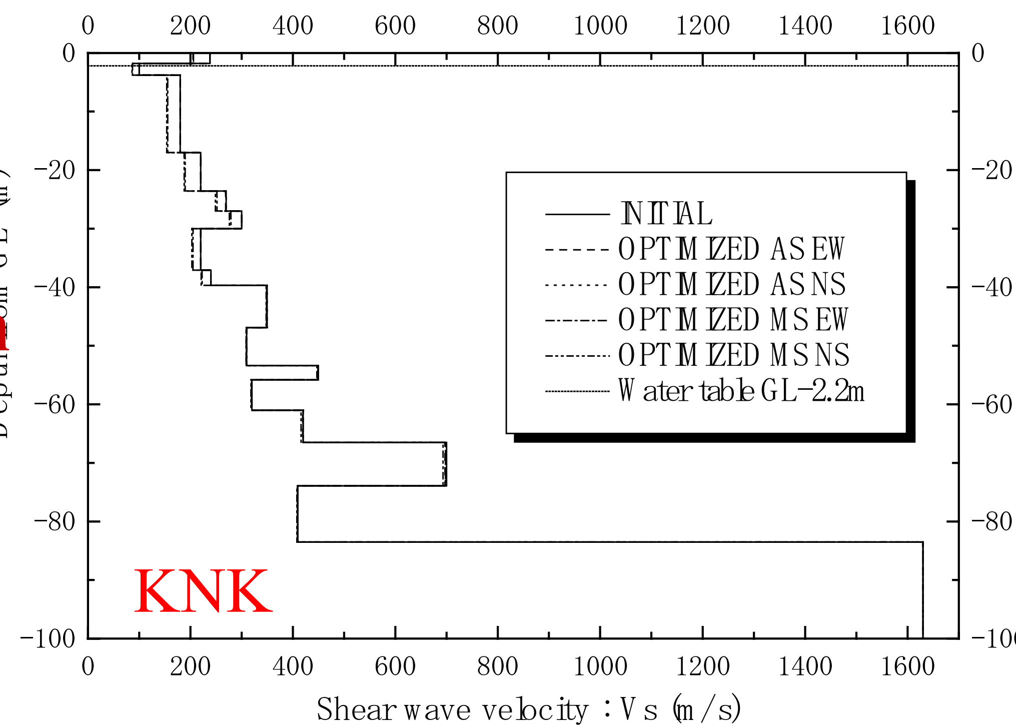
Comparison of inversion and observation (Main shock: TKS & KNK)



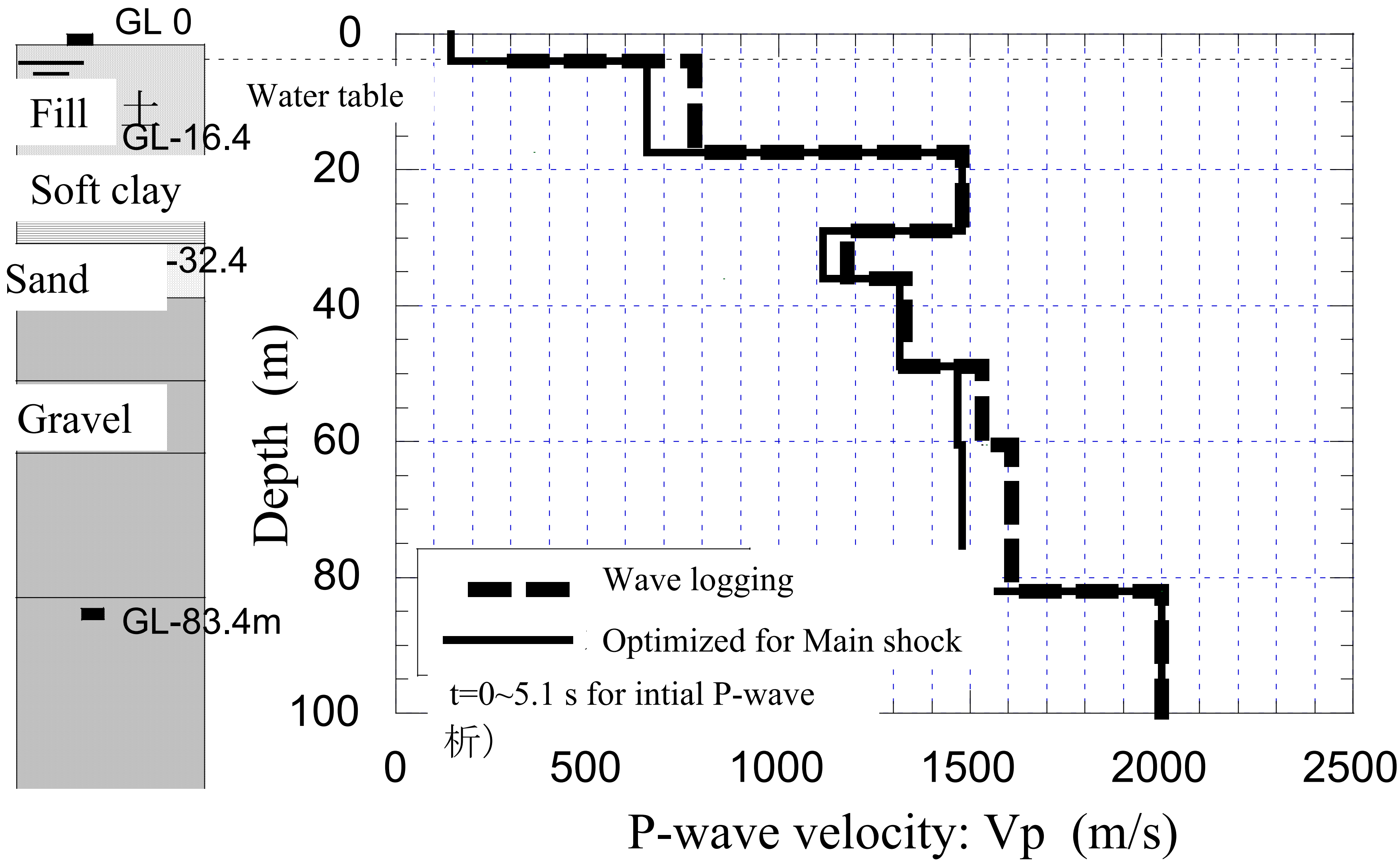


Optimized Vs distribution along depth for MS & AS compared with wave-logging (PI & SGK)

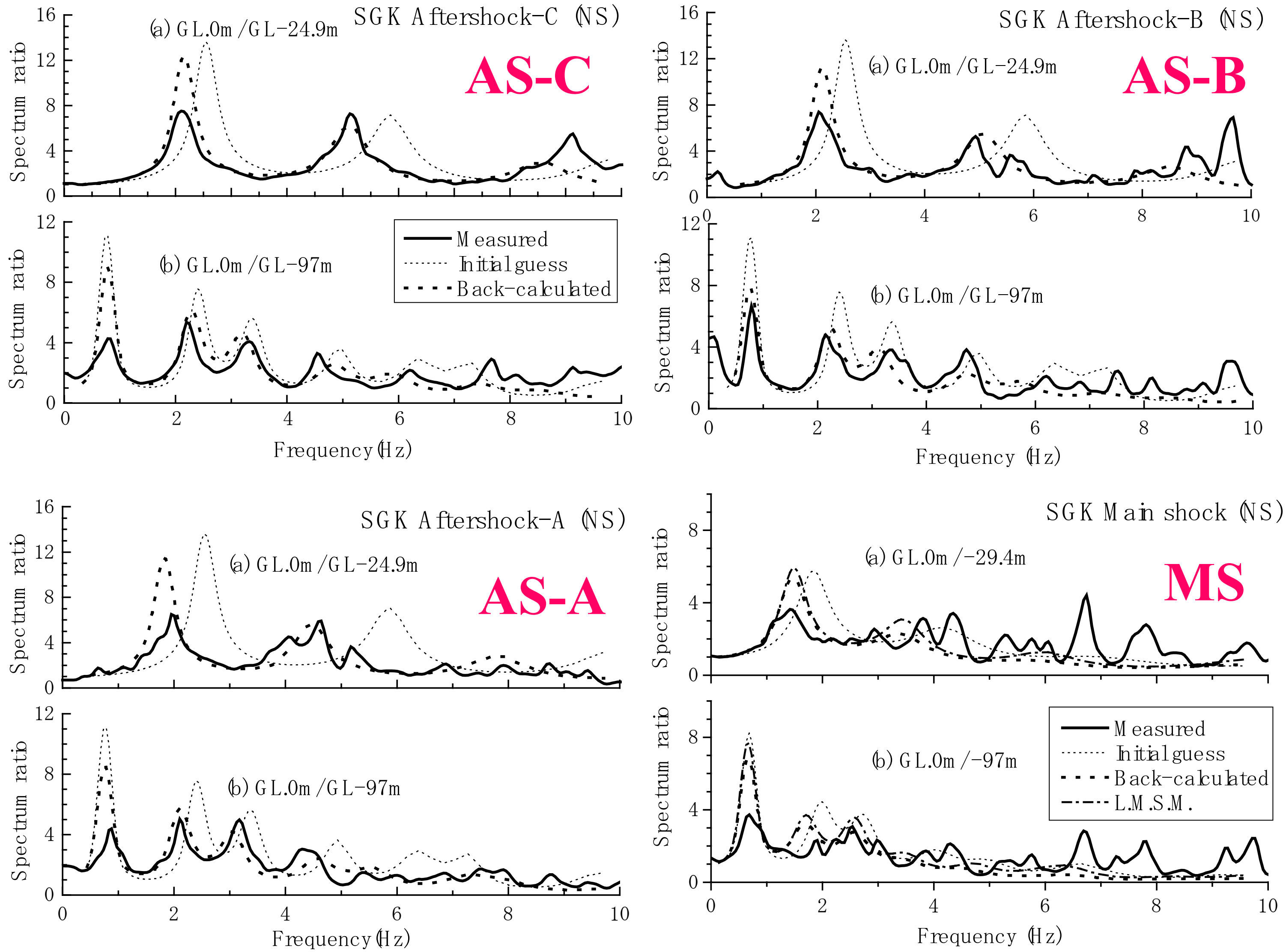




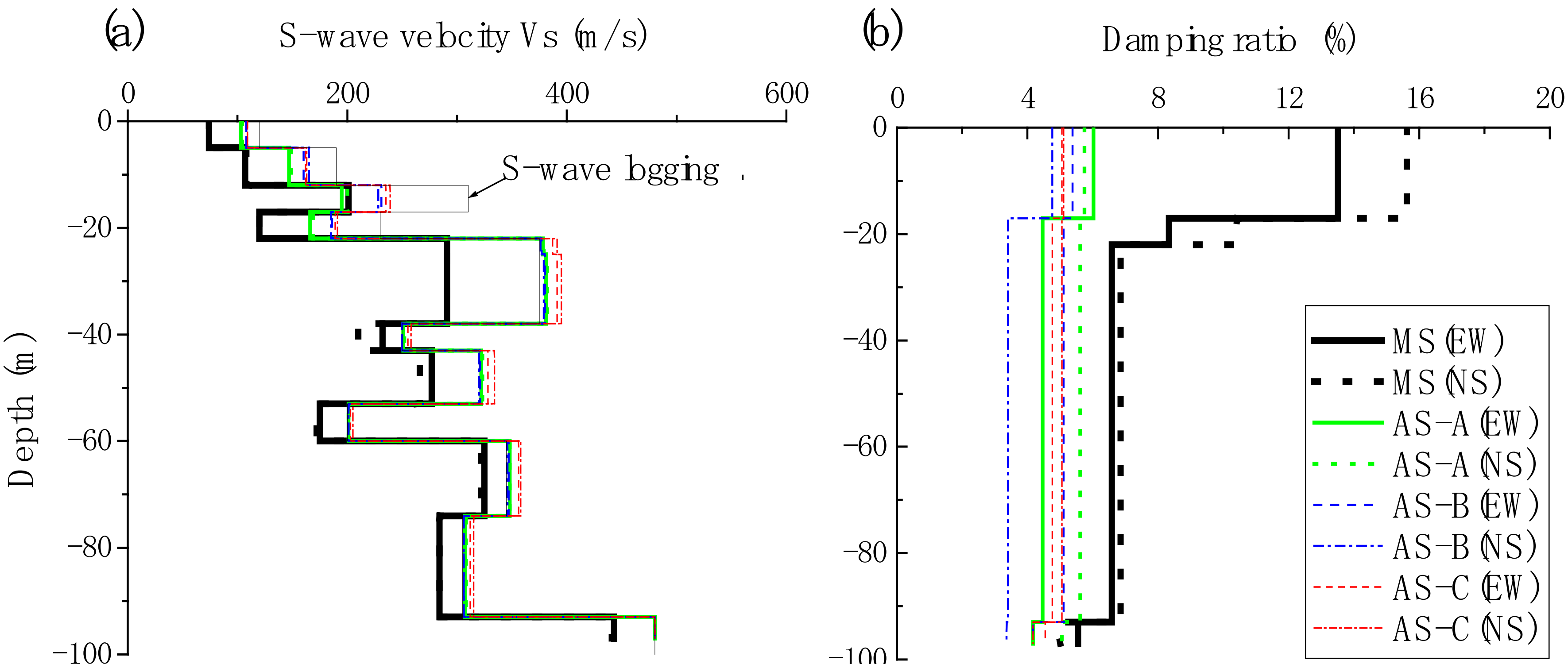
Optimized Vs distribution along depth for MS & AS compared with wave-logging (TKS & KNK)



Comparison of inversion and observation (Main shock: PI) Vertical

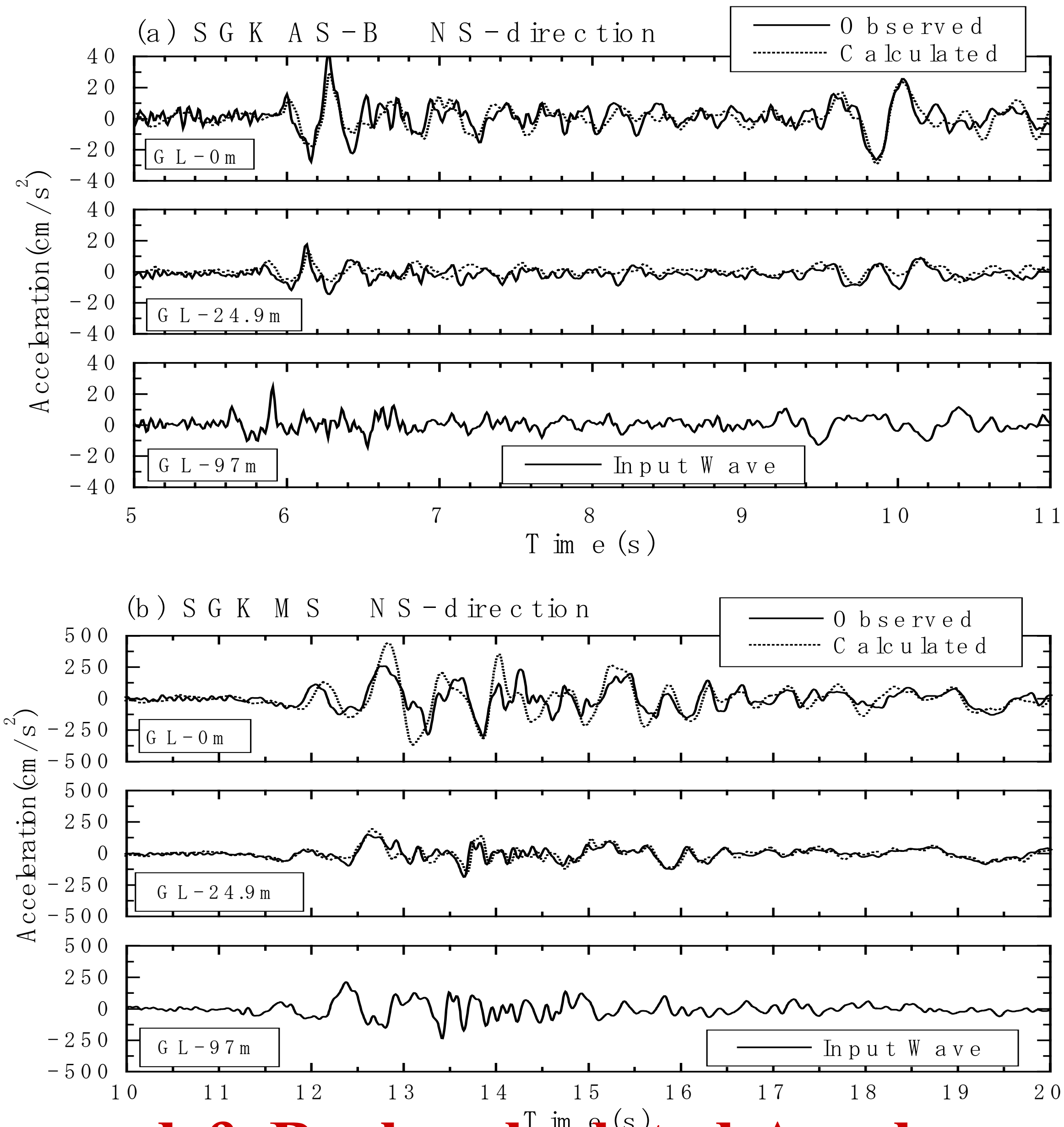


Measured & Back-calculated spectrum ratios compared in SGK for Aftershocks C, B, A and Main Shock

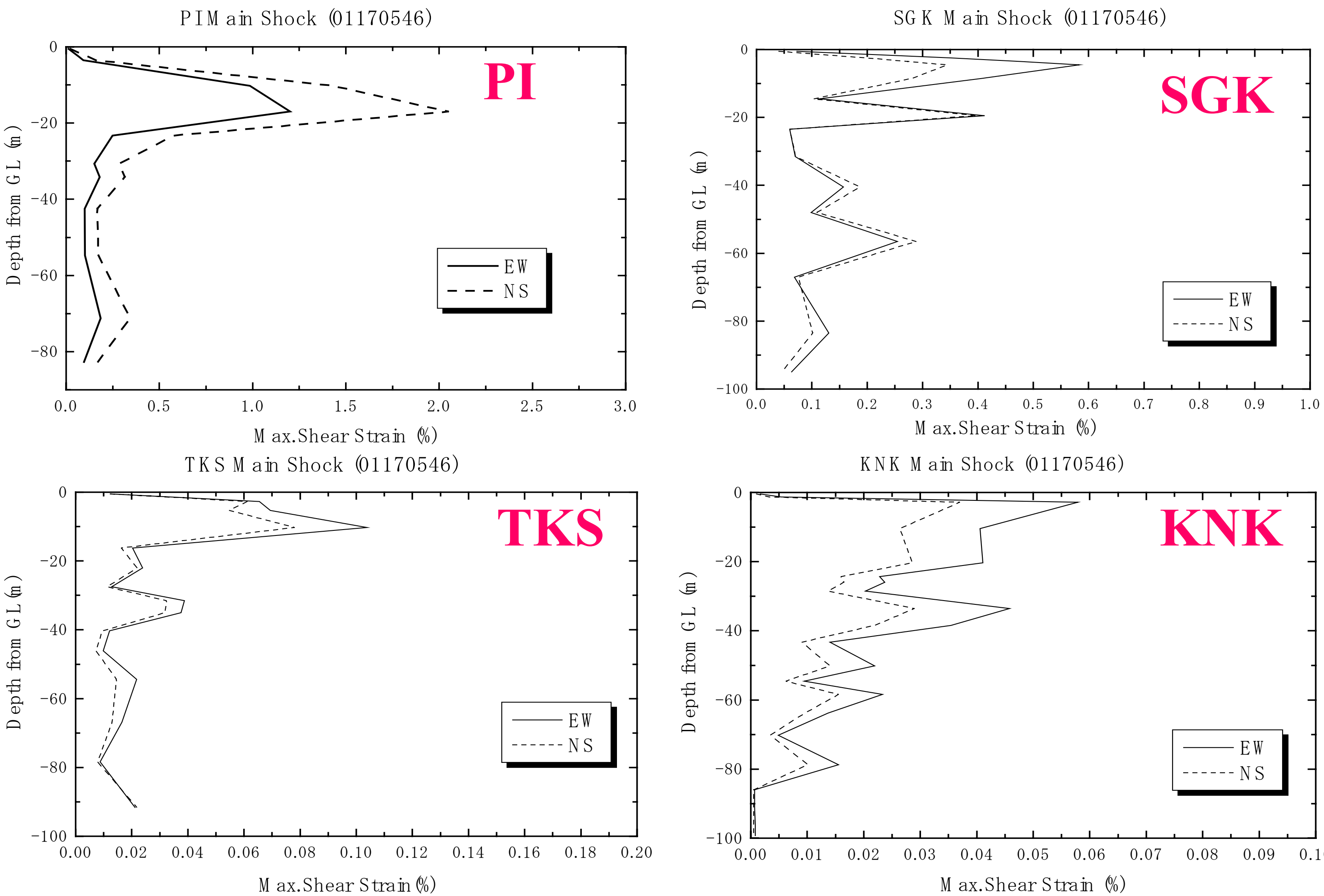


$$G/G_0 = \left(Vs_{MS}/Vs_{AS}\right)^2$$

Back-calculated S-wave velocity and Damping in SGK for Aftershocks and Main Shock



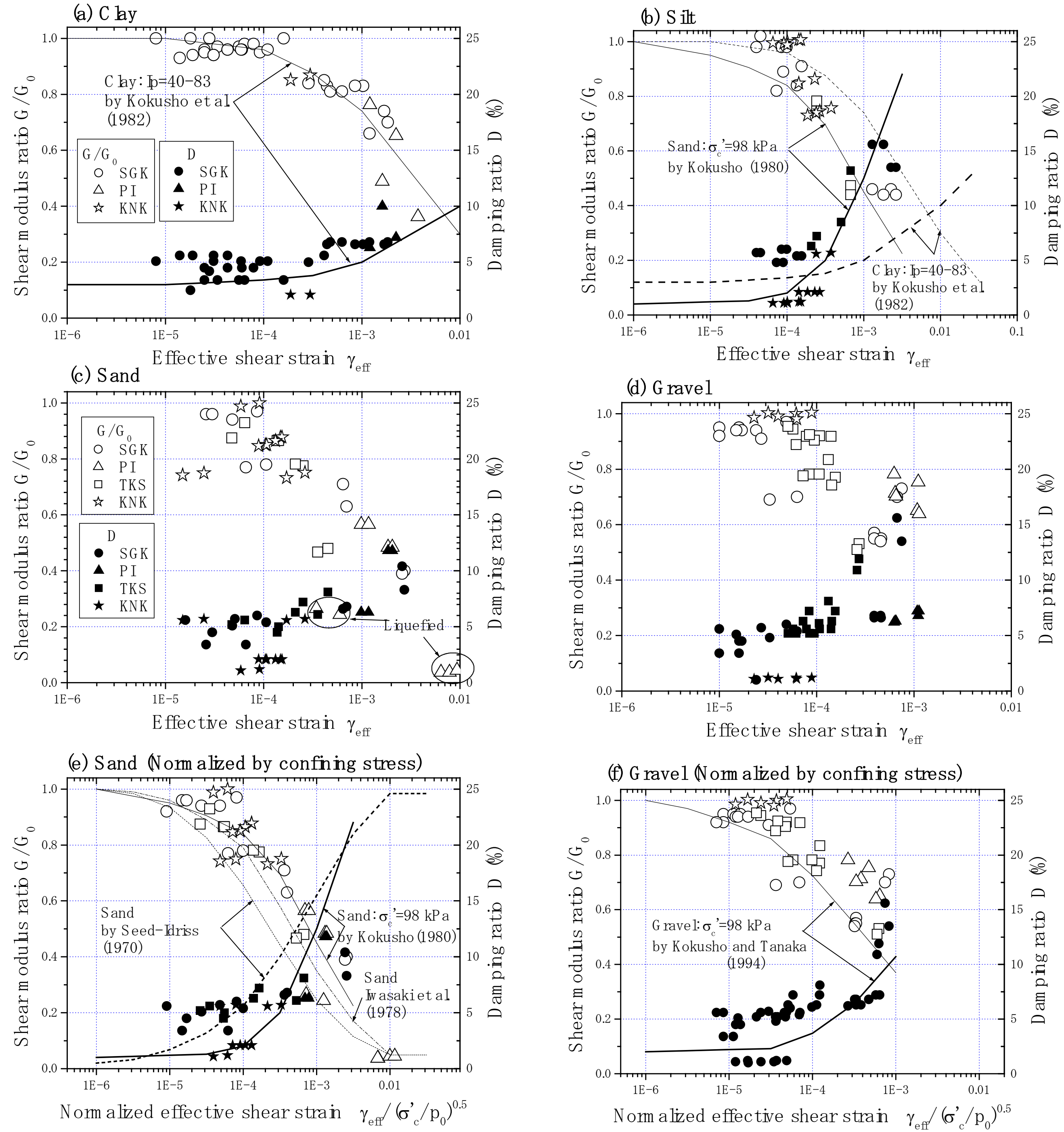
Measured & Back-calculated Accelerograms compared in SGK for Aftershocks and Main Shock



$$\gamma_{eff} = 0.65 \cdot \gamma_{\max}$$

Computed Max. shear strain versus Depth in 4 vertical array sites

$G/G_0 \sim \gamma_{eff}$ relationships for different soils



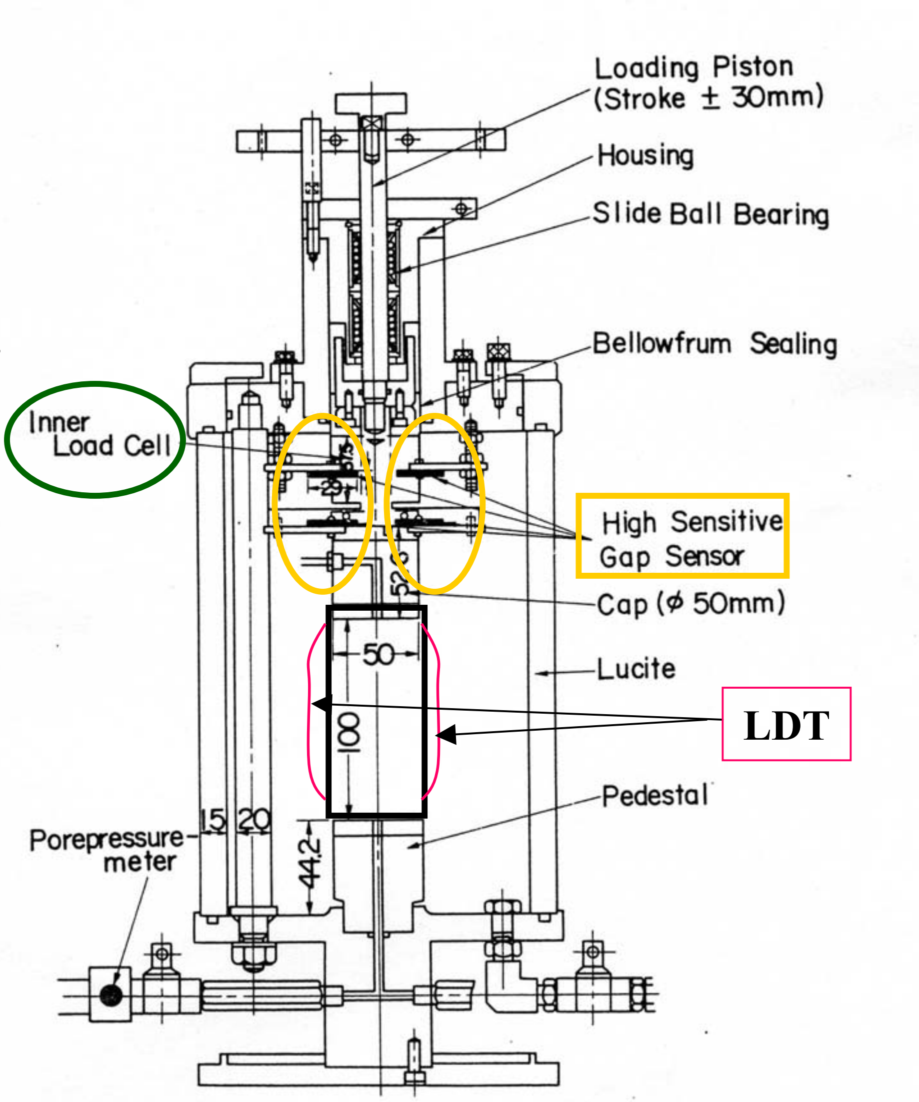
In Japan, How to evaluate strain-dependent shear modulus and damping ratio in laboratory.

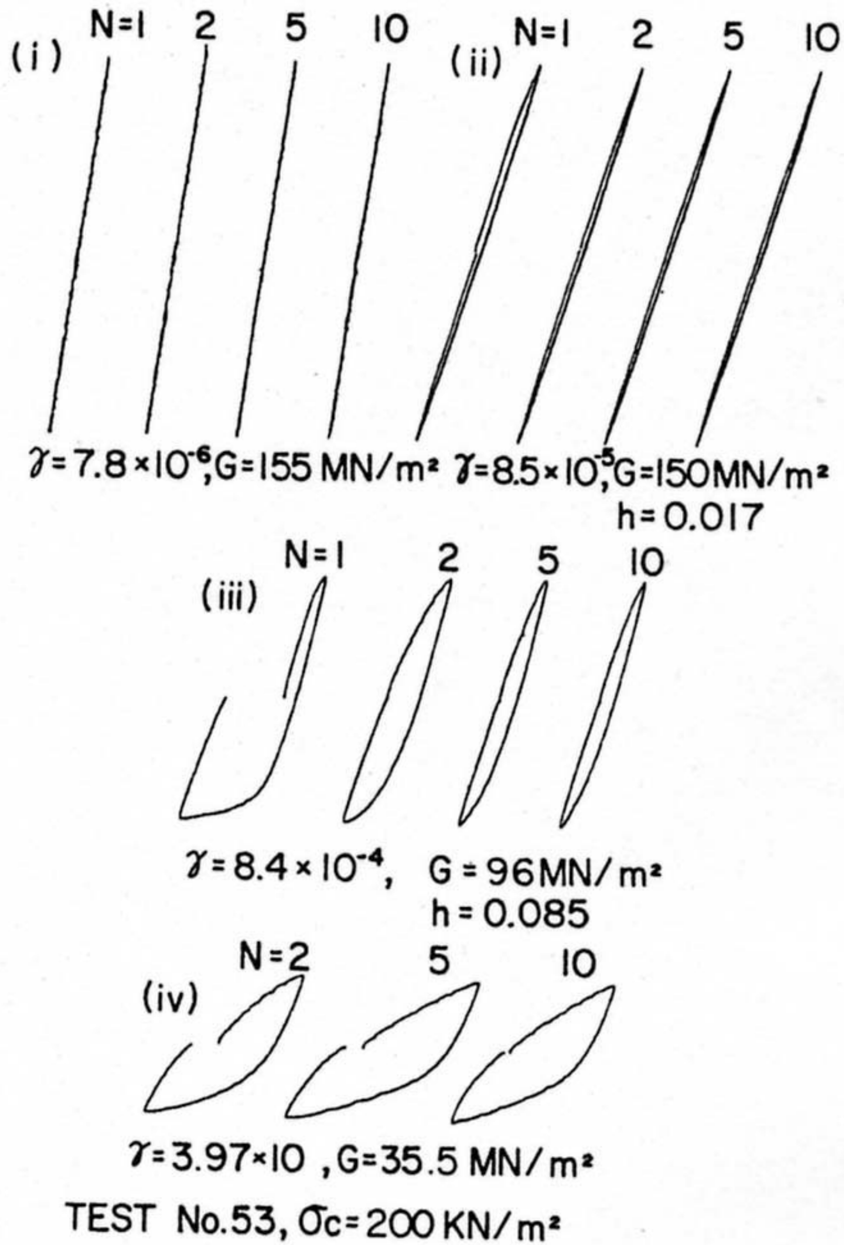
1) Use triaxial device **with inner load cell.**

2) Employ **high-sensitivity gap sensors or LDT** for vertical disp. measurement.

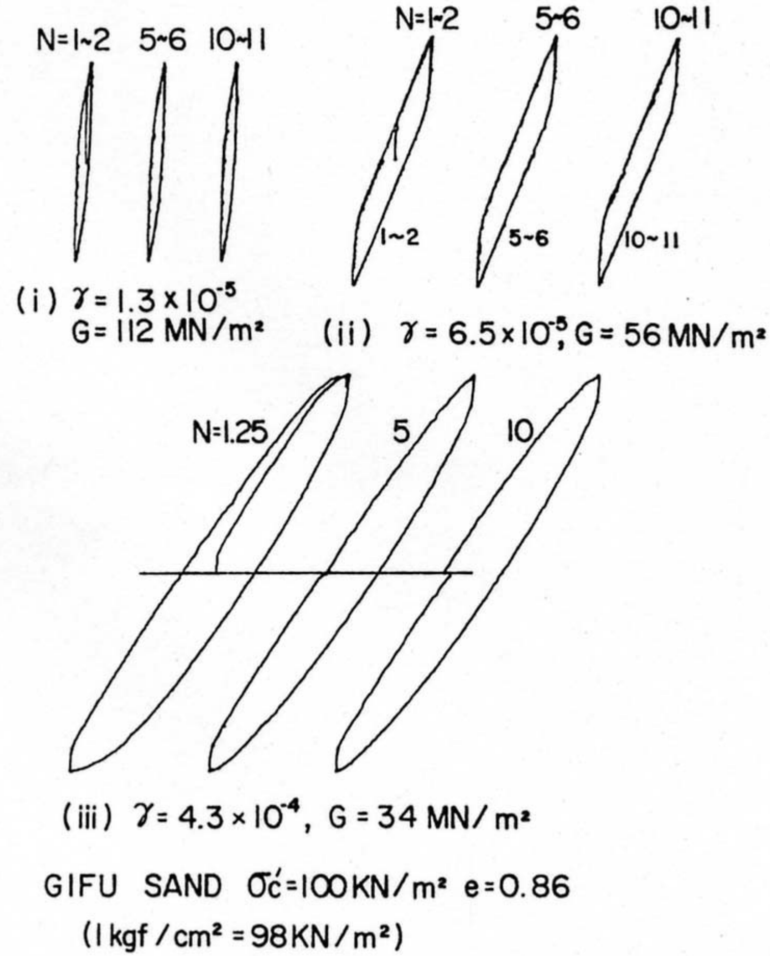
3) Undrained cyclic loading test for f=1~0.1 Hz **shear modulus** and **damping for wide strain range of 10^{-6}-10^{-2}**.

4) For small strain modulus, pulse tests or bender element test are also employed. Resonant column test is not so popular.



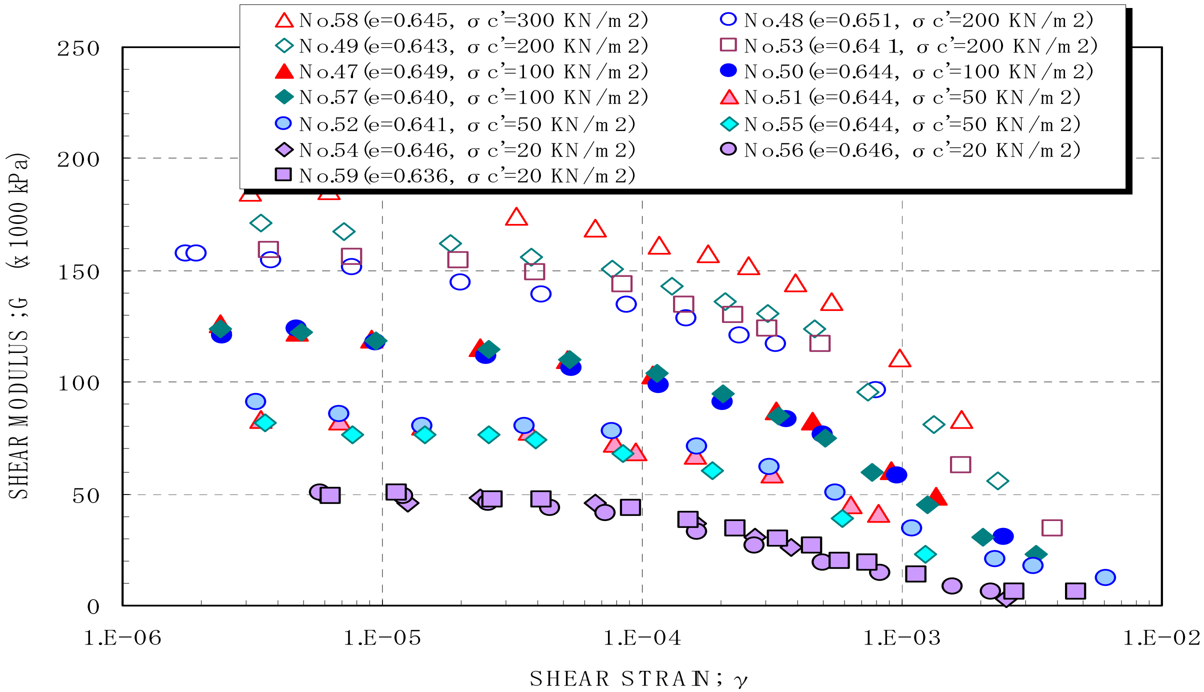


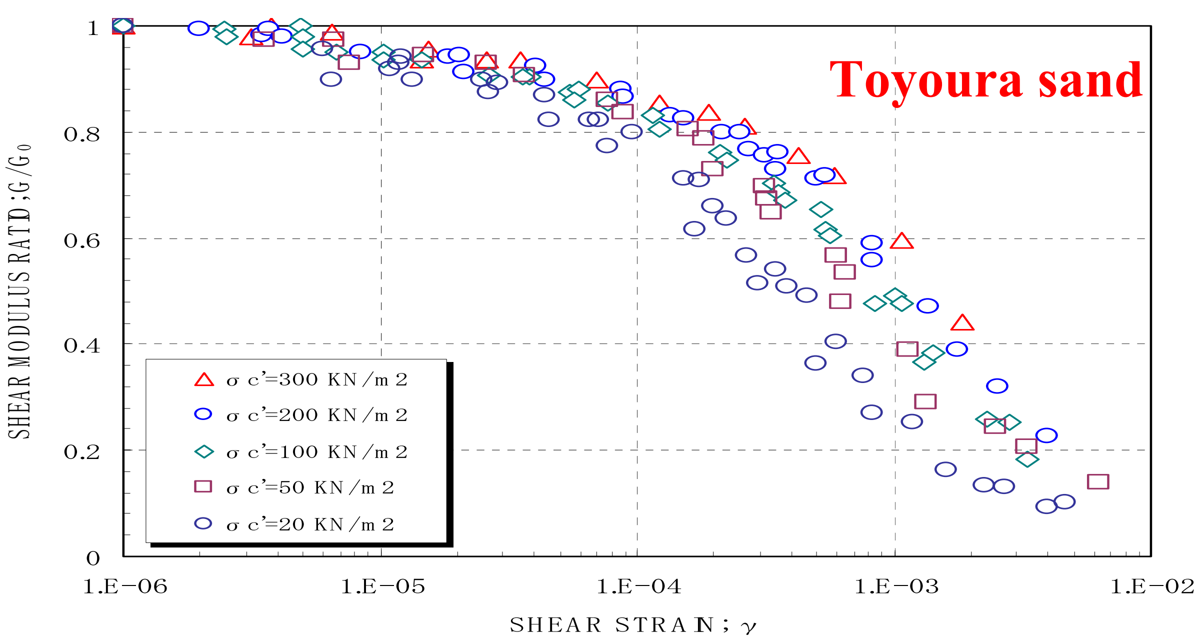
Measured by gap sensor



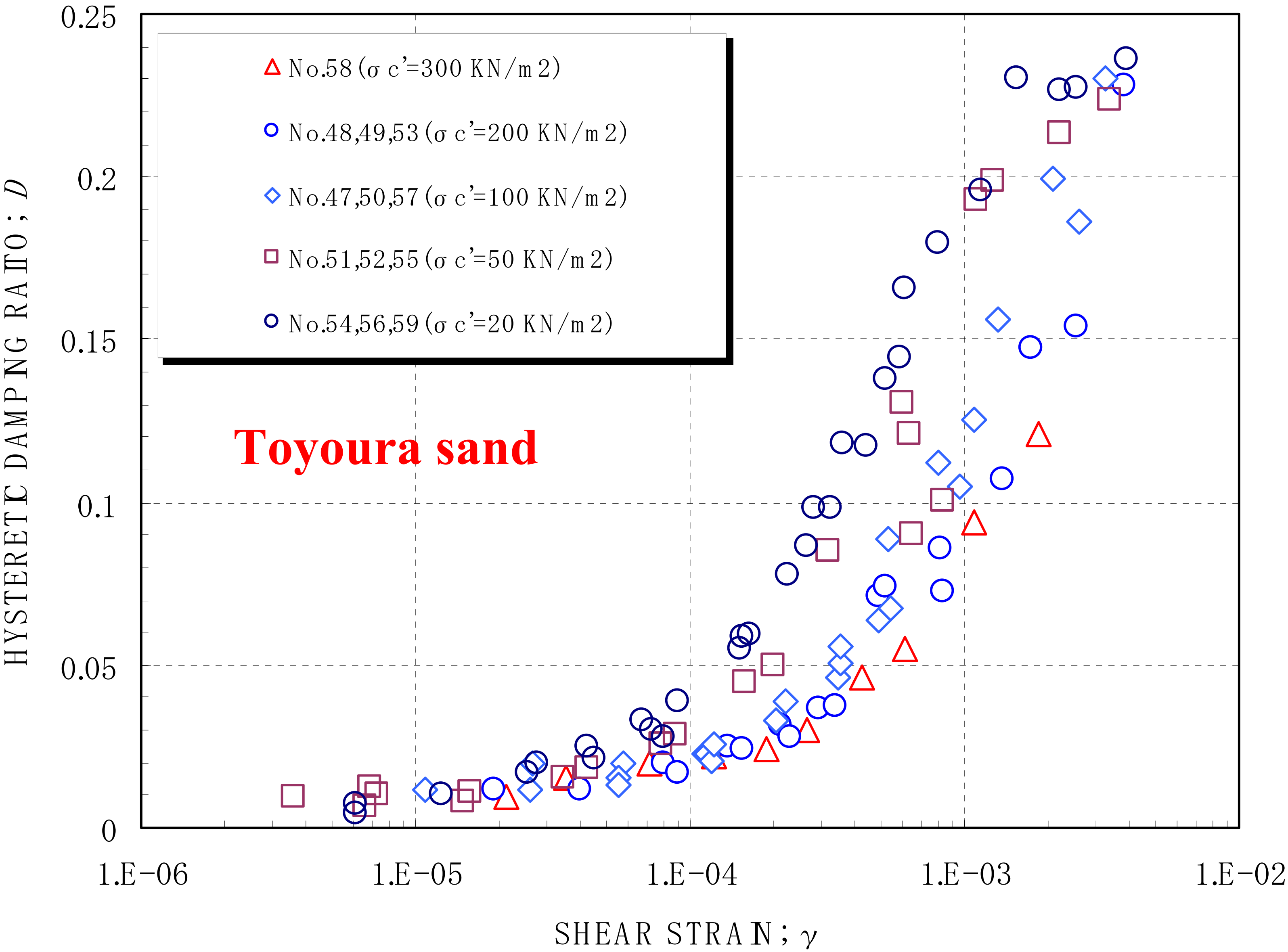
Measured by conventional sensor

kokusho (1980)

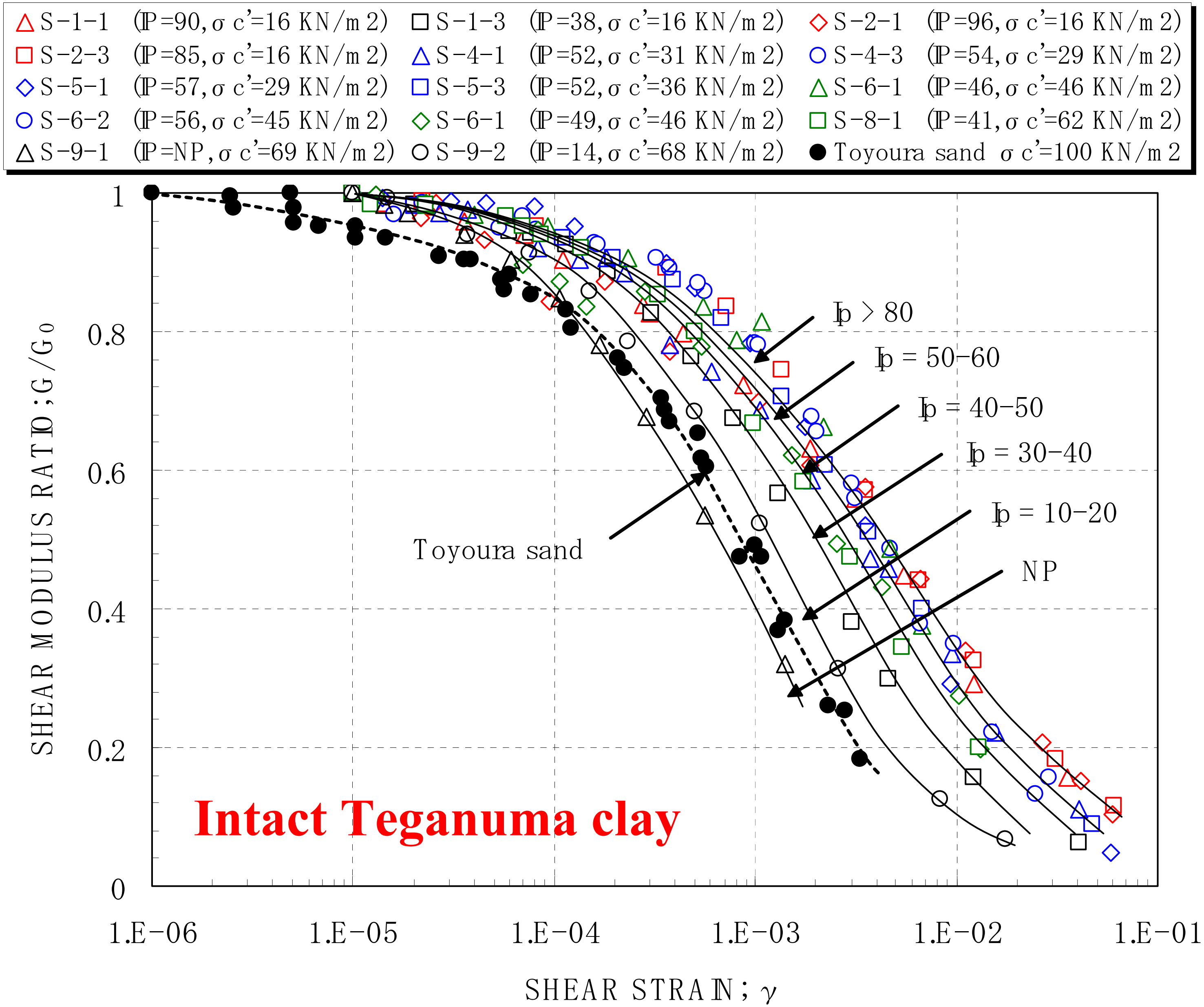




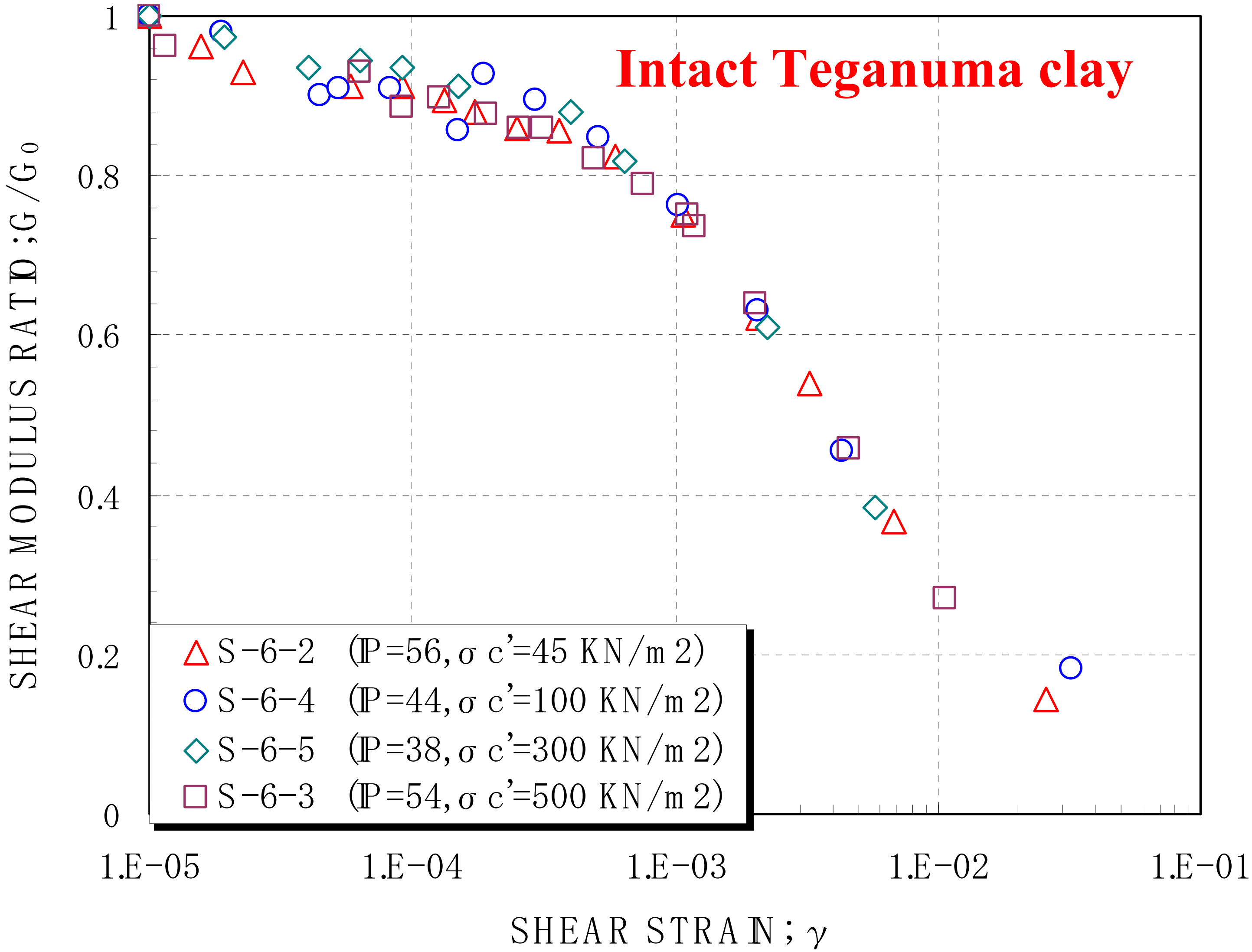
Shear modulus versus strain of sand for different confining stress



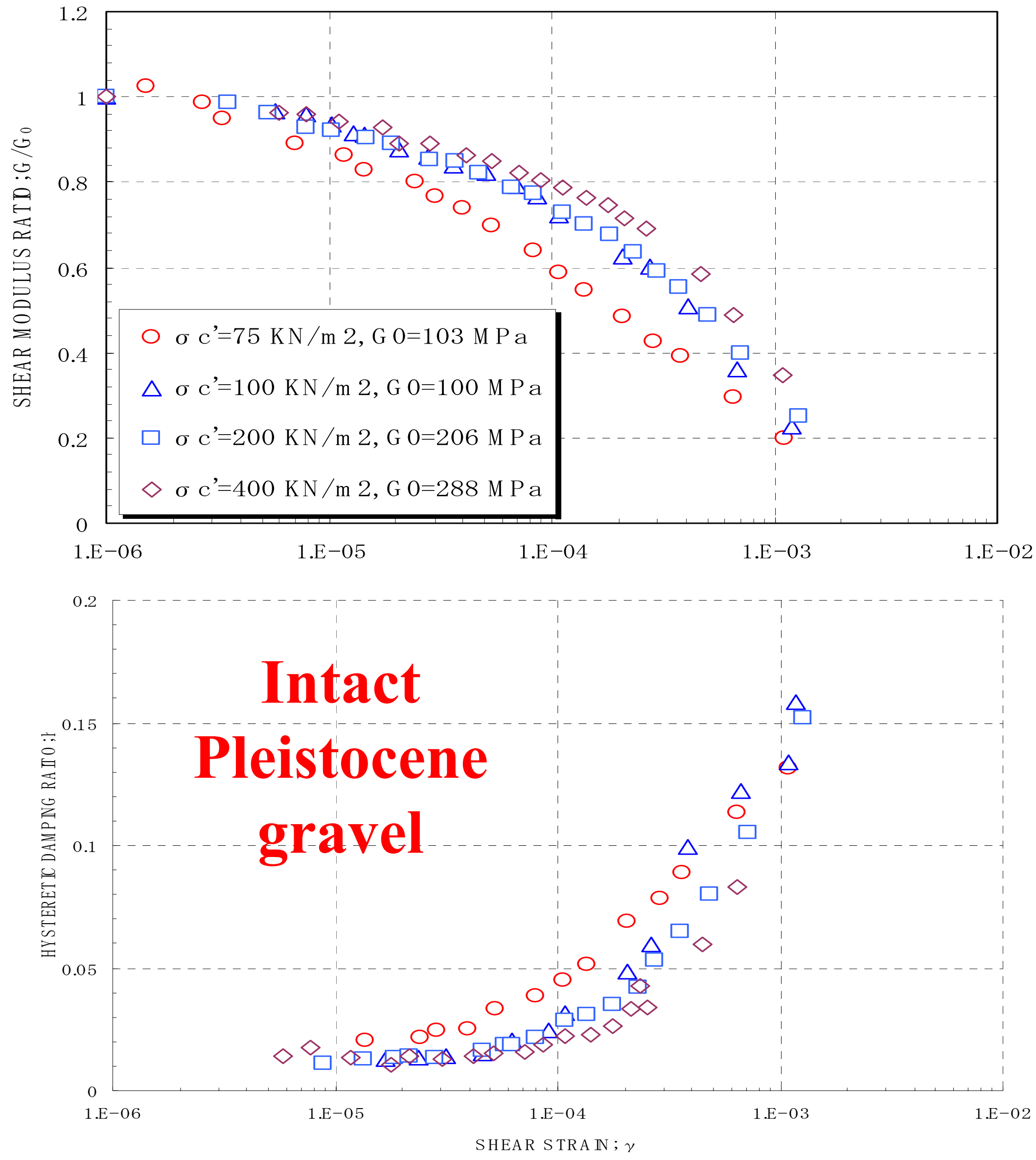
Hysteretic damping ratio of sand for different confining stress



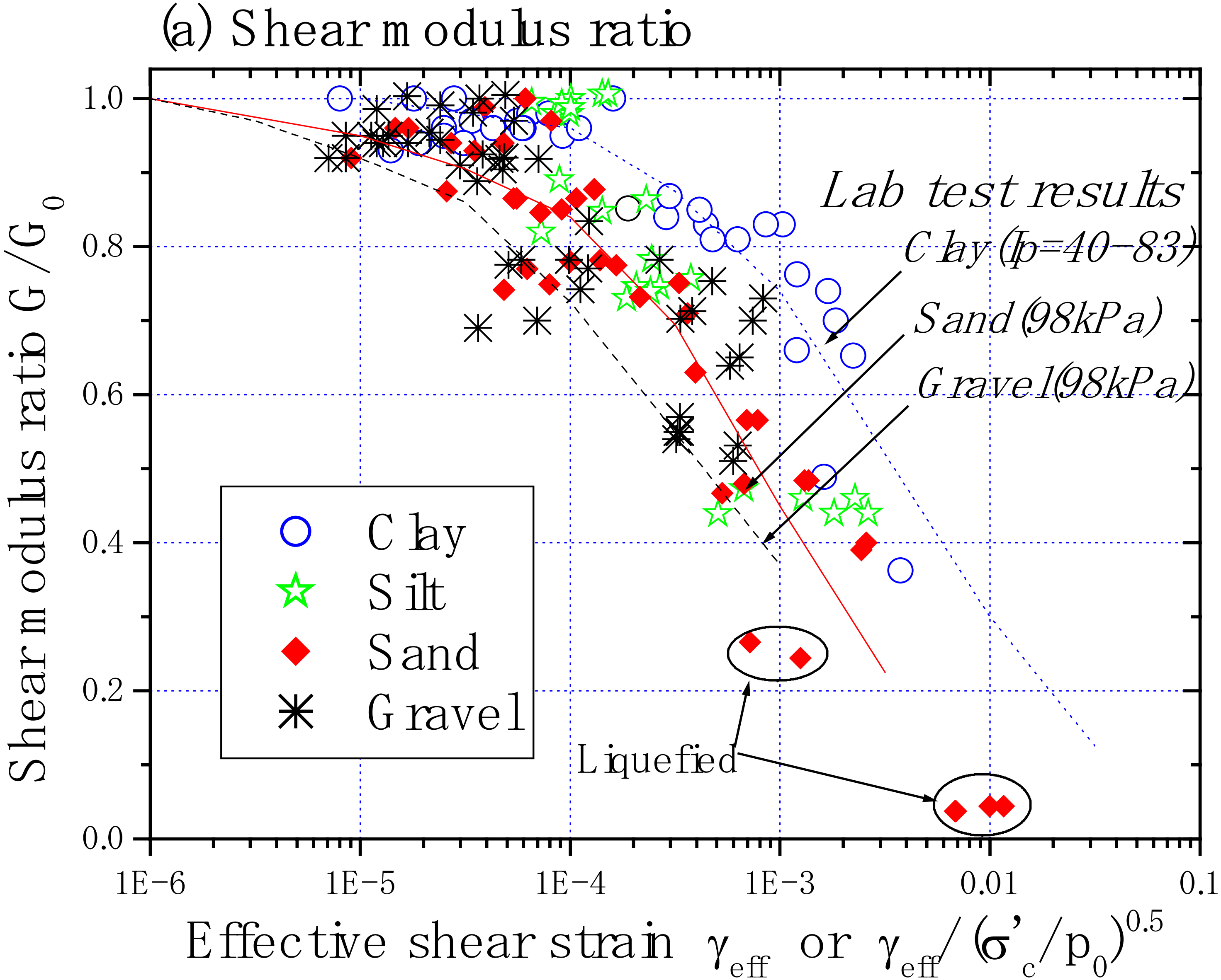
Shear modulus ratio versus strain of clay for different Ip



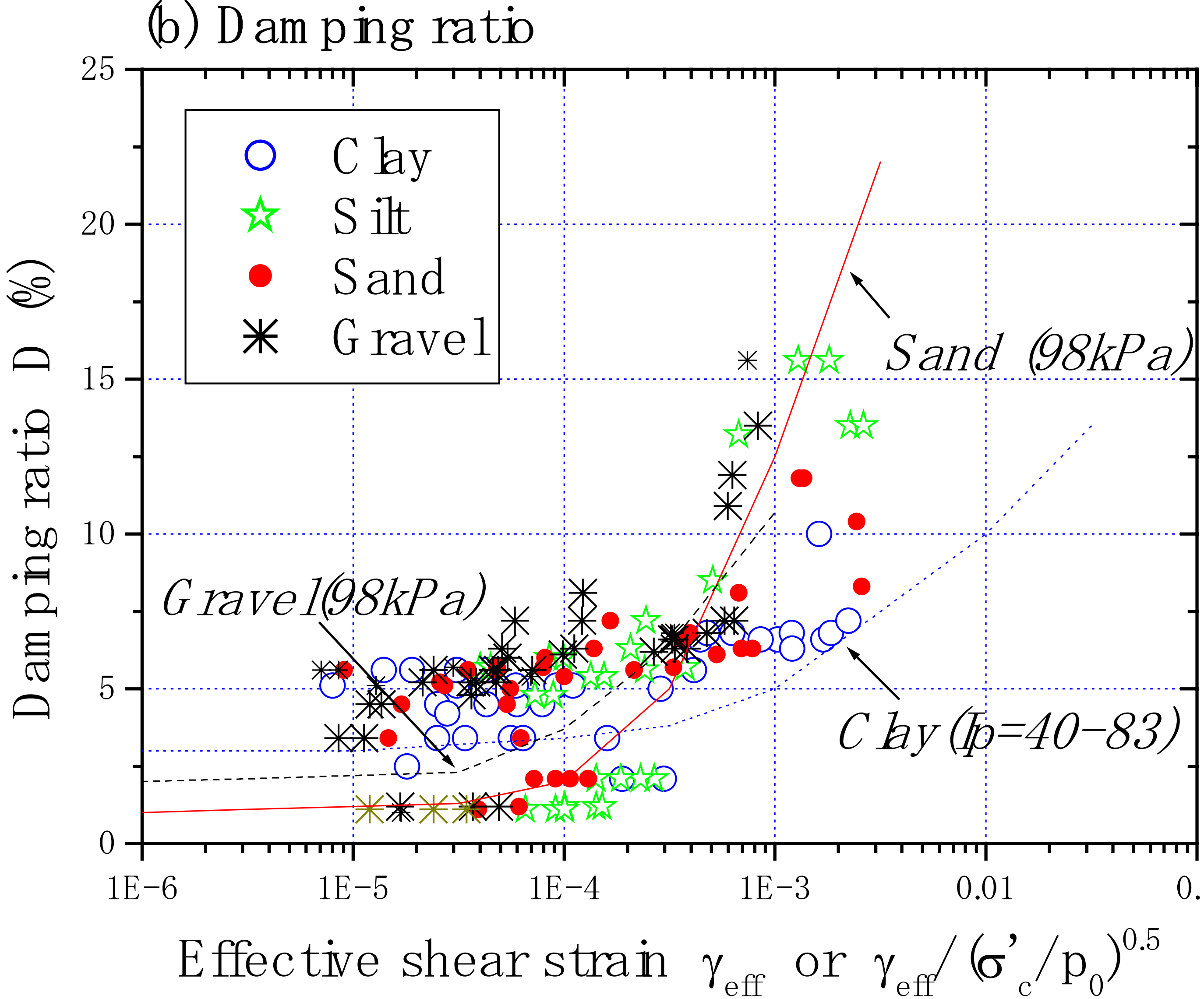
Effect of confining stress on modulus degradation



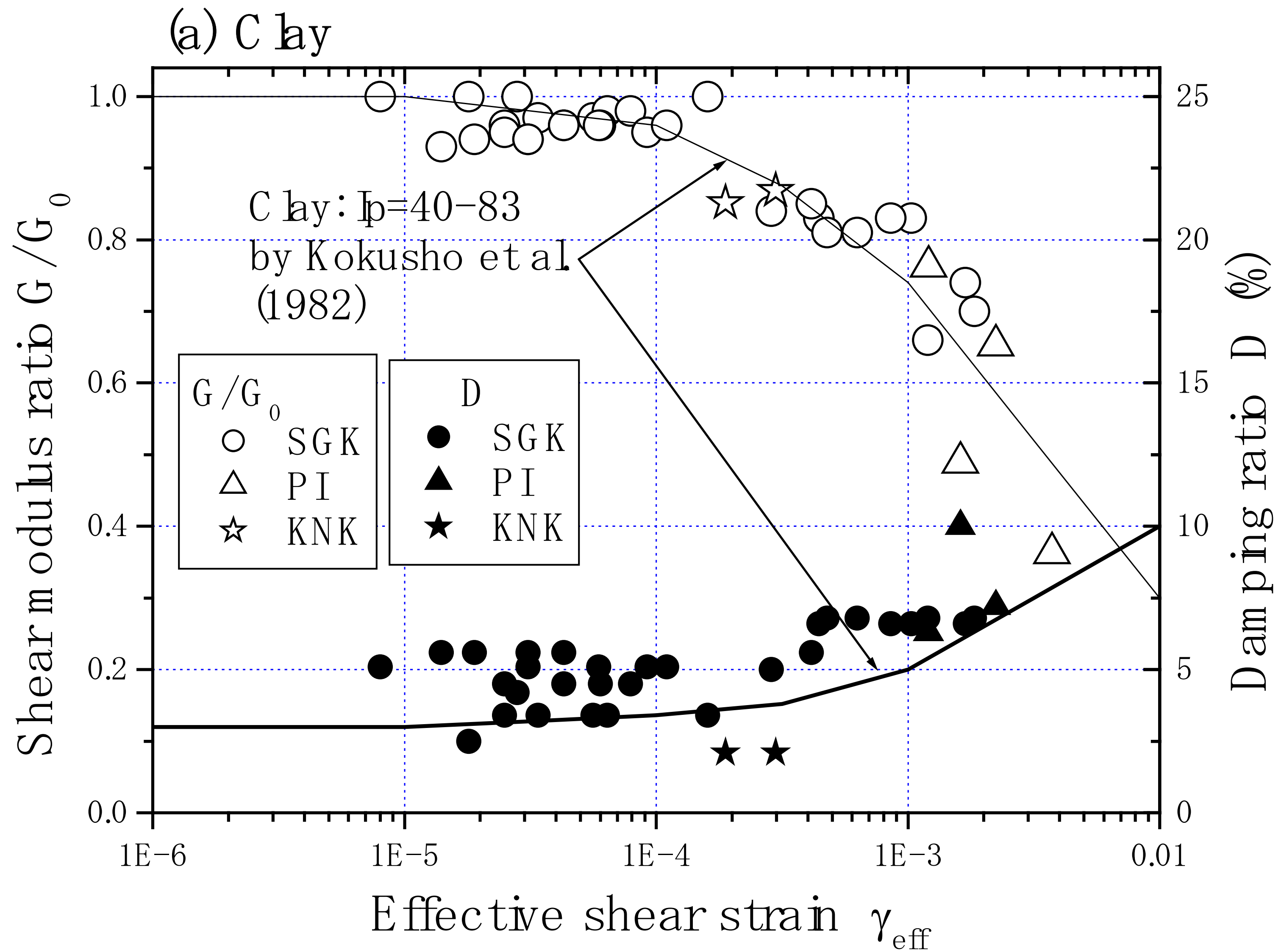
Modulus & Damping ratio versus strain of gravel for different confining stress



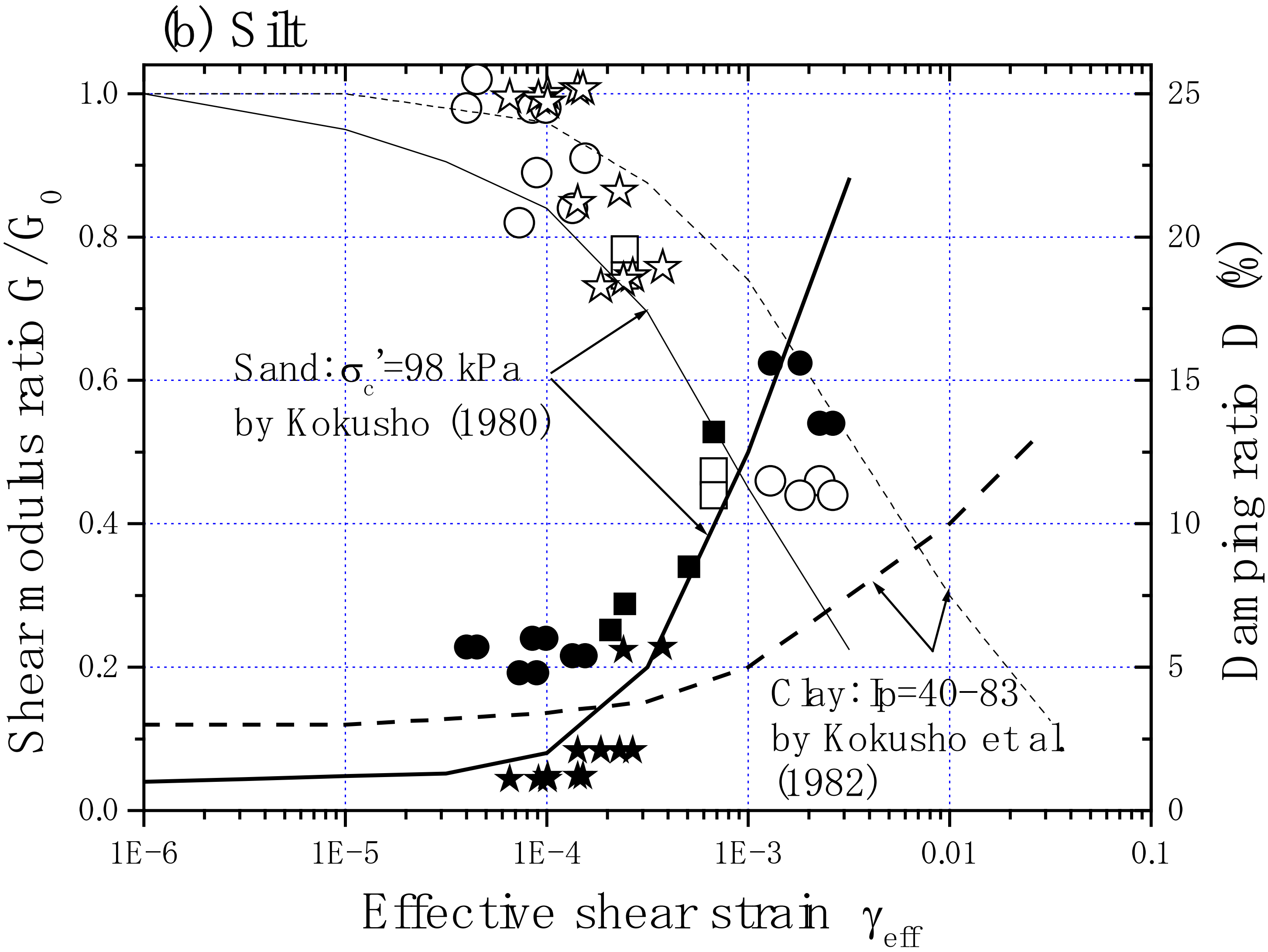
Back-calculated strain-dependent modulus degradations of 4 types of soils compared with previous lab tests



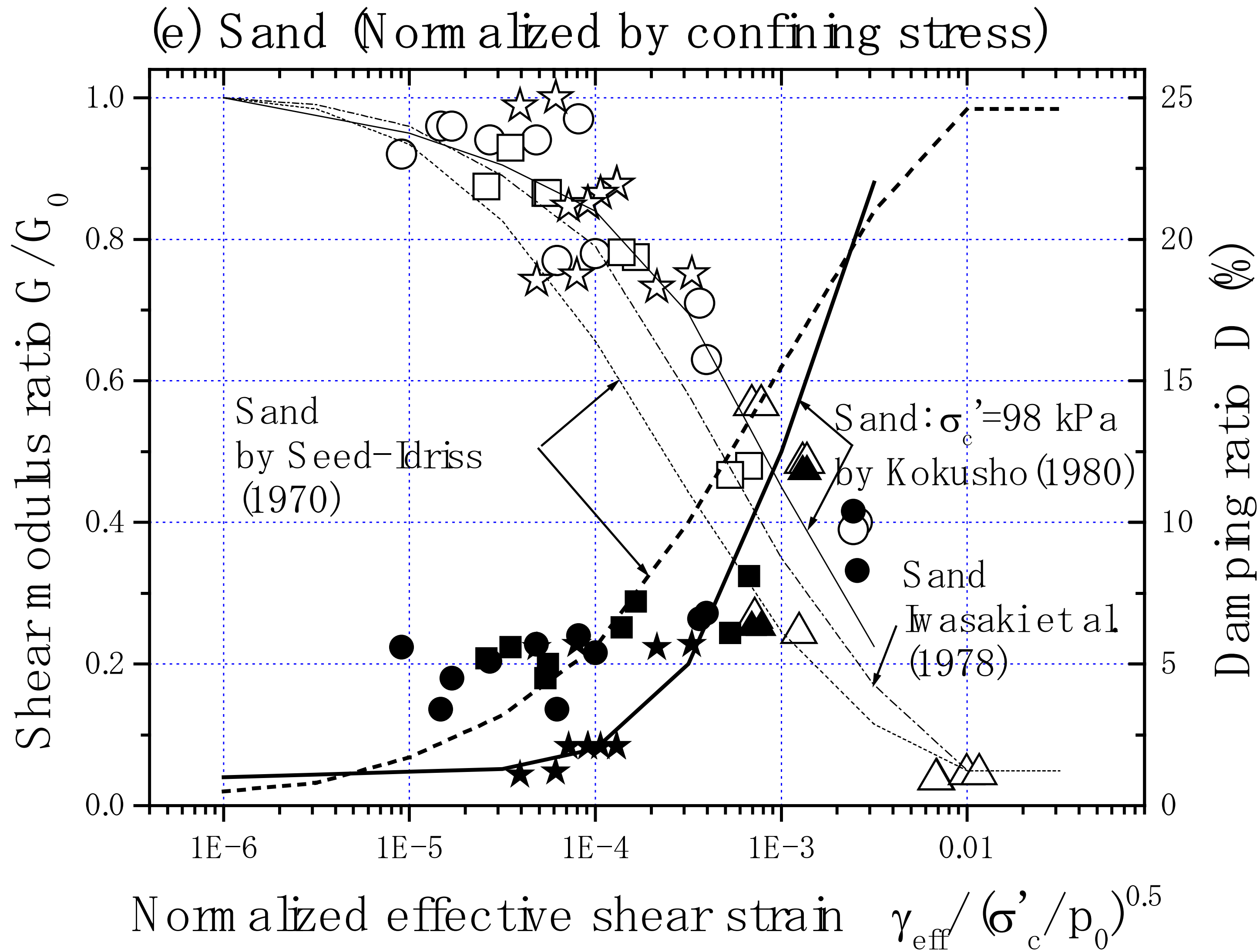
Back-calculated damping ratios versus strain of 4 types of soils compared with previous lab tests



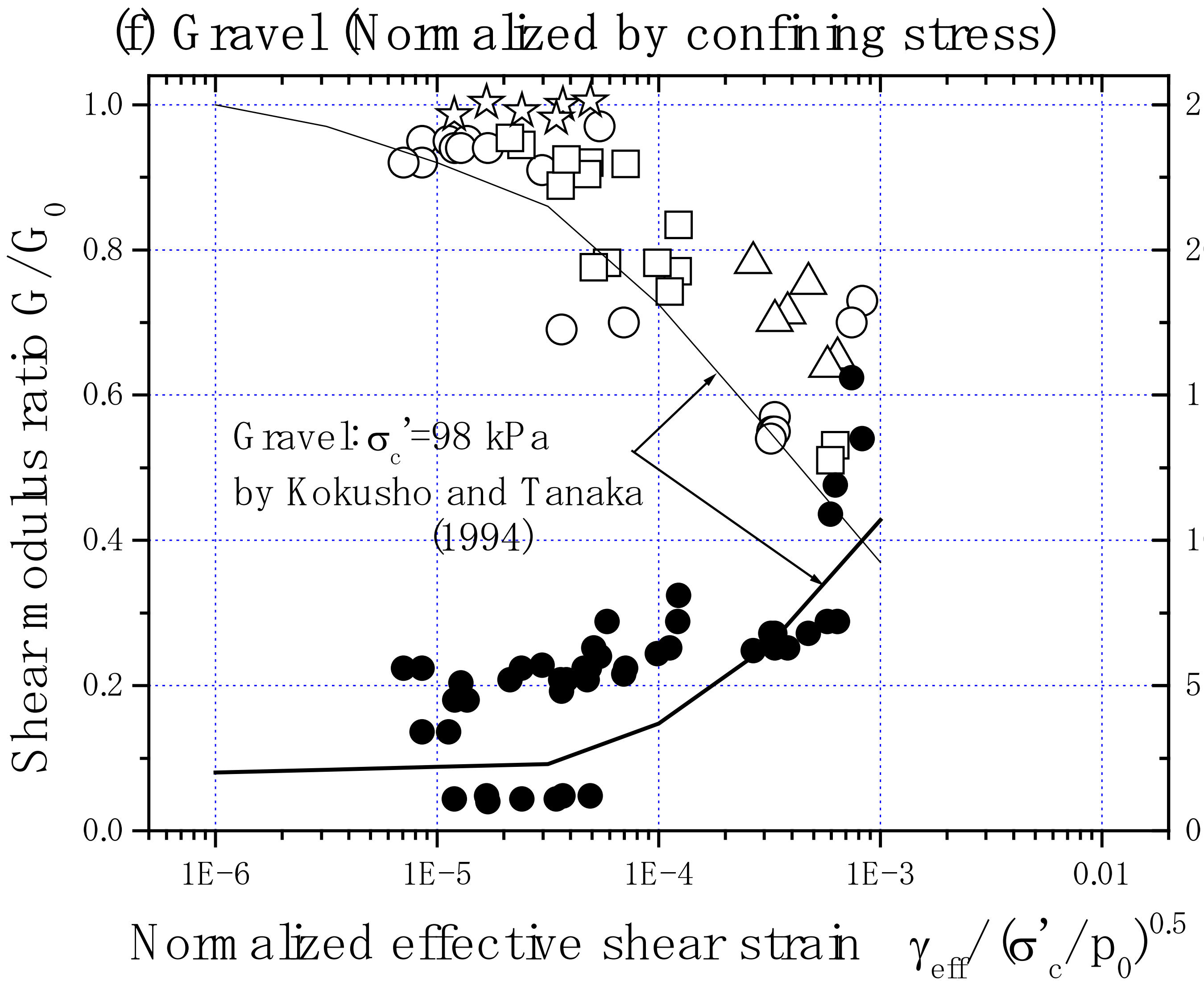
Back-calculated modulus degradation and damping compared with lab test (Clay)



Back-calculated modulus degradation and damping compared with lab test (Silt)



Back-calculated modulus degradation and damping compared with lab test (Sand)



Back-calculated modulus degradation and damping compared with lab test (Gravel)

SUMMARY ON BACK-CALCULATED PROPERTIES (I)

In spectrum ratios, back-calculation overestimates lower frequency peaks and under-estimates higher frequency peaks compared to observation presumably due to strain-dependency and frequency-dependency of properties.

Clear differences in S-wave velocities are recognized not only between the main shock and aftershocks but also among aftershocks of different intensities.

Damping ratios for the main shock are evidently larger than aftershocks.

Clear modulus degradations can be identified from the back-calculated S-wave velocities.

Degradations are almost consistent at 4 sites, from which soil-specific curves can be differentiated for clay, silt, sand and gravel.

SUMMARY ON BACK-CALCULATED PROPERTIES (II)

Confining stresses have significant effect on the degradations of non-cohesive soils in situ, too.

Back-calculated damping ratios increase with increasing effective strains for 10^{-4} or larger. Damping ratio in liquefied sand layers may be back-calculated as very large values (46-52%).

The majority of back-calculated damping ratios in small strain ranges are a few percent higher than laboratory test results despite apparent splits in the back-calculated damping values (1-6%).

A fair agreement in modulus degradation can be recognized between back-calculation and lab test results for clays and sands except for large strain level.

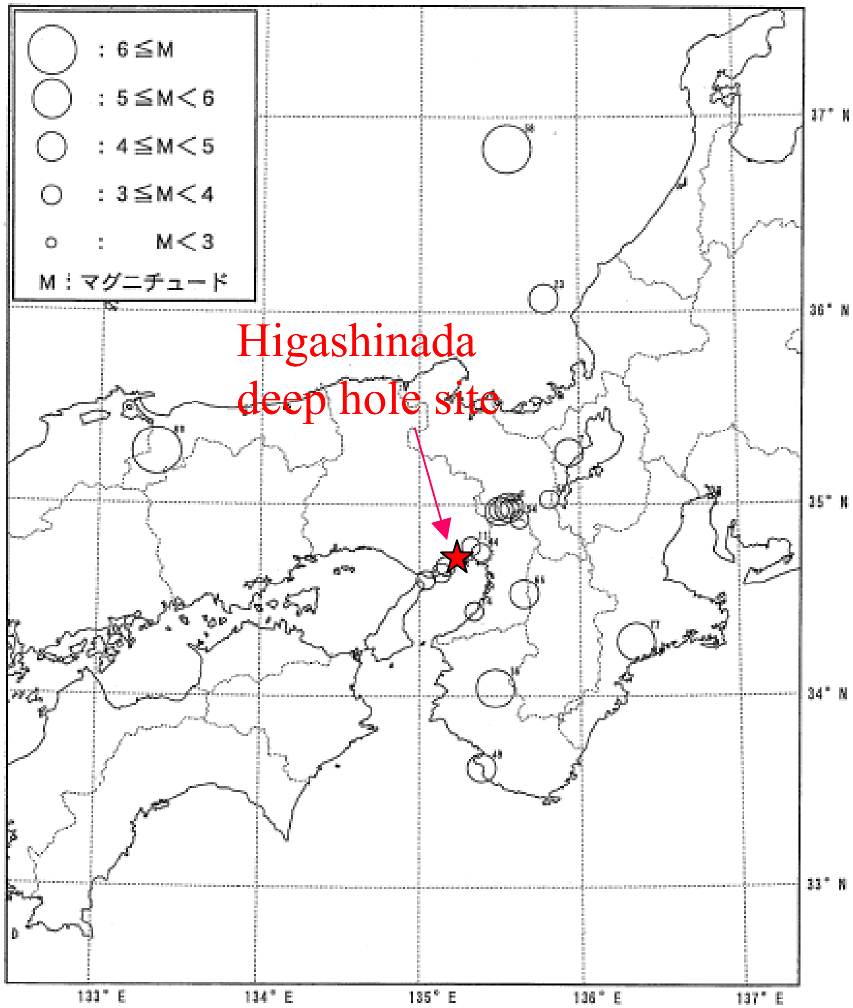
For gravels, back-calculated degradations are milder than laboratory tests presumably reflecting appreciable fine content in in situ soils.

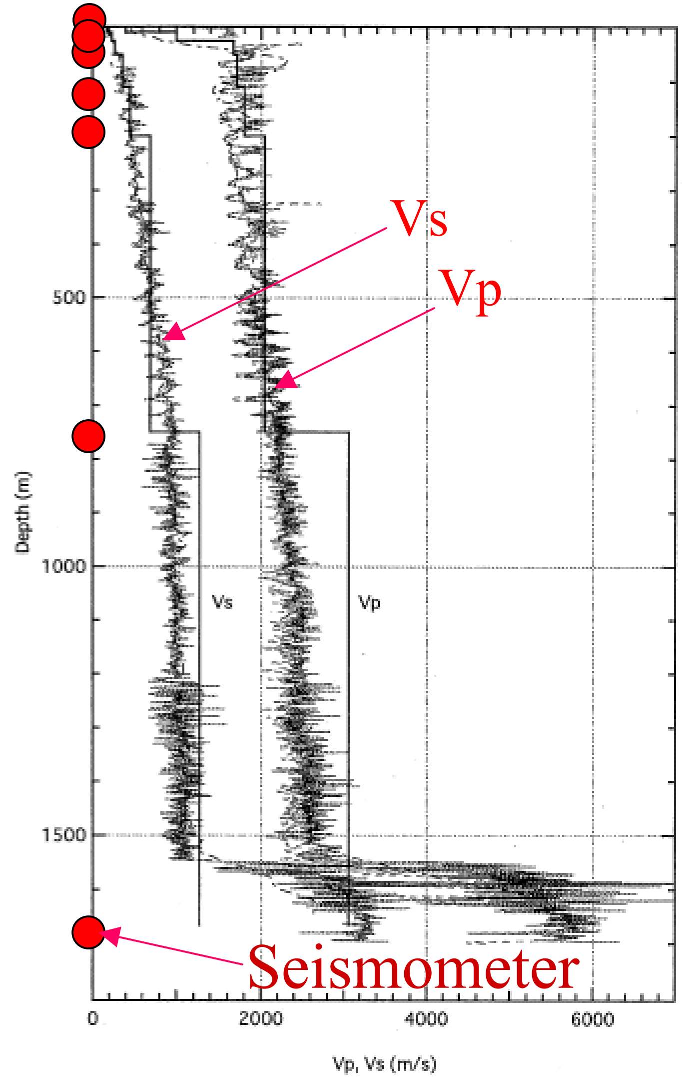
Topics of the presentation:

Seismic site amplification during strong earthquakes based on vertical array records

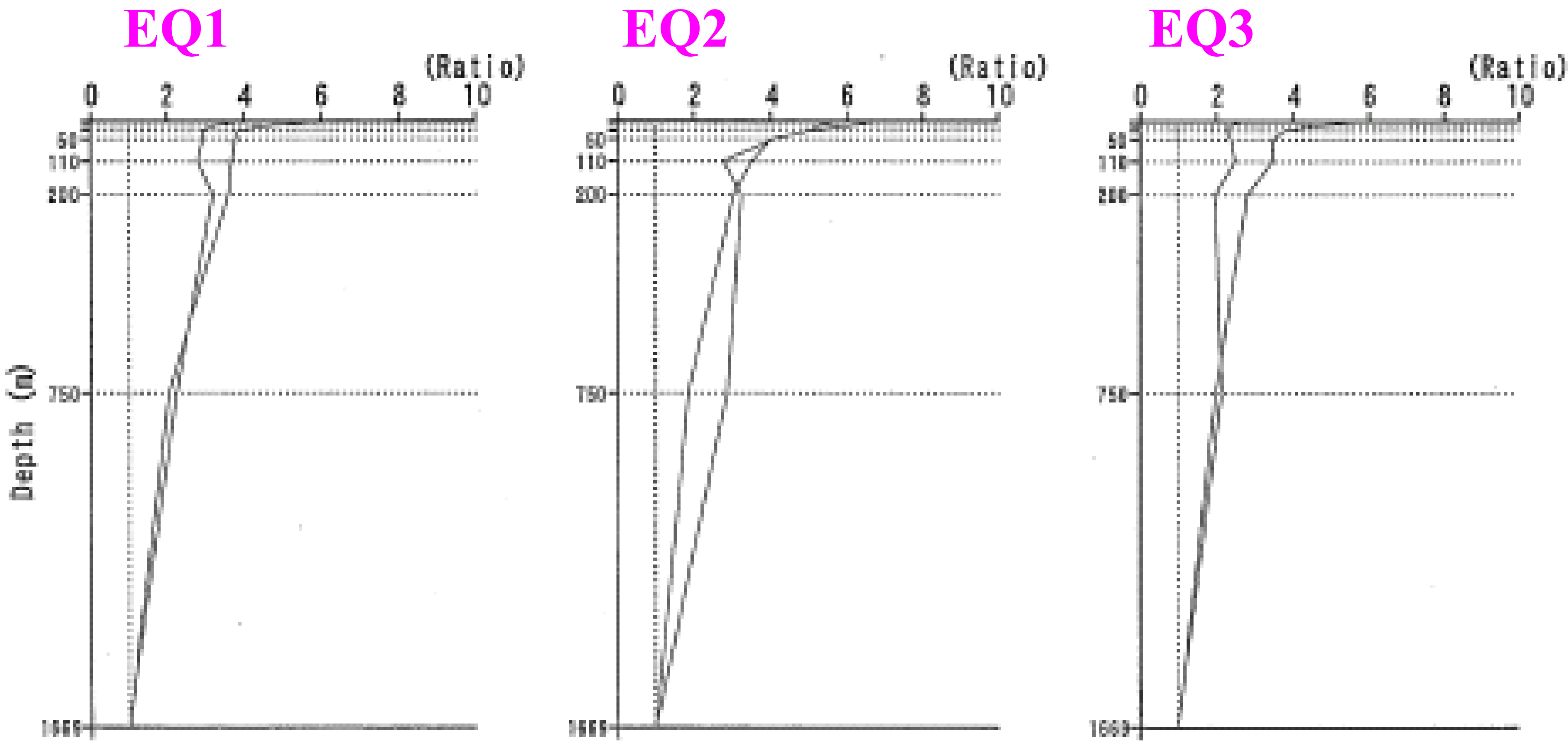
Back-calculated in situ soil properties versus lab data

Soil properties for deep soil response

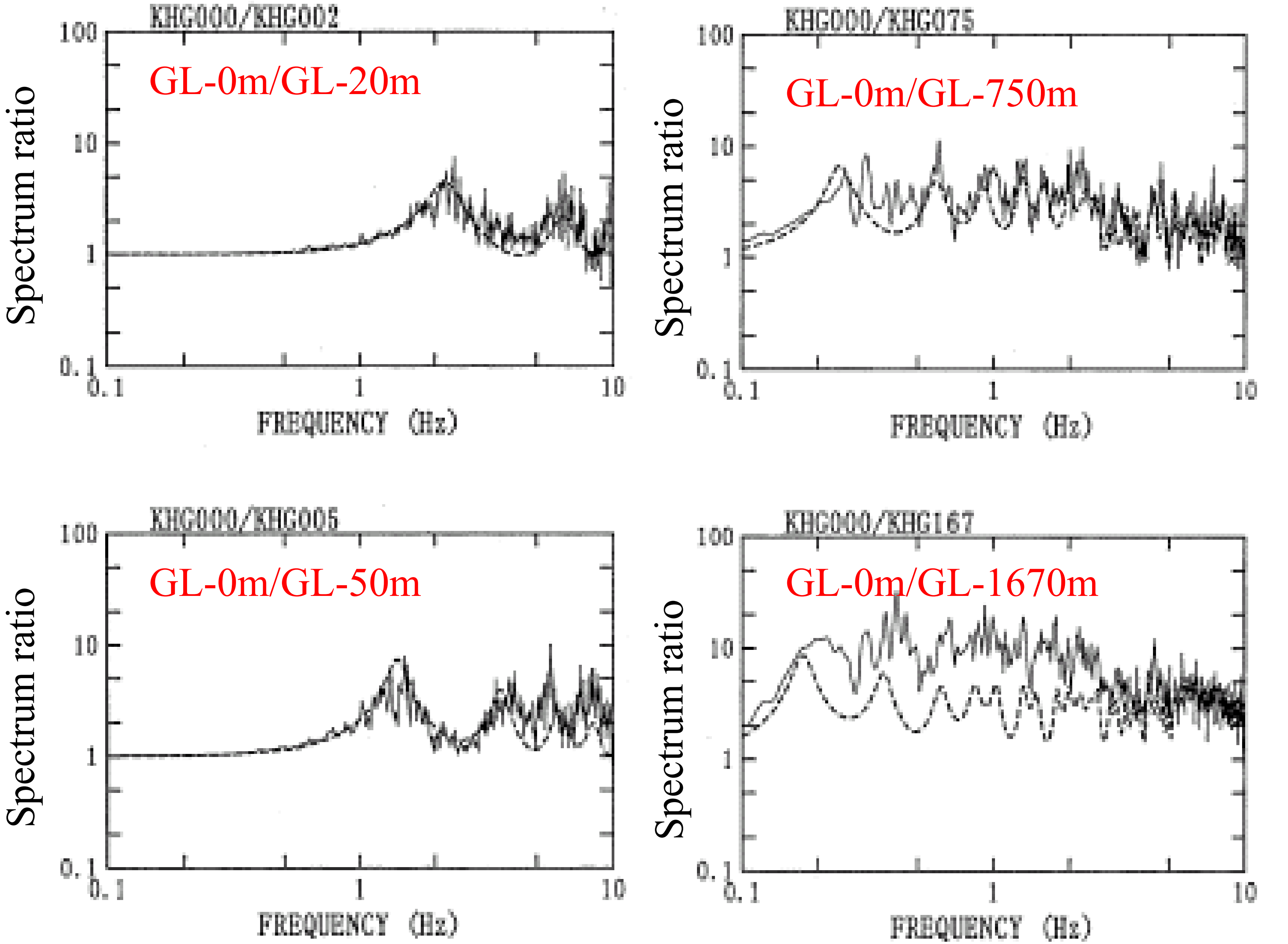




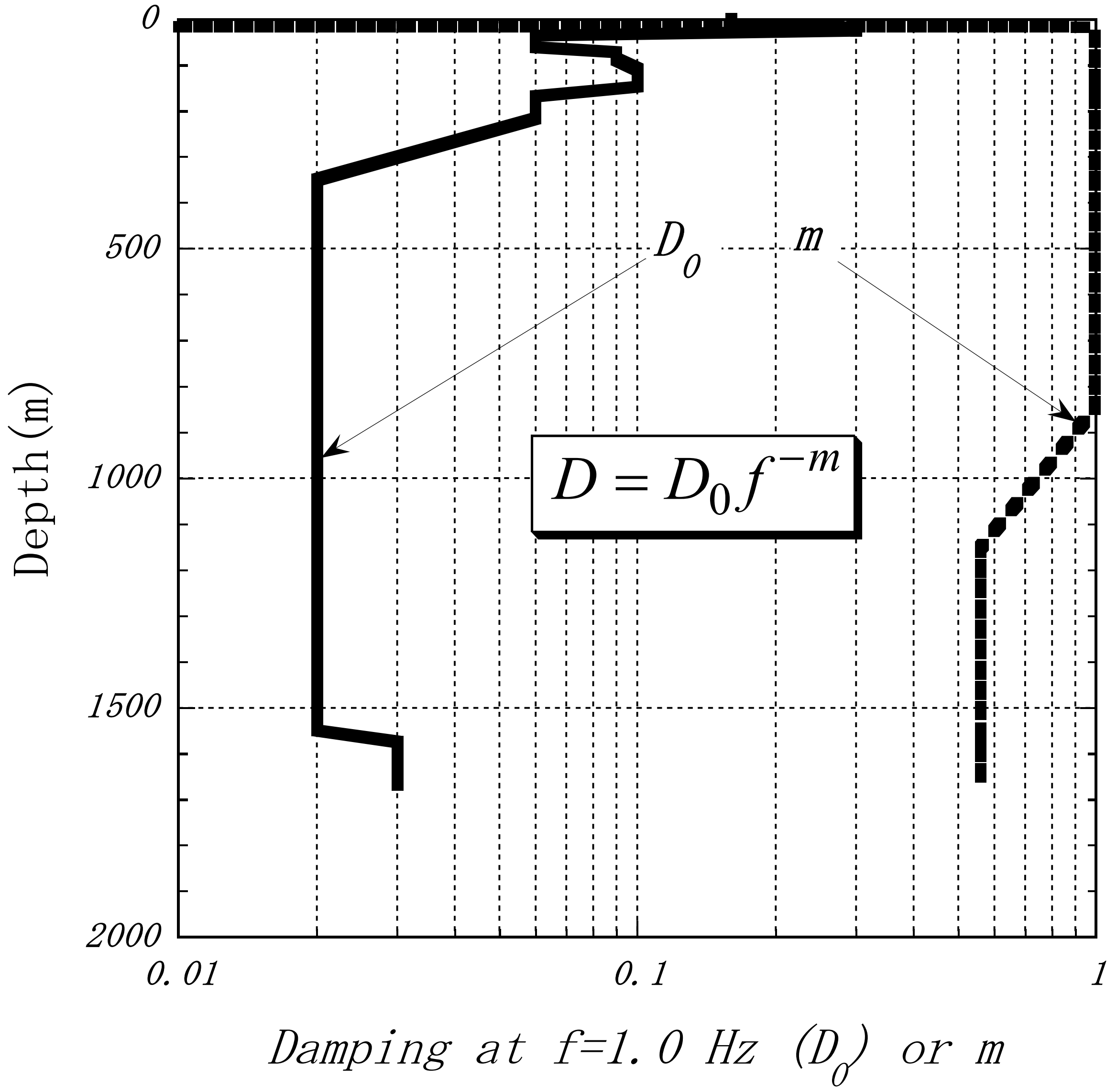
Higashinada deep hole site (GL-1670m), seismometer installation levels and Vs, Vp distribution along depth



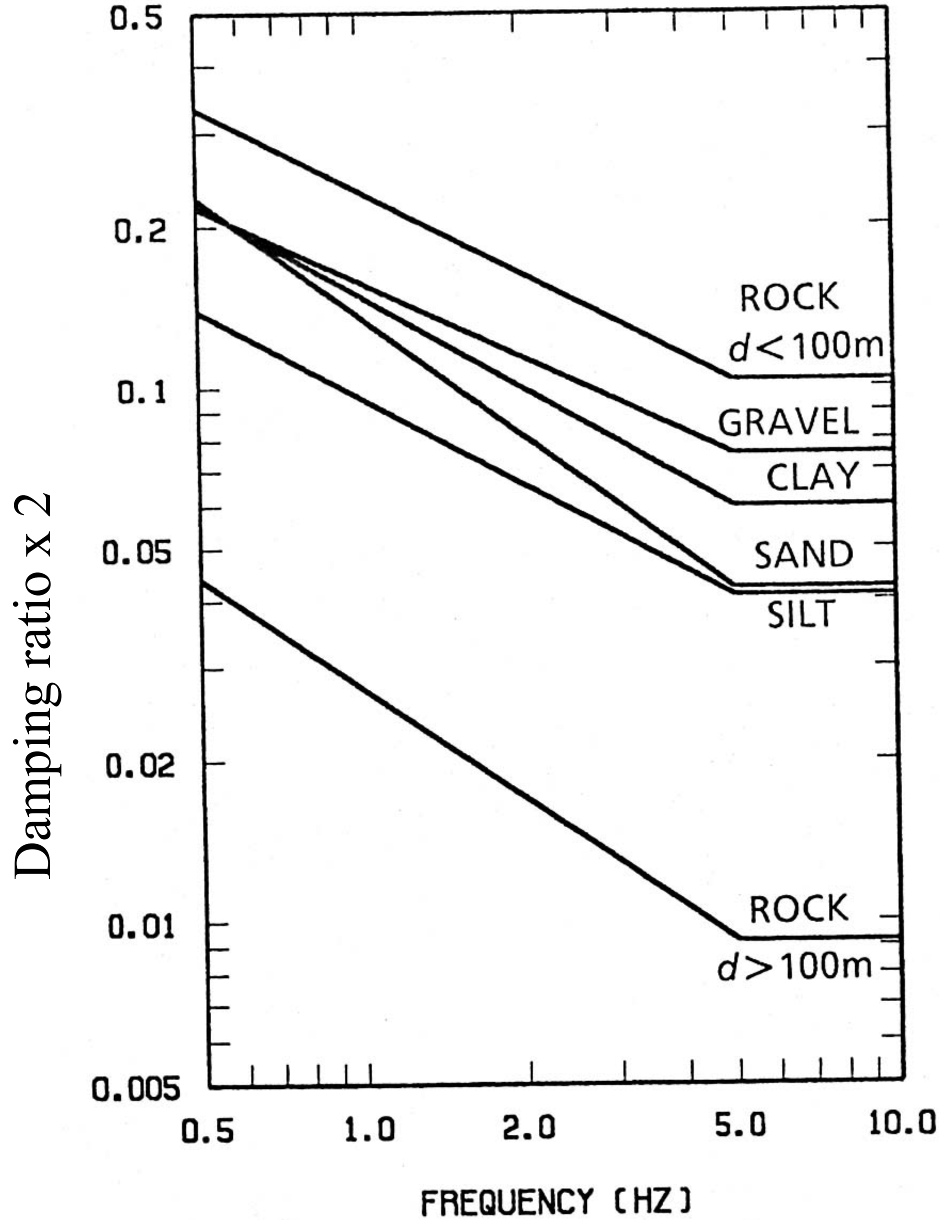
Acceleration amplification in deep soil ground for 3 larger earthquakes (M>6.0, Max.Surf. Acc~10 cm/s^2)



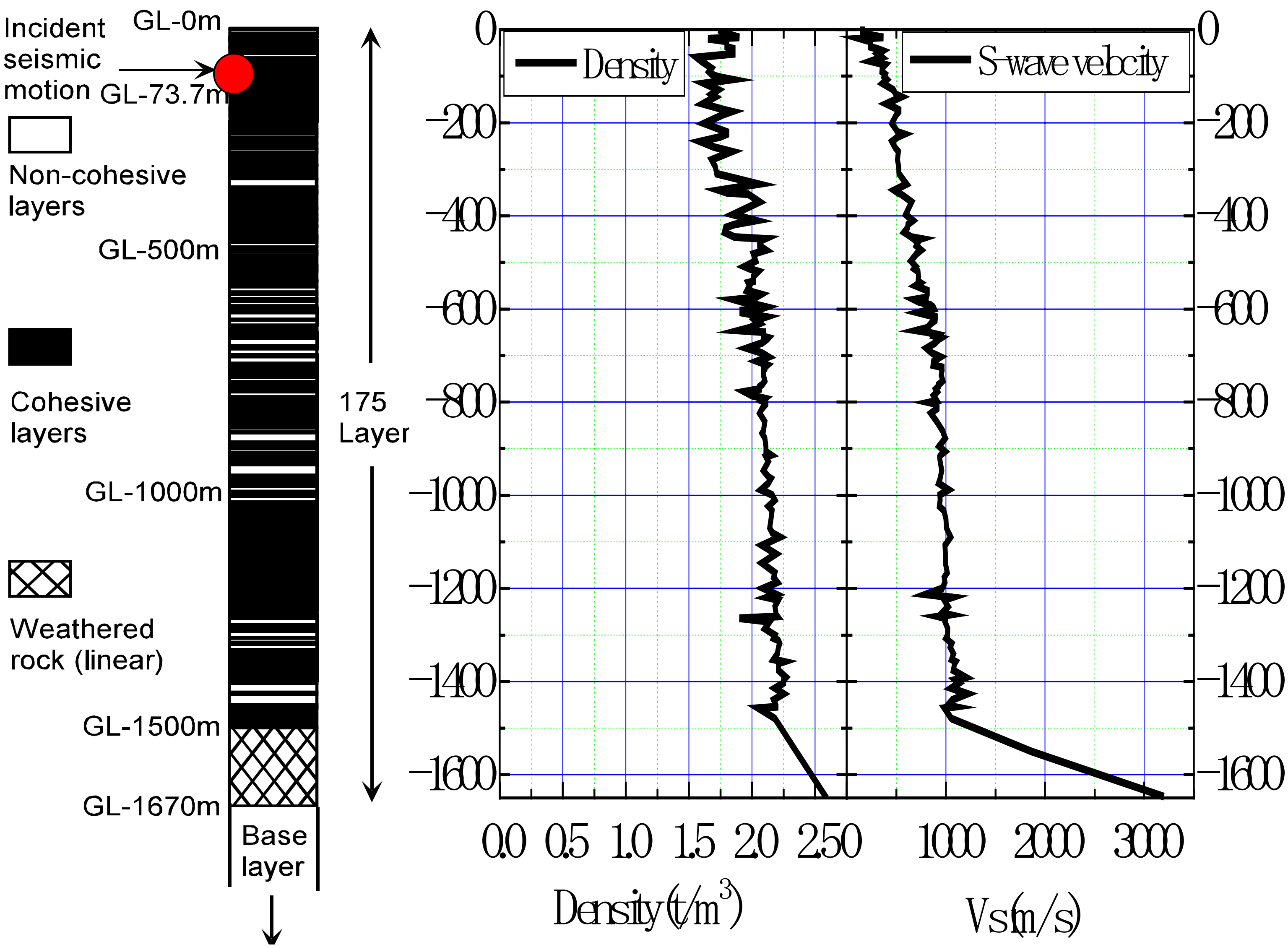
Spectrum ratio (3 larger earthquakes M>6.0)



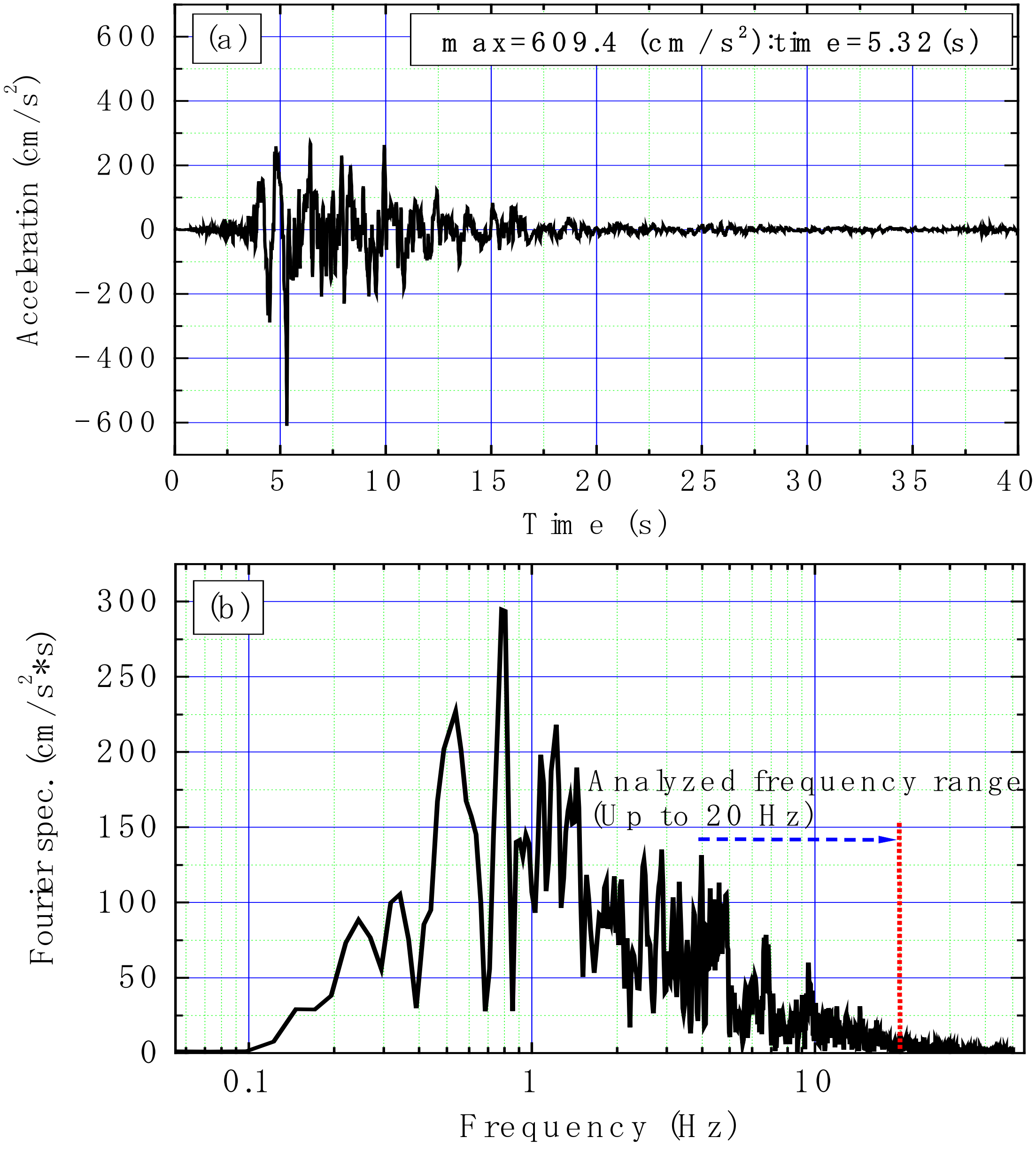
Variation of D_0 and *m* along depth for frequency-dependent damping ratio



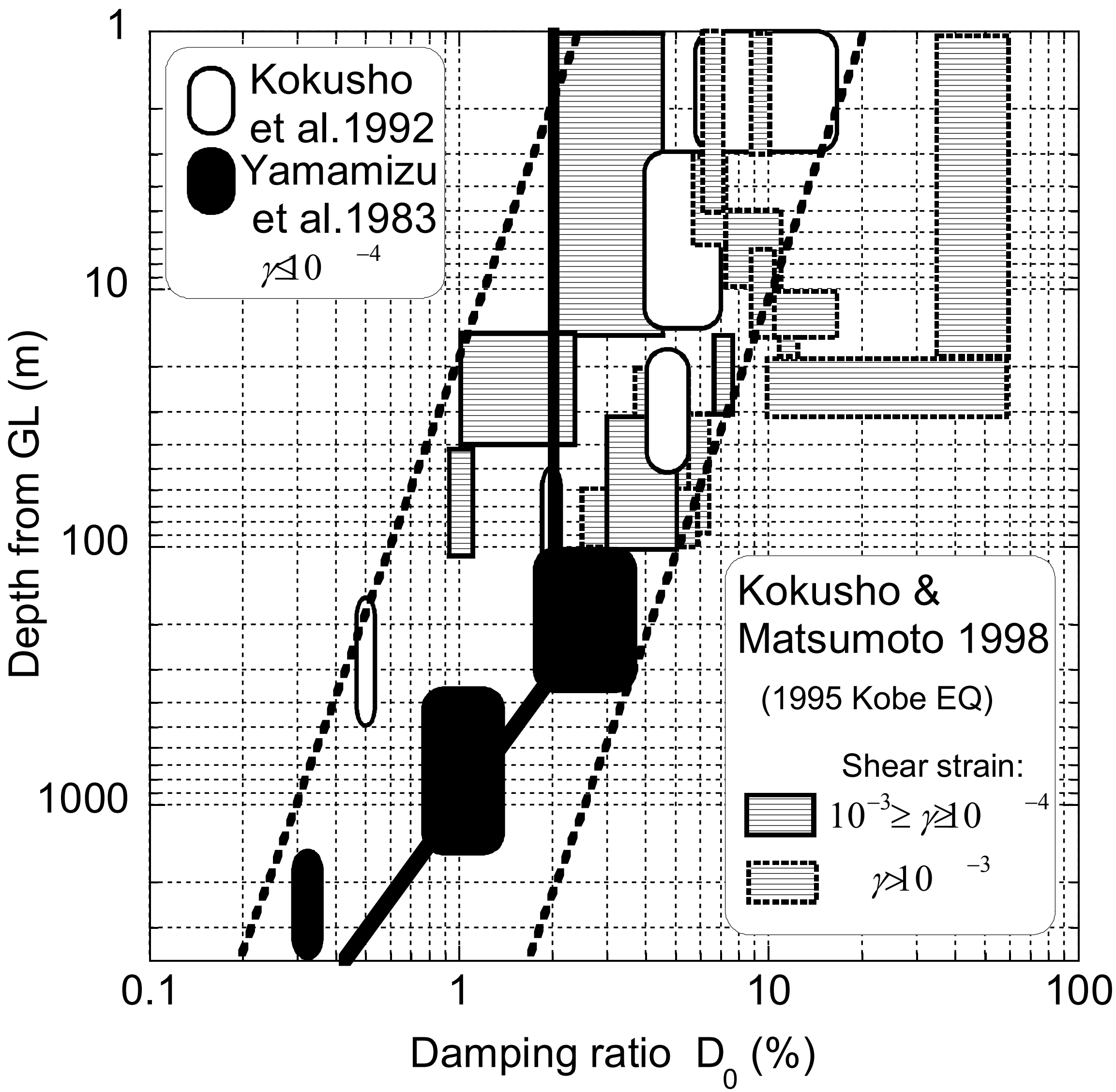
In situ frequency-dependent damping ratio based on previous papers (Fukushima and Midorikawa, 1994)



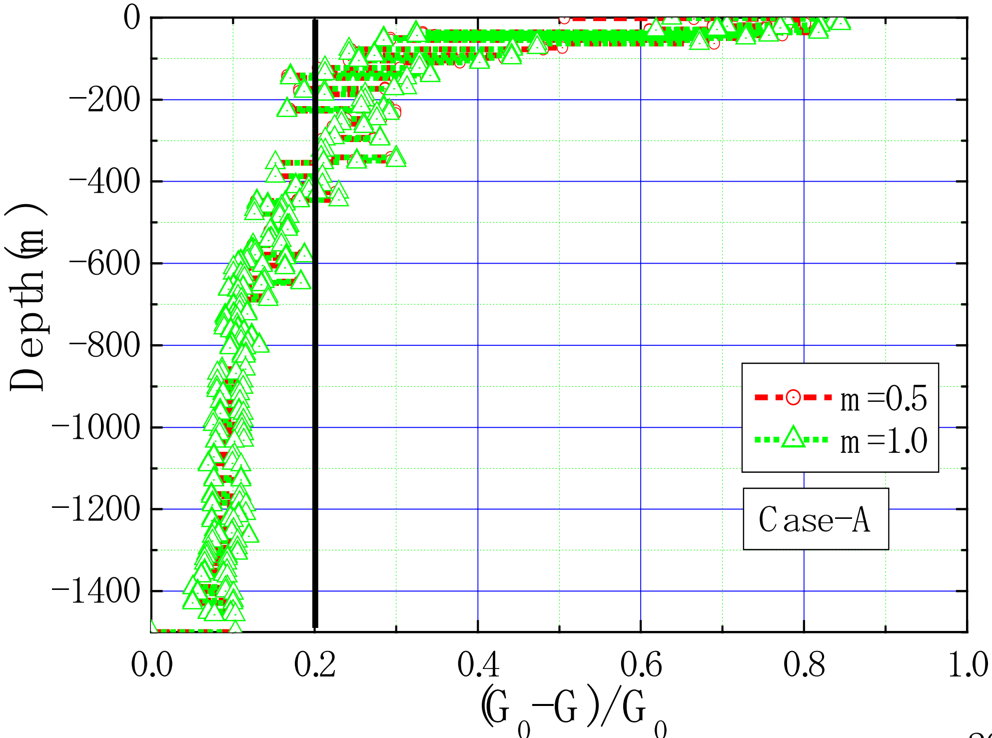
Soil model, Vs and density distribution along depth



Accelerogram and Fourier spectrum of input motion (PI)



Damping ratio in deep soil ground assuming $D = D_0 \cdot f^{-m}$



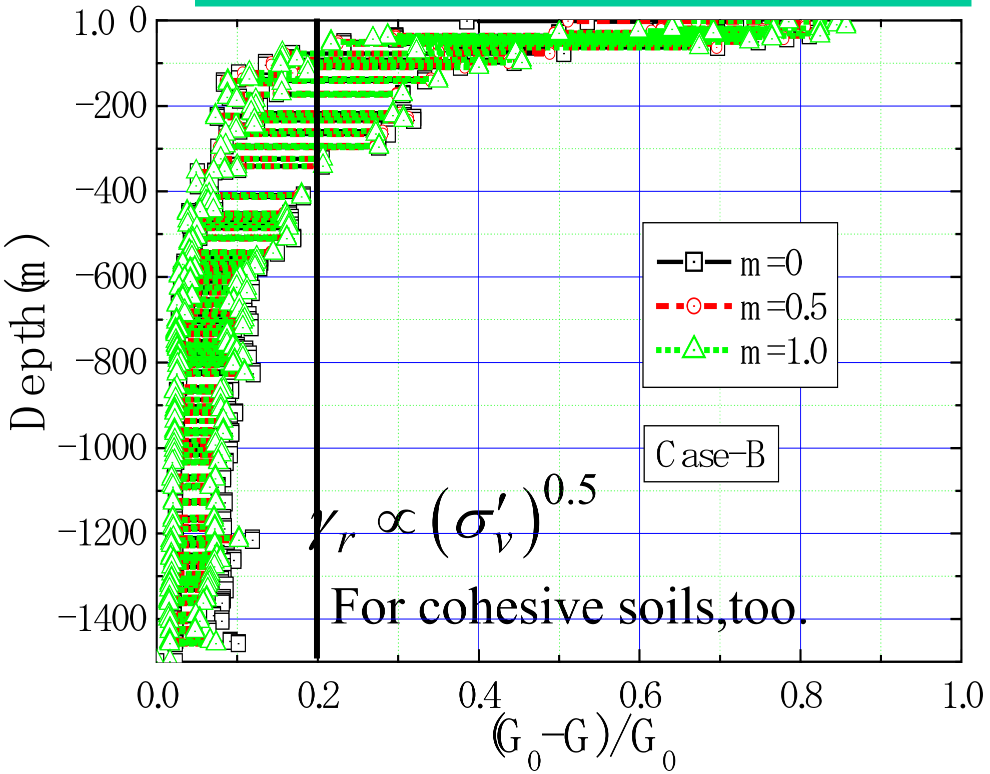
$\gamma_r = const.$ for cohesive soils.

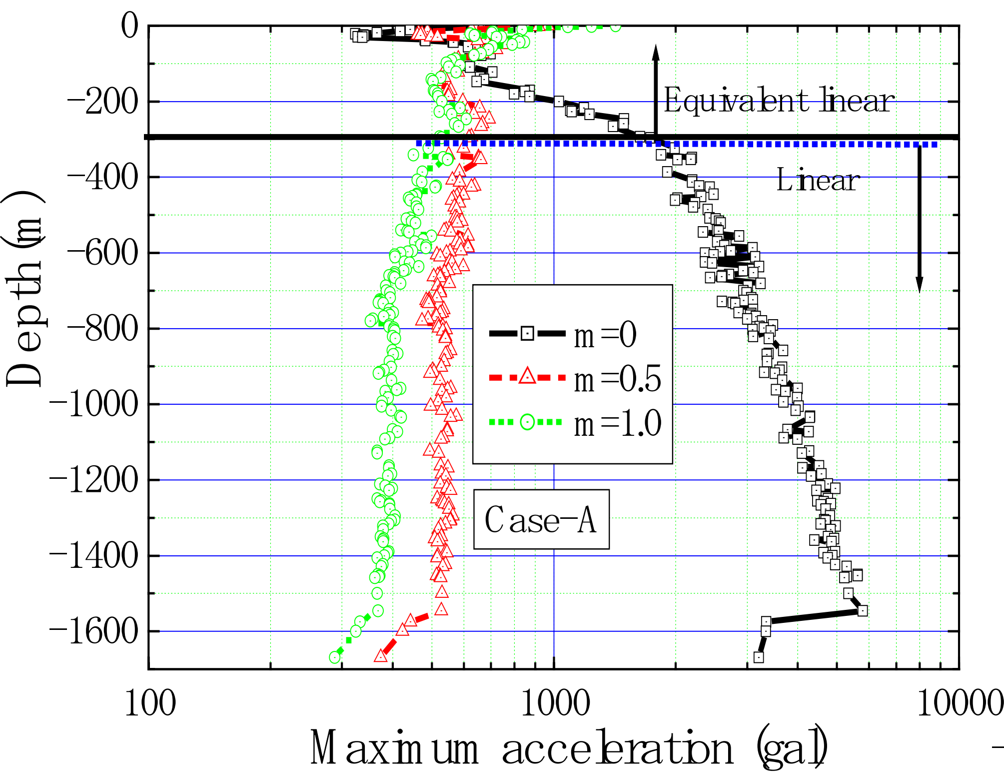
Degree of nonlinearity

$$(G_0 - G)/G_0$$

versus depth

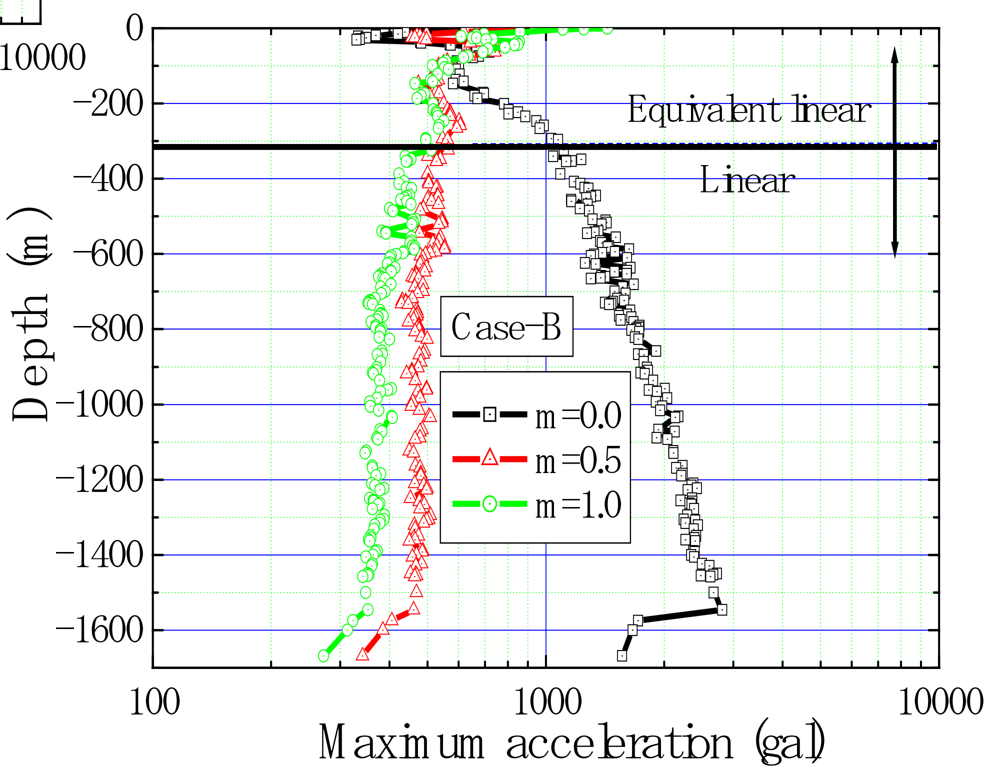
$\gamma_r \propto (\sigma_v')^{0.5}$ for cohesive soils,too.



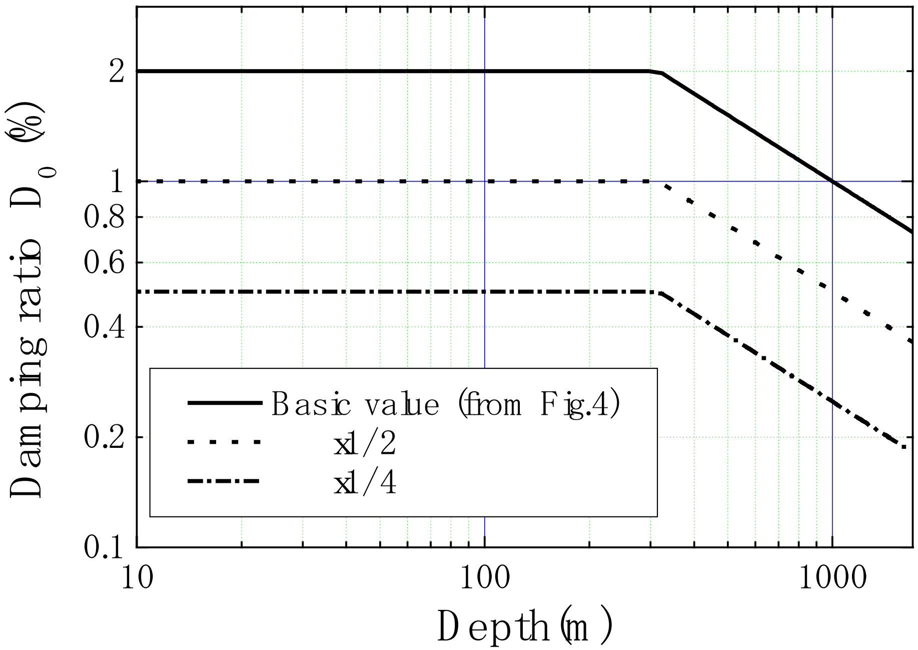


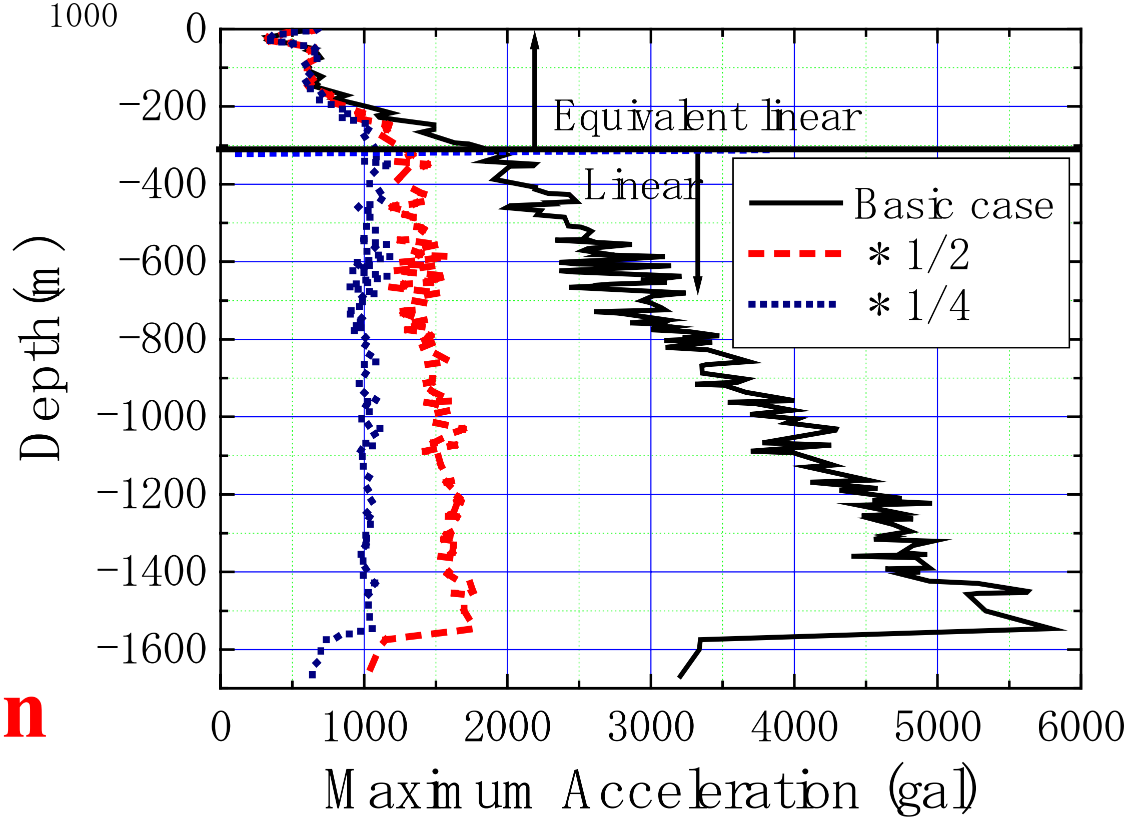
$\gamma_r = const.$ for cohesive soils.

$\gamma_r \propto (\sigma_v')^{0.5}$ for cohesive soils,too.

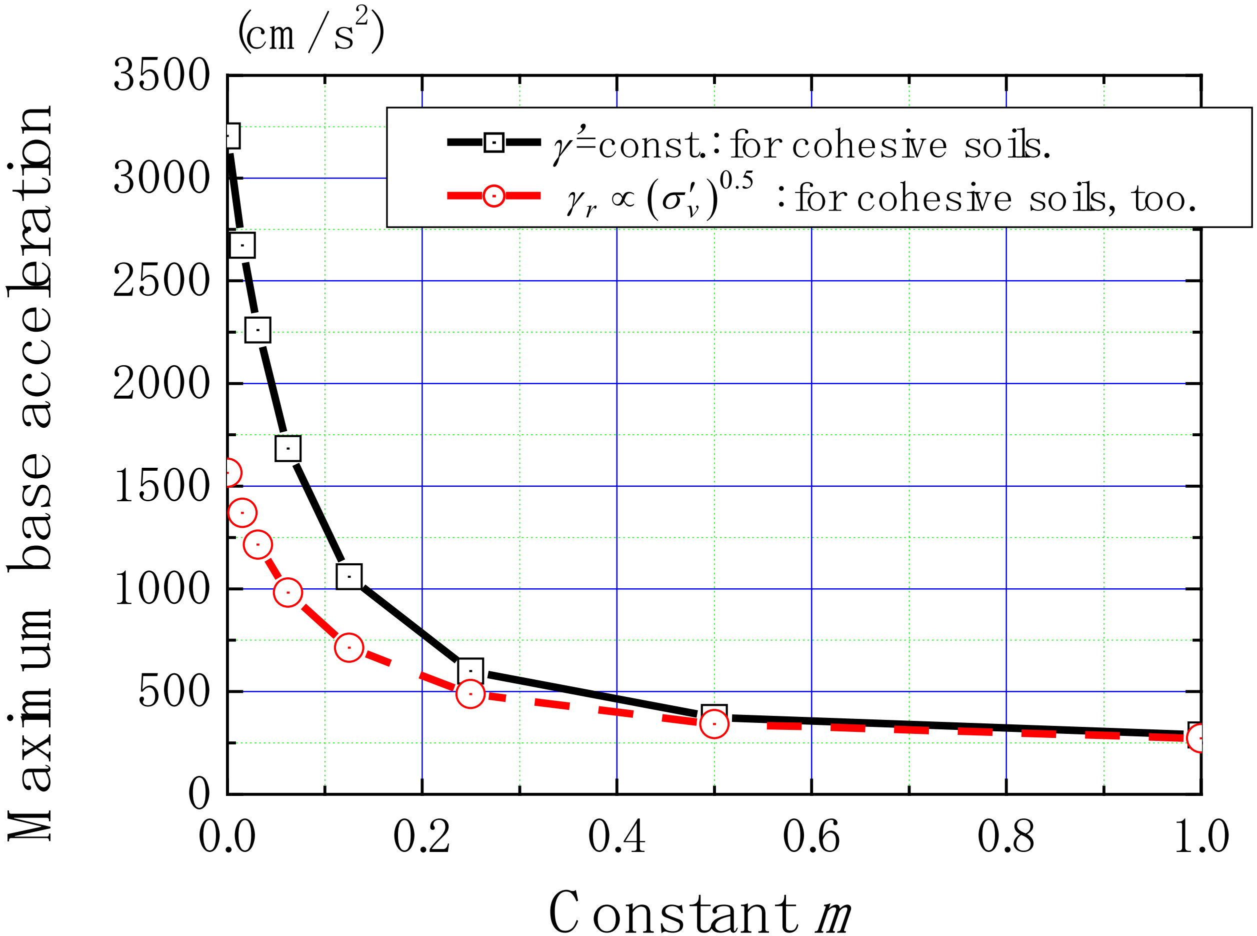


Effect of *m* on Max. Acc. versus Depth relationship





Effect of reducing damping ratio on Max.Acc. distribution



$$D = D_0 \cdot f^{-m}$$

Effect of *m* on Max. Base Acc. (GL-1670 m)

SUMMARY ON RESPONSE IN DEEP SOIL GROUND

Even during the destructive Kobe earthquakes, calculated modulus degradation is milder than 20% deeper than about 300m.

Acceleration tends to increase with increasing depth in analyses based on frequency-independent damping, indicating that the damping should inevitably be frequency-dependent in analyzing deep ground.

Assumptions on soil properties such as frequency-dependency in damping or reference strain have a great effect in analytical seismic response in deep soil ground.

SUMMARY & FURTHER RESEARCH (I)

In Situ Properties

Laboratory modulus degradation for individual soil types are applicable to the field at least up to medium strain range. Field damping is only qualitatively consistent with lab test damping.

More quantitative research for in situ properties;

- -Modulus degradation for large strain range considering strain-dependency and PP-buildup. -
- -Damping ratio for small strain and its mechanism
- -Large strain damping considering cyclic mobility and PP-buildup.

SUMMARY & FURTHER RESEARCH (II)

In vertical motions, little nonlinearity of amplification and back-calculated Vp.

Deep Soil Properties

Strain-dependent soil nonlinearity may be ignorable in depth of a few hundred meters of soil ground even during destructive earthquakes.

Based on deep-hole data analyses, damping is no doubt frequency-dependent.

Effect of high overburden stress on modulus and damping in deep soil should be investigated further.