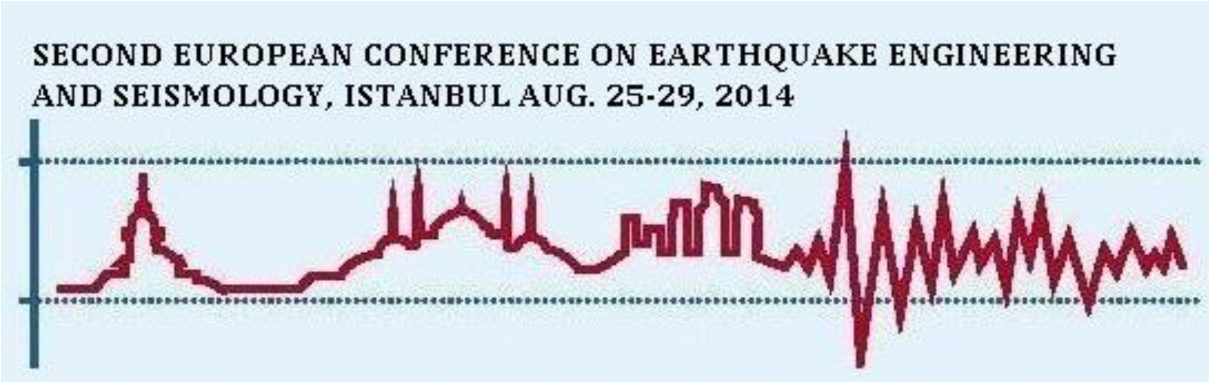

DAMAGE SURVEY AND OBSERVED DATA ANALYSIS OF LONG RC BUILDING WITH IRREGULAR PILE SUPPORTING STRATUM AFTER THE 2011 TOHOKU EARTHQUAKE

Kazuya MITSUJI[1], Susumu OHNO[2] and Masato MOTOSAKA[3]

ABSTRACT

Damage of the long building with irregular pile supporting stratum is surveyed after the 2011 Tohoku earthquake. Results from microtremor measurements and earthquake observation are discussed in related to damage survey. Natural frequencies of the building are estimated for base-fixed model and dynamic soil-structure interaction model based on the results from microtremor measurements. Motion of foundations in TR(NS) direction is coupled with UD direction because of the irregularity of pile supporting stratum. Predominant frequency of reclaimed soft subsurface layer is estimated 2.5Hz based on the results from the analysis of earthquake observation records. Shea wave velocity of the subsurface layer is also estimated 180 to 240m/s indicating good accordance with damage survey.

INTRODUCTION

After the 2011 Tohoku earthquake, a lot of buildings were found to have been damaged by strong shaking of main shock (AIJ, 2012). In the eastern area of the city of Sendai consisting of alluvial plain, some buildings were damaged due to large acceleration amplified by soft subsurface layers. As one of the damage surveys of damaged buildings, dynamic characteristics of long RC building supported by pile foundations are investigated using microtremor measurements and aftershock observation records in this paper.

Dynamic characteristics of long structure are complicated because input motions are different dependent on the foundations. Each frame has its own dynamic characteristics in longitudinal direction of long building, so torional motion tends to appear in resonance curve of superstructure, and sometimes causes heavy damage to structure. This effect is crucial to seismic design of long building.

One of the important characteristics of this building is the fact that pile lengths are different on each foundation. It is estimated that pile supporting stratum is inclined from south to north according to the design documents and fill and cut distribution map of this area. Thickness of subsurface soft layer on north side of the building is larger than on south side. Amplification characteristics of ground will be quite different on north and south side of the building. Those are considered to be related to damage of the building.

In this paper, damage survey of the long building with irregular pile supporting stratum is reported. Results of data analysis of microtremor measurements and earthquake observation records after damage survey are discussed to understand the dynamic characteristics of long building with irregular pile supporting stratum. Finally, the estimated dynamic characteristics of the building are

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compared to the extent of damage, and causes of the damage of the building are quantitatively studied based on the observed records.

OUTLINE OF THE BUILDING

In this paper, causes of the building damaged by the 2011 Tohoku earthquake are discussed where its structural and geotechnical characteristics are focused. Location of the building is shown in Figure 1 and 2. The building exists in the eastern part of Sendai city where are about 300km north from Tokyo and 120km west from the epicentre of the 2011 Tohoku earthquake (Figure 1). Eastern part of Sendai city widely consists of soft alluvial plain. Hill area in the vicinity of the centre of Sendai had been developed for extension of residential area after 1960's. Subsurface layer of fill area is reclaimed by soft soil on undulating rigid Tertiary formation. Therefore geological conditions of man-made residential area are complicated by distribution of fill and cut area.

The building was constructed in those man-made residential area about 5km north-east from the centre of Sendai in 1971. Building site and neighbouring fill area distribution are shown in Figure 2. The building studied in this paper is called "building A" in Figure 2. Building A is five-storey RC frame structure and constructed in 1971 that was also suffered from the 1978 Miyagi earthquake. Plan of the building is long rectangular shape of 103m in longitudinal and 9m in transverse direction. Photo 1 shows the panoramic view of building A. Vicinity of the site is reclaimed area by banking, and the building exits at around the edge of fill area. Blue covered area in Figure 2 indicates fill area reclaimed by development of residential site (Fukken Gijutsu Consultant, 2008). According to the design documents, piles in north frames are longer than south frames. Difference of pile length between north and south is about 10m at most. Schematic figure of section of building A including pile foundations and ground is shown in Figure 3. Seismic behaviour of the building is considered to have been affected by subsurface layer of fill area with the irregularity of pile supporting stratum.

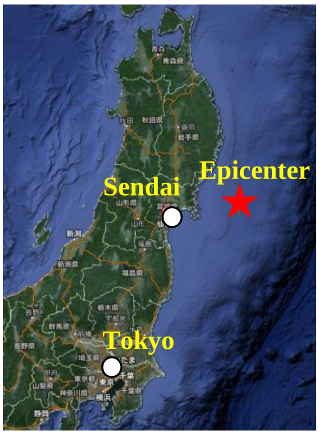


Figure 1. Location of Sendai

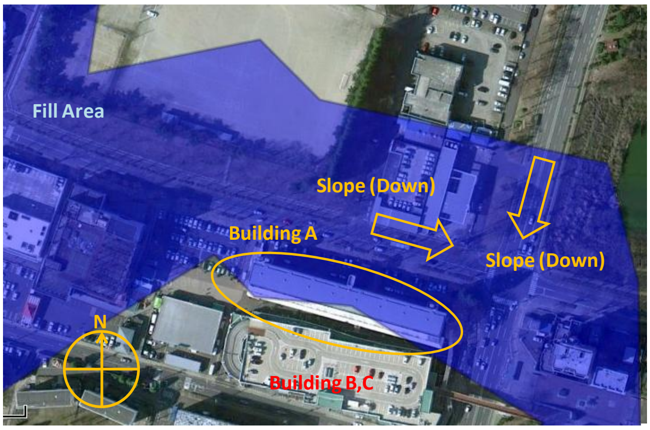


Figure 2. Building site and fill area distribution

Photo 1.Panoramic view of building A

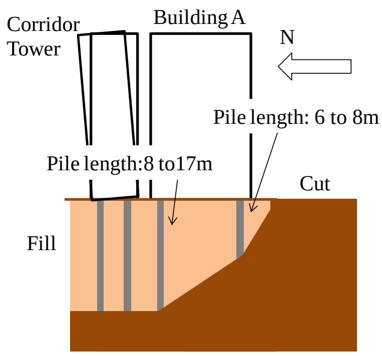


Figure 3. Schematic section of building A

DAMAGE SURVEY AFTER THE 2011 TOHOKU EARTHQUAKE

The authors conducted damage survey of building A after the 2011 Tohoku earthquake. Outline of the damage of building A is shown in Figure 4. The building A has three staircase towers. One of the most specific characteristics of the damage is the leaning staircase tower due to damage at the foot of the tower. All of the three towers indicated the leaning to the north. Bending failure at the foot of the tower was observed in the first and second towers. Severe damage at the pile head may have been occurred in the third tower, because minor and intermediate cracks were observed, but any significant failure couldn't be found at the foot of the third tower. On the other hand, superstructure didn't show any significant structural damage, but large shear cracks on non-structural walls of a lot of housing units and large bending cracks at the centre of girder at the east edge of the building were observed.

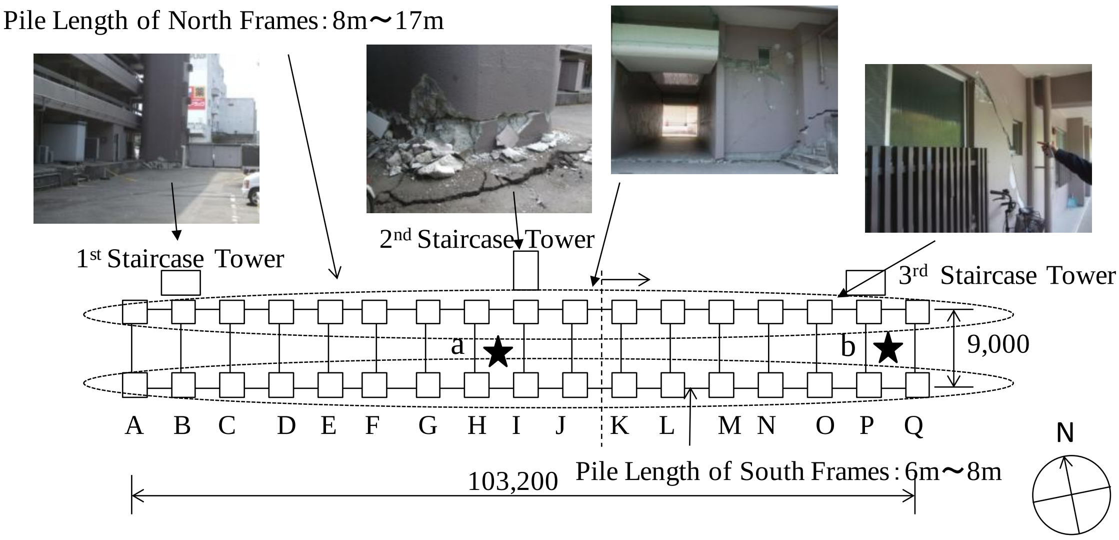


Figure 4. Damage distribution of building A after 2011 Tohoku earthquake

Specific severe damages of building A caused by the strong shaking of the 2011 Tohoku earthquake are shown in Photo 2 to 5. Photo 2 is damage at the foot of the 1st staircase tower. Three staircase towers have rectangular plan and the 1st and 3rd tower have those strong axes in NS direction, while the 2nd tower has its strong axis in EW direction as shown in Figure 4. Bending failure at the foot of tower shown as Photo 2 was observed in all the towers. One of the characteristics of building A is difference of the height of the first floor. The height of the first floor on the west from frame "J" is 3360mm, and that on the east from frame "K" is 3950mm. Difference of the height may have caused shear cracks on the wall of the first floor around frame "J" and "K" as shown in Photo 3.

Photo 2. Damage at the foot of staircase tower

Photo 3. Damage caused by the different height of the first storey

Bending crack on the girder of the second floor was observed at around frame "O" as shown in Photo 4. Damage is severer at the east side of the building than west, and the corridor of the east side at the second floor was temporarily reinforced by steel plate as shown in Photo 5.

Photo 4. Crack of the girder of the second floor

Photo 5. Temporary reinforcement of the east edge of corridor of the second floor

MICROTREMOR MEASURMENTS

Microtremor measurements were carried out after the earthquake to estimate dynamic characteristics of the building. The effects of long structure, dynamic soil-structure interaction, and irregularity of pile supporting stratum are discussed.

Results of microtremor measurements are mainly estimated by spectral amplitude ratios between two observation points. Sampling frequency is 100Hz and duration of measurement is 10 minutes. Small time window of 40.96 seconds is applied to the entire duration of observed records and moving from the beginning to the end by step of which width is equal to the half of the window (20.48 seconds). Transfer functions are derived for every small section divided by the window of 40.96 seconds and the results are averaged all through the duration.

Estimated natural frequencies of structural frames from C to O and 3rd staircase tower based on microtremor measurements are summarized in Table 1. Transverse direction (TR) of the building is NS direction, and supposed to be strongly affected by the irregularity of pile supporting stratum. Amplitude ratios of superstructure of building A derived from transfer functions are shown in Figure 5. Natural frequencies are fluctuating dependent on the frames, but they can be estimated about 3.5Hz for fixed-base system (5F/1F) in TR (NS) direction. On the other hand, natural frequencies for dynamic soil-structure system (5F/FF) can be estimated about 3.2 to 3.3Hz in TR (NS) direction. The effect of soil-structure interaction is estimated about 10% in TR (NS) direction. Amplitude ratios of LN (EW) direction have peaks at around 3.0Hz for fixed-base system (5F/1F), and 2.9Hz for dynamic soil-structure system (5F/FF). Results of LN (EW) direction are more stable than TR (NS) direction.

Amplitude ratios of the 3rd staircase tower are shown in Figure 6. Natural frequencies are estimated 2.8Hz in TR (NS), 3.9 in LN (EW) direction for fixed-base system (5F/1F), and 2.6Hz in TR (NS) and 3.7Hz in LN (EW) direction for dynamic soil-structure system (5F/FF).

While amplitude ratio curves of superstructure have multiple peaks indicating torsional motion and higher modes as shown in Figure 5, amplitude ratio curve of staircase tower has one distinctive peak indicating the bending type first mode. Natural frequency in TR (NS) direction is lower than LN (EW) direction. This is the effect of the rectangle plan with strong axis in NS and weak axis in EW direction. Small peak is observed indicating torsional motion in TR (NS) direction right after the first mode close to the natural frequency of LN (EW) direction. It is also interesting that UD direction has spectral peak at almost the same as TR (NS) direction. This is because the tower has been inclined by damage of the earthquake; therefore spectral peak of UD direction indicates coupling effect to TR (NS) direction by the leaning.

Table 1. Estimated natural frequencies of each frame of building A and 3rd staircase tower

(Pile lengths of north frames are described in parentheses)

	5F/1F (Hz)		5F/FF (Hz)	
	TR(NS)	LN(EW)	TR(NS)	LN(EW)
C(16m)	3.69	3.00	3.27	2.91
G(10m)	3.56	3.08	3.25	2.91
I (8m)	3.44	3.05	3.22	2.91
K(10m)	3.27	3.00	3.22	2.88
O(12m)	3.86	3.05	3.56	2.91
3rd tower (18m)	2.78	3.91	2.64	3.69

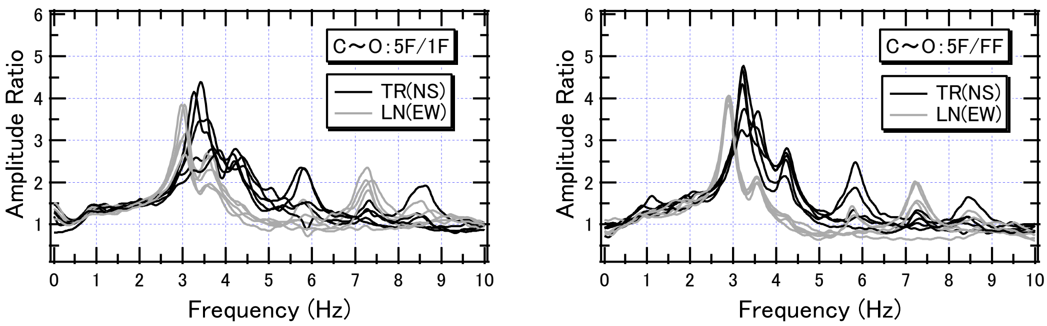


Figure 5. Amplitude ratios of frames (from C to O) based on microtremor measurements

(Left: fixed-base system (5F/1F), Right: dynamic soil-structure interaction system (5F/FF))

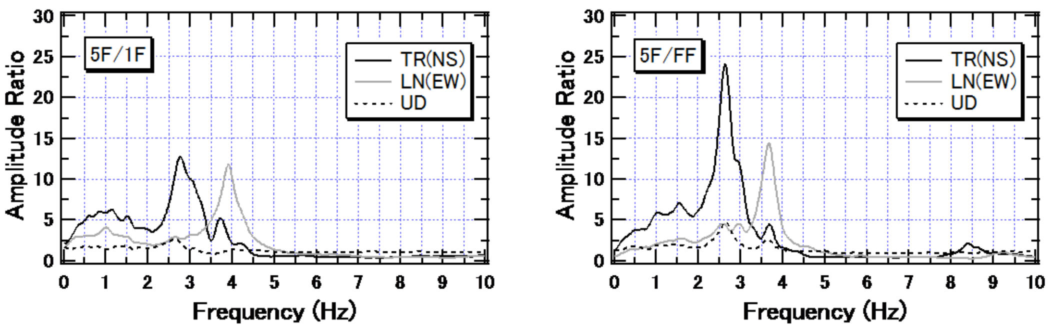


Figure 6. Amplitude ratios of the 3rd staircase tower based on microtremor measurements

(Left: fixed-base system (5F/1F), Right: dynamic soil-structure interaction system (5F/FF))

The effects of long structure and the irregularity of pile supporting stratum to dynamic characteristics of superstructure are discussed by comparison of amplitude ratios between foundations. Spectral amplitude ratios between foundations of frame C and H, and M and H are described in Figure 7. Position of each frame is described in Figure 4. Results between foundations of C and H are related to dynamic characteristics of west edge to centre of the building, and results between foundations of M and H are those of east edge to centre of the building. Spectral peaks at 3.5Hz can be found in TR (NS) and UD direction in the results of C and H, and M and H. This frequency is almost the same as natural frequency of superstructure (base-fixed system). Namely, motion of foundation is amplified in TR (NS) direction and coupled with motion in UD direction at around the first natural frequency of superstructure. The irregularity of pile supporting stratum and difference of pile length can be considered to give the significant effect to the coupling effect.

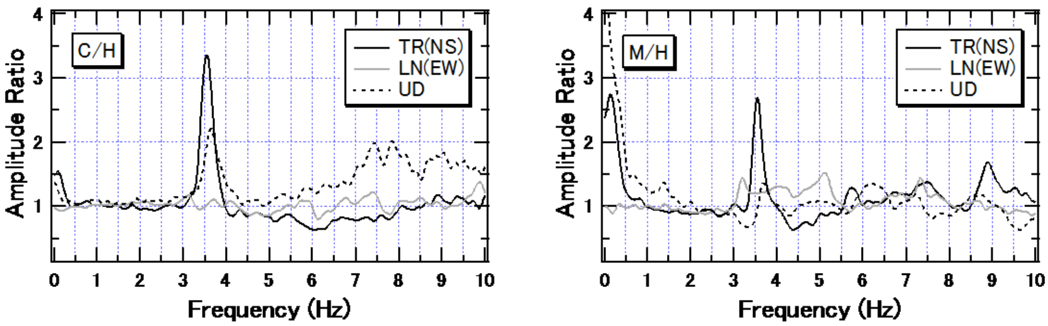


Figure 7. Amplitude ratios between foundations based on microtremor measurements

(Left: amplitude of west to centre, Right: amplitude of east to centre)

EARTHQUAKE OBSERVATION

Earthquake observation at the first floor of building A was conducted for about one year since October 2012 to collect aftershock records. Two sets of seismometers were installed at the centre and east part of the building to compare the difference of response characteristics of the centre and east part of the long building. Positions of seismometers are illustrated in Figure 4 where “a” is the seismometer for centre, and “b” is the seismometer for east of the building. Earthquake observation records of other two sites are available. One is the site of “TRG” that is governed by IRIDeS (International Research Institute of Disaster Science) of Tohoku University, the other is “MYG013” (K-NET Miyagi) that is one of the observation sites of strong motion seismograph network of NIED, Japan. The site of TRG is about 500m west, and MYG013 is about 3km south-southeast from the site of building A. Soil conditions of the site are considered relatively rigid rock site for TRG, and alluvial soft plain of which depth is about 20m for MYG013. Soil conditions of TRG are estimated by the cut and fill area distribution information. MYG013 soil condition is referred to the web site of K-NET (NIED, 2014).

Details of observed earthquakes at the two positions of building A are summarized in Table 2. Number of earthquakes observed at both seismometers of “a” and “b” are 11 from April to October, 2013. Although many of the observed earthquakes are small of which maximum accelerations are about 10 to 20 gal, maximum accelerations are 81.5 gal in TR (NS), 84.8 gal in LN (EW), and 32.5 gal in UD direction. Epicentre distribution is shown in Figure 8. Earthquakes from Miyagi, Fukushima, Sanriku offshore dominate in the list, and one is outer-rise type occurred from east of the Japan Deep.

Seismometers are installed in accordance with the directions of building. Therefore, TR direction rotates from NS direction about 15 degrees for building A, and 35 degrees for TRG from NS to EW. Compensation on difference of the direction was not conducted in the observed records analysis.

Maximum acceleration distributions in horizontal direction (NS-EW) are shown in Figure 9. Distributions are summarized for each observation site. Maximum accelerations of TRG and MYG013 don’t indicate specific distributions dependent on the direction. Maximum accelerations of EW direction are larger than NS direction in case of large amplitude. On the other hand, maximum accelerations of building A indicate the trend that NS direction is larger than EW direction, although there are a few exceptions in large amplitude. This is considered the effect of the irregularity of pile supporting stratum. As shown in Figure 3, soil condition is rigid bedrock (cut area) on the south of the building, and pile supporting stratum is deeper in north due to reclaimed soft soil layer. The effect of the irregular ground appears on maximum acceleration distributions of building A. In the figure of (a) of Figure 9, maximum accelerations of centre (“a”) and east (“b”) of the building are compared. Maximum accelerations of east part (“b”) tend to be larger by about 10% than centre (“a”) of the building together with the information in Table 2.

Table 2. Details of observed earthquakes

No.		Date		M	Depth (km)	Epc. Dist. (km)	Location of Source	SI	Max. acc.(gal)		
									NS(TR)	EW(LN)	UD
1	a	4/17	21:03	5.9	58	64	N38.46, E141.62	3.4	32.3	71.6	27.8
	b							3.4	46.8	84.8	23.3
2	a	7/20	1:39	5.4	45	102	N37.51, E141.57	1.9	13.2	7.2	9.5
	b							1.8	13.5	8.2	9.4
3	a	7/22	18:45	4.1	52	67	N38.33, E141.69	1.4	12.3	7.4	3.6
	b							1.3	11.4	8.5	3.5
4	a	7/31	9:14	5.0	18	104	N38.09, E142.09	1.7	10.0	4.5	3.8
	b							1.6	8.2	4.3	3.4
5	a	8/4	12:29	6.0	58	77	N38.16, E141.8	3.7	70.0	56.7	31.5
	b							3.6	81.5	46.7	32.5
6	a	8/25	18:18	4.1	55	60	N38.31, E141.61	1.4	9.6	7.8	3.1
	b							1.3	7.4	8.8	3.5
7	a	9/4	9:19	6.8	445	934	N29.93, E139.42	2.1	6.2	7.2	2.5
	b							2.1	7.2	5.7	2.7
8	a	9/20	2:25	5.9	17	137	N37.05, E140.69	2.2	22.1	10.0	4.9
	b							2.3	24.0	11.0	6.1
9	a	10/20	0:14	5.1	51	68	N38.17, E141.7	2.2	14.2	10.6	7.0
	b							2.1	12.8	9.5	6.7
10	a	10/22	10:18	5.3	26	106	N37.73, E141.92	1.6	8.0	6.6	3.8
	b							1.6	10.6	6.3	3.4
11	a	10/26	2:10	7.1	56	342	N37.2, E144.57	2.9	23.9	21.5	15.7
	b							2.9	26.7	20.7	12.1

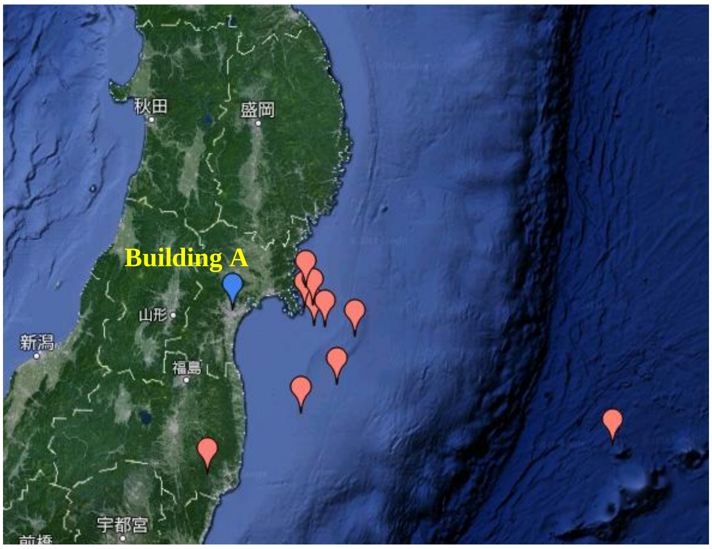
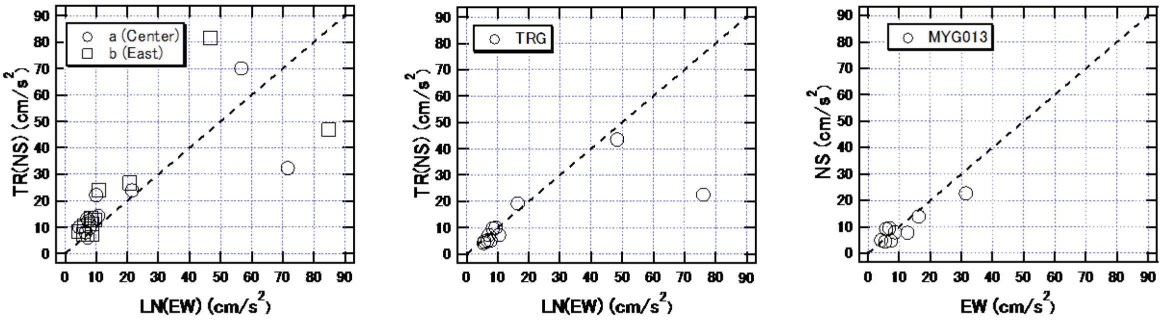


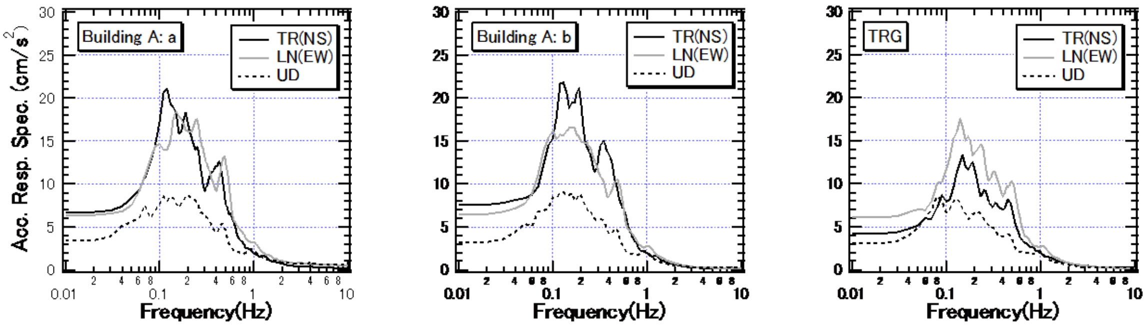
Figure 8. Epicentre distribution of observed earthquakes

Average response spectra of observed earthquakes of “a” and “b” of building A, and TRG are shown in Figure 10. Results are expressed the average of response spectra for each earthquakes. Comparison of amplitude characteristics between building A and TRG are focused. Spectral peak in TR (NS) direction appear around 0.1 to 0.2 (s) for centre (“a”) and east (“b”) of the building. Peak of LN (EW) direction slightly shifts to longer range of period in the result of centre (“a”). Small peak can also be found at around 0.4 to 0.5 (s) in both horizontal directions. It is interesting that average response spectrum of TRG in LN (EW) direction is larger than TR (NS) direction. This result meets good agreements with the maximum acceleration distributions in Figure 9. This is because of the effect of the irregularity of pile supporting stratum. It should be also noted that amplitude of response spectra of building A are larger than those of TRG. The effects of reclaimed soft soil layer of the site of building A appear in the results.



(a) Building A (b) TRG (c)MYG013 (K-NET Sendai)

Figure 9. Maximum acceleration distributions in horizontal directions

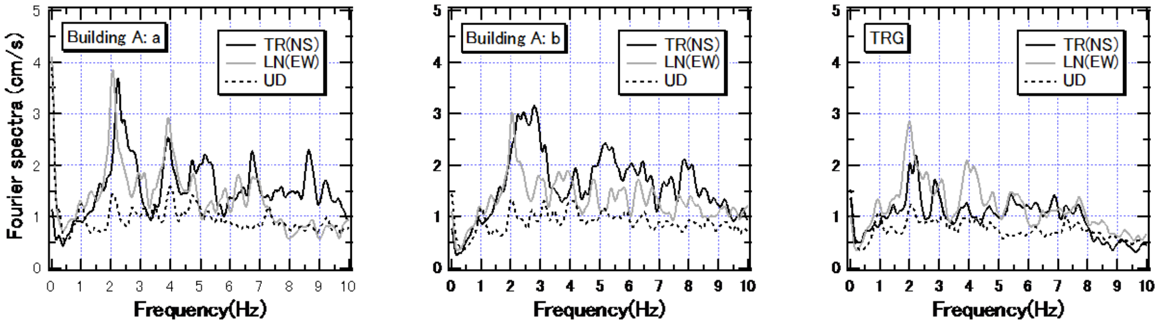


(a)Building A (b) TRG (c)MYG013 (K-NET Sendai)

Figure 10. Average response spectra of observed earthquakes

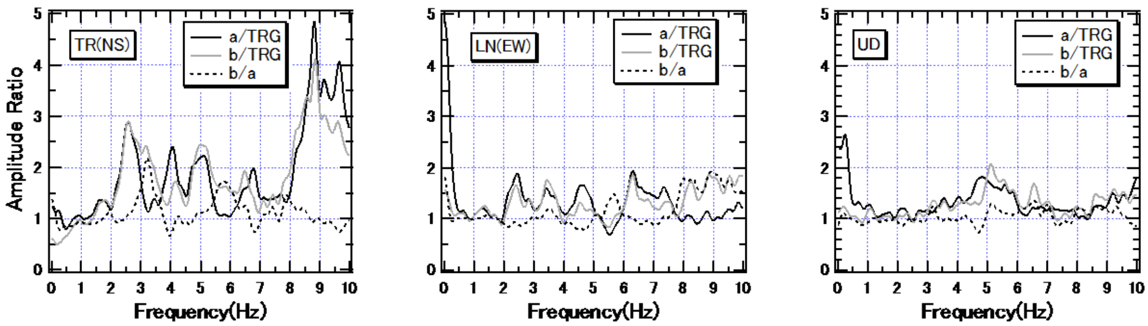
Average Fourier spectra are shown in Figure 11. First spectral peaks are observed around 2Hz in both centre (“a”) and east (“b”) of building A that are considered to be the characteristics of one-dimensional wave propagation in reclaimed soft soil layer. Some small peaks are also found at about 4Hz, 5Hz and higher frequencies that are the effect of the irregularity of pile supporting stratum. However, distinctive peak at about 2Hz is also observed in the average Fourier spectra of TRG that are supposed to rigid bedrock site. The reason will be studied furthermore in the near future.

Relative relations between observation sites are discussed by the results of Figure 12 where average amplitude ratios between centre (“a”), east (“b”) of the building and TRG are compared in the three directions. Amplitude ratios of a/TRG and b/TRG indicate the clear peaks at about 2.5Hz in both TR (NS) and LN (EW) direction. Peaks of TR (NS) direction are more outstanding. This result leads to the assumption that one-dimensional dynamic characteristics of reclaimed soft soil layer of the site of building A can be considered 2.5Hz in horizontal directions. Some small peaks appear in 4Hz, 5Hz and higher frequencies that are considered the effect of the irregularity of pile supporting stratum. The effect is more remarkable in TR (NS) direction. Those results are in accordance with the results of average Fourier spectra of Figure 11. Specific spectral peak cannot be observed in UD direction while motion of foundation of UD direction is relevant to that of TR (NS) direction in the results of mocrotremor measurements as shown Figure 7. Seismometers (“a” and “b”) were installed in the almost centre of the plan in NS direction shown in Figure 4. On the other hand, censers for microtremor measurements were placed at the north side of the building. Therefore, the effect of the coupling of TR (NS) and UD direction cannot be observed in the results of earthquake observation records, but only in the results of microtremor measurements. Difference of amplitude ratio between centre (”a”) and east (“b”) of the building can be found in TR (NS) direction. Spectral peak is located at 3.0 to 3.5Hz that is close to natural frequency of superstructure by microtremor measurements. This can also be considered the effect of the irregularity of pile supporting stratum.



(a)Building A (b) TRG (c)MYG013 (K-NET Sendai)

Figure 11. Average Fourier spectra of observed earthquakes



(a) TR (NS) (b) LN(EW) (c) UD

Figure 12. Average amplitude ratios between observation sites

Based on the results from earthquake observation records analysis, attempts to estimate one-dimensional wave propagation characteristics of reclaimed soft soil layer are conducted. Predominant frequency of soft soil layer is assumed 2.5Hz from the results of Figure 12. According to design documents of building A, pile lengths of north frames are 8 to 17m. Two cases are prepared for the estimation where 15m (Case 1) and 20m (Case 2) of depth of subsurface layer are assumed. Using the information of predominant frequency and depth of subsurface layer, shear wave velocity of subsurface layer is estimated 180m/s for Case 1, and 240m/s for Case 2 by eq. (1). Shear wave velocity of damaged man-made reclaimed residential area of hill side of Sendai is approximately estimated 180m/s by surface wave method in the damage survey after the 2011 Tohoku earthquake (Sendai city, 2012). The results estimated from the earthquake observed records meet good agreements with the damage survey of man-made reclaimed residential area.

$$f = \frac{V_s}{H} \tag{1}$$

CONCLUSIONS

On the damaged long building with irregular pile supporting stratum after the 2011 Tohoku earthquake, damage survey, microtremor measurements and earthquake observation records analysis are reported. Results of observed records analysis are discussed related to damage survey. Conclusions are summarized in the followings.

1) Severe bending failures at the foot of staircase tower adjacent to superstructure are quite distinctive. Shear cracks on the non-structure walls and bending crack on the girder around the frames where the first floor heights change in longitudinal direction.

2) Based on the results from microtremor measurements, natural frequencies of building are estimated 3.5Hz in TR (NS) and 3.0Hz in LN (EW) direction for base-fixed system, 3.2Hz in TR (NS) and 2.9Hz in LN (EW) direction for dynamic soil-structure interaction system. Natural frequencies of the 3rd staircase tower are estimated 3.5Hz in TR (NS) and 3.0Hz in LN (EW) direction for base-fixed system, 2.6Hz in TR (NS) and 3.7Hz in LN (EW) direction for dynamic soil-structure interaction system. Motion of foundation in TR (NS) direction is coupled with UD direction that is caused by the irregular pile supporting stratum.
3) Motion of foundation is amplified in TR (NS) direction and coupled with motion in UD direction at around the first natural frequency of superstructure of 3.5Hz.
4) Maximum accelerations tend to be larger in TR (NS) direction than LN (EW) direction because of the irregular pile supporting stratum. Comparison of maximum accelerations of centre to east of the building leads to the fact that seismic response of east part of the building is larger by about 10% than centre of the building.
5) Response spectra of observed earthquake in building A show spectral peaks in 0.1-0.2 (s). Amplitude ratios of the first floor of building A show spectral peaks in 2.5Hz compared to TRG. Therefore, predominant frequency of reclaimed soft soil layer is estimated 2.5Hz.
6) Shear wave velocity of reclaimed soft soil layer is estimated 180m/s for the case of 15m, 240m/s for the case of 20m of depth of subsurface layer. The results meet good agreements with the results from surface wave methods at damaged reclaimed residential area of hilly sites of Sendai.

In this paper, microtreor and earthquake observed records analyses are mainly discussed to investigate the causes of damage after the 2011 Tohoku earthquake. Superstructure, pile foundations of damaged building and subsurface ground should be organized as the numerical model for numerical simulations in the near future. The effects of long building and the irregularity of pile supporting stratum will be discussed in more detail.

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