Simulated Nonlinear Response of High-rise Buildings for the 2003 Tokachi-oki Earthquake Mw8.3

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1. Introduction

Seismic waves from large subduction earthquakes are rich in long periods waves that may be especially large in regions with local site amplification. The long-term global goal of our research is to investigate how well-designed modern high-rise buildings may perform in giant subduction earthquakes (e.g. Cascadia). Towards this goal, we are studying the Tokachi-oki 2003 earthquake (Mw8.3) which is the largest well recorded earthquake till now and was recorded by 276 strong motion stations located in Hokkaido Island. We use records from these stations to simulate the fully nonlinear seismic responses of 6- and 20- story steel moment-frame buildings designed according to both the U.S. 1994 UBC and also Japanese building code published in 1987. We consider buildings with both perfect welds and also with brittle welds whose fracture characteristics are similar to those observed in the 1994 Northridge earthquake.

From this research, we find that although Japanese code buildings are stronger, they are also stiffer which tends to increase the global forces experienced by Japanese buildings by more than 20% compared with U.S code buildings. The net effect is that when considering collapse potential, the Japanese buildings can sustain motions about 6% larger than the U.S. buildings. Moreover, our simulations indicate the building would have been strongly excited throughout the coastal region, with the potential for collapses in some locations.

2. The 2003 Tokachi-oki Earthquake Mw8.3

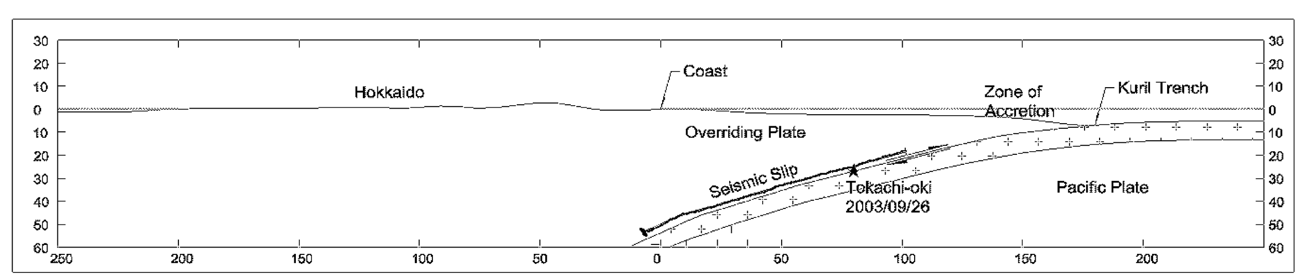
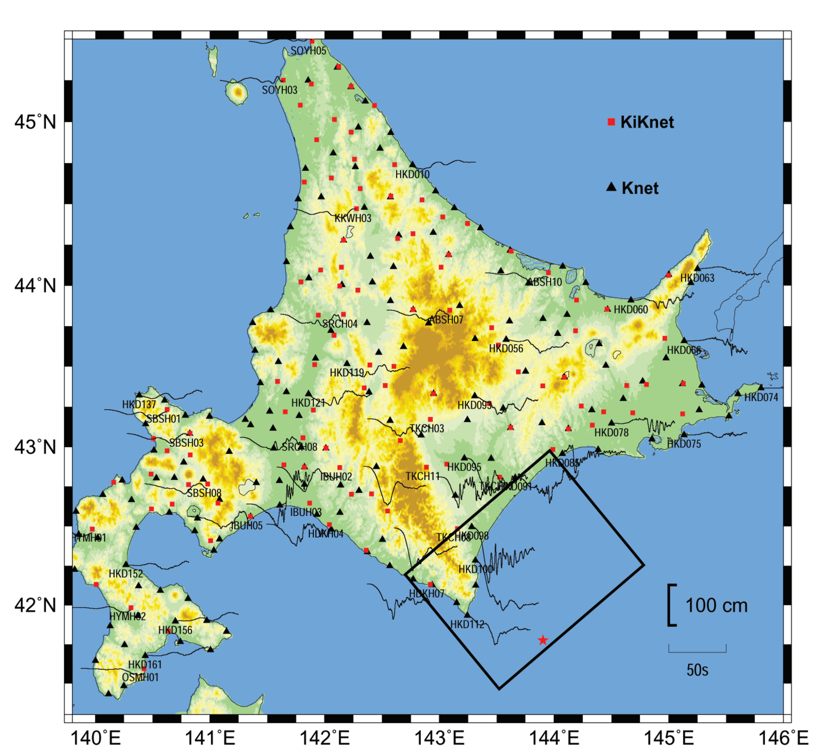


Figure 1: Cross section of the approximate geometry of the rupture surface with respect to the island of Hokkaido. This event occurred on the main subduction interface of the highly active Kuril trench. The Pacific plate is subducted toward N60° W beneath Hokkaido region at a rate of about 8 mm/year.

Table 1: Summary of maximum values for ground motions

	Maximum peak-to-peak value	Location
Ground Acceleration	1622 cm/s^2	HKD100
Ground Velocity	157 cm/s	IBUH03
Ground Displacement	88 cm	HKD098
Pseudo Acceleration of Response spectra (5% damping) at 1.5 sec (natural period of U6)	1422 cm/s^2	TKCH07
Pseudo Acceleration of Response spectra (5% damping) at 3.5 sec (natural period of U20)	452 cm/s^2	HKD098



Information about this event:
Epicenter Depth: 27 km
Distance: 80 km east-south east of Cape Erimo, Hokkaido
Strike, dip, rake =230°, 20°, 109°
Source duration: 40 sec
Maximum slip: 5.8 m
Average slip: 2.6 m

Figure 2: The radial components of ground displacements for selected stations. We use the method of Boore (2001), combined with GPS data, to best determine the static displacements for selected stations.

3. Computational Models

We use Frame 2-D, a finite element method based on a fiber-element model that includes both material nonlinearities as well as geometric nonlinearities.

Steel Moment-Frame Building Models (symmetric):

Heights: 6-story and 20-story buildings (plus one basement)
Design Codes: 1994 UBC at seismic zone 4 and Japanese building code (1987)
Welds conditions: brittle (prone to fracture) and perfect (won't fracture)

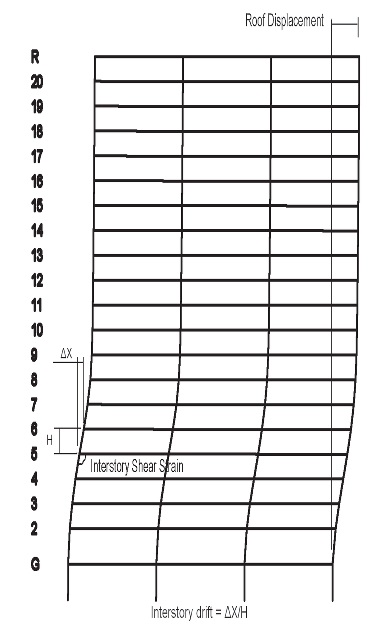


Figure 3: Definitions of the response parameters.

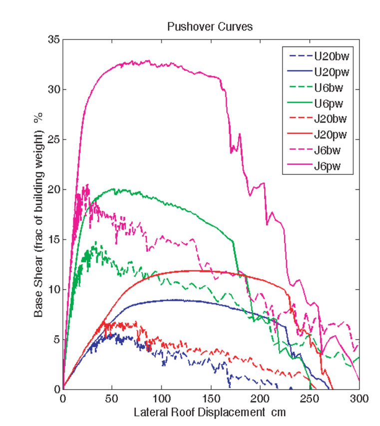


Figure 4: Pushover curves for 6-story and 20-story buildings. This analysis measures the actual strength of buildings. We can find that Japanese buildings are stronger than U.S. buildings and the presence of brittle welds significantly decreases the strength of a building.

Table 2: Property values for the building models

Building Type	U20	J20	U6	J6
Natural Period	3.5 sec	3.05 sec	1.5 sec	1.17 sec
Base Shear Yield Force (fraction of building weight) %	pw: 8.9 bw: 5.9	pw: 11.8 bw: 7.1	pw: 21.5 bw: 15.2	pw: 32.7 bw: 20.6

4. Simulated Nonlinear Responses

All eight buildings models were considered to locate at each station. The summary of their maximum response parameters are listed in table 3. The contour map of the maximum inter-story drift for the US-code 20-story buildings assuming brittle welds is shown in Figure 6.

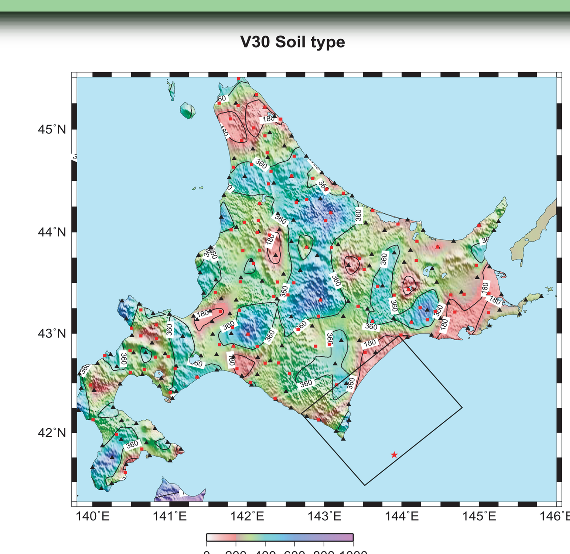


Figure 5: The distribution of average shear wave velocity of soil down to 30 m in Hokkaido area. By comparing with the soil type building response distribution, we see that basins amplify the response of high-rise buildings even far away from the epicenter.

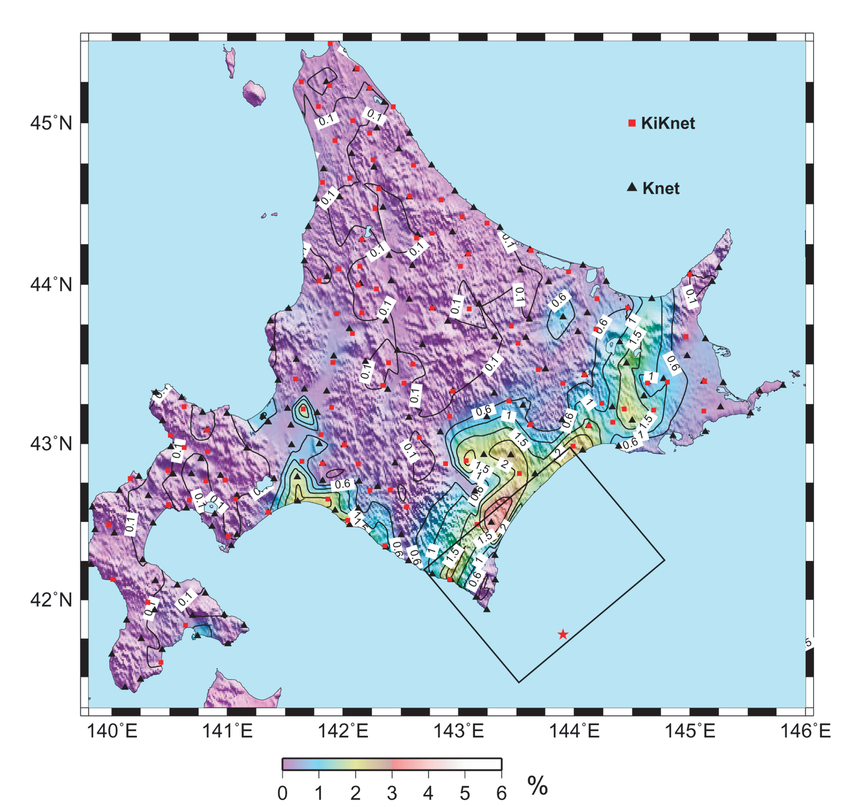


Figure 6: Maximum inter-story drift (in percent) for the U20 (20-story steel frame designed to UBC94) with brittle welds (bw). The maximum value is 3.84% and occurred at HKD098.
Notice the buildings located in the northeast and the south-west regions in Hokkaido will suffer strong shaking although they are almost 200 km away from the epicenter.

Table 3: Summary of responses for each type of buildings

Response	Building Type	Maximum Value	Location
Inter-story drift	U20 bw (brittle welds)	3.84 %	HKD098
	J20 bw	3.35 %	HKD098
	U6 bw	5.53 %	TKCH07
	J6 bw	4.75 %	IBUH03
Roof displacement	U20 bw	93 cm	HKD098
	J20 bw	103 cm	HKD098
	U6 bw	79 cm	TKCH07
	J6 bw	75 cm	IBUH03
Fracture welds	U20 bw	38 %	IBUH03
	J20 bw	36 %	IBUH03
	U6 bw	55 %	IBUH03
	J6 bw	58 %	IBUH03
Inter-story drift	U20 pw (perfect welds)	2.09 %	HKD098
	J20 pw	2.51 %	HKD098
	U6 pw	4.00 %	TKCH07
	J6 pw	2.77 %	TKCH07
Roof displacement	U20 pw (perfect welds)	129 cm	HKD098
	J20 pw	144 cm	HKD098
	U6 pw	70 cm	TKCH07
	J6 pw	49 cm	TKCH07

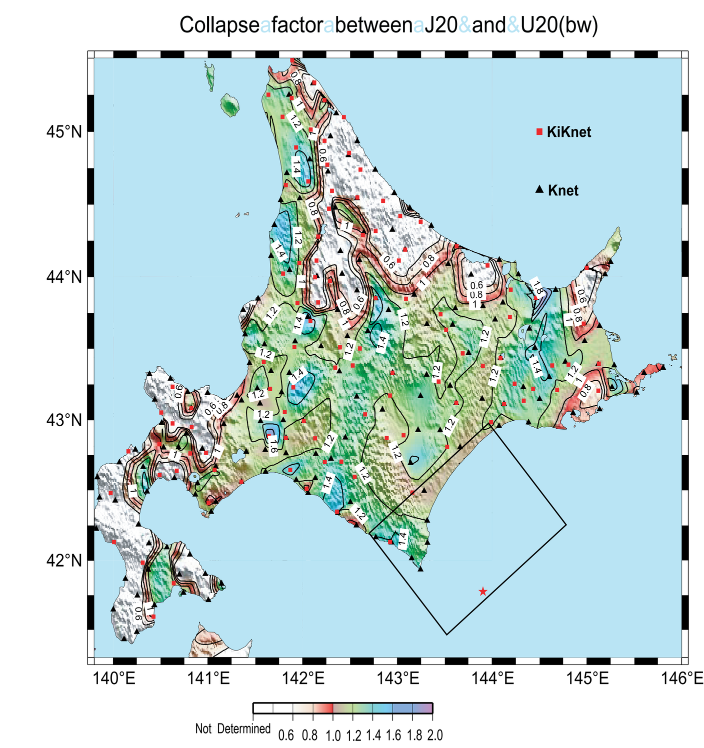


Figure 8: Collapse factor ratio between J20bw and U20bw. The white color shows where the collapse factor is too large to be of interests. As expected, in most areas, J20 is safer than U20 and the ranger is from 1 to 1.4. However for stations close to collapse, the difference between collapse factors for two codes is only 6 %, which is much smaller than the 20% difference in strength of buildings.

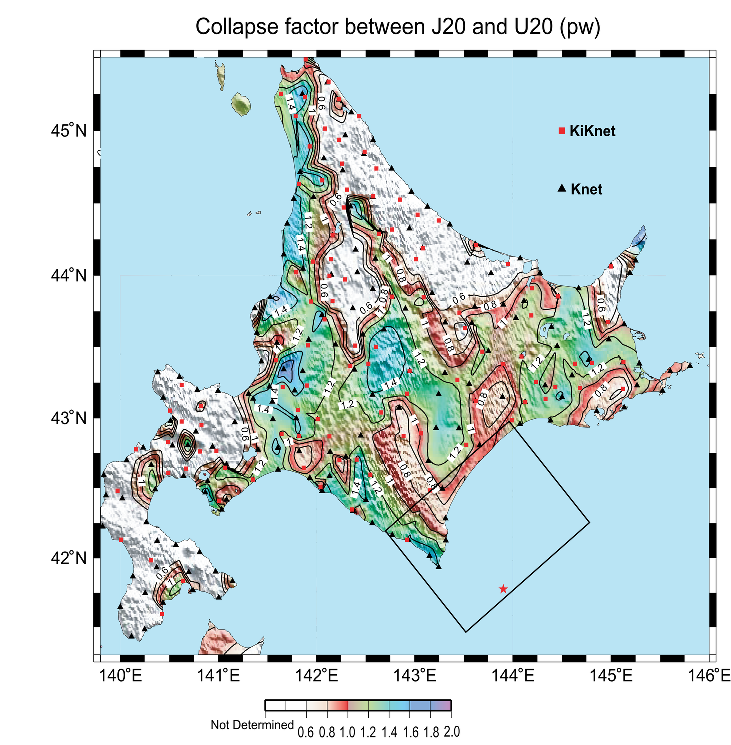


Figure. 9. Collapse factor ratio between J20pw and U20pw. The ratio at HKD098 is 1, which means that the collapse factors for J20pw and U20pw are exactly the same. Unlike figure. 8. in some strongly shaken areas, collapse factors of J20pw are even smaller than that of U20pw.

5. Collapse Factor

We introduce a new parameter named the "collapse factor" to describe the collapse possibility associated with simulated buildings. This safety factor is defined to be the scalar multiplier of the recorded ground motion that is required to cause collapse of the simulated building.

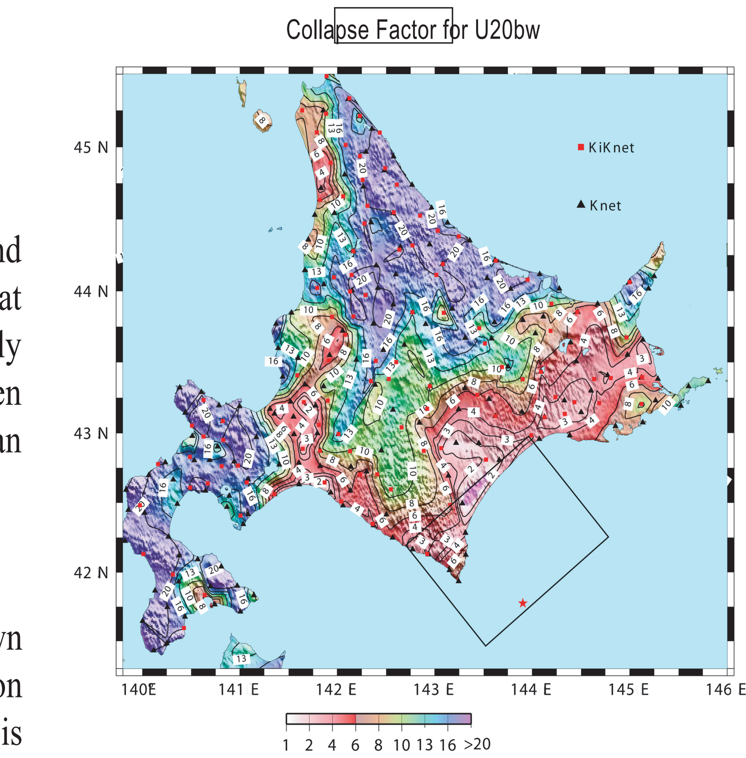
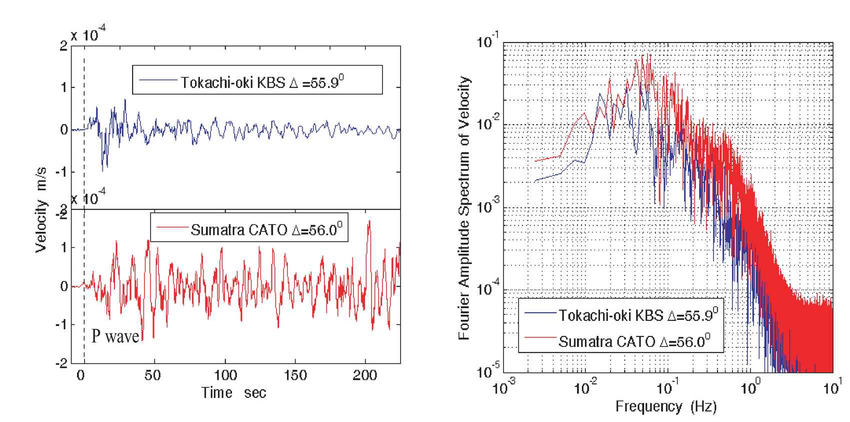


Figure 7: Collapse factor for U20bw. Although no buildings shown collapse in these simulations, increasing the amplitude of station HKD098 by only 6 % caused simulated collapse for U20bw. This is well within the uncertainty of this type of calculation.

Figure 7.

6. Future Work

We plan to simulate strong ground motions of the 2004 Sumatra earthquake by considering the strong motion recordings from the 2003 Tokachi-oki earthquake as empirical Green functions. Simulation the broad-band teleseismic body waves in the frequency band of interest is important for providing constraints on the strong motion simulation.



Right figure 10 show the teleseismic body waves velocities and their freuqncy contents for 2003 Tokachi-oki and 2004 Sumatra earthquakes.

7. Conclusions

- The long-period ground motions recorded in the 2003 Tokachi-oki earthquake would have caused large inter-story drifts in 20-story flexible steel moment-resisting frame buildings designed according to both current U.S. and Japanese building codes.
- Although Japanese buildings are 20%~30% percent stronger than U.S. buildings, their capacity to resist collapse does not proportionally increased. Japanese buildings with brittle welds can sustain motions only 6% larger than corresponding U.S. buildings for station with significant collapse potential. And in some areas, Japanese buildings with perfect welds can sustain motions even smaller than U.S. buildings.
- Local soil geology plays an important role in the performance of high-rise buildings. Some basin areas which locate more than 200 km away from the epicenter amplify the long period motions large enough so that one could expect irreparable damage for 20-story buildings.
- The fracture of welds in the connections of beams and columns would dramatically reduce the strength of the buildings as

ACKNOWLEDGEMENT:
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