Mid period strong motion observed in the western part of Tokyo during large magnitude events

T. Toshinawa
Meisei University, Japan

15 WCEE
LISBOA 2012

SUMMARY:
The 2011 Tohoku-Pacific Ocean earthquake oscillated high rise buildings in Tokyo including a 17 story building of Meisei University. It is found that 1.6-sec ground motion with a polarity of NE-SW direction was locally observed and enlarged the response of the X direction (N50˚E) of the building which has a natural period of about 2 sec. Seismograms observed at the K-NET TKY04 station during large magnitude events from 1996 to 2011 are employed and the acceleration response spectra for the records are obtained. It is found that strong motions from the events in the east of Tohoku area have a marked peak at about 1.6 sec. The mid period component of the acceleration records has a polarity of NE-SW to ESE-WNW direction. The result suggests that large magnitude, incident angle to the area and deep surface geology locally caused the mid period strong motion.

Keywords: The 2011 Tohoku-Pacific Ocean earthquake, Mid-period strong motion, Ground-motion polarity

1. INTRODUCTION

The M_j 9.0 Tohoku-Pacific Ocean earthquake occurred at 5:46 (GMT) on March 11 2011 generated strong and long period ground motion throughout the eastern part of Japan and oscillated many high-rise buildings in Tokyo which is located about 400km to the southeast of the epicentre. A 17 story SRC building of Meisei University in the western part of Tokyo was one of those, responded 0.3G acceleration in the X direction (N50˚E) and subjected non-structural damage including slight movement of partition walls, exfoliation of coatings and overturning of bookshelves and stands.

Photographs 1.1 and 1.2 show the top floor of the building immediately after the event. Objects and stands overturned in the X(longitudinal)-direction showing that the building was strongly oscillated in the longitudinal direction during this event.

Photographs 1 & 2. Overview of the top floor of the building immediately after the event on March 11 2011.

It is widely accepted that a building with simple structural plan tends to be oscillated in the transverse direction rather than in the longitudinal direction. According to seismic records observed before the event this building has the typical trend (Takeyama, 2011). In this paper the author discussed how this building oscillated in the longitudinal direction during the 2011 Tohoku-Pacific Ocean earthquake on the view point of mid-period ground motion locally generated in the western part of Tokyo.

2. RESPONSE OF THE BUILDING AND ICIDENT WAVE

2.1. Response of the Building

Figure 1 shows time history of acceleration observed on the top floor of the building and Figure 2 shows displacement time history obtained from the two-time integration of the acceleration. The peak accelerations are 0.34G in the X-direction and 0.24G in the Y-direction while the corresponding peak displacements are respectively 32 and 22cm showing that the building was especially oscillated in the X-direction.

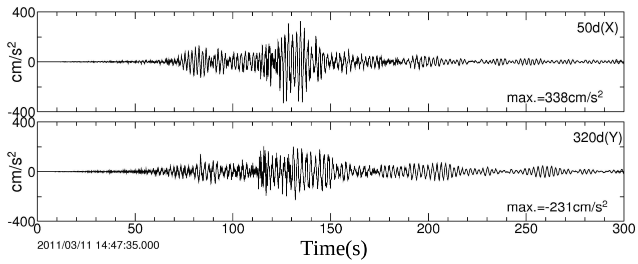

Figure 1. Time history of acceleration observed on the top floor of the building during the Tohoku-Pacific Ocean earthquake of March 11 2011.

Figure 3 shows Fourier spectra of acceleration observed on the top (15F) and basement (B2F) floors of the building during the 2011 Tohoku-Pacific Ocean earthquake and Figure 4 shows spectral ratio of the top with respect to the basement for the event. The Fourier spectra demonstrate that acceleration amplitudes in the X direction are larger than the Y direction both on the top and the basement while spectral ratio in the Y direction is larger than the X direction indicating that larger seismic wave incidence in the X direction (N50˚E) occurred during this event.

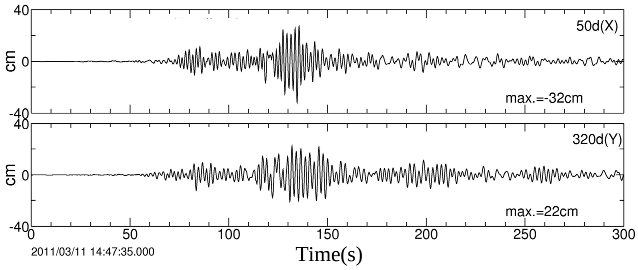

Figure 2. Time history of displacement on the top floor of the building during the Tohoku-Pacific Ocean earthquake of March 11 2011.

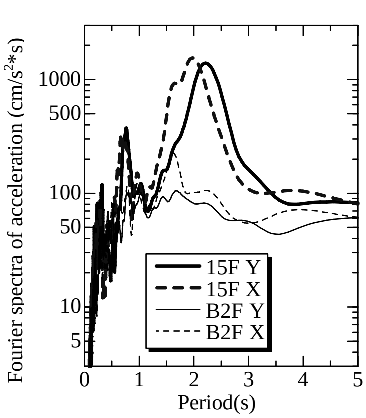

Figure 3. Fourier Spectra of acceleration observed on the top (15F) and basement (B2F) of the building during the 2011 Tohoku-Pacific Ocean earthquake.

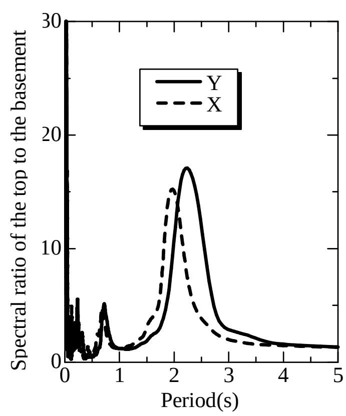

Figure 4. Spectral ratio of the top (15F) with respect to the basement (B2F) for the 2011 Tohoku-Pacific Ocean earthquake.

Figures 5 and 6 respectively show plots of peak value and predominant period of spectral ratio of the top to the basement against peak acceleration for large magnitude events tabulated in Table 2.1. The spectral peak value ranges from 10 to 25 and the value for the Y-direction is 1.0- to 1.6- time larger than the X-direction. It is also found that peak value does not exceed 20 over 100-cm/s^2 peak acceleration. As for predominant period, the period exceeds 2.0 sec over 100-cm/s^2 peak acceleration and the period in the Y-direction is about 1.1-time longer than the X-direction. According to the structural design the building has the natural periods of 1.79 and 1.98 sec for the X- and Y- directions, respectively (Kajima Design, 2004).

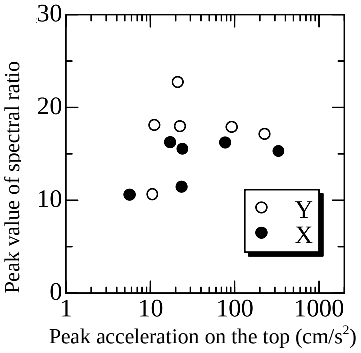

Figure 5. Plot of peak value of spectral ratio of the top to the basement against peak acceleration on the top for the events in Table 2.1.

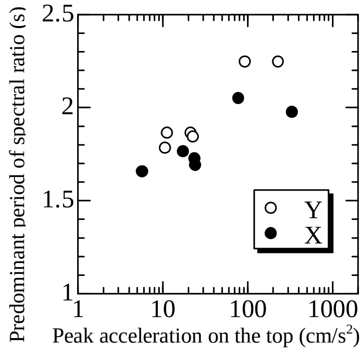

Figure 6. Plot of predominant period of spectral ratio of the top to the basement against peak acceleration for the events in Table 2.1.

Table 2.1. Seismic Parameters of Large Magnitude Events Used for Figures 5 and 6.

Date(mm/dd/yy)	Origin Time (GMT)	M_j	Depth(km)	Hypocentral Region
08/09/2009	10:55:52	6.8	333	Far South off Tokai District
08/10/2009	20:07:06	6.5	23	Southern Suruga Bay Region
08/12/2009	22:48:52	6.6	57	East off Hachijyojima Island
03/14/2010	8:08:04	6.7	40	East off Fukushima Prefecture
03/11/2011	05:46:18	9.0	24	Far East off Miyagi Prefecture
03/11/2011	06:15:34	7.7	43	Far East off Ibaraki Prefecture

2.2. Incident Wave

Figure 7 shows particle orbits of acceleration at the top of the building and adjacent free-field station (Station A) with the orientation of the building for the event on March 11 2011. The acceleration is low-pass filtered at 1.0 Hz. It is evident that mid-period ground motion with a polarity of NE-SW direction was applied to the building, enlarged the response in the X-direction.

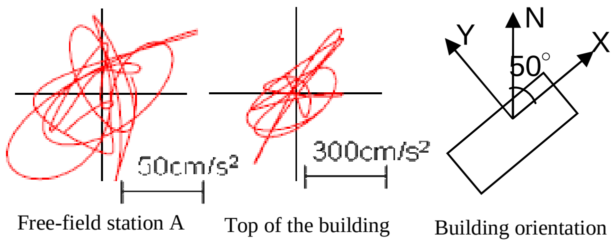

Figure 7. Horizontal particle orbits of acceleration at the top of the building and reference station on March 11 2011.

3. STRONG MOTION IN THE WESTERN PART OF TOKYO ON MARCH 11 2011

3.1. Response Spectra

Figure 8 shows a location of K-NET stations deployed in the western part of Tokyo (Kyoshi Network K-NET) with a location of the building (referred as “Meisei BLDG.”). Station TKY04 is located about 2km to the south of the building. Apart from the free-field station adjacent to the building (as referred as “station A” in Figure 7) another free-field record was observed in the vicinity of the building on March 11 2011. The station is to be referred as “Station B”.

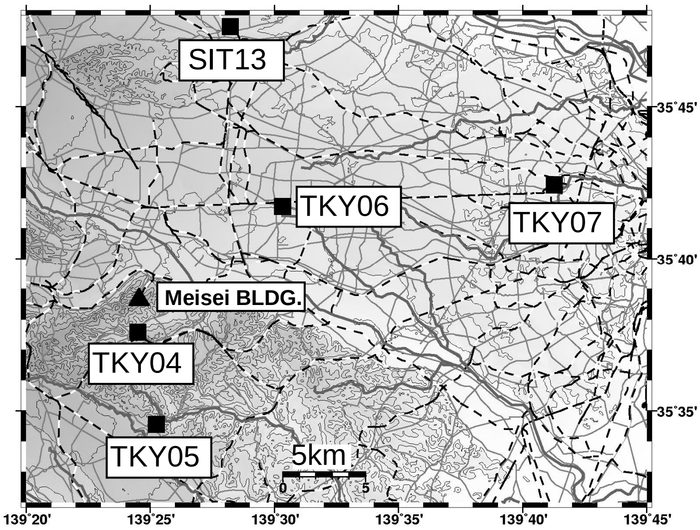

Figure 8. Location of K-NET stations deployed in the western part of Tokyo.

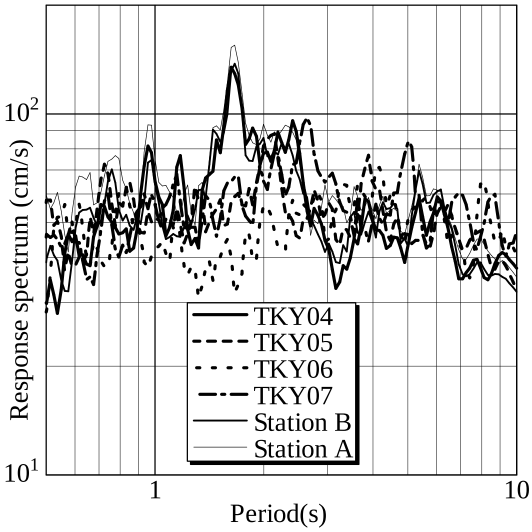

Figure 9. Velocity response spectra of free-field stations in the western part of Tokyo.

Figure 9 shows 2%-damped velocity response spectra of K-NET stations in the western part of Tokyo and stations A and B. Each spectrum is obtained from the resultant of NS and EW spectra. It is evident that TKY04, stations A and B have marked peaks at 1.6 sec.

3.2. Polarity

Figure 10 shows horizontal particle orbit of acceleration of stations TKY04, TKY05, TKY06 and TKY07. The acceleration is low-pass filtered at 1.0 Hz. TKY04 has a marked polarity of NE-SW direction from 100 to 130 sec as was seen in station A's horizontal particle orbit in Figure 7. TKY05 has the similar polarity from 110 to 120 sec but TKY06 and TKY07 don't.

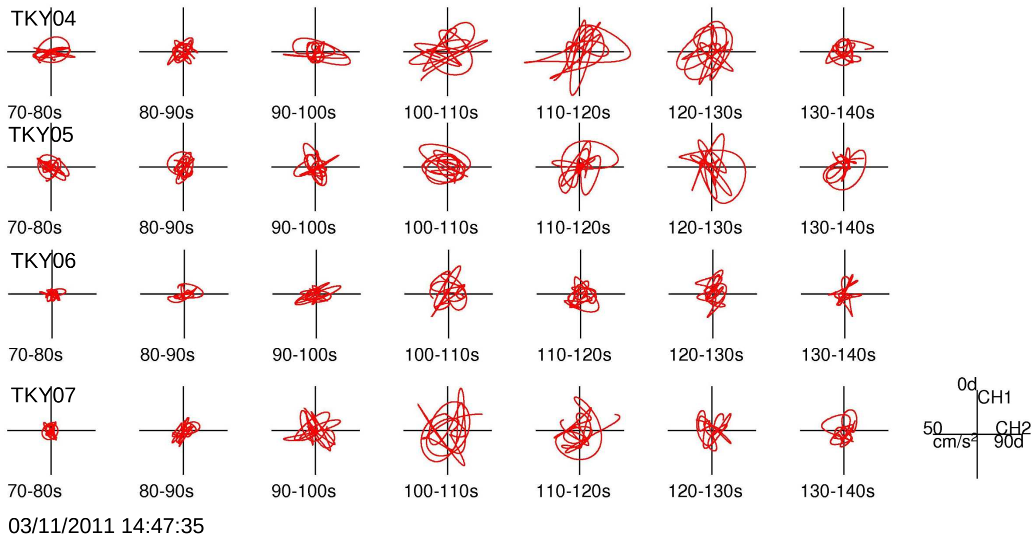

Figure 10. Horizontal particle orbit of acceleration of K-NET stations.

3.3. Area in Which 1.6-s Strong Motion Generated

Figures 9 and 10 demonstrated that mid-period (1.6 sec) ground motion with a polarity of NE-SW direction was locally generated in the vicinity of Meisei BLDG. and TKY04. This period seems to be long if shallow subsurface soil structure resonated ground motion while it seems to be short and local if the ground motion is due to surface waves propagated throughout Kanto Plain.

4. EVENTS WHICH GENERATED 1.6-S STRONG MOTION IN THE AREA

In order to investigate the generation cause of the mid-period ground motion, response spectra of 74 seismograms observed at TKY04 during large magnitude events (over M_j 6.0) from 1996 to mid-September 2011 are obtained. Figure 11 shows 2%-damped velocity response spectra which have 1.6-sec marked peak (Each spectrum is obtained from the resultant of NS and EW spectra as was made in Figure 9). Open circles in Figure 12 are the epicentres of the events which generated 1.6-s strong motion while seismic parameters of which are tabulated in Table 4.1. In Figure 12, open triangles are the events which generated marked peaks in the period range 1 to 2 sec but not exactly at 1.6 sec while crosses are the events which did not cause mid-period ground motion at TKY04 (The solid square in the figure is the location of TKY04). Apart from the Off-Noto Peninsula earthquake of March 25 2007, the epicentres of the events which generated 1.6-sec ground motion at TKY04 are located in East off Miyagi Prefecture and East off Fukushima Prefecture region.

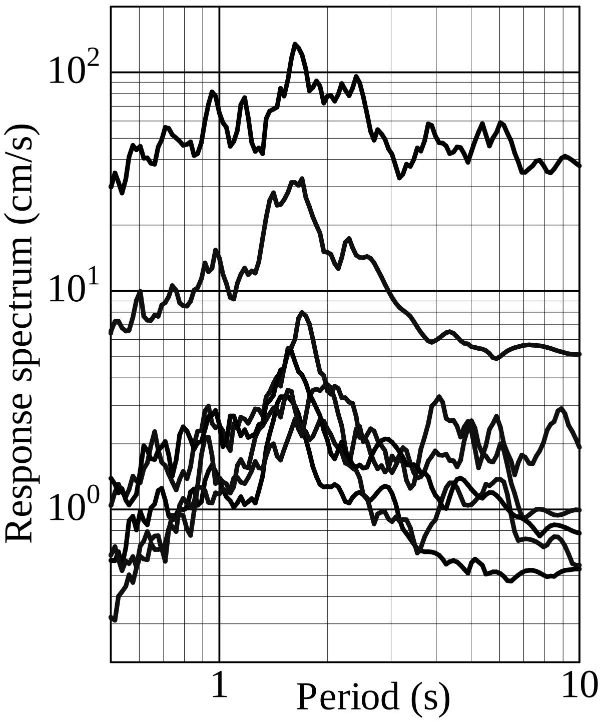

Figure 11. Velocity response spectra which have 1.6-sec marked peak.

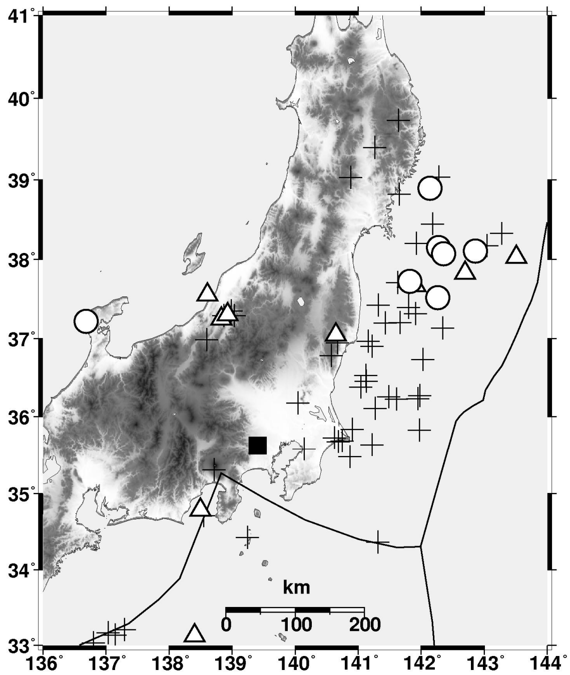

Figure 12. Epicenters which generated 1.6-sec ground motion at TKY04.

Table 4.1. Seismic Parameters for Events Generated Mid-period Strong Motion in the Area.

Date(mm/dd/yy)	Origin Time(GMT)	M_j	Depth(km)	Hypocentral Region
11/03/2002	3:37	6.3	46	Kinkazan Region
08/16/2005	2:46	7.2	42	East off Miyagi Prefecture
12/02/2005	13:13	6.6	40	East off Miyagi Prefecture
03/25/2007	00:41	6.9	11	Off Noto Peninsula
07/19/2008	02:39	6.9	32	East off Fukushima Prefecture
03/14/2010	8:08	6.7	40	East off Fukushima Prefecture
03/11/2011	05:46	9.0	24	Far East off Miyagi Prefecture

Figure 13 shows horizontal particle orbits of displacement at TKY04 for the events which caused 1.6-sec ground motion. The displacement is band-pass filtered at 1.6 sec. It can be seen that the polarity of the mid-period ground motion is among NE-SW to ESE-WNW.

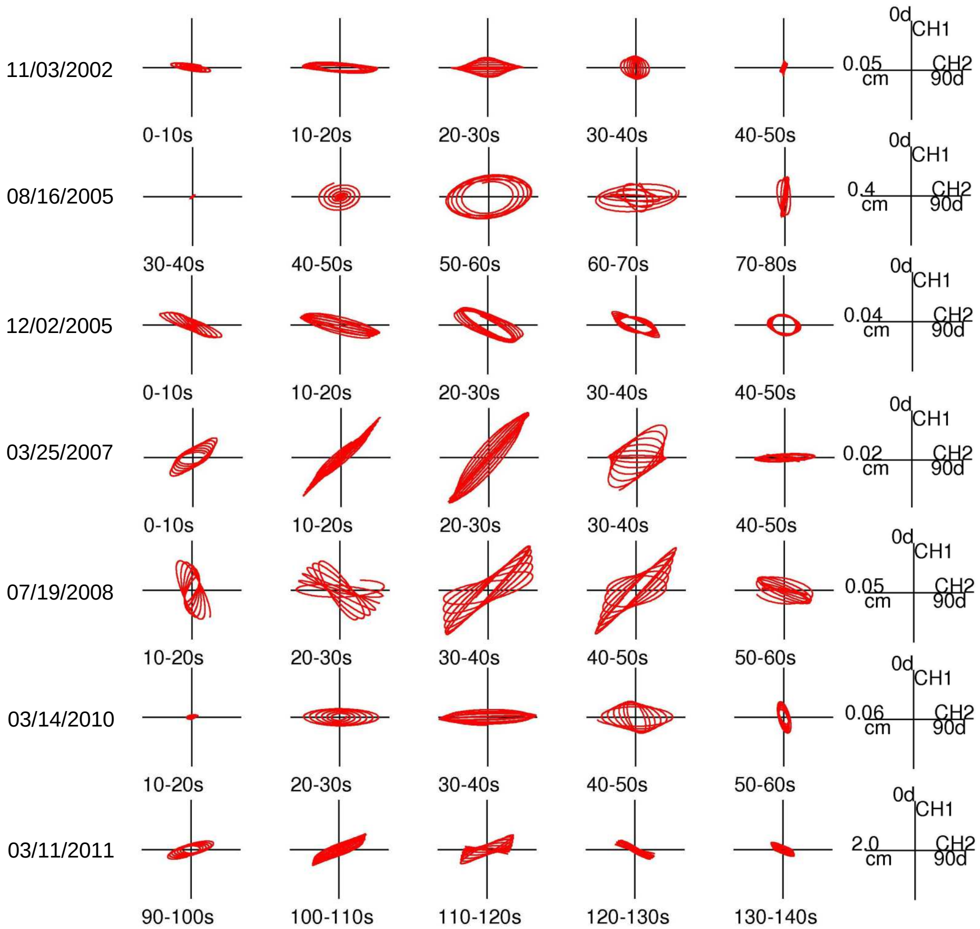

Figure 13. Horizontal particle orbits of displacement at TKY04 for the events in which 1.6-sec ground motion was generated.

5. FACTORS OF 1.6-S STRONG MOTION CAUSED IN THE AREA

5.1. Underground Structure and Natural Period of Ground

In this chapter the author investigates how 1.6-s ground motion was locally generated in this particular area on the view point of mid-period ground motion locally generated in the western part of Tokyo.

In Kanto Plain deep underground structure up to seismic bedrock has been evaluated by using explosion test and microtremor array observation (e.g., Seo and Kobayashi, 1980; Yamanaka and Yamada, 2002). Yamanaka and Yamada (2006) compiled those results and made contour maps of the depths to the top of layers having 3.0-, 1.5- and 1.0- km/s S-wave velocity layers and distribution of S-wave velocity of the top layer. From the contour map deep underground structure is obtained as tabulated in Table 5.1. Note that the 1.5-km/s S-wave velocity layer is omitted herein as this layer is supposed to be very thin around this area.

Table 5.1. Deep Underground Structure in the TKY04 Area.

Layer	S-wave Velocity(km/s)	Mass Density(t/m^3)	Thickness(km)	Depth(km)
1	0.8	1.9	0.2	0.2
2	1.0	2.2	0.3	0.5
3	3.0	2.5	-	-

From this structure amplification factor of SH wave is obtained as shown in Figure 14. The figure demonstrates that this structure has 2-sec fundamental period. The period is slightly longer but close to 1.6 sec, the ground motion of which has sometimes been observed in the area.

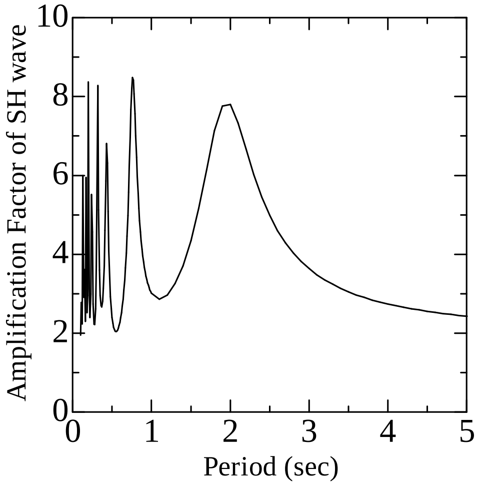

Figure 14. Amplification factor of SH waves obtained from deep underground structure as tabulated in Table 5.1.

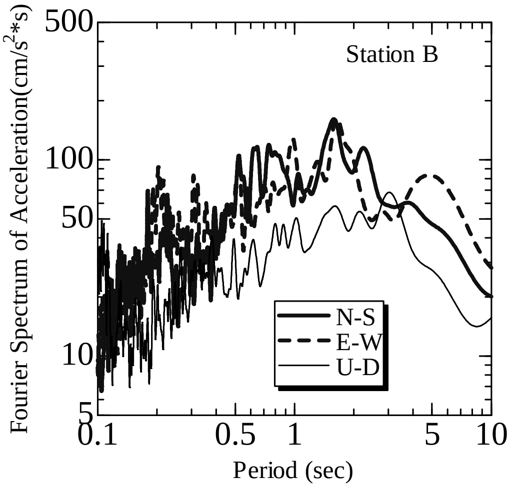

Figure 15. Fourier spectrum of acceleration in three components at Station B on March 11 2011.

5.2. Wave Propagation Characteristics

Figure 14 showed that the 1.6-sec ground motion observed in the area is due to deep underground structure in the area. However, this mid-period ground motion was only observed during the large events, the hypocentral regions of which are Noto Peninsula, East off Miyagi Prefecture and East off Fukushima Prefecture regions. Then the mid-period ground motion might be due to surface wave, generated at the western edge of Kanto Plain, propagated into the basin, amplified by the deep underground structure around the area during large events with limited hypocentral regions.

Figure 15 shows Fourier spectrum of acceleration in three components at Station B during the event on March 11 2011. No significant vertical amplification is found at 1.6 sec indicating that Love wave was propagated around the area if the 1.6-sec ground motion was due to surface waves.

Figure 15 shows coherence and phase between Stations A and B for the NS component during the event on March 11 2011 (Station B is the reference). Coherence is high enough in the period range longer than 1.5 sec indicating that the mid-period ground motion observed at the two stations is coherent enough. As for the phase, the value approaches zero showing that the seismograms are successfully synchronized; marked peak is found around 1.6 sec showing that the stations have a significant phase difference due to horizontal wave propagation.

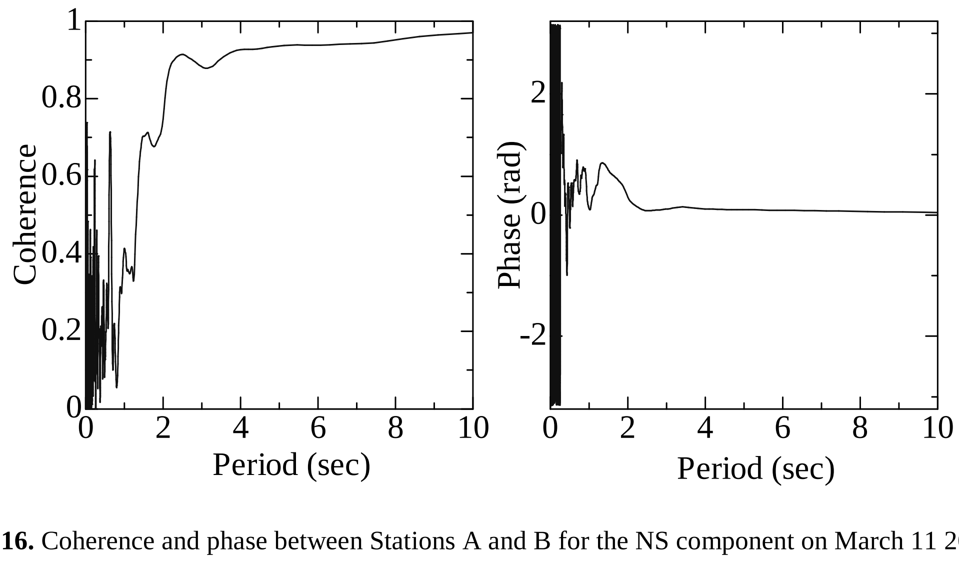

Figure 16. Coherence and phase between Stations A and B for the NS component on March 11 2011.

Figure 17 shows horizontal particle orbits in displacement of Stations A and B during the event on March 11 2011. Time in the figure originates at 14:47:35 on 03/11/2011. During 100-120 sec, which is principal motion of this event, polarities of the motion are N40˚E (Station B) and N35˚E (Station A).

When Love wave propagation is assumed in this event, the propagation direction is perpendicular to the polarity. Figure 18 shows location of Stations A and B and Meisei BLDG. Propagation distance can be estimated to be 290m if the polarity of Love wave is N35˚E.

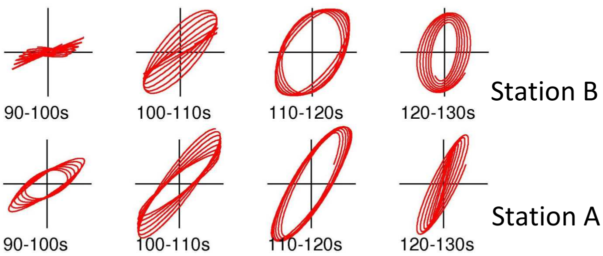

Figure 17. Horizontal particle orbits in displacement of Stations A and B on March 11 2011 band-pass filtered at 1.6 sec.

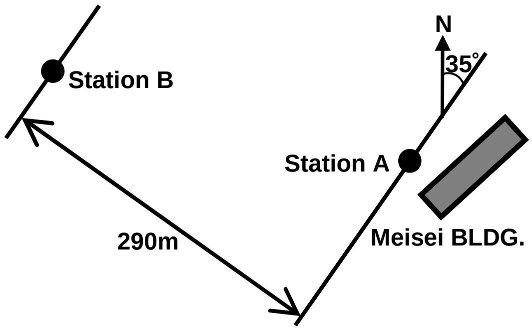

Figure 18. Location of Stations A and B and Meisei BLDG.

Figure 19 shows displacement and envelope time histories of Stations A and B during the event on March 11 2011 in N35˚E, band-pass filtered at 1.6 sec. It can be seen that wave group arrived earlier at Station B rather than Station B indicating that the wave group was propagated from northwest where Kanto Plain is bounded by the western mountains. Time difference between the envelope peaks is approximately 1.7 sec. Thus group wave velocity can be estimated to be 170 m/s. Figure 20 shows a plot of the estimated group velocity against period. Solid line is theoretical group velocity of 1st-mode Love wave obtained from the structure tabulated in Table 5.1. The estimated group velocity is much slower than the theoretical one. One of the reasons for the discrepancy is that the 1.6-sec ground motion was affected by other underground structure where the wave group was propagated.

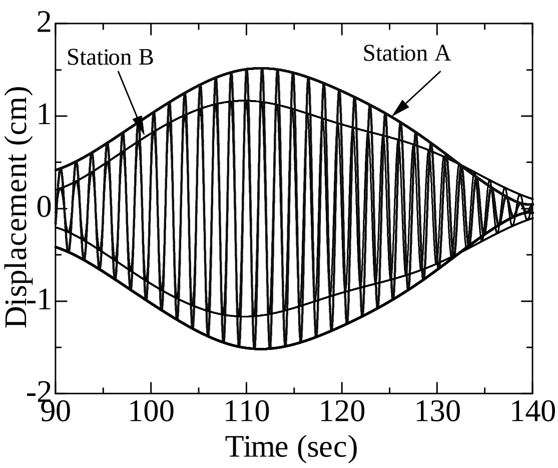

Figure 19. 1.6-sec band-pass filtered displacement and envelope time histories in N35˚E of Stations A and B on March 11 2011.

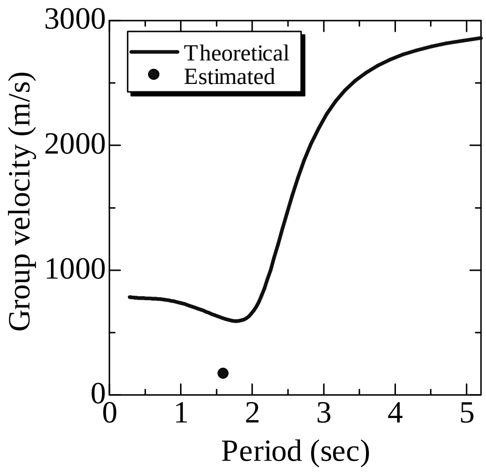

Figure 20. Group velocity plotted against period. Solid line: Theoretical for the 1st-mode Love wave. Solid circle: Estimated.

6. CONCLUSIONS

The author made an investigation and discussion relating mid-period ground motion observed in the western part of Tokyo during the 2011 Tohoku-Pacific Ocean earthquake on March 11 2011. Followings are findings obtained herein:

1. The polarity of 1.6-sec ground motion observed during the 2011 Tohoku-Pacific Ocean earthquake was the NE-SW direction, which accords with the longitudinal direction of a 17-story building of Meisei University, and resonated the response of the building in the longitudinal direction. The 1.6-sec ground motion was locally observed in the vicinity of the building during the event.
2. Apart from the 2011 Tohoku-Pacific Ocean earthquake, the 1.6-sec ground motion has been observed during large events occurred in East off Miyagi Prefecture, East off Fukushima Prefecture and Off-Noto Peninsula regions.
3. The 1.6-sec ground motion is supposed to be due to Love wave generated at the western edge of Kanto Plain, propagated into the basin, amplified by the deep underground structure.

AKCNOWLEDGEMENT
The author wishes to thank to Dr. Kenichi Kato (Kobori Research Complex Inc.), Prof. Kazuki Kohketsu and Mr. Minoru Sakaue (Earthquake Research Institute, University of Tokyo) for their support in the earthquake observation. Seismograms at stations TKY04, 05, 06 and 07 were obtained from K-NET.

REFERENCES

Kajima Design (2004), Structural Design of the School of Science and Engineering Building, Meisei University (in Japanese).
Kyoshi Network K-NET. http://www.k-net.bosai.go.jp
Seo, K. and Kobayashi, H. (1980). On the Seismic Prospectings in the Southwestern Part of the Tokyo Metropolitan Area. *Journal of the Seismological Society of Japan*. **Vol 33:** 23-36 (in Japanese with English abstract).
Takeyama, K. (2011). Vibration Characteristics of the 29th Building in Meisei University Based on Seismic Observation. *Graduation Thesis of Meisei University.* (in Japanese).
Yamanaka, H. and Yamada, N. (2002). Estimation of 3D S-wave Velocity Model of Deep Sedimentary Layers in Kanto Plain, Japan, using Microtremor Array Measurements. *BUTSURI-TANSA.* **Vol 55:** 53-65 (in Japanese with English abstract).
Yamanaka, H. and Yamada, N. (2006). Modeling 3D S-wave velocity structure of Kanto Plain for estimation of earthquake ground motion. *BUTSURI-TANSA.* **Vol 59:** 549-560 (in Japanese with English abstract).