Seminar on the 1st Anniversary of the Great East Japan Earthquake and Tsunami of March 11, 2011
Lisbon, Portugal

Ground-Motion and Tsunami-Induced Damage of Structure due to the 2011 Great East Japan Earthquake with an Emphasis on Damage to Bridges

March 9, 2011

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Risk of Earthquakes by Ground Motion, Fire and Tsunami

Plate-boundary EQS

1923 Kanto (M7.9)	142,000
1933 Sanriku (M8.1)	3,064
1944 Tonankai (M7.9)	1,223
1946 Nankai (M8.0)	1,330
1952 Tonankai (M8.2)	28
1964 Niigata (M7.5)	26
1968 Tokachioki (M7.9)	52
1978 Miyagi-ken-oki(M7.4)	28
1982 Nihonkai-chubu (M7.7)	104
1993 Kushiro-oki (M7.5)	2
1993 Hokkaido-nansei(M7.8)	202
2003 Tokachi-oki (M8.9)	1
2008 Tokachi-oki(M7.1)	0
2011 Great East J	About 19,130

Inland Earthquakes

1891 Nohbi (M8.0)	7,273
1927 Kita-Tango (M7.3)	2,925
1943 Tottori (M7.2)	1,083
1945 Mikawa (M6.8)	2,306
1948 Fukui (M7.1)	3,769
1978 Izu-Ohshima(M7.0)	25
1984 Nagano-ken-seibu	39
1995 Kobe (M7.3)	6,434
2000 Tottori (M7.3)	0
2004 Niigata-Chuetsu(M6.8)	68
2008 Iwate-Miyagi (M7.2)	13

Various Hazards by an Earthquake

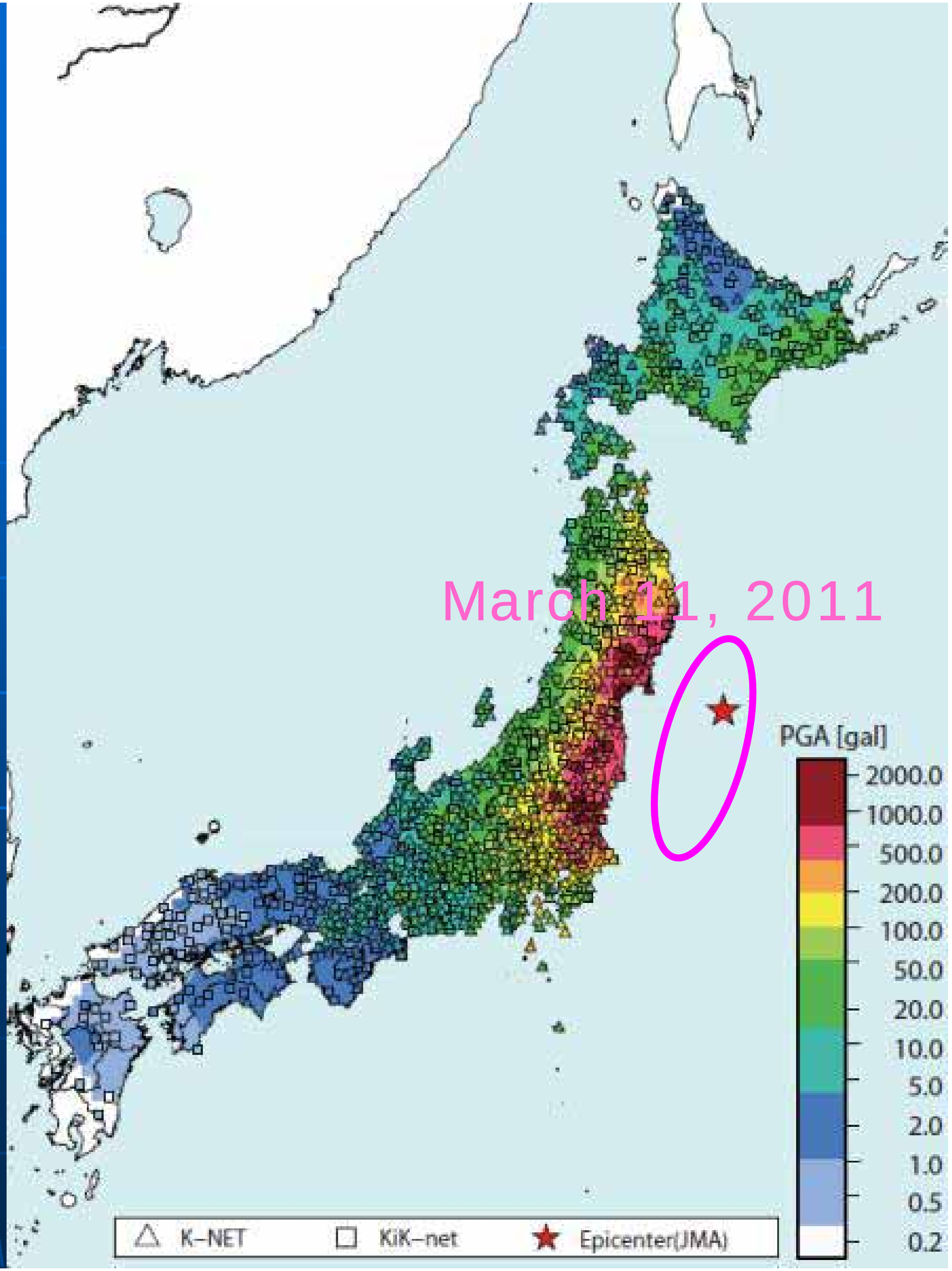
- Ground motion: 1995 Kobe earthquake, 1994 Northridge, USA earthquake
- Fire: 1923 Great Kanto Earthquake, 1906 San Francisco earthquake
- Tsunami: 2011 Great East Japan Earthquake, 2004 Indian Ocean earthquake
- Fault displacement: 1999 Chi Chi, Taiwan, earthquake
- Liquefaction: 1964 Niigata earthquake

Extensive Damage by 1923 Kanto Earthquake

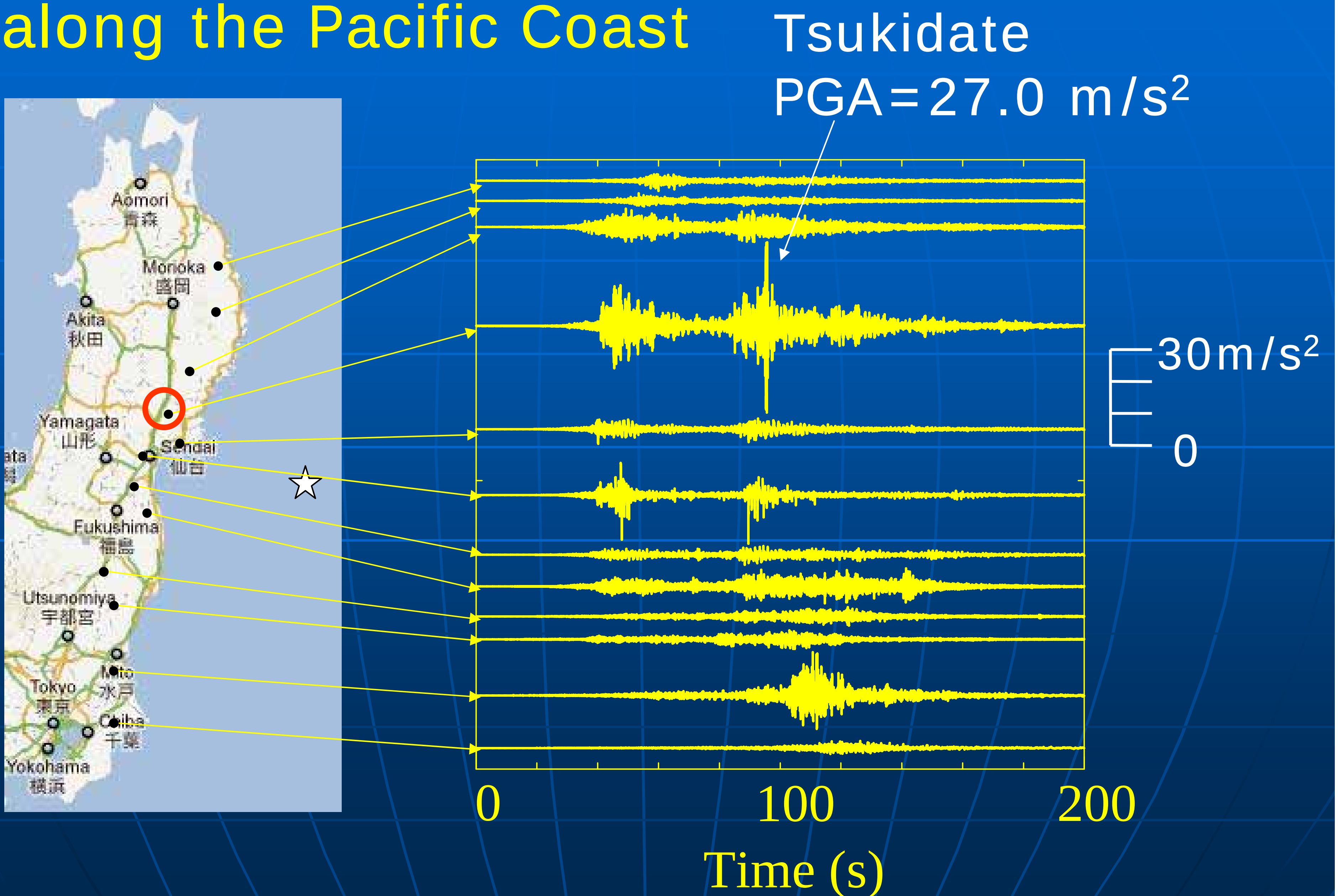
Starting Point of Developing Japanese Own Seismic Design

Over 30,000 peoples died due to fire at only this factory yard

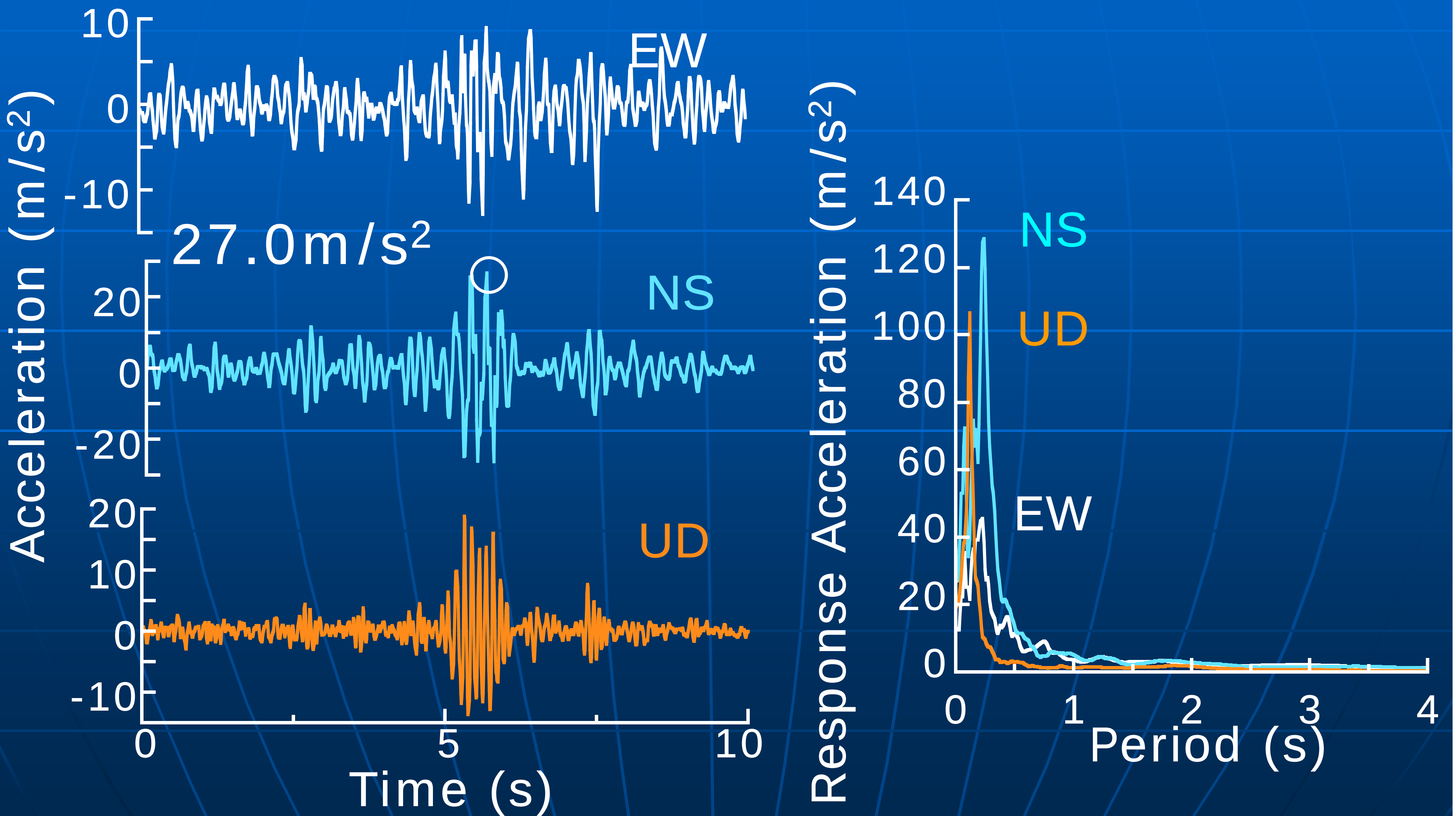
A number of strong motion accelerations were recorded at K-NET, KiK-net and JMA-net sites



Acceleration Records along the Pacific Coast

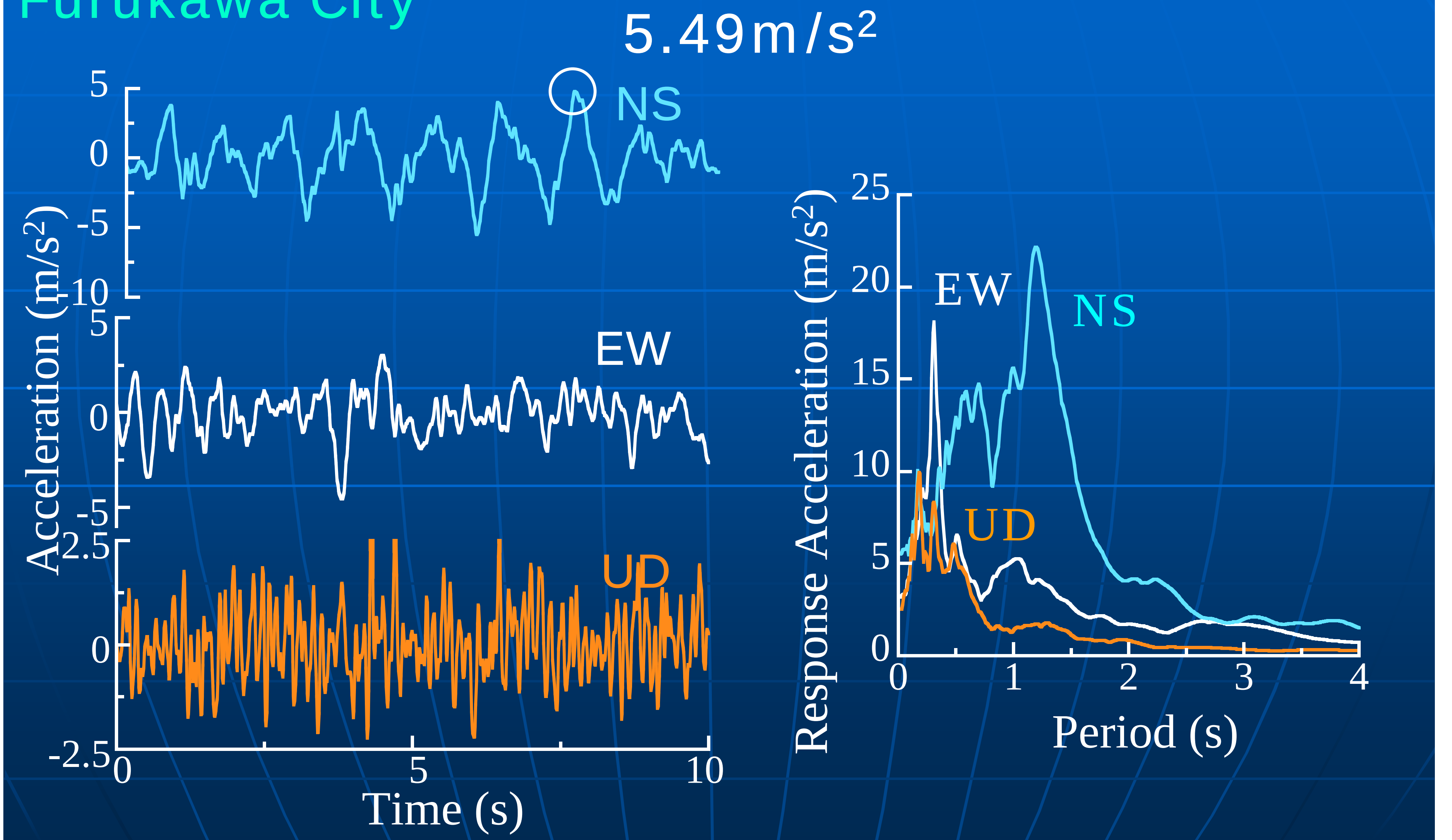


Acceleration near the peak at Tsukidate where the highest PGA was recorded (Stiff soils site)

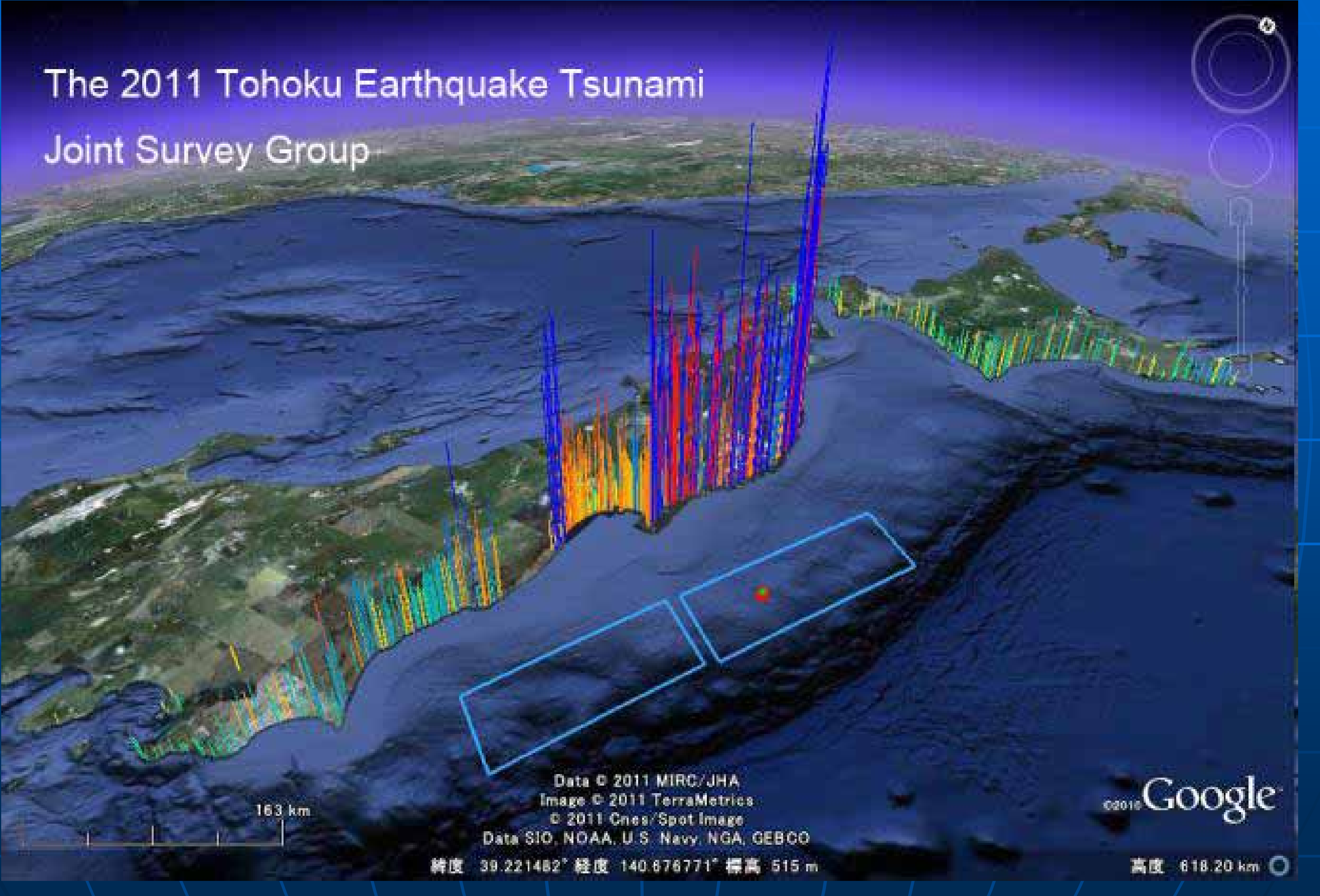


At a few soft soil sites, response acceleration at 1-2 second was quite high

Furukawa City

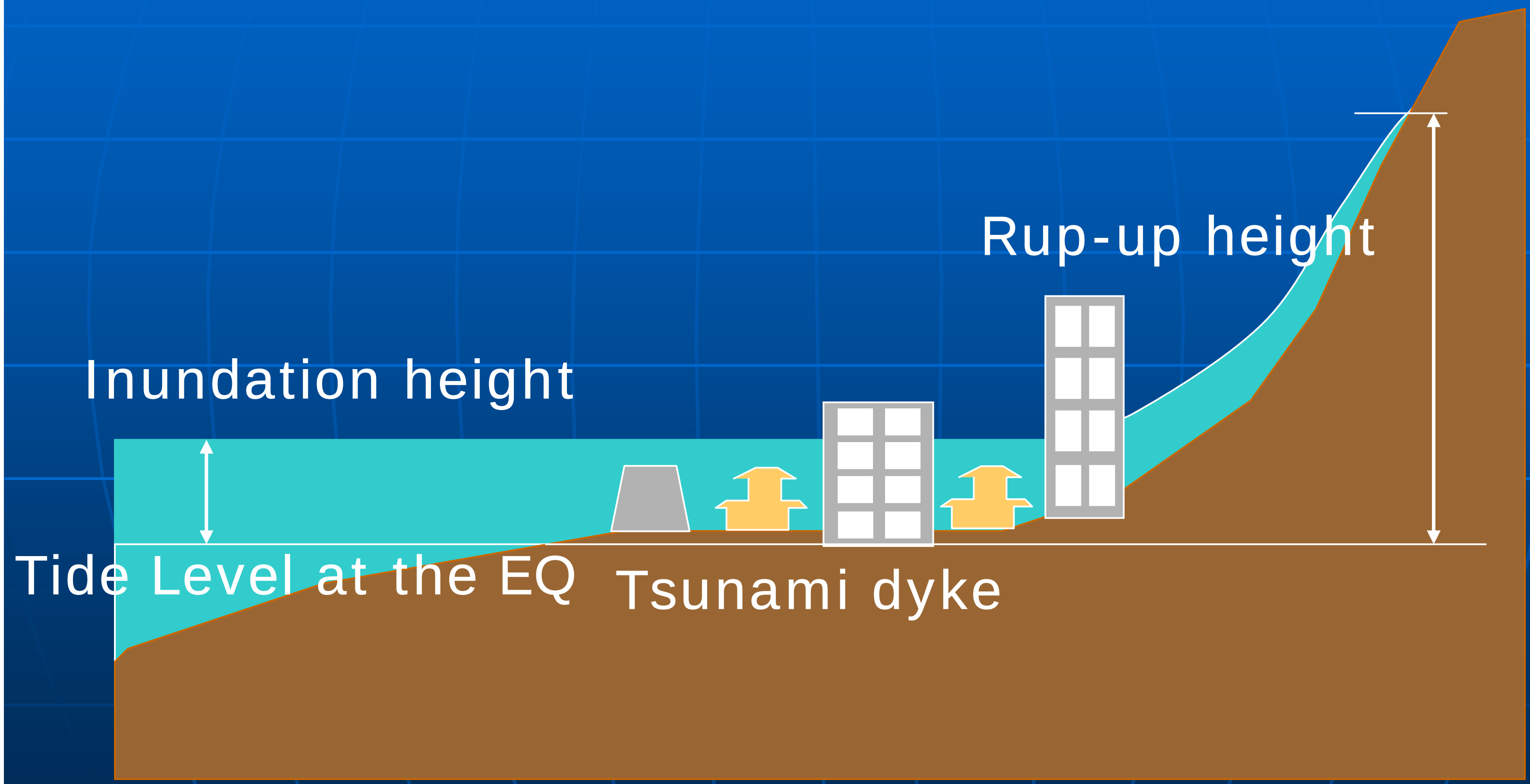


Extensive damage was developed by tsunami

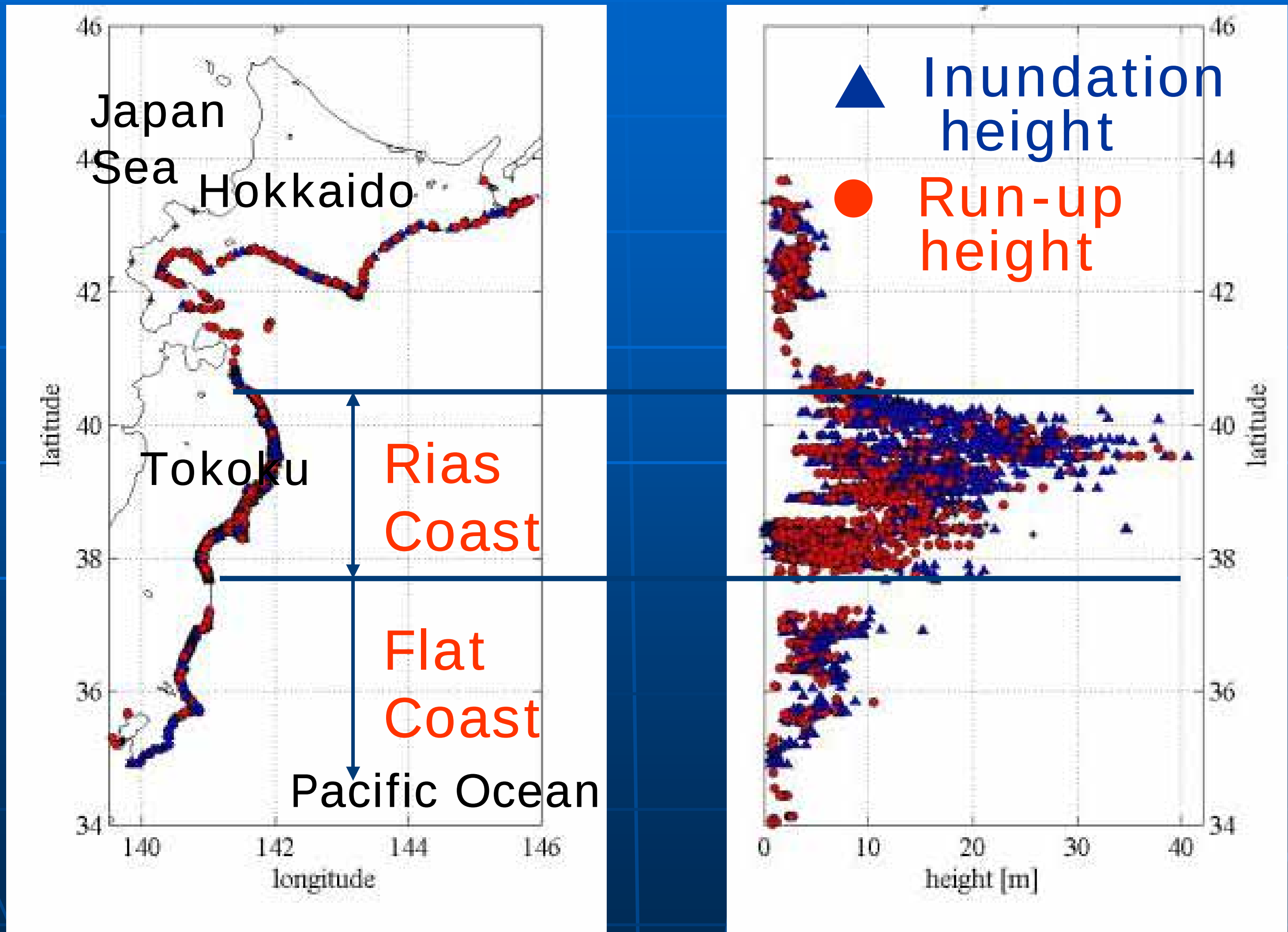


Tsunami Joint Survey Group The 2011 Tohoku Earthquake (2011). "NATIONWIDE FIELD SURVEY OF THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE TSUNAMI", Journal of JSCE, B2, 67(1), 63-66

Inundation Height vs. Run-up Height

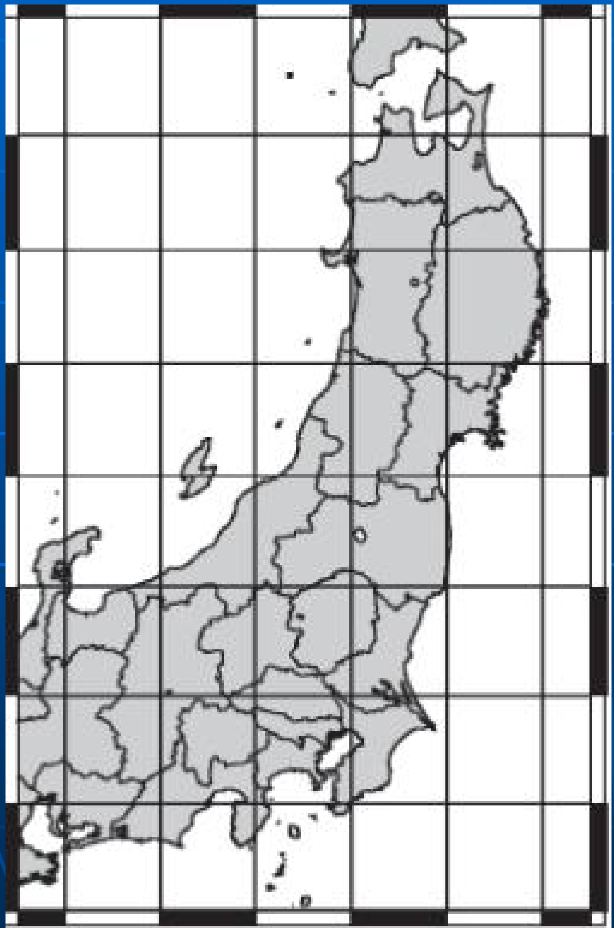


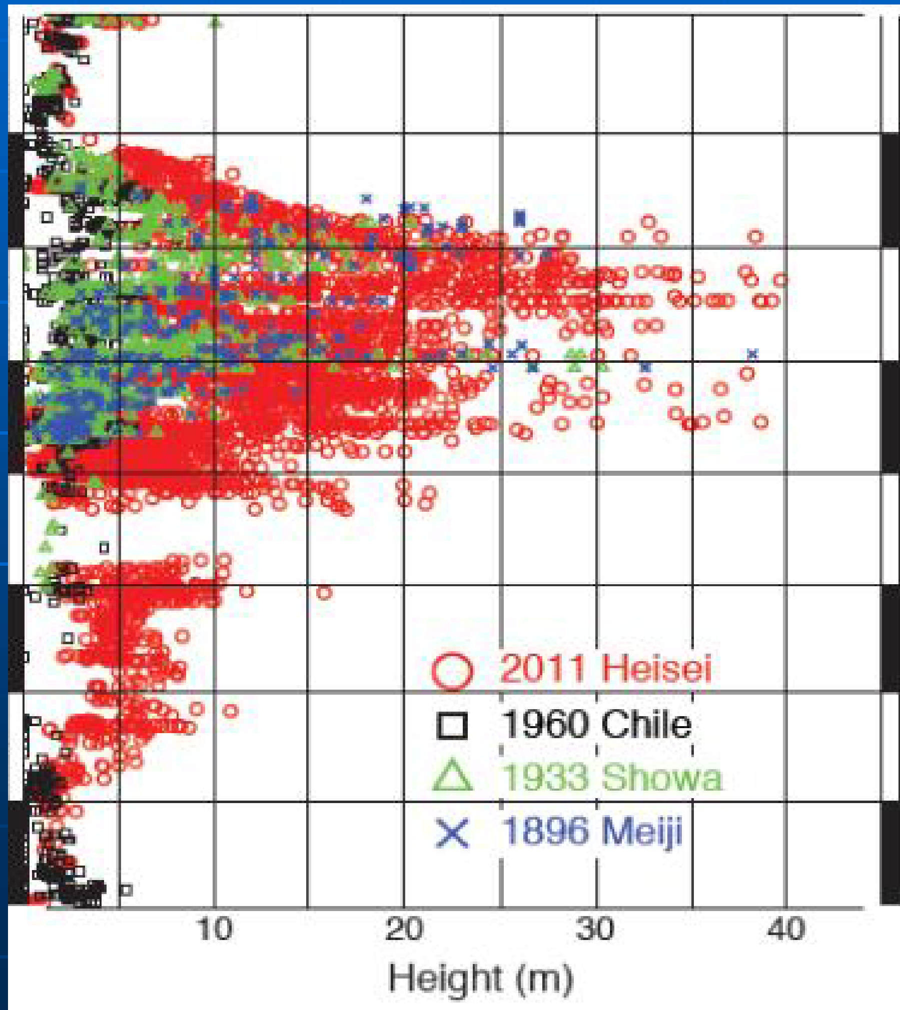
Measured Inundation & Run-up Height



Tsunami Joint Survey Group The 2011 Tohoku Earthquake (2011). "NATIONWIDE FIELD SURVEY OF THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE TSUNAMI", Journal of JSCE, B2, 67(1), 63-66

Tsunami was much higher in 2011 EQ than 1896 Sanriku EQ, 1960 Chile EQ, and 1933 Sanriku EQ





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North Area repeatedly suffered damage from tsunami

History of Taro Village is a history of fighting with tsunami

- By 1611 Keicho earthquake (M8.1), the village was almost all collapsed
- By 1896 Meiji earthquake (M8.2-8.5), 83% peoples (1867 among 2248) was killed
- By 1933 Syowa earthquake, 32% (911 among 2773) was killed

Taro Town

Long history for competing with tsunami

NHK

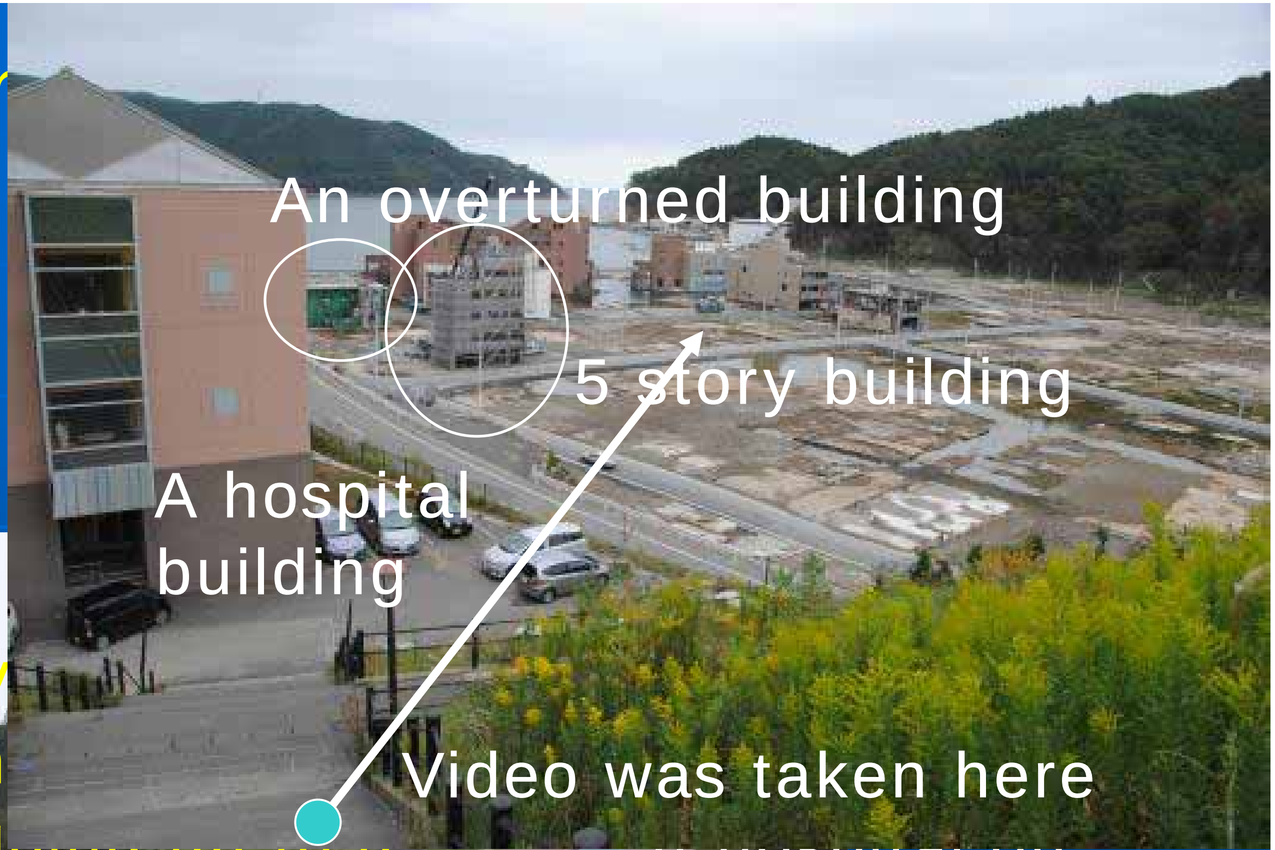
Tsunami Attack to Taro Town

NHK

Tsunami Dyke after the Earthquake
Taro Town

Well Prepared Ts

Tsunami at Or



V
h
going up to a
shrine

A hospital on
a 18m tall hill

Video was taken here

Old and Poor Foundation in the Overturned Building

Extensive Liquefaction at Tokyo Bay Area

Urayasu, Chiba

Some 20km west of Tokyo

Reclaimed land

Web

Removal of sand by liquefaction
Urayasu City

Web

Liquefaction resulted in settlement and tilting of a number of houses

Urayasu City

Web

2011 Great East Japan earthquake was a good opportunity to learn whether damage of bridges was mitigated as a consequence of recent code upgrading

- Since an earthquake occurs infrequently, it is very rare to have an opportunity to evaluating how effective the upgrading of seismic code and implementation of seismic retrofit were
- 33 Years Ago, we had 1978 Miyagi-ken-oki earthquake (M_{JMA}7.4) in the same areas in the north Miyagi and south Iwate
- In terms of the response accelerations, the ground accelerations during the 1978 Miyagi-ken-oki earthquake were generally smaller than or equivalent to the ground accelerations during the 2011 Great East Japan earthquake.

1978 Miyagi-ken-oki Earthquake (M_{JMA}7.4)

Damage concentrated to RC columns at lap splice zones of longitudinal bars

Sendai Bridge

Extensive Damage of Steel Bearings

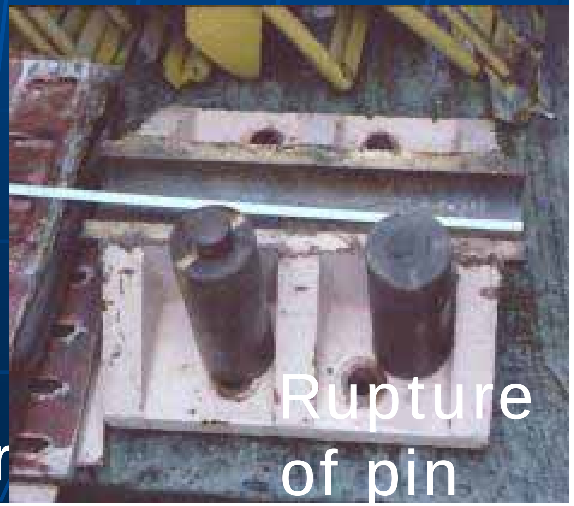
- Almost all side stoppers suffered damage
- Pin and roller bearings were vulnerable to damage

Damaged side stoppers

Failure of pier at bearing

Pull-out of anchor bolts

Pull-out of roller

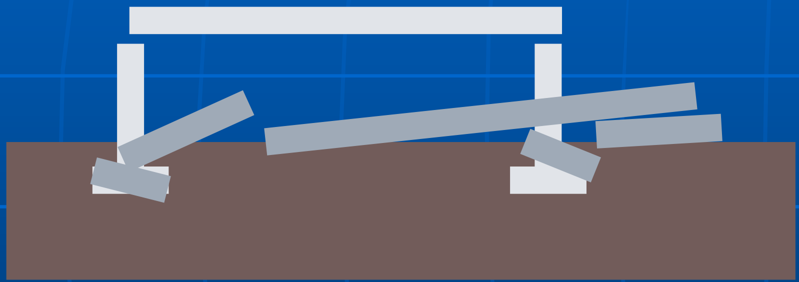


Rupture of pin

1978 Miyagi-ken-oki earthquake
-An Important Turning Point in Design

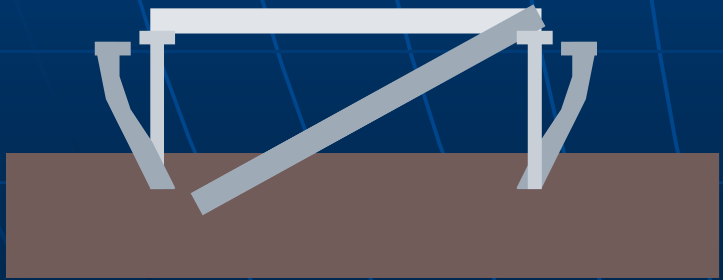
If we look back the past design,……

Stage 1: Days when seismic design was not conducted or it was insufficient (1868-1945)



Overturning, sliding or settlement of foundations
---→ Collapse

Stage 2: Days when we were not aware of liquefaction and unseating prevention devices were not yet developed (1964 Niigata EQ)



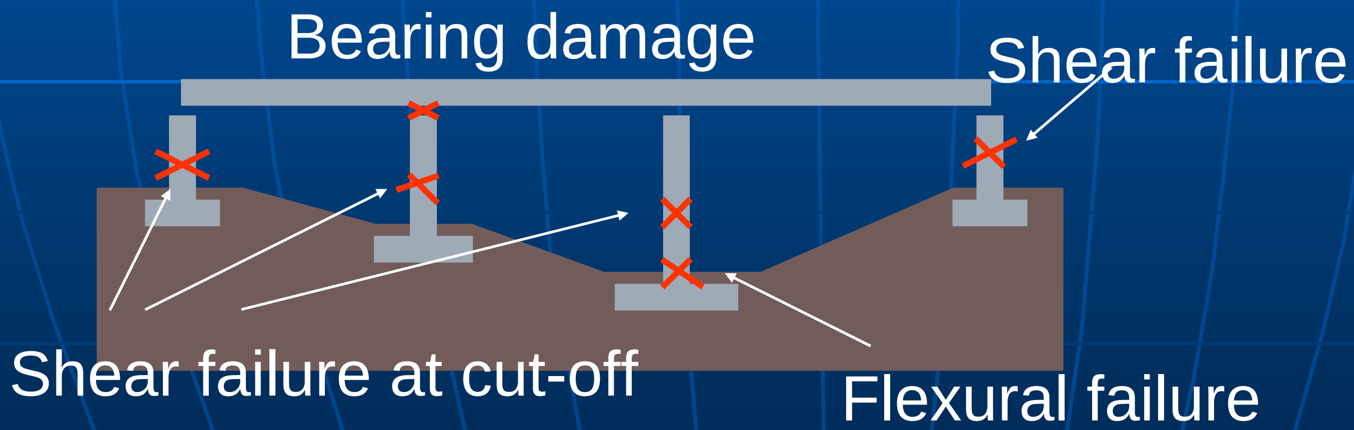
Excessive response of foundations & piers
----→ Collapse

1978 Miyagi-ken-oki earthquake
-An Important Turning Point in Design (2)

Stage 3: Days when we were not aware of the importance of ductility capacity of piers

Enhancing the past weak links led to damage in the next weak link. This became apparent during 1978 Miyagi-ken-oki EQ and 1982 Urakawa-oki EQ;

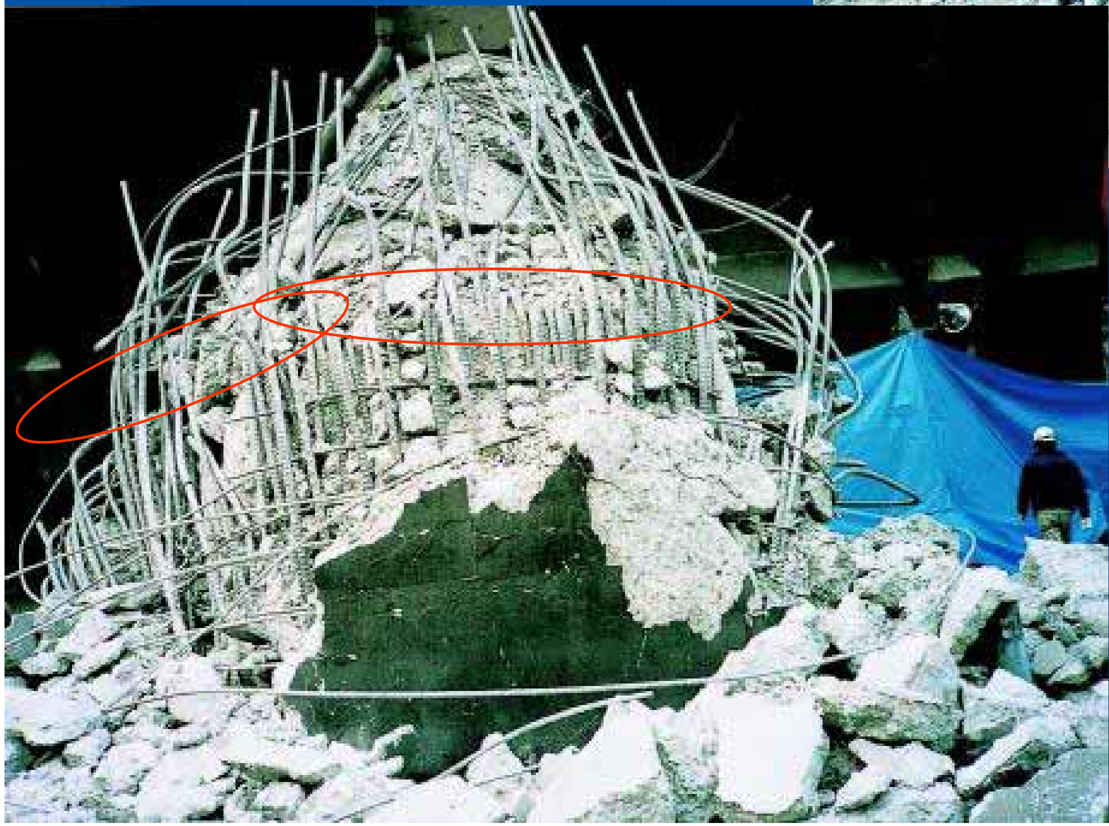
- Piers & columns
- Bearings



This type of damage extensively occurred during 1995 Kobe earthquake

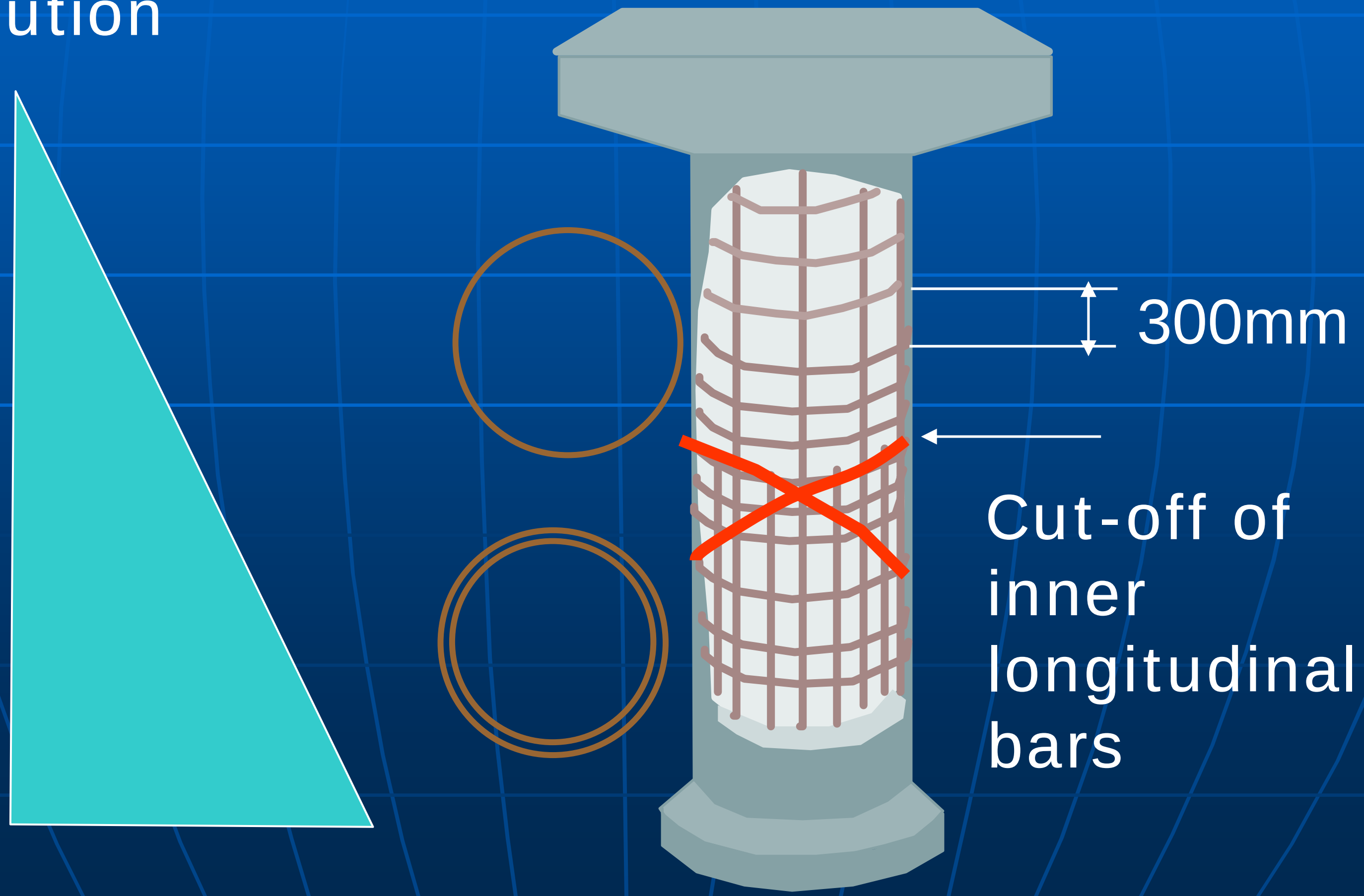
1995 Kobe, Japan Earthquake

Shear Failure at Cut-off of Longitudinal Rebars



Shear Failure at Cut-off of Longitudinal Rebars A mandate Practice for saving cost prior to 1980

Bending Moment Distribution

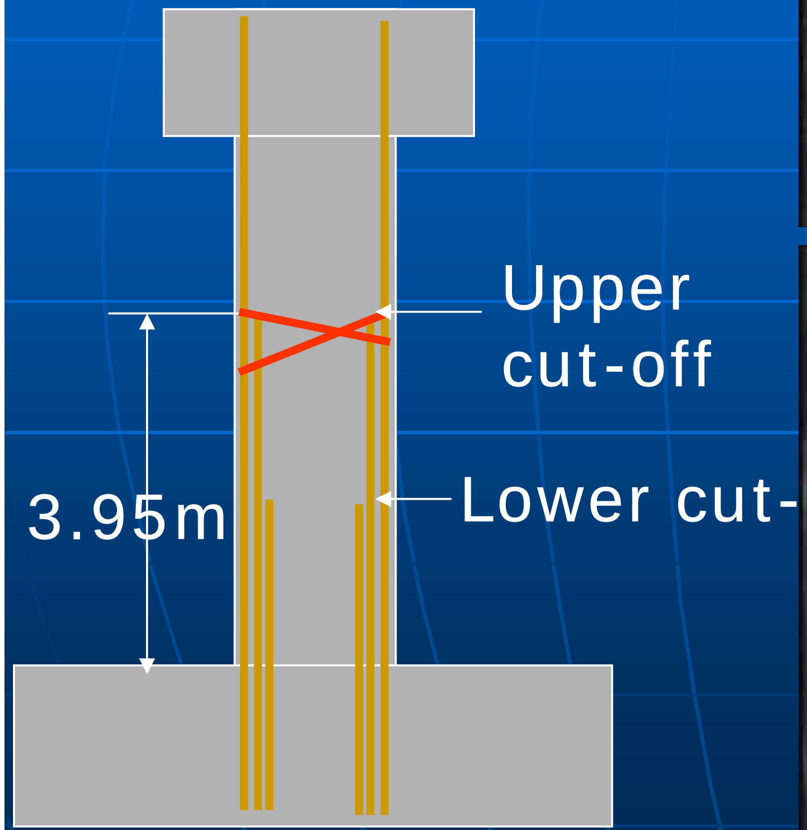


Shear Failure Dominant Column: C1-2

E-Defense, NIED

M

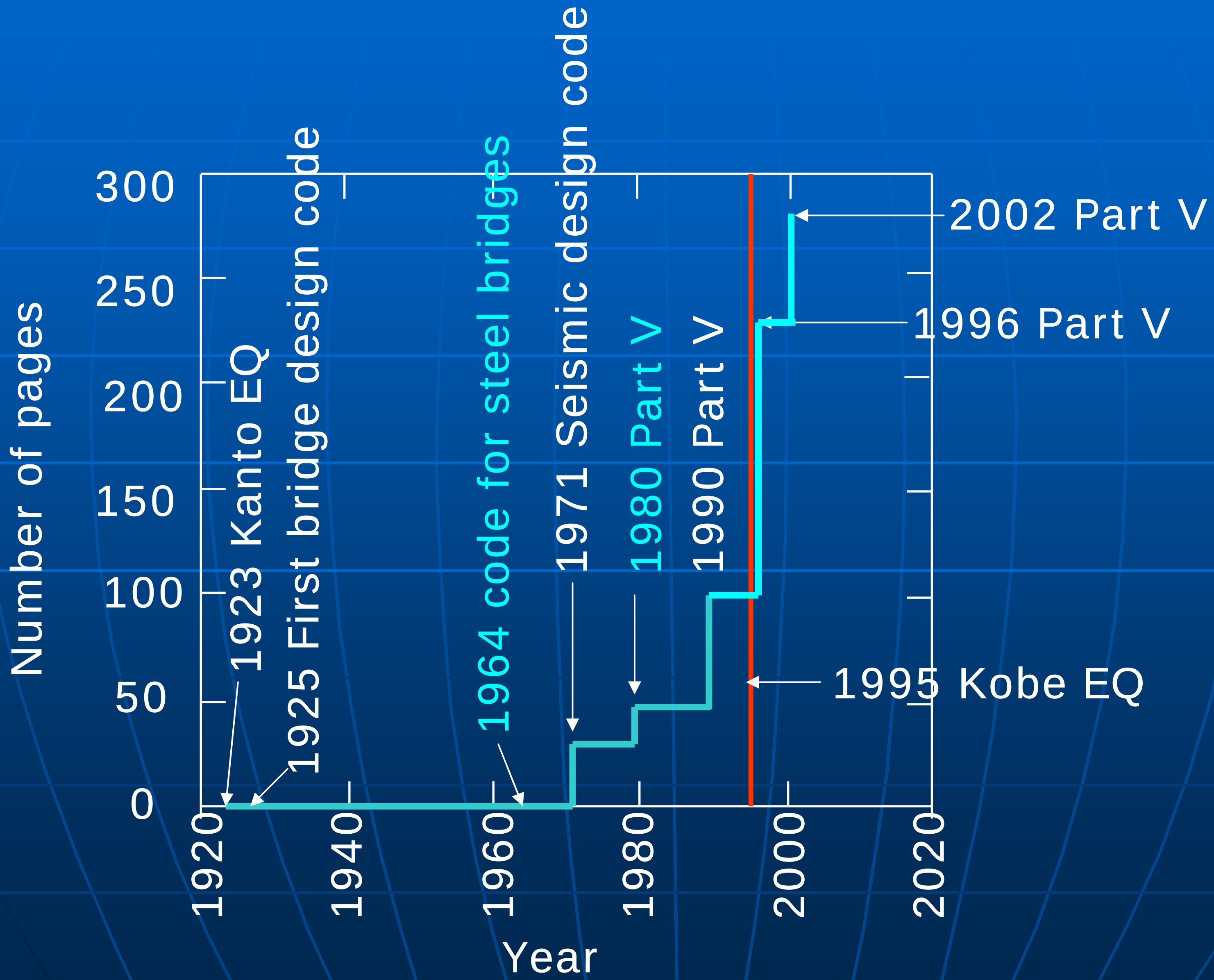
C1-2 Column which fails in Shear



E-Defense, NIED

Shear & Flexural Failure Resulted in Extensive Damage

Number of Page of Codes Related to Seismic Design of Bridges



Departure from Classical Elastic Static Analysis to Current Seismic Design (Post-1990 Code)

The day before Yesterday & Yesterday Pre-1990

- Static elastic analysis
- 0.2-0.3g design response acceleration (L1)
- Allowable stress design
- Linear dynamic analysis
- Unseating prevention devices

Departure from Classical Elastic Static Analysis to Current Seismic Design (Post-1990 Code)

Today, Post-1990

- Static inelastic analysis
- 0.7-2.0 g design response acceleration (L2)
- Linear & nonlinear dynamic analysis
- Unseating prevention devices with higher seismic performance
- Inertia force evaluation for continuous bridges
- Ductility enhancement for RC and steel columns
- Residual displacement
- Seismic isolation
- Use of elastomeric bearings including LRB & HDR for replacement of vulnerable steel bearings

Departure from Classical Elastic Static Analysis to Current Seismic Design (Post-1990 Code)(2)

● Type I GM (1990-)

✓M8 Subduction events at middle-field

✓Long duration

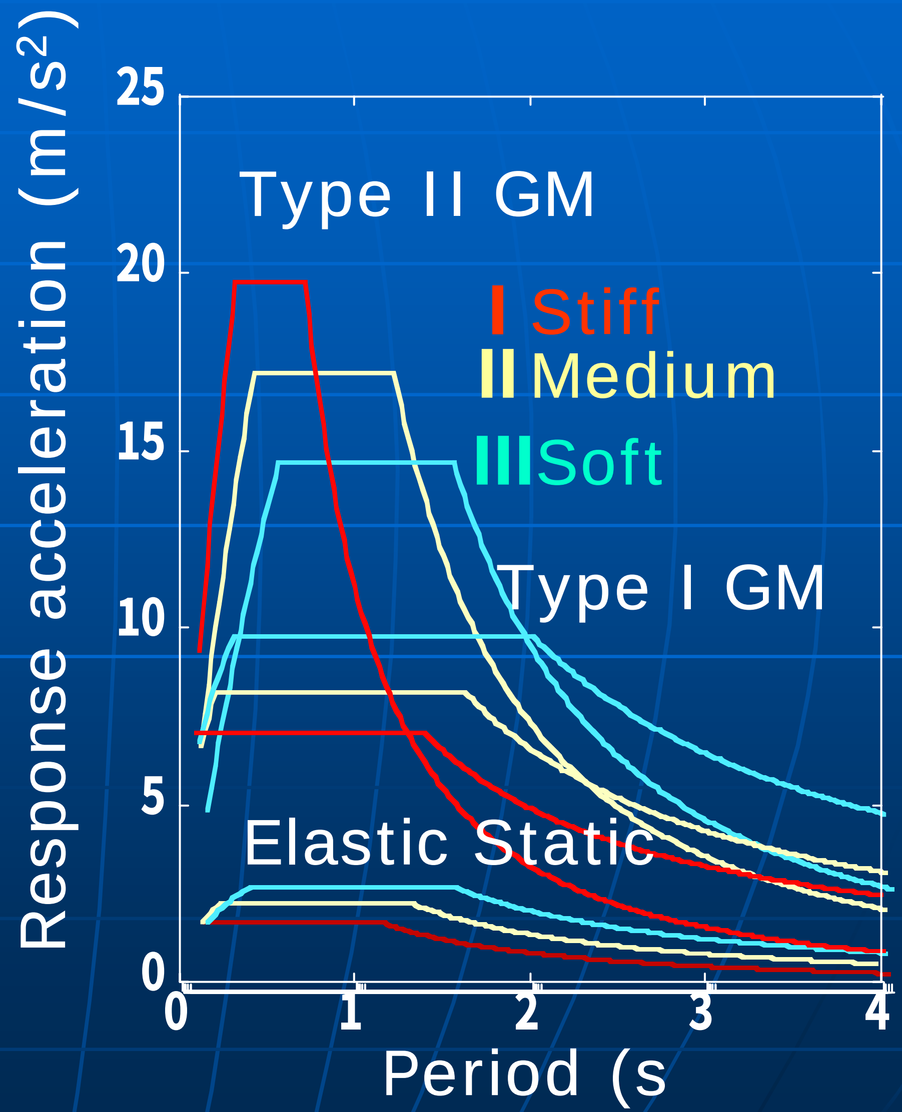
✓Typical GMs in Tokyo during the 1923 Kanto EQ

● Type II GMs (1995-)

✓Near-field GM by M7 Events

✓Short duration with High Intensity

✓Typical GMs in Kobe during the 1995 Kobe EQ



Seismic Retrofit

- RC jacket (standard for columns in water)
- Steel jacket (standard for column on land)
- Carbon fiber wrapping
- Prestressed jacket
- Aramid fiber jacket
- ....
- Implement of seismic isolation/ structural control

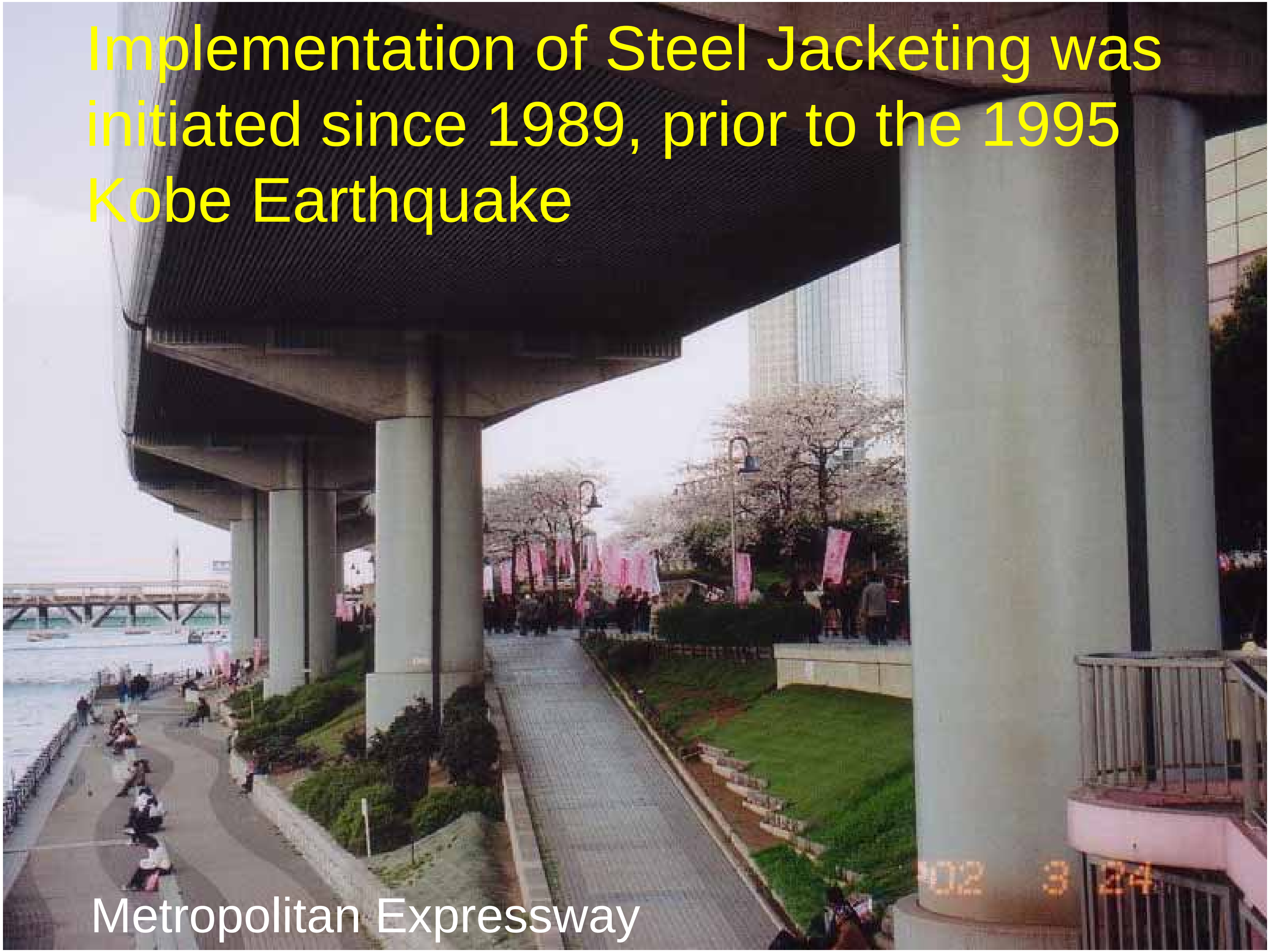
Some 30,000 piers & columns were retrofitted since 1995

Full Size Static Loading Experiment to Steel Jacket with Controlled Enhancement of Flexural Capacity

2.4m x 2.4m x9m tall

Public Works Research Institute

Implementation of Steel Jacketing was initiated since 1989, prior to the 1995 Kobe Earthquake



Metropolitan Expressway

Damage of steel bearings still continued to occur in the bridges which were repaired using the same steel bearings after the 1978 earthquake

Tenno Bridge
National road 45
Built in 1959

Buckling/rupture of braces

Steel bearings and their support which suffered damage during 1978 Miyagi-ken-oki earthquake again suffered damage

Tennoh Bridge

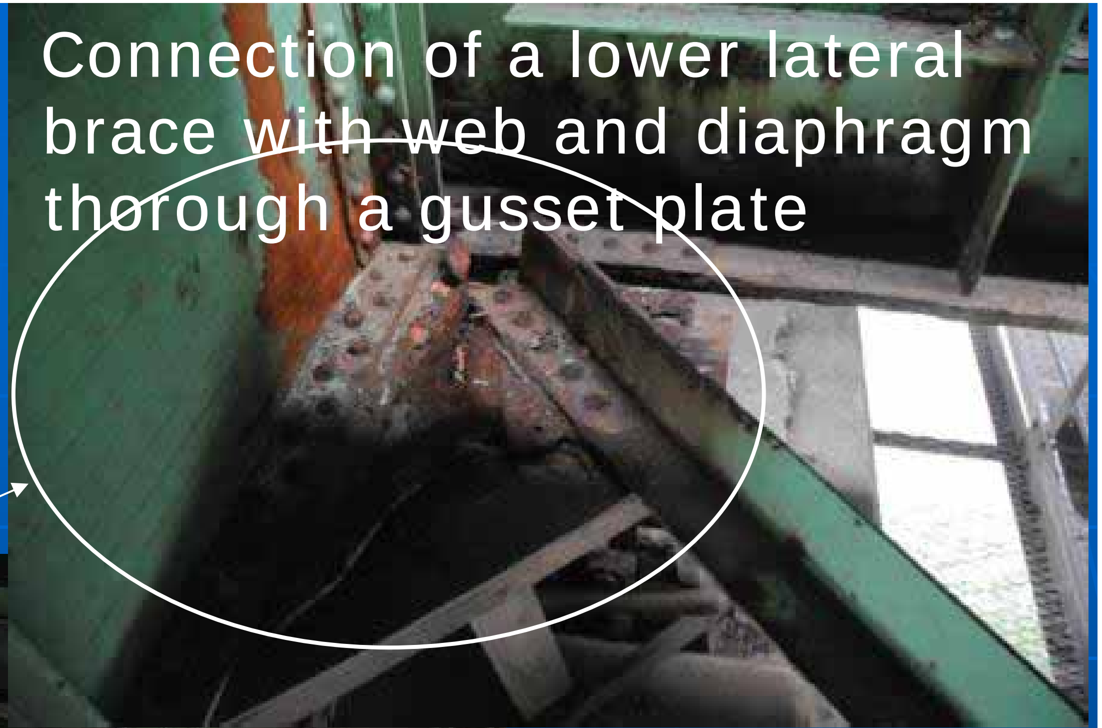
Bridge was about to collapse due to aftershocks 1978 Miyagi-ken-oki EQ

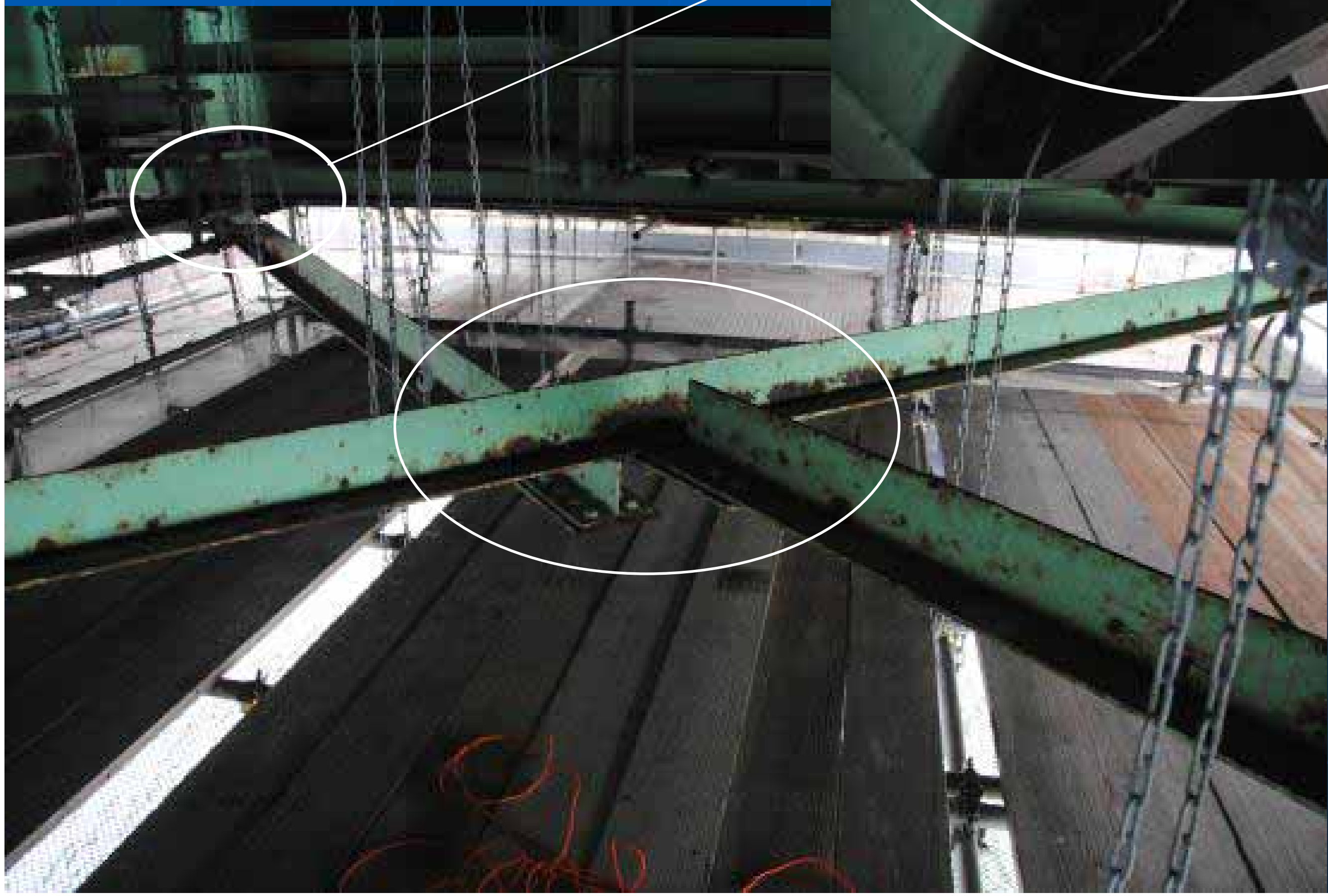
Repair by RC jacketing after 1978 Miyagi-ken-oki EQ

Roller bearing

2011 Great east Japan earthquake

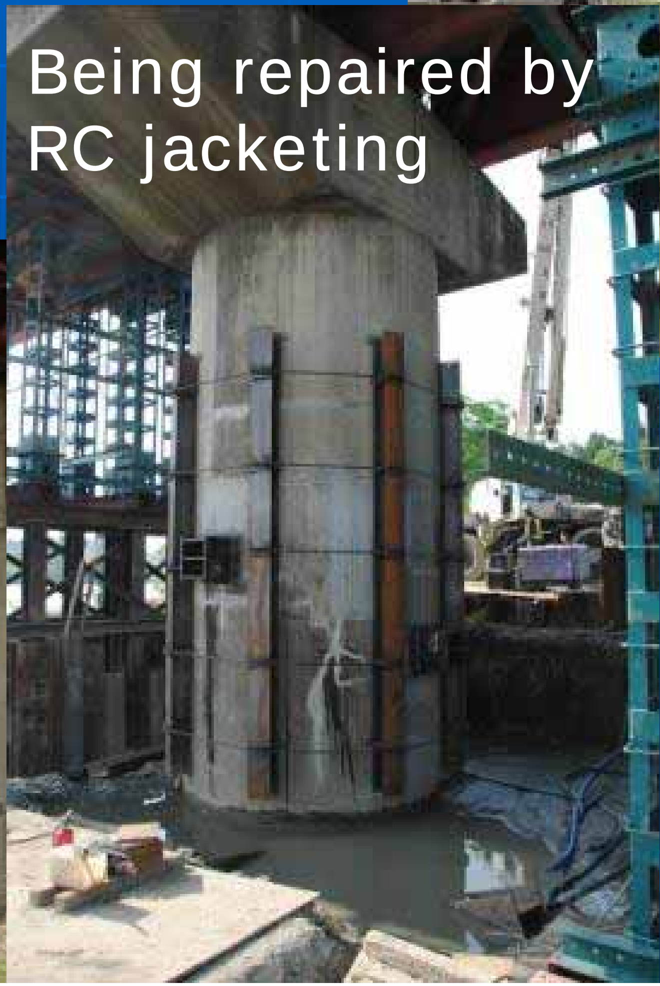
Lower lateral braces ruptured



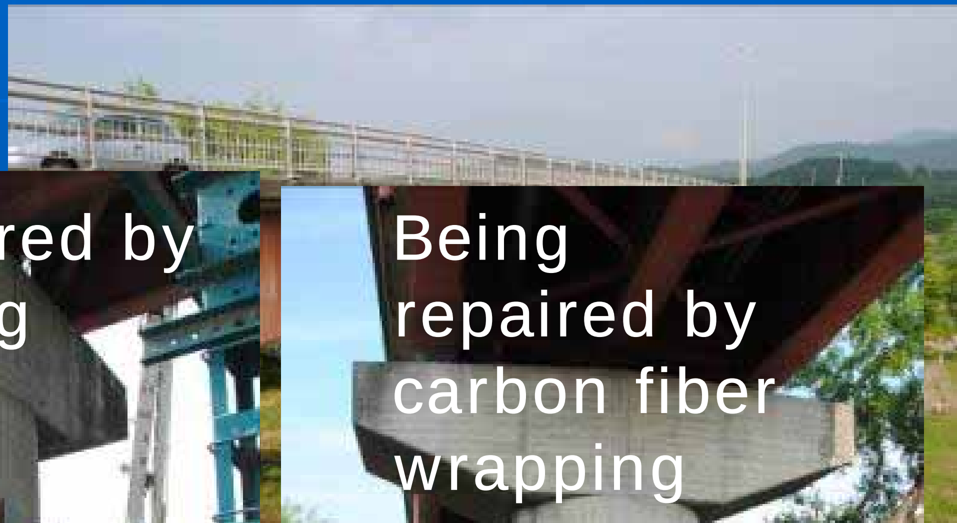


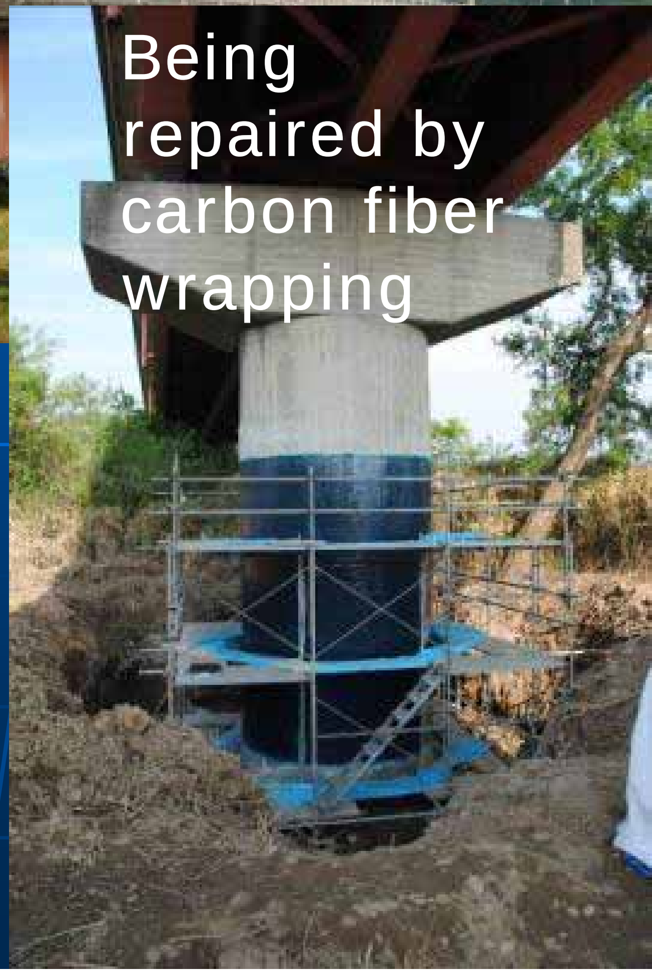
Shear failure at cut-off occurred at the bridges where seismic retrofit have not yet been completed

Fuji Bridge, Iwate-ken



Being repaired by RC jacketing





Being repaired by carbon fiber wrapping

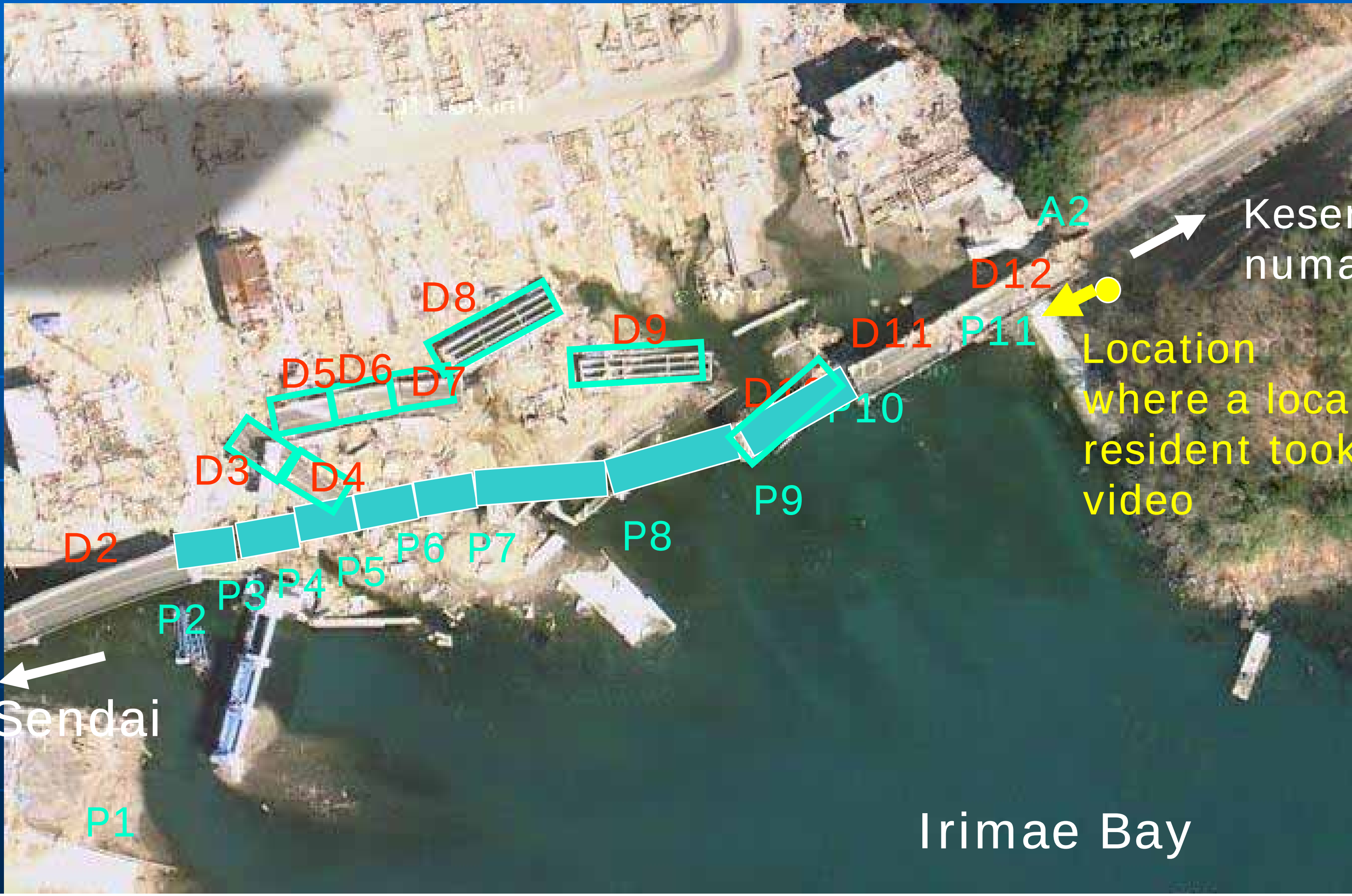
Bridges which were retrofitted based on the post-1990 code did not suffer damage

Bridges which were designed based on the post-1990 design code suffered no damage

Tsunami-induced damage was extensive

Utazu Bridge

National Road 45, Minami-Sanriku Town




Center of Utatsu Town
Courtesy of Mr. Katsuya Oikawa

Courtesy of Mr. Katsuya Oikawa


Tsunami reached
at least this level
Utatsu Bridge
6m high from
the road surface
Courtesy of Mr. Katsuya Oikawa


Courtesy of Mr. Katsuya Oikawa

Tsunami flowed from As side


Courtesy of Mr. Katsuya Oikawa


Utatsu Bridge
歌津大橋
At least 6m from the road surface
Courtesy of Mr. Katsuya Oikawa


Utatsu High School
Utatsu Junior High School
Center of Utatsu Town
Utatsu Bridge
Courtesy of Mr. Katsuya Oikawa

PC girder decks floated by tsunami

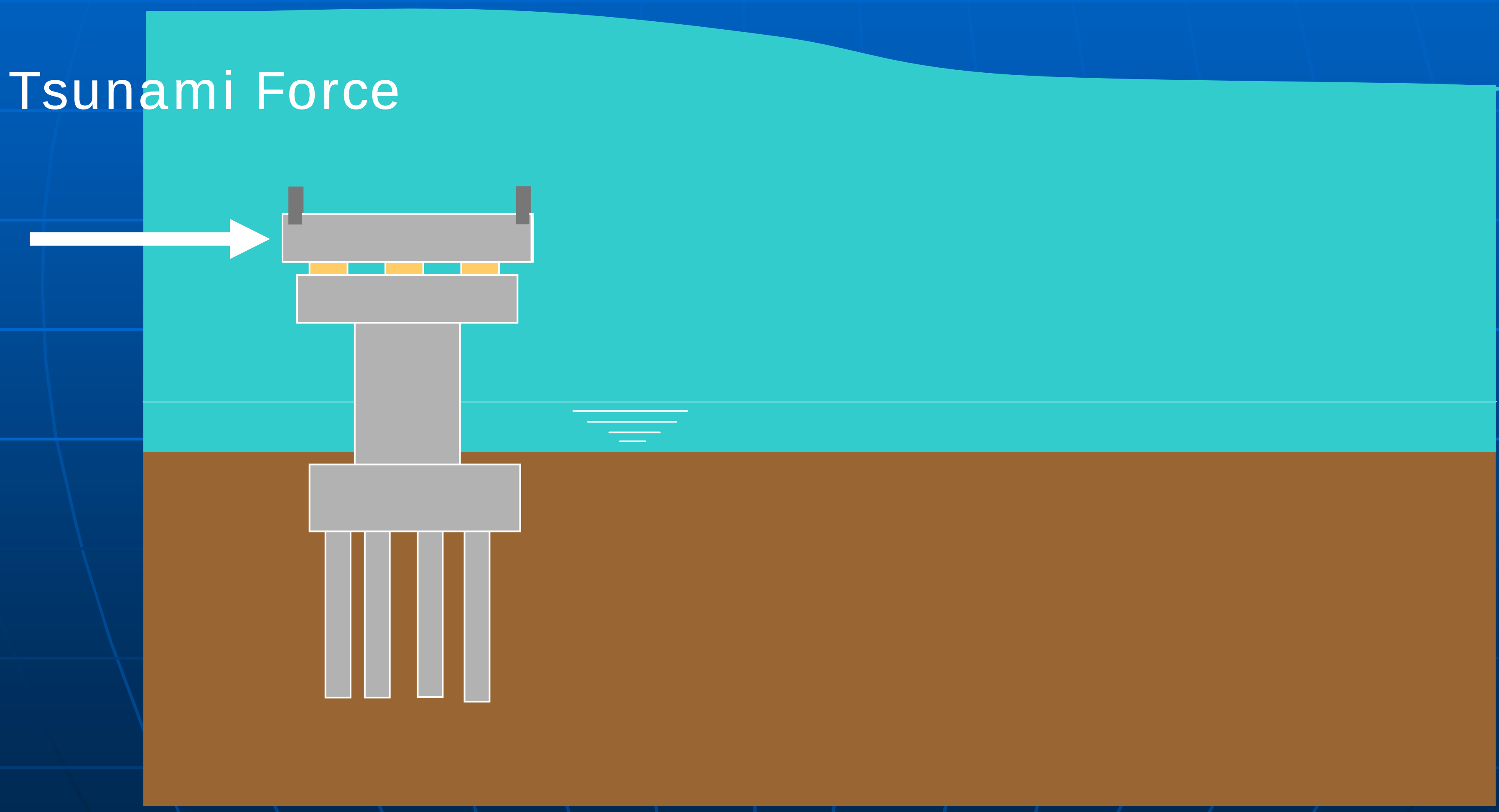
Utazu Bridge, Route 45, Rikuzen-Takada City

Short span decks were simply dragged by tsunami

P2

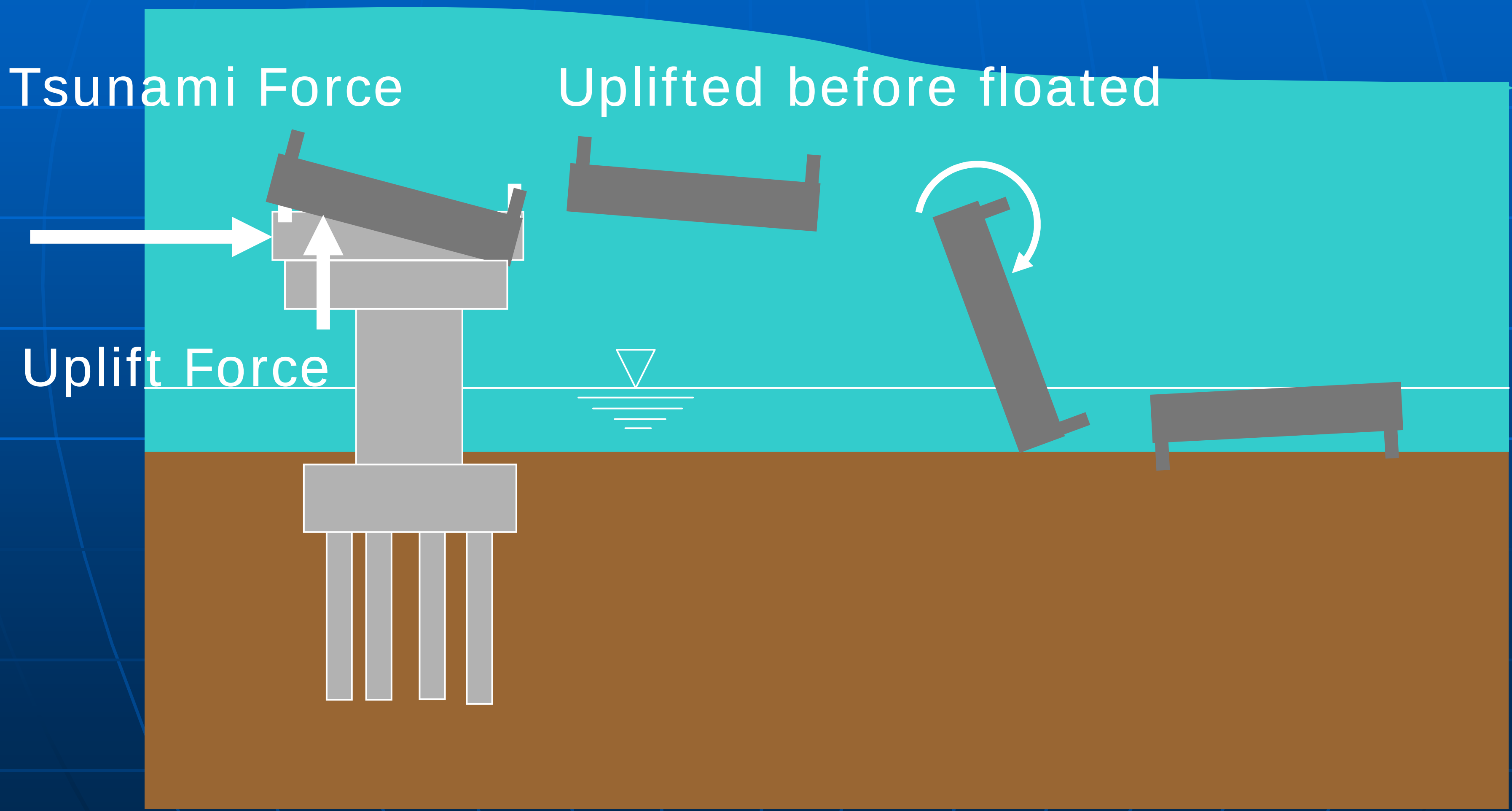
Stoppers for preventing excessive deck displacement in the longitudinal direction

A Possible Failure Mechanism of Short-span Decks due to Tsunami

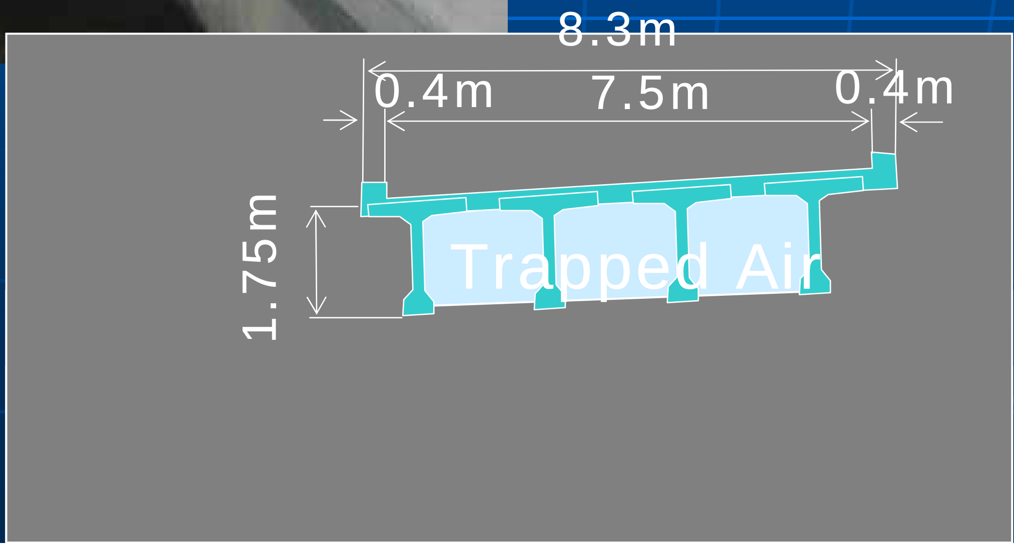


Steel stoppers were provided, but they were ineffective for preventing transverse deck movement & uplift by tsunami

Most Probable Failure Mechanism of Medium-span decks due to Tsunami



Uplift due to Air Trapped under a PC Deck



Damage of I-10 Bridges due to Hurricane Katrina

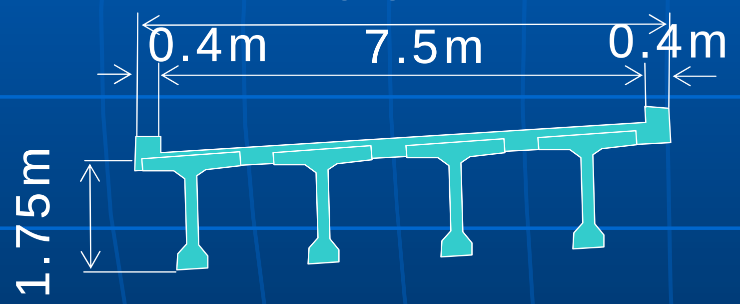
Courtesy of Arturo Aguirre, FHWA

Effect of Hurricane

Courtesy of Arturo Aguirre, FHWA

Uplift force which is close to the dead weight can be developed at medium span decks

D9-D12 (1.85m x 29.8m)



	Uplift force due to trapped air per deck	Deck weight
D9-D12 (1.85m x 29.8m)	4300kN	5800kN

Was drag force large enough to drag decks in the transverse direction?

A Preliminary Estimate

Tsunami drag force

Mass of sea water including mud

Drag coefficient (1.4)

$$F_{df} = \frac{1}{2}\rho_w c_d {v_w}^2 A_d$$

Side area of a deck

Flow velocity of tsunami (6m/s)

The lateral capacity of steel bearings

Over strength factor (2.0)

Static seismic coefficient (= 0.25)

$$F_{br} = \alpha k_h W_d$$

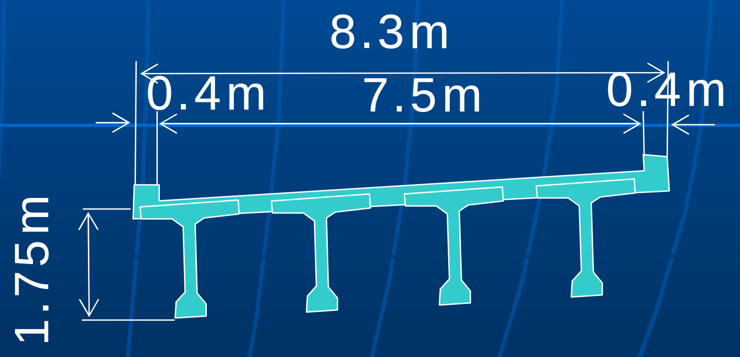
Dead load of a deck

Was drag force large enough to drag decks in the transverse direction? (2)

A Preliminary Estimate

Tsunami drag force	Lateral capacity of bearings per deck
1390kN	1800kN

D9-D12 (1.85m x 29.8m)

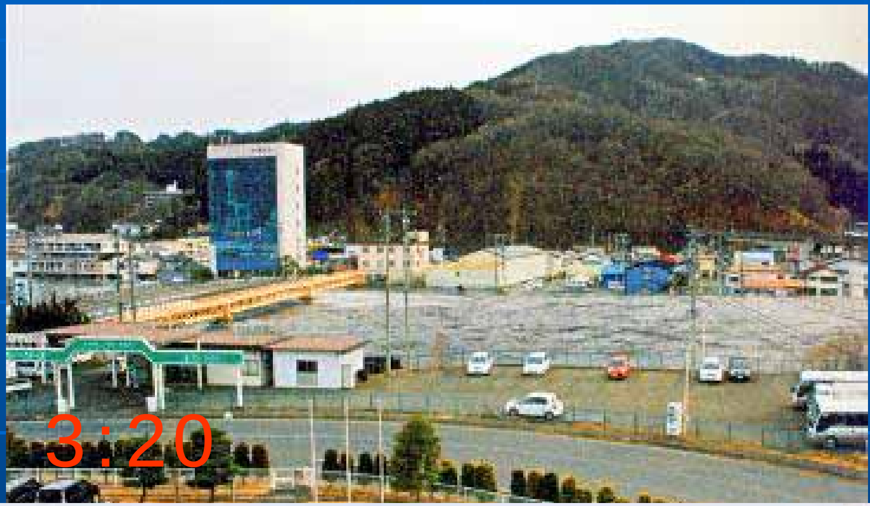


Many bridges survived whereas they were at critical locations and were totally covered by tsunami

Yanoura Bridge,Kamaishi

Kamaishi City

National Road 45



After Kozo Sawada, Sunday Maichi, Special Issue for E-J EQ, No.2

Yano-ura Bridge after the earthquake