Measured period of vibration of high-rise buildings recorded on video movies opened to the public excited by the 2011 off the Pacific coast of Tohoku Earthquake

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Abstract

The long-period earthquake motion of the 2011 off the Pacific coast of Tohoku Earthquake excited high-rise buildings with long-period natural vibration. These situations of visible shaking can be seen on internet as YouTube as video movies recorded by the general public there. Author read out period and amplitude from these movies opened to the public and compared them to the number of the floors, the height, and the result of the microtremor measurement before and after the event and so on. Then author examined the relationship between the natural period and the height or the change of the natural period by the earthquake motion. As a result, it was found that it is possible to grasp a natural period and amplitude with tremendous precision from video movies, and a building with relative long natural period is said to tend to issue large deformation but it is difficult to grasp the risk of the building only form the natural frequency. Furthermore, there is no significant difference on the earthquake motion characteristics derived both from microtremor and earthquake motion.

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1. Introduction

Because the 2011 off the Pacific coast of Tohoku Earthquake (hereafter the 3.11 earthquake) excited long period earthquake motion due to the large fault rapture motion, structures with long natural period like skyscrapers are discernibly shaken. Consequently, many shaking buildings were shot at various sites and the videos can be seen on web sites as YouTube. The author interprets the period and the amplitude of shaking buildings from these video files and considers relationships between period and height or the change of the natural period caused by the earthquake motion, comparing the result of the interpretation to the floor numbers, height or the result of microtremor before and after the earthquake.

2. Data set and interpretation method

2.1. Data set

Data set is consisted of the video files interpretable the period and amplitude with stable observing point. The period and the amplitude are carefully interpreted based on this data set. In addition, although these video files seemed to be started recording after reaching a large motion, a clock appeared in movies shows a time around 14:50, so the main part of the long period earthquake motion seems to be recorded.

The specifications and the characteristics of skyscrapers are based on characteristics data sheet of the database of measured dumping (edited at 2000.10) [1] or other detail information on buildings on web sites. Because this characteristics data sheet conceals the name of the building, that is identified from number of stories, eaves height or completed year. The buildings in video movies are also grasped the characteristics corresponding to datasheet from the name of the buildings.

2.2. Interpretation method on period and amplification

(1) Direct interpretation

It is necessary for interpretation of the building motion to appear the objects for reference. If the objects for reference can be assumed a

fixed point, it is rather easy to interpret the period and the amplitude. Here, the objects for reference was chose a structure far away or neighbor building. In case of comparing the neighbor building, relative displacement is combined from characteristics of the both buildings. Similar period or amplitude for each other causes beat. The frequency of the beat is the difference of the frequency of each building and it is possible to fix the predominant frequency of each building noticing that the apparent frequency is the averaged frequency of both building. It is difficult to understand clearly the beat frequency because it is rather long for building with long period. So the natural frequency easy to interpret first, and then the natural frequency of another building is estimated using the apparent frequency interpreted from relative variability for both building and the fixed frequency.
Amplitude is interpreted roughly in 10cm seemed to be the maximum amplitude.

(2) Indirect interpretation

The vibration of the building in the video files is very tiny and it was often difficult to grasp it quantitatively. In such a case, potential phenomenon for period determination were found out with repeatedly careful confirmation of the video file. The phenomenon is, for example, sequential vibrating sound of a building, reflection on a glass wall of a building, behavior of neighboring building reflected on a wall, vibration of a movable shelf, opening and closing a door and so on. Although it was difficult to clarify the amplitude with these clues, it seemed to be possible to estimate the period with considerable accuracy.

3. Predominant period and amplitude interpreted from video files

Totally 50 buildings between 5 stories and 70 stories were interpreted the frequency and so on from video files. The vibration frequency was interpreted for at least one direction of each building and partly two directions, so the total number of data is more then 50. The result of the interpretation is listed in Table 1, and examined in more depth below.

***Table 1.** Predominant Vibration Excited by the 2011Off the Pacific Coast of Tohoku Earthquake*

No.	Building Name	Comple-tion	Number of Floors			Height	Vibration Excited by the Quake				Analytic Design	Measured before Quake Predominant Vibration				Noise before Quake '06/01/30measured		Noise after Quake '11/10/19measured		Structure
							Predominant Period		Max. Amp.	Max. Drift Ang.	Period	Period in second			Damp.	Period	Amp.	Period	Amp.	
			Ab.	B.	Pent.	in m	in sec.	Direction	cm	%	in sec.	Wind	Noise	Quake	%	in sec.	times	in sec.	times	
1	Shinjuku C	Oct-79	54	4	3	216	6.00	Short: NS	50	0.23	5.65		6.00	6.00				5.85	2.1	S
			54	4	3	216		Long side			5.35		4.97	4.97				4.55	4.8	
2	Shinjuku N	Jun-78	50	5	3	203	5.20	Short side	100	0.49	5.42		4.80		0.39			4.94	11.2	S
			50	5	3	203		Long side			4.27		3.43		0.37			3.22	6.2	
3	Shinjuku AT	Jan-95	44	4	2	189	4.50	Long: NS	90	0.48										S, partially SRC
4	Shinjuku SJ	Mar-76	43	6	2	193	4.80	Short side	150	0.78										
5	Shinjuku M	Sep-74	55	3		210	4.25	Short side												S(2F-55F), SRC(under 1F)
			55	3		210	3.60	Long side												
6	Shinjuku K	Jun-71	47	3	2	170	4.50	Short: EW	80	0.47	3.85		4.30		0.50					S(3F-47F), SRC(1F, 2F),
			47	3	2	170	3.85	Long: NS	40	0.24	4.30		3.10		0.80					RC(BF)
7	Asakusa C		10			40	1.20	Short side	30	0.75										
8	Roppongi AM	Mar-86	37	4		153	3.75	Short side	60	0.39										S, partially SRC and RC
9	Roppongi IG	Jul-02	32	2		116	3.20	EW	30	0.26										SRC
10	Shinjuku JE	Sep-97	28	4	1	149	3.40	Long side	30	0.20										
11	Shinjuku ST	Feb-98	36	4	1	147	3.60	Long side	30	0.20										S
12	Shinjuku MT	Sep-95	34	3	2	161	4.50	Short side	80	0.50										S, SRC
13	TokyoCityHall1S	Mar-91	48	3		242	5.17	Short: EW	110	0.45	5.56		5.00		0.46			4.72	5.6	S(2F-48F), SRC(under 1F)
			48	3		242	4.74	Long: NS	80	0.33	5.20		4.29		0.75			4.05	2.6	
	TokyoCityHall1N		48	3		242		Short: EW			5.56							5.11	10.2	
			48	3		242		Long: NS			5.20							4.04	5.9	
14	Kanda ST	1980	14	2		56	1.50	Long side	20	0.36										S, SRC(under 1F)
15	Kanda N	Mar-84	8	4		32	1.20	Short side	10	0.31										SRC
16	Akasaka SP	Mar-11	16	2		64	1.91	along Road	20	0.31										S
17	Roppongi MT	Mar-03	54	6	2	238	6.00		200	0.84										
18	TokyoCityHall2	Mar-91	34	3		162	3.61	Short side	60	0.37	3.98		2.92		0.78					S, SRC and RC
			34	3		162		Long side			3.91		2.73		0.73					
19	Ikebukuro S	Apr-78	60	3	3	227		Short side			6.25	6.25			1.56					S(Upper and Middle),
			60	3	3	227	4.70	Long side	100	0.44	5.88	4.55								SRC(Lower)
20	Marunouchi TN	Sep-03	19	3	2	100	5.00	Short side	60	0.60										S, patiallySRC
21	Marunouchi TM	Nov-08	37	4	2	178	5.00	Short side												S(CFT), partially SRC
22	Marunouchi ST	Apr-07	35	4	1	165	3.10	Long side												S(CFT column)
23	Marunouchi A	Jul-71	29	4	2	110	3.00													S, partially SRC
24	Shinjuku W	Jun-91	13	2		52	1.50	Long side	20	0.38										SRC
25	Shinjuku CT	Oct-08	50	3	2	204	3.70	NS	60	0.29										S, partially SRC
26	Shinjuku LT	Jun-89	31	5	1	122	2.70	Short: NS	60	0.49	2.99		2.60	2.80	0.90					SRC
			31	5	1	122	2.70	Long side			3.00		2.38	2.55						
27	Shibuya CT	Mar-01	41	6		184	4.68													S, partially SRC and RC
28	Harumi TX	Mar-01	44			183	4.40		20	0.11										
29	Harumi TY	Mar-01	39			175	4.20		30	0.17										
	Harumi TZ	Mar-01	33			155	4.70		30	0.19										
30	Yokohama LT	1993	70	3	3	282	4.54	NE	60	0.21	6.02	4.60	5.22		0.70					
31	Yokohama QA	Jun-97	36	5	2	172	4.50	Short side	40	0.23										SRC
			36	5	2	172	4.70	Long side												
32	Yokohama MM	Mar-03	28	3	2	147	4.00													S, under ground SRC
33	Shinagawa GT	Mar-03	32	3		148	3.96	Long side												
34	Shinagawa T	Mar-03	30	3		148	3.33													
35	Shinagawa ET	Mar-03	32	3		152	4.00													S and SRC
36	Marunouchi M	Aug-02	37	4		179	4.30	Short side												S, under ground SRC
			37	4		179	4.50	Long: EW	150	0.84										
37	Marunouchi NM	Apr-07	38	4	1	177	4.50	Long: EW	80	0.45										S, under ground SRC
38	Shinjuku S	Mar-74	52	4	2	200		NE			5.07		4.44		0.74			4.79	17.8	S, partially SRC and RC
			52	4	2	200		NW			5.07		4.44		0.80			4.33	15.2	
39	Roppongi T	1994	9			36	1.17	Short side	20	0.56										
40	Roppongi U	Nov-73	7	1		28	1.56	Short side	20	0.71										RC
41	Roppongi N	1948	7	1		28	0.54	Short side												SRC
42	Roppongi G	Sep-95	9	3		36	0.70													SRC
43	Ohfuna K	Jul-77	5			20	0.98	Short side	15	0.75										
44	Daikanyama D	Jul-05	12			48	1.50		40	0.83										
45	Shinbashi N	Apr-03	32	4	2	193	4.10	Short side												
46	Shiodome R	Apr-03	38	4	2	172		Long side												
47	Shinbashi D	Oct-02	48	5	1	210	6.10	Short side	120	0.57	5.40									
			48	5	1	210		Long side			4.60									
48	Kasumigaseki K	Apr-68	36	3	2	147	4.80	Short side	70	0.48	5.14		3.74		1.02	4.12	14.7			
			36	3	2	147		Long side			5.04		3.38		1.31	3.53	5.3			
49	Kasumigaseki CGW	Sep-07	38	3	1	174	4.14	EW												
50	Shinagawa CST	Mar-03	29	4	1	148	3.80													

3.1. Predominant period

(1) Comparison of the predominant period before and after the earthquake

Microtremor measurements were conducted for high-rise buildings; C, N and S at Shinjuku, and both of observation floors of the first building of Tokyo metropolitan city hall, between 17 o'clock and 18 o'clock on October 19, 2011, seven months after the 3.11 earthquake. The result of the microtremor measurements are compared with that before the earthquake found out from the characteristics data sheet.

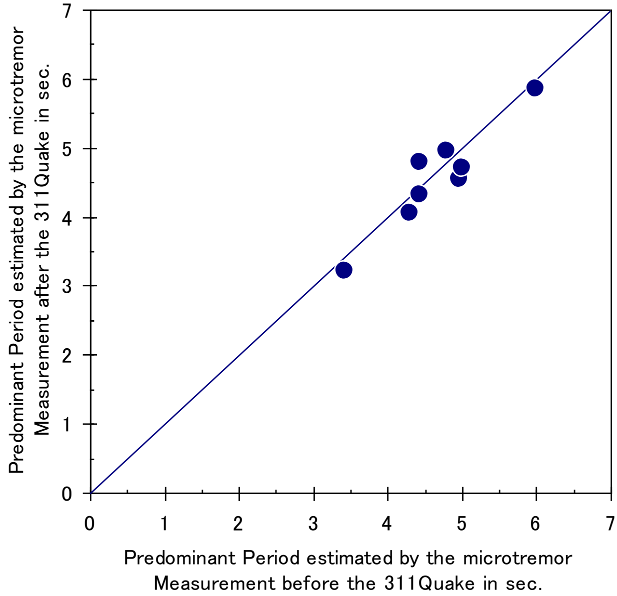

Figure 1. *Comparison of the Predominant Period Before and After the 3.11 Earthquake*

Figure 1 show that the predominant period before the earthquake is rather longer than that after the earthquake but that is almost same level, so it seems that the predominant frequency has not changed remarkably before and after the earthquake.

(2) Comparison between the predominant period excited by the earthquake motion and the measured predominant period before and after the earthquake

Figure 2 compares the predominant period of microtremor before the earthquake and that excited by the earthquake motion of the 3.11 earthquake. This figure shows that predominant period for all buildings without LT building at Yokohama is lengthened at the time of the 3.11 earthquake. It may cause a quantity of reduction of rigidity. Predominant period of the LT building at Yokohama is 5.22 seconds from the microtremor before the 3.11 earthquake and around 4.6 seconds for the wind response with HMD, hybrid mass dumper. The

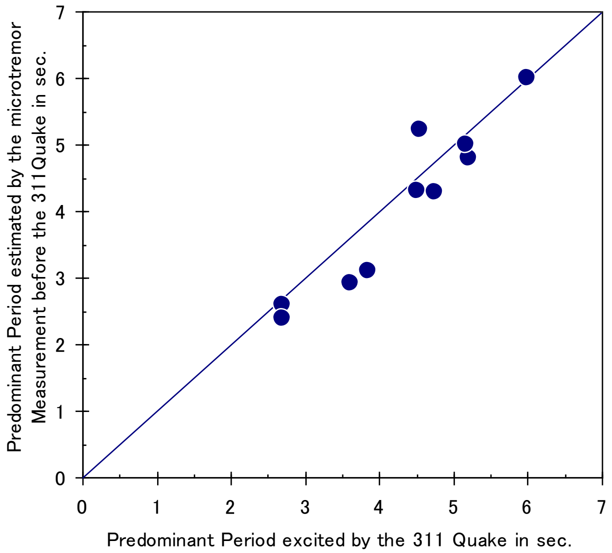

Figure 2. *Comparison of the Predominant Period Excited by the 3.11 Earthquake and Before the Event*

predominant period excited by the earthquake motion of the 3.11 earthquake is interpreted 4.54 seconds from the video file and it corresponds to that of the wind response, so it is concerned that HMD worked at the time of the 3.11 earthquake.

Although the change of the predominant period of almost all the other buildings was less than 10%, that of both the second building of Tokyo metropolitan city hall and K building at Shinjuku was close to 20 %.

Figure 3 show the comparison between the predominant periods measured after the 3.11 earthquake and that excited by the 3.11 earthquake. According to this figure, the periods after the earthquake seem to be short. There is a possibility that the decreased rigidity is recovered after the earthquake.

(3) Relationship between the predominant period and the height or the number of stories of building

Figure 4 shows the relationship between the height of the building H (m) and the predominant period T (second) before the earthquake derived from the characteristics data sheet.

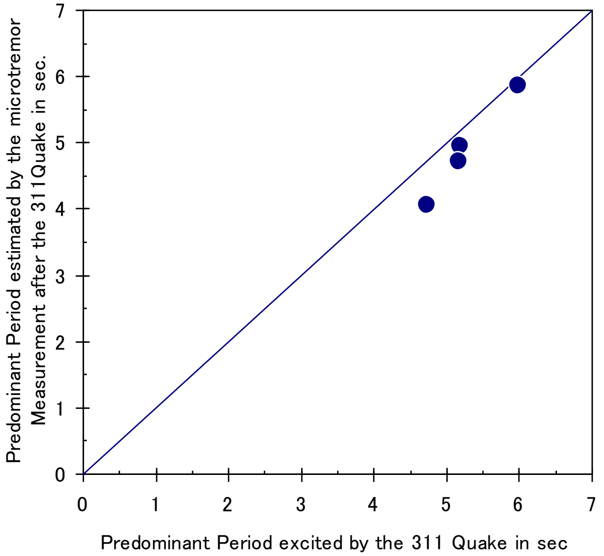

Figure 3. *Comparison of the Predominant Period Excited by the 3.11 Earthquake and that After the Event*

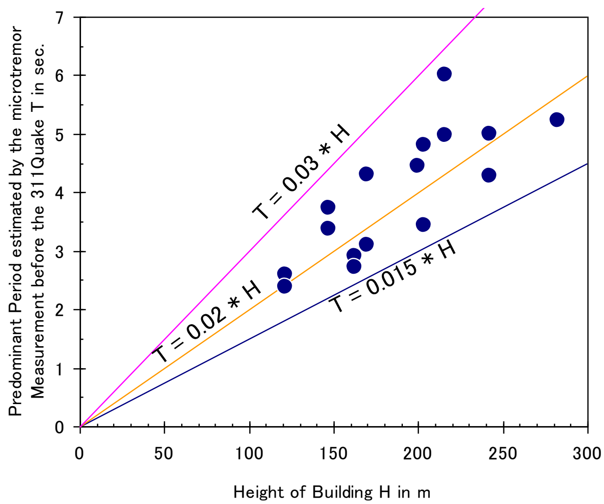

Figure 4. *Relationship between the Predominant Period Before the 3.11 Earthquake and the Height of Buildings*

In general, the relation ship between T and H is given in a formula below.

$$T = k \times H$$

On figure 4, the coefficient k below mostly scatters between 0.015 and 0.03 centering on around 0.02.

Figure 5 shows the relationship between the height of the building H (m) and the predominant period T (second) excited by the strong motion of the 3.11 earthquake. The coefficient k basically scatters between 0.015 and 0.03 as same as the relationship between the height of the building H (m) and the predominant period T (second) before the earthquake, and mostly between 0.02 and 0.03. However some of buildings deviated from the relationship, indicating as a red marker. The buildings with a red marker seem to be caused large deformation more than 1/180 of averaged story drift calculated from the approximated number of interpreted maximum amplitude and the height of the building. The accuracy of the interpretation from the video file is low and it seems that the error of interpretation for lower buildings is large. Because it is clear from the video that the buildings vibrated relative larger than neighbor buildings, it must be noticed that the

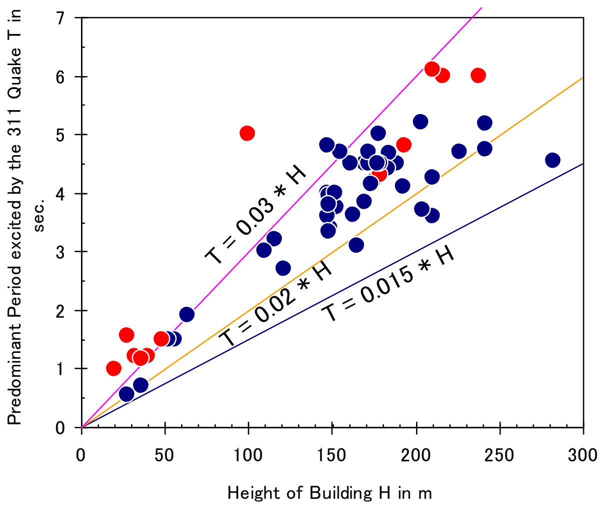

Figure 5. *Relationship between the Predominant Period Excited by the 3.11 Earthquake and Height of Buildings*

other low buildings without a red marker have a possibility to cause large deformation.

Figure 6 shows the relationship between the number of stories of the building N and the predominant period T (second) excited by the strong motion of the 3.11 earthquake. Most building shows longer period than that derived from an equation T=0.06N, and many of them shows longer period than that derived from an equation T=0.1N. It is impressive that the possible deformed buildings are plotted over the relationship $T = 0.1N$.

Figure 7 shows the relationship between the height H and the number of stories N of target buildings. Because there is no information of the height for most of the target buildings lower than 20 stories, the height is estimated by the relation below indicating in Figure 7.

$$H = 4.0 \times N$$

3.2. Amplitude of the earthquake motion interpreted from the movie files

Figure 8 shows the relationship between the approximate value of the amplitude from the video files and the height of the buildings.

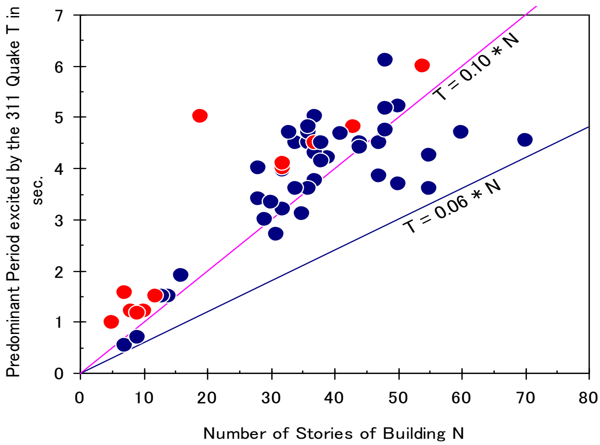

Figure 6. *Relationship the Predominant Period Excited by the 3.11 Earthquake and the Number of Stories of Buildings*

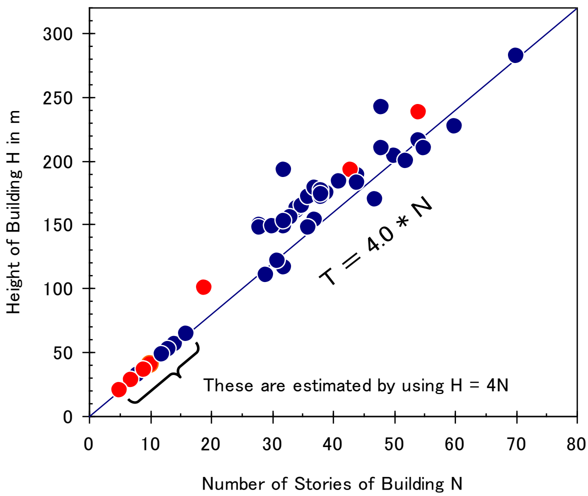

***Figure 7.** Relationship between the Height and the Number of Stories of the Buildings*

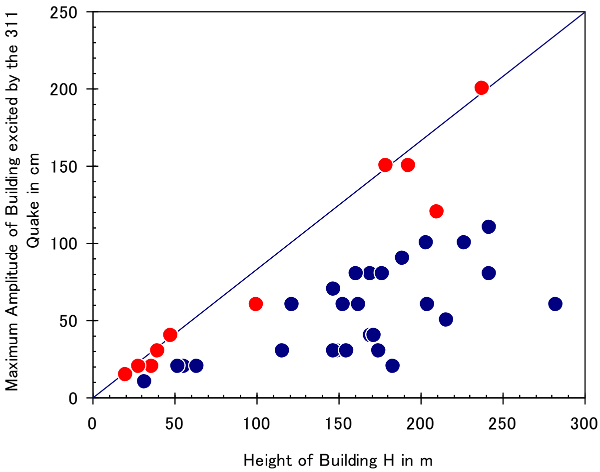

***Figure 8.** Relationship between the Amplitude Excited by the 3.11 Earthquake and the Height of Buildings*

This figure is just for a reference because of possible large error.

Red marks indicate estimated buildings with shear deformation more than 1/180. A low building at left end of this figure is given quite different result by a variation of 10cm. It is necessary to notice that the

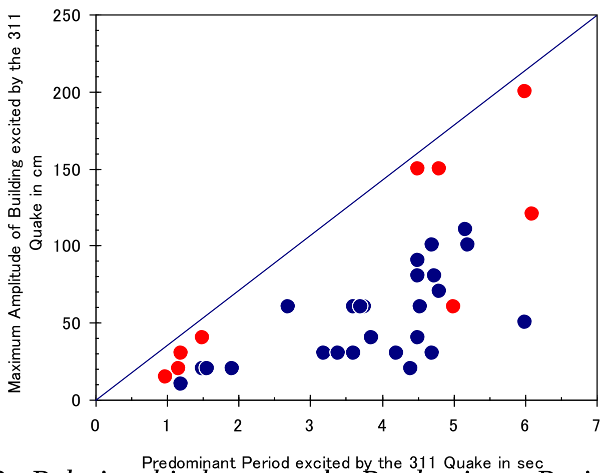

Figure 9. *Relationship between the Predominant Period and the its Amplitude of Buildings Excited by the 3.11 Earthquake*

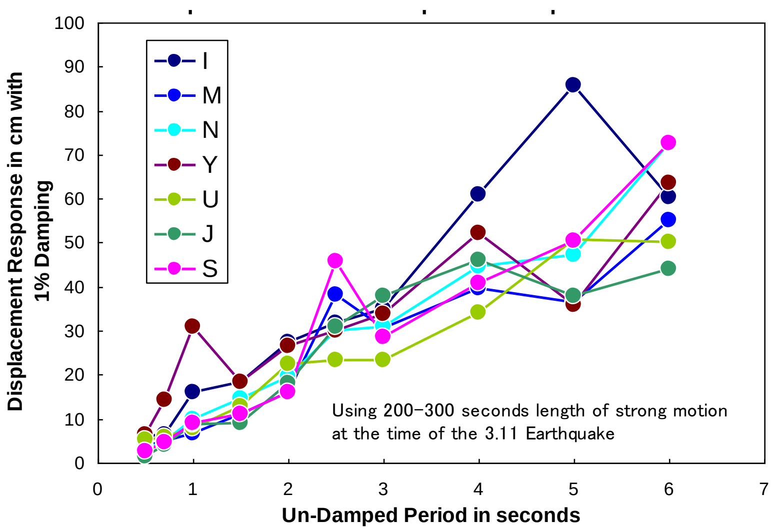

Figure 10. *Displacement Response Spectrum calculated from Recorded Strong Motion of the 3.11 Earthquake at the Various Sites near the Buildings in this Paper*

low building at left end clearly behaves as biased vibration in the video file although the building is not marked red.

Figure 9 shows the approximate value of the amplitude corresponding to the predominant period excited. This figure gives that the longer predominant period, the larger amplitude. Also this figure can be thought to correspond to response spectra. So the displacement response spectra is calculated from strong motion records of sites nearby and compared in the next section.

4. Displacement response spectra using strong motion records

It seems that the displacement interpreted from video files may reach 1/120 at the time of the 3.11 earthquake. Displacement response spectra corresponding to the period concerned are calculated from the strong motion records of the 3.11 earthquake to verify the validity of the interpreted deformation, because the situation with such large deformation seems to be serious. The buildings concerned locate at Shinjuku, Ikebukuro, Roppongi, Akasaka, Kanda, Shinagawa, Yokohama and so on. The displacement response spectra with 1% dumping are calculated for the strong motion records of sites S, I, M, J, U, N and Y, close to the buildings concerned. Un-damped period set to 0.5, 0.7, 1.0, 2.0, 2.5, 3.0 4.0, 5.0 and 6.0 seconds. Figure 10 shows the displacement response spectra. The displacement response spectra increase towards long period as 30-60cm at 4 second of period, 40-80cm at 5 second of period and 50-70cm at 6 second of period. It agrees to the interpreted amplitude in order. On the other hand, although the displacement response spectra almost agree to overall trend for all the sites, the site characteristics is also appeared, so it suggests the necessity of consideration of the site characteristics for the long period characteristics.

5. Conclusion

This paper examines to grasp the dynamic characteristics of high rise buildings shaken by the earthquake motion of the 3.11 earthquake with analyzing video files opened public. As a result, the period and the amplitude are accurately grasped and it is possible to understand clearly the relationship between the predominant period and the height or the number of stories. Although it is possible to say generally that the relative longer the predominant period of buildings, the larger the deformation to lead damage, it is confirmed to be difficult to understand the dangerousness of buildings only from the predominant period. Also there is no significant difference of the characteristics against earthquake motion derived from microtremor and earthquake motion of the 3.11 earthquake.

Acknowledgement

The author expresses my heartfelt thanks with respect to people who took shaking buildings on video with quick action against abnormal seismic motion of the 3.11eaerthquake and open to public via website like YouTube.

References

[1] Small Working Committee for Damping Data of Buildings, Load Management Committee (2000), “Database of Measured Damping for Buildings in Japan edited at October 2000”, Architectural Institute of Japan.