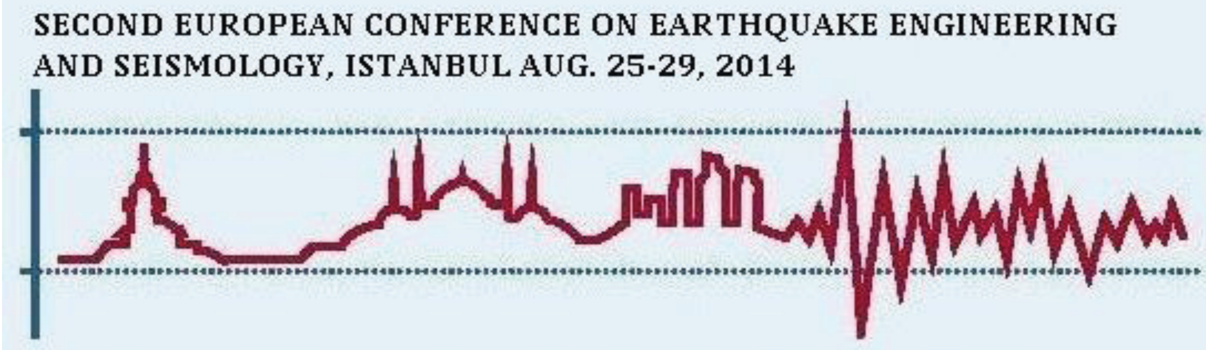

DRIFT ISSUES OF TALL BUILDINGS DURING THE MARCH 11, 2011 M9.0 TOHOKU EARTHQUAKE, JAPAN - IMPLICATIONS

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ABSTRACT

Performances of tall buildings in many seismically active regions of the world or those tall buildings affected by long distance long period effects by sources at a distance are of interest to the earthquake engineering community. The M9.0 Tohoku, Japan earthquake of March 11, 2011 provided numerous examples of tall buildings that were subjected to long duration (>10 minutes) shaking. Recorded responses of four tall buildings during the 2011 Tohoku event are studied. A 55-story building in Osaka (at 770 km from epicenter) resonated and almost reached an average of 0.5% drift ratio with a ground level input motion of ~3% g is significant. For a 54-story building in Tokyo at ~ 375 km from epicenter, average drift ratio may have reached ~0.3% and maximum drift ratio likely was > .3%. – sizeable since the maximum drift ratio allowed by Japanese practice for buildings is 1% .

INTRODUCTION

The M9.0 Tohoku, Japan earthquake of March 11, 2011 occurred at 05:46:23 UTC (local time 14:46:23) offshore from the east coast of Honshu, Japan (38.322°N, 142.369°E) at 32 km depth; http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/, last accessed July 15, 2011). The earthquake caused a major disaster in Japan and affected economies throughout the world. It generated one of the most significant tsunamis, a tsunami which left its mark by destroying the four-unit Fukushima nuclear power plant and by causing the largest percentage of the 15,776 fatalities[1] associated with this event. Furthermore, it caused widespread destruction and damage of major port and other facilities on a wide portion of north-east coast of main island of Honshu (Japan). It is widely reported that material loss may reach $300B.

Aside from the disaster, however, copious data on the earthquake were collected which present new opportunities for research and learning opportunities on all aspects of earthquake science and earthquake engineering. One of the more significant characteristics of the earthquake from an engineering perspective is the long-duration strong (>10 minutes) shaking over large distances that affected the built environment. In particular tall-buildings in Tokyo (~350-375 km from the epicenter) and in places as far as Osaka (~770 km from the epicenter) shook for several minutes. Although none collapsed, the strong shaking caused many of the tall buildings not to be functional for days and weeks.

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[1] From The Japanese National Police Agency (http://www.npa.go.jp/archive/keibi/biki/higaijokyo.pdf) as confirming 15,597 deaths, 5,694 injured and 4,980 people missing across eighteen prefectures, as well as over 125,000 buildings damaged or destroyed.

The purpose of this paper is to discuss the drift ratio issues related to tall buildings in Japan affected by long period ground motions at far distances from the epicenter of the Tohoku earthquake of March 11, 2011 (M=9.0). We review the inferred long period long distance effects of the ground motions from recorded response data from four tall buildings in Osaka and Tokyo and the spectral properties of ground motions recorded from stations nearby these buildings. The scope of the paper is limited to the study of the recorded tall building response data and does not include in-depth study of the ground motion parameters that affect long-period structures at large distances. Such studies are important in USA also due to the fact that many several large metropolitan areas may also be affected by long-period ground motions generated by earthquake sources at far distances. Therefore, three other relevant topics are also discussed in this paper:

a. Past observations of long distance long period effects and implications for United States.
b. Long period effects as demonstrated by response spectra of ground motions recorded during the same event.
c. Maximum allowable drift ratios in Japan and other seismic areas of the world.

The performances of buildings discussed in this paper are inferred from computations of average drift ratios because the accelerometer deployed in the tall buildings are sparse. It is important to note that drift ratios are the best measure to infer damage occurrence or likelihood during design/analyses processes and also during analyses of recorded response data if exist (Çelebi et al.,2004, Çelebi,2008, Browning et al. 2000). The effect of long period ground motions to buildings and other long period structures is demonstrated by the four cases presented herein.

All of the four examples indicate that considerably high drift ratios for relatively low (~3% g) to moderate (10-20% g) input ground motions were affecting the functionality of tall buildings at large distances from the epicenter of the Tohoku event. Published documents to date on performances of tall buildings during the Tohoku event in general do not describe actual observed or unobserved possible hidden damages [Hisada et al., 2012a and b, Takewaki et al., 2011, Kashima et al., 2012, Çelebi et al., 2013). While no-collapses were reported, there is no certainty that hidden damages in some of the buildings do not exist.

PAST OBSERVATIONS OF LONG DISTANCE LONG PERIOD EFFECTS AND IMPLICATIONS FOR THE UNITED STATES

One of the earliest observations in the United States was during the M=7.3 Kern County earthquake of July 7, 1952, that shook many tall buildings in Los Angeles and vicinity, about 100-150 km away from the epicenter (http://earthquake.usgs.gov/earthquakes/states/events/1952_07_21.php, last accessed July 15, 2011) (Hodgson, 1964). The March 28, 1970, M=7.1 Gediz earthquake in inland western Turkey damaged several buildings at a car-manufacturing factory in Bursa, 135 km northwest from the epicenter (Tezcan and Ipek, 1973). One of the most dramatic examples of long-distance effects of earthquakes is from the September 19, 1985, Michoacan, Mexico, M 8.0 earthquake during which, at approximately 400 km from the coastal epicenter, Mexico City suffered more destruction and fatalities than the epicentral area due to amplification and resonance (mostly around 2 sec) of the lakebed areas of Mexico City (Anderson et al.,1986, Çelebi et al, 1987). To the best knowledge of the authors, however, there are no publicly available records of the responses of tall structures from these past earthquakes. Therefore, records obtained from numerous instrumented tall buildings during the Great East Japan earthquake of March 11, 2011 offer a rare opportunity to study and understand how structures characterized by predominantly long-period responses behave during medium to large events originating at long-distances. Such effects have consequences for large metropolitan areas in Japan, but also in other parts of the world, including the United States (*e.g.*, Los Angeles area from Southern California earthquakes, Chicago from NMSZ and the Seattle (WA) area from large Cascadia subduction zone earthquakes). For example, the recent M=5.8 Virginia earthquake of August 23, 2011 was felt in 21 states of the Eastern and Central U.S., that include large cities such as New York and Chicago (http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/se082311a/#summary , last accessed July 15, 2011). During this event, occupants of a 28-story building at MIT Campus in Cambridge, MA experienced the shaking (Toksoz, *pers. comm.*, 2011) but no records were obtained.

DISCUSSION ON LONG PERIOD AND LONG DISTANCE EFFECTS DURING TOHOKU EARTHQUAKE AND RESPONSE SPECTRA ISSUES

Based on a study by Okawa et al.(2010), four months before the Tohoku event, the Japanese Government Ministry of Land, Infrastructure, Transport and Tourism [MLIT] released regulation proposals for upgrading the design of high-rise buildings under long-period ground motions (MLIT, 2010a and b) and solicited public and professional opinions. However, immediately after the end of the period for opinion solicitation, the Tohoku earthquake occurred. Following the Tohoku event, MLIT started to revise the document with collected opinions and new data from the earthquake. As of writing of this paper, the revision process is still on-going.

In the MLIT (2010a) document, total of 9 areas in Japan were specified (4 in Tokyo, 3 in Nagoya and 2 in Osaka). For each one of these areas, simulated acceleration and velocity time-histories were specified. Takewaki et al(2011) report that velocity response spectra of all the simulated ground motions have significant large peaks within 2-8 s range. It is important to state that in this report, Shinjuku area of Tokyo, where tall buildings are discussed later in this paper, the KNET Shinjuku station (TKY007) motions exhibit predominant peaks between 3-8 s range.

In this paper, we present acceleration and velocity response spectra of ground motions recorded during Tohoku earthquake from 2 stations. As an example, for Osaka Bay, spectra of motions from KIKNET station OSKH02 are provided in Figure 1 and display the long periods both at surface and downhole. This station is closest to the example building in Osaka Bay discussed also later in the paper. In Figure 2, we present spectra of motions from KNET stations TKY007 (representative of motions in the Shinjuku area of Tokyo, as discussed above). These spectra clearly display the long periods capable of affecting responses of the tall buildings. TKY007 was also examined by Takewaki et al (2011).

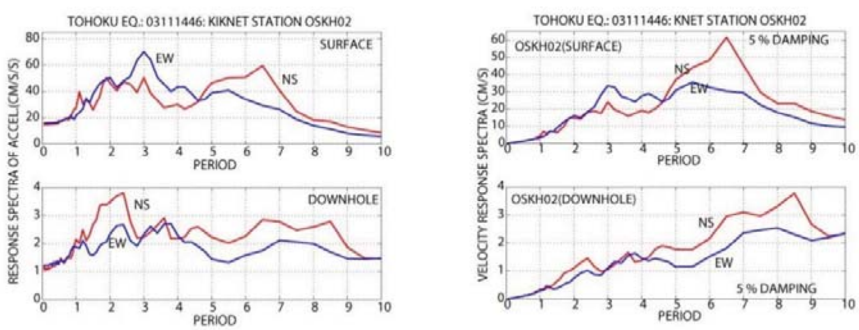

Figure 1. (left) NS and EW acceleration response spectra and (right) velocity response spectra of ground motions recorded at surface and downhole during Tohoku event at KIKNET OSKH02 station in Osaka Bay. Velocity response spectra exhibit the large amplitudes between 5-7 seconds.

To elaborate on effect of possible increased input motions and consequential response of a tall building, we compute an estimate of pga from GMPE equation of Boore and Atkinson (2008) for reverse earthquakes. Assuming M=7.5, spectral period t=5.0 s, PSA= 60cm/s/s, Vs_{30}=225 m/s and R=10km, estimated pga is ~ 0.24 g. In case of Osaka Bay, this may be a possible scenario.

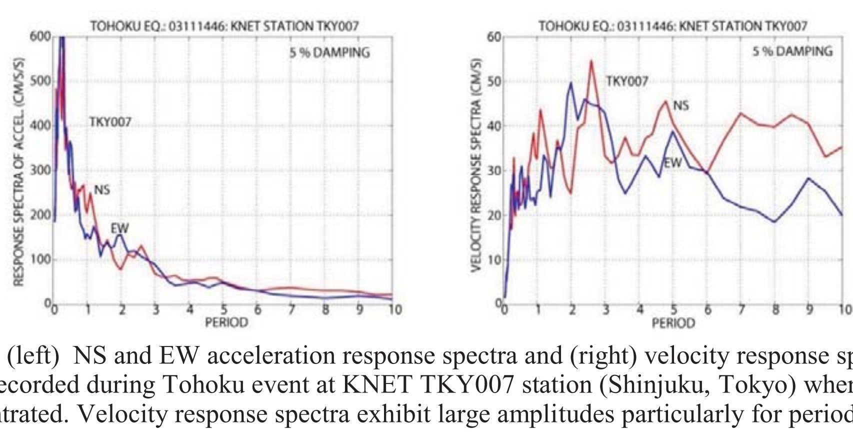

Figure 2. (left) NS and EW acceleration response spectra and (right) velocity response spectra of ground motions recorded during Tohoku event at KNET TKY007 station (Shinjuku, Tokyo) where talbuildings are concentrated. Velocity response spectra exhibit large amplitudes particularly for periods > 2 seconds.

DRIFT RATIOS OF DIFFERENT COUNTRIES

Before presenting drift issues relative to the four buildings, it is important to review practiced drift ratio limits of a few seismically active countries and also that of Eurocode 8 (2003). Comparison of the drift ratios of 5 countries and Eurocode 8 (2003) are provided in Table 1. The table exhibits drastic variability in practice of drift ratio limits from 0.2% to 2.5 %.

Table 1. Upper Limits of Drift Ratios (Japan, Chile, USA, Turkey, New Zealand and Eurocode 8).

Code	Upper Limit Drift Ratio (%)	Comment	Reference
Chile	0.2	Results in elastic design	Nch433.Of96 (1996)
Japan	1.0	Max for buildings taller than 60 m. For collapse prevention (level 2) motions	Building Center of Japan 2001a, b.
USA	2.0	No collapse state	ASCE7-10 (2007)
Turkey	2.0	Can be increased by 50 % in case of some steel frames	DBYYHY: Section 2.10.1.3, Eqn: 2.19 in Turkish Code (2007)
New Zealand	2.5		NZS1170.5(2004)
Eurocode 8	1.0 (max)	For buildings having non-structural elements fixed in a way so as not to interfere with structural deformations, or without non-structural elements	Section 4.4.3.2, Eqn:4.33 Eurocode 8 (2008)

BUILDINGS

Building A at Osaka bay ~ 770 km from epicenter of the earthquake

Detailed discussion of the building, data and analyses are provided in a recent paper by Çelebi et al (2013). Figure 3 shows vertical sections and locations of tri-axial accelerometers as well as plan views, orientation of the building and location of accelerometers at the 52nd floor.

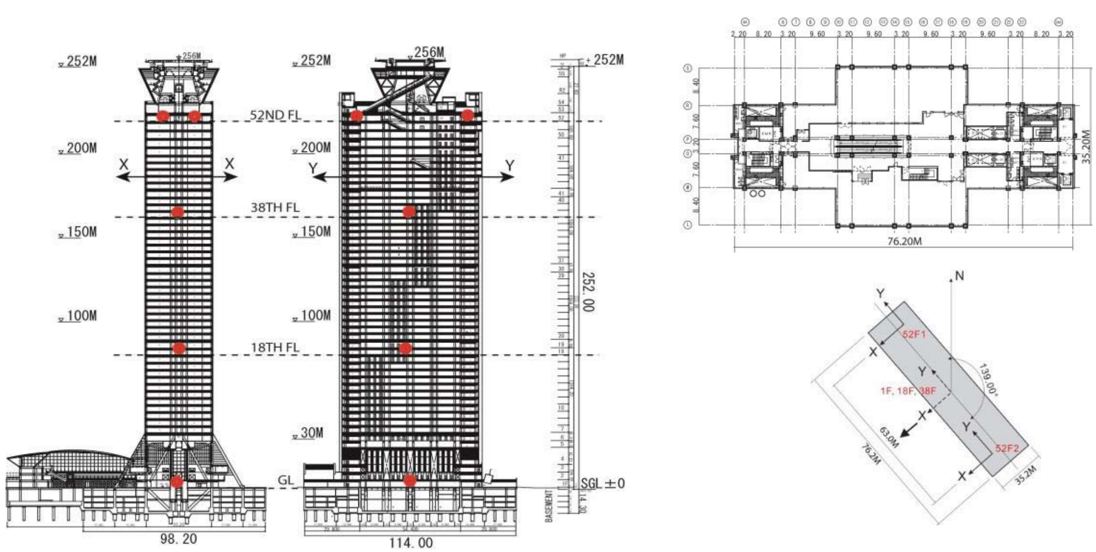

Figure 3. (Left) Vertical sections and plan views of the building showing major dimensions and locations of tri-axial accelerometers on the 52n, 38th, 18th and ground level (1st Floor). X and Y denote principal axes of the building (from [8]). (Right Top) Typical plan view (the figure shows 52nd floor) and (Right Bottom) orientations (from [8]).

The building was subjected to an input motion at ground level with peak accelerations of ~3% g during the Tohoku earthquake. Furthermore, the building was founded at a site with a site frequency (period) of 0.13-0.17 Hz (5.88-7.69 s) as seen in Figure 4 (left) and presented in detail elsewhere [8] and also in Figure 4. The building exhibited fundamental frequencies (periods) of 0.152Hz (6.58 s) in the X-direction and 0.145 Hz (6.90) in the Y-direction as seen in Figure 4 (right) . Such close frequencies are clear confirmation of resonance that led to prolonged responses (~1000s recorded) and long duration high amplitude shaking as exhibited in Figure 5 which shows average drift ratios.

The average drift ratios (Figure 5) computed from relative displacements between many floors indicate that maximum average drift ratios experienced during the mainshock were between 0.5-1.0 % for the X-direction and 0.2-0.4% for the Y-direction. These average drift ratios are less than the maximum 1% limit usually used in Japan for collapse protection level motions (level 2 used for buildings 60 m or taller [19,20]. However, average drift ratios are much larger than expected for an input motion with a small peak acceleration in the order of only 3% g. In the United States, the comparative maximum drift ratio for tall buildings for Risk Category 1 or 2 is 2% (Table 12.12 ASCE7-10, 2007).

Detailed studies of the Osaka basin are presented in Yamada and Horike(2007), Sekiguchi et al (2007) and Iwaki and Iwata (2008), but they have not addressed local site transfer function issues. Instead, we computed the site transfer functions using software developed by C. Mueller (*pers. comm.*, 1997) which is based on linear propagation of vertically incident SH waves, and has, as input, data related to the layered media (number of layers, depth of each layer, corresponding V_S, damping, and density), desired depth of computation of transfer function, computation frequency (df), half space substratum shear wave velocity and density. Damping (ξ) in the software is introduced via the quality factor (Q), a term used by geophysicists that is related to damping by $\xi = 1/(2Q)$.

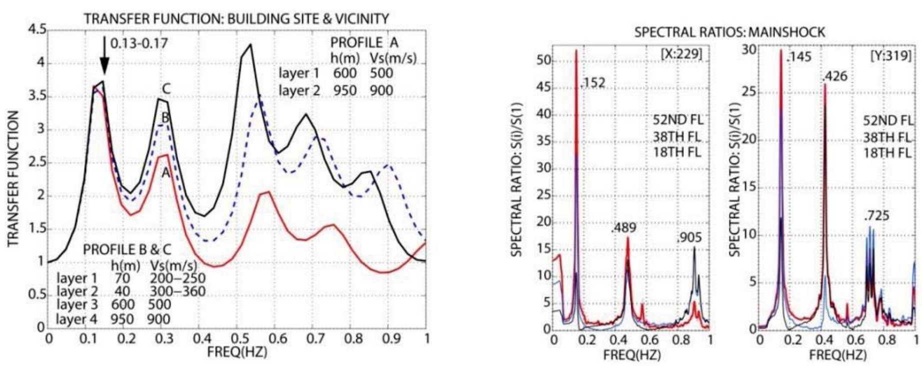

Figure 4. (Left) Transfer functions computed for Profile A (near the OSKH02 strong-motion site, www.kik.bosai.go.jp/, last accessed 09/16/2011)) and Profiles B and C below the building. The depth of the softer upper two layers (to about 1500 m depth) below the building do not significantly change the position of the peaks in the transfer function, particularly for the fundamental mode of the site. (Right) Spectral Ratios of amplitude spectra at 52nd floor, 38th floor and 18th floor with respect to that at first floor. Note that 3rd mode in X-direction is identified from the ratios. Different colors (red, black and blue) are used only to distinguish lines corresponding to different floors in descending order.

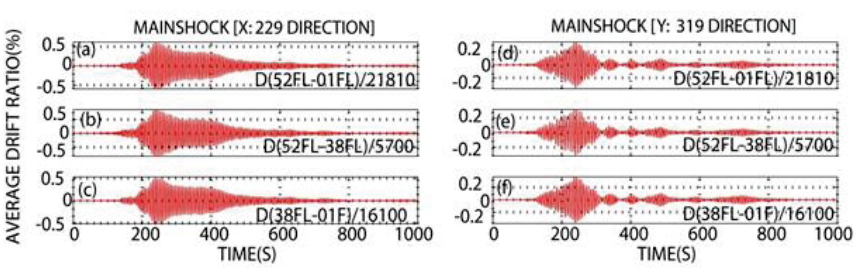

Figure 5. Average drift ratios computed from displacements between 52nd, 38th and 1st floors. In each frame, the numbers in denominators are distances (in cm) between the designated floors.

In summary, during the Tohoku event, the building was subjected to ground level input acceleration of 3% of g. But the deformations were large enough (to realize sizeable average drift ratios) that the building lost its functionality for several weeks. Elevator cables were entangled. This case, along with others, deserves further studies as to how tall buildings would respond if the ground input accelerations were 20-30% of g with similar low frequency content that could be caused by a closer earthquake (e.g. ~100 km or less) [e.g. similar to 1923 Kanto and 1995 Kobe earthquakes]. It is important to note that same elevator cable tangling problems also occurred in several tall buildings in the Shinjuku area of Tokyo, Japan [4,5].

Furthermore, the actual drift ratios computed from relative displacements divided by story heights between some of the pairs of two consecutive floors are certainly to be larger than the average drift ratios computed from differential displacements between several floors, due to sparse deployments of instruments, as in this case. The average is therefore the lower bound of the maximums.

Building B – 55 Story Shinjuku Center Building in Shinjuku, Tokyo

According to EERI Special Earthquake Report (2012), the 54-story Shinjuku Center Building was constructed in 1979. The report states: "The structure's height is 223m, and the first natural period of the structure is 5.2 and 6.2 seconds in two perpendicular directions. In 2009, the building was retrofitted from the 15th to 39th floor with 288 oil dampers that were configured to exhibit a form of deformation dependency, in addition to velocity dependency. In the March quake, the dampers were calculated to have reduced the maximum accelerations by 30% and roof displacements by 22%." Figure 6 shows a picture of the building and the oil dampers installed in 2009.

Figure 6 (Left) Picture of Shinjuku Center Building , and (right) dampers installed in 2009 [27].

Figure 7 (figure adopted from *pers. comm.* J. Moehle, 2012 and revised pers comm. Y. Sinozaki) shows display of recorded acceleration time-history at first floor and displacements computed by double integration of the acceleration at roof during the Tohoku earthquake at ~375 km from the epicenter. Without the actual data being available, as shown in Figure 7, the maximum roof displacement is in the transverse (Y) direction and reported as 54.2 cm. Hosozawa et al (2012) as well as Takewaki et al (2011) also confirm these displacements. Assuming that this is the same as the maximum relative displacement between ground floor and the roof, with a height of 216 m (*pers comm* Y. Sinozaki), the average drift ratio can be assumed to be ~54/21600 ~.25% (see Table 2). This is the average. Hence, the maximum drift ratio is >.25% even with claimed reductions in maximum accelerations and displacements thanks to the dampers. Without actual data, it is not possible to compute possibly how much larger than 0.25% is the drift ratio between any two consecutive floors.

Table 2: Maximum observed responses (from Hosozawa et. al [28] and *pers. com*. Y. Sinozaki, 2012)

	Max. Accel. (cm/s/s)		Max Displ. (cm)	
	Long. (X)	Trans.(Y)	Long. (X)	Trans.(Y)
Roof	236.0	161.3	49.4	54.2
28^{th} Floor	112.7	171.3	26.3	33.3
1^{st} Floor	94.3	142.1		

Again, similar to the discussion related to Building A, the actual drift ratios computed from relative displacements divided by story heights between some of the pairs of two consecutive floors are certainly to be larger than the average drift ratio computed using the maximum roof displacement divided by the height of the building, due to unavailable detailed data, as done in this case.

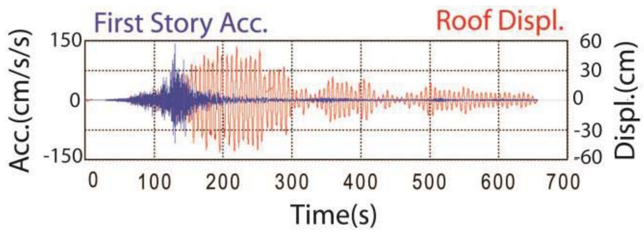

Figure 7. Recorded first story accelerations (max ~14% of g) and computed roof displacements (max ~ 54cm) during Tohoku earthquake (figure adopted from J. Moehle and Y. Sinozaki).

Buildings C and D – Two Tall Buildings at Kogakuin University Campus, Shinjuku, Tokyo

Without mentioning drift ratios, detailed studies of two buildings on the Kogakuin University Shinjuku, Tokyo campus are provided by Hisada et al (2012a and b). Figure 8 (left) (adopted from Hisada et al [2012a and b]) shows the vertical sections of the two subject buildings as well as instrumented floors. Using the available sparse data, average drift ratios using time-histories of relative displacements between any two instrumented floors were computed to be approximately ~0.3-0.4 % and are presented in Figure 8 (center and right) and also in Table 3. Detailed study of these buildings are reported separately (Çelebi, et al, 2014).

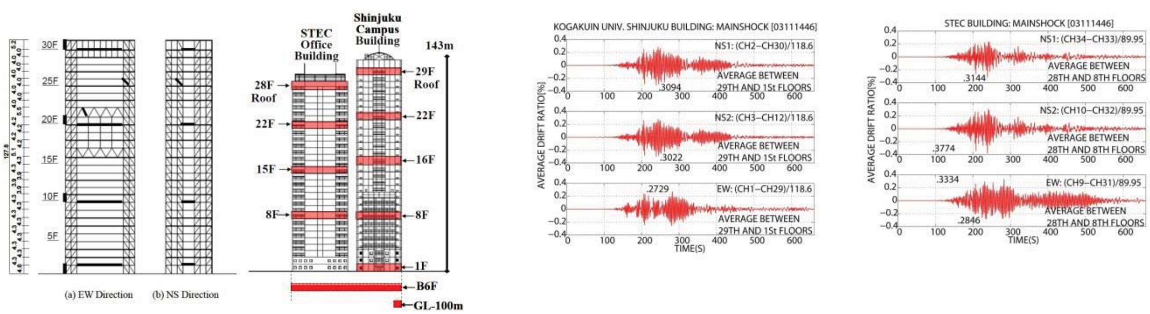

Figure 8. (left) Vertical sections showing instrumented floors of Building C (30 story Shinjuku Campus Building) and Building D (28 story STEC Office Building) in Shinjuku area of Tokyo, Japan (Figure adopted from [Hisada et al, 2012a and b]). (Center and Right) Average drift ratios computed from recorded data of Building C and D.

DISCUSSION AND CONCLUSIONS

During the M9.0 Tohoku earthquake of March 11, 2011 tall buildings in Tokyo (~350-375 km from epicenter) and Osaka (~770 km from the epicenter) shook for long durations.

Long period dominance of ground motions at far distances from the epicenter of the earthquake are confirmed by velocity response spectra of ground motions. These spectra confirm also the recommended design spectra issued 4 months before the Tohoku earthquake by MLIT (2010a and b) that accounts for the effects of long periods on tall buildings in 9 regions of Japan that include the buildings discussed herein. Building A is in one of these regions in Osaka and Buildings B, C and D are all in another region in Shinjuku area of Tokyo.

For small ground level input ground motions as in the two cases presented herein, these four tall buildings deformed significantly to experience sizeable drift ratios as summarized in Table 3.

Table 3. Epicentral distances, peak accelerations and displacement and computed average drift ratios of the buildings supplemented by peak accelerations of ground motions recorded at stations in proximity to the buildings.[H=height of building used to computed average drift ratios, DR=drift ratio].

Bldg	Epicentral Distance (km)	Peak Acc. at Ground level(gals)	Peak Accel. At top floor (gals)	No of floors	Rel. Displ (cm)	H Height (m)	(Ave) DR (%)
A	767	30	130	54	~130	218	~.5
B*	~375	142	236	54	54.2	216	~.2
C**	~375	92	340	31	33.4	119	~.3
D**	~375	92	302	29	34.9	90	~.4
*from Sinozaki (pers.comm, 2012), **from Hisada et al (2012a and b)							
Peak accelerations (gals) at Free-Field Stations in vicinity of the buildings							
Free-Field station		NS	EW				
KIKNET:OSKH02\surface KIKNET:OSKH02\downhole		13 1	15 1				
KNET: TKY007		198	165				

Finally, the following points are made:

1. Behavior and performances of these particular tall buildings far away from the strong shaking source of the M9.0 Tohoku earthquake of 2011 and large magnitude aftershocks should serve as a reminder that, in the United States as well as in many other countries, risk to such built environments from distant sources must always be considered.
2. The potential risk from closer large-magnitude earthquakes that could subject the buildings to larger peak input motions should be assessed in light of the substantial drift ratios under the low peak input motions experienced during and following the Tohoku earthquake of 2011.

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