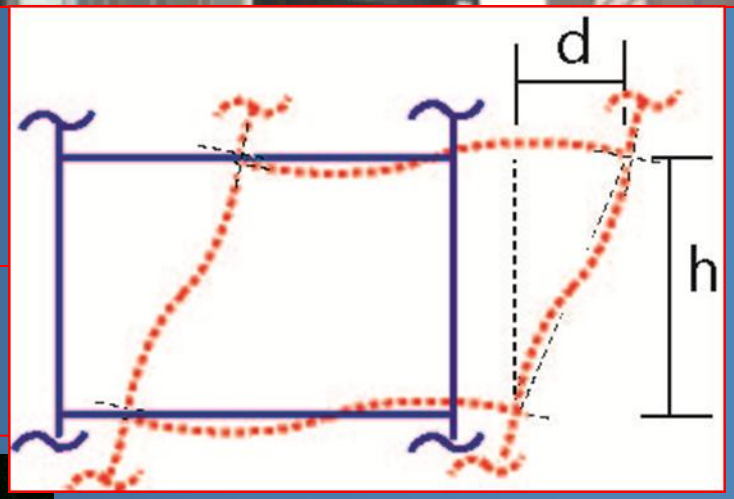
DRIFT ISSUES OF TALL BUILDINGS DURING THE MARCH 11, 2011 M9.0 EARTHQUAKE, JAPAN - IMPLICATIONS



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Outline

- 1. Why this subject?
  - Long-period ground motions due to earthquake at far distances (long-period long-distance)
  - Discussion of INTERRUPTED functionality of buildings at low ground level input motions caused by event at far distances.
  - Discussion of what may happen at larger input motions with similar frequency content.
  - Discussion of DRIFT RATIOS w.r.t. codes (Japan, USA, Chile)
- 2. Four cases:
  - Building A (~770 km from epicenter)
  - Building B (~350-375 km from epicenter)
  - Buildings C & D (~350-375 km fro epicenter)
- 3.CONCLUSIONS

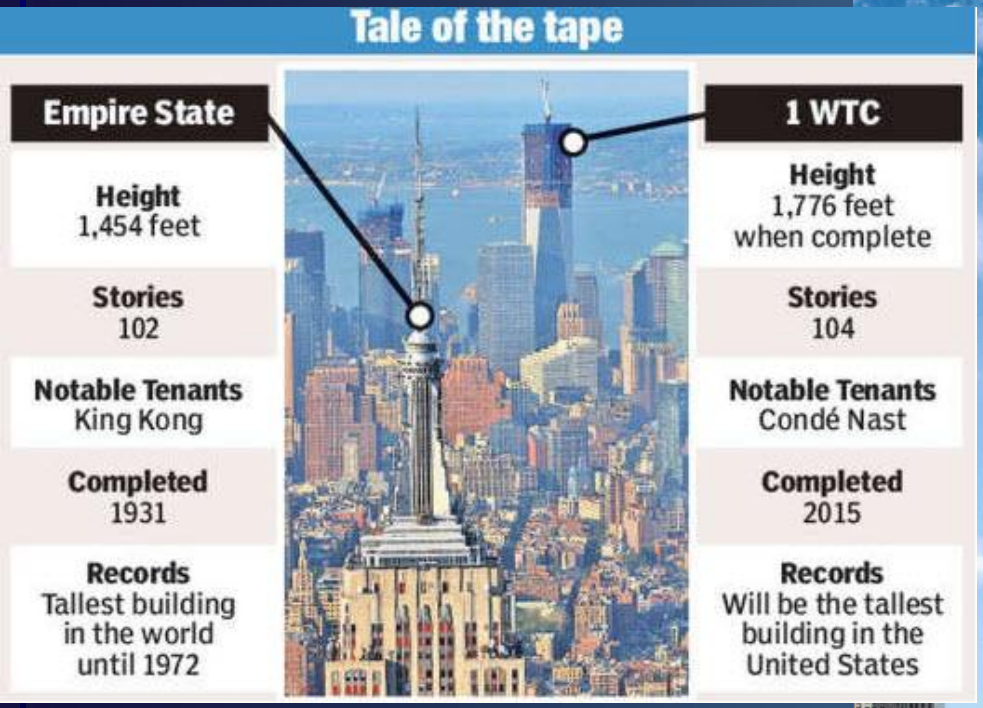
Background (Long Period/Long Distance Effects) 1/2

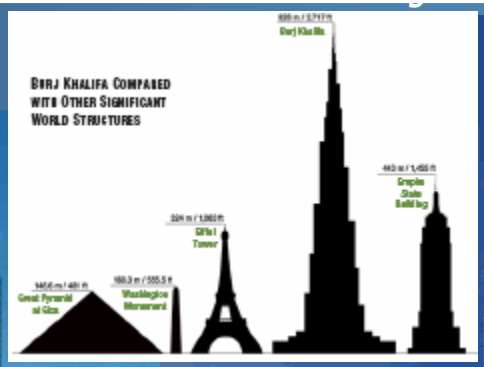
- One of the earliest observations in the United States was during the M=7.3 Kern County earthquake of July 7, 1952, that shook many taller buildings in Los Angeles and vicinity, about 100-150 km away from the epicenter (http://earthquake.usgs.gov/earthquakes/states/events/1952_07_21.php)
- One of the 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 and others, 1986, Çelebi and others, 1987).

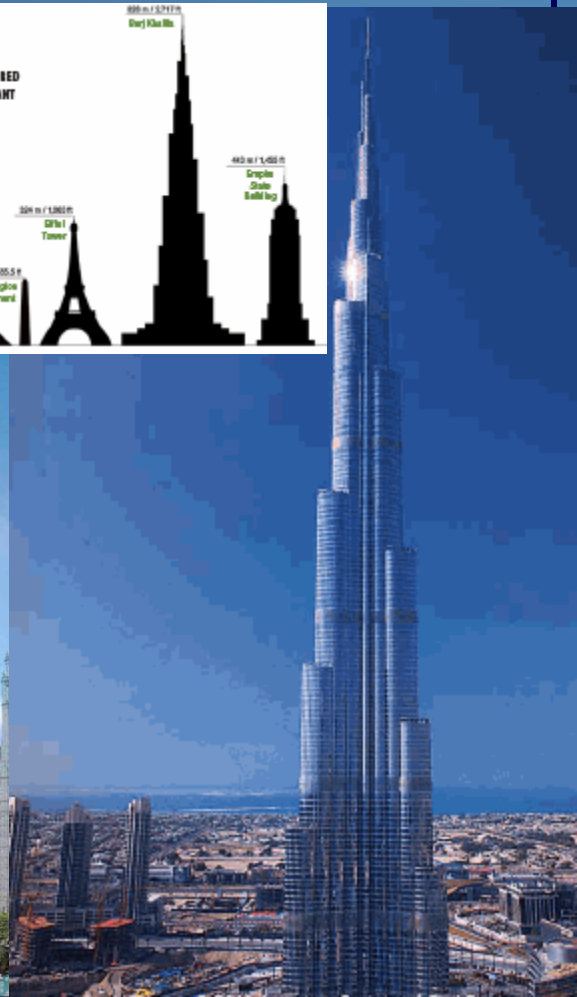
Tokyo: ~1500 high-rise bldgs, ~1000 base-isolated bldgs (from J. Moehle)

Tall Buildings Inventory Increasing!

- More and more taller RC buildings are designed/constructed in the US as well as other parts of the world: Freedom Tower in NYC, 92 story Trump Tower (Chicago), 828 m tall Bhuj Tower in Dubai).<u>Their performances are yet to be assessed and/or observed!</u>







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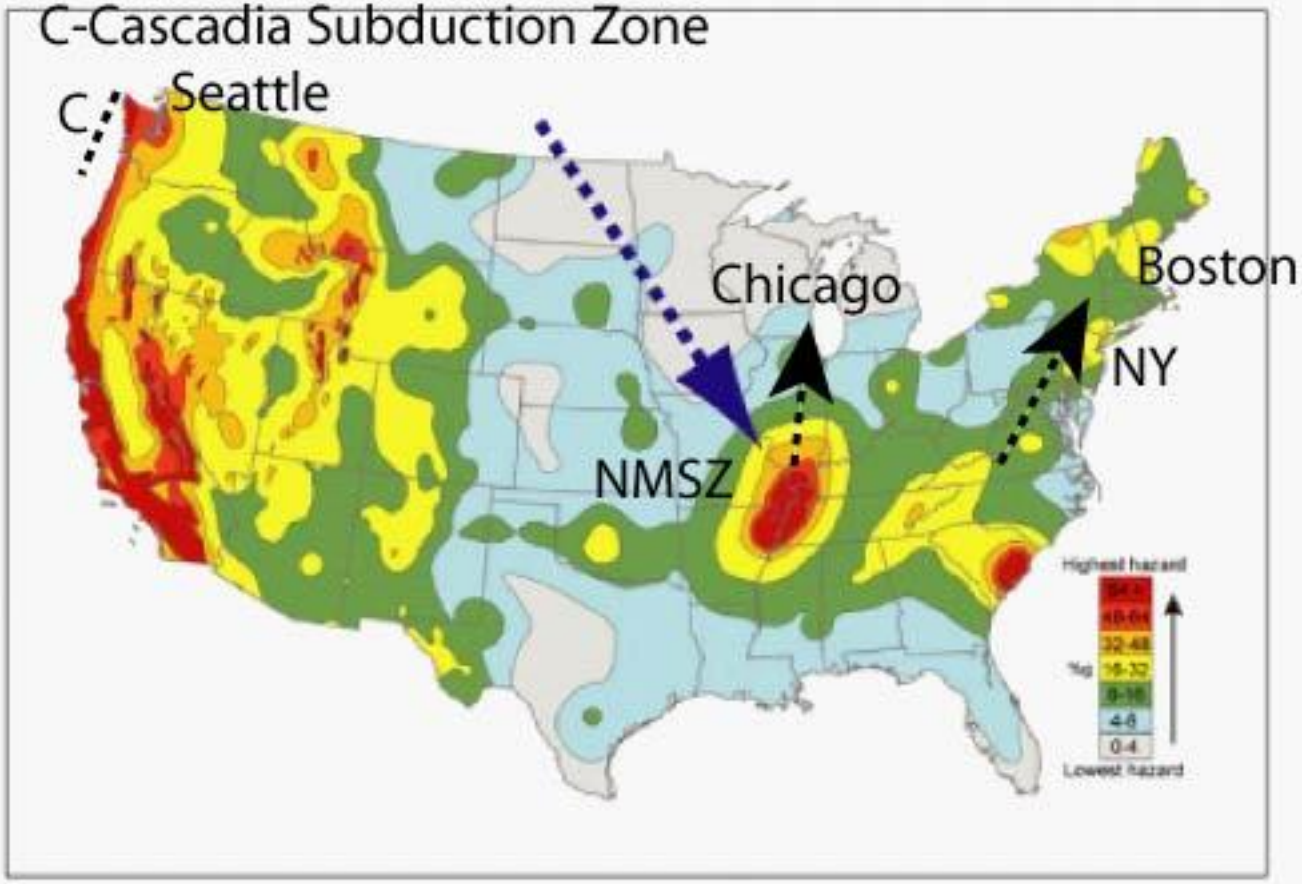
What is the risk to tall buildings from earthquakes originating at NMSZ or Charleston, SC or Cascadia Subduction Zone? Should we consider what may happen to tall buildings in Chicago, New York, Boston or Seattle?



Tall Buildings in Chicago, Boston and Seattle

According to Wikipedia:

In Chicago: 72 bldgs taller than 555ft (168 m) [37-108] stories

In Boston :27 buildings taller than 400 feet (120 m). "

In Seattle, 15 buildings >400 ft(122m), 24 buildings>400 ft under constrruction

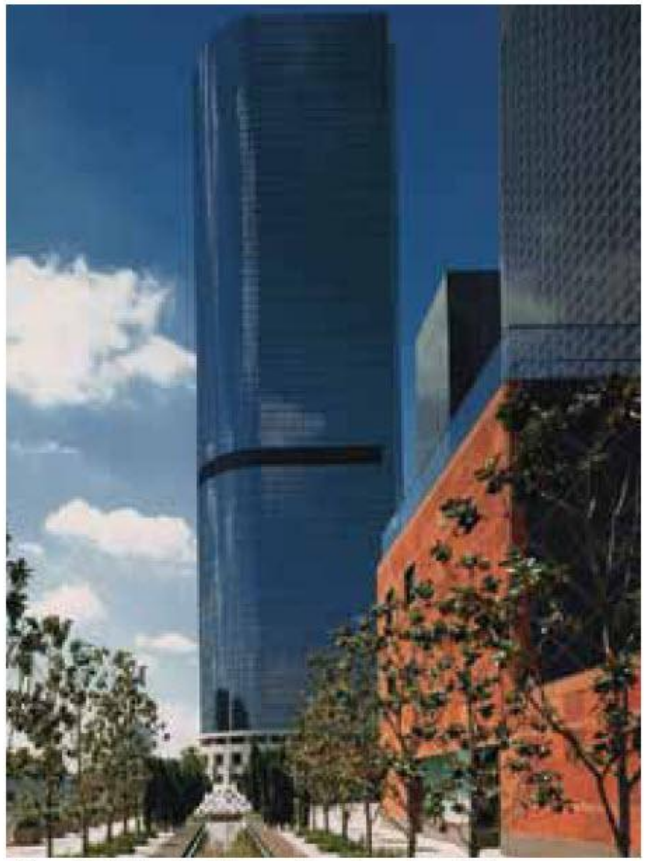
- How will they perform during a strong event from distant sources??? [pictures from Wikipedia]

New Buildings in Los Angeles

From ASCE STRUCTURE Magazine, June 2012 (by R. Gerges, K. Benuska and C. Kumabe)

Fox Plaza Century City, Los Angeles, CA.

777 Tower, Los Angeles, CA.



One California Plaza, Los Angeles, CA.

CHILE: TALL BUILDINGS

- ~ 3,000 tall buildings (>10- stories) in Chile. (left: Parque Araucano, right: Titanium Bldgs)

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Why important?
Potential Long Period/Long Distance Effects in the US (2/2)

- Tall buildings in Los Angeles area from Southern California earthquakes,
- Tall buildings in Chicago from NMSZ,
- Tall buildings in Seattle (WA) area from large Cascadia subduction zone earthquakes).
- Let us remember that 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, July 15, 2011).

What about ground motions at long distances? Long Periods in Osaka and Tokyo [Not surprising! In fact MLIT report (Dec 2010) indicates awareness]

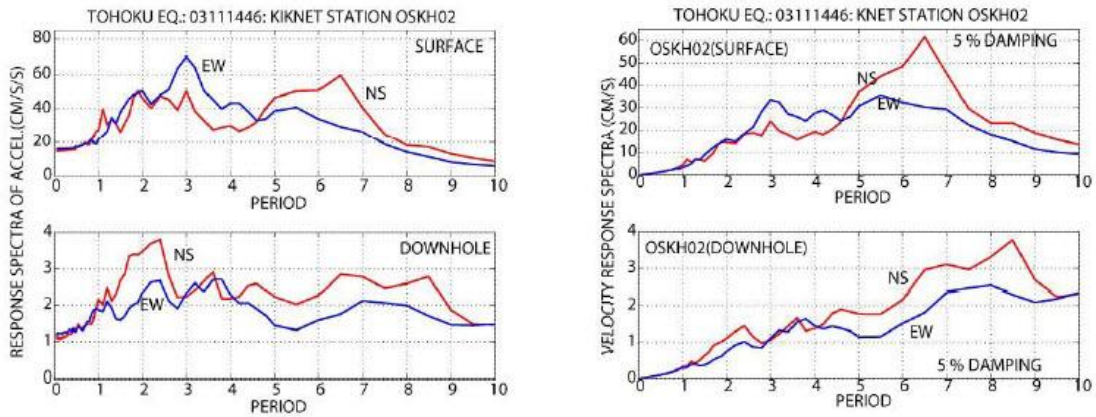


Figure 1. (left) NS and EW acceleration response spectra and (right) velocity response spectra of ground motions recorded at surface and downhole during Tohoku event at KIKNET OSKH02 station in Osaka Bay. Velocity response spectra exhibit the large amplitudes between 5-7 seconds.

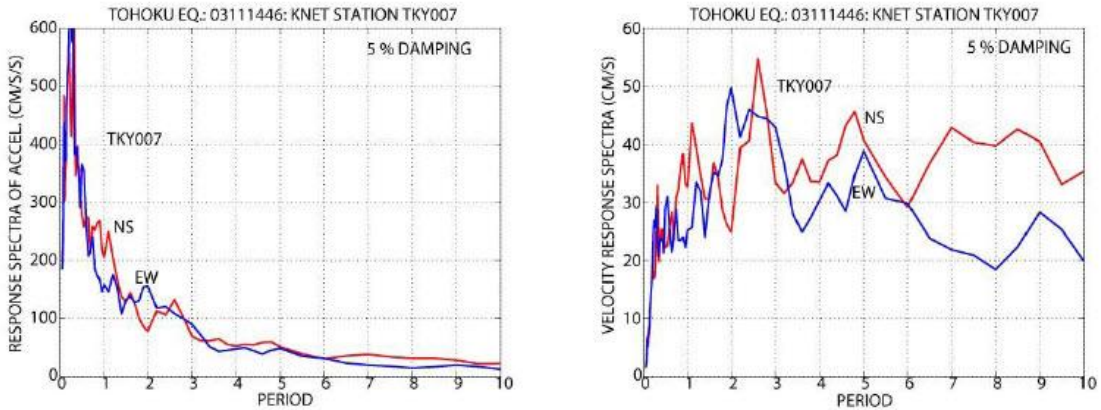
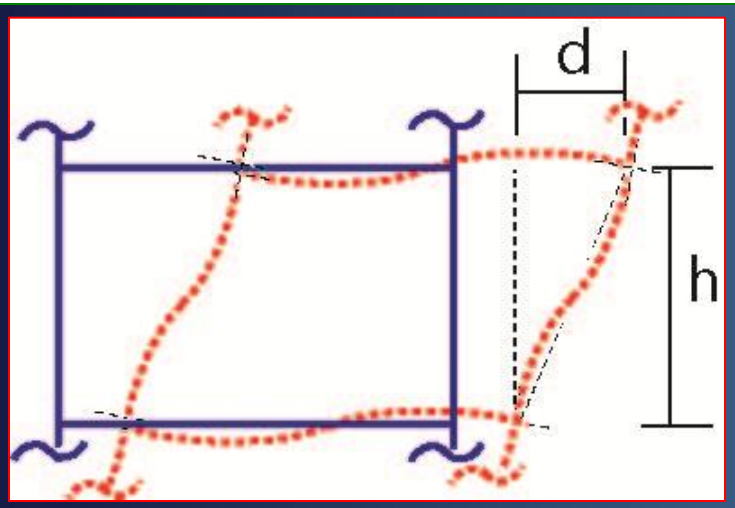
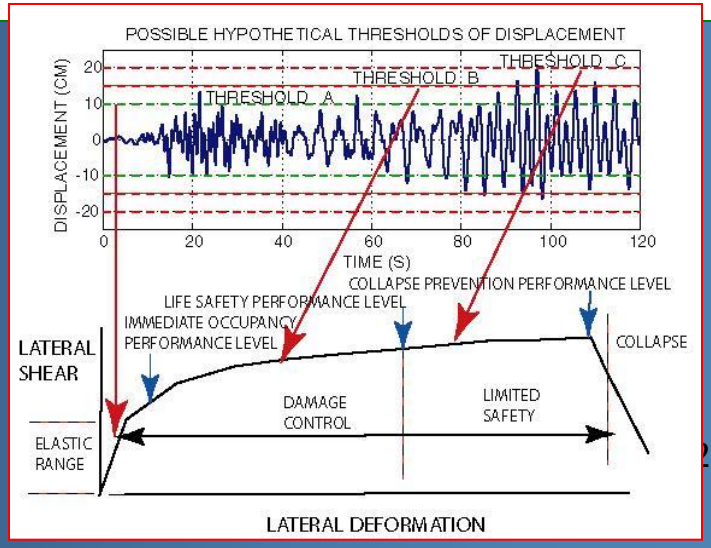


Figure 2. (left) NS and EW acceleration response spectra and (right) velocity response spectra of ground motions recorded during Tohoku event at KNET TKY007 station in Shinjuku area of Tokyo where tall buildings are concentrated. Velocity response spectra exhibit the large amplitudes particularly for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

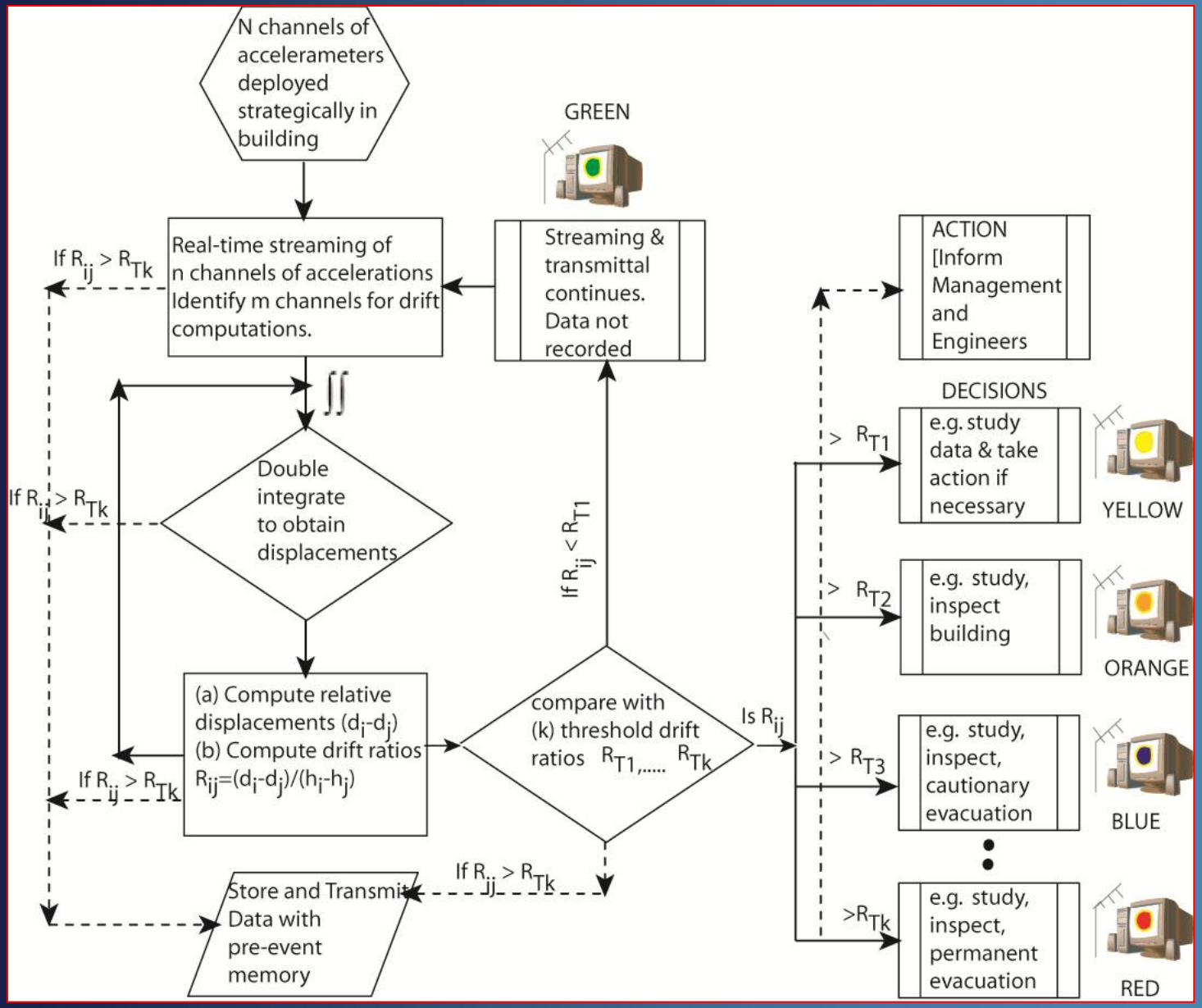
Why Drift Ratio? Connection to Performance

- The most relevant parameter to assess performance is the measurement or computation of actual or average story drift ratios. Specifically, the drift ratios can be related to the performance- based force-deformation curve hypothetically represented in Figure 1 [modified from Figure C2-3 of *FEMA-274* (ATC 1997)]. When drift ratios, as computed from relative displacements between consecutive floors, are determined from measured responses of the building, the performance and as such "damage state" of the building can be estimated as in the figure (below).





APPROACH 2: Displacement via Real-time Double Integration [softwares are marketed…many applications, Celebi (2008)]



DRIFT RATIO APPLICATIONS in CODES

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 (2007): 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)

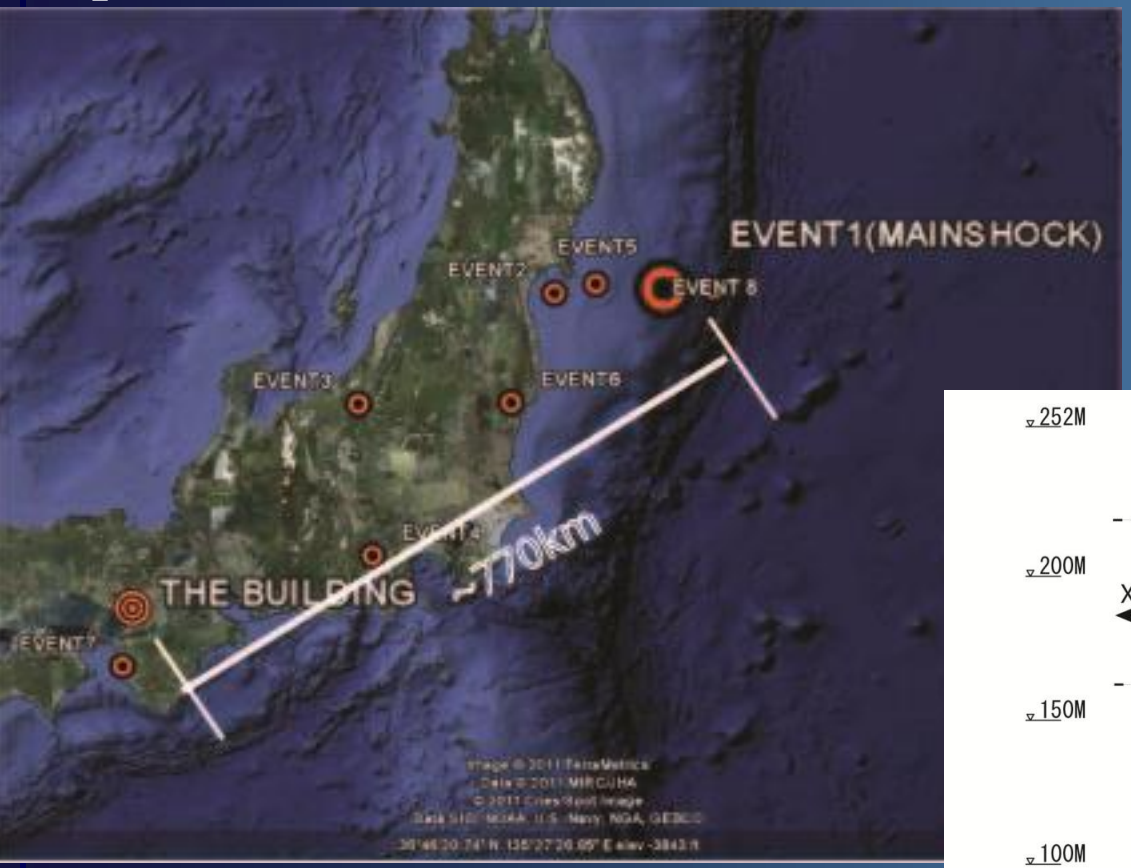
FOUR CASES:

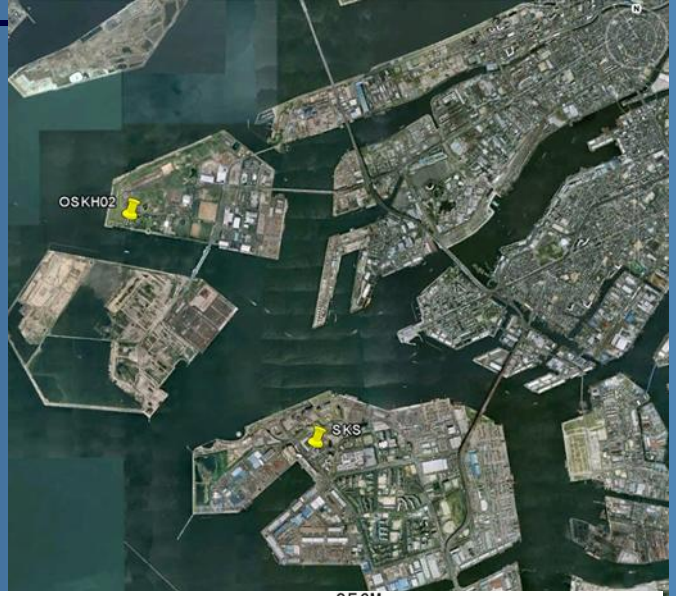
Building A: ~770 km from epicenter

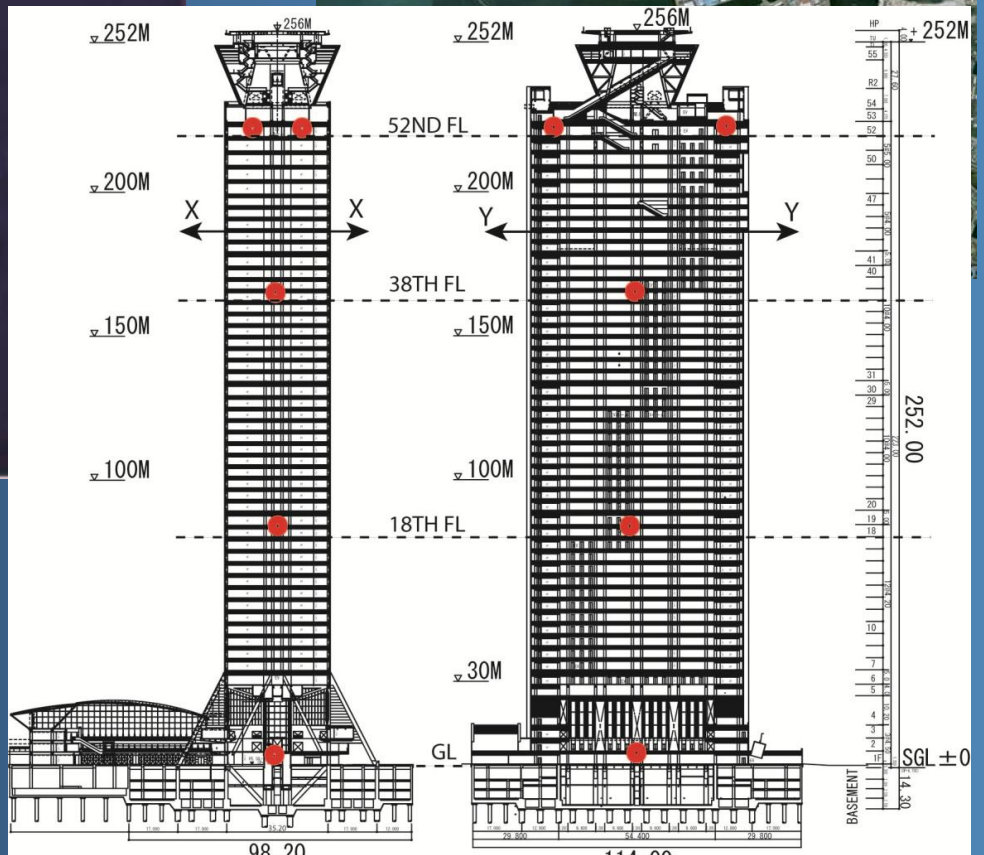
Building B:~350-375 km from epicenter

Buildings C & D: ~ Shinjuku, Tokyo

Building A; in Osaka Bay ~770 Km from epicenter of March 11, 2011 main-shock

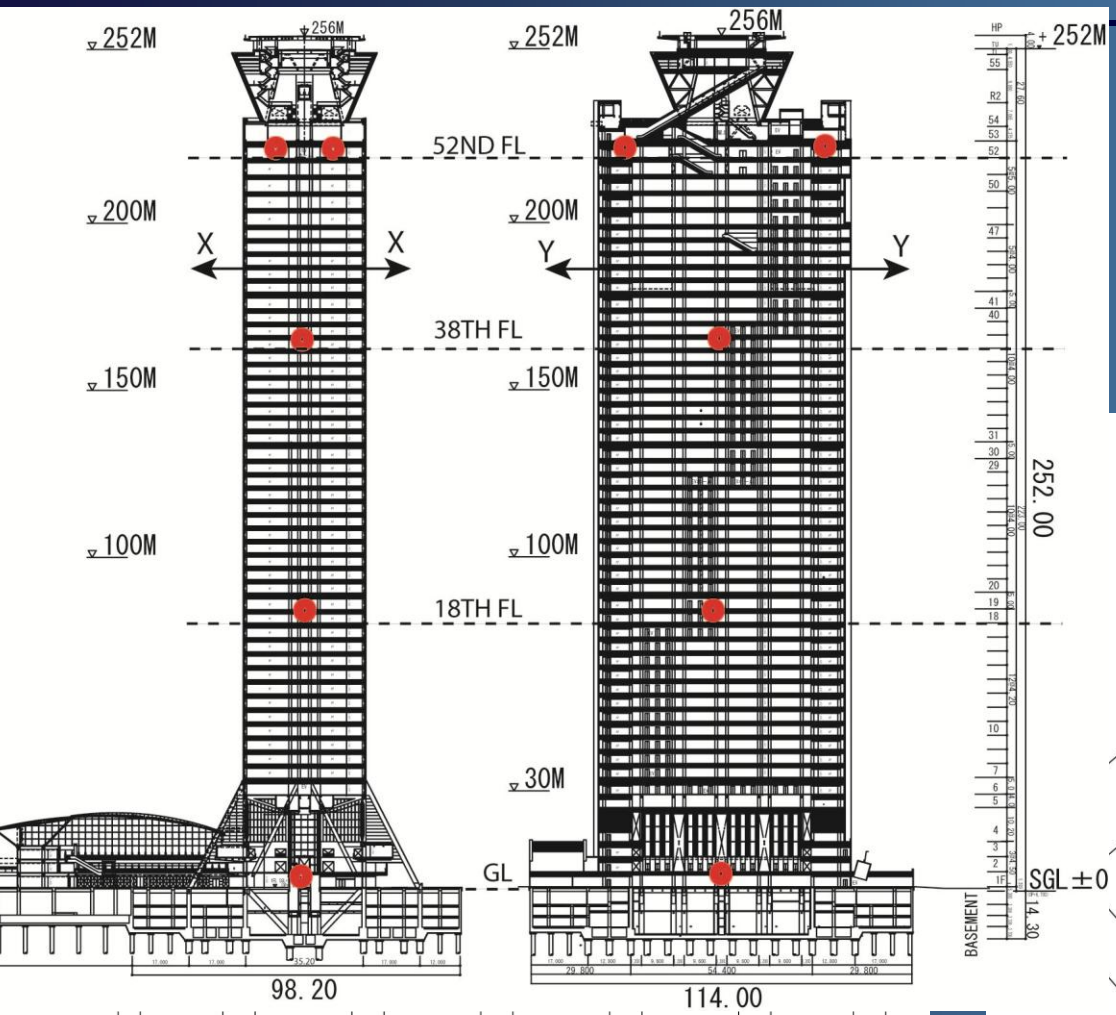


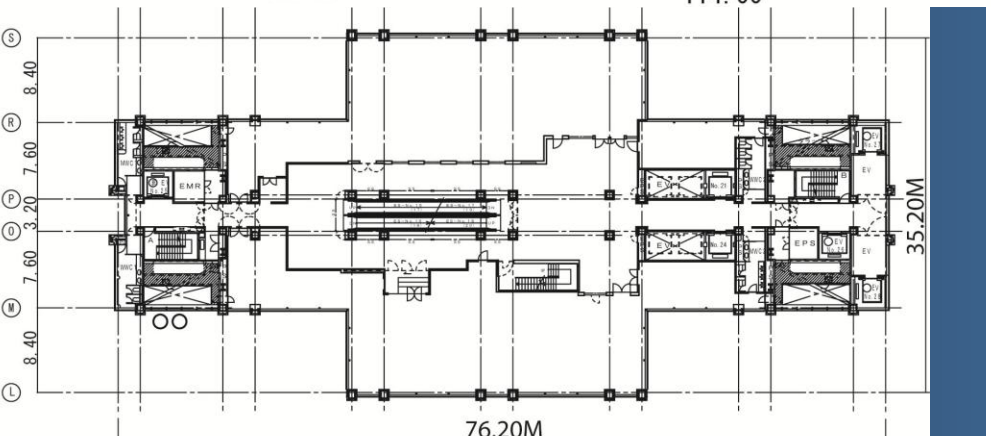


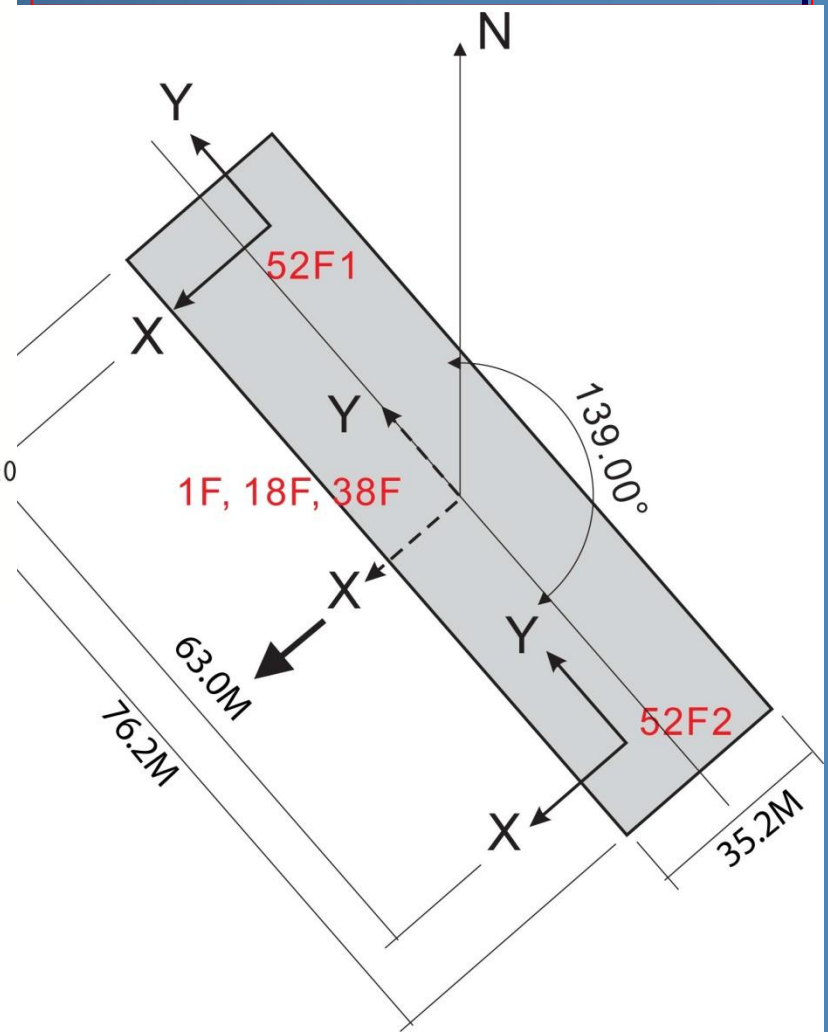


- 256 m tall (55 stories+3 story basement)
- Construction finished in 1995 (pre-1995 code, pre-(KIK-NET/K-NET). Vertically irregular, steel, moment-frame (rigid truss-beams/10 floor). No shear walls around elevator shafts
- 60-70 m long piles below foundation

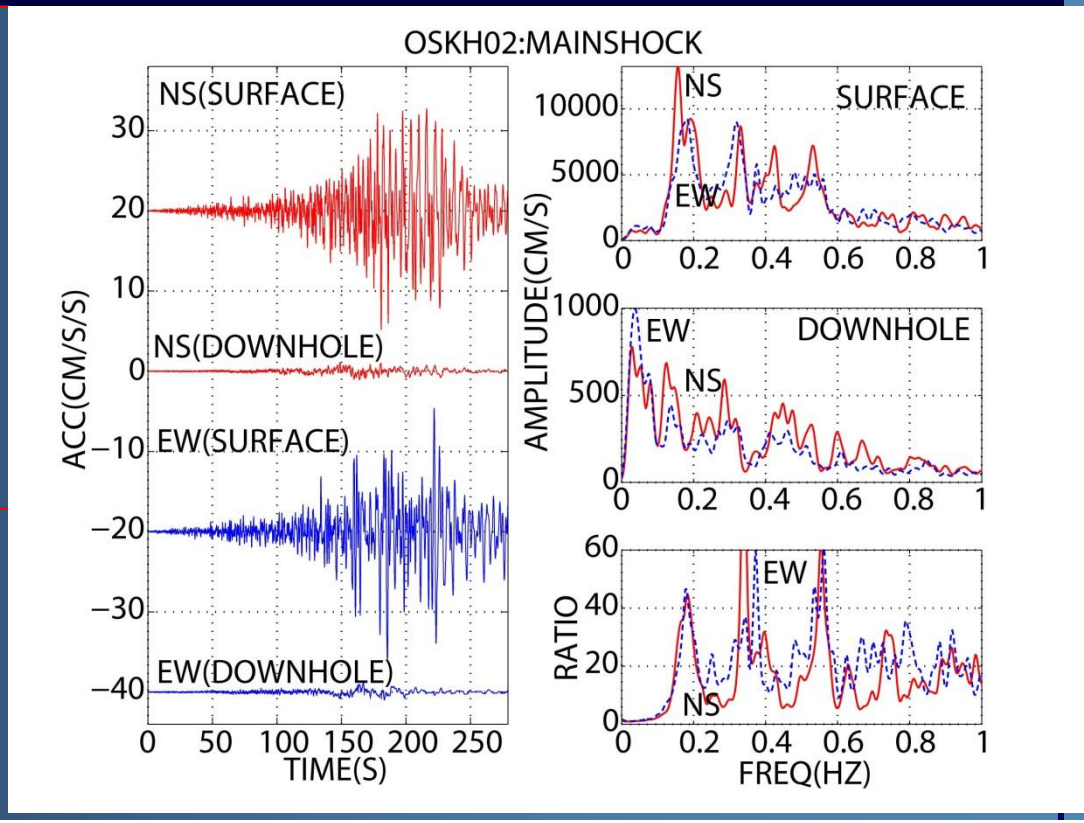
The building & instrumentation (sparse)

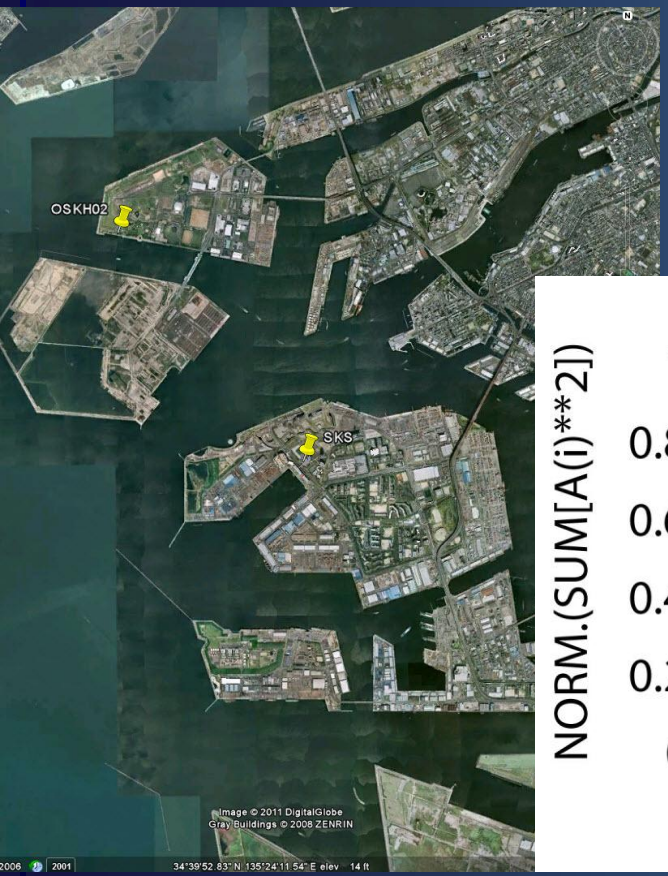


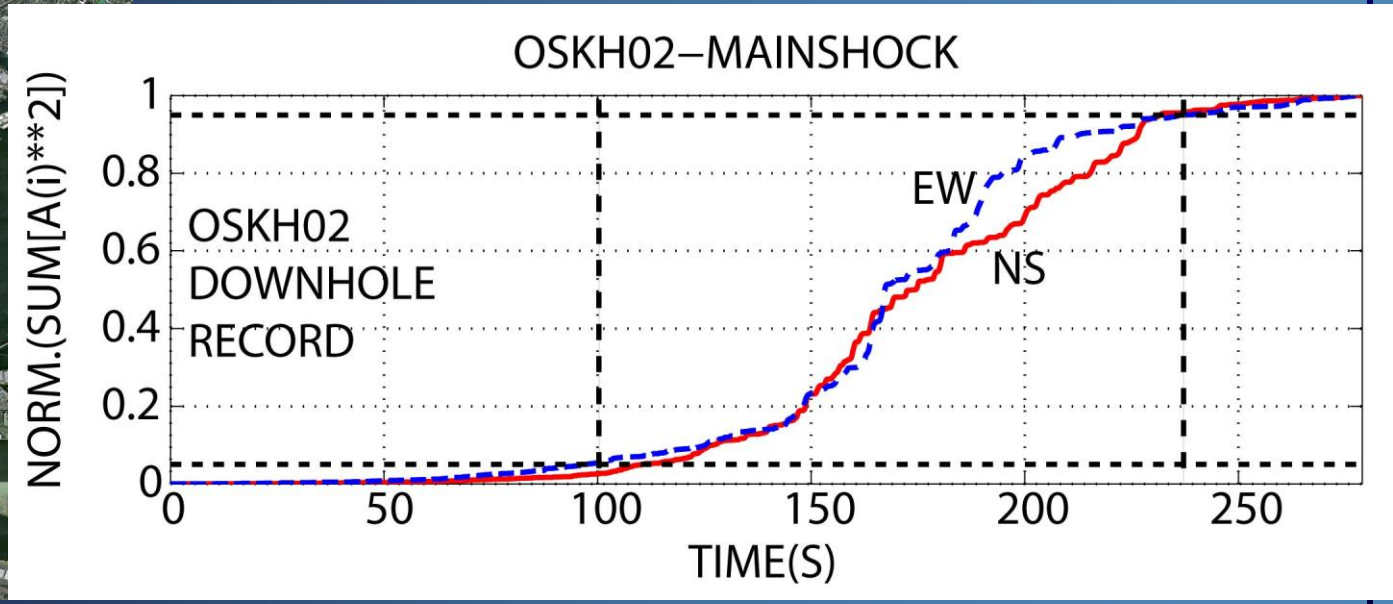




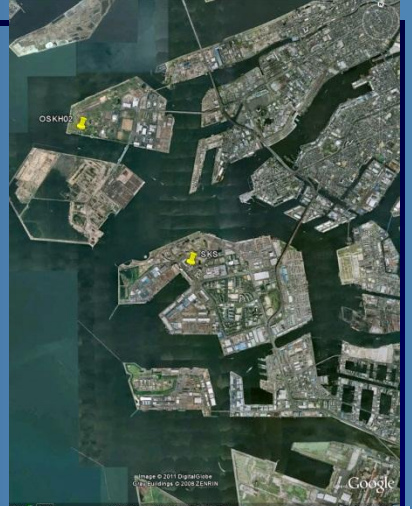
Closest Free-Field Station: OSKH02 (KIK_NET) Record indicates [(a) site frequency from actual data (~.14-.18 Hz) & (b) shaking duration]

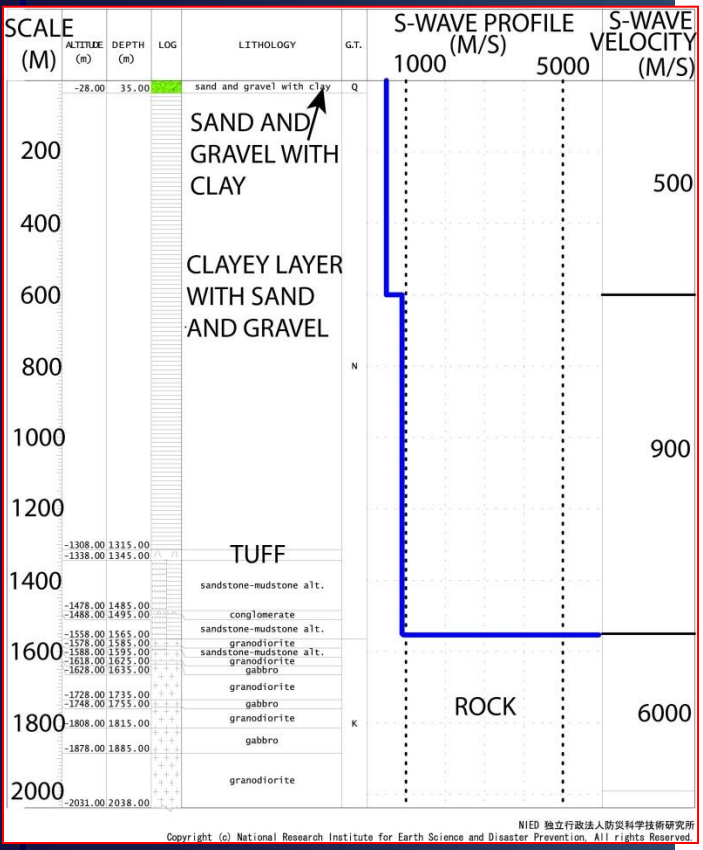


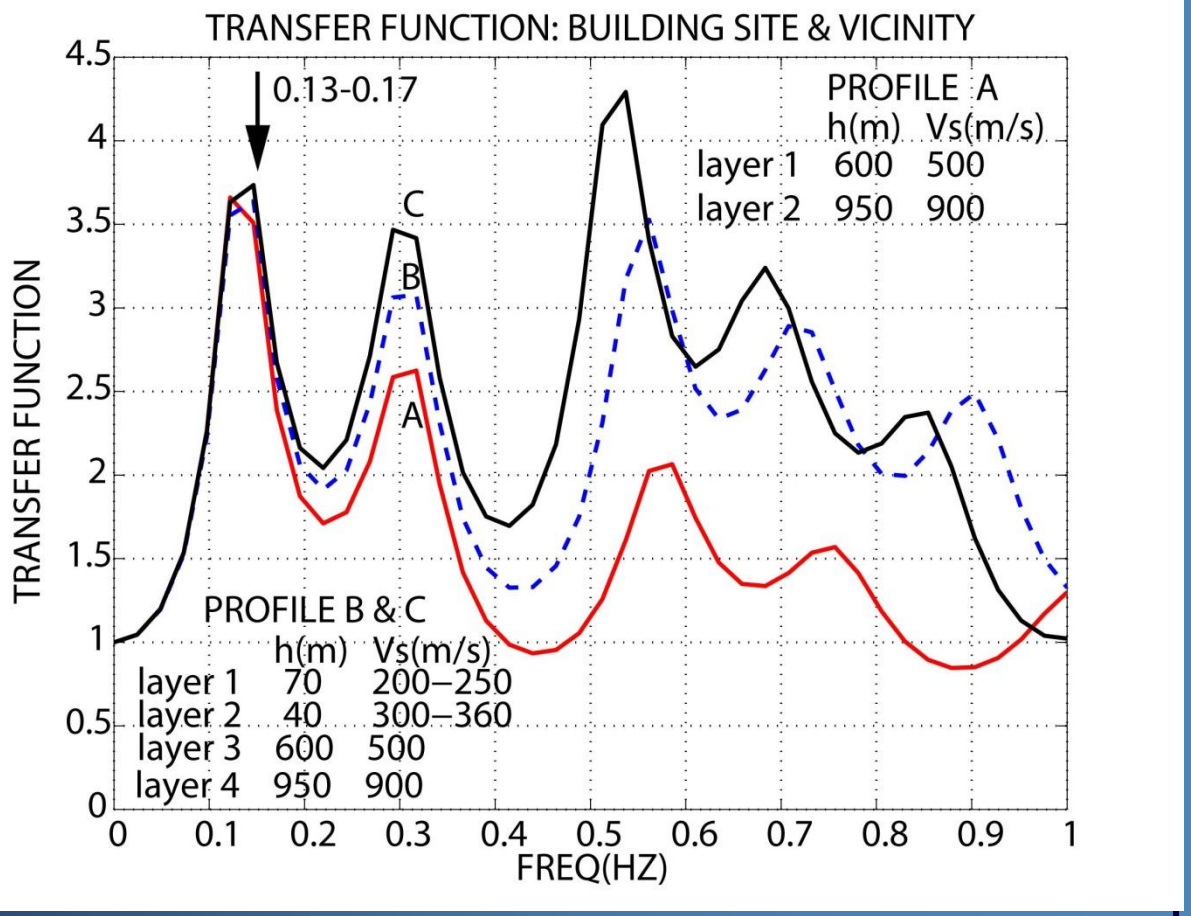


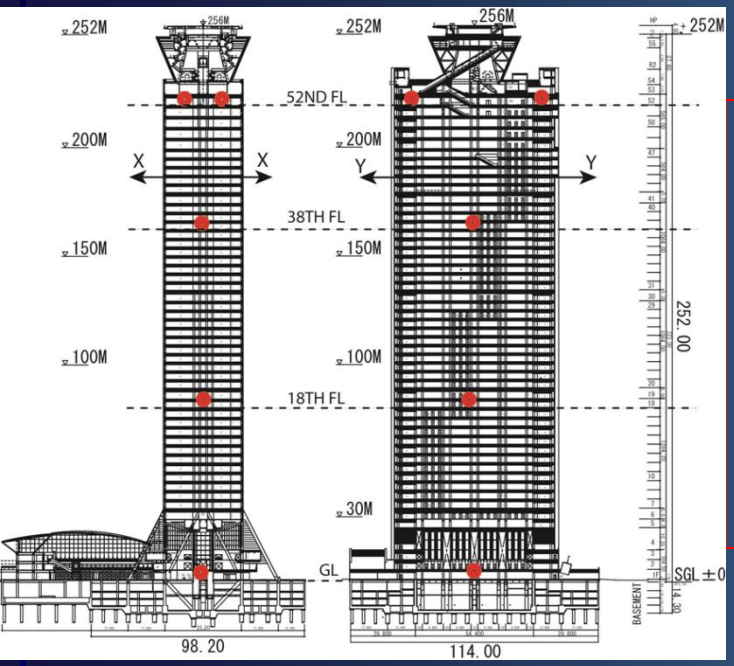


Site Info from OSKH02 and building site indicate similarities and hence result in similar site frequency as that of strong shaking data [f(site)~0.13-0.17 Hz]



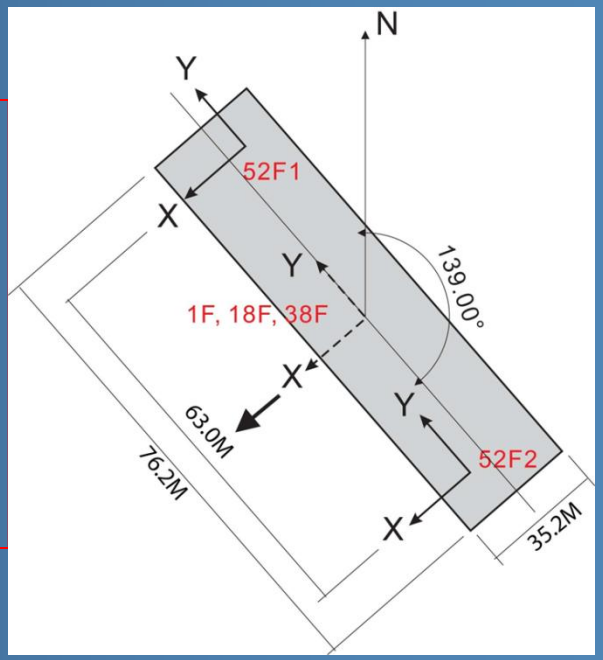


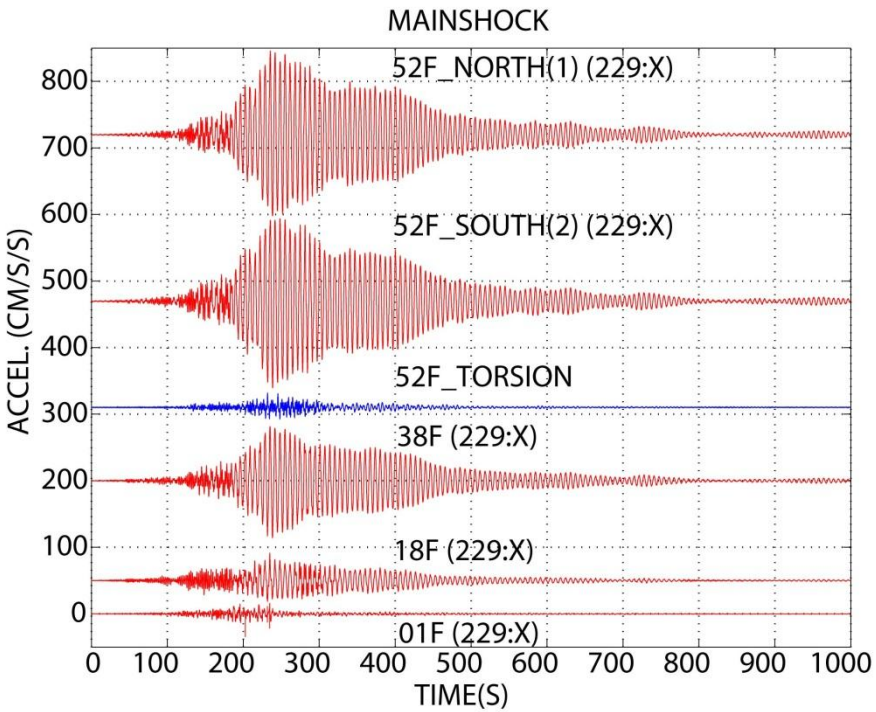


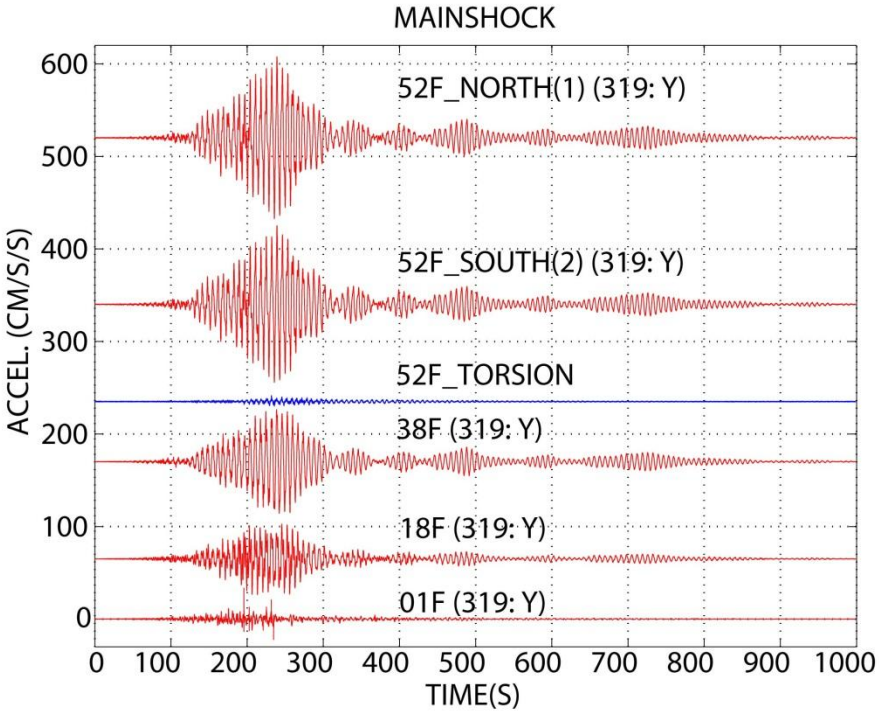


ACCELERATIONS RECORDED (MAIN-SHOCK)

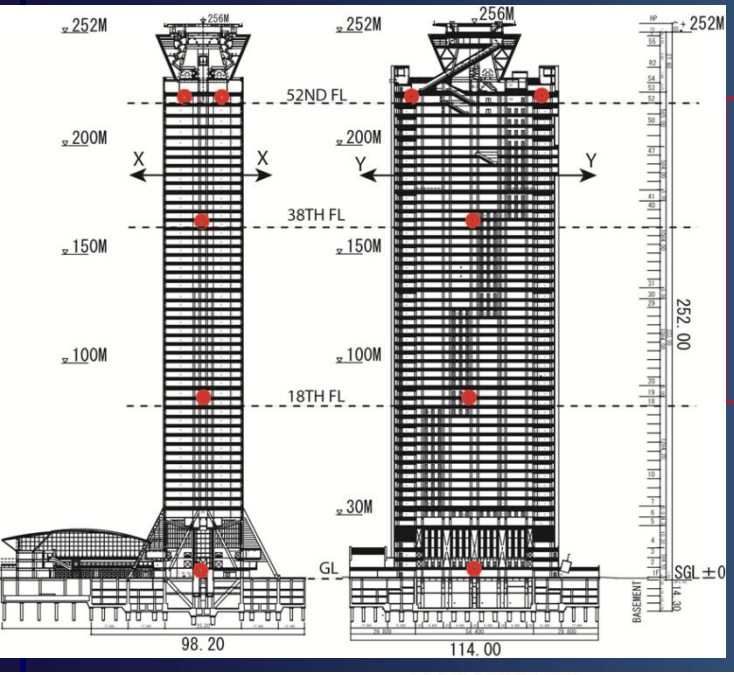
Note long duration of record and strong shaking

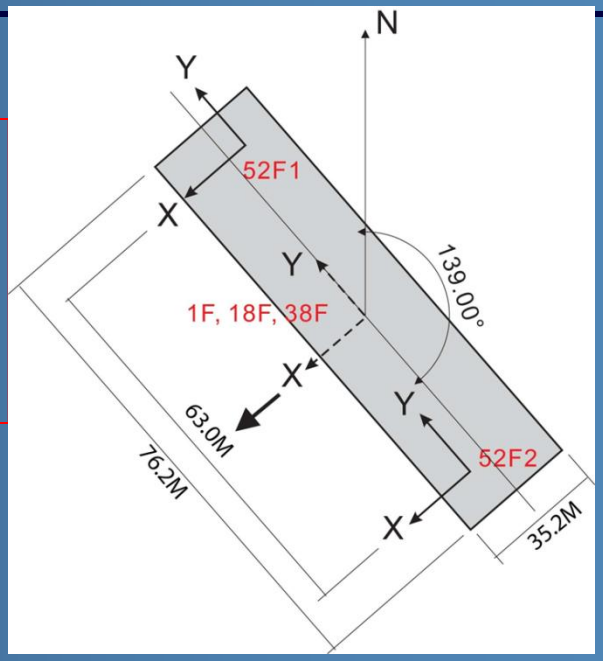


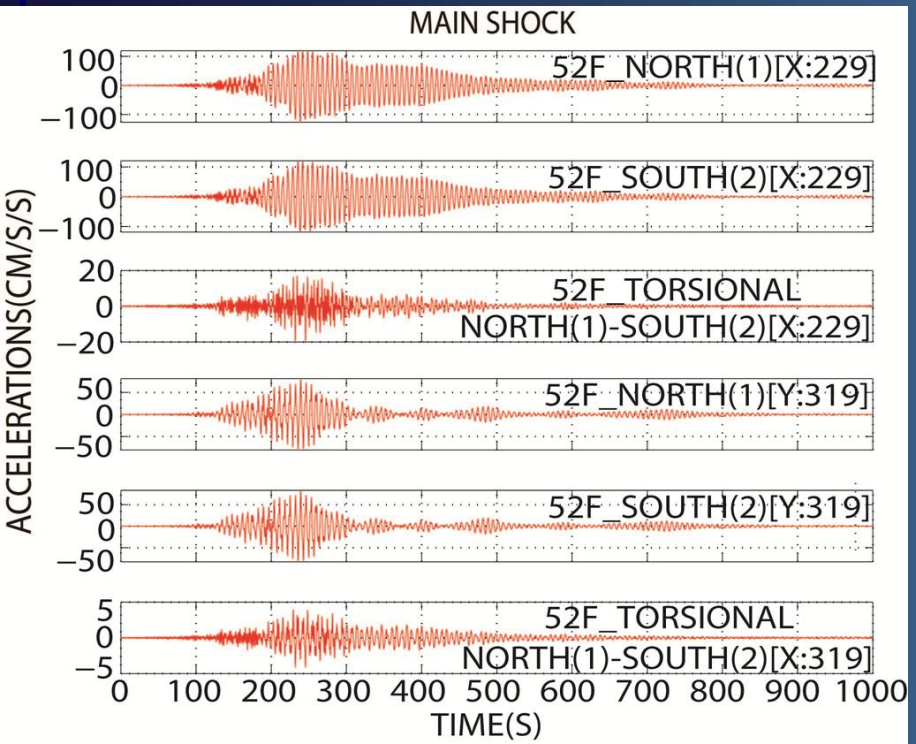


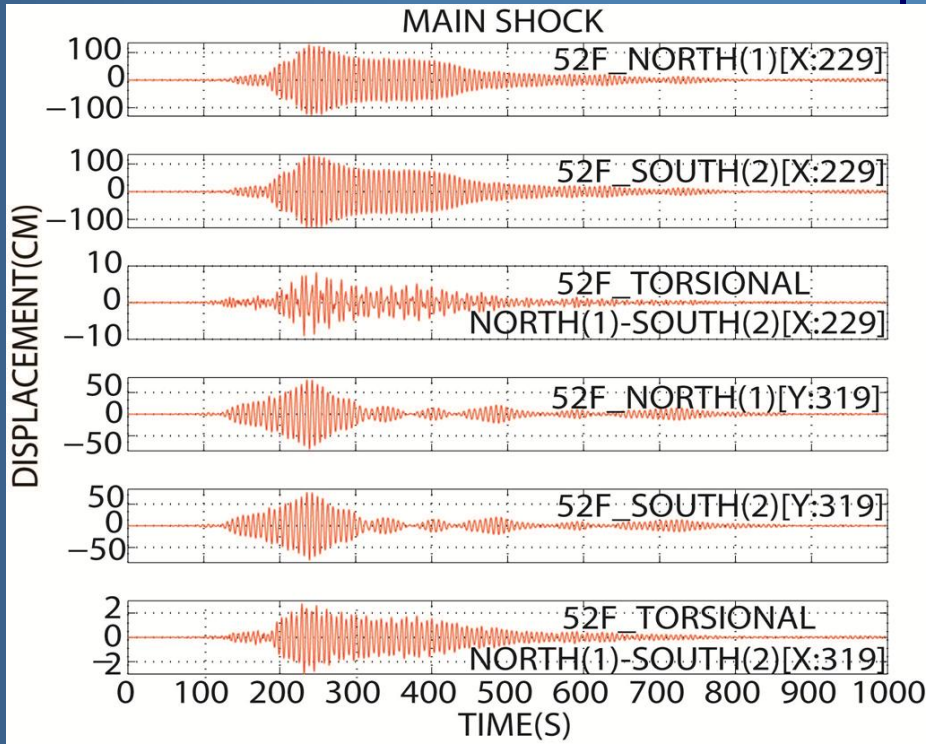


ACCELERATIONS & DISPLACEMENTS AT 52ND FLOOR



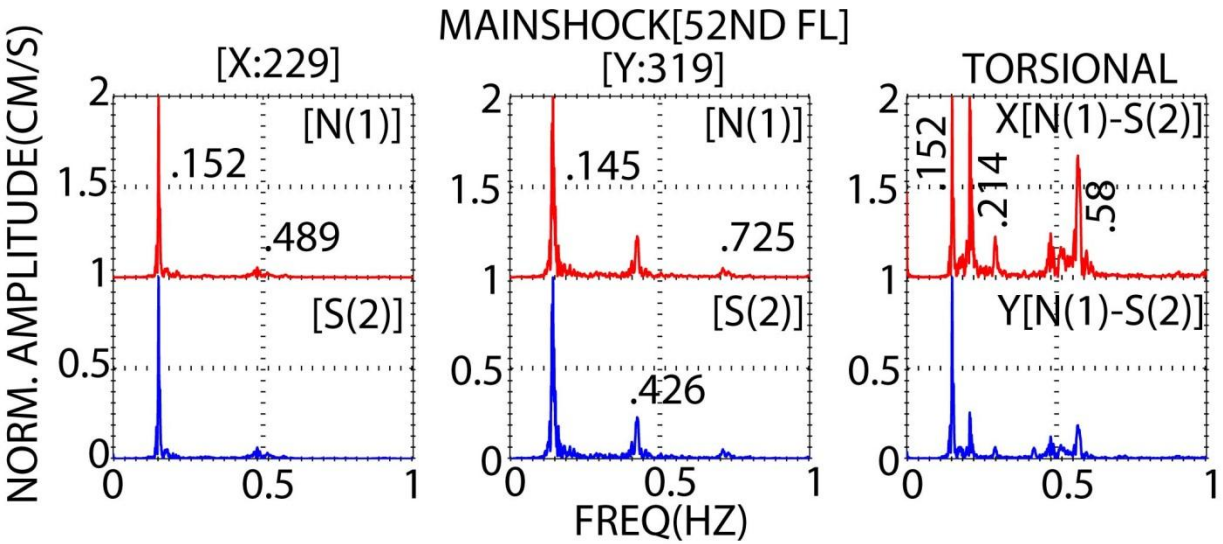


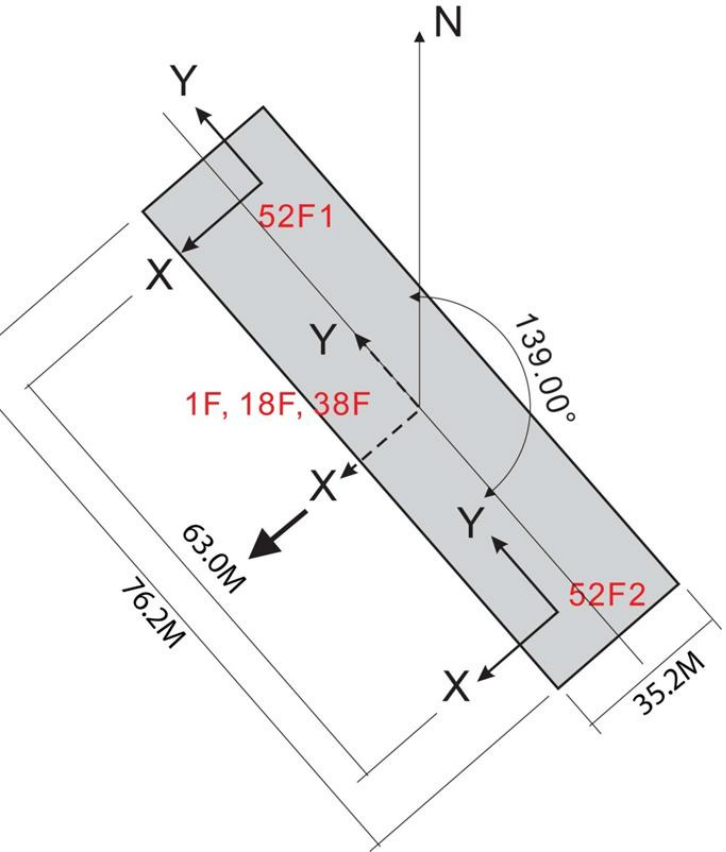


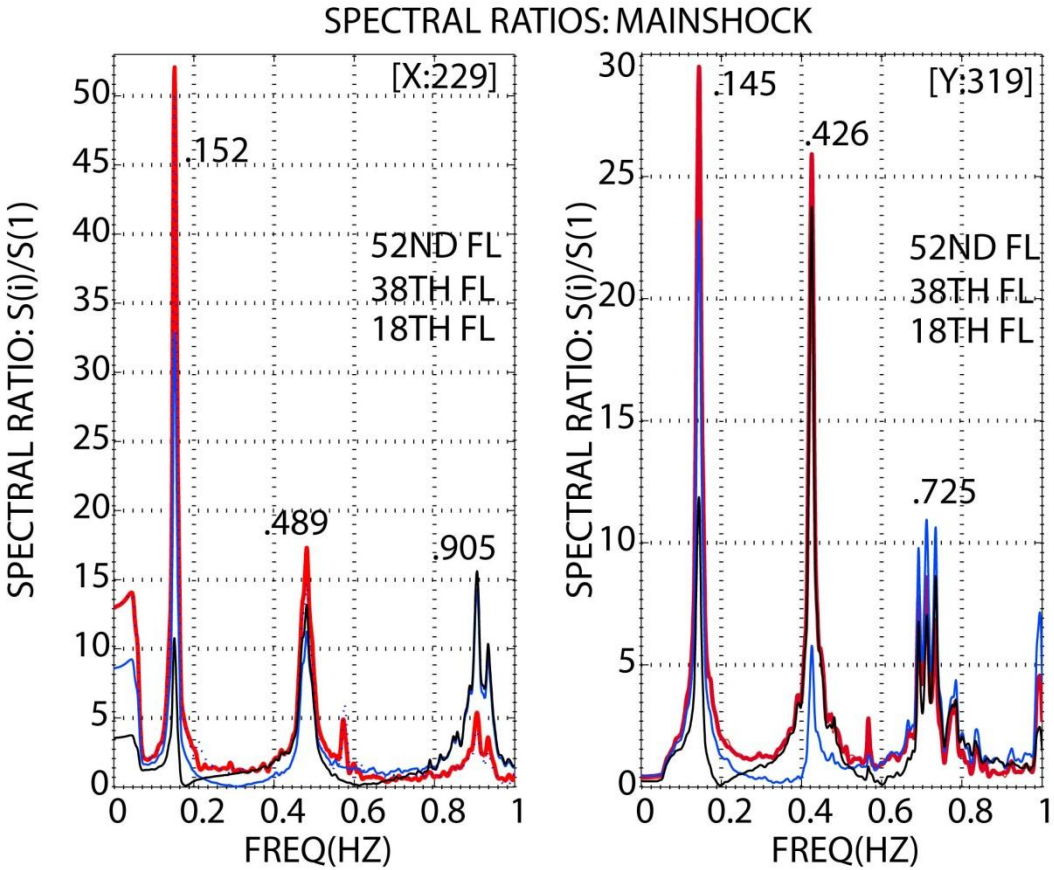


Amplitude Spectra and Spectral Ratio (w.r.t 1st Floor)

Note: $f_{bldg} \sim f_{site}$

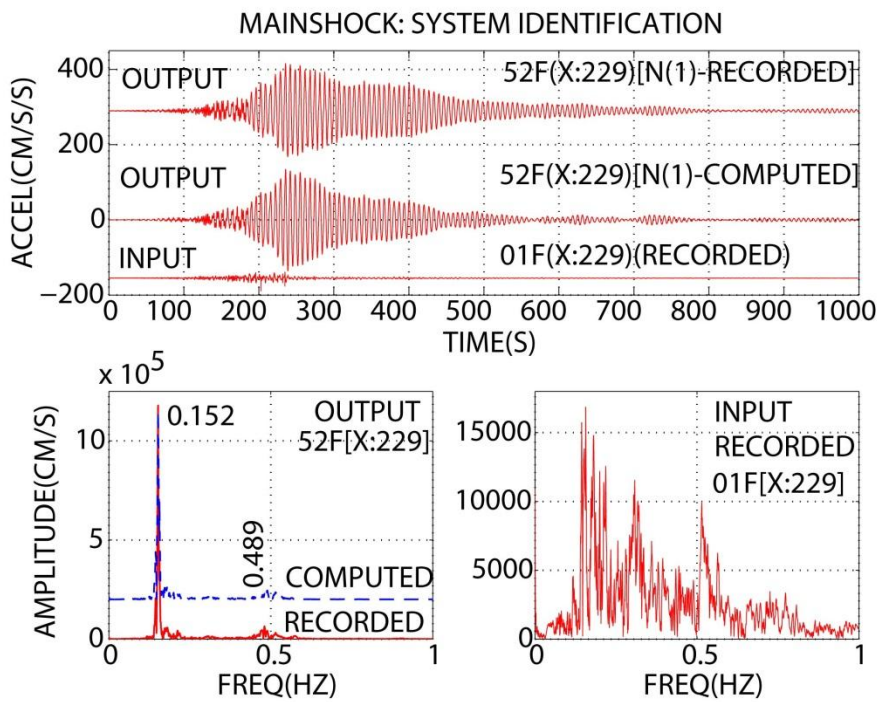


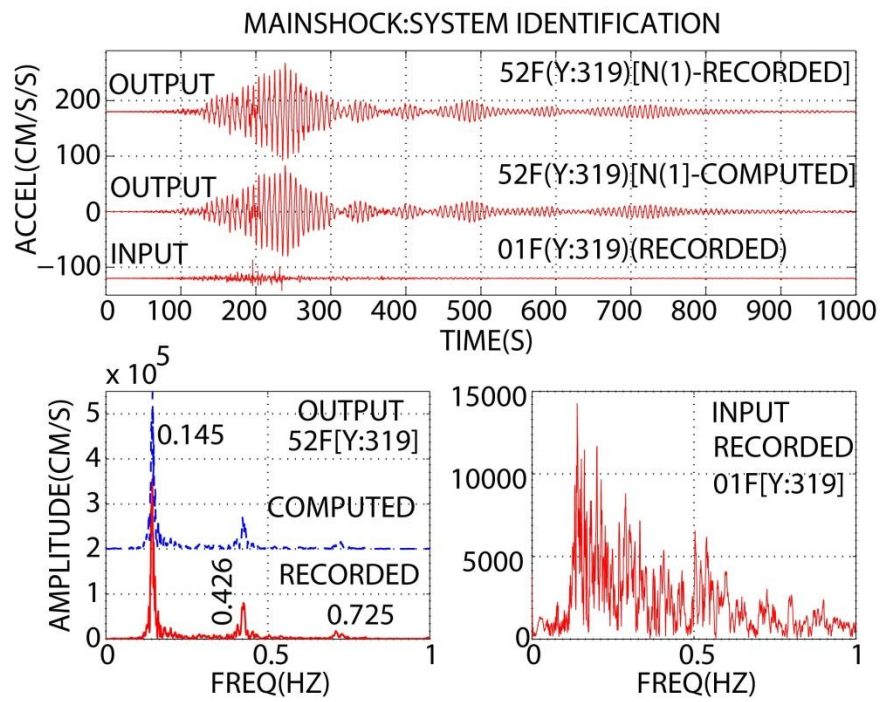




System Identification

ORIENTATION	X[229]			Y[319]			TORSION	
MODES	1	2	3	1	2	3	1	2
SYSTEM IDENTIFICATION								
MAINSHOCK [EVENT 1] (System Identification)								
Freq(Hz) [T(s)]	0.1524 [6.56]	0.4887 [2.05]	N/A	0.1447 [6.91]	0.4264 [2.35]	0.7250 [1.38]		
Damping (ξ)	0.012	0.020		0.016	0.001	0.020		



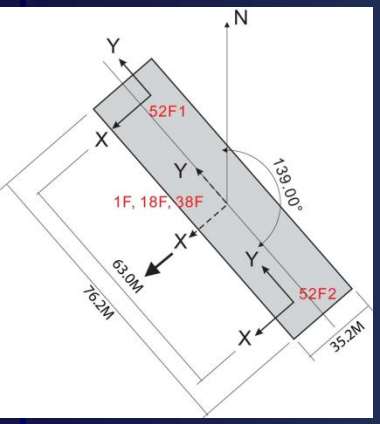


Design Analyses, Spectral Analyses & System Identification [NOTE: LOW DAMPING!!]

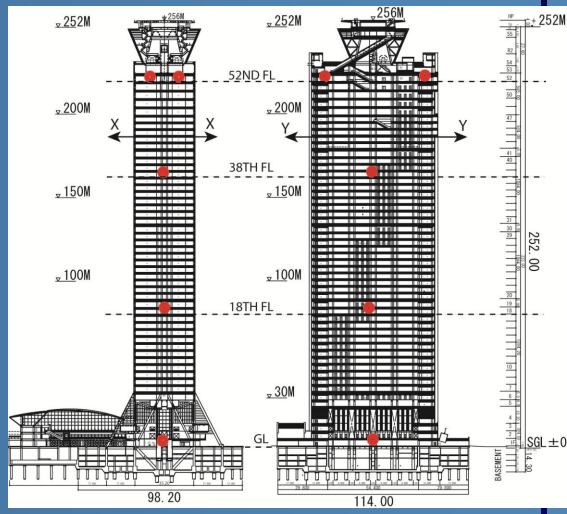
ORIENTATION	X[229]			Y[319]			TORSION	
MODES	1	2	3	1	2	3	1	2
ANALYSES DURING DESIGN								
Freq(Hz) [T(s)]	.1887 [5.3]			.1724 [5.8]			.2703 [3.7]	
MAINSHOCK [EVENT 1] (Spectral Analyses)								
Freq(HZ) [T(s)]	0.152 [6.58]	0.489 [2.06]	0.905 [1.11]	0.145 [6.90]	0.426 [2.34]	0.725 [1.38]	.213 [4.69]	.58 [1.72]

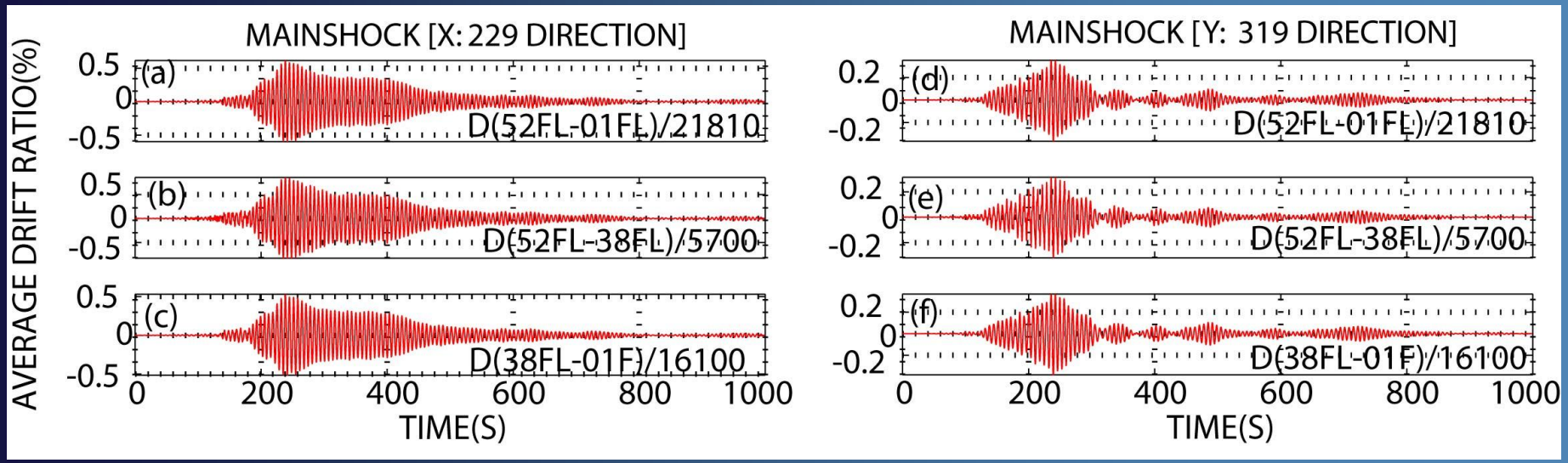
SYSTEM IDENTIFICATION							
MAINSHOCK [EVENT 1] (System Identification)							
Freq(Hz) [T(s)]	0.1524 [6.56]	0.4887 [2.05]	N/A	0.1447 [6.91]	0.4264 [2.35]	0.7250 [1.38]	
Damping (ξ)	0.012	0.020		0.016	0.001	0.020	

AVERAGE DRIFT RATIO



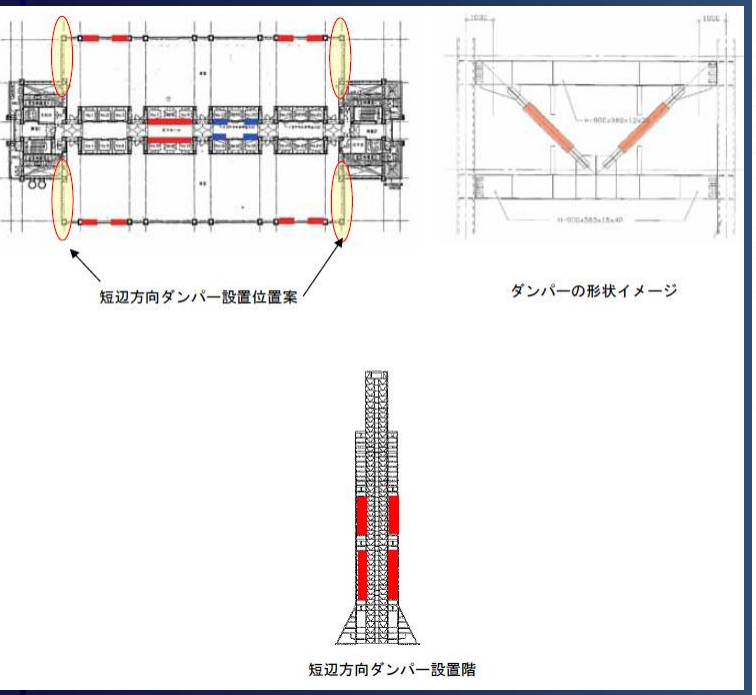
- Why average drift ratio?
- Sparse instruments
- ~.005 (or ~.5%) drift ratio (X-Dir)
- Implications(!!): 3%g input motion, ~.5% drift ratio: not-acceptable

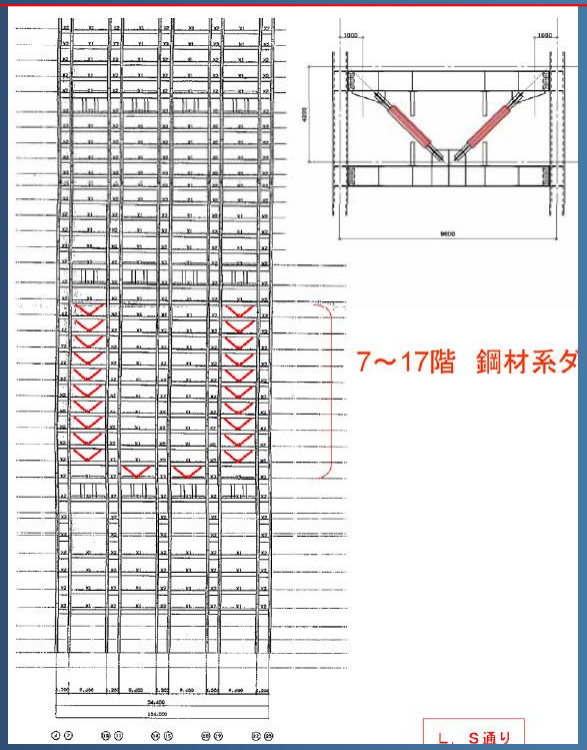


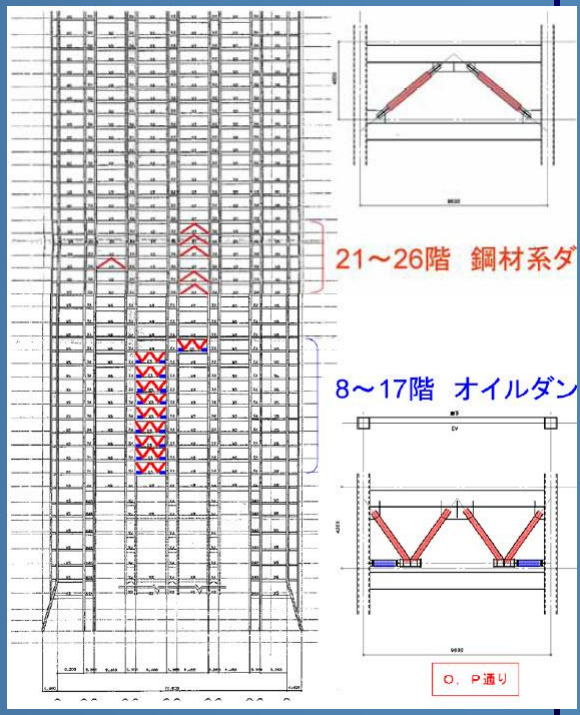


Building A:CONCLUSIONS AND REMEDIES

- Building lost functionality for many days due to elevator cable entanglements and other problems.
- Resonance occurred and still occurs because f(building)~f(site)
- Damping is too low [ambient tests could have provided some clues]
- (average) Drift Ratios are high for a 3% g input motion. What if input a>.2g?
- Sparse instrumentation
- Implications (US): tall buildings in Chicago, NY, Boston from far sources
- Structural Response Modification Technologies (being designed – see below)



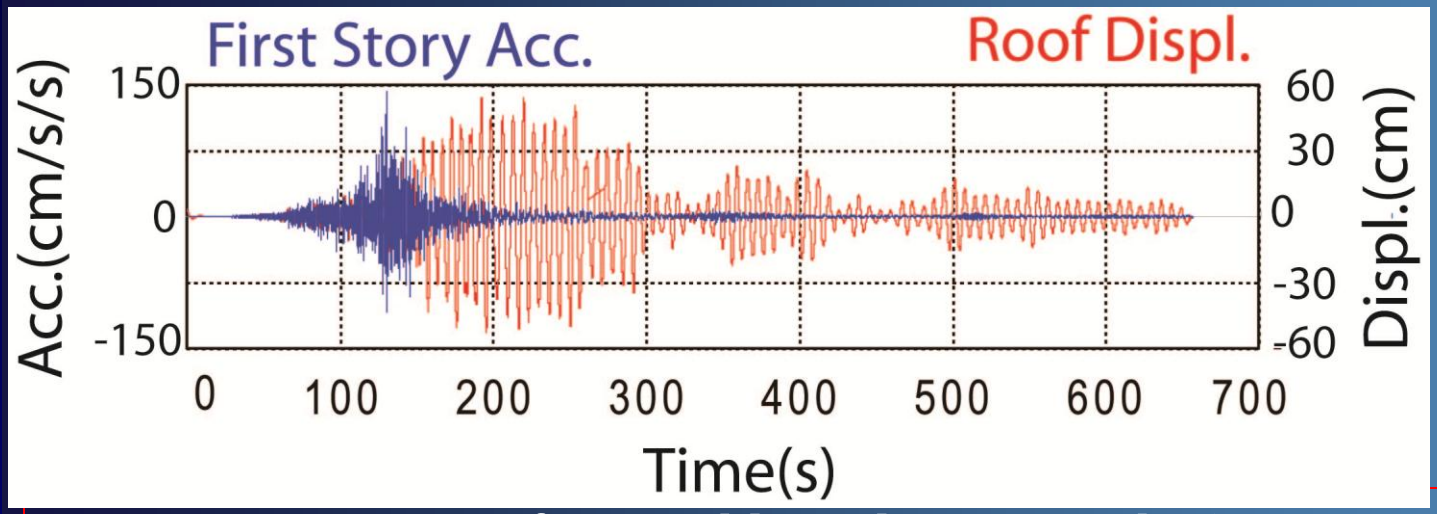




Building B: 55-Story Shinjuku Center Building in Shinjuku, Tokyo (~350-375 km from Epicenter)

According to EERI Special Earthquake Report (EERI Newsletter, 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. The dampers were calculated to have reduced the maximum accelerations by 30% and roof displacement by 22% ".

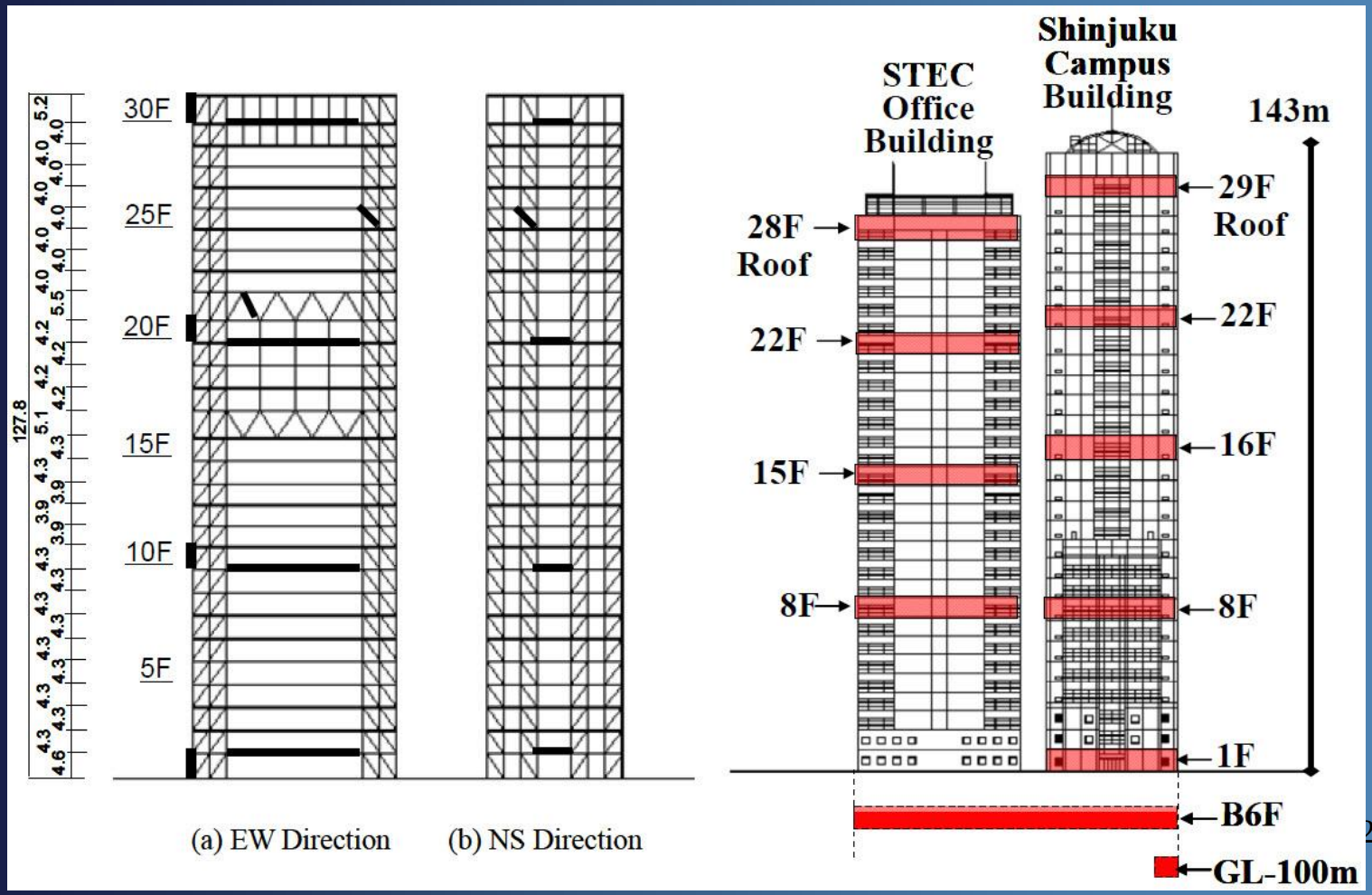
Building B: Shinjuku Center Building



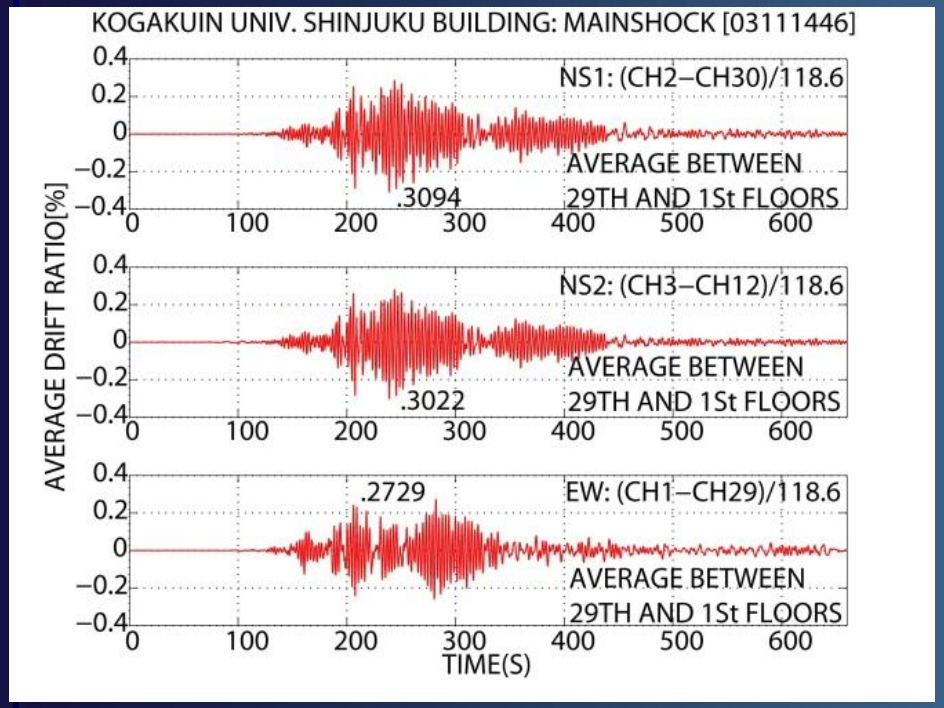
- Figure courtesy of J. Moehle and Y. Sinozaki (Taisei Corp)
- Recorded first story acceleration (BLUE~max ~0.15g).
- Roof level displacement time history (RED : max~54 cm) Most notable is the long duration motion over 10 minutes.
- <u>AVERAGE</u> DRIFT RATIO: 54/21600 = ~0.25% < 1% according to Japanese practice.
- However: 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

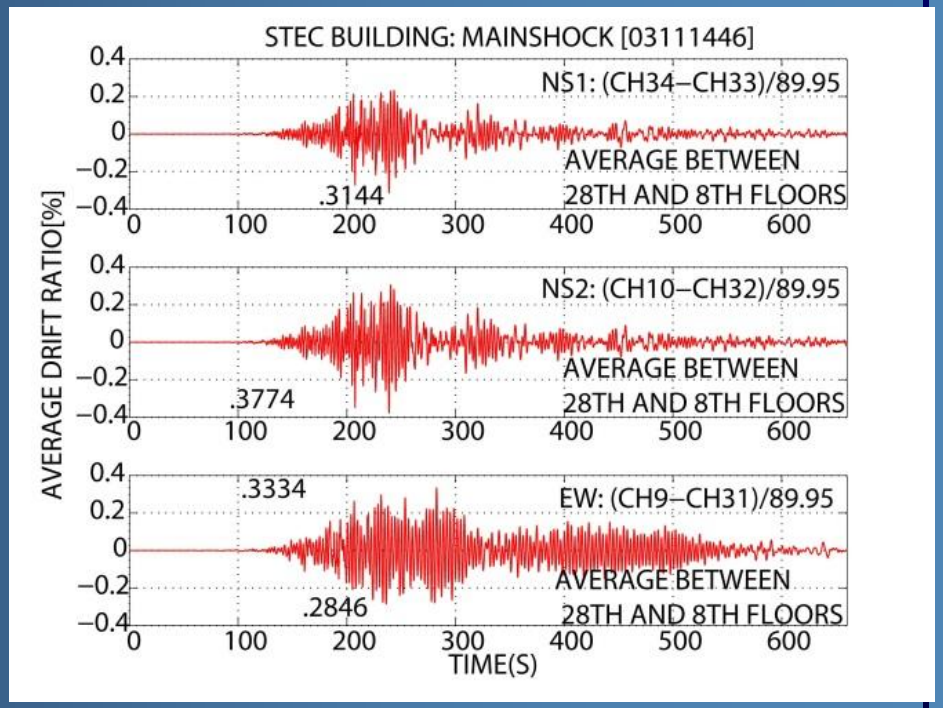
Buildings C & D

Vertical sections showing instrumented floors of Building C (30 stories) and Building D (28 stories) in Shinjuku area of Tokyo, Japan (Figure adopted from Hisada and others (2012a and 2012b).



Average drift ratios computed from recorded data of Building C and D.





SUMMARY

Bldg	Epicentral Distance (km)	Peak Accel. 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 and others (2012a and 2012b)							
Peak accelerations (gals) at Free-Field Stations in vicinity of the buildings							
Free-Field station		NS	EW				
KIKNET:OSKH02\surface		13	15				
OSKH02\downhole		1	1				
KNET: TKY007		198	165				

QUESTION: CLOSER LARGER INPUT ACCELERATIONS WITH SIMILAR FREQUENCY CONTENT – what happens?

Some GMPE computations suggest this is possible!

CONCLUSIONS (1/2)

- 1. For small ground level input ground motions as in the two cases presented herein, these two tall buildings deformed significantly to experience sizeable drift ratios.
- 2. Collection of such data is essential (a) to assess the effect of long period ground motions on long period structures caused by sources at large distances, and (b) to consider these effects and discuss whether the design processes should consider reducing drift limits to more realistic percentages (c) finally, further applications of unique response modification features are feasible to reduce the drift ratios.

CONCLUSIONS (2/2)

- 3. 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.
- 4. The risk from closer large-magnitude earthquakes that could subject the buildings to larger peak input motions (with similar frequency content) 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.

THANK YOU!

Q?