Seismic and Tsunami Damage on Building Structures Caused by the 2011 Tohoku Japan Earthquake

MIDORIKAWA Mitsumasa

Hokkaido Univ.

Damage to Buildings Caused by Ground Shaking and Tsunami

Summary of damage reconnaissance by the Steel Structures Committee of AIJ

1) Summary of ground motions and tsunami
2) Damage caused by ground motions (Miyagi, Fukushima)

- Damage to structural and nonstructural components

3) Damage caused by tsunami (Sendai, Shiogama, Ishinomaki, Onagawa, Minamisanriku, Kesennuma, Rikuzentakada, Ohfunato, Kamaishi, Otsuchi, Miyako, Kuji)

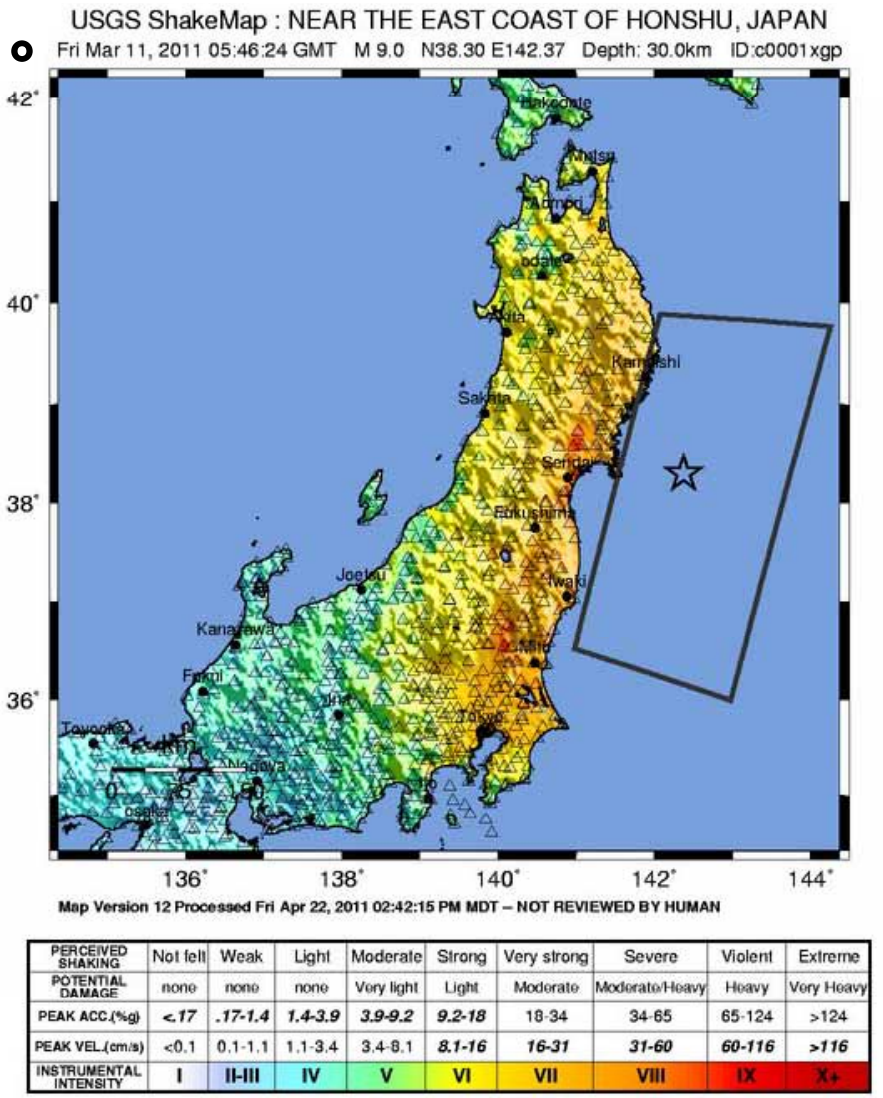
- Port facilities, Fish processing facilities, Refrigeration facilities, Freight facilities, Factories, Commercial facilities

4) Other damage caused by ground deformation and fire
5) Summary

The 2011 Tohoku Earthquake

- March 11, 2011, 14:46
- Epicenter: east longitude 142.9 °
  north latitude 38.1 °
- Depth: 24 km
- M_w 9.0
- Aftershocks (over *M*7)

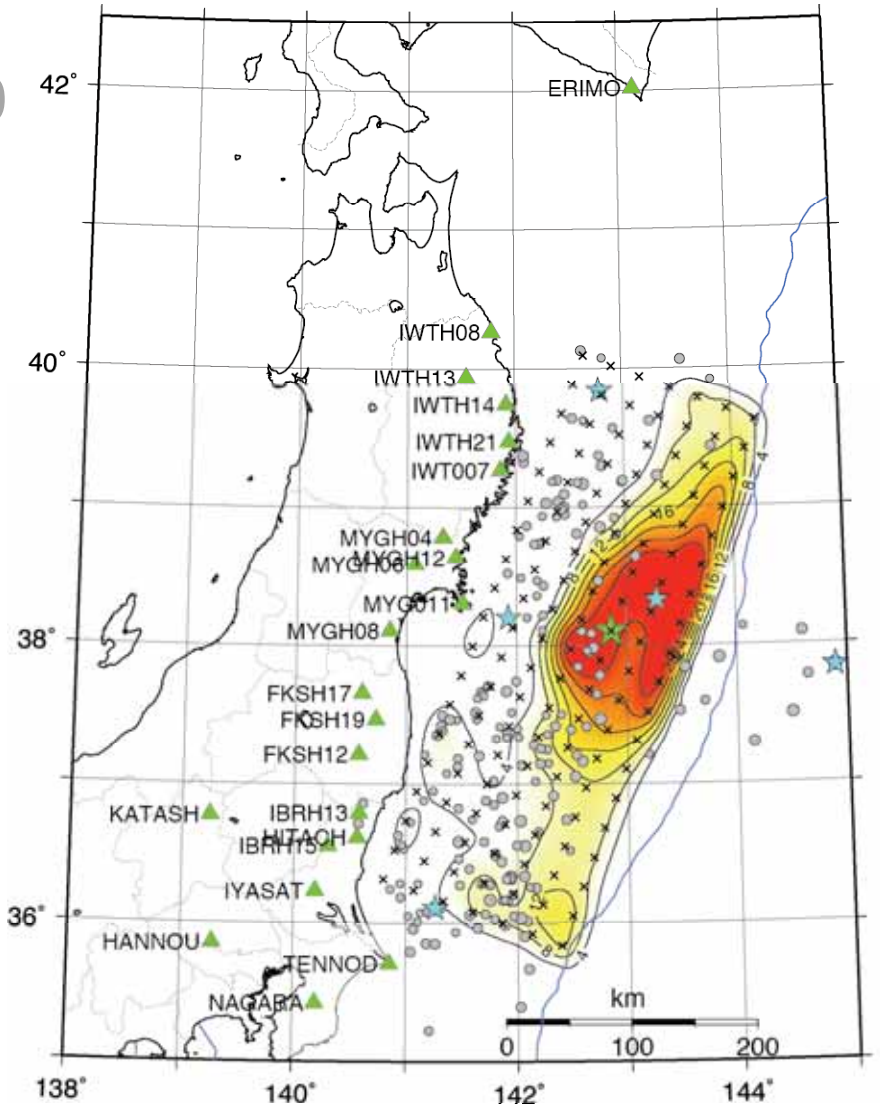
3/11	15:08 off Iwate	M_j 7.4
3/11	15:15 off Ibaraki	M_j 7.6
3/11	15:25 off Sanriku	M_j 7.5
4/7	23:32 off Miyagi	M_j 7.2
4/11	17:16 Hamadoori, Fukushima	M_j 7.0
7/10	09:57 off Sanriku	M_j 7.3



http://earthquake.usgs.gov/earthquakes/

The 2011 Tohoku Earthquake

- March 11, 2011, 14:46 M_w9.0
- Many aftershocks
- Death toll: 15,835
- Missing: 3,669
- Damaged houses
  Full collapse 120,142
  Half collapse 188,570
  Partial damage 594,508
  Flooded over floor 10,965
  Flooded under floor 13,677
  (2011.11.7 The number includes the damage caused by aftershocks.)
- Evacuee: 470,000
- Amount of damage:
  ¥16.9 trillion (US$200 billion)



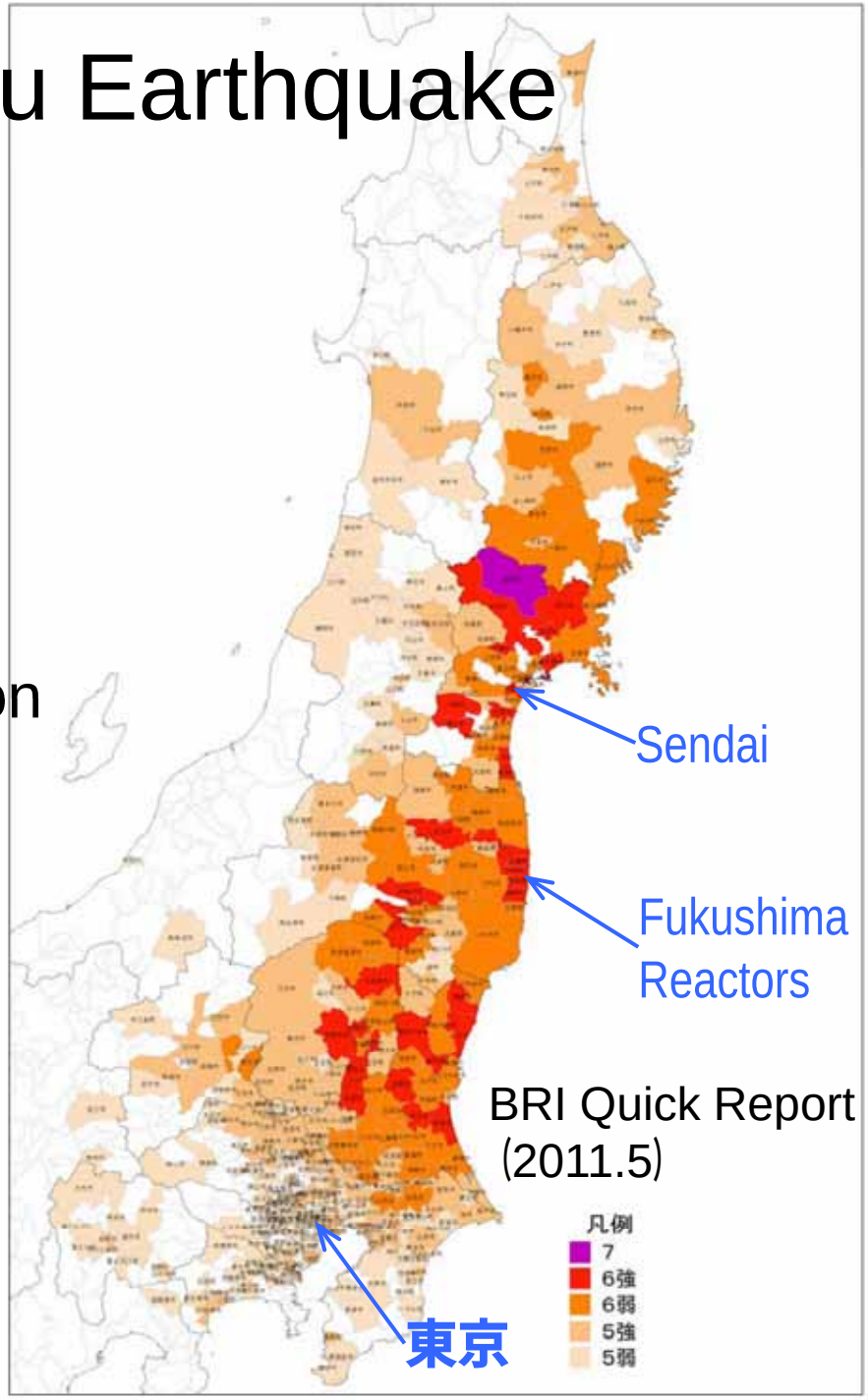
Slip distribution on the fault

Meteorological Research Institute, JMA

http://www.mri-jma.go.jp/Dep/sv/2011tohokutaiheiyo/source-process2.pdf/

The 2011 Tohoku Earthquake

- March 11, 2011, 14:46 M_w9.0
- Many aftershocks
- JMA seismic intensity
  VII: 1 station
  VI+: 40 stations
- 10.00 m/s^2 or larger: 18 stations
- Less 1.00 m/s except for 1 station



BRI Quick Report
(2011.5)

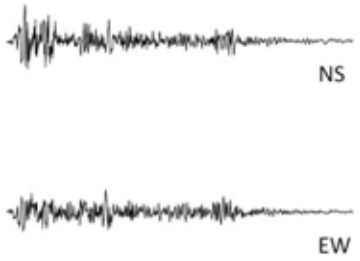
The 2011 Tohoku Earthquake

- JMA seismic intensity
  VII: 1 station
  Tsukidate, Kurihara (MYG004)
  27.00 m/s^2 NS
  12.69 m/s^2 EW
  18.80 m/s^2 UD
  (PGV=1.094 m/s resultant)
  VI+: 40 stations
- 10.0
- Less

The 2011 Tohoku Earthquake

- JMA seismic intensity
  VII: 1 station
  VI+: 40 staions
  Nigatake, Miyagino, Sendai (MYG013)
  15.15 m/s^2 NS
  9.77 m/s^2 EW
  2.90 m/s^2 UD
  (PGV=0.816 m/s resultant)
- 10.00 m/s2 or larger: 18 stations
- Less 1.00 m/s except for 1 station

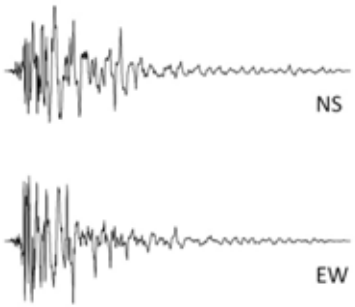
Strong Motion Records



El Centro

PGA = 3.42 m/s^2 (NS)

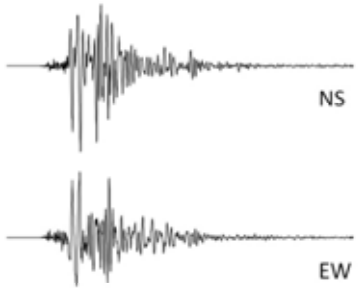
2.10 m/s^2 (EW)



JR Takatori

PGA =6.11 m/s^2 (NS)

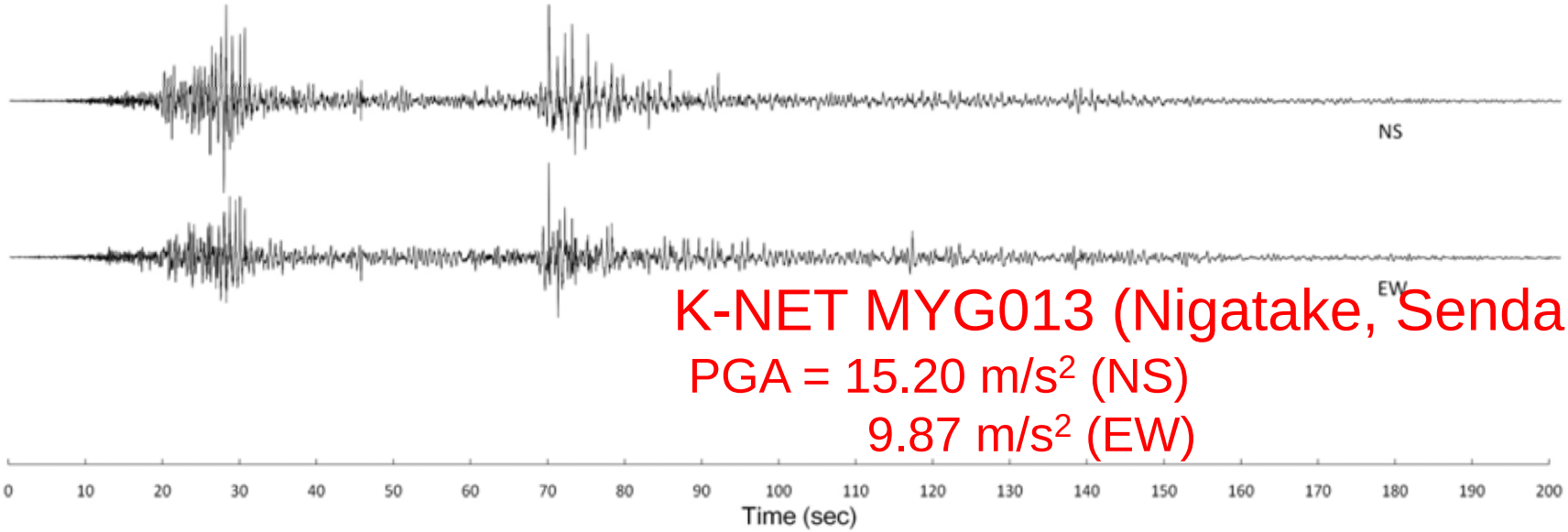
6.14 m/s^2 (EW)



JMA Kobe

PGA =8.18 m/s^2 (NS)

6.17 m/s^2 (EW)

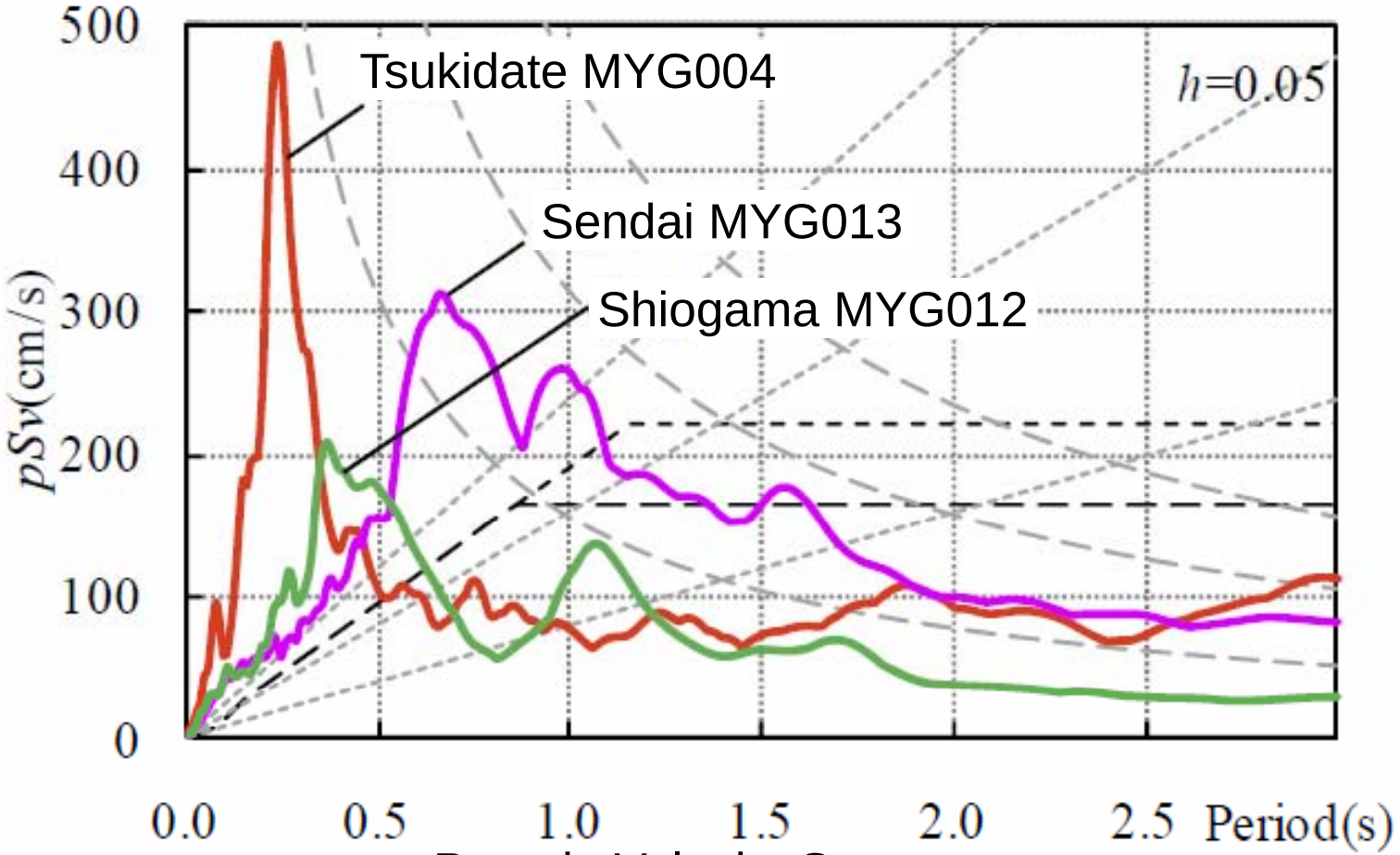


K-NET MYG013 (Nigatake, Sendai)

PGA = 15.20 m/s^2 (NS)

9.87 m/s^2 (EW)

Psuedo Velocity Response Spectra

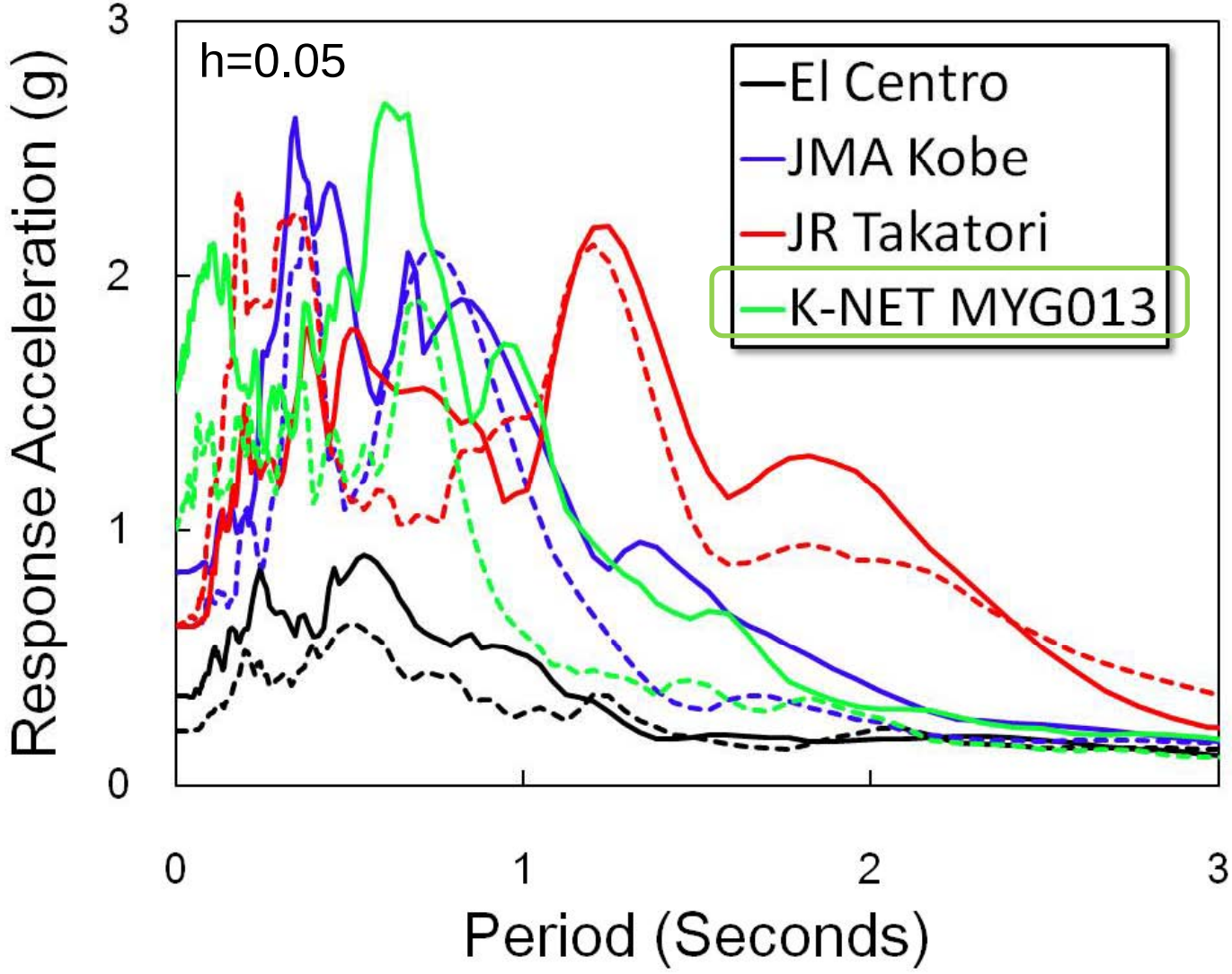


Psuedo Velocity Spectra
K-NET MYG004, MYG012, MYG013

NILIM, MLIT and BRI: Quick Report of the Field Survey and Research on “The 2011 off the Pacific coast of Tohoku Earthquake” (the Great East Japan Earthquake), Technical Note No. 636, NILIM/Building Research Data, No.132, 2011.5

Notes: 1)Psuedo velocity is calculated based on response displacement composed of two horizontal components. 2) Black broken and dotted lines represent response spectra corresponding to soil-type II and III of the seismic provisions of BSLJ. 3) Grey dotted and broken lines correspond psuedo acceleration of 5, 10, 15 m/s^2 and spectral displacement of 0.25, 0.50, 0.75 m, respectively.

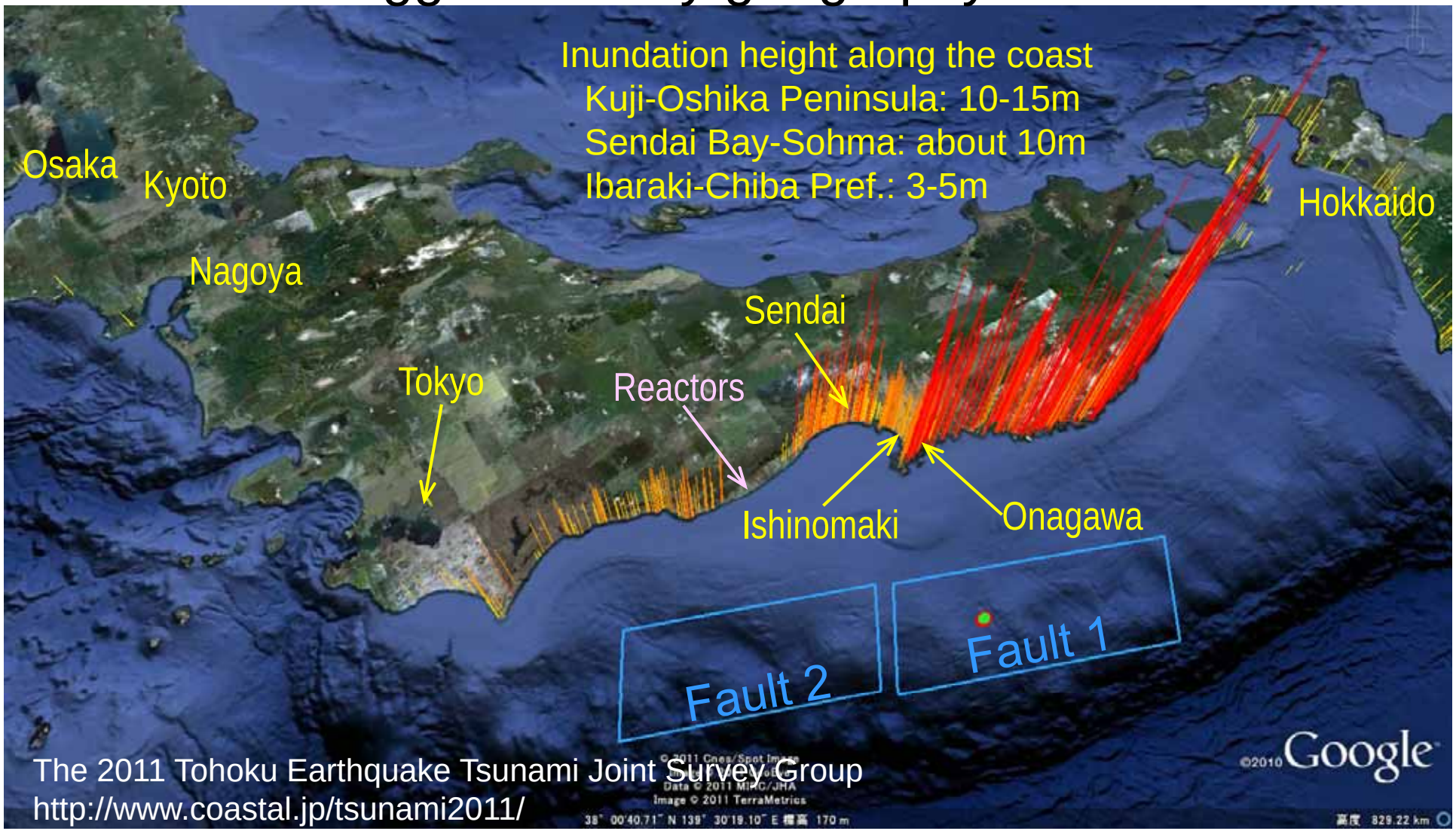
Acceleration Response Spectra



Acceleration Response Spectra

Tsunami Height Map

- The coast was close (100 km) to the faults
- Tsunami aggravated by geography

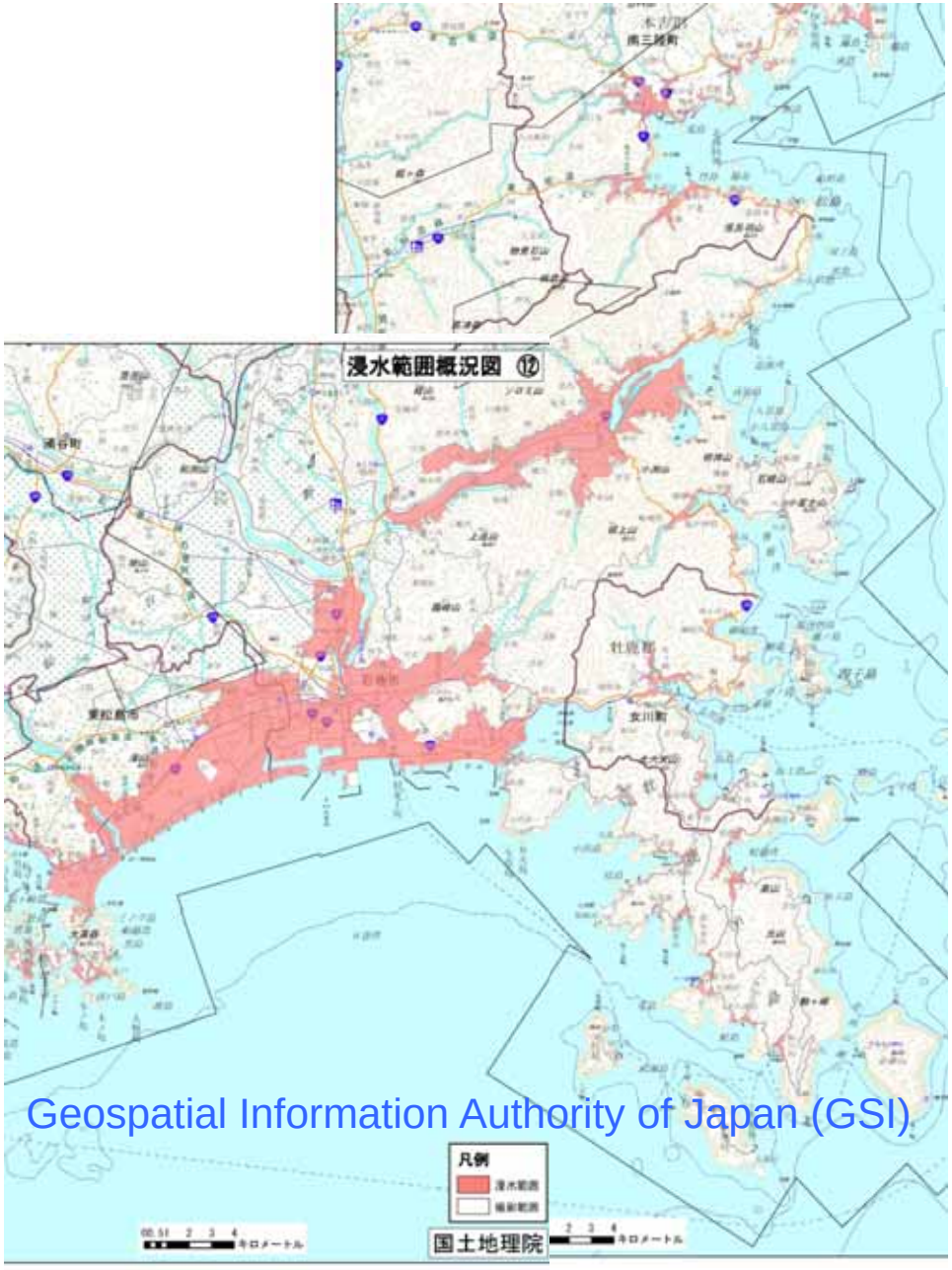


The 2011 Tohoku Earthquake Tsunami Joint Survey Group
http://www.coastal.jp/tsunami2011/

Areas of Sendai and Vicinity

Fishing Ports along the Sanriku Coast

Inundated Area Map



Geospatial Information Authority of Japan (GSI)

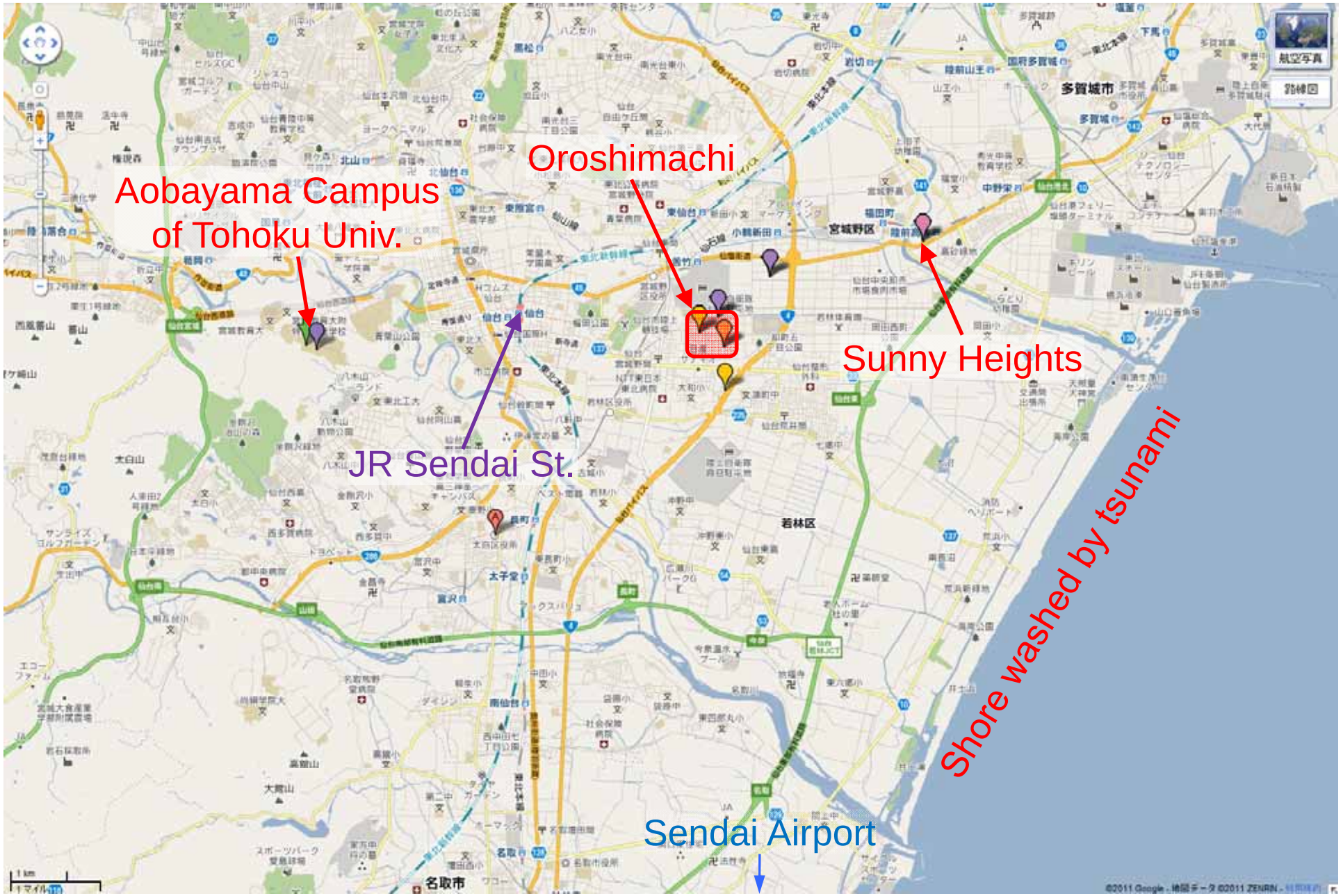
Damage Caused by Earthquake Ground Motions

Damage Caused by Earthquake Ground Motions

- Eastern half of Honshu Island was affected.
  - ✓ Damage to residential timber houses, reinforced concrete and steel buildings
  - ✓ Extensive liquefaction in reclaimed land/soft ground around Tokyo bay area/reaches of Tone River
  - ✓ Resonance of high-rise buildings far away
- Very many aftershocks and derivatives (hundreds M_w5+)
- The same fault (Fault 1) has produced many earthquakes 1793, 1835, 1861, 1897, 1936, 1978, 2011
- There were two main events in Sendai

  March 11, 14:46:18 M_w9.0 (JMASI 6-major)
  April 7, 23:32:43 M_w7.2 (JMASI 6-major)

Damage in and around Sendai



Sunny Heights Takasago (SRC, 14F, 189 units)-1

Sunny Heights Takasago (SRC, 14F)-2

Angle of inclination 1/56
(Top drift 70 cm to south)
Increased to 1/45 by aftershock on 4/7

Shear failure of nonstructural walls

Sunny Heights Takasago (SRC, 14F)-3

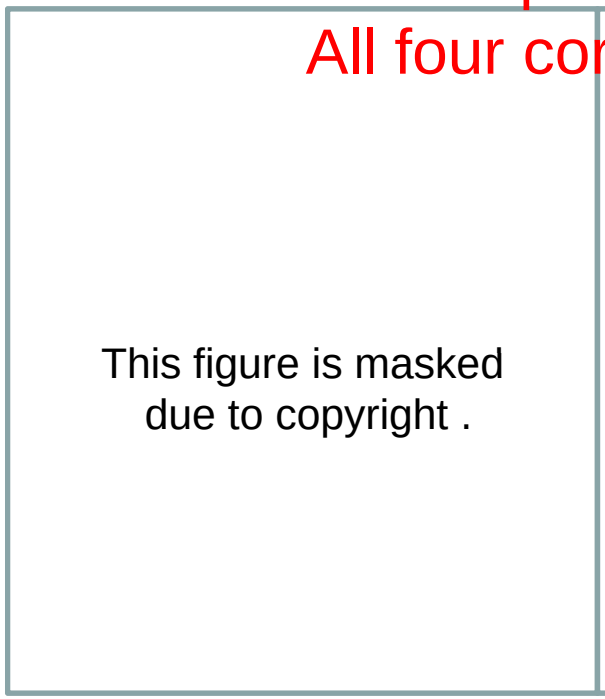
Tohoku Univ. (SRC, 9F)-1 Civil Engrg. & Architecture

Aoba, Sendai
School, SRC, 9F, Completed in 1969
Damaged by 1978 EQ
Strengthened with RC shear walls after 1978 EQ
Strengthened with steel braces in 2000

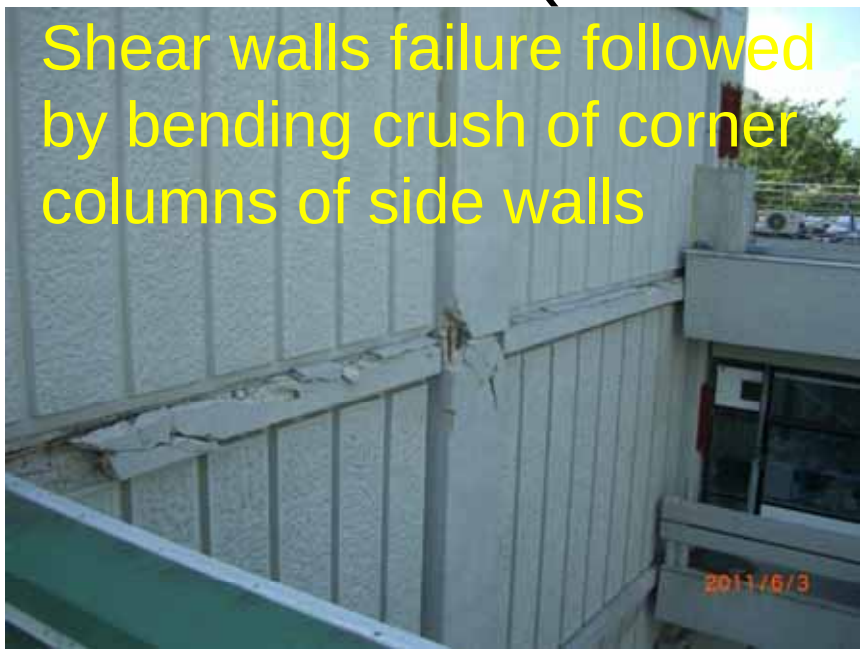
Bending failure of outer columns of side walls at setback level (3F)
Fracture and buckling of re-bars and steel members

Tohoku Univ. (SRC, 9F)-2 Civil Engrg. & Architecture

Failure progress by aftershock on 4/7
All four corner columns crushed in bending



Tohoku Univ. (SRC, 9F)-3 Civil Engrg. & Architecture

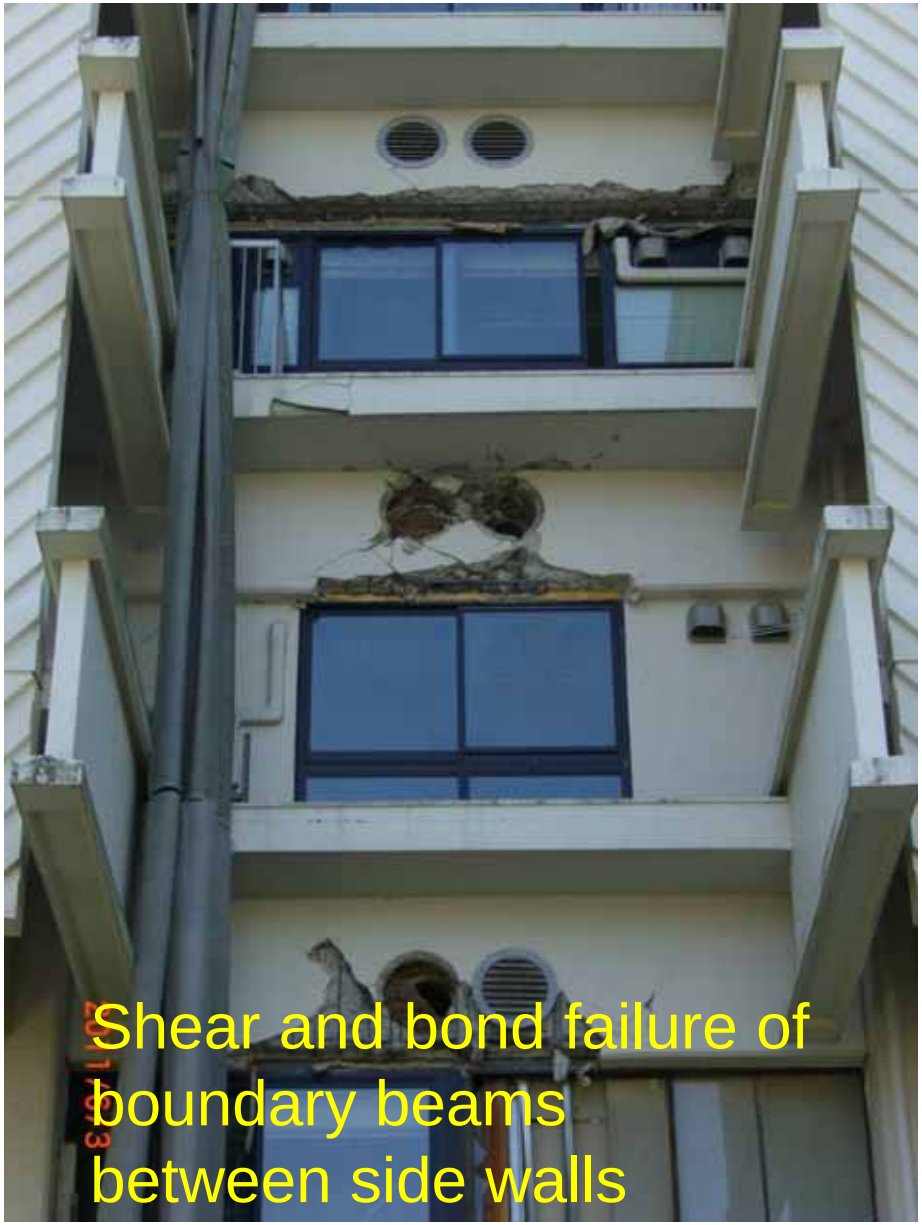


Tentative strengthening of crushed column (lower view)

Tohoku Univ. (SRC, 8F)-1 Electrical Engrg. & Applied Physics

Tohoku Univ. (SRC, 8F)-2 Electrical Engrg. & Applied Physics

Damage from main shock on 3/11
Damage progress from aftershock on 4/7



Shear and bond failure of boundary beams between side walls

Tohoku Univ. (RC, 2F) Electrical Engrg. & Applied Physics

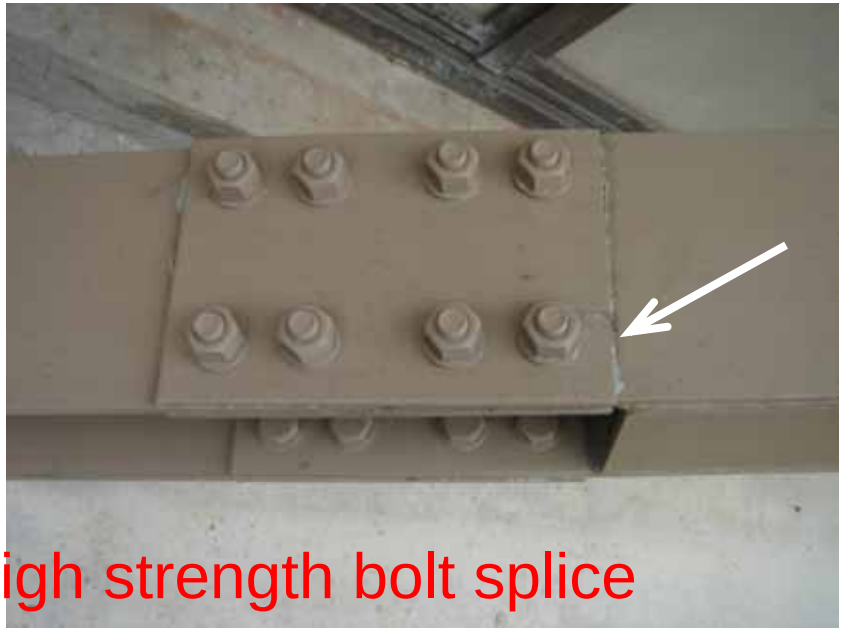
Aoba, Sendai
School, RC, 2F
Completed in 1966

Shear failure of
first story columns

Tohoku Univ. (RC, 6F) Chemical and Biomolecular Engrg.

Aoba, Sendai
School, RC, 6F

Seismic upgrade completed
Minor damage

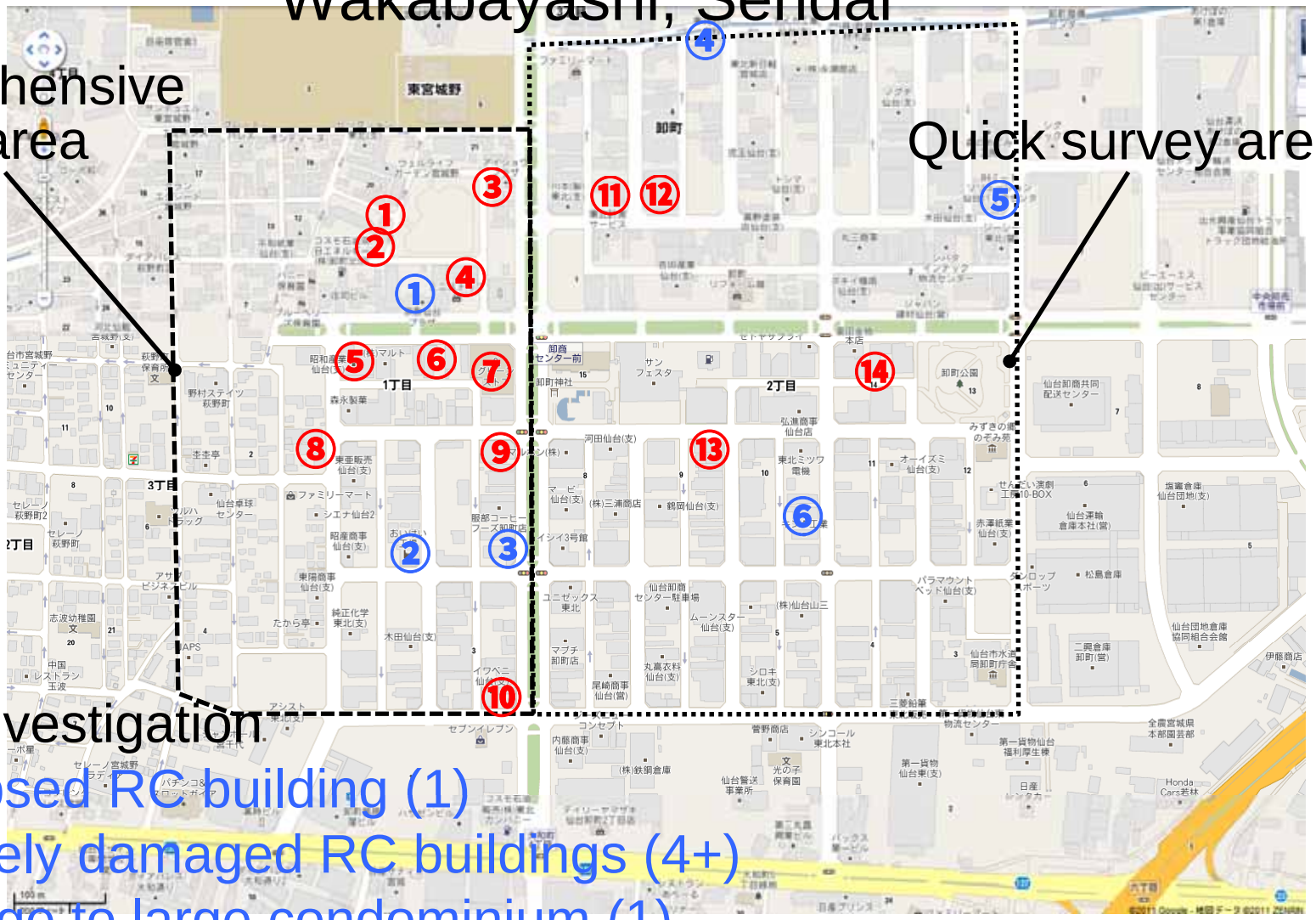


Evidence of slippage at high strength bolt splice

Damage Survey in and around Oroshimachi, Wakabayashi, Sendai

Comprehensive survey area

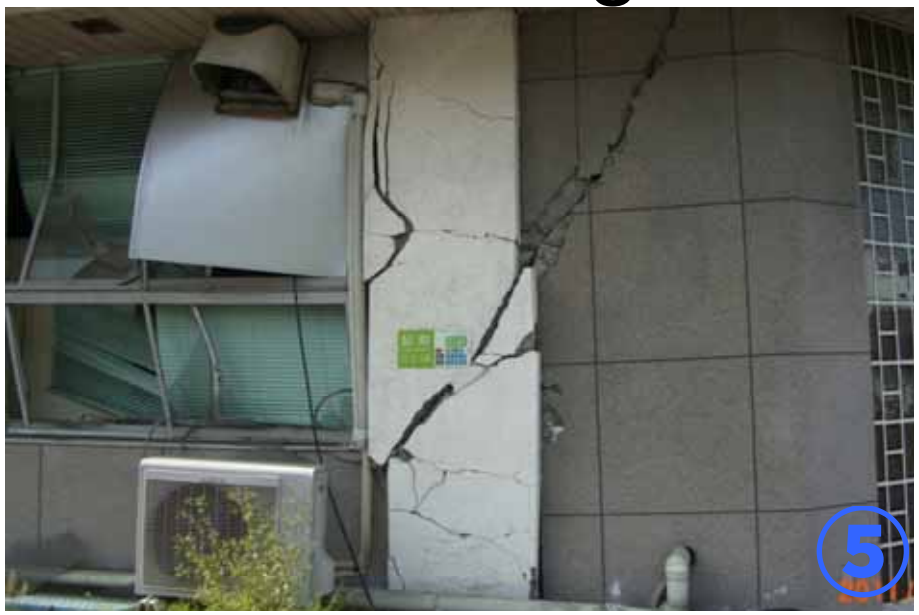
Quick survey area



From investigation

- Collapsed RC building (1)
- Severely damaged RC buildings (4+)
- Damage to large condominium (1)
- Cladding damage to steel buildings (many)
- Poorly designed steel parking garage (1)

Severe Damage to RC Buildings



Severe damage to RC Building (3F) 1-1

Oroshimachi, Wakabayashi, Sendai
Office, RC, 3F, Completed in 1969
Shear failure of first story columns
Torsional behavior caused by eccentric core

Severe damage to RC Building (3F) 1-2

Longitudinal bars & tie:
round bars

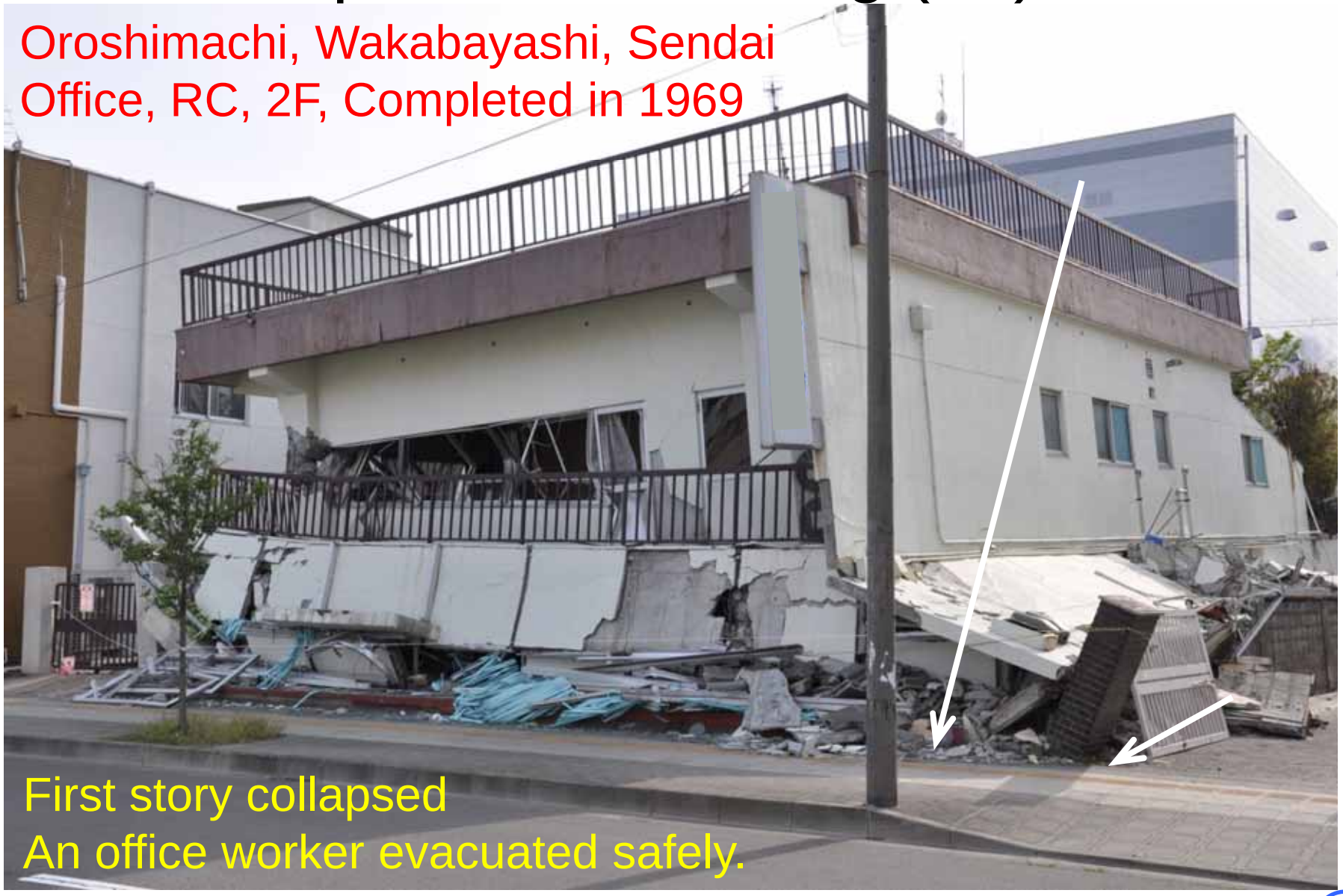
Column tie spacing 30cm

Severe Damage to RC Building (3F) 2-1

Higashimiyagino, Miyagino, Sendai
Office, RC, 3F
Shear failure of first story columns

Severe Damage to RC Building (3F) 2-2

Collapsed RC Building (2F) 3-1



Collapsed RC Building (2F) 3-2

Longitudinal bars: deformed bars
Tie: round bars

2010.2.27 Chile Maule EQ, Concepcion

Damaged SRC Building (11F)

Nonstructural members

Haginomachi, Miyagino, Sendai
Condominium, SRC, 11F
Completed in 1975

Shear failure of
nonstructural wall at entrance

Shear failure of
nonstructural walls at every story

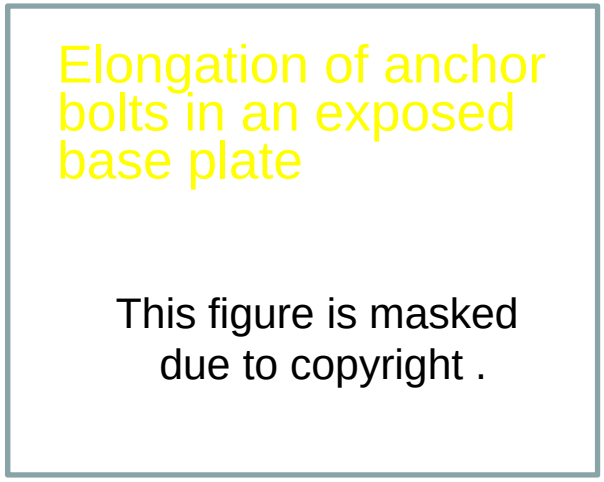
Pounding at EX.J

①

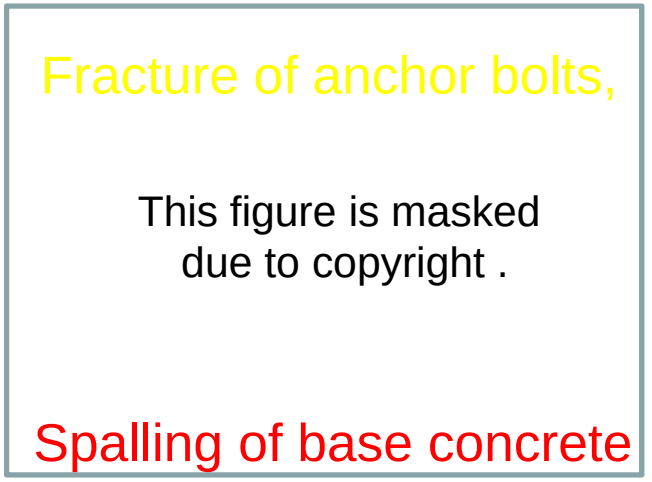
Damage to Steel Structures 1

Yielding of an older built-up column

Elongation of anchor bolts in an exposed base plate



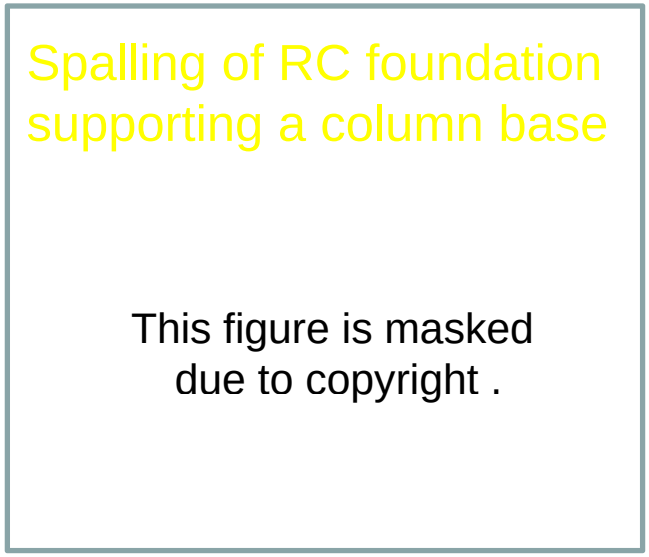
Fracture of anchor bolts,



Spalling of base concrete

Local buckling in HSS brace

Spalling of RC foundation supporting a column base



Collapse of sky bridges

Severe Damage to Steel Building (4F) 2-1

Severe Damage to Steel Building (4F) 2-2

Net section fracture of gusset plate at brace end connection

Bending of middle gusset plate in an X-brace

Severe Damage to Steel Building (4F) 2-3

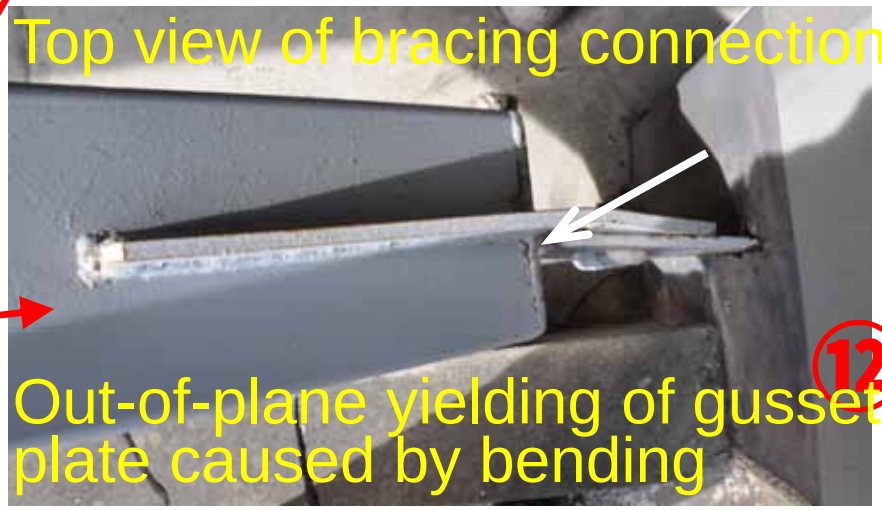
No damage to beam-to-column connections

Failure of column base concrete

Minor Damage to Parking Garage (2F) 3-1

Oroshimachi, Wakabayashi, Sendai
Parking Garage, Steel, 2F

Side view of
bracing connection



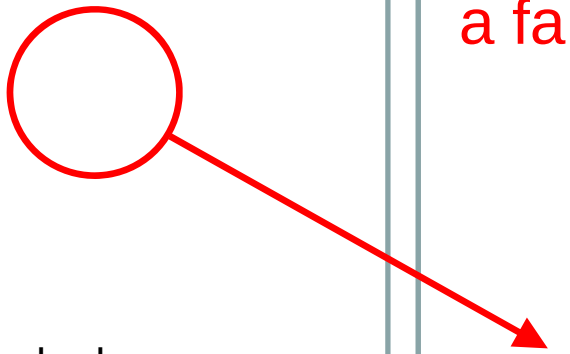
Top view of bracing connection

Out-of-plane yielding of gusset plate caused by bending

Minor Damage to Parking Garage (2F) 3-2

Fracture of Shear Tab in Beam Connection 4

Rifu
Large commercial
Steel



This figure is masked due to copyright .

A child was killed by a fallen ceiling.

This figure is masked due to copyright .

This figure is masked due to copyright .

Fracture of shear tab in beam end connection in a parking ramp

Severe Damage to Parking Garage (2F) 5-1

Severe Damage to Parking Garage (2F) 5-2

Severe Damage to Parking Garage (2F) 5-3

Severe Damage to Parking Garage (2F) 5-4

No Structural Damage to Steel Buildings

In and around Oroshimachi, Wakabayashi, Sendai

Light-gauge residential

Parking garage

Moment frame

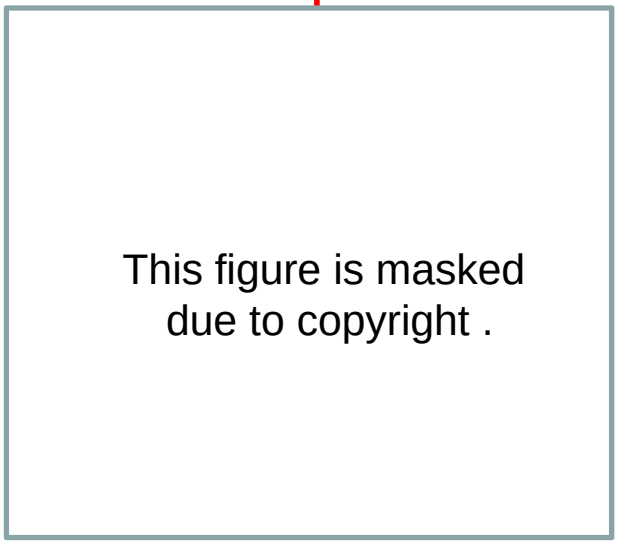
Small commercial

Damage to Nonstructural Elements of Steel structures 1

Ceiling

Metal lath-and-mortar

ALC-panel



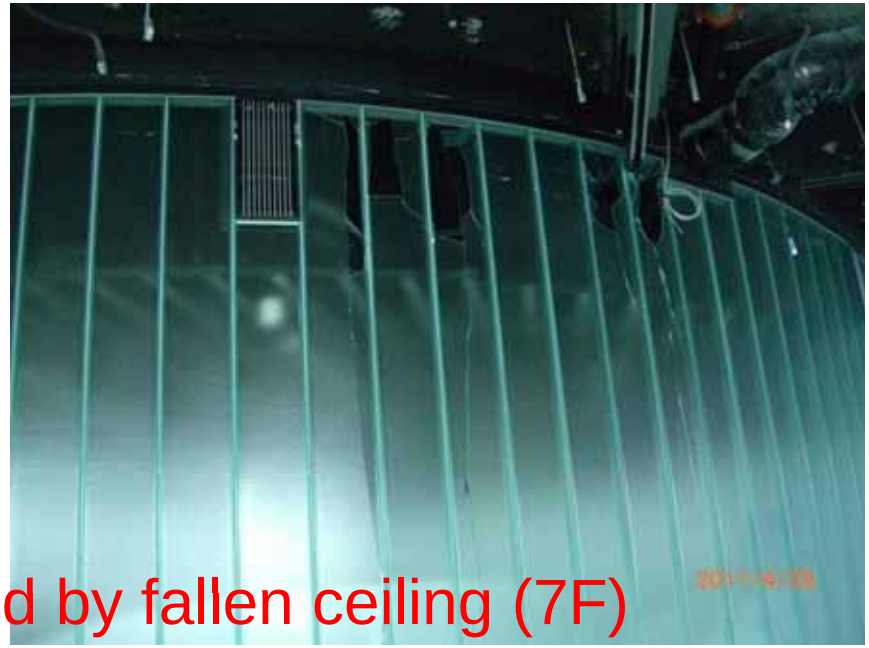
Damage to Exterior Finishes 2-1: Large Steel Structures

Damage to Exterior Finishes 2-2: Mid-size Structures

Damage to Exterior Finishes 2-3：Smaller Structures

Nonstructural Damage to Steel Building 3-1: Sendai Mediatheque

Nonstructural Damage to Steel Building 3-2: Sendai Mediatheque



Glass walls damaged by fallen ceiling (7F)

Three readers evacuated safely in between bookstacks (7F)

No fallen ceiling in an office room (6F)

Nonstructural Damage to Steel Building 3-3: Sendai Mediatheque

Temporary exterior glass for repair (3F)

Failure of rib glass (1F)

Break of lock pins at bottom of large front door

Nonstructural Damage to Steel Building 4

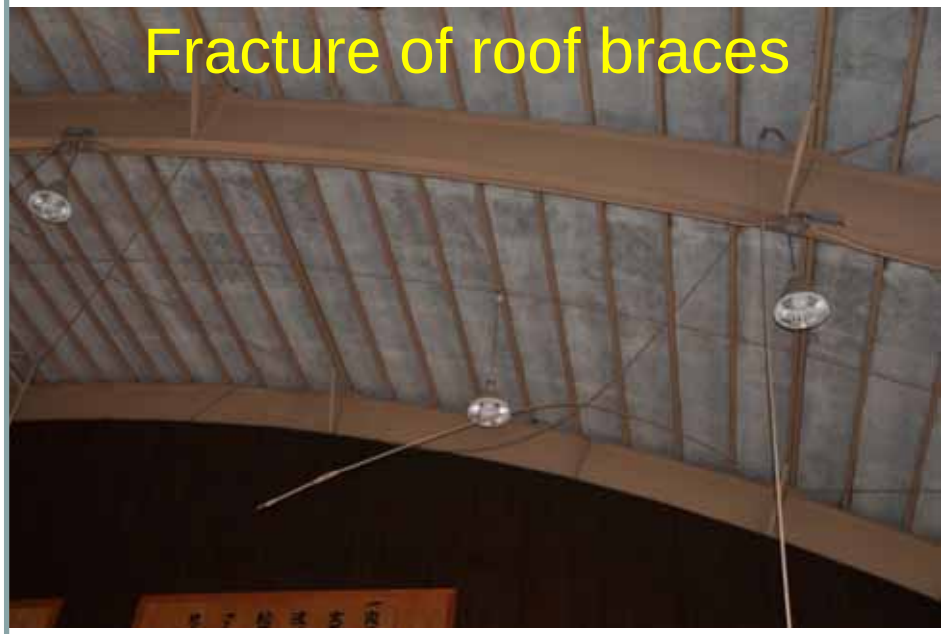
Seismic Damage to Steel Structures: Tsunami Area 1

This figure is masked due to copyright .

Higashimatsushima
(Inundation depth 1 m)
Elementary school gymnasium

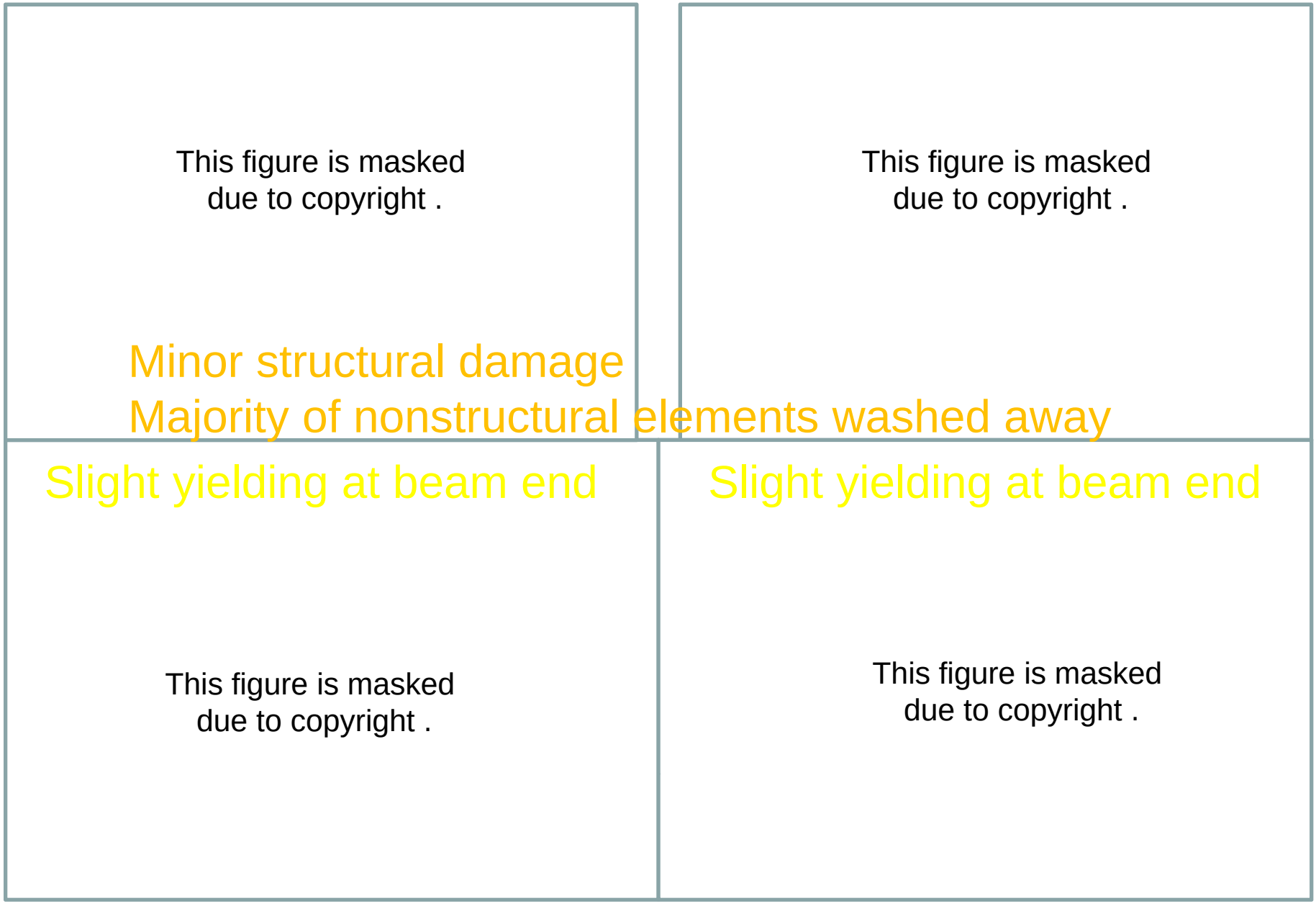
Flexural buckling of 2F brace

This figure is masked due to copyright .



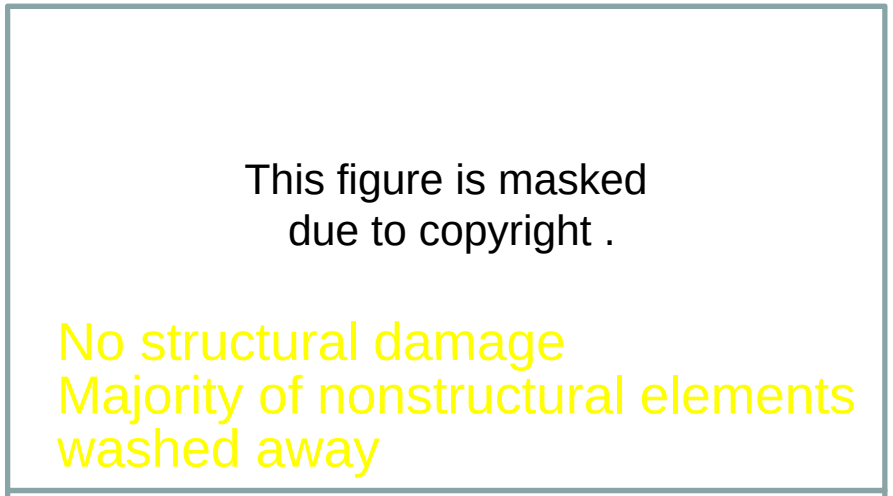
Seismic Damage to Steel Structures: Tsunami Area 2

Minamisannriku (Inundation height 13-15 m)

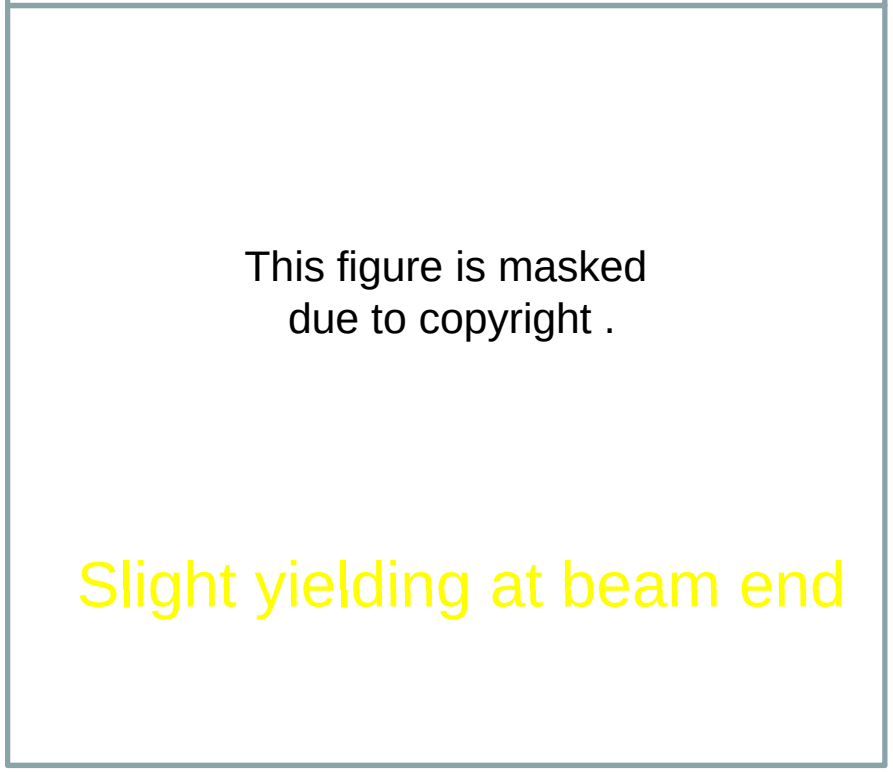


Seismic Damage to Steel Structures: Tsunami Area 3

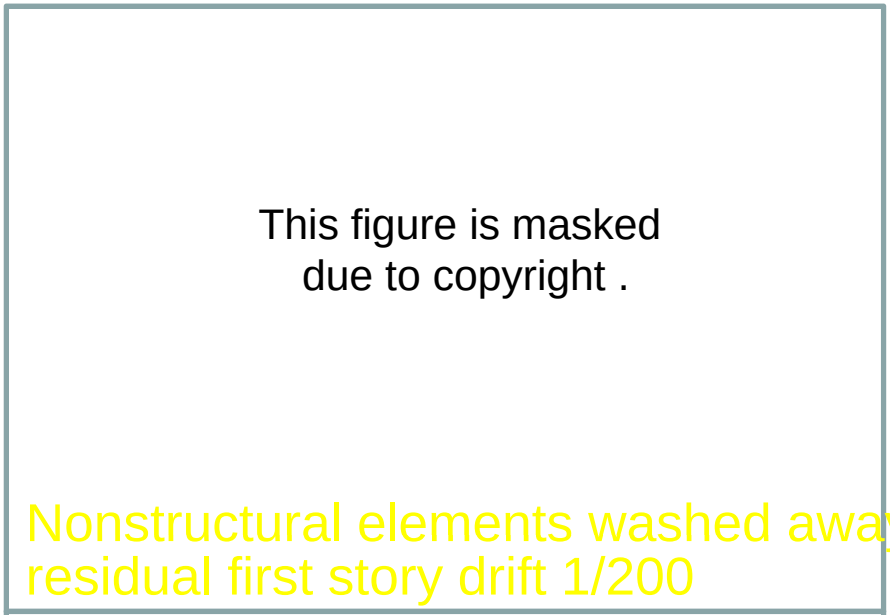
Minamisannriku (Inundation height 13-15 m)



No structural damage
Majority of nonstructural elements washed away



Slight yielding at beam end



Nonstructural elements washed away
residual first story drift 1/200

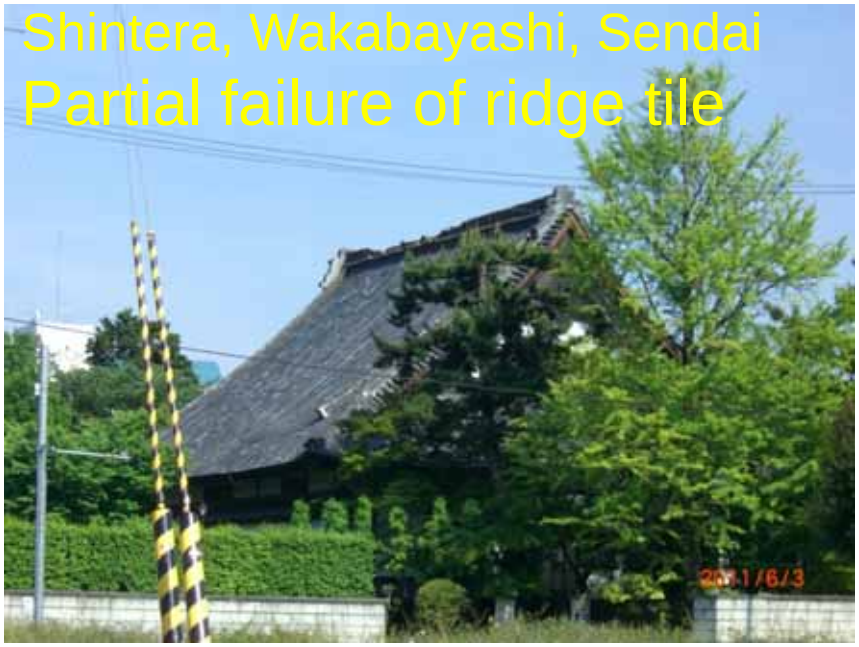
Slight yielding at beam end

Seismic Damage to Nonstructural Elements of Steel Structures: Tsunami Area; Ishinomaki (Inundation height 5 m)

Damage to Timber Construction

Haginocho, Miyagino, Sendai
Failure of ridge tile

Fukumuro, Miyagino, Sendai
Collapse of old timber const.



Shintera, Wakabayashi, Sendai
Partial failure of ridge tile

Failure of exterior walls
Miyagino, Sendai

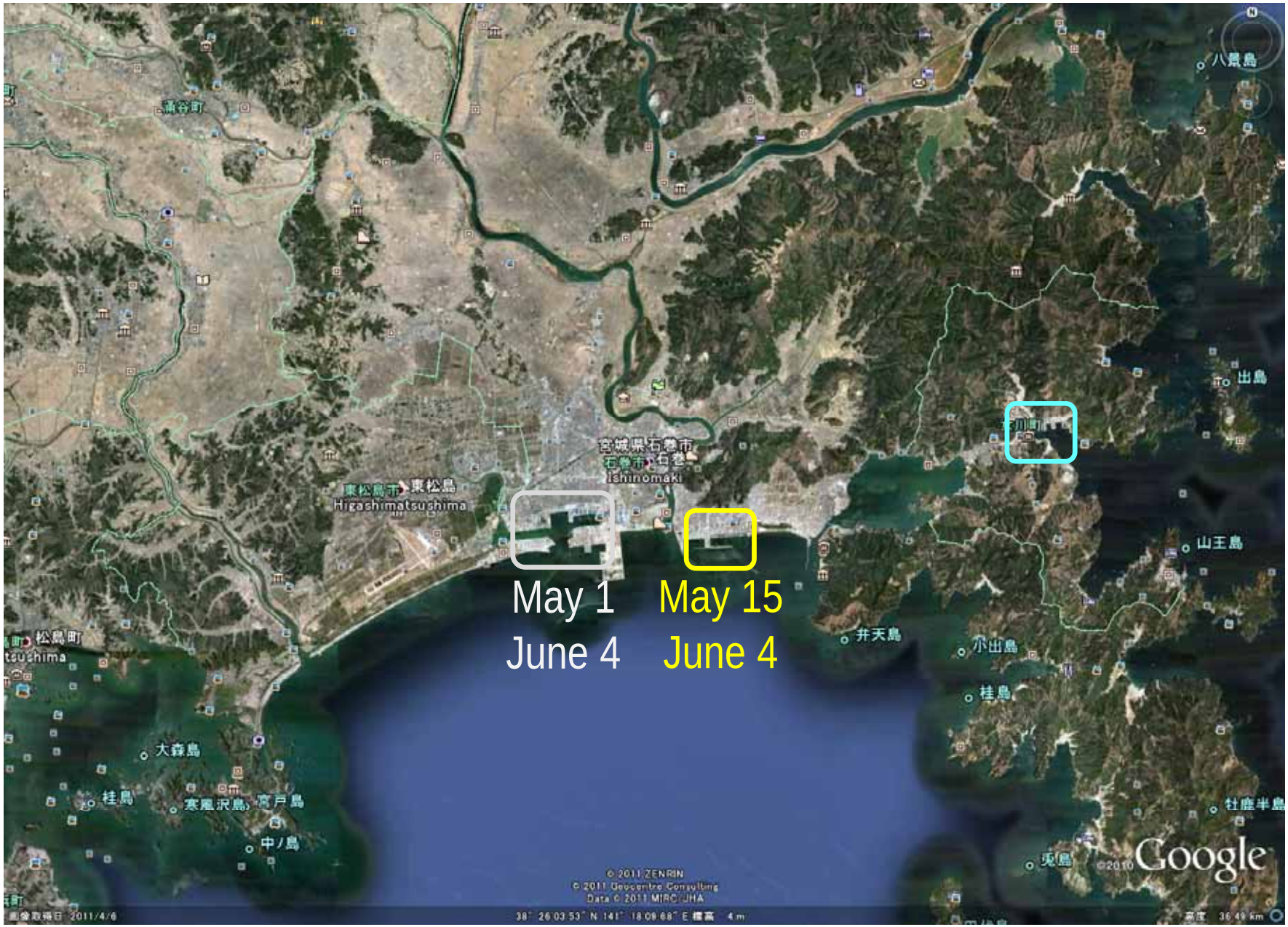
Damage Caused by Tsunami

Damage Caused by Tsunami

- Tsunami hit a coast with many ports and harbors.
- The coast has been hit by tsunami many times: 1611, 1677, 1763, 1793, 1856, 1896, 1933, 1960, 2011
- Majority of timber residential buildings were completely destroyed.
- Many reinforced concrete (RC) and steel buildings survived in the devastating tsunami areas.

- The probable reason of survival of RC and steel buildings is that column bases are firmly connected to a foundation.

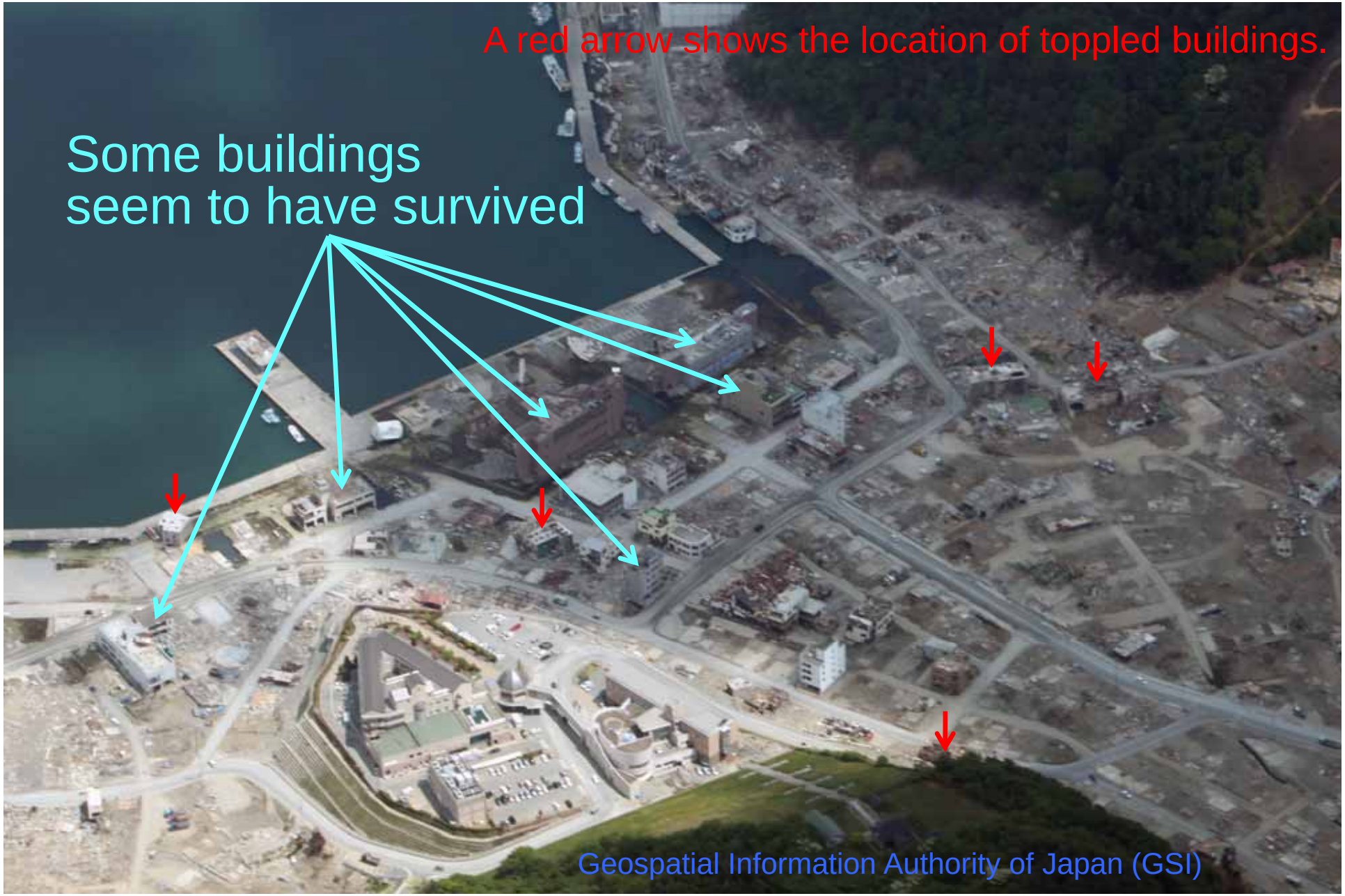
Tsunami Area: Ishinomaki & Onagawa



Tsunami Area: Onagawa 1

Tsunami Area: Onagawa 2 2011.5.25

Tsunami Area: Onagawa 3 2011.5.25

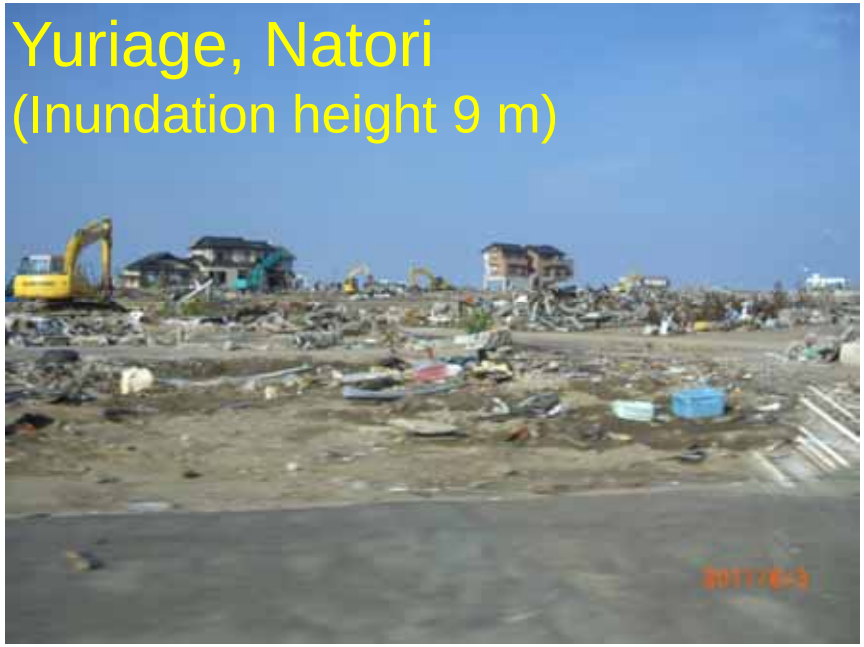


Tsunami Area: Ishinomaki 1 2011.5.25

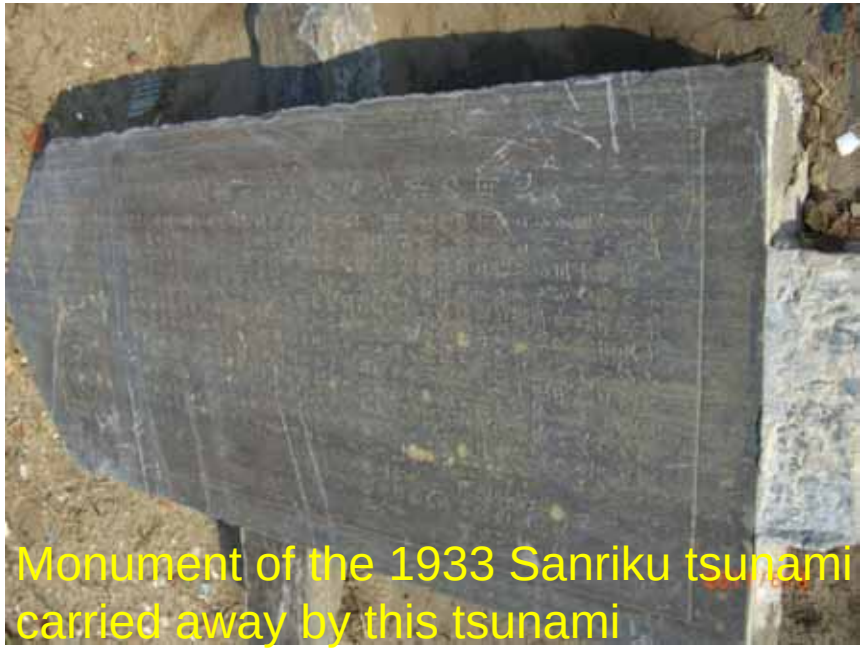
Tsunami Area: Ishinomaki 2

Tsunami Damaged Area: Slope Region

Tsunami Damaged Area: Flat Region 1



Tsunami Damaged Area: Flat Region 2



Another Tsunami Damage: 2010.2.27 Chile Maule EQ.

Tokyo just after 1923.9.1 Kanto EQ.

This figure is masked

due to copyright .

Tsunami Damage to Buildings 1

Ishinomaki (Inundation height 5 m)

This figure is masked due to copyright .

This figure is masked due to copyright .

Minor structural damage

This figure is masked due to copyright .

This figure is masked due to copyright .

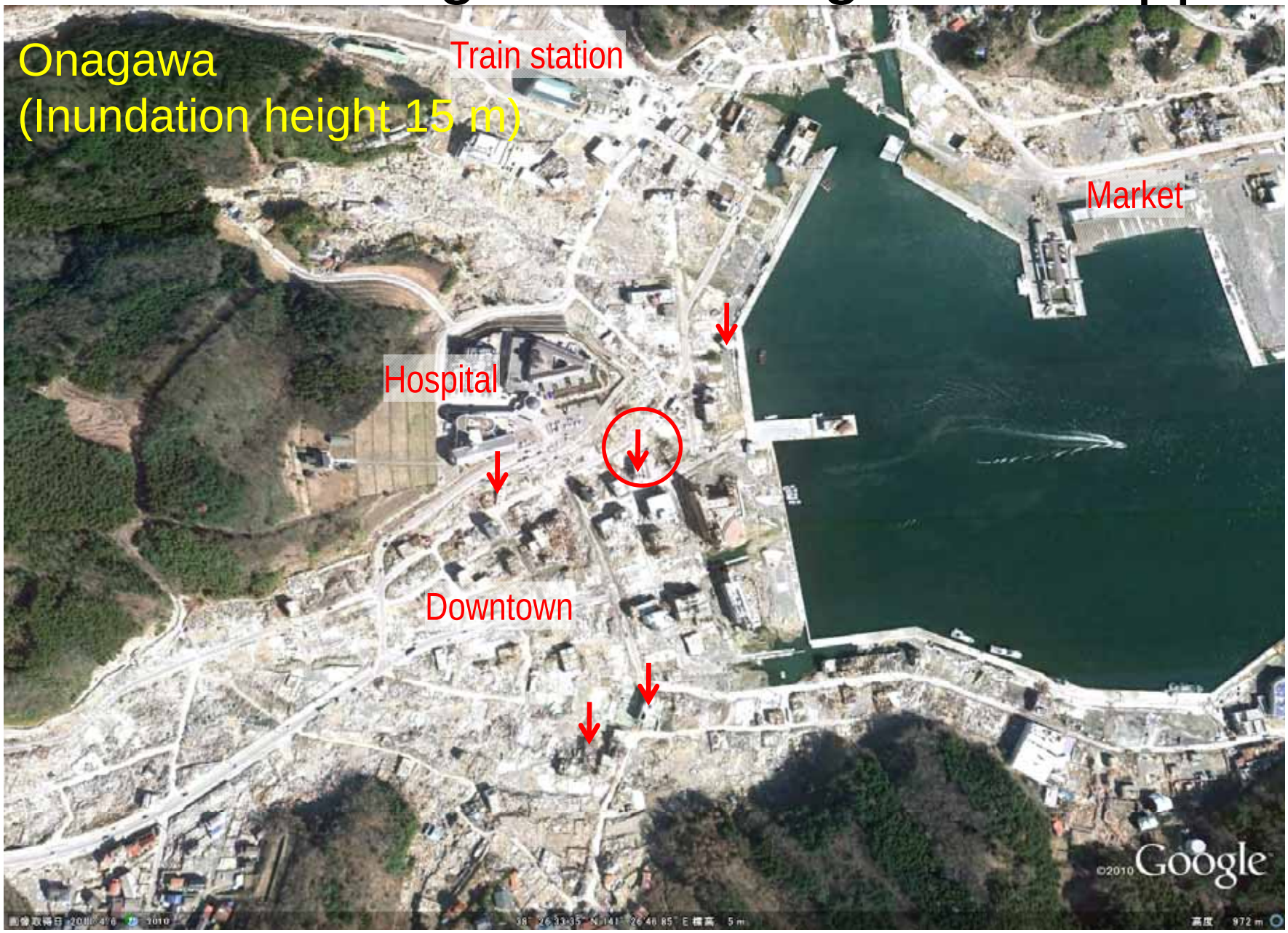
Structural damage caused by debris impact

This figure is masked due to copyright .

Toppling

Scour

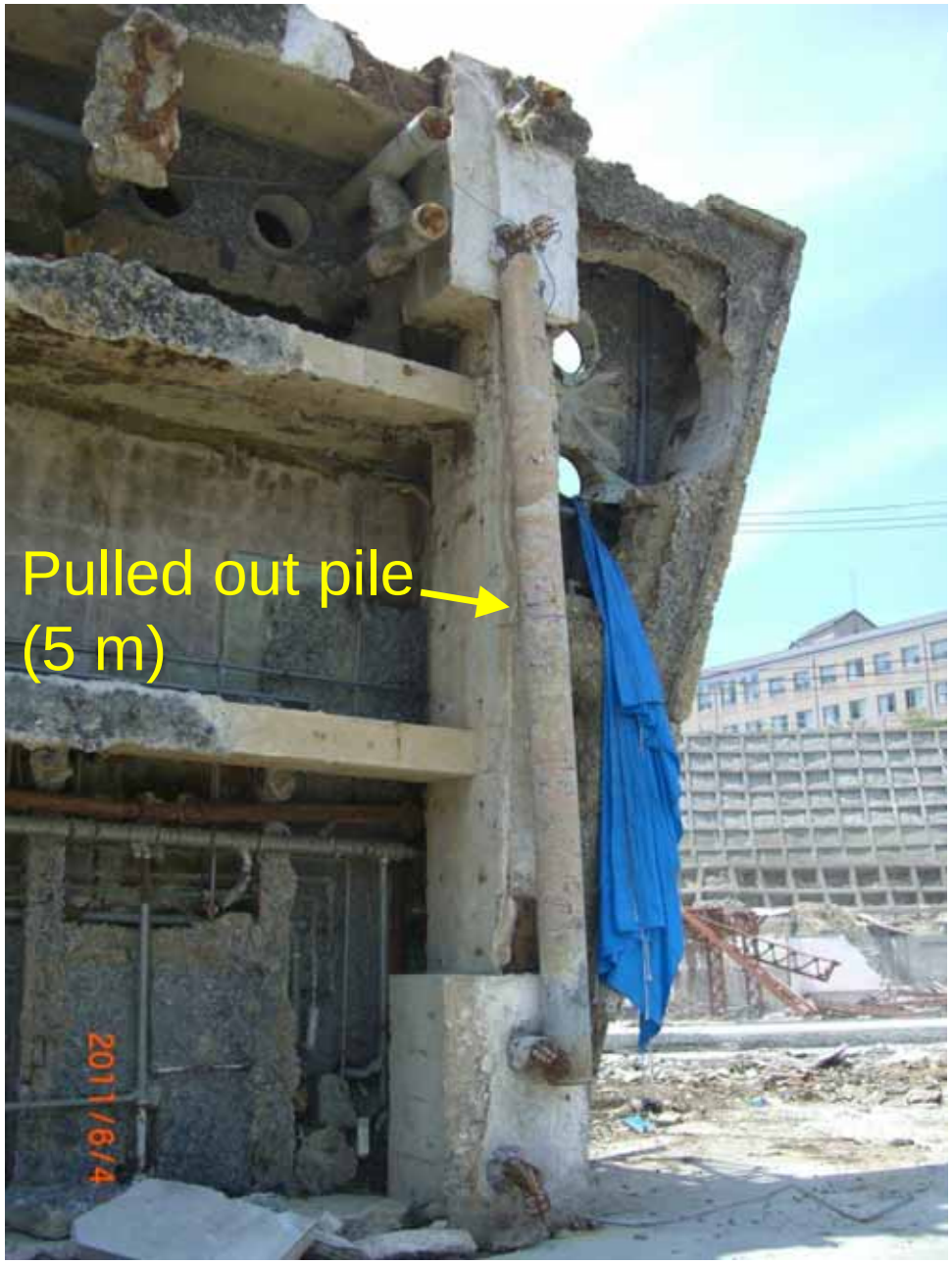
Tsunami Damage to Buildings 2-1: Toppling



Tsunami Damage to Buildings 2-2: Toppling (Steel)

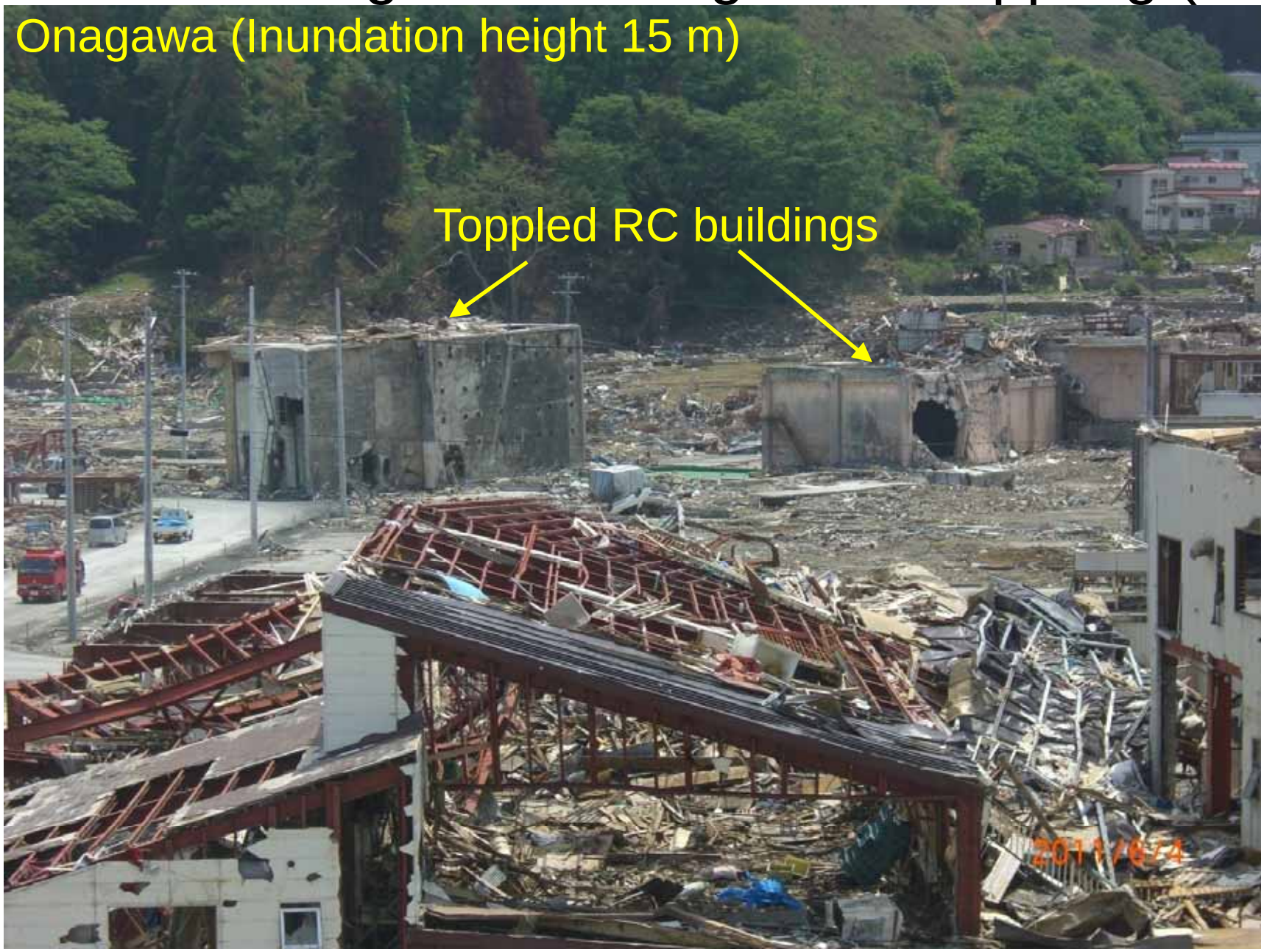
Tsunami Damage to Buildings 2-3: Toppling (Steel)

Tsunami Damage to Buildings 2-4: Toppling (Steel)



Tsunami Damage to Buildings 2-5: Toppling (RC)

Tsunami Damage to Buildings 2-6: Toppling (RC)



Tsunami Damage to Buildings 2-7: Toppling (RC)

Tsunami Damage to Buildings 3-1: Scour

Tsunami Damage to Buildings 3-2: Scour

Tsunami Damage to Buildings 3-3: Scour

Onagawa (Inundation height 15 m)

Steel, 3F

Subsidence caused by foundation scour

Foundation scour

Tsunami Damage to Buildings 4-1: Debris Impact

Tsunami Damage to Buildings 4-2: Debris Impact

Tsunami Damage to Buildings 4-3: Debris Impact

Tsunami Damage to RC Buildings 5-1

Onagawa (Inundation height 15 m)

Tsunami Damage to RC Buildings 5-2

Arahama, Wakabayashi, Sendai (Inundation height 9 m)

Tsunami Damage to Steel Structures 6-1

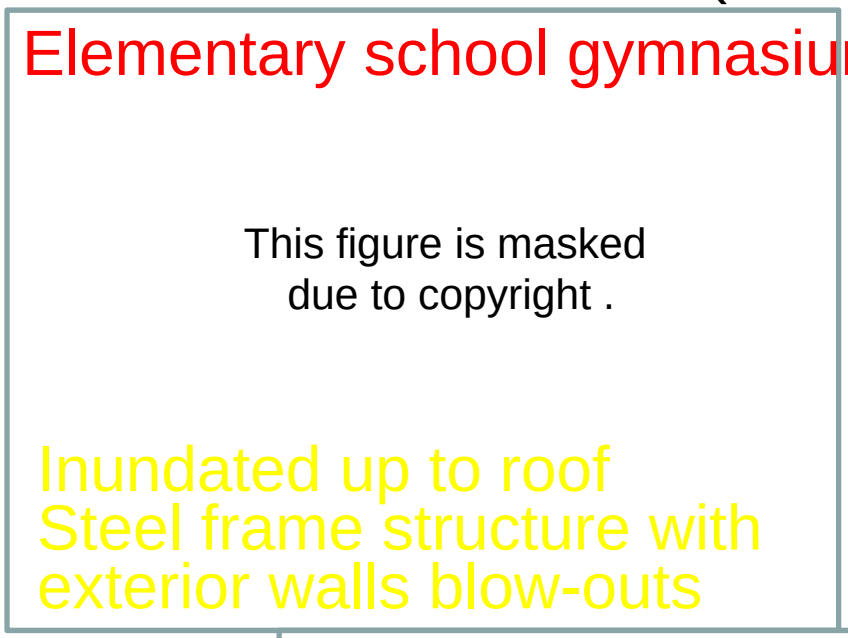
Onagawa (Inundation height 15 m)

Left standing just beside quay This figure is masked due to copyright .	This figure is masked due to copyright . Complete collapse	Refrigeration facility This figure is masked due to copyright .
This figure is masked due to copyright . Contents washed away	Fractured column connection This figure is masked due to copyright .	Failed column base This figure is masked due to copyright .

Tsunami Damage to Steel Structures 6-2

Minamisanriku (Inundation height 13-15 m)

Elementary school gymnasium



Inundated up to roof
Steel frame structure with
exterior walls blow-outs

Collapsed roof truss

Failed column base

Tsunami Damage to Steel Structures 6-3

Kesennuma (Inundation height 4-10 m)

Warehouse This figure is masked due to copyright . Complete collapse	Partially severe damage caused by debris This figure is masked due to copyright . Residual story drift 1/160	Factory: Majority of cladding washed away This figure is masked due to copyright . Residual story drift 1/200
Deformed beams/columns This figure is masked due to copyright .	Fractured beam-to-column connections This figure is masked due to copyright .	This figure is masked due to copyright . Yielding of column panel zone

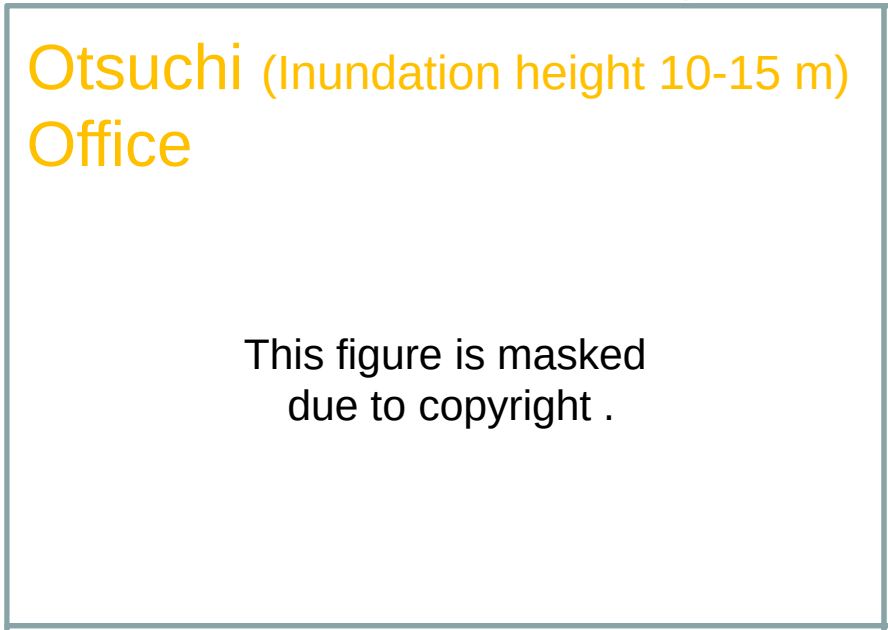
Tsunami Damage to Steel Structures 6-4

Rikuzentakada (Inundation height 12-16 m)

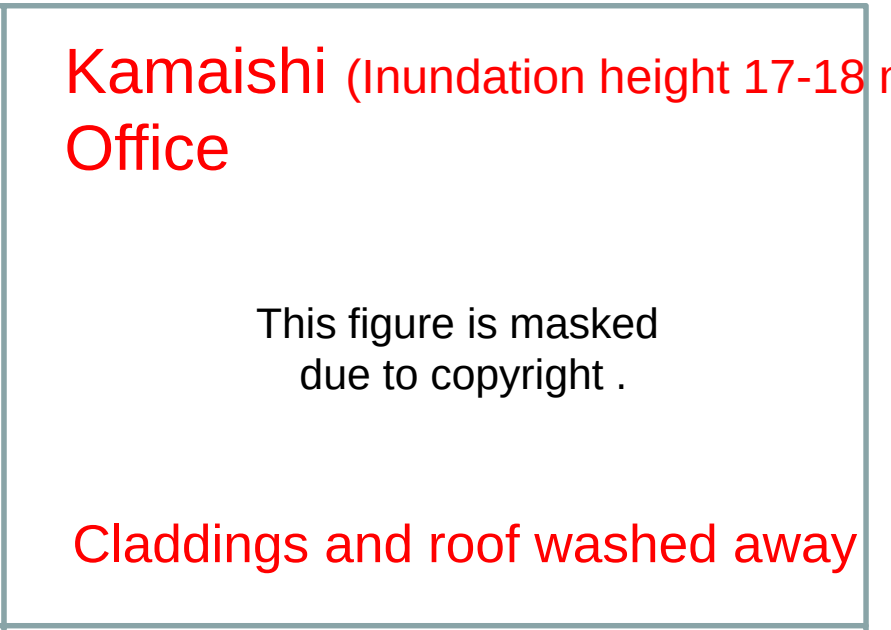
Office This figure is masked due to copyright .	Factory This figure is masked due to copyright .	This figure is masked due to copyright . High school gymnasium
Failed ALC-panels This figure is masked due to copyright .	Deformed column panel zone This figure is masked due to copyright .	Distance shifted by 20 m This figure is masked due to copyright . Failed column base

Tsunami Damage to Steel Structures 6-5

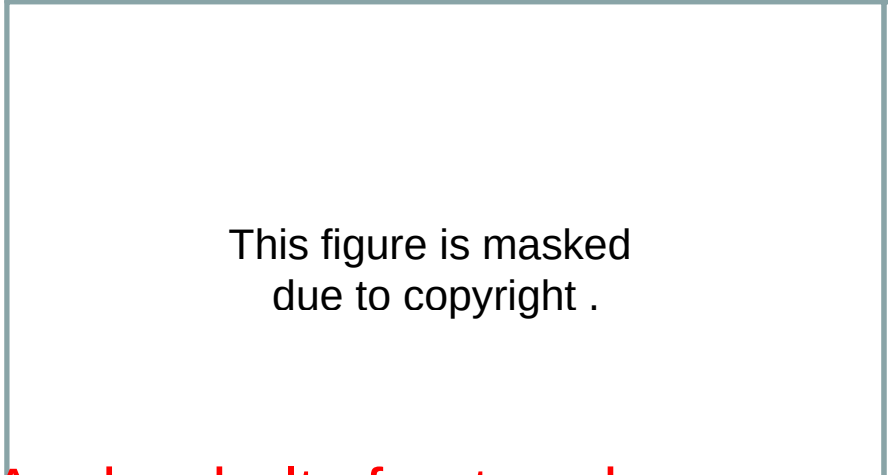
Otsuchi (Inundation height 10-15 m)
Office



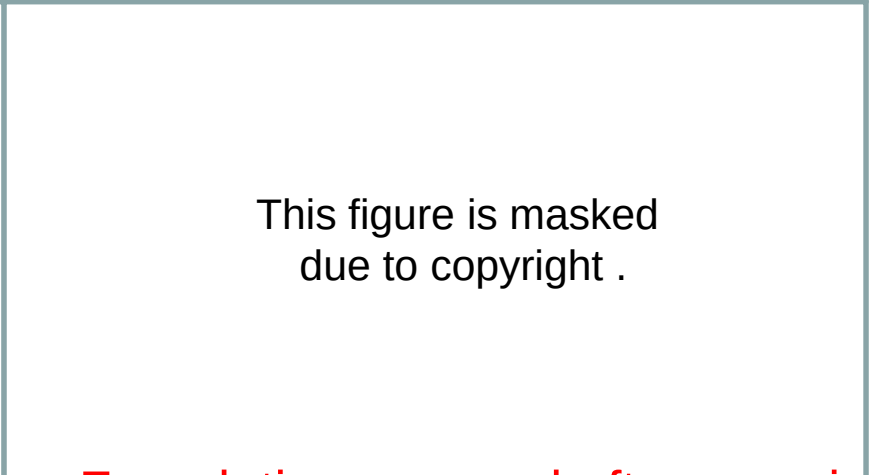
Kamaishi (Inundation height 17-18 m)
Office



Claddings and roof washed away



Anchor bolts fractured
Building leaning on next building



Foundation exposed after scouring

Tsunami Damage to Steel Structures 6-6

Arahama, Wakabayashi, Sendai (Inundation height 9 m)

Arahama Elementary School Gymnasium

Inundated over 2nd floor level

Net section fracture of brace

Tsunami Damage to Steel Structures 6-7

Ishinomaki (Inundation height 5 m)

High school gymnasium

Slight structural damage

Uplifted supports under floor

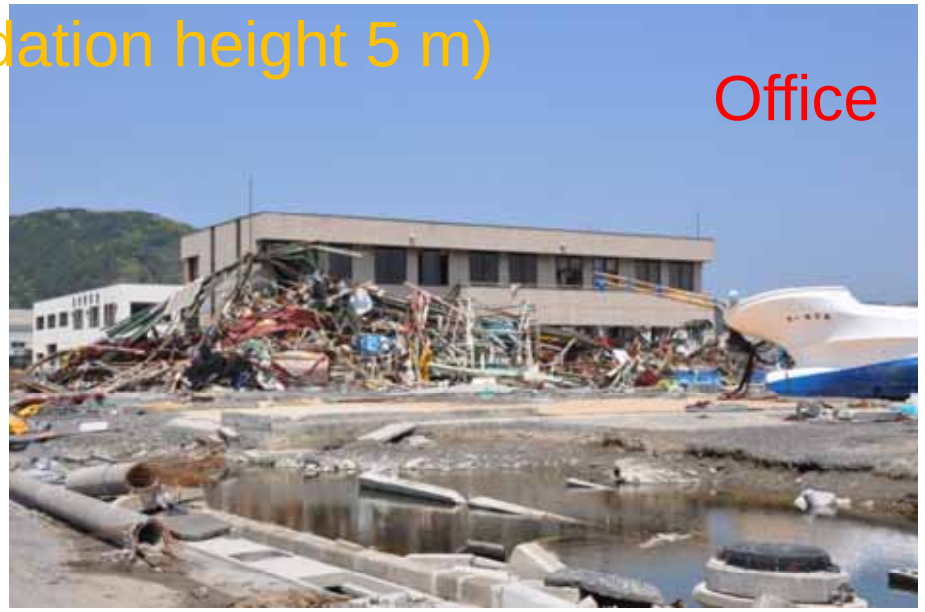
Failed roof brace

Tsunami Damage to Steel Structures 6-8

Ishinomaki (Inundation height 5 m)

Refrigeration facility

Office



Factory

Tsunami Damage to Steel Structures 6-9

Severely Damaged; Mostly Smaller Residential

Ishinomaki (Inundation height 5 m)

Tsunami Damage to Steel Structures 7-1

Minimal Structural Damage

Otsuchi (Inund. height 10-15 m)	Kuji (Inund. height 8-9 m)	Miyako (Inund. height 13 m)
Warehouse This figure is masked due to copyright . Cladding washed away	Factory This figure is masked due to copyright . First floor cladding washed away	Hotel This figure is masked due to copyright . 1st-3rd floors claddings washed away
	This figure is masked due to copyright .	This figure is masked due to copyright .

Almost no residual story drift

Tsunami Damage to Steel Structures 7-2

Minimal Structural Damage

Shiogama (Inundation height 4 m)	Sendai Port (Inundation height 8 m)	
Warehouse This figure is masked due to copyright .	Office This figure is masked due to copyright .	Office This figure is masked due to copyright .
This figure is masked due to copyright . Far right-end subsided	This figure is masked due to copyright . Under- ground piping exposed after scouring	This figure is masked due to copyright . Nonstructural damage in first story

Tsunami Damage to Steel Structures 7-3

Minimal Structural Damage

Ishinomaki (Inundation height 5 m)

Tsunami Damage to Steel Structures 7-4

Minimal Structural Damage

Ishinomaki (Inundation height 5 m)

Tsunami Damage to Steel Structures 7-5

Minimal Structural Damage

Ishinomaki (Inundation height 5 m)

Tsunami Damage to Steel Structures 7-6

Minimal Structural Damage

Ishinomaki (Inundation height 5 m)

Tsunami Damage to Steel Structures 7-7

Minimal Structural Damage

Ishinomaki (Inundation height 5 m)

Slight structural damage

Damage to cladding and ceiling

Fallen ceiling

Tsunami Damage to Timber Construction 8-1

Ishinomaki (Inundation height 5 m)

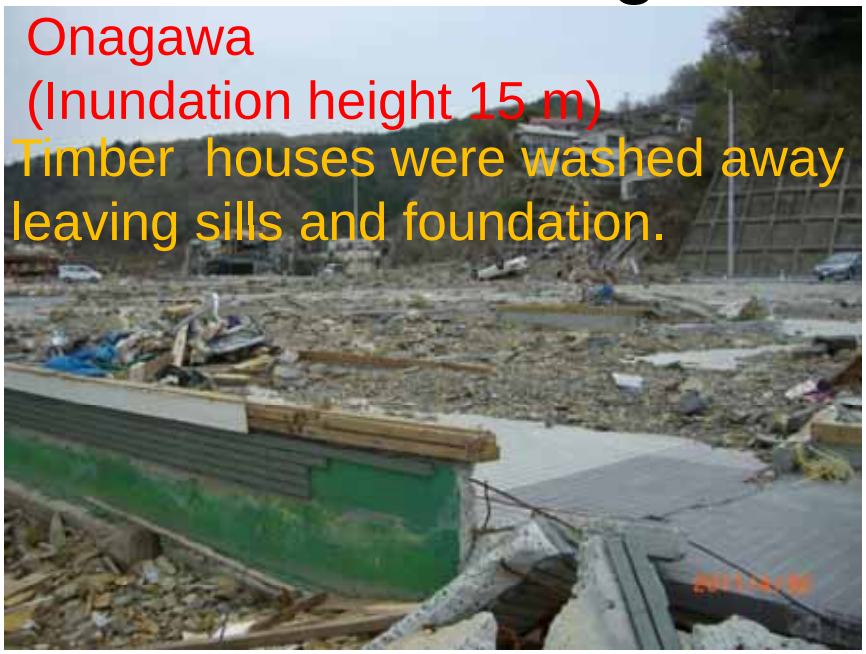
Majority of residential timber buildings were washed away leaving sills and foundation.

Tsunami Damage to Timber Construction 8-2

Shichigahama (Inundation height 12 m)

Definite difference of damage depending on a height above the sea level

Tsunami Damage to Timber Construction 8-3



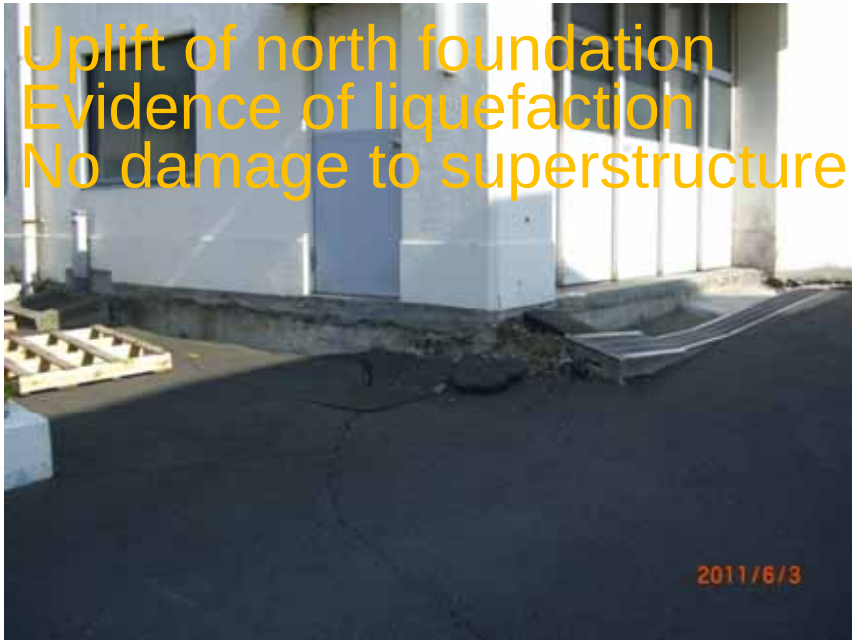
Foundation after scouring

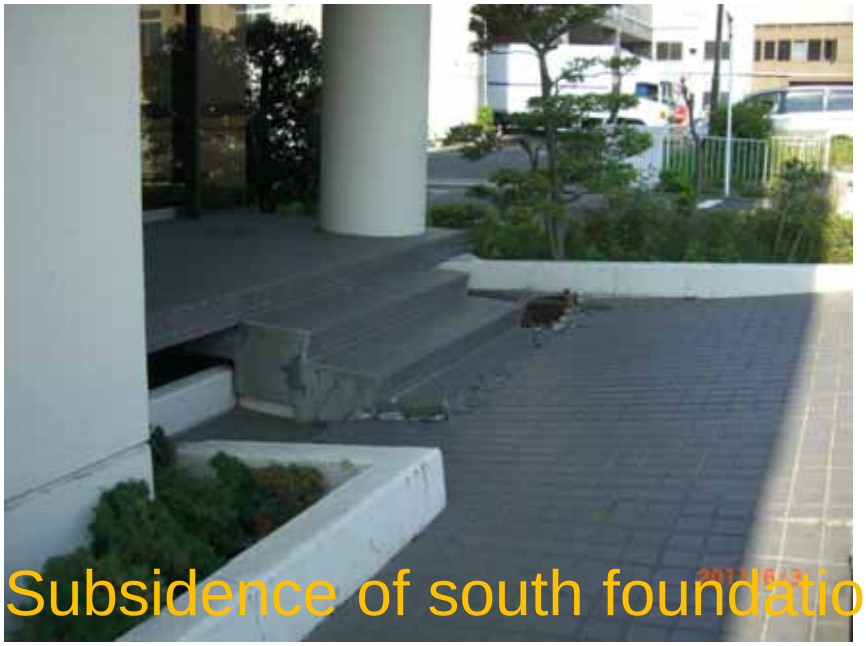
Tsunami Damage to Timber Construction 8-4

Yuriage, Natori (Inundation height 9 m)

Damage Caused by Ground Deformation and Fire

Damage Caused by Ground Deformation 1





Damage Caused by Ground Deformation 2

Damage Caused by Ground Deformation 3

Tsunami Area

Iwanuma (2km from the shore)
Office, Steel, 2F

Differential settlement by liquefaction

Evidence of liquefaction and tsunami

Damage Caused by Fire 1: Tsunami Area

Sendai Port (Inundation height 8 m)
Freight facility

Cladding washed away

Roof collapsed by fire after tsunami

Damage Caused by Fire 2: Tsunami Area

Sendai Port (Inundation height 8 m)
Factory

Cladding washed away
Damage by fire after tsunami

Onagawa (Inundation height 15 m)
Factory

RC structure damaged by fire

Sendai Airport (Inundation height 12 m)
Freight facility

This figure is masked
due to copyright .

Summary-1

(1) Damage Caused by Earthquake Ground Motions

1) The ground motion caused limited structural damage to buildings despite the large seismic intensity because the shorter period components were predominant in the strong motion records.

2) Buildings constructed by current code after 1981:

- No building constructed according to the current code suffered severe damage nor over.

3) Buildings constructed by previous code before 1981:

- Damage to buildings constructed according to the previous code was extensive.

Summary-2

(1) Damage Caused by Earthquake Ground Motions (cont'd)

4) Damage to nonstructural elements:

- Nonstructural damage to internal and external finishes and ceilings was extensive regardless of construction age.

5) Damage caused by ground deformation:

- Damage to buildings at a site of soft ground, such as reclaimed land/land developed for housing subdivision, particularly raised land and filled valley, was extensive.

- Landslide in land developed housing subdivision and liquefaction in reclaimed land were seen.

6) Damage aspects mentioned above are the same modes of damage observed from past earthquakes.

Summary-3

(1) Damage Caused by Earthquake Ground Motions (cont'd)

7) Reinforced concrete (RC) structures:

- Severe and collapse damage was seen in buildings constructed according to the previous code, particularly serious damage in buildings constructed before 1971.
- The majority of buildings constructed according to the current code and seismically upgraded remained within slight or minor damage.
- Subsidence and tilt of a foundation caused by failure of piles and ground were seen.
- Shear and axial failure of a column were seen.
- Failure and spalling of concrete were seen in a connection with steel or timber members.

Summary-4

(1) Damage Caused by Earthquake Ground Motions (cont'd)

8) Steel structures:

- The ground motion caused limited structural damage to buildings constructed after major update in the Building Standard Law was implemented in 1981.
- Older building constructed prior to 1981 saw notable damage caused by ground motion.
- Severe ground motion caused damage to beam-to-column connections, buckling of diagonal braces, cracking of concrete overlaying the column base, yielding and fracture of anchor bolts.
- Nonstructural damage to internal and external finishes and ceilings was extensive regardless of construction age.

Summary-5

(1) Damage Caused by Earthquake Ground Motions (cont'd)

9) Timber construction:

- Residential timber houses suffered severe and collapse damage in a superstructure widely in eastern half of Honshu Island.
- Residential timber houses with less seismic elements and longer natural period saw severe and collapse damage in the area of soft ground such as a river basin.
- Falling of ridge/roof tiles and exterior finishes was seen in a widespread area.

Summary-6

(2) Damage Caused by Tsunami

1) The majority of timber construction were washed away in areas attacked by violent tsunami.

2) Many reinforced concrete (RC) and steel buildings survived in the devastating tsunami areas.

3) The probable reason of survival of RC and steel buildings is that column bases are firmly connected to a foundation.

Summary-7

(2) Damage Caused by Tsunami (cont'd)

4) Steel structures:

- A large proportion of industrial and commercial facilities in the tsunami affected area were constructed in steel. Widespread damage was seen in these steel buildings.

- In areas attacked by violent tsunami, some buildings saw limited structural damage because their internal and external finishes were immediately washed away. Many buildings were damaged by debris impact.

- In areas attacked by less violent tsunami, steel buildings saw varying degrees of nonstructural damage depending on the tsunami height. However, the majority of buildings saw limited structural damage.

Summary-8

(2) Damage Caused by Tsunami (cont'd)

5) RC structures:

- Many RC buildings survived in areas attacked by violent tsunami.

- Toppling of small RC buildings completely submerged was seen in areas attacked by violent tsunami.

6) Timber construction:

- The majority of timber construction were washed away in areas attacked by violent tsunami.

[Reference]

1) AIJ: Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake, Architectural Institute of Japan, 2011.7