Application of Seismic Interferometry in the Osaka Basin for Validating the Three-dimensional Basin Velocity Structure Model

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SUMMARY:
The seismic interferometry technique can be used to investigate the surface wave propagation and amplification inside the large sedimentary basin, which occasionally causes the seismic damage due to the strong ground motions to the large cities located inside the basins. We have started the temporary continuous microtremor observation at 15 sites over the Osaka basin and apply the seismic interferometry to this dataset in order to extract inter-station Green's functions. Since all the sensors are installed on the ground surface level in our observation, the cross-correlation function between seismic wave fields for each station-pair is expected to have signals mainly related to the surface wave component (Rayleigh and Love waves) of inter-station Green's function. Both Rayleigh- and Love-wave type signals are identified. By analysing the group velocities and waveform characteristics of these observations, we obtain constraints on the S-wave velocity structure model inside the Osaka sedimentary basin.

Keywords: Basin velocity structure model, seismic interferometry, Osaka sedimentary basin, microtremor

1. INTRODUCTION

The seismic interferometry technique using continuous microtremor or ambient noise records are applied to wide area of pure and engineering seismology in the last decade (e.g., Shapiro and Campillo, 2004; Sabra *et al.*, 2005; Bensen *et al.*, 2007; Yamanaka *et al.*, 2010). It can be used to investigate the surface wave propagation and amplification inside the large sedimentary basin, which occasionally causes the seismic damage due to the strong ground motions to the large cities located inside the basins. An inter-station Green's function can be extracted by stacking correlations of diffuse wave fields recorded at two stations over large amount of data. The inter-station Green's function extracted from the ambient seismic noise fields recorded by a dense seismic network might enable us to obtain independent data set for this kind of study, because the excitation of microtremor and microseism will not depend on the seismicity in the target region. For example, Ma *et al.* (2008) extracted inter-station Green's functions by correlating the vertical component of ambient seismic noise recorded at 56 broadband stations with dense coverage in the greater Los Angeles area, and they tested two community velocity models developed by the Sothern California Earthquake Center (SCEC) by comparing the observed inter-station Green's functions with those calculated by the finite element method.

In this study, we focus on the Osaka sedimentary basin, southwest Japan. The Osaka sedimentary basin is filled by the Plio-Pleistocene Osaka group, terrace deposits, and alluvium deposits with thickness of 1 to 2 km over the bedrock, and it is surrounded by the Arima-Takatsuki Tectonic Line, the Ikoma active fault system, and the Median Tectonic Line. The Uemachi active fault system underlies the Osaka urban area. In order to predict the strong ground motions from a future event of the Uemachi fault, the precise underground velocity structure model is indispensable as well as the detailed source fault model. The underground velocity structure of the Osaka sedimentary basin has been well investigated by using techniques such as gravity anomaly measurements, refraction surveys, seismic air gun reflection, boring explorations, and microtremor measurements. Based on these surveys and ground motion simulations for observed moderate events, the three-dimensional basin velocity structure models of the Osaka basin have been developed and improved for decades (e.g., Kagawa *et al.*, 1993; Horikawa *et al.*, 2003; Iwata *et al.*, 2008; Iwaki and Iwata, 2011).

We deployed the temporary continuous microtremor observation network in the Osaka basin since March 2011. The seismic interferometry technique is applied to this dataset in order to extract the inter-station Green's functions for validating and updating the present basin velocity structure model.

2. TEMPORAL CONTINUOUS MICROTREMOR OBSERVATION IN THE OSAKA BASIN

As of March 2012, fifteen temporal seismic stations are installed in the Osaka sedimentary basin (Fig. 2.1). Most of temporal stations are located close to permanent strong motion observation sites of other institutes. The inter-station distance ranges from 3.1 km to 47.1 km. Since all the sensors are installed on the ground surface level in our observation, the cross-correlation function between seismic wave fields for each station-pair is expected to have signals mainly related to the surface wave component (Rayleigh and Love waves) of inter-station Green's function.

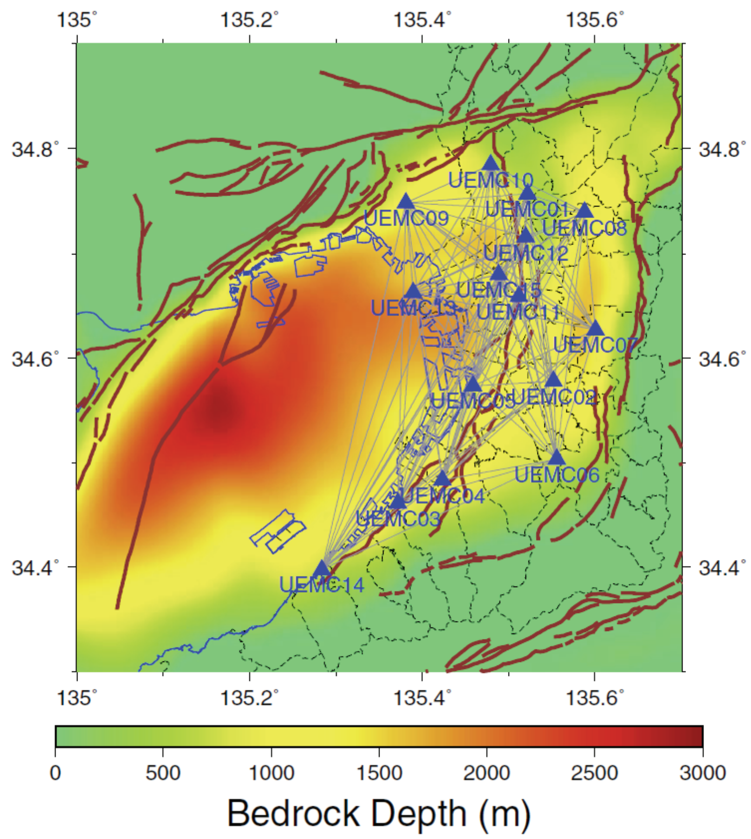

Figure 2.1. Temporal observation sites in the Osaka sedimentary basin (blue triangles).

The temporal seismic station consists of a three-component servo velocity sensor TOKYO SOKUSHIN VSE-15D6 (1V per cm/s) and a data logger with 24bit Δ-Σ A/D DATAMARK LS-8800, and an Uninterruptible Power Supply (UPS) unit. Some of stations used another 24bit data logger DATAMARK LS-7000XT. This velocity sensor has flat response in 0.1–70 Hz. The sensor is located on the surface outside or inside a garage or an observatory house. Ground motions are continuously digitized and stored in a 32GB Secure Digital High Capacity (SDHC) card (LS-8800) or a 2GB Compact Flash (LS-7000XT) at a sampling frequency of 100Hz per channel. Timing of the data logger is continuously synchronized using the Global Positioning System (GPS). The observed data are regularly collected from the data logger.

3. APPLICATION OF SEISMIC INTERFEROMETRY TECHNIQUE

3.1. Theoretical Background

The cross-correlation of the velocity wavefields at two stations $\mathbf{x}_A$ and $\mathbf{x}_B$ can be written as the superposition of the causal and acausal velocity Green's functions (e.g., Wapenaar and Fokkema, 2006).

$$\left\langle C_{qp}^{vel}(\mathbf{x}_B,\mathbf{x}_A,t)\right\rangle \approx \left\{\dot{G}_{qp}(\mathbf{x}_B,\mathbf{x}_A,t)+\dot{G}_{qp}(\mathbf{x}_B,\mathbf{x}_A,-t)\right\} * S(t) \tag{3.1}$$

where the $\dot{G}_{qp}(\mathbf{x}_B,\mathbf{x}_A,t)$ is the time derivative of the Green's function, which is the q-th component of the particle velocity at station $\mathbf{x}_B$ due to a unit force source in the p-th direction at station $\mathbf{x}_A$. $S(t)$ is the auto-correlation of the noise source time function. $\langle\ \rangle$ means the ensemble average. The cross-correlation $C_{qp}^{vel}(\mathbf{x}_B,\mathbf{x}_A,t)$ between two stations is given in the time domain by the following definition.

$$C_{qp}^{vel}(\mathbf{x}_B,\mathbf{x}_A,t)=\frac{1}{T}\int_0^T v_p(\mathbf{x}_A,\tau)v_q(\mathbf{x}_B,\tau+t)d\tau \tag{3.2}$$

$v_i(\mathbf{x}, t)$ is the i-th component of the ground velocity observed at station $\mathbf{x}$, and T is the window length for the time series. Eqn. 3.1 can be rewritten in the frequency domain.

$$\left\langle v_p^*(\mathbf{x}_B,\mathbf{x}_A,\omega)v_q(\mathbf{x}_B,\mathbf{x}_A,\omega)\right\rangle \approx 2\Re\left\{\dot{G}_{qp}(\mathbf{x}_B,\mathbf{x}_A,\omega)\right\}S(\omega) \tag{3.3}$$

ω is the angular frequency, and * is complex conjugate. If source of microtremor are distributed homogeneously in azimuth, the causal and acausal signals should be identical. However, considerable asymmetry in amplitude and spectral content is typically observed, which indicates differences in both the source process and distance to the source in the directions radially away from the stations (Bensen *et al.*, 2007).

3.2. Data Processing Procedure

The observed continuous time-series data are divided into time-windows with duration of 30 min (1800 s). The time-windows are overlapped by 50%. The time-series data in each time-window is band-pass filtered between 0.08 and 2 Hz (period 0.5–12.5 s) using the Chebyshev-type recursive filter after removing the mean. Temporal normalization is applied to the data in order to supress the effects of earthquakes, instrumental irregularities, and local non-stationary noise source around the stations by a one-bit normalization (e.g., Shapiro and Campillo, 2004). Then spectral normalization by whitening spectra is applied after calculating Fourier spectrum.

Cross-correlations between all possible station-pairs are computed in the frequency domain. After the cross-correlations are returned to the time domain they are stacked to correspond to longer time-series. The resulting cross-correlations are two-sided time functions with both positive (causal) and negative (acausal) time coordinates or correlation lags.

3.3. Obtained Inter-station Green's Functions

Figure 3.1 displays all nine components of stacked cross-correlation for some station-pairs. The left panel of Fig. 3.1 is the cross-correlations between UEMC06 and UEMC09 stations, whose inter-station distance is 31.6 km, and the right panel of Fig. 3.1 is the cross-correlations between UEMC09 and UEMC13 stations, whose inter-station distance is 9.5 km. In our notation, Z, R, and T mean vertical, radial, and transverse components, respectively. The Z-R component is the cross-correlation between the vertical component of wavefield at station A and the radial component of wavefield at station B. That is the radial component of response at station B due to the unit force in the vertical direction at station A.

The dominant signals emerged in Z-Z, Z-R, R-R, and R-Z components correspond to Rayleigh wave of inter-station Green's function and the dominant signal emerged in T-T component correspond to Love wave of inter-station Green's function.

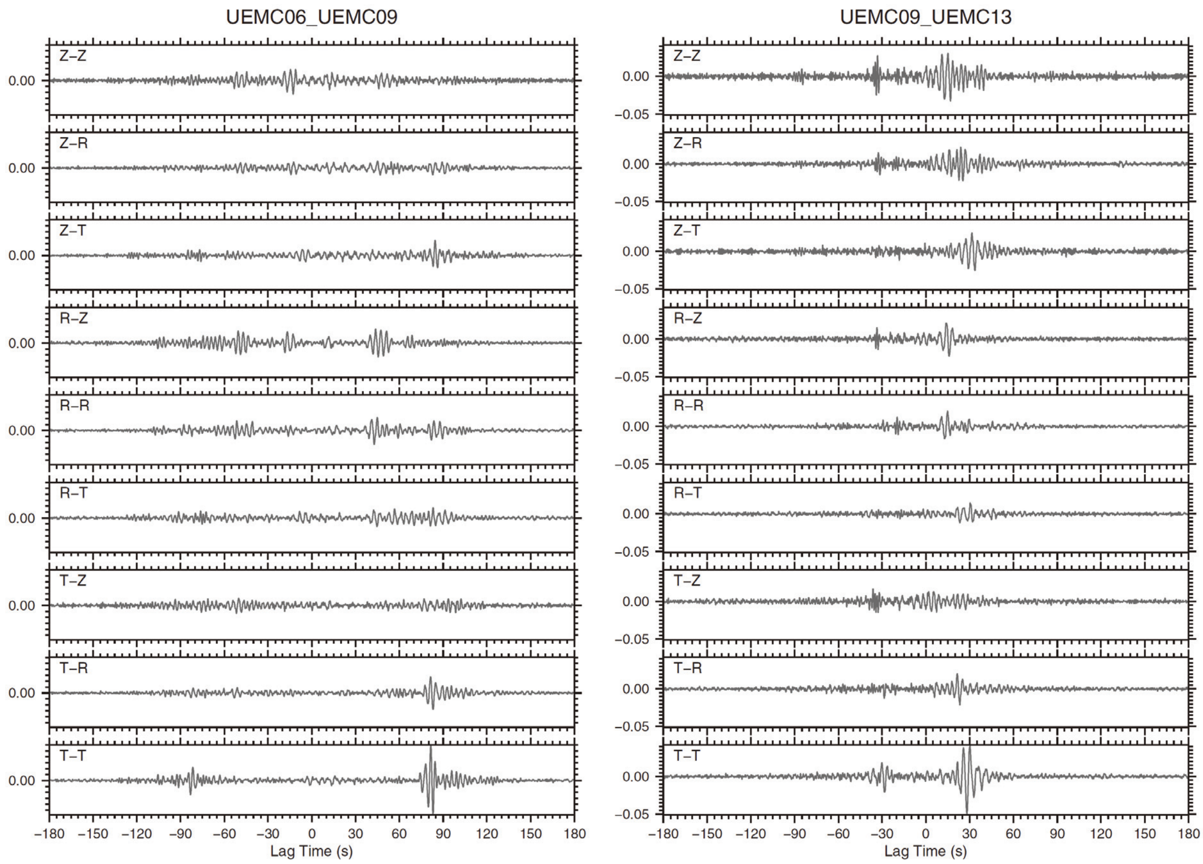

Figure 3.1. Example of stacked inter-station cross-correlations (Z: Vertical, R: Radial, T: Transverse comp.)

Figure 3.2 shows R-R and T-T components of inter-station Green's functions ordered by the inter-station distance. From this figure, emergence of signals propagating according to the distance is clearly recognised. These signals could be interpreted as Rayleigh and Love waves propagating in the Osaka sedimentary basin.

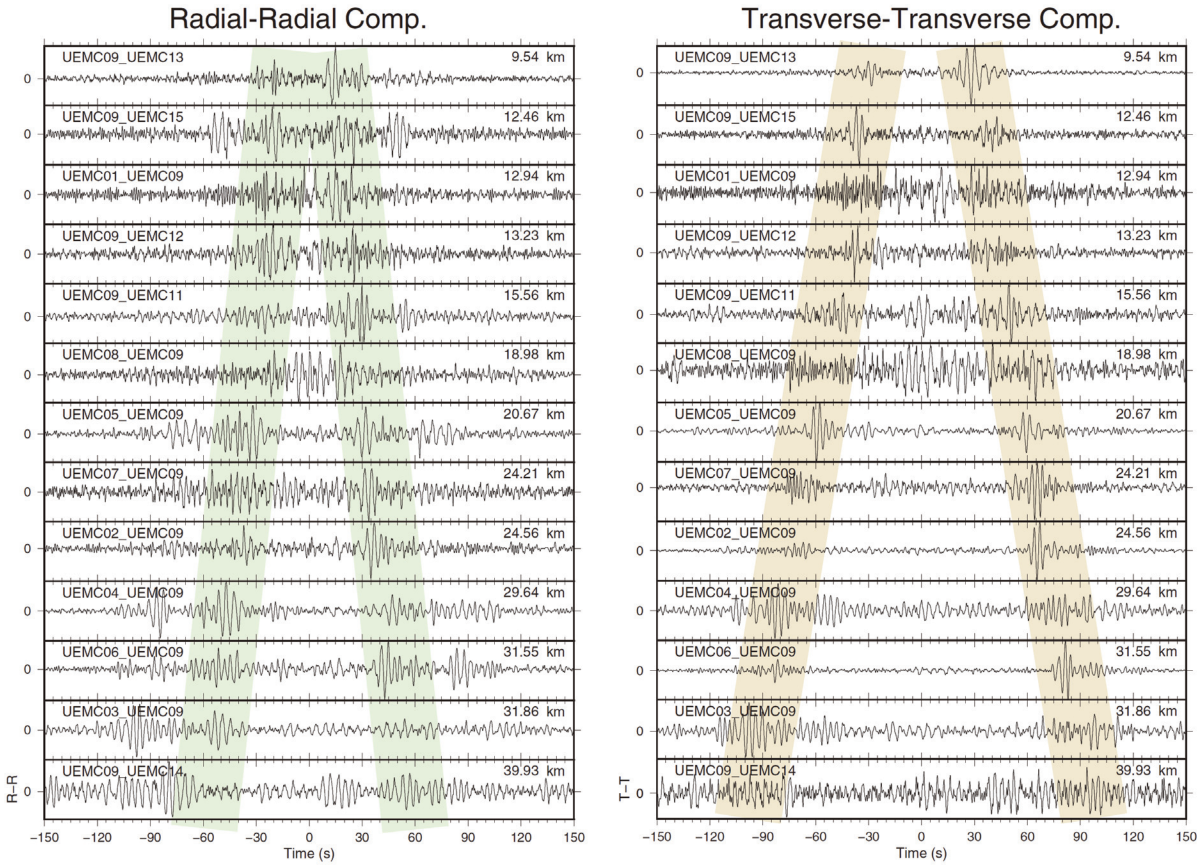

Figure 3.2. R-R and T-T components of inter-station Green's functions ordered by the inter-station distance

4. ESTIMATION OF GROUP VELOCITY OF SURFACE WAVE

In order to obtain the quantitative information for validating and improving the present three-dimensional basin velocity structure model, the group velocities of Rayleigh and Love waves propagating between two stations are estimated from the observed cross-correlations or inter-station Green's functions using the multiple filter analysis by Dziewonski *et al.* (1969). In this analysis, two-sided signal is compressed into a one-sided signal by averaging causal and acausal parts of the cross-correlations.

Figure 4.1 shows the envelopes of inter-station Green's functions in eighteen different period ranges along the path between UEMC05 and UEMC09, which is a path along the Osaka bay area. The bedrock depth along this path is more than 1 km. The central period of each period range is indicated beside the trace in Fig. 4.1. In the shortest period (1–2 s), the signal-to-noise ratio appears to be still insufficient to for stable estimation of group velocities.

The group velocities of Rayleigh and Love waves at each central period or frequency estimated from above analysis are plotted in Fig. 4.2. The theoretical dispersion curves of group velocities are also plotted for comparison. The theoretical dispersion curve is calculated using DISPER80 (Saito, 1988) assuming a one-dimensional velocity structure just below the station from the three-dimensional velocity structure model by Iwata *et al.* (2008) with modification of depth ratios of sedimentary layers by Iwaki and Iwata (2011). This basin velocity structure model consists of three homogeneous sedimentary layers above the bedrock, and the thickness of each sedimentary layer is proportional to the bedrock depth.

In this case, the observed group velocity of Love wave seems to match the theoretical dispersion curve, but the observed group velocity of Rayleigh wave lower than 0.2 Hz is systematically slower than the theoretical dispersion curve. It is likely because a part of travelling path between two stations has deeper sediments than just below the stations (Fig. 2.1).

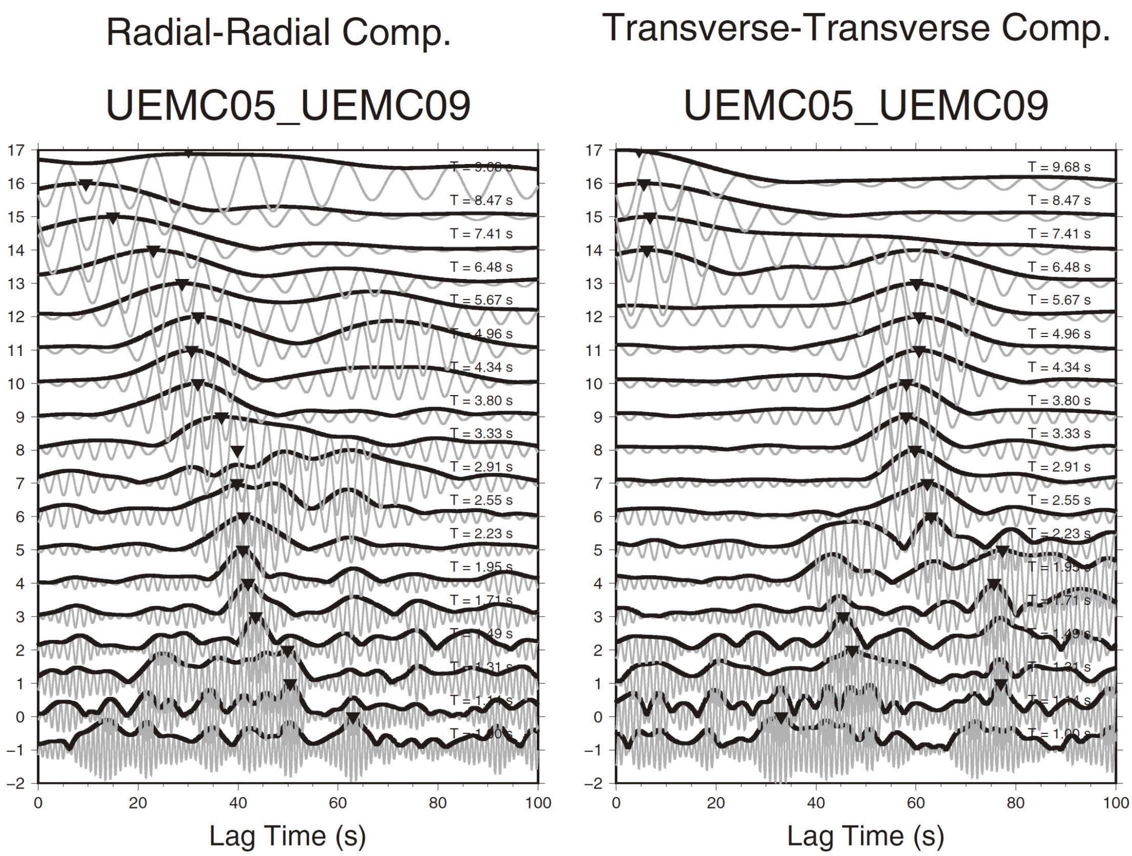

Figure 4.1. Envelopes of R-R and T-T components of inter-station Green's function from UEMC05 to UEMC09

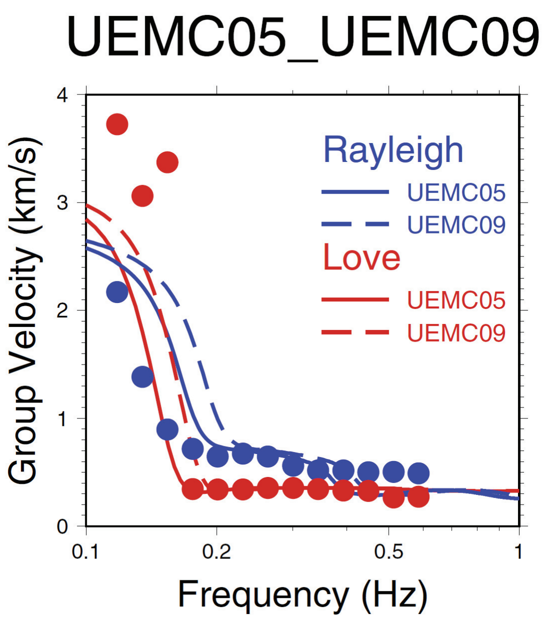

Figure 4.2. Dispersion curve of Rayleigh and Love wave group velocity between UEMC05 and UEMC09

5. CONCLUSIONS

We have started temporary continuous microtremor observation at fifteen sites in the Osaka sedimentary basin. The seismic interferometry technique is applied to this dataset in order to extract the inter-station Green's functions for validating and updating the present basin velocity structure model. We could see the emergence of signals corresponding to Rayleigh and Love waves propagating in the Osaka sedimentary basin. In order to increase the signal-to-noise ratios for observed cross-correlations, it is necessary to continue the observation for accumulating more data. The difference in dispersion characteristics of group velocities between observation and present basin velocity structure model will be discussed in the next step.

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REFERENCES

Bensen, G. D., Ritzwoller, M.H., Barmin, M.P., Levshin, A.L., Lin, F., Moschetti, M.P., Shapiro, N.M. and Yang, Y. (2007). Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements. *Geophyical Journal International* **169:3**, 1239–1260.

Dziewonski, A., Bloch, S. and Landisman, M. (1969). A technique for the analysis of transient seismic signals. *Bulletin of the Seismological Society of America* **59:1**, 427–444.

Horikawa, H., Mizuno, K., Ishiyama, T., Satake, K., Sekiguchi, H., Kase, Y., Sugiyama, Y., Yokota, H., Suehiro, M., Yokokura, T., Iwabuchi, Y., Kitada, N. and Pitarka, A. (2003). A three-dimensional subsurface structure model beneath the Osaka sedimentary basin, southwest Japan, with fault-related structural discontinuities. *Annual Report on Active Fault and Paleoearthquake Researches* **3**, 225–259 (in Japanese with English abstract).

Iwaki, A. and Iwata, T. (2011). Estimation of three-dimensional boundary shape of the Osaka sedimentary basin by waveform inversion. *Geophysical Journal Internatinal* **186:3**, 1255–1278.

Iwata, T., Kagawa, T., Petukhin, A. and Ohnishi, Y. (2008). Basin and crustal velocity structure models for the simulation of strong ground motions in the Kinki area, Japan. *Journal of Seismology* **12:2**, 223–234

Kagawa, T., Sawada, S., Iwasaki, Y. and Nanjo, J. (1993). Modeling the deep sedimentary structure in the Osaka basin. *Proceedings of the 22nd JSCE Earthquake Engineering Symposium*, Kyoto, 199–202 (in Japanese).

Ma, S., Prieto, G.A. and Beroza, G.C. (2008). Testing Community Velocity Models for southern California using the ambient seismic field. *Bulletin of Seismological Society of America* **98:6**, 2694–2714.

Sabra, K. G., Gerstoft, P., Roux, P., Kuperman, W.A. and Fehler M. C. (2005). Extracting time-domain Green's function estimates from ambient seismic noise. *Geophysical Research Letters* **32:3**, L03310, doi: 10.1029/2004GL021862.

Saito, M. (1988). DISPER80: A subroutine package for the calculation of seismic normal mode solutions. in Seismological Algorithms, edited by D. J. Doornbos, Academic Press, 293–319.

Shapiro, N. M. and Campillo, M. (2004). Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise. *Geophysical Research Letters* **31:7**, L07614, doi: 10.1029/2004GL019491.

Wapenaar, K. and Fokkema, J. (2006). Green's function representations for seismic interferometry. *Geophysics* **71:4**, SI33–SI46.

Yamanaka, H., Chimoto, K., Moroi, T., Ikeura, T., Koketsu, K., Sakaue, M., Nakai, S., Sekiguchi, T. and Oda, Y. (2010). Estimation of surface-wave group velocity in the southern Kanto area using seismic interferometric processing of continuous microtremor data. *BUTSURI-TANSA* (*Exploration Geophysics*), **63:5**, 409–425 (in Japanese with English abstract).