Elongation of the dominant period of long-period ground motions in the Tokyo bay area

K. Yoshimoto[1], K. Kajikawa[2], K. Masuda[3] and S. Takemura[4]

1. Corresponding Author, Professor, Department of Material System Science, Graduate School of Nonobioscience, Yokohama City University, 22-2 Seto, Kanazawa-ku, Yokohama, Japan. Email: k_yoshi@yokohama-cu.ac.jp

2. Graduate Student, Department of Material System Science, Graduate School of Nonobioscience, Yokohama City University, 22-2 Seto, Kanazawa-ku, Yokohama, Japan. Email: n155209f@yokohama-cu.ac.jp

3. Graduate Student, Department of Material System Science, Graduate School of Nonobioscience, Yokohama City University, 22-2 Seto, Kanazawa-ku, Yokohama, Japan. Email: n155226b@yokohama-cu.ac.jp

4. Research Fellow, National Research Institute for Earth Science and Disaster Resilience, 3-1 Tennodai, Tsukuba, Ibaraki, Japan.
   Email: shunsuke@bosai.go.jp

Abstract

By analyzing waveforms of shallow moderate to large earthquakes recorded in the Tokyo metropolitan area, we found elongation of the dominant period of long-period ground motions (LPGs) in the Tokyo bay area. We tested whether this observation could be explained by 3D simulations of LPGs using a seismic velocity structure model called the Smoothed Basin Velocity Structure Model (SBVSM). Our simulations indicated that the SBVSM could not satisfactorily explain our observations, implying inadequate modelling of the seismic velocity structure in the Tokyo bay area. Regarding this result, we modified the SBVSM to include a detailed structure of low-velocity sedimentary layers beneath northeastern Tokyo bay and used this revised model to perform 3D simulations of LPGs. Our simulations show that the local modification of shallow sedimentary structure beneath the Tokyo bay is not enough to explain the observed elongation of LPGs and suggest the necessity of improving our understanding of the shallow sedimentary structure beneath the eastern inland area of the Tokyo bay.

Keywords: Long-period ground motion, Dominant period, Tokyo bay area

1. Introduction

Long-period ground motions (LPGs) with dominant periods from several to ten seconds or longer are frequently observed during shallow moderate to large earthquakes, especially in large sedimentary basins (e.g., Beck and Hall, 1986; Koketsu and Miyake, 2008). The LPGs often cause significant resonance and severe damage of large-scale man-made structures such as high-rise buildings, oil-storage tanks, and long bridges. Therefore, for disaster mitigation in case of future large earthquakes, it is important to investigate the characteristics of LPGs in densely-populated large sedimentary basins.

In the Tokyo metropolitan area, which is located on the Kanto Basin, LPGs are often observed during shallow local and regional earthquakes. By analyzing strong motion records of shallow earthquakes (magnitude = 5.5–7.5), Yoshimoto and Takemura (2014b) reported that the dominant period of LPGs tends to increase in proportion to bedrock depth until it reaches approximately 7 s; however, it is almost constant for bedrock depths greater than 2 km. In our latest study, we conducted a detailed analysis of LPGs and found the elongation of the dominant period of LPGs to be as high as approximately 9 s in the Tokyo bay area, where low-velocity (*S*-wave velocity V_S ~ 0.5 km/s) sedimentary layers are developed by the depositional environment in the Kanto Basin (e.g., Suzuki 2002). This observation should be considered in the estimation of LPGs of future large earthquakes in the Tokyo metropolitan area.

In this study, we test whether the elongation of the dominant period of LPGs in the Tokyo bay area could be explained by 3D simulation of LPGs using our Smoothed Basin Velocity Structure Model (SBVSM) (Masuda et al. 2014; Takemura et al. 2015). In addition, we revise the SBVSM to include a detailed structure of the low-velocity sedimentary layers beneath northeastern Tokyo bay and perform 3D simulation using this model. We compare simulation results from these models, and discuss the effect of low-velocity sedimentary layers on the dominant period of LPGs and a preferable seismic structure model for evaluating LPGs in the Tokyo bay area.

2. Characteristics of LPGs in the Tokyo bay area

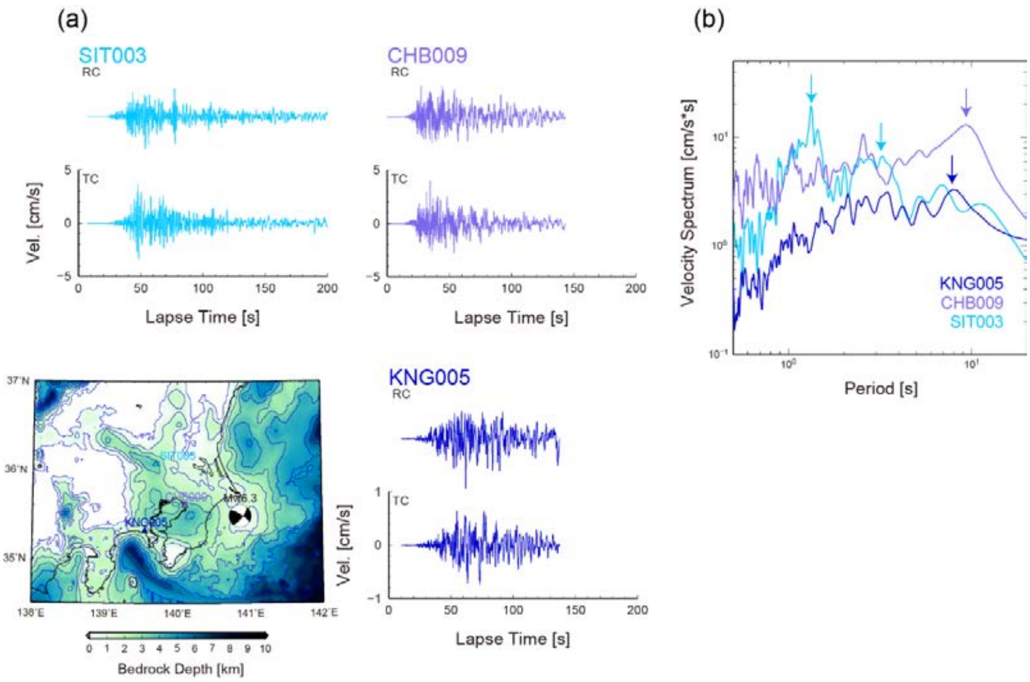

Figure 1. An example of observed strong motions in the Tokyo metropolitan area during the offshore eastern Chiba shallow earthquake ($M_W = 6.3$) on 12 April 2011. (a) Observed waveforms. Radial and transverse components (RC and TC, respectively) are shown. (b) Fourier amplitude spectra of horizontal strong motions. Arrow indicates dominant peak of spectral amplitude.

The LPGs in the Tokyo metropolitan area have been recorded by a dense network of K-NET/KiK-net (Okada et al., 2004) and SK-net (Takano and Uehara, 2014). It is reported that the characteristics of LPGs are strongly influenced by both the sedimentary structure and the bedrock geometry of the basin (e.g., Koketsu and Kikuchi, 2000; Yamanaka and Yamada, 2006; Furumura and Hayakawa, 2007; Yoshimoto and Takemura, 2014a,b).

We analyzed eight shallow moderate to large earthquakes (M_W = 5.8–6.9) with a wide coverage of epicentral directions, and confirmed a tendency that the predominant period of LPGs is elongated up to approximately 9 s only in the Tokyo bay area. Figure 1 is an example plot of the velocity waveforms recorded at three stations during the offshore eastern Chiba earthquake on 12 April 2011 (depth = 26 km) to show elongated predominant period of LPGs at CHB009 and KNG005 in the Tokyo bay area. This observation is not in accordance with the report of Yoshimoto and Takemura (2014b) regarding the average characteristics of the dominant period of LPGs in the Kanto Basin for moderate to large earthquakes. We conducted 3D numerical simulations of this earthquake to investigate the contribution of the local shallow velocity structure beneath the Tokyo bay to the elongation of the dominant period of LPGs.

3. 3D numerical simulation of LPGs

3.1 Velocity structure model

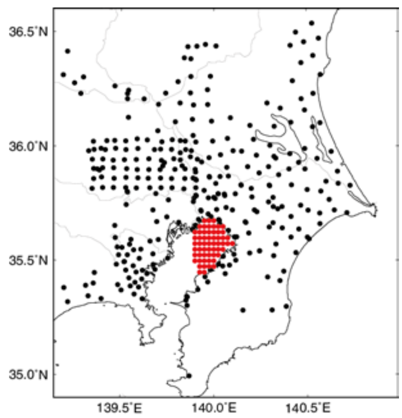

Figure 2. Distribution of 301 sites (black dots) that were used for estimating spatial variations of V_0 and α of the SBVSM (Masuda et al. 2014; Takemura et al. 2015). Red dots indicate 57 grid-points used for the revised version of the SBVSM.

We used two 3D sedimentary velocity structure models for 3D finite-difference model (FDM) simulations of long-period ground motions in the Tokyo bay area. The first model is the SBVSM proposed by Takemura et al. (2015). This model, which represents the sedimentary velocity structure of the Kanto Basin, was extended by Masuda et al. (2014) by using spatial interpolation of 301 local sedimentary velocity structure data (Figure 2). In this model, the depth-dependent *S*-wave velocity at a certain site is represented by the following simple equation (Ravve and Koren, 2006):

$$V_S(z) = V_0 + \Delta V\left[1-\exp\left(-\frac{\alpha z}{\Delta V}\right)\right], \tag{1}$$

where z is the depth below the surface, V_0 is the *S*-wave velocity at the surface, ΔV is the increment of the *S*-wave velocity at large depths, and α is a positive constant that determines the velocity–depth gradient. Assuming that $\Delta V = 3.2$ km/s, which is the bedrock *S*-wave velocity of the Japan Integrated Velocity Structure Model (JIVSM) of

Koketsu et al. (2012), local *S*-wave velocity structure in the Kanto Basin can be represented by using two parameters (V_0 and α). For other technical details, including the modelling of other elastic parameters, the reader is referred to Takemura et al. (2015). A shortcoming of the SBVSM is that it was not constructed by using sufficient local structure data in the Tokyo bay and the southeastern part of the Kanto Basin.

The second model was constructed as a revised model of the SBVSM to include information on the shallow sedimentary structure beneath the northeastern Tokyo bay (Figure 2). Although, the sedimentary structure in the Tokyo bay had not been fully investigated, the structure model of Chiba Prefecture (2004) may be useful for improving the SBVSM. Using the Chiba Prefecture model, we sampled 57 grid-point depths with a bottom surface layer of $V_S = 0.5$ km/s beneath the northeastern Tokyo bay (Figure 3a bottom) and evaluated the spatial variation of V_0 and α in the Tokyo bay area (Figure 3b right) by using the method of Takemura et al. (2015).

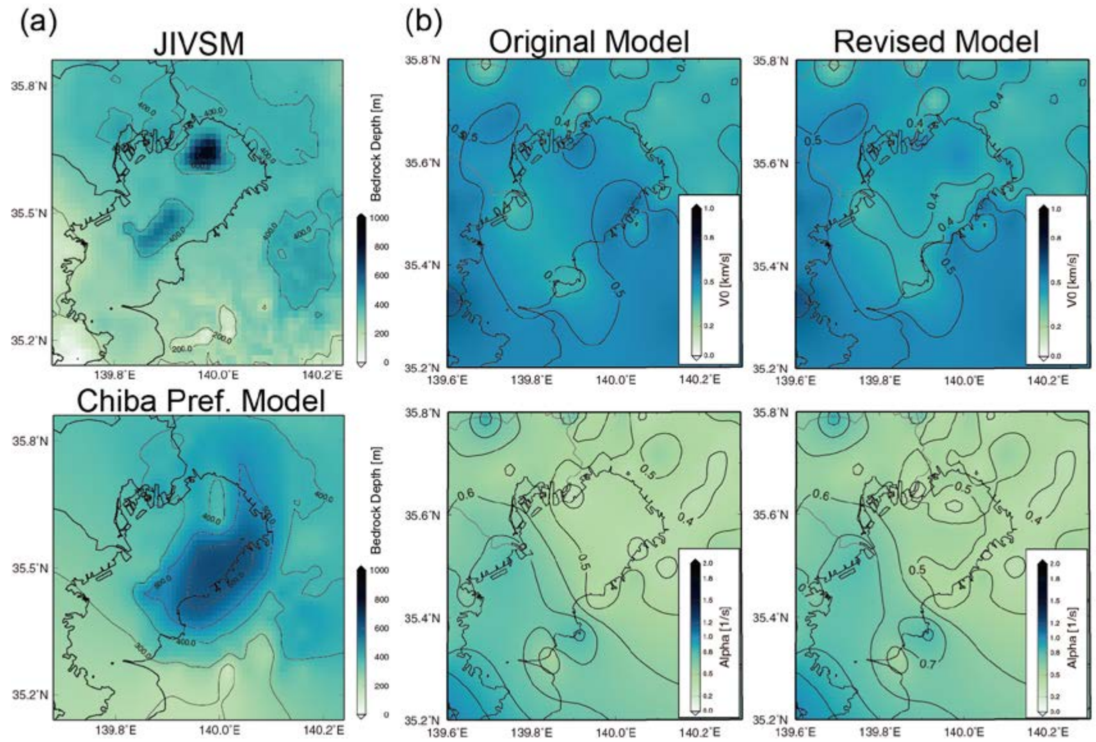

Figure 3. Shallow sedimentary structure in the Tokyo bay area. (a) Bottom surface depth of $V_S = 0.5$ km/s layer from the JIVSM (upper panel) and the Chiba Prefecture (2004) model (lower panel). (b) Spatial variation of V_0 and α in the SBVSM (left panels) and the revised model (right panels).

3.2 3D FDM simulations

The model for FDM simulations covered the zone of 315×225×72 km^3 (red rectangle of a map in Fig. 4), which was discretized by grid intervals of 0.15 km in the horizontal directions and 0.1 km in the vertical direction. A double-couple point source was assumed, referring to the F-net moment tensor (MT) solution of the target earthquake. Other technical details, such as source time function, anelastic attenuation, and solid/air boundary condition, are the same as in Takemura et al. (2015). Based on the grid size and minimum *S*-wave velocity (0.3 km/s), our numerical simulations could evaluate the propagation of seismic waves with periods longer than 4 s.

3.3 Results of numerical simulation: SBVSM

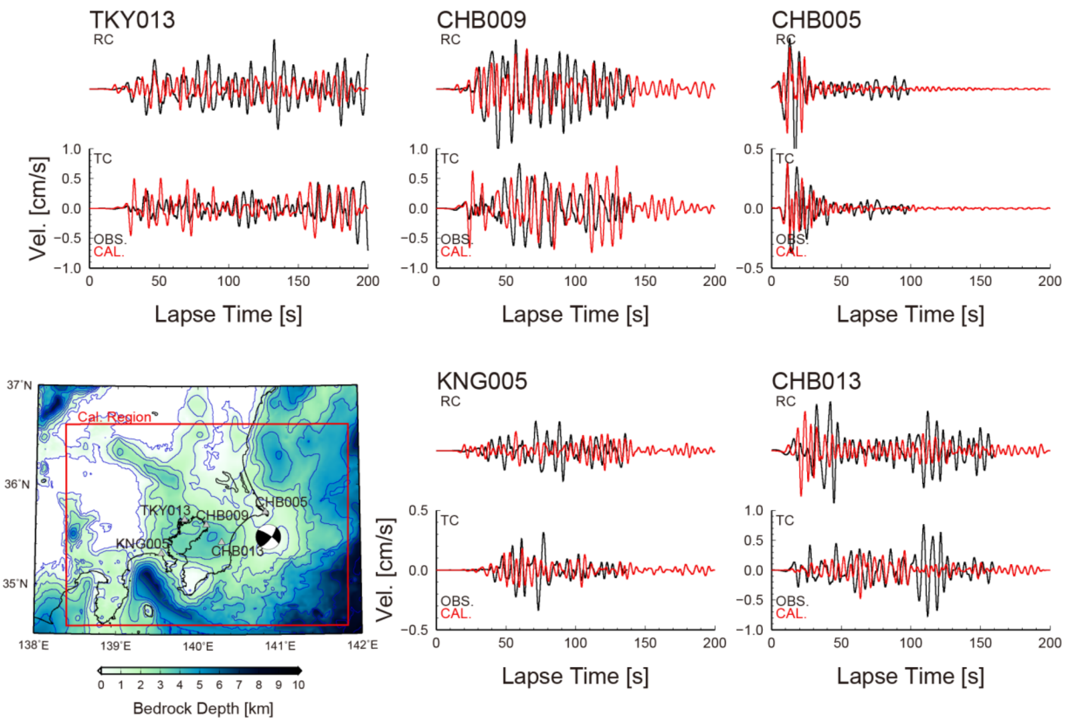

Figure 4. Comparative plots of waveforms from observation (black) and the SBVSM simulation (red). Waveforms of radial and transverse components for periods of 4 to 20 s are compared. The solid red rectangle shows the simulation area. The plotted focal mechanism was used in the simulations.

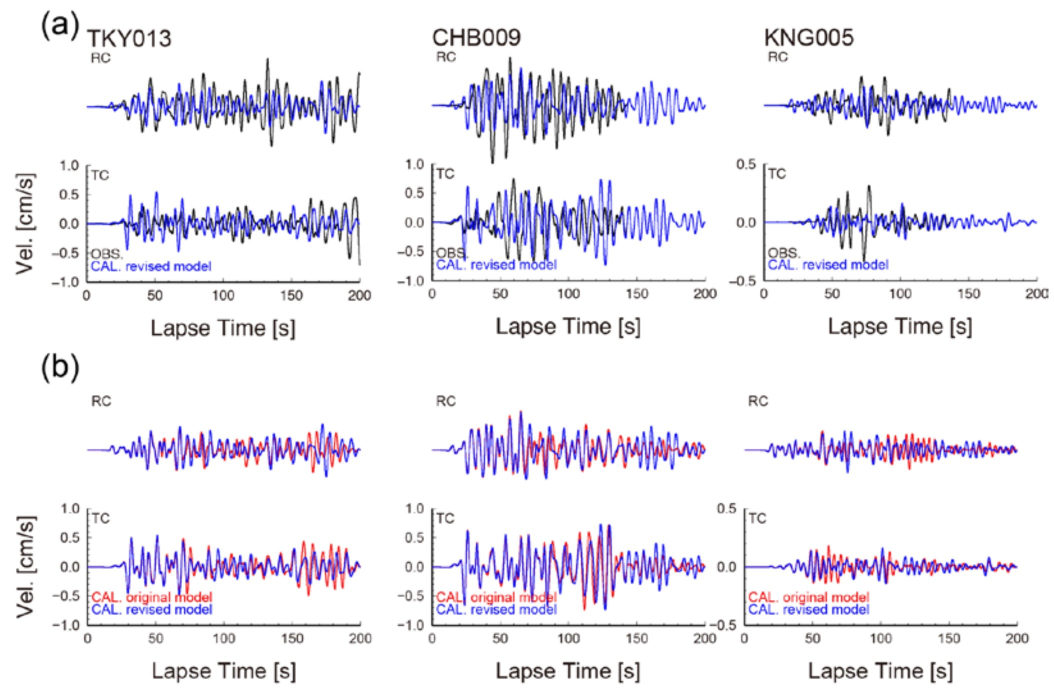

Figure 5. Comparison of waveforms. (a) Comparison between observation (black) and the revised model simulation (blue). (b) Comparison between simulated waveforms from the SBVSM (red) and the revised model (blue). Waveforms of radial and transverse components for period of 4 to 20 s are compared.

Figure 4 shows a comparative plot of long-period waveforms from observation and SBVSM simulation. The simulation results successfully explained LPGs near the epicenter (CHB005). On the contrary, simulation results failed to explain the amplitude of LPGs at the northwestern and western coast of the Tokyo bay (TKY013 and KNG005). Moreover, simulation results underestimated the dominant period of LPGs at CHB009, CHB013 and KNG005.

3.4 Results of numerical simulation: revised model

Figure 5a shows a comparative plot of long-period waveforms from the observation and the revised model simulation. No apparent improvement in the waveform fit was detected by this simulation. Figure 5b shows a comparison of waveforms from two simulations using different structure models: the SBVSM and the revised model. Waveforms of two simulations are very similar to each other and discrepancies are found only in the lapse time after approximately 50 s.

4. Discussion and conclusions

We conducted waveform analysis of shallow moderate to large earthquakes and found elongation of the dominant period of LPGs to be as high as approximately 9 s in the Tokyo bay area. Our 3D FDM simulation of LPGs using the SBVSM failed to explain this observation. Additional simulation using a revised model, which included information on the shallow sedimentary structure beneath the northeastern Tokyo bay, also failed to explain the observed characteristics of LPGs. These results imply that the elongation of the dominant period of LPGs in the Tokyo bay area is presumably caused by not only local sedimentary structure beneath the Tokyo bay but also the sedimentary structure beneath the eastern seaboard of the Tokyo bay, including the CHB013 site. In future research, information on sedimentary structure beneath the eastern inland area of the Tokyo bay should be included in the SBVSM.

Acknowledgments

The KiK-net and K-NET waveform data and the F-net MT solutions were provided by the National Research Institute for Earth Science and Disaster Resilience, Japan (NIED). We also used SK-net waveform data that were provided by the Earthquake Research Institute, the University of Tokyo. Numerical simulations were conducted on the computer system of the Earthquake and Volcano Information Center at the Earthquake Research Institute, the University of Tokyo. The research performed by KY was in part supported by JSPS KAKENHI Grant Number 15K05272. The Generic Mapping Tools (Wessel and Smith, 1998) and Seismic Analysis Code (SAC) were used for making figures and signal processing, respectively.

References

Beck J. L. and Hall J. F. (1986) Factors contributing to the catastrophe in Mexico City during the earthquake of September 19, 1985, Geophys Res Lett, 13, 6, 593-596, doi:10.1029/GL013i006p00593.

Chiba Prefecture (2004) Report of the underground structure survey of Chiba Prefecture on 2004, http://www.hp1039.jishin.go.jp/kozo/Chiba9frm.htm (in Japanese).

Furumura T. and Hayakawa T. (2007) Anomalous propagation of long-period ground motions recorded in Tokyo during the 23 October 2004 M_W 6.6 Niigata-ken Chuetsu, Japan, earthquake, Bull Seismol Soc Am, 97, 3, 863–880, doi:10.1785/0120060166.

Koketsu K. and Kikuchi M. (2000) Propagation of seismic ground motion in the Kanto Basin, Japan, Science, 288, 1237-1239, doi:10.1126/science.288.5469.1237.

Koketsu K. and Miyake H. (2008) A seismological overview of long-period ground motion, J Seismol, 12, 133–143, doi:10.1007/s10950-007-9080-0.

Masuda K., Yoshimoto K., Takemura S. and Akatsu M. (2014) A modeling of Kanto Basin structure including velocity-depth gradients: Toward a better estimation of long-period ground motions, Program and Abstracts of the 2014 Fall Meeting of the Seismological Society of Japan, Niigata, Japan, S16-P13, Nov. 24–26, 2014 (in Japanese).

Okada Y., Kasahara K., Hori S., Obara K., Sekiguchi S., Fujiwara H. and Yamamoto A. (2004) Recent progress of seismic observation networks in Japan: Hi-net, F-net, K-NET and KiK-net, Earth Planets Space, 56, xv–xxviii.

Ravve I. and Koren Z. (2006) Exponential asymptotically bounded velocity model: Part I - Effective models and velocity transformations, Geophysics, 71, 3, T53-T65, doi:10.1190/1.2196033.

Suzuki H. (2002) Underground geological structure beneath the Kanto plain, Japan, Report of the National Research Institute for Earth Science and Disaster Prevention, 63, 1-19 (in Japanese with English abstract).

Takano K. and Uehara M. (2014) Current status of data collection in the seismic Kanto strong motion network in metropolitan area: SK-net, Technical Research Report, Earthquake Research Institute, the University of Tokyo, 20, 1-10 (in Japanese).

Takemura S., Akatsu M., Masuda K., Kajikawa K. and Yoshimoto K. (2015) Long-period ground motions in a laterally inhomogeneous large sedimentary basin: observations and model simulations of long-period surface wave in the northern Kanto Basin, Japan, Earth Planets and Space, 67, 33, doi:10.1186/s40623-015-0201-7.

Wessel P. and Smith W. H. F. (1998) New improved version of generic mapping tools released, EOS, Trans Am Geophys Union, 79, 47, 579, doi:10.1029/98EO00426.

Yamanaka H. and Yamada N. (2006) Estimation of 3D *S*-wave velocity model of the Kanto Basin, Japan, using Rayleigh wave phase velocity, Bull Earthq Res Inst, Univ Tokyo, 81, 295-301.

Yoshimoto K. and Takemura S. (2014a) Surface wave excitation at the northern edge of the Kanto Basin, Japan, Earth Planets Space, 66, 16, doi:10.1186/1880-5981-66-16.

Yoshimoto K. and Takemura S. (2014b) A study on the predominant period of long-period ground motions in the Kanto Basin, Japan, Earth Planets Space, 66, 100, doi:10.1186/1880-5981-66-100.