Sloshing Damage to Oil Storage Tanks due to Long-Period Strong Ground Motions during the 2011 Tohoku, Japan Earthquake

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Overview of Tsunami Damage to Oil Tanks during 3.11

- Largest-scale oil tank disaster due to a tsunami worldwide ever.
- Totally 417 oil tanks damaged.
- 157 oil tanks washed away, drifted away, slid, floated, or tipped.
- Several tanks burned in a spreading fire caused by the tsunami.

Kesen'numa, Miyagi

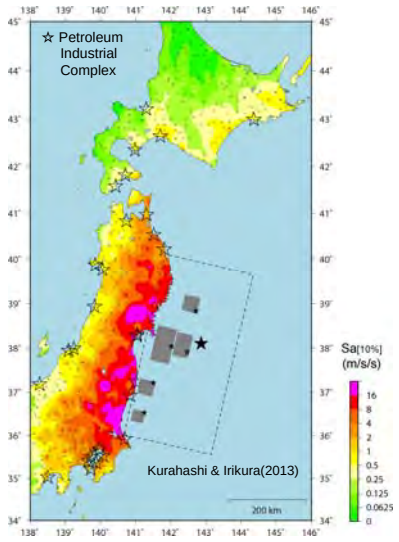
Sendai, Miyagi

Strong Ground Motion Distribution Observed during 3.11

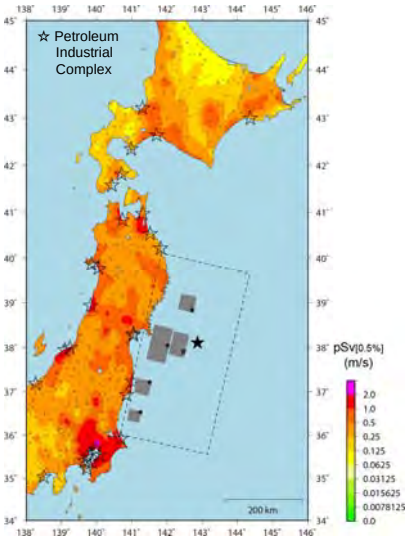
Short Periods (1 to 15 Hz)

Long Periods (5 to 15 s)

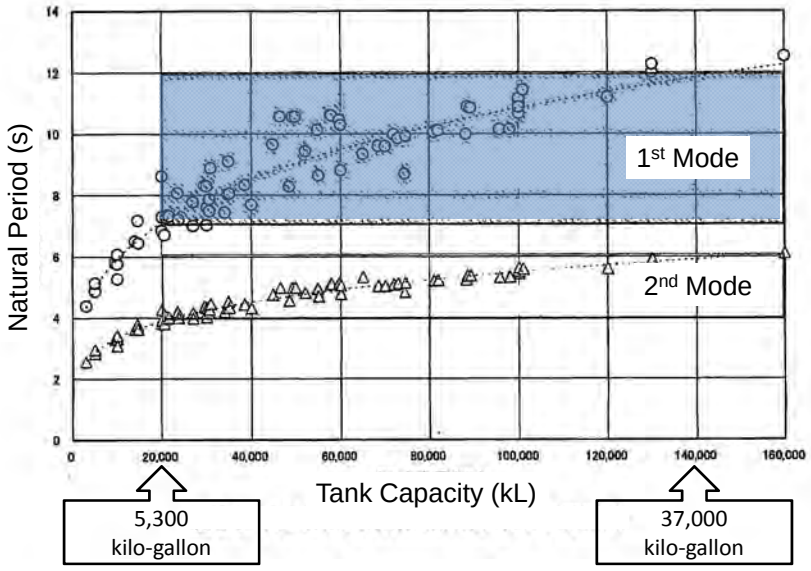
Spectral Acceleration



Pseudo Spectral Velocity



Natural Period of Liquid Sloshing of Large Tanks



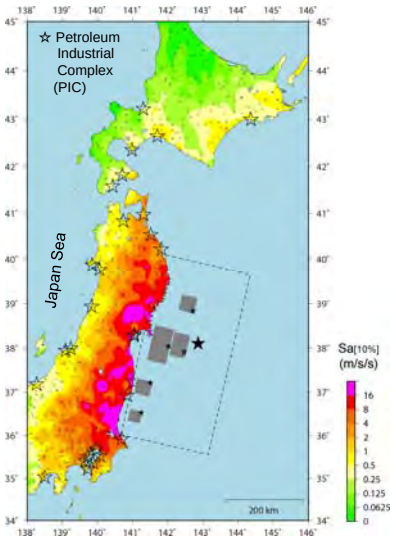
[Yamauchi(2006)]

Strong Ground Motion Distribution Observed during 3.11

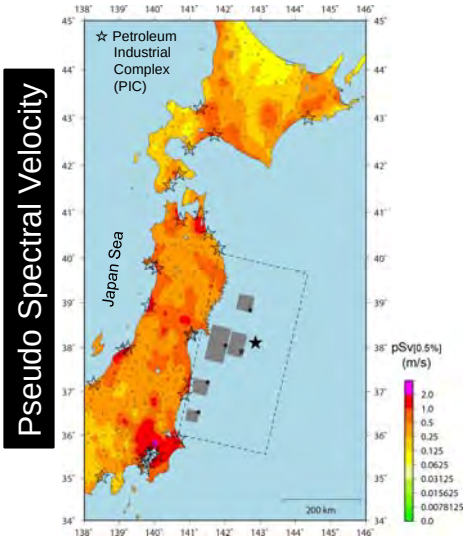
Short Periods (1 to 15 Hz)

Long Periods (5 to 15 s)

Spectral Acceleration



Pseudo Spectral Velocity



Overview of Ground Motion Damage to Oil Tanks during 3.11

■ Damage by Short-Period (1-15 Hz) Ground Motion

- No damage directly caused by short-period strong ground motions.
- Some oil tanks damaged due to deformation of the foundation ground caused by liquefaction.

■ Damage by Long-Period (3-15 s) Ground Motion

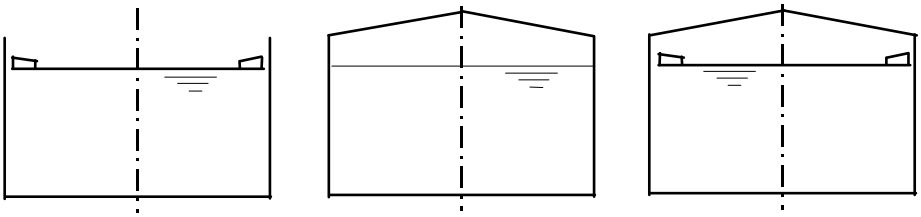
- Severe sloshing damage (sinking of the floating roof & complete collapse of the internal floating roof) to 2 tanks;
- Quasi-severe damage to 21 tanks.
- No tank fire caused by sloshing.
- Less serious disaster than that of the 2003 Tokachi-oki eq. (Mw8.0).

Outline

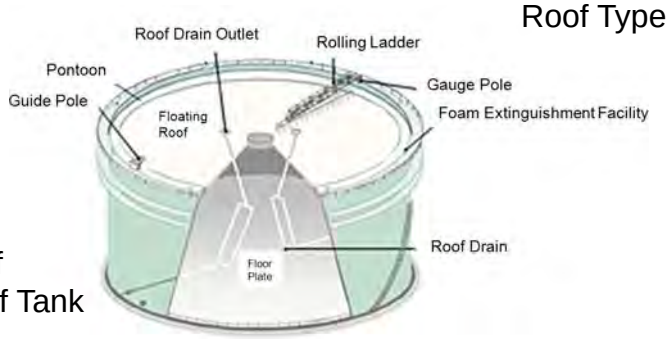
- Sloshing Damage to Oil Tanks due to Long-Period Ground Motion (LPGM) during 3.11
- Comparison of Sloshing Damage between 2011 Mw9.0 Tohoku Eq. & 2003 Mw8.0 Tokachi-oki Eq.
- Implication for LPGM Microzoning from Observed Spatial Variation of Sloshing Amplitudes

Sloshing Damage in 2011 Mw9.0 Tohoku Eq.

Roof Types of Oil Tanks



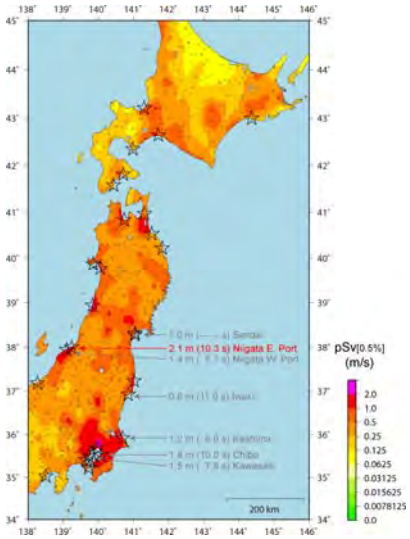
Floating Roof Type | Fixed Roof Type | Internal Floating Roof Type



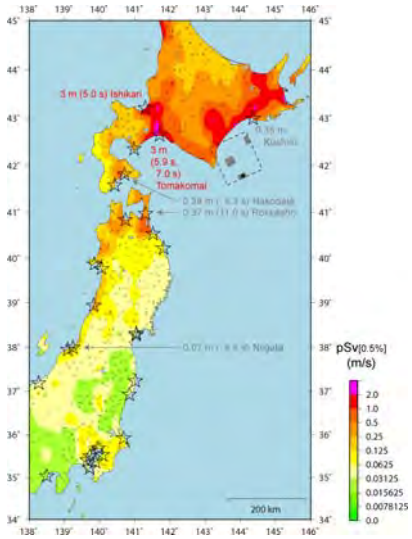
Schematic of Floating Roof Tank

Observed Sloshing Amplitude at Oil Tanks

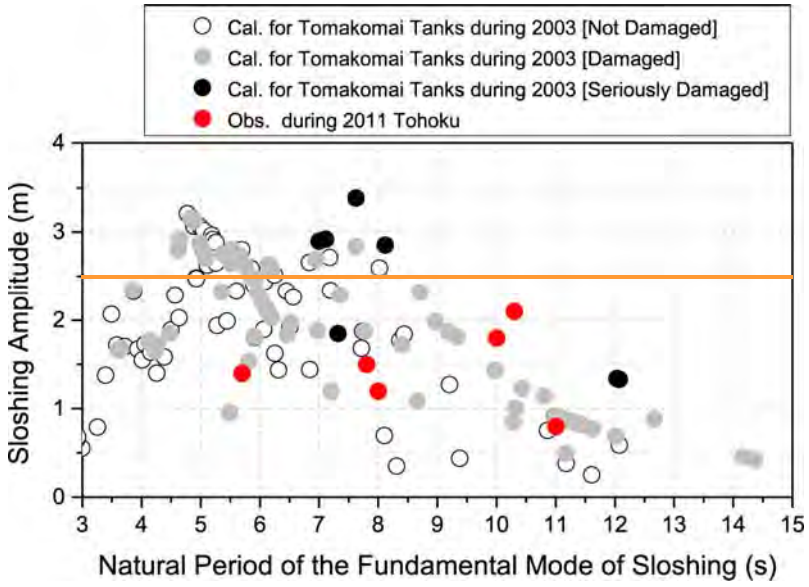
2011 Mw9.0



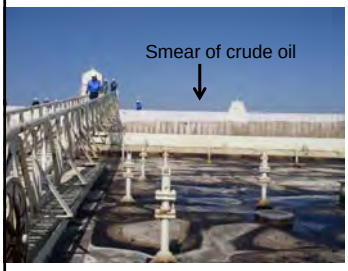
2003 Mw8.0 Tokachi-oki



Sloshing Amplitude: 2011 Tohoku (Mw9.0) & 2003 Tokachioki (Mw8.0)



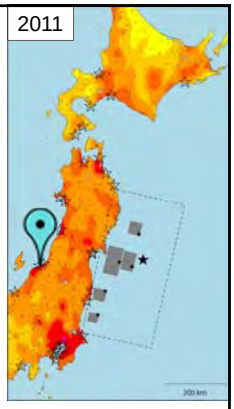
Sloshing Damage in Niigata during 3.11



Oil spill onto the floating roof

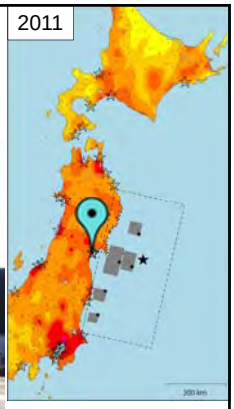
Infiltration of oil into pontoons (Wh~1.9 m)

Deformation of the gauge pole (Wh~1.4 m)



Sloshing Damage during 3.11: Running-off of the rolling ladder in Sendai

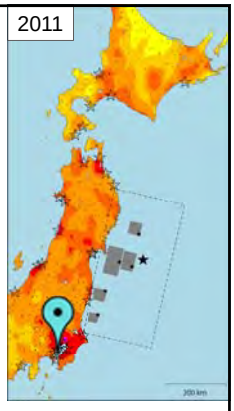
2011



Severe Sloshing Damage during 3.11: Sinking of the floating roof in Kawasaki

[Image taken by Dr. Haruki Nishi]

2011

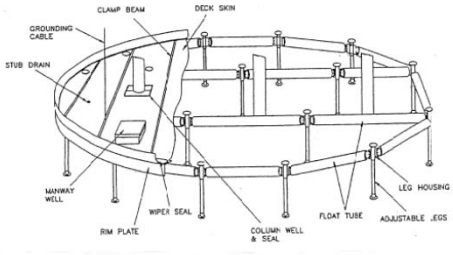


Heavy Oil
C_L = 20,000 kL
D = 38.7 m
H_{Lmax} = 16.4 m
H_L = 8.9 m
Ts = 7.8 s
$\eta_{max(obs)}$ = 1 ~ 1.5 m
$\eta_{max(cal)}$ = 1.3 m

Severe Damage during 3.11: Complete collapse of the internal floating roof in Sakata

Gasoline
C_L = 2,700 kL
D = 15.5 m
H_T = 16.7 m
H_L = 9.3 m
Ts = 4.2 s
$\eta_{max(cal)}$ = 2.0 m

Fractured deck skin and float tube



Schematic of Internal Floating Roof

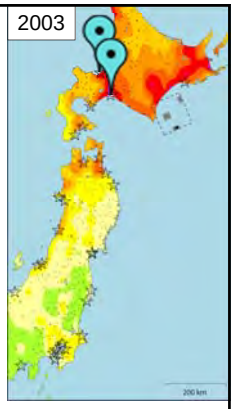
Fractured float tube

[Image taken by Dr. Haruki Nishi]

Comparison of Sloshing Damage between 2011 Mw9.0 & 2003 Mw8.0 Tokachi-oki Eq.

Severe Sloshing Damage to Tanks: 2011 & 2003

Damage during the 2003 Tokachi-oki Eq.



	2011 Tohoku (Mw9.0)		2003 Tokachi-oki (Mw8.0)	
Fire	0		2	Tomakomai
Sinking of floating roofs	1	Kawasaki	7	Tomakomai
Complete collapse of internal floating roofs	1	Sakata	1	Ishikari

Why Less Serious Sloshing Disaster in 2011 than in 2003?

1. Long Period Ground Motion

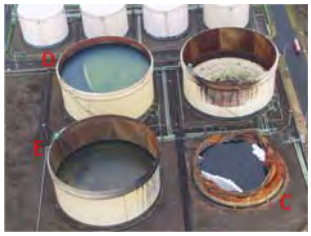
2. Oil Tank Distribution

3. Countermeasures in Seismic Codes of the Fire Service Act taken after the 2003 Tokachi-oki earthquake

Why the Open-Top Fire Occurred in 2003?

Open-Top Fire
- Occurred 2 days later.
- Lasted for 2 days.

ignition

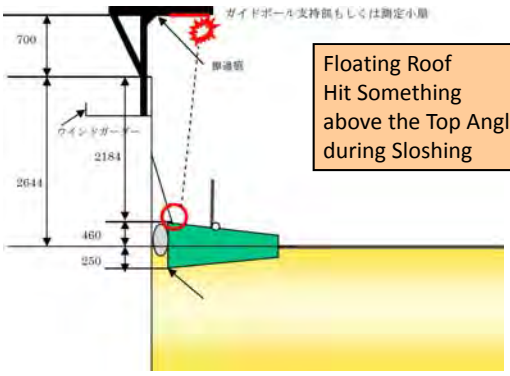


Sinking of the Floating Roof
➡ Oil Surface Exposed to the Atmosphere

Preventing sinking of the floating roof is important for fire prevention.

Legally-require pontoons ensure resistance against oscillation of the floating roof in the areas where large LPGM is predicted (by 2017).

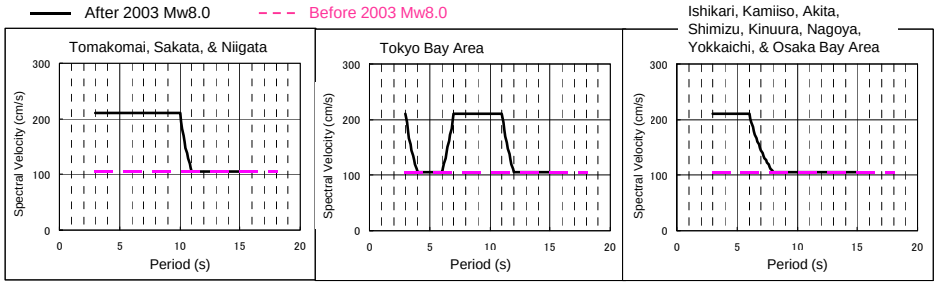
Why the Ring Fire Occurred in 2003?



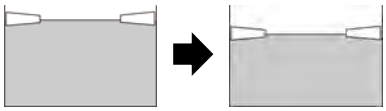
Floating Roof
Hit Something
above the Top Angle
during Sloshing

Lowering the oil level at tanks should prevent tank fires and spill-out of oil.

Raise the seismic design spectra against sloshing of oil tanks.

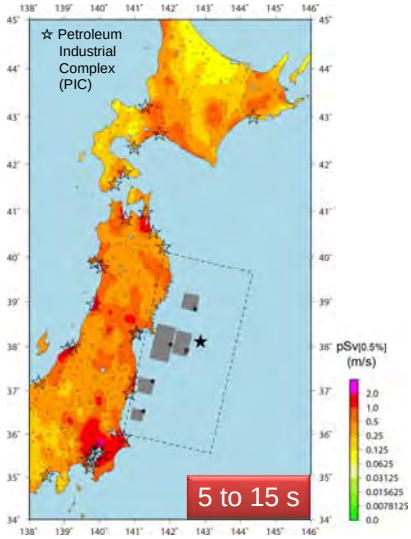


Legally-require to lower the oil level at tanks in the areas where large LPGM is predicted (completed).

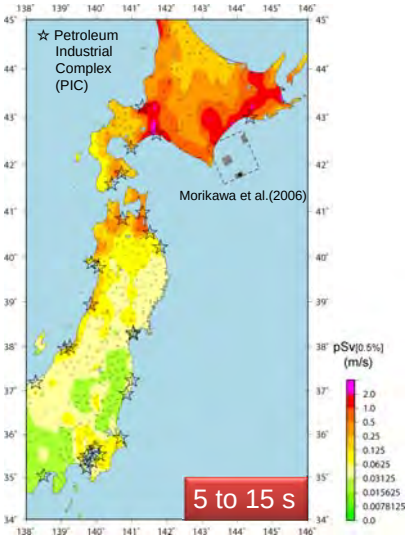


Observed Long-Period Ground Motion: 2011 & 2003

2011 Tohoku (Mw9.0)

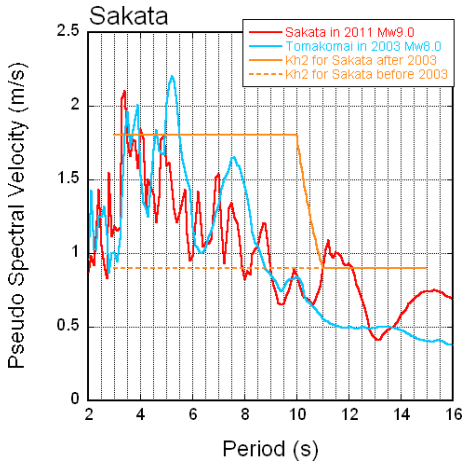


2003 Tokachi-oki (Mw8.0)



Observed Long-Period Ground Motion: 2011 & 2003

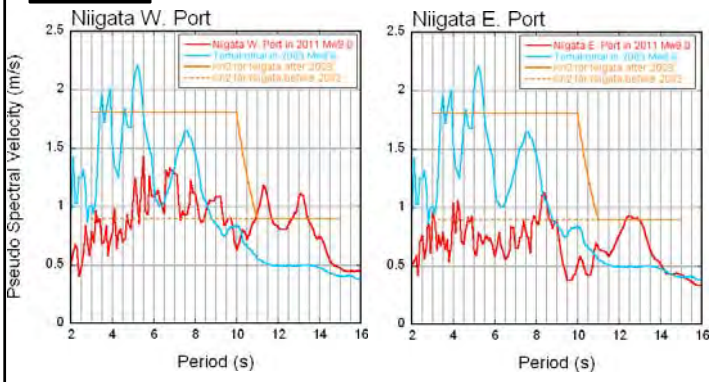
Sakata



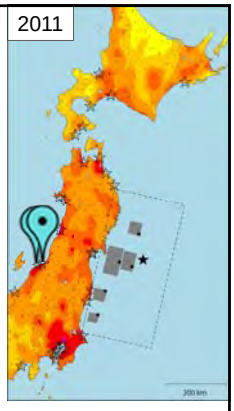
2011

- The largest LPGM observed at Sakata.
- Comparable level to the 2003 Tomakomai.
- No floating roof tank located in Sakata.
- Only one internal floating roof tank placed in Sakata.
- This tank's roof collapsed completely.

Niigata

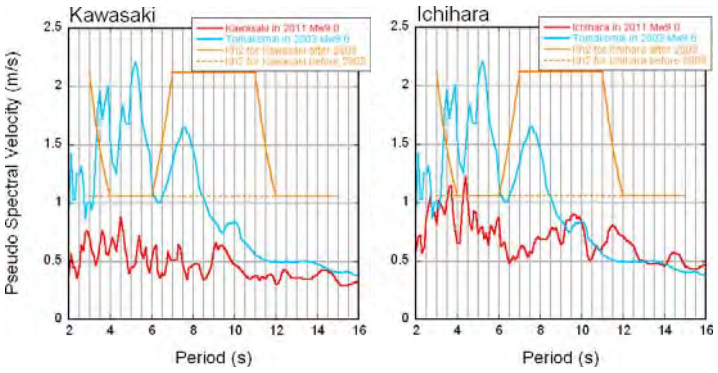


2011

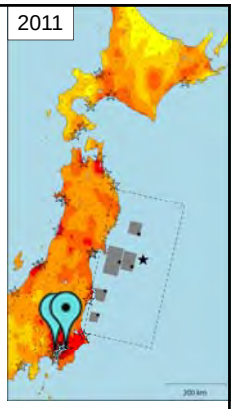


- Niigata W. Port exceeding the design spectrum before the post-2003 revision.
- If the design spectrum had not been raised, oil might have spilt out of the tanks.

Tokyo Bay Area



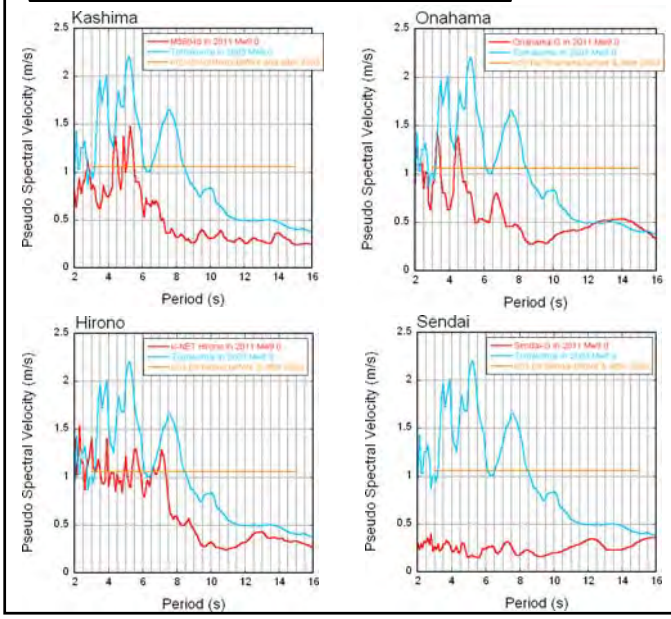
2011



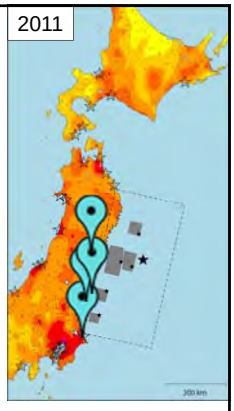
- Observations fall below the design spectrum before the post-2003 revision.
- The reason of the sinking of floating roof is not understandable.

Observed Long-Period Ground Motion: 2011 & 2003

Pacific Coast of Tohoku & Kanto



2011

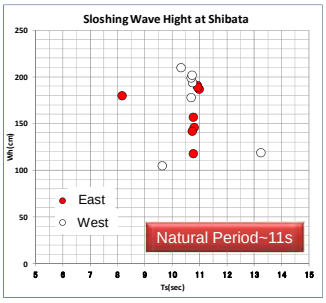


Observations basically fall below the design.

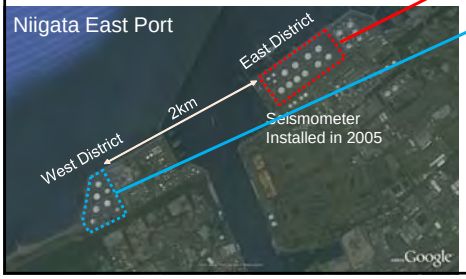
Implication for LPGM Microzoning from Obs. Sloshing Heights

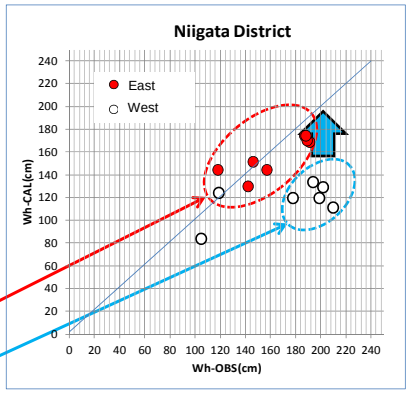
Spatial Variation of Sloshing Heights within Short Distances

→ Suggesting Significant Spatial Variation of LPGM within Short Distances?



Observed Sloshing Heights



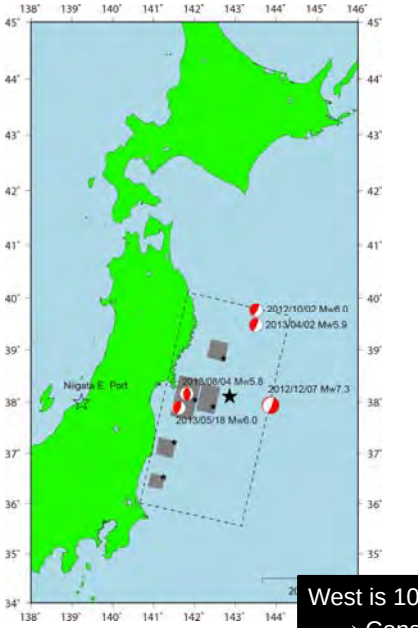


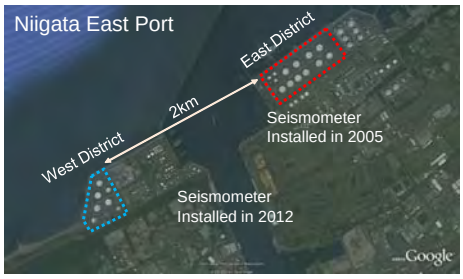
Comparison of Observed Sloshing Heights with Sloshing Heights Calculated from the 2011 Niigata-E Seismogram

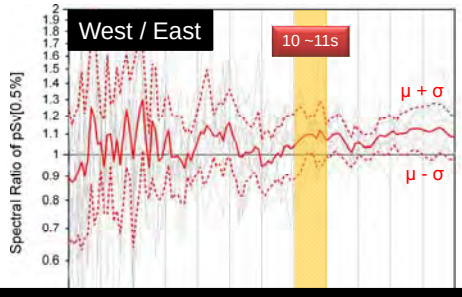
If W. District LPGM is 50% larger than E. District, the observed sloshing amplitudes in W. District will be reproduced.

[Zama (2013)]

E. District vs. W. District: Aftershocks Mw5.8 ~ 7.3



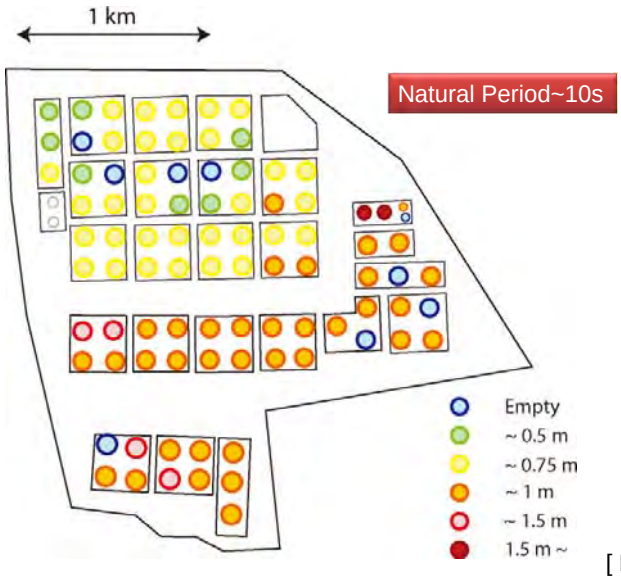




West is 10 – 30% larger than East ON AVERAGE.
→ Consistent with the observed sloshing amplitudes.

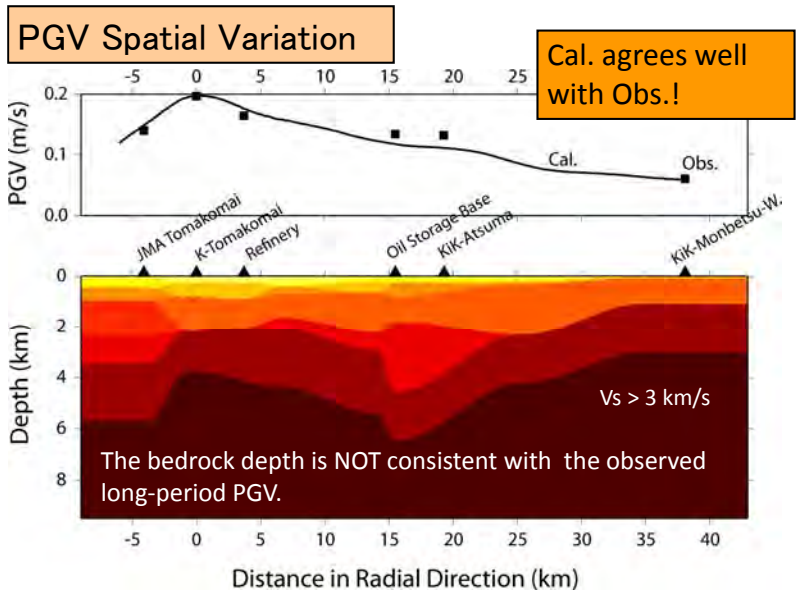
Spatial Variation of Observed Sloshing Amplitudes

~ Tomakomai during the 2003 Tokachi-oki ~

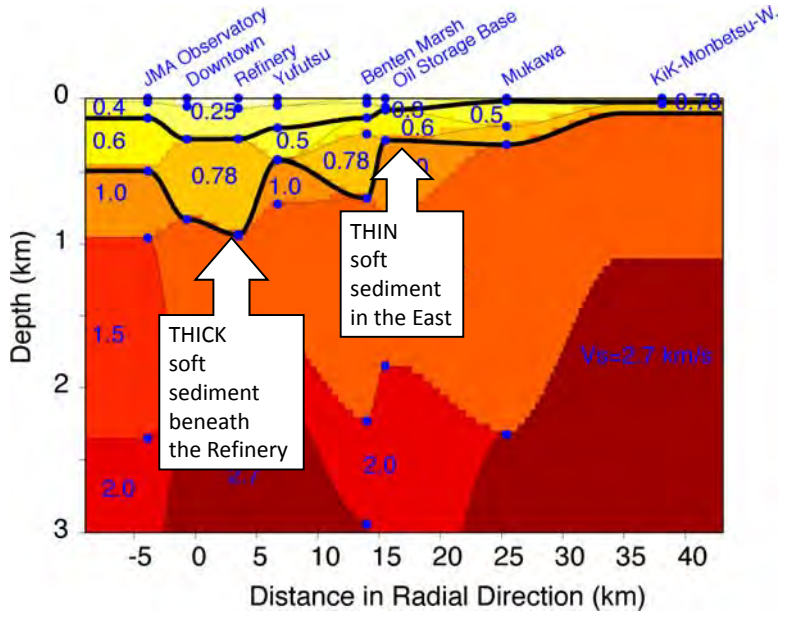


[Kaita (2004)]

Obs. vs. Cal.: PGV (Period: 6.5 – 15 s)



Characteristics in the Shallow Part



Summary

- Less serious sloshing disaster was observed in the 2011 Mw9.0 event than in the 2003 Mw8.0 event: no sloshing-induced tank fire, severe damage to 2 tanks (sinking of the floating roof & complete collapse of internal floating roof).

- This is basically because of :

(1) Smaller Long-Period Ground Motions (LPGM) observed at Petroleum Industrial Complexes (PIC) in 2011 than 2003;

(2) No floating roof tank at Sakata PIC where comparable LPGM to the largest of 2003 (Tomakomai) was observed;

(3) Legally-required countermeasures taken after the 2003 event.

- A significant spatial variation in long-period (11 s) GM levels (10 to 30%) and the consequent sloshing (50%) at oil tanks was observed within short distances (2 km), repeatedly suggesting the necessity of MICROZONING of LPGM for RISK REDUCTION.

Correction in your Handout!

Severe Sloshing Damage to Tanks: 2011 & 2003

	2003 Tokachi-oki ~~2011 Tohoku (Mw9.0)~~ (Mw8.0)		2003 Tohoku ~~2003 Tokachi-oki (Mw8.0)~~ (Mw9.0)	
Fire	2	~~Tomakomai~~	0	
Sinking of floating roofs	7	Tomakomai	1	Kawasaki
Complete collapse of internal floating roofs	1	Ishikari	1	Sakata

Damage due to the 2003 Tokachi-oki Eq.