Assessment of Design Long-Period Earthquake Motions for High-rise and Base-isolated Buildings

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Summary

Empirical formulae giving long-period earthquake motions with moment magnitude, fault distance both in spectral and phase properties are proposed. Revised formulae are herein presented, where source location and its effect on site coefficients regarding site response and group delay time are considered. The revision was made with additional earthquake data from 2011 Tohoku earthquake and its aftershocks.

In addition, simulation of the long-period motions in time history was made for multi-connected large subduction-zone earthquake from Nankai trough applying the proposed empirical formulae.

Design motions and criteria

For high-rise buildings (taller than 60 meters) requiring the minister's construction permit

Design motions

(1) Scaled recorded motions

(2) Notification wave assigned nationwide

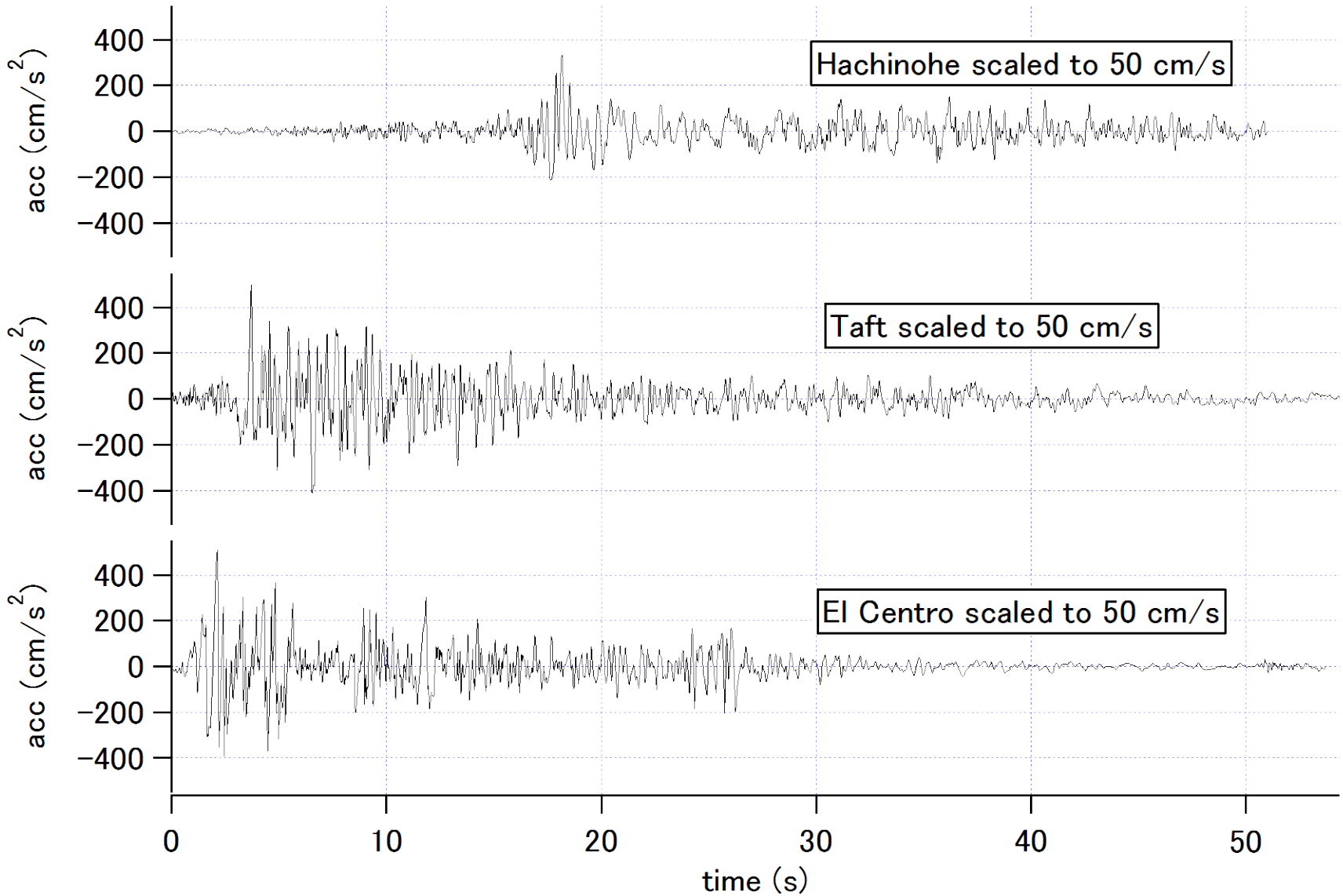
(3) Site-specific motions

Design criteria for superstructure

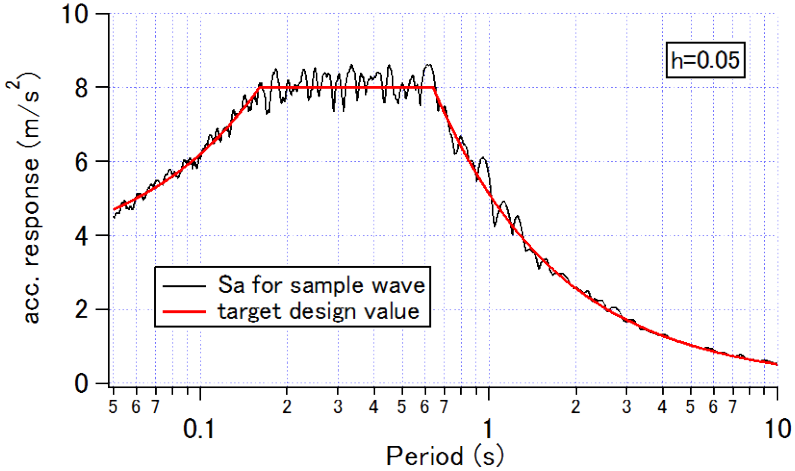
(1) Story drift ratio <= 1/100

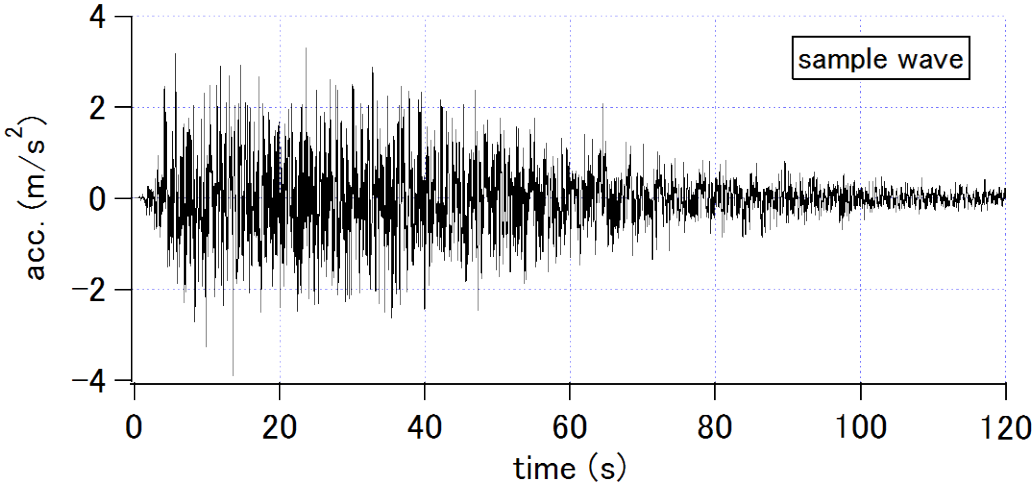
(2) Story ductility ratio < 2.0

Scaled recorded motions



BSL-notification wave

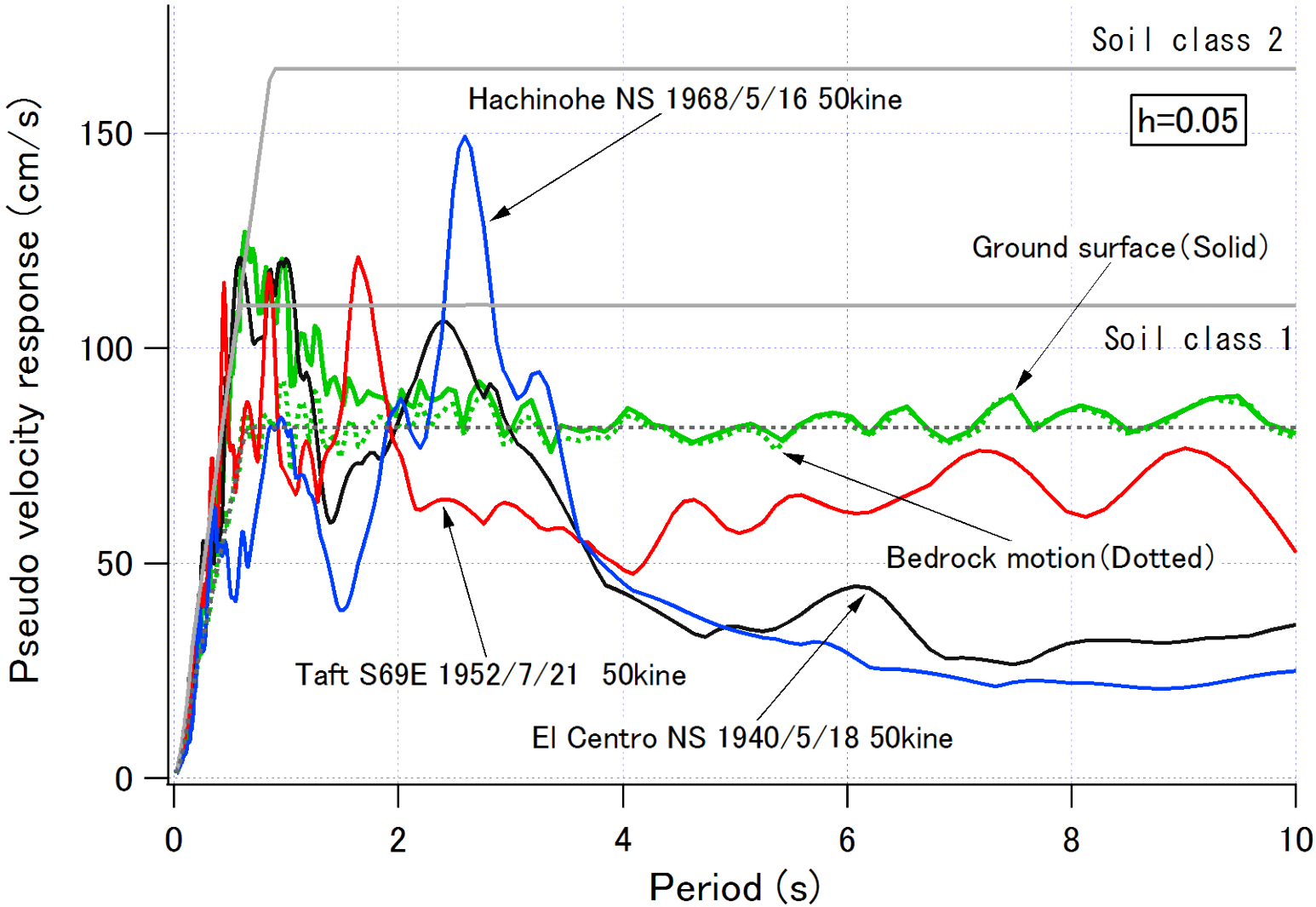




Design spectrum **Design earthquake motion**

Above ground motion is for exposed engineering bedrock. Amplification with surface soil needs to be considered when the surface motion is required in response history analysis.

Design Ground Motion for Tall Buildings



Long-duration and long-period ground motion prediction method based on observation at about 1600 stations

ORIGINAL EVALUATION MODEL

MLIT PROPOSAL FOR DESIGN MOTION
CALL FOR PUBLIC COMMENTS, 2010

2011.3.11 Tohoku EQ.

Revision of the model

Long-period motion properties
- Spectral amplitudes from large earthquakes
- Duration of motions with each frequency band

(additional factors)

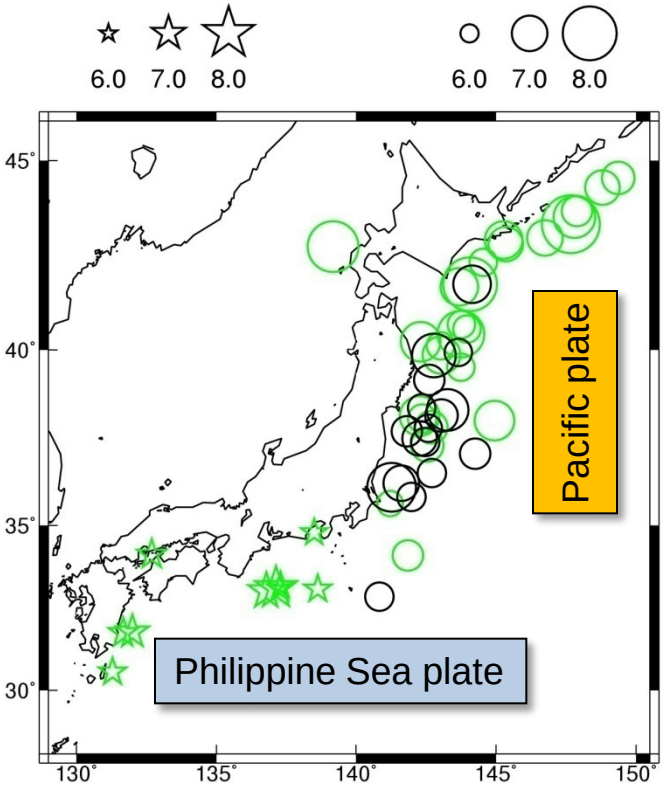
- **earthquake magnitude**
- **distance**
- **site specific coefficients**

+

Epicenters, Paths

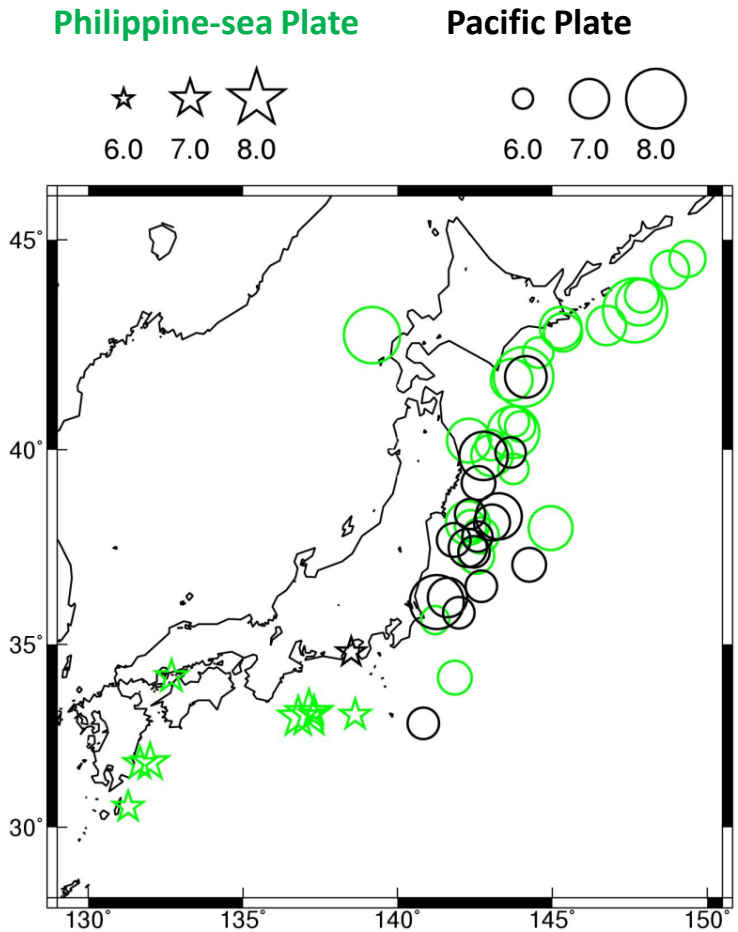
Revised evaluation method

Simulation of large subduction earthquakes

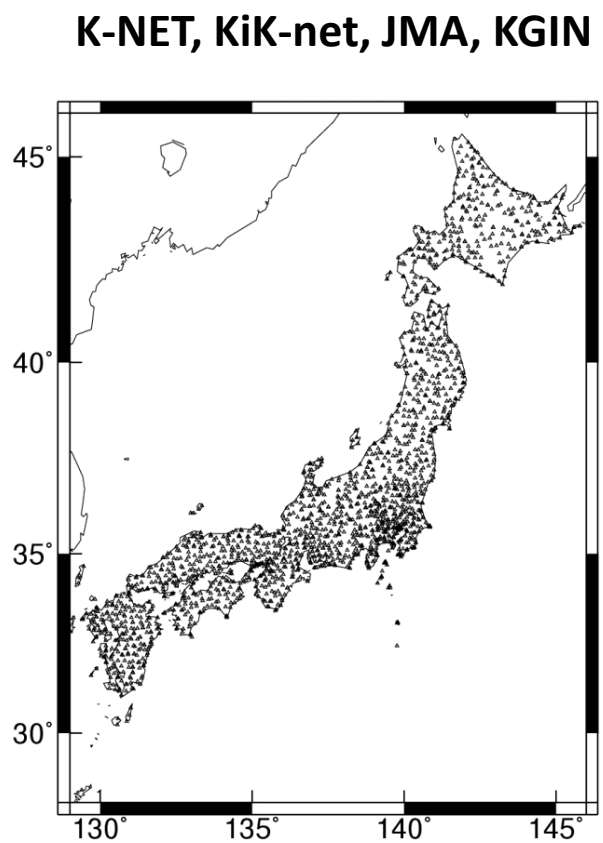


Earthquakes used in the analyses

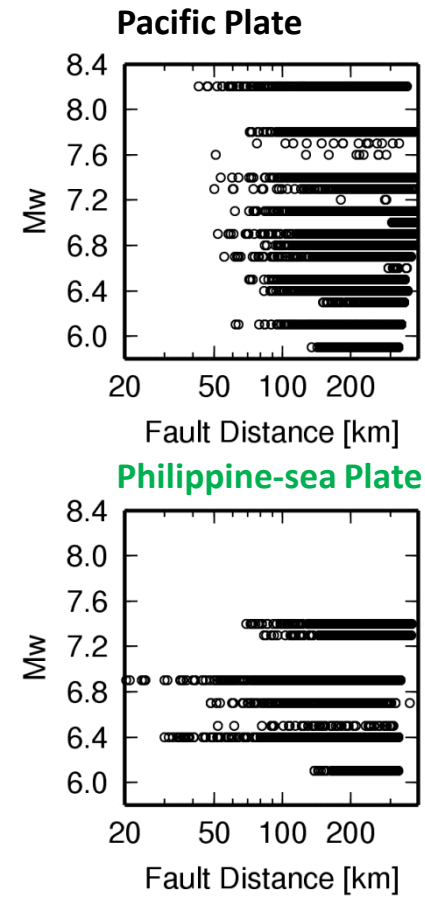
Earthquake data used for empirical formula on long-period earthquake motions



Epicenters



Recording stations



Data distributions

Revised Empirical Formulae

$$\log_{10} Sa(T) = a_1(T)M_w + a_2(T)M_w^{\ 2} + be(T)R + bw(T)R$$
$$-\log_{10}(R^{p(T)} + d(T)10^{0.5M_w}) + c_0(T) + c_j(T) + c_{wj}(T)$$

$$\mu_{tgr}(f) = A_{1tgr}(f)M_0^{\ 1/3} + Be_1(f)X + Bw_1(f)X + C_{1j}(f) + Cw_{1j}(f)$$

$$\sigma^2_{tgr}(f) = A_{2tgr}(f)M_0^{\ 1/3} + Be_2(f)X + Bw_2(f)X + C_{2j}(f) + Cw_{2j}(f)$$

Sa(T): acceleration response spectrum in cm/s^2 with 5% damping, T: Period in second

$\mu_{tgr}(f)$: average value for group delay time in frequency band centered at f (Hz)

$\sigma^2_{tgr}(f)$: variance value for group delay time in frequency band centered at f (Hz)

M_w: moment magnitude, M_0: seismic moment in dyne · cm

R: shortest distance in kilometer to the fault plane

X: hypocentral distance in kilometer

$a_1(T)$, $a_2(T)$, be(T), bw(T), p(T), d(T), $c_0(T)$, $c_j(T)$, $c_{wj}(T)$, $A_{1tgr}(f)$, $A_{2tgr}(f)$, $Be_1(f)$, $Be_2(f)$, $w_1(f)$, $c_0(T)$: site coefficient regarding site response with respect to standard recording site

$Bw_2(f)$, $C_{1j}(f)$, $C_{2j}(f)$, $Cw_{1j}(f)$, $Cw_{2j}(f)$: coefficients determined with the Least Square Analysis

be(T), $Be_1(f)$, $Be_2(f)$ are used only for the events occurring in the Pacific plate

bw(T), $Bw_1(f)$, $Bw_2(f)$ are used only for the events occurring in the Philippine sea plate

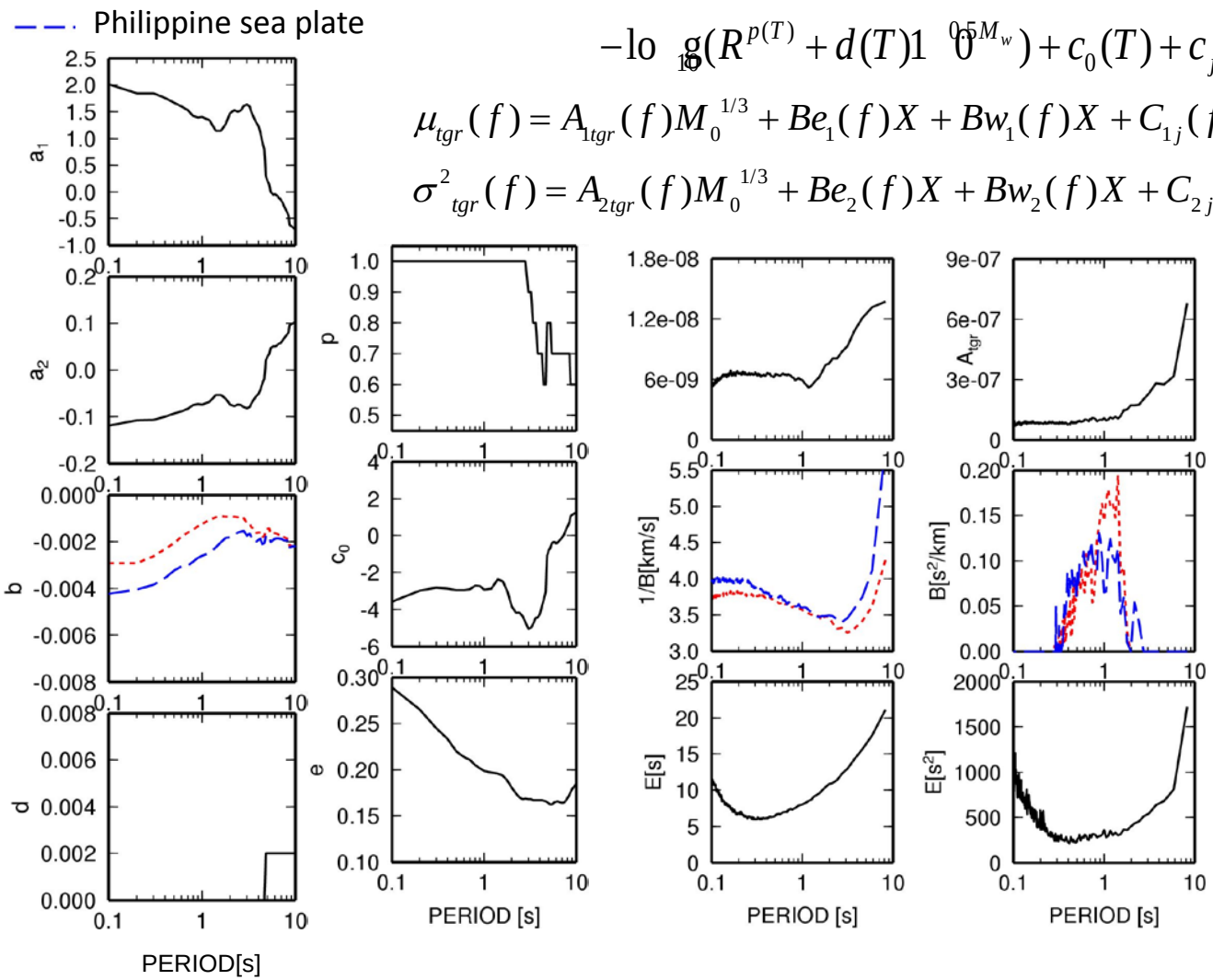
$cw_j(T)$, $Cw_{1j}(f)$, $Cw_{2j}(f)$ are used if Tz3.2>1 s in Kanto area only for the events occurring in the Philippine sea plate, otherwise, c_j (T), $C_{1j}(f)$, $C_{2j}(f)$ shall be used. Tz3.2 is defined as the wave travelling time from base layer (Vs=3.2km/s) to upper surface of engineering base layer (Vs=0.5km/s for Kanto area)

Coefficients in empirical equations

$$\log_{10} Sa(T) = a_1(T)M_w + a_2(T)M_w^2 + be(T)R + bw(T)R$$
$$-\log_{10}(R^{p(T)} + d(T)10^{0.5M_w}) + c_0(T) + c_j(T) + c_{wj}(T)$$

$$\mu_{tgr}(f) = A_{1tgr}(f)M_0^{1/3} + Be_1(f)X + Bw_1(f)X + C_{1j}(f) + Cw_{1j}(f)$$

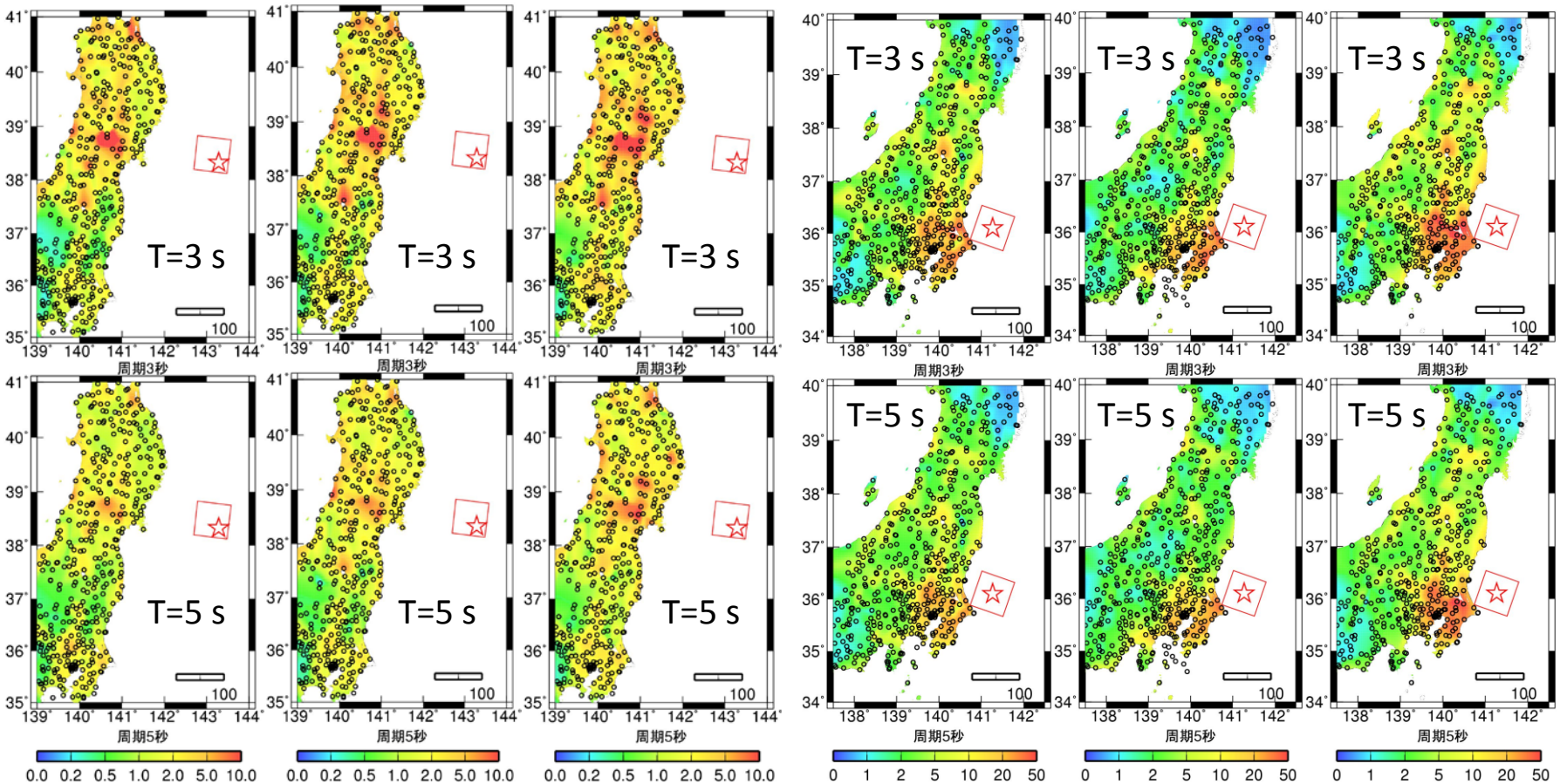
$$\sigma^2_{tgr}(f) = A_{2tgr}(f)M_0^{1/3} + Be_2(f)X + Bw_2(f)X + C_{2j}(f) + Cw_{2j}(f)$$



For Site amplification

For Group delay time

Comparison between observed and predicted with empirical formulae



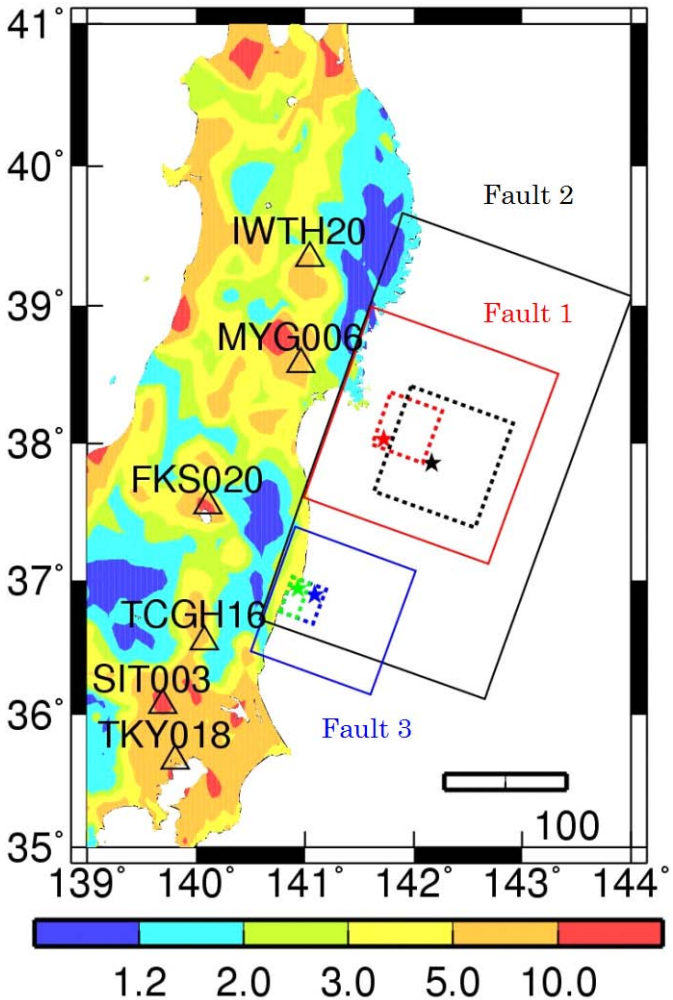
Observed **Revised** **Original**

March 9th, 2011 earthquake Mw=7.4

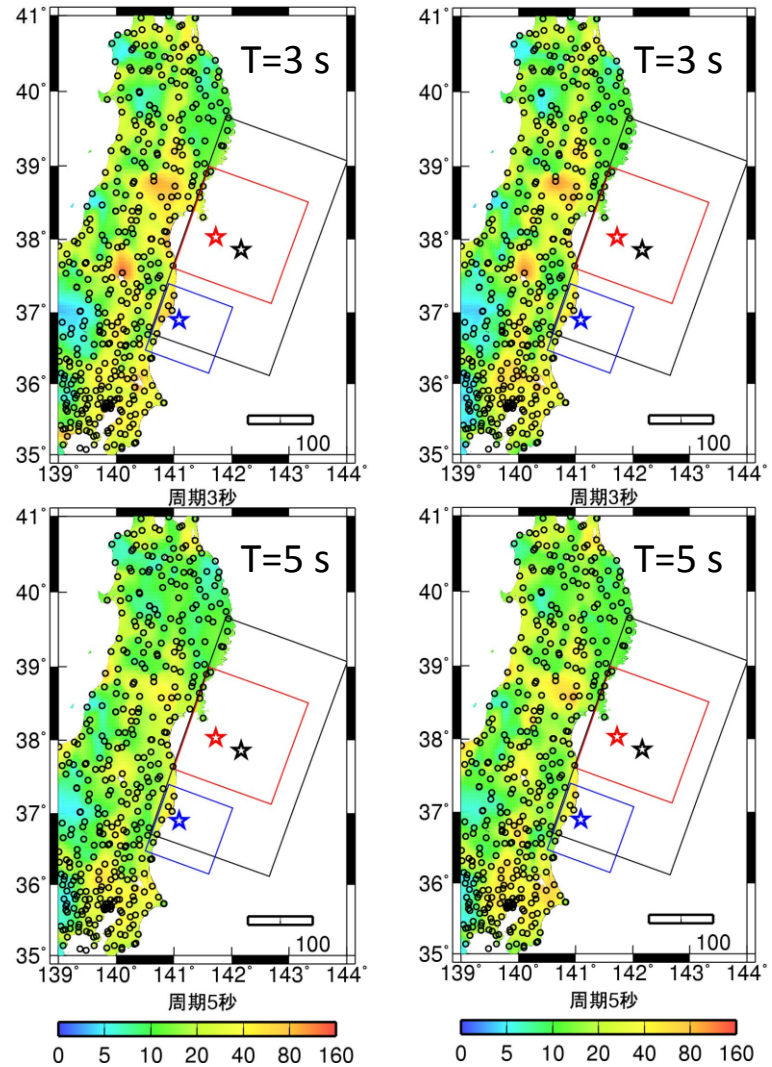
Observed **Revised** **Original**

March 11th, 2011 earthquake Mw=7.8 (largest aftershock)

Simulation of the 2011 Tohoku earthquake

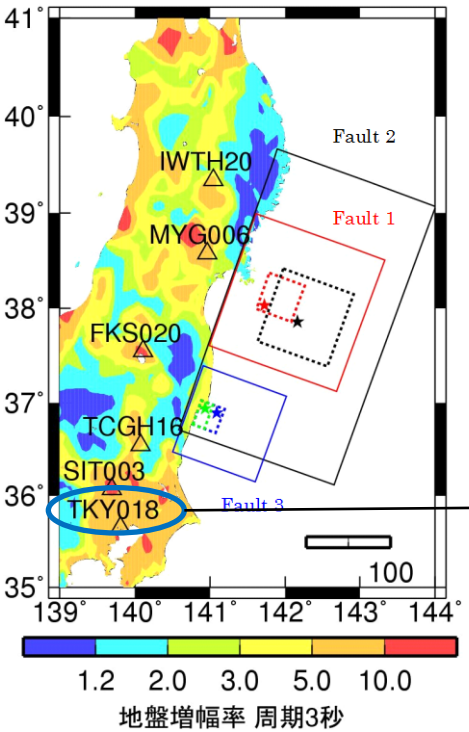


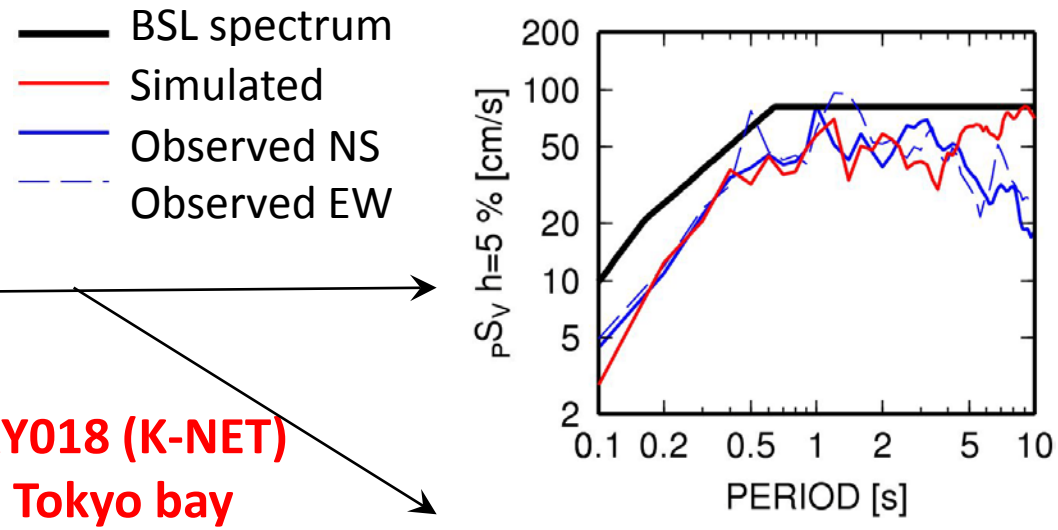
The three-connected fault source models representing the 2011 Tohoku earthquake, and distribution of site amplification coefficients (Fault1: Mw=8.4, Fault2: Mw=8.8->8.4, Fault3: Mw=8.1)



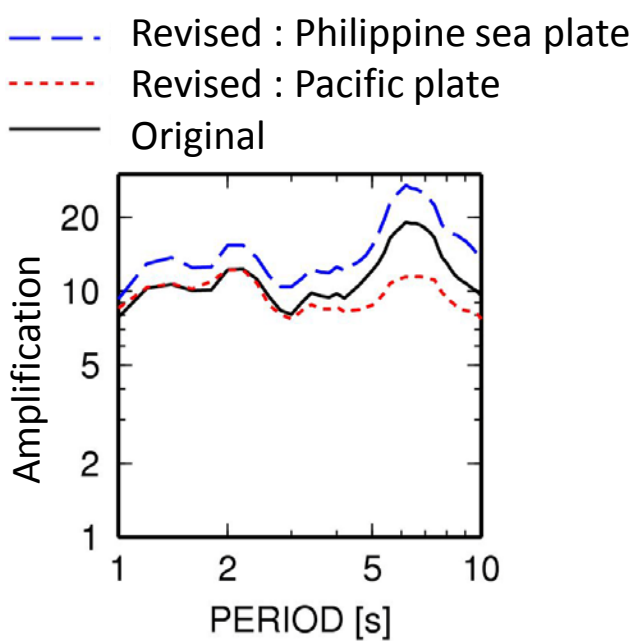
Comparison of observed (left) with simulation (right) applying the revised empirical formulae

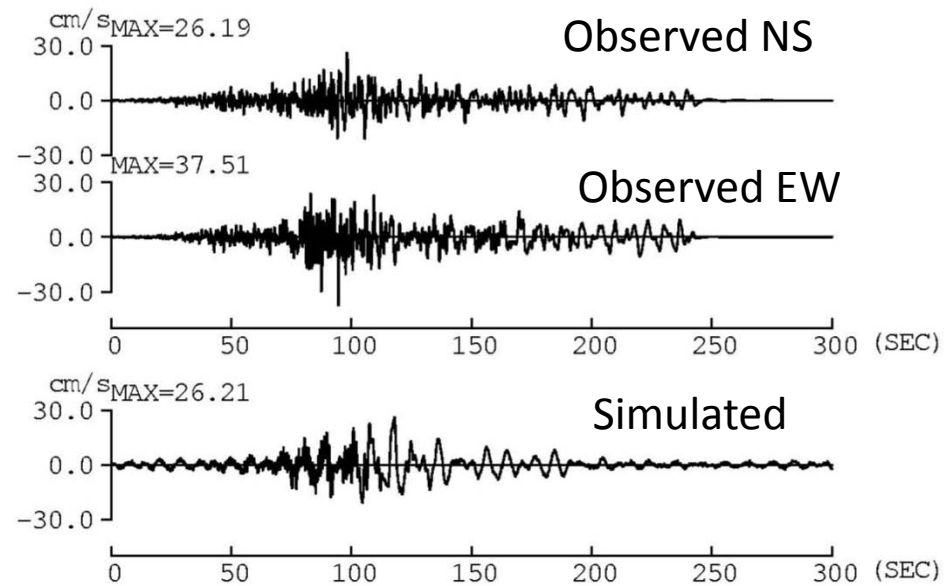
Example of simulations



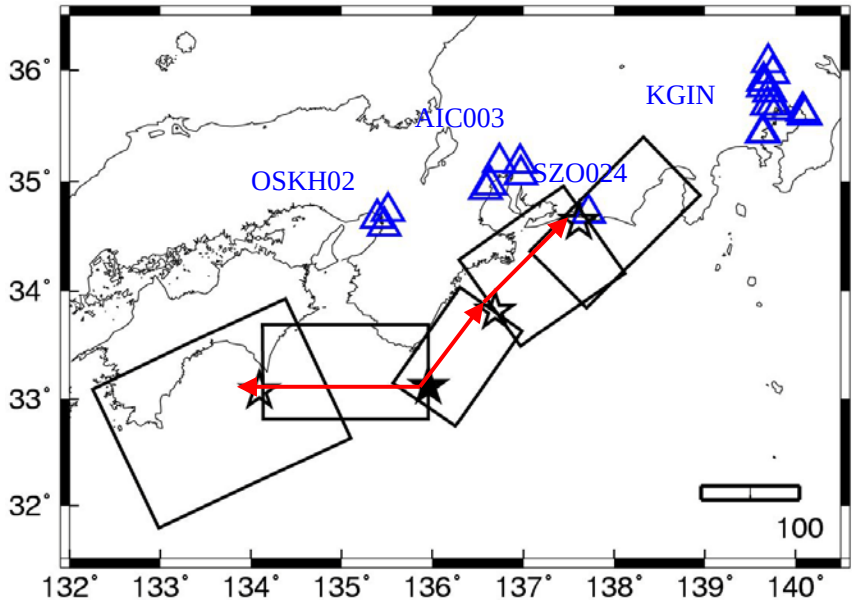


Site: TKY018 (K-NET) on Tokyo bay

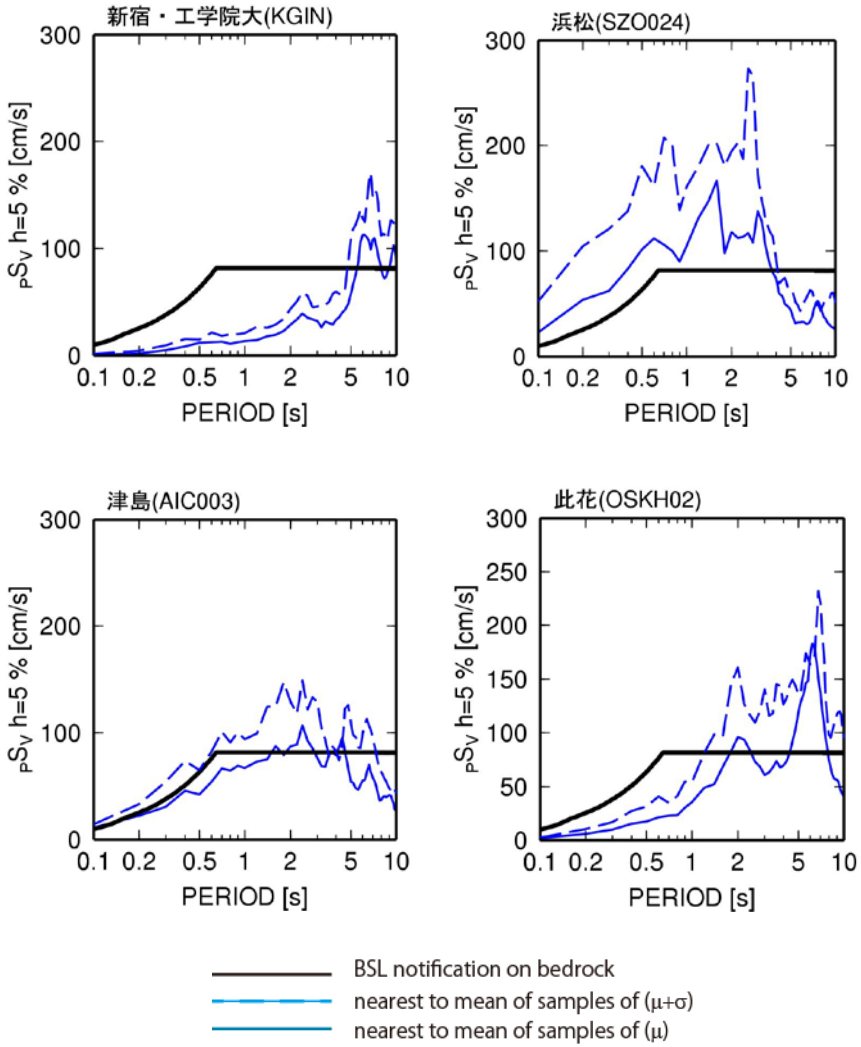




Prediction of future large earthquake



Multi-connected subduction-zone earthquake expected to occur in near future on Nankai Trough is simulated. KGIN from Tokyo, SZO024 from Shizuoka, AIC003 from Aichi, and OSKH02 from Osaka are the objective sites shown here.



This study is intended to apply for appropriate evaluation of design earthquake motions for long period building structures such as high-rise and base-isolated buildings.

Story Drift Ratio for Steel buildings

S	Dir.	Period (s)	3-connected average				3-connected average+sd			
			Konohana	Tsushima	Hamamatsu	Shinjuku	Konohana	Tsushima	Hamamatsu	Shinjuku
100m	X	2.3	1/137	1/125	1/120	1/276	1/121	1/96	1/82	1/249
	Y	2.75	1/159	1/115	1/106	1/333	1/87	1/87	1/69	1/186
120m	X	2.6	1/247	1/220	1/153	1/475	1/147	1/138	1/93	1/318
	Y	2.9	1/264	1/220	1/147	1/414	1/132	1/147	1/114	1/311
140m	X	3.69	1/135	1/125	1/119	1/341	1/73	1/118	1/75	1/171
	Y	3.79	1/136	1/113	1/104	1/291	1/68	1/101	1/75	1/176
200m	X	5.74	1/81	1/155	1/156	1/115	1/78	1/111	1/100	1/97
	Y	5.08	1/92	1/155	1/148	1/170	1/56	1/88	1/104	1/122
230m	X	6.5	1/69	1/185	1/144	1/135	1/69	1/104	1/122	1/72
	Y	5.5	1/66	1/123	1/141	1/97	1/62	1/101	1/83	1/74
250m	X	5.8	1/65	1/148	1/180	1/84	1/52	1/100	1/104	1/69
	Y	5.3	1/70	1/127	1/127	1/122	1/64	1/79	1/81	1/83

Story Drift Ratio for RC buildings

RC	Dir.	Period (s)	3-connected average				3-connected average+sd			
			Konohana	Tsushima	Hamamatsu	Shinjuku	Konohana	Tsushima	Hamamatsu	Shinjuku
90m	X	2	1/231	1/215	1/151	1/649	1/121	1/115	1/79	1/347
	Y	1.9	1/247	1/221	1/159	1/745	1/142	1/136	1/89	1/386
115m	X,Y	2.16	1/191	1/193	1/138	1/450	1/64	1/127	1/68	1/323
130m	X	3.1	1/101	1/101	1/141	1/244	1/48	1/53	1/99	1/161
150m (1)	X	2.37	1/213	1/183	1/183	1/559	1/63	1/164	1/94	1/303
	Y	3.48	1/104	1/164	1/142	1/375	1/59	1/92	1/125	1/167
150m (2)	X	2.9	1/93	1/158	1/140	1/444	1/51	1/77	1/97	1/208
	Y	3.3	1/99	1/125	1/128	1/455	1/62	1/99	1/96	1/192
180m	X	4.23	1/67	1/199	1/179	1/101	1/48	1/101	1/91	1/51
	Y	4.31	1/68	1/195	1/172	1/95	1/53	1/104	1/84	1/51
240m	X,Y	5.44	1/133	1/199	1/163	1/123	1/91	1/142	1/106	1/77

Story Ductility Ratio for Steel buildings

S	Dir.	Period (s)	3-connected average				3-connected average+sd			
			Konohana	Tsushima	Hamamatsu	Shinjuku	Konohana	Tsushima	Hamamatsu	Shinjuku
100m	X	2.3	1.1	1.3	1.4	0.6	1.4	1.7	2.1	0.7
	Y	2.8	1.0	1.3	1.4	0.5	1.8	1.8	2.3	0.8
120m	X	2.6	0.9	1.0	1.5	0.5	1.6	1.6	2.6	0.7
	Y	2.9	0.7	0.8	1.3	0.4	1.4	1.5	1.8	0.6
140m	X	3.7	1.6	1.7	1.8	0.6	3.0	1.8	3.0	1.2
	Y	3.8	1.4	1.7	1.9	0.6	3.1	2.0	2.8	1.0
200m	X	5.7	2.2	1.1	1.1	1.7	2.4	1.6	1.8	2.0
	Y	5.1	2.5	1.1	1.2	1.2	4.1	2.0	1.6	1.8
230m	X	6.5	3.1	1.1	1.5	1.5	3.0	2.1	1.8	2.8
	Y	5.5	2.7	1.3	1.3	1.7	2.9	1.7	2.4	2.4
250m	X	5.8	2.5	0.9	0.7	1.9	3.2	1.6	1.2	2.4
	Y	5.3	1.6	0.9	1.0	0.8	1.8	1.5	1.4	1.3

Story Ductility Ratio for RC buildings

RC	Dir.	Period (s)	3-connected average				3-connected average+sd			
			Konohana	Tsushima	Hamamatsu	Shinjuku	Konohana	Tsushima	Hamamatsu	Shinjuku
90m	X	2	0.8	0.8	1.2	0.2	1.7	1.7	2.9	0.5
	Y	1.9	0.9	1.0	1.7	0.3	2.2	2.4	5.1	0.6
115m	X,Y	2.2	0.6	0.6	0.8	0.2	2.0	0.9	1.9	0.3
130m	X	3.1	1.5	1.6	1.2	0.6	3.3	3.2	1.5	1.0
150m (1)	X	2.4	0.7	0.8	0.9	0.3	2.4	0.9	1.6	0.5
	Y	3.5	1.0	0.6	0.9	0.3	2.1	1.2	1.1	0.6
150m (2)	X	2.9	1.7	1.0	1.3	0.4	3.0	2.0	1.8	0.9
	Y	3.3	2.0	1.0	1.2	0.4	3.0	1.9	1.7	0.9
180m	X	4.2	2.0	0.7	0.9	1.3	2.8	1.2	1.8	2.8
	Y	4.3	1.9	0.7	0.9	1.4	2.5	1.2	2.0	2.7
240m	X,Y	5.4	1.1	0.8	0.9	1.2	1.9	1.0	1.9	2.3

High-rise building models

(1) For OSKH02 motion, representing the Osaka bay area, responses of building taller than 150 meters to average (μ) motion exceeded the criteria. All models failed to satisfy the criteria to $\mu+\sigma$ (standard deviation) motion. It showed difficulties to satisfy the criteria even with some retrofit countermeasure works.

(2) For AIC003 motion, representing Nagoya area, all models satisfied the criteria for average (μ) motions, all models satisfied the criteria, for $\mu+\sigma$ motion, models except for 150 meter satisfied the criteria.

(3) For KGIN motion, representing Shinjuku area in Tokyo, most of the models lower than 200 meters satisfied the criteria. However, models taller than 200 meters exceeded the criteria.

(4) For SZO024 motion, Hamamatsu in Shizuoka area locating above the source area, larger story drift ratios exceeding the criteria were found for $\mu+\sigma$ motions with any heights of building models.

Base-isolated building models

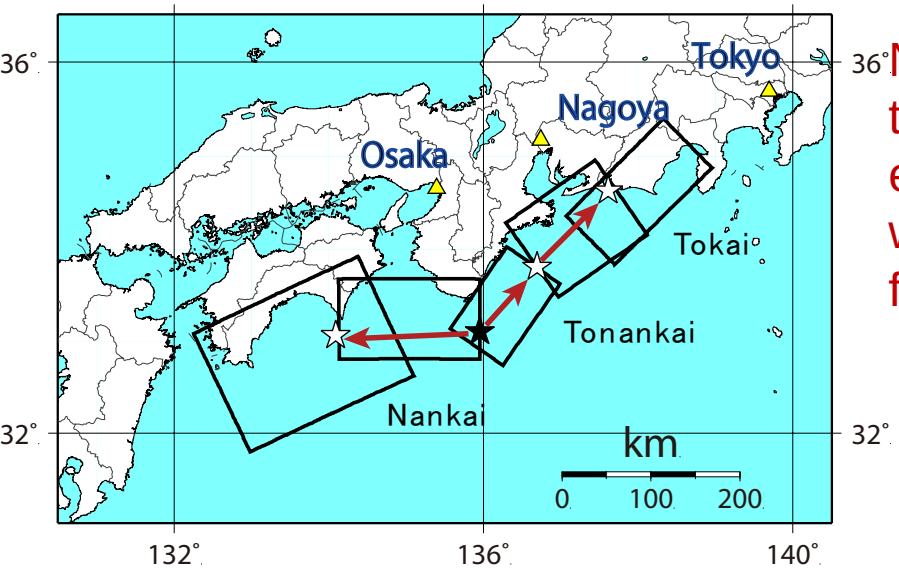
Building models are used here from 22 existing buildings. They vary with construction age (1987-2008), height of superstructure (11.9-140 meters), Devices (LRB, NR, HDR, SD,LD, OD etc.). The natural periods of superstructures are 0.1-3.5 sec. and those for 200% device strain level are 1.8-6.4 sec.

(1) For average (μ) motions, most of the superstructures are in the state within the short term allowable limit.

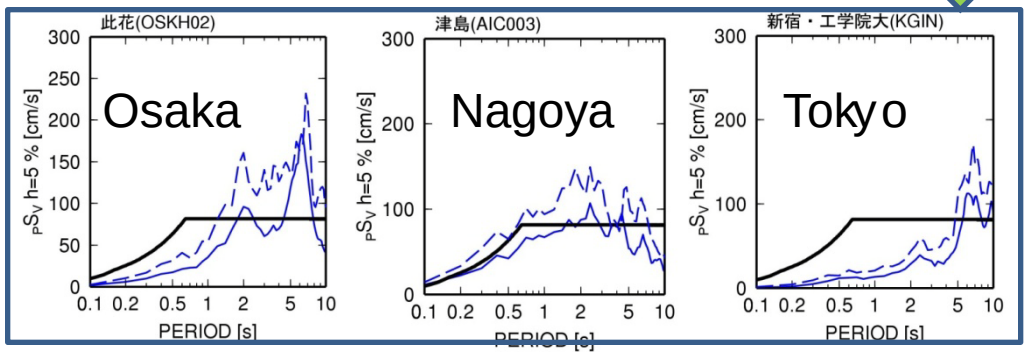
(2) For ($\mu+\sigma$) motions, 5 to 8 percentile superstructures exceeded with bearing capacity for OSKH02 and SZO024 motions. Totally 15 percentile models exceeded the elastic limit. Deformations of devices exceeded the limits for models with longer natural periods for OSKH02 motions.

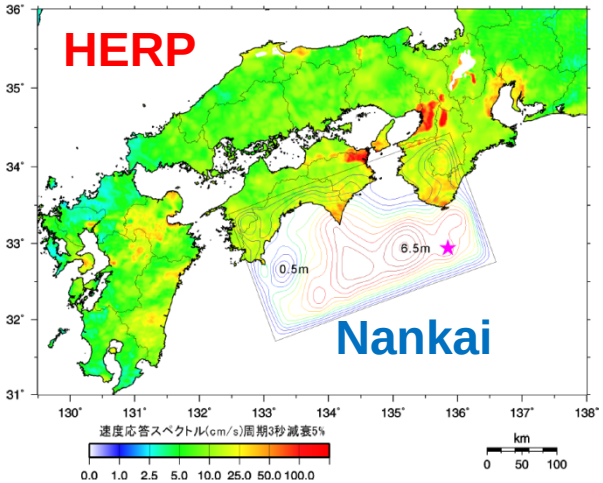
Long-duration and long-period ground motion prediction method based on observation at about 1600 stations

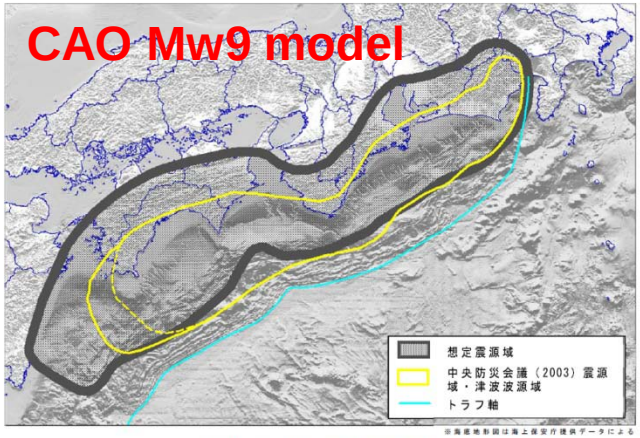
Long-period motions were evaluated for major urban areas with two-, three-connected earthquakes, by HERP, CAO, AIJ, etc.
MLIT is going to propose a design long-period motions for tall and base-isolated buildings. The MLIT-funded project is underway for the purpose.



Nankai-trough three-connected earthquake model with revised model for major areas







図Ⅴ.2　新たな想定震源域

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