(1) Seismic Damage of Urban Infrastructures in Past Earthquakes

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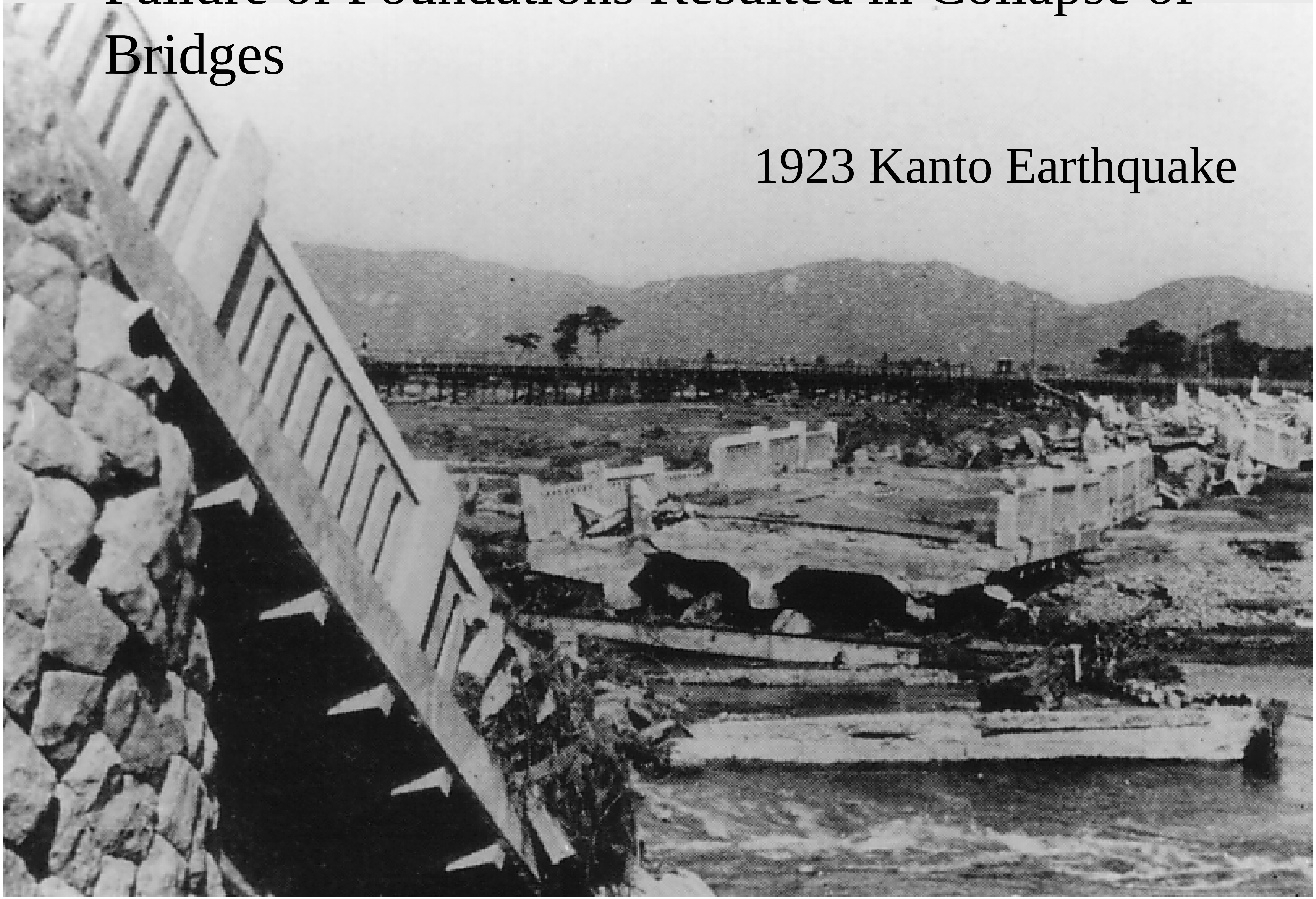
Past Experience:
What damage did we have in the past?

Stage I: Damage which occurred at the days when seismic effect was not considered or poorly considered in design

1923 Kanto Earthquake (M7.9)

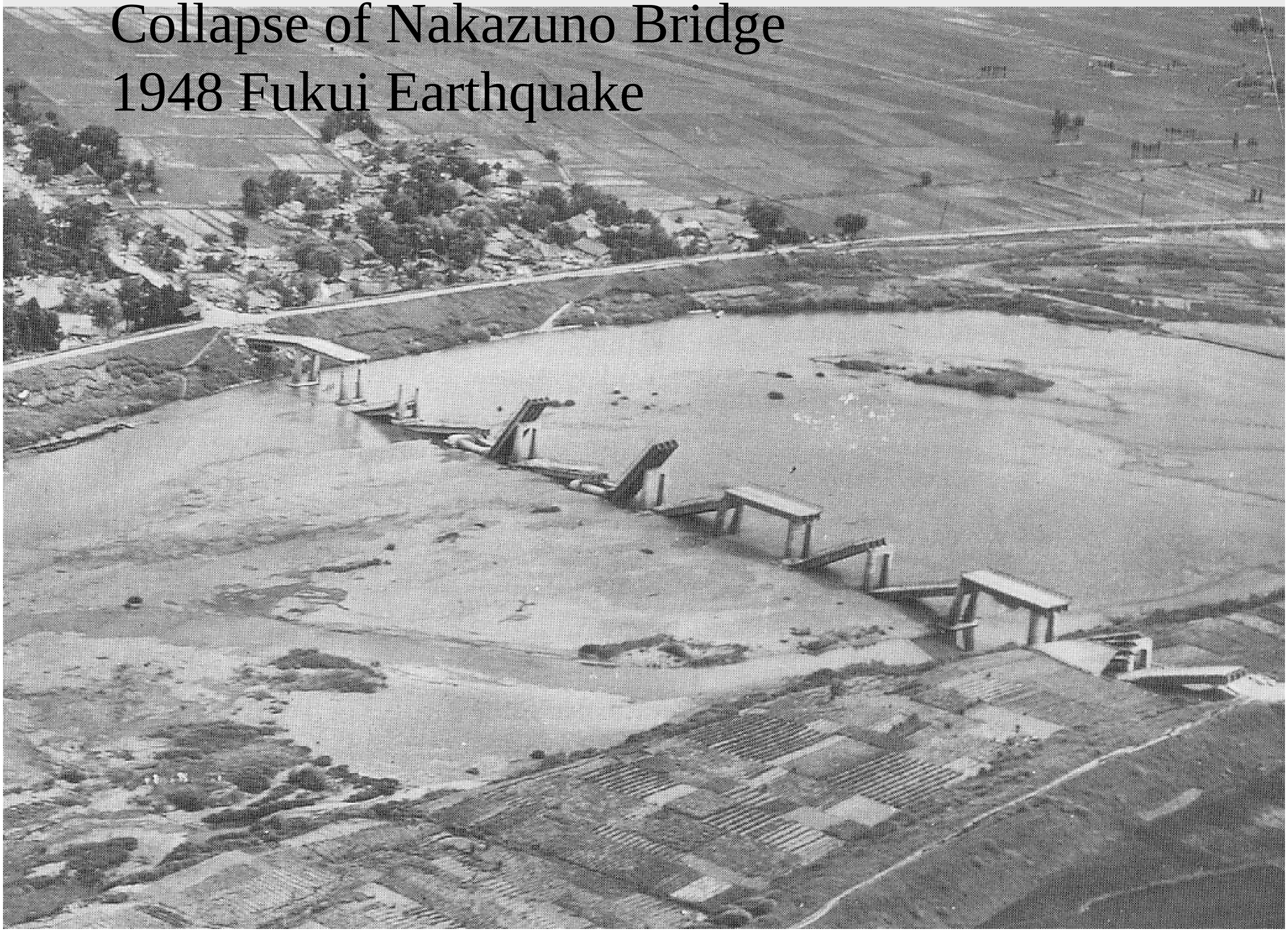
1948 Fukui Earthquake (M7.1)

Failure of Foundations Resulted in Collapse of Bridges

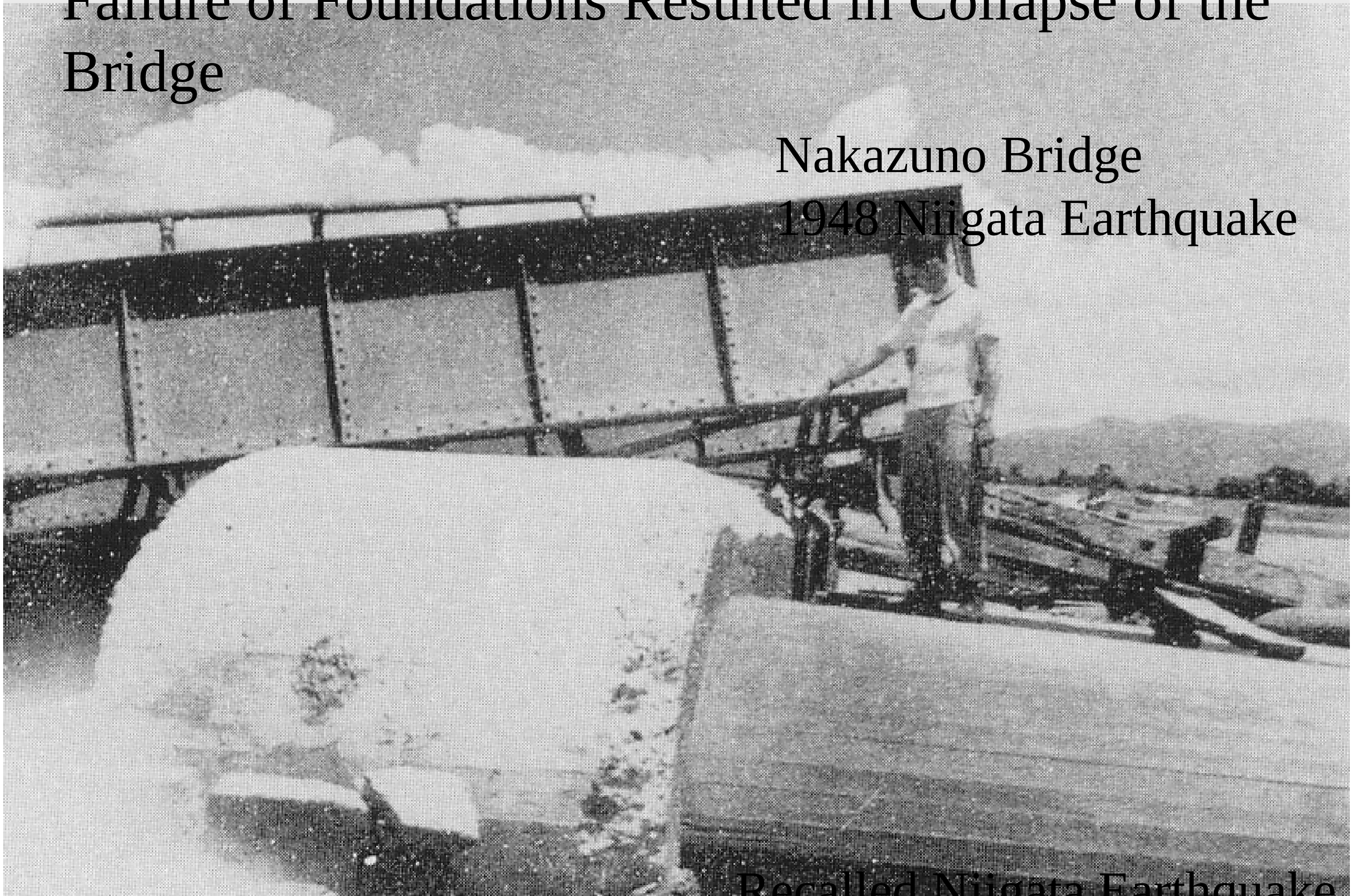


1923 Kanto Earthquake

Collapse of Nakazuno Bridge
1948 Fukui Earthquake



Failure of Foundations Resulted in Collapse of the Bridge



Nakazuno Bridge
1948 Niigata Earthquake

Recalled Niigata Earthquake

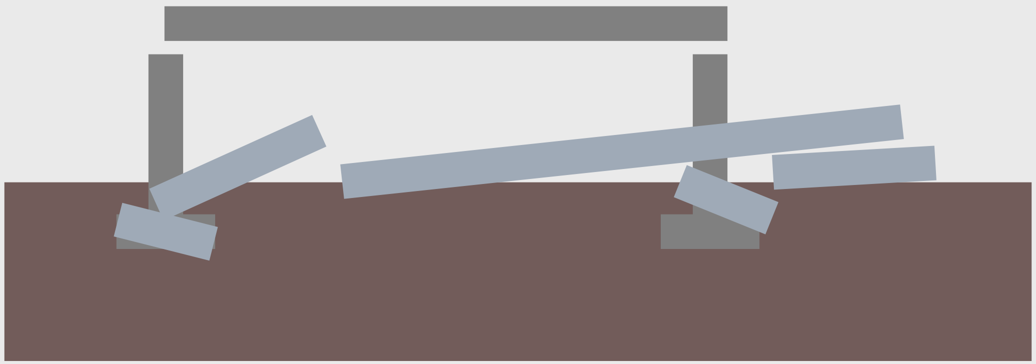
Topological & Geological Conditions

- Being located in the monsoon area, the high-rate erosion developed thick soft sedimentation at the mouth of large rivers in the Asian region.
- Most cities with large population are resting on the thick sedimentation in the Asian region
- Foundation suffered damage resulted from instability of clayey soil and liquefaction and lateral spreading of sandy soils.

Stage I (-1950s)

Seismic effects were not considered or poorly considered in design

1923 Kanto Earthquake
1946 Nankai Earthquake
1948 Fukui Earthquake



Tilting, Overturning and Settlement of Foundations

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Collapse

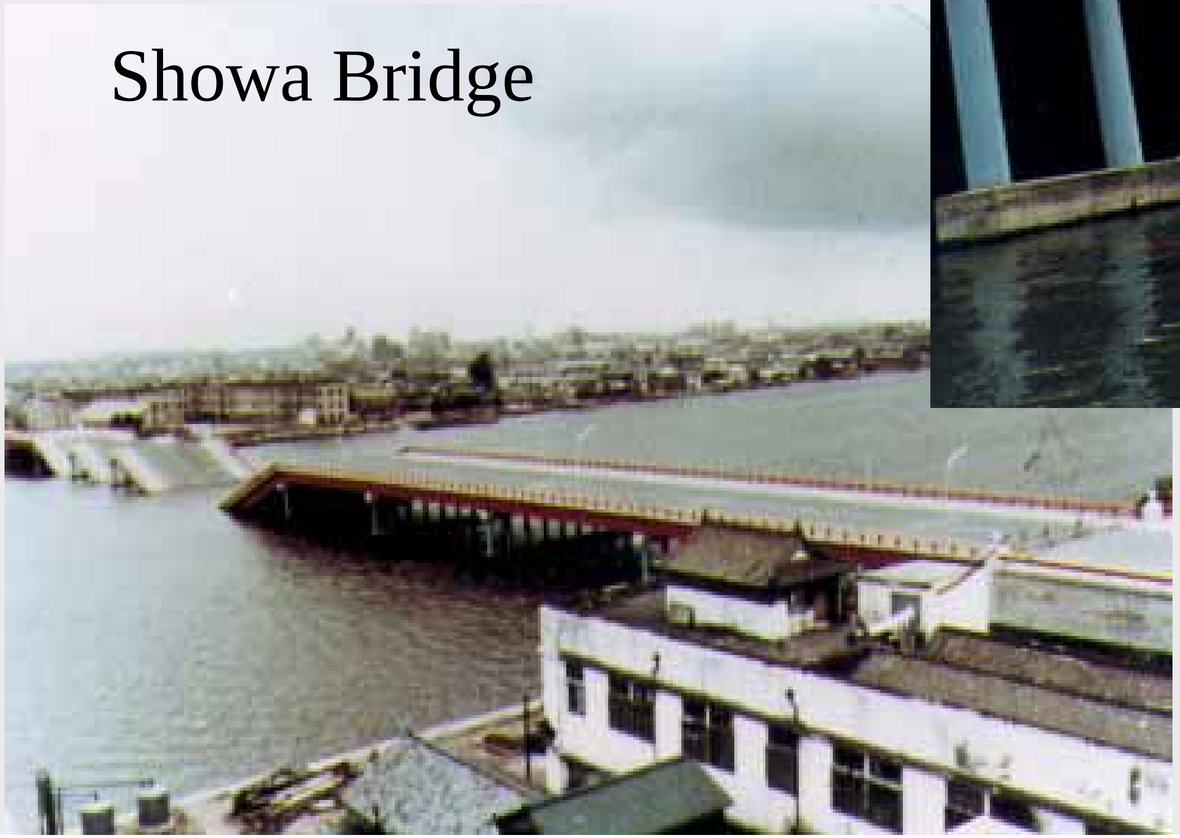
As a consequence of the extensive damage in the 1923 Kanto earthquake, seismic design was initiated in 1925

- Elastic static seismic design using 0.2-0.3 seismic coefficients based on the allowable stress design approach
- Construction of massive & rigid piers with large sections started

Stage II (1960-1970s): Importance of considering soil liquefaction and unseating prevention devices was first recognized

1964 Niigata Earthquake

Showa Bridge



Soil Liquefaction

- In old documents there are many descriptions that soil spread out from cracks of ground, and that wells were filled out by sand during earthquakes.
- After 1964 Niigata earthquake, this phenomena was first defined as “liquefaction” by a Japanese professor (Professor Mogami), and scientific research was initiated worldwide on the mechanism of liquefaction.
- Fact on ground movement (lateral spreading) was described in damage reports on Niigata earthquake, however research was directed to liquefaction after Niigata earthquake. It was late 1980s when importance on lateral spreading was pointed out by Professor M. Hamada.

This damage resulted in the first development of unseating prevention devices

- ✓ Restrainers
- ✓ Seat Length
- ✓ Avoid Bearings with One Anchor Bolts

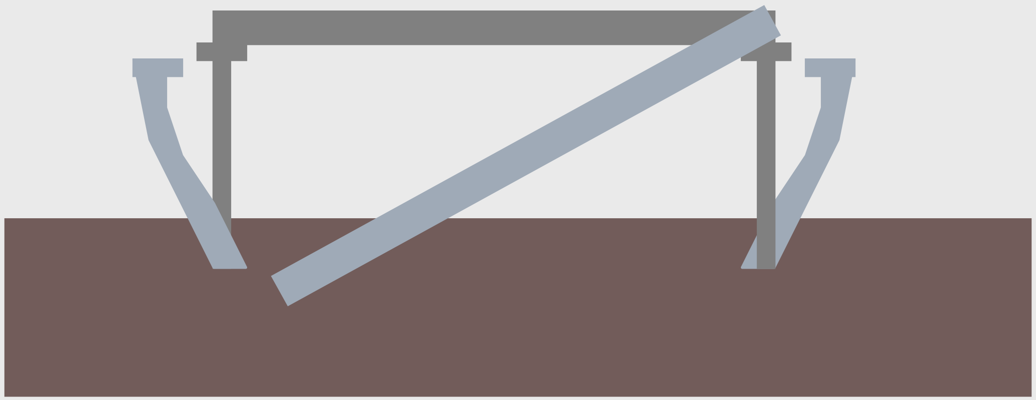
Unseating Prevention Devices

- Effectiveness of unseating prevention devices was recognized by Japanese engineers who investigated the damage of bridges in 1964 Niigata earthquake.
- They proposed to
  - ✓extend the seat length
  - ✓provide connection between adjacent decks
  - ✓connect the deck to the substructures
- They were incorporated in seismic retrofit first, and then incorporated in the 1971 JRA Guide Specifications on Seismic Design. The practice was then spread worldwide.

Stage II: Damage which occurred before the importance of soil liquefaction and unseating prevention devices was recognized

- Consideration to soil liquefaction and unseating prevention devices were not included in seismic design practice prior to 1964

- Excessive relative displacement of decks resulted from soil liquefaction



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Collapse

1971 Guide Specifications on Seismic Design of Highway Bridges

- Modified seismic coefficient method which incorporated natural period, soil condition and importance dependence of the seismic coefficient was introduced
- Evaluation of vulnerability for liquefaction was first included
- Unseating prevention devices were first included

Stage-III: Damage resulted from insufficient ductility of columns and strength of bearings

1982 Urakawa-oki Earthquake

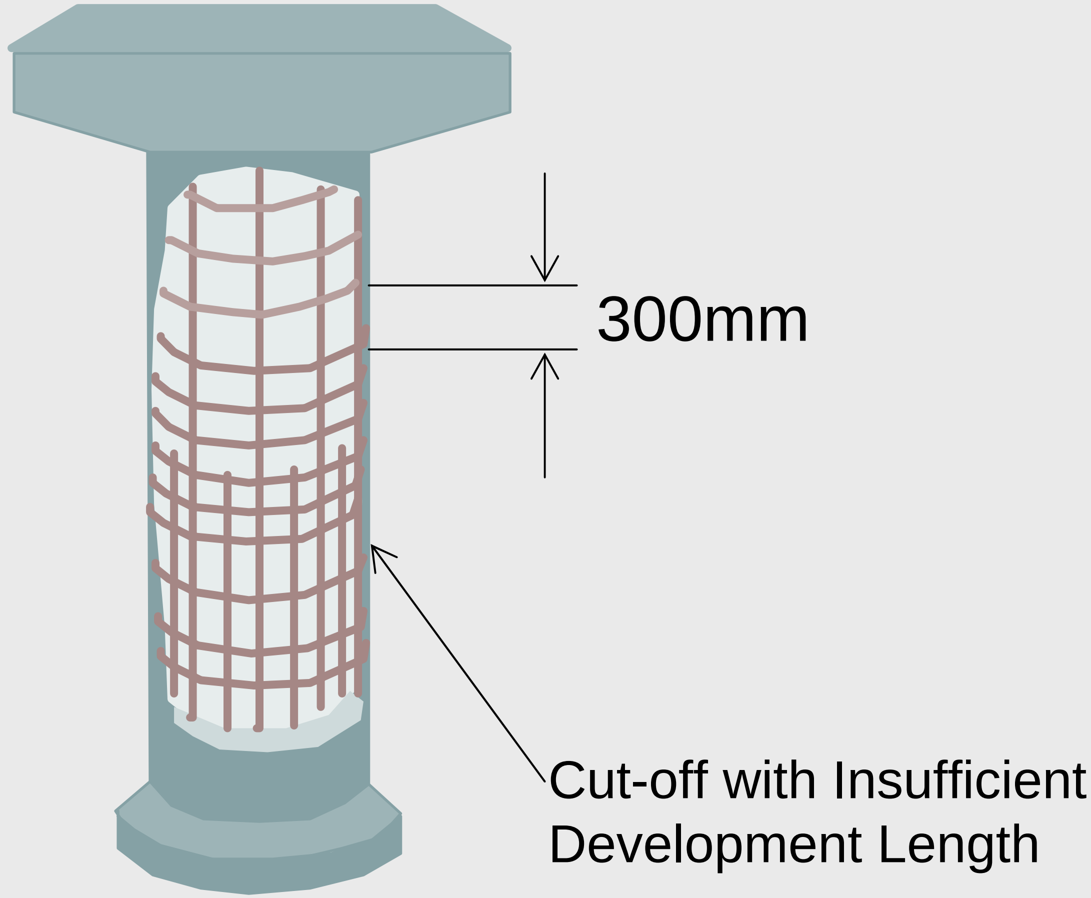
Shear failure of RC Columns

Shizunai Bridge

Premature Shear Failure of RC Piers

Premature Shear Failure of Reinforced Concrete Piers Resulting from Insufficient Development Length

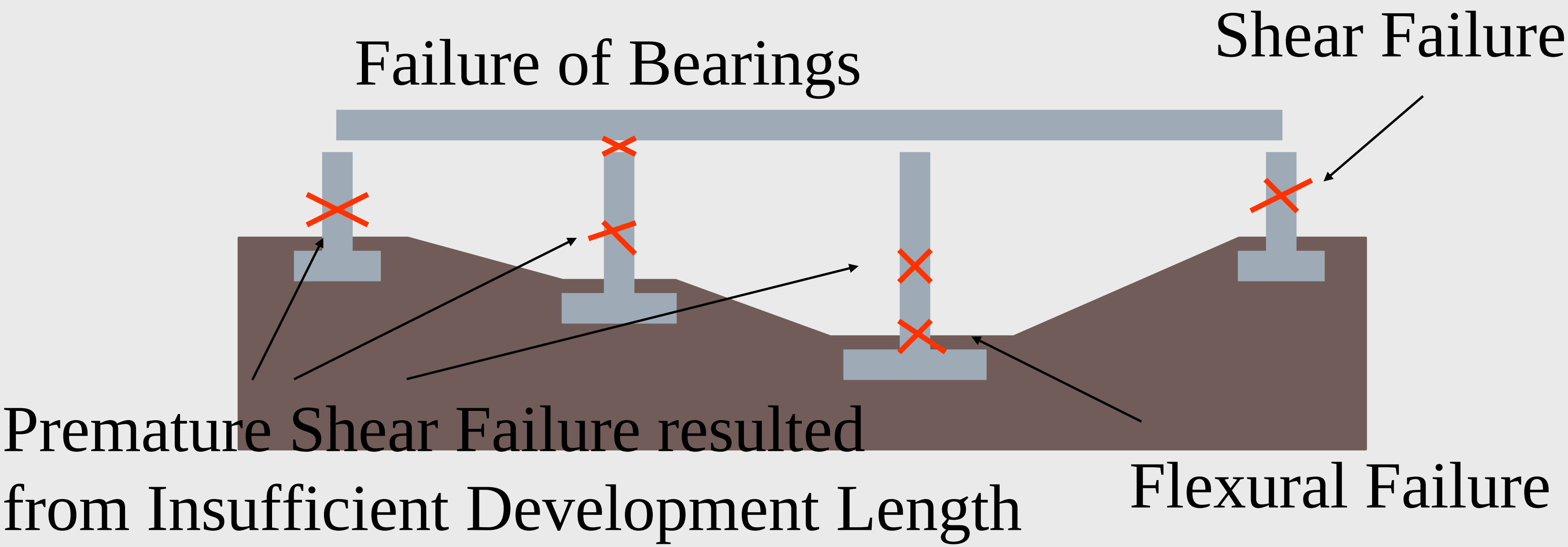
Common Design Practice prior to 1985



Shake Table Experiment at E-Defense

Stage-III: Damage resulted from insufficient ductility of columns and strength of bearings

1978 Miyagi-ken-oki Earthquake
1982 Urakawa-oki Earthquake
1993 Hokkaido-toho-oki EArthquake



Features of Japanese Seismic Design Practice

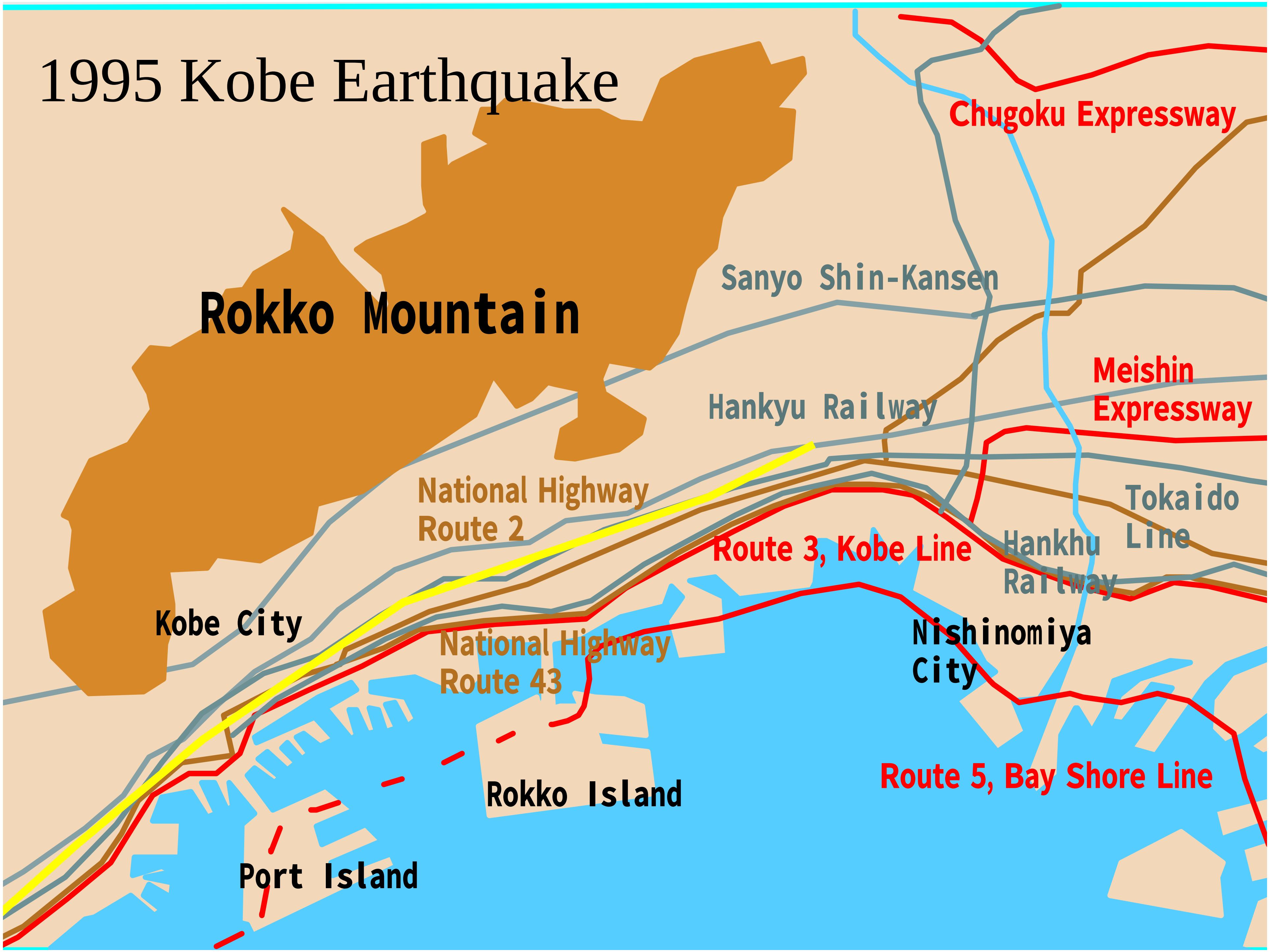
A Number of Seismic Experiences

- Larger seismic design force
- Unseating Prevention Devices
- Countermeasures for Liquefactions

Number of Collapsed Bridges

✓ 1923 Kanto EQ	M7.9	6
✓ 1946 Nankai EQ	M8.1	1
✓ 1948 Fukui EQ	M7.3	4
✓ 1964 Niigata EQ	M7.5	3
✓ 1978 Miyagi-ken-oki EQ	M7.4	1

Large Impact of 1995 Kobe, Japan Earthquake



1995 Kobe Earthquake
Rokko Mountain
Sanyo Shin-Kansen
Chugoku Expressway
Hankyu Railway
Meishin Expressway
National Highway Route 2
Tokaido Line
Route 3, Kobe Line
Hankhu Railway
Kobe City
National Highway Route 43
Nishinomiya City
Rokko Island
Route 5, Bay Shore Line
Port Island

Bridges are vital component of urban areas

The most extensive damage occurred at a 18-span viaduct. This bridge collapsed due to failure of RC columns resulted from the premature shear failure.

Collapse of 18-Span Fuka
Hanshin Expressway
1995 Kobe Earthquake

Premature Shear Failure of RC Columns Resulted from Insufficient Development Length

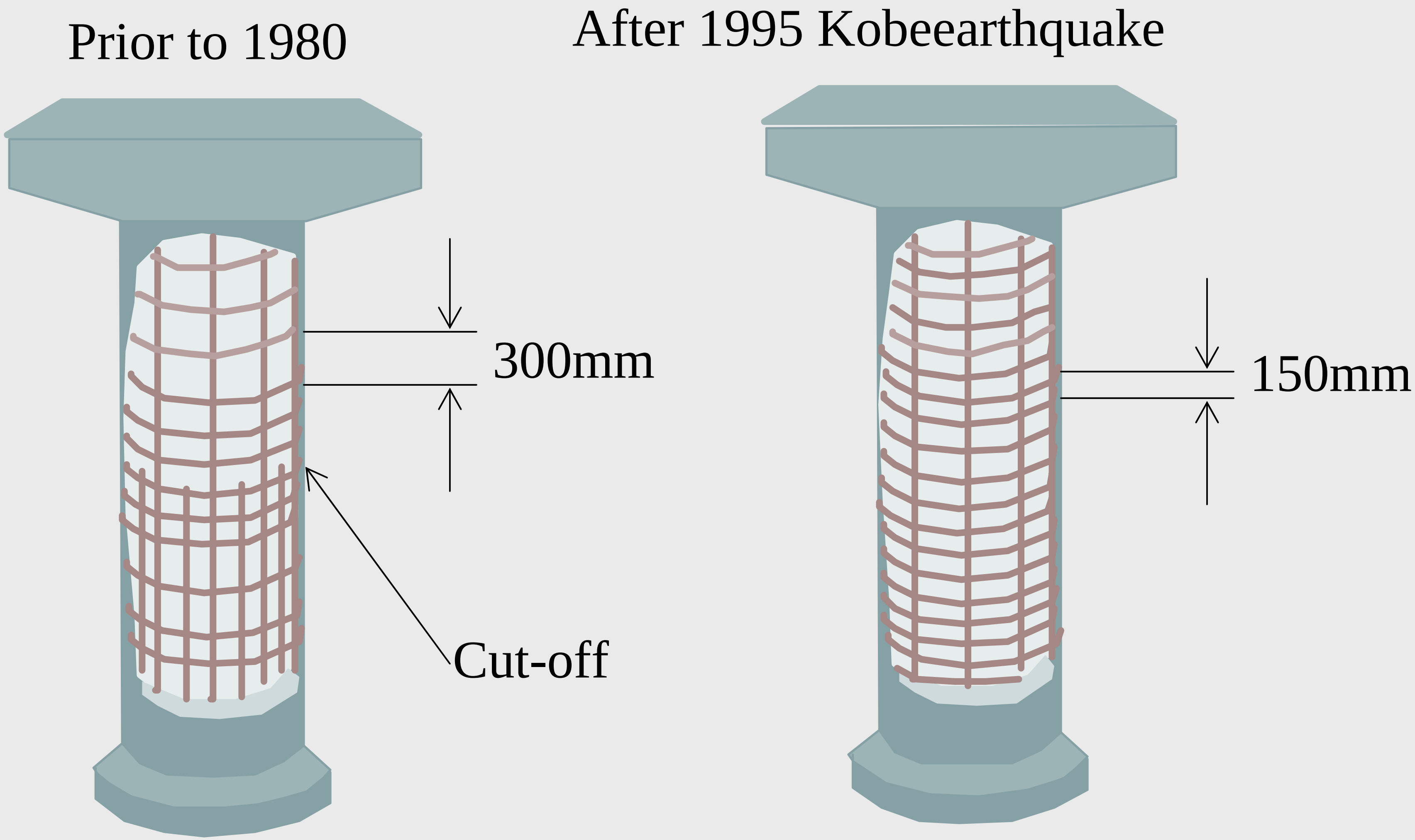

Shear Failure

Insufficient Confinement

Collapse of a 18-span viaduct in the 1995 Kobe Earthquake

NHK

Enhancement of Ductility Capacity



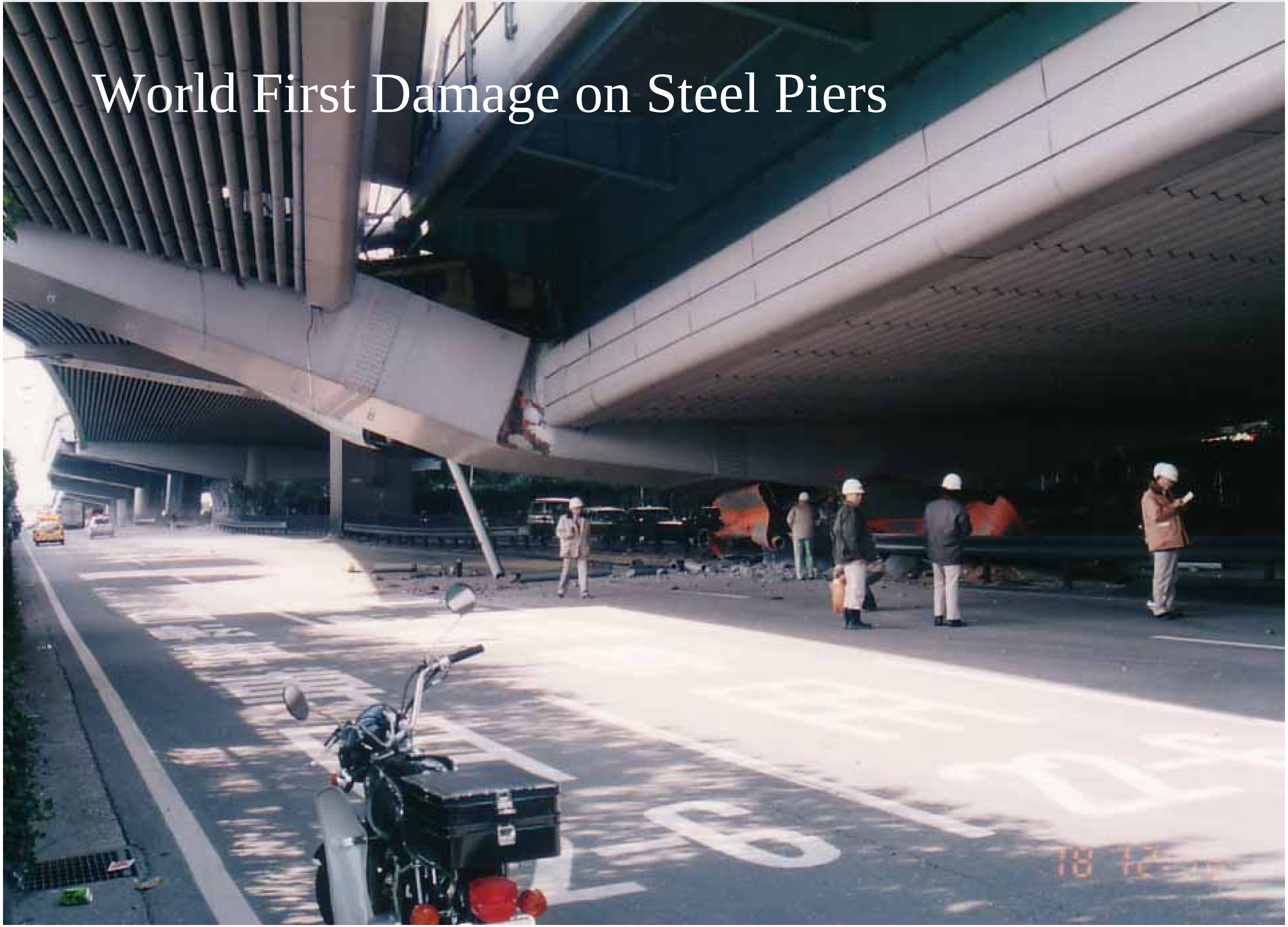
Shear Failure of RC Columns

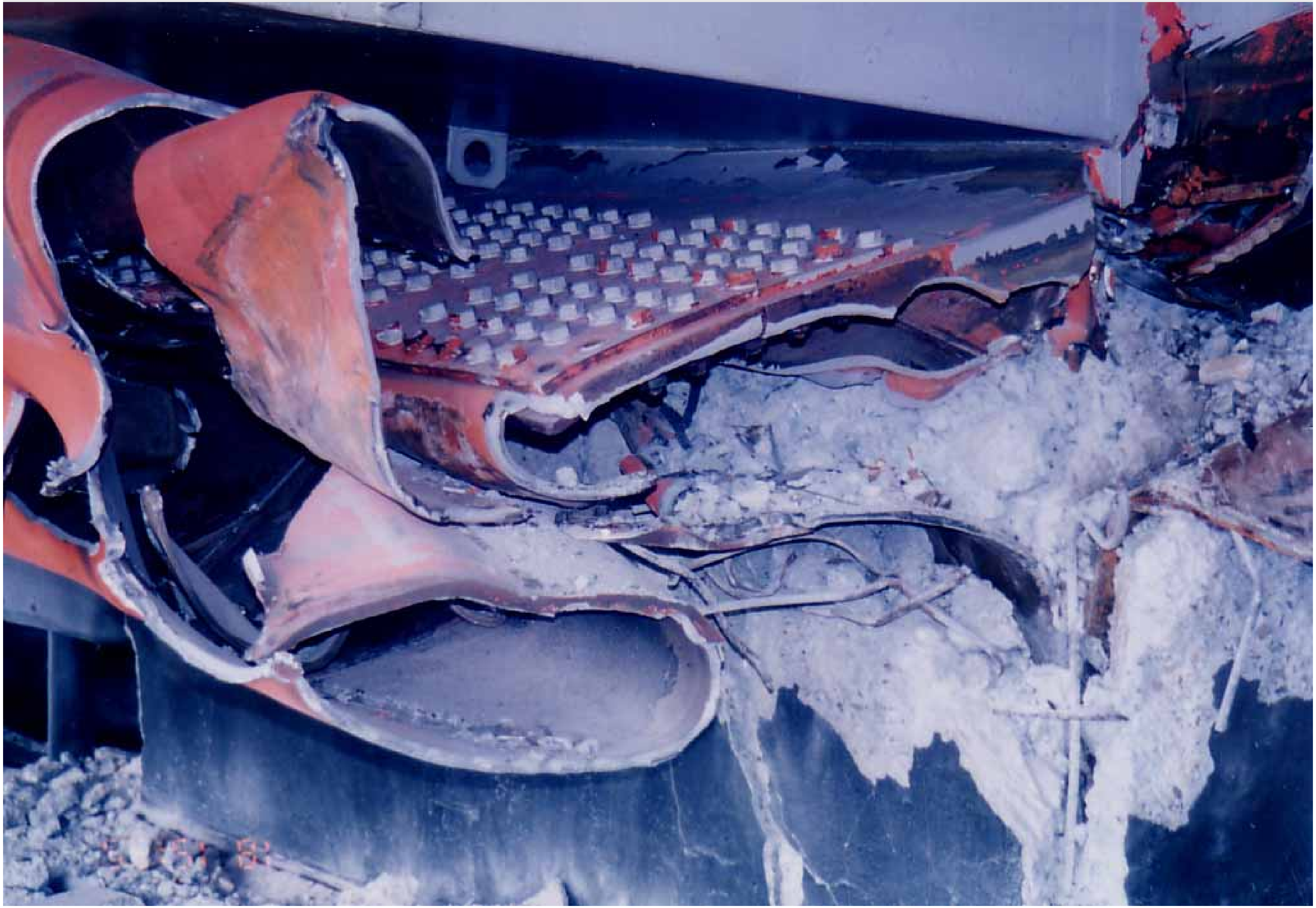
Shear Failure

Shear Failure

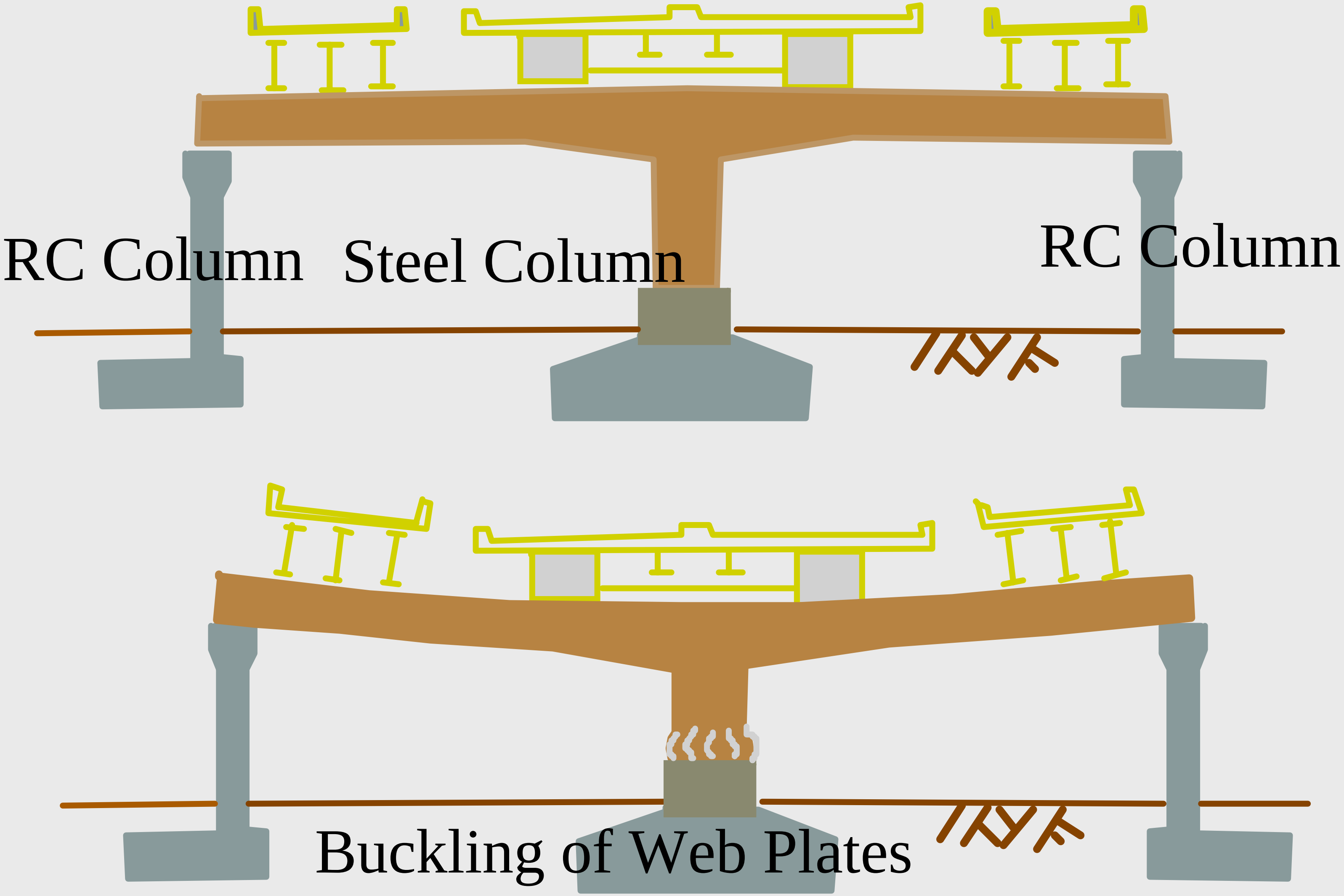
Failure of Steel Piers

World First Damage on Steel Piers

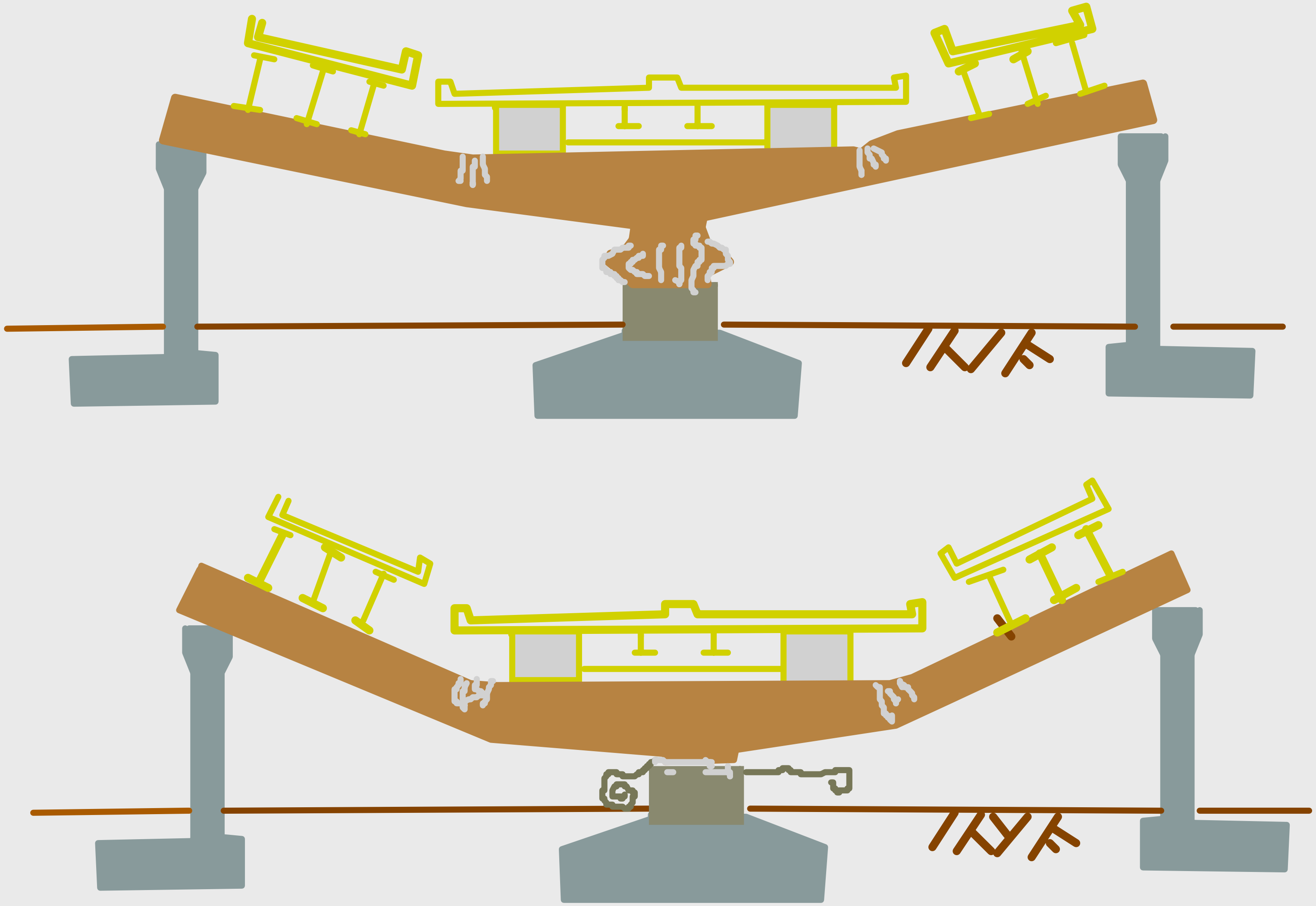




Progress of Failure of Steel Columns



Progress of Failure of Steel Columns (continued)

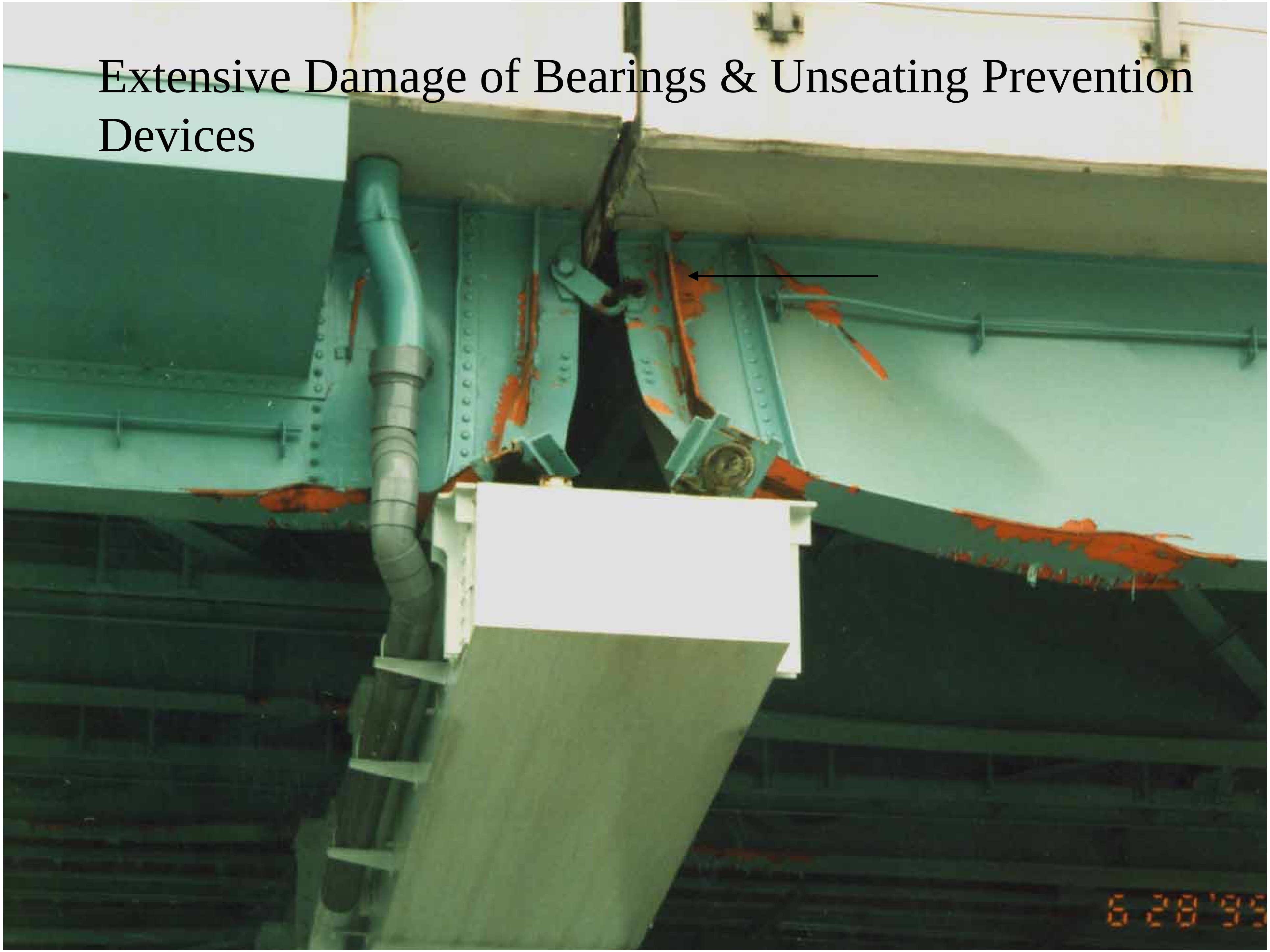


Damage of Foundations

Damage of foundations was less, but none

Extensive Damage of Bearings

Extensive Damage of Bearings & Unseating Prevention Devices

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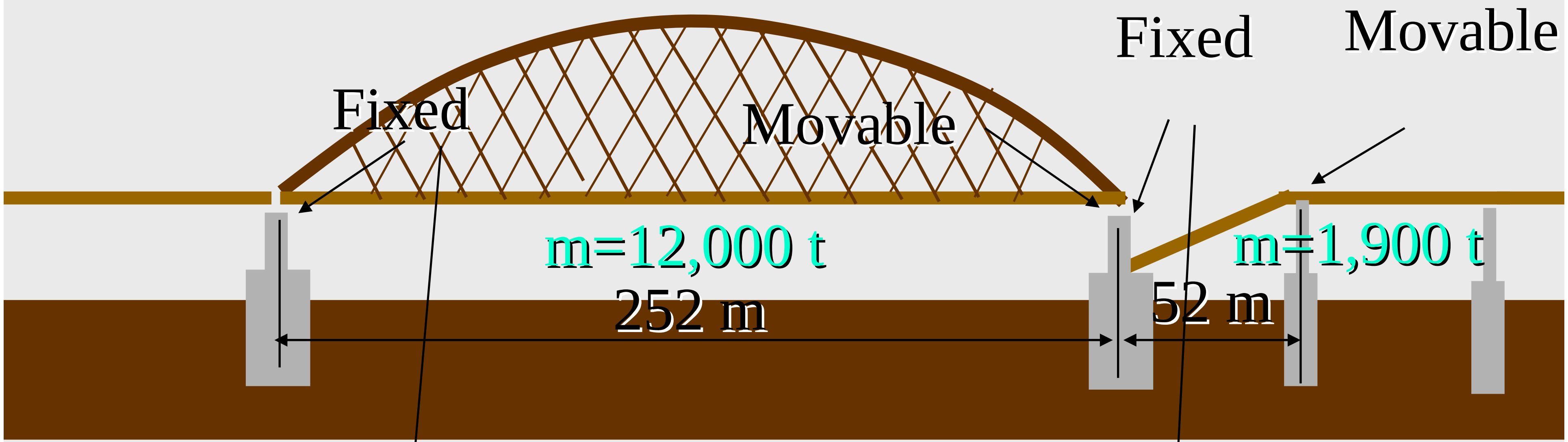
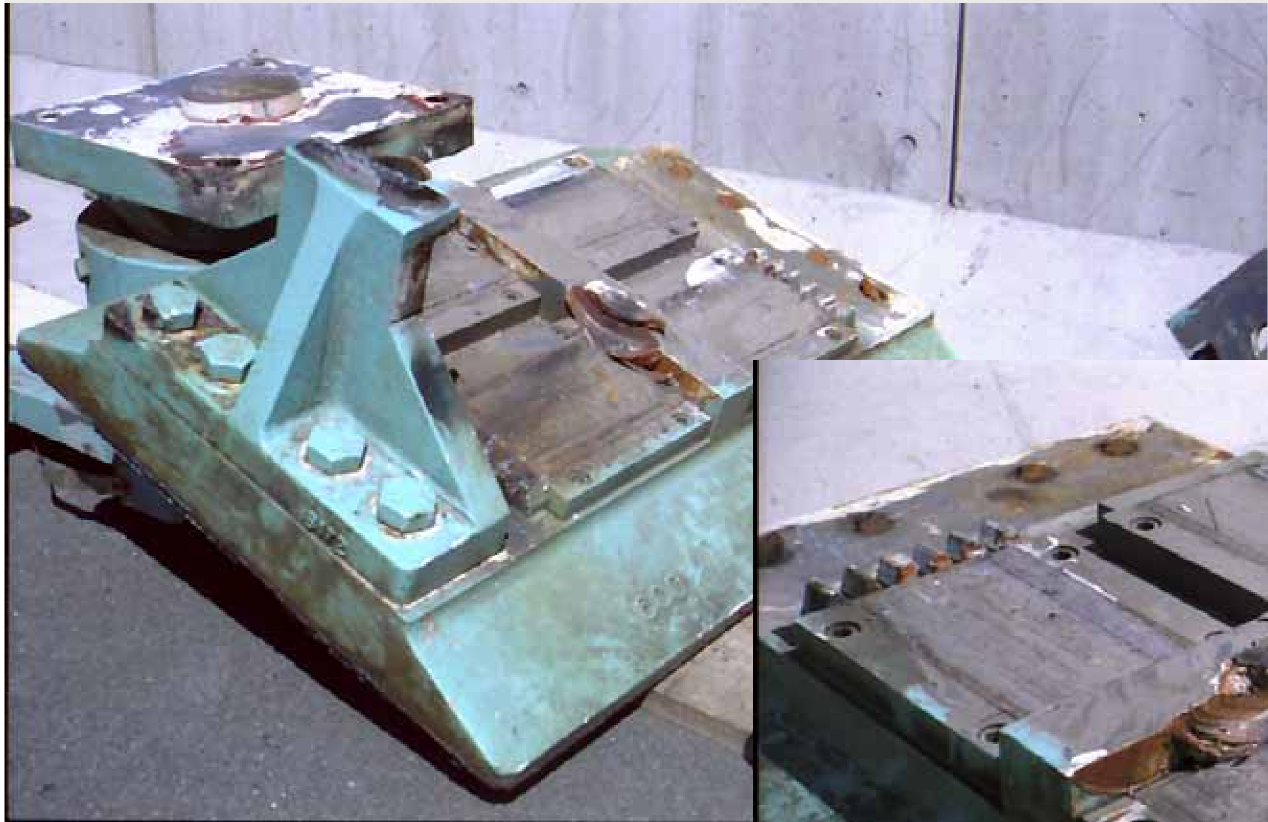
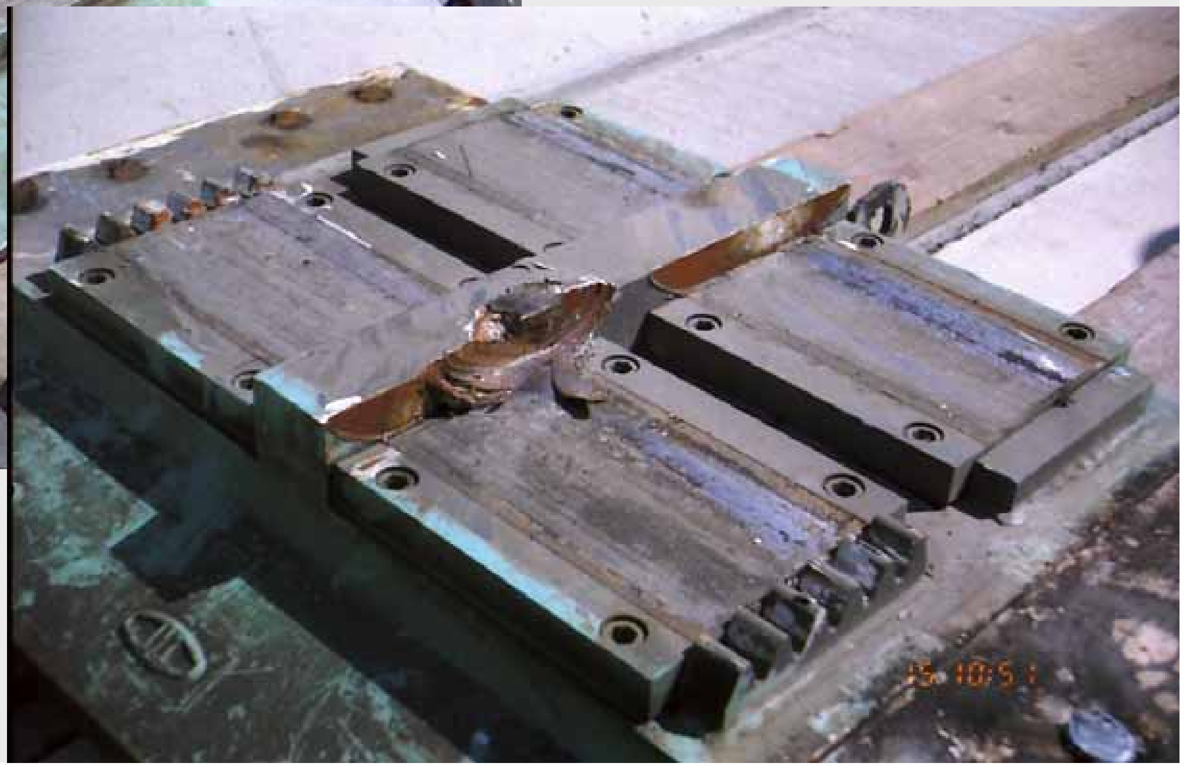
Collapse of an Approaching Span

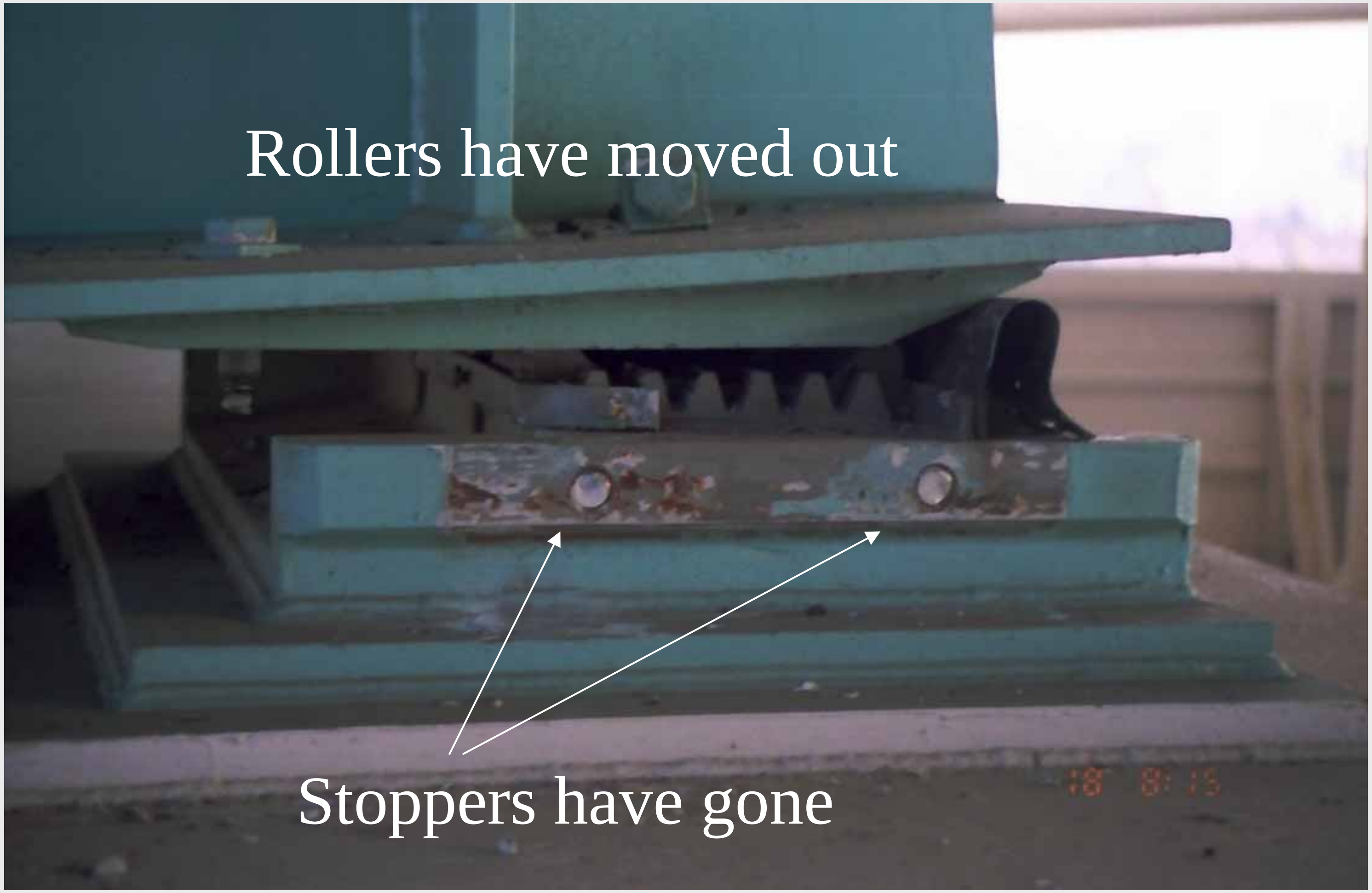


Vulnerable Steel Pin & Roller Bearings





Vulnerable Steel Roller Bearings



Failure of Steel Bearings

Change of Design Practice on Bearings after 1995 Kobe Earthquake

- Damage of bearings (steel bearings) was an issue of discussion at every time when a damaging earthquake occurred.
- However there was always an argument that bearing damage was a fuse to restrict extensive damage at the substructures. As a consequence, only minor upgrading had been adopted for design of bearings.
- However it was so obvious that bearing damage was not a fuse for restricting damage of substructures, but it was one of the main causes of the extensive damage in the 1995 Kobe earthquake.

Consequence of the 1995 Kobe Earthquake (cont.)

- It was recommended in the 1995 & 1996 codes that elastomeric bearings including LRB and HDR should be used.

- Steel bearings have the following deficiencies:
  - ✓Insufficient strength and weak for shock
  - ✓Structures with insufficient lateral and vertical capacity
  - ✓Insufficient lengnth of movement

- As a consequence, about 98% of the total bearing was steel bearing before 1995, but 90% is now elastomeric bearings.

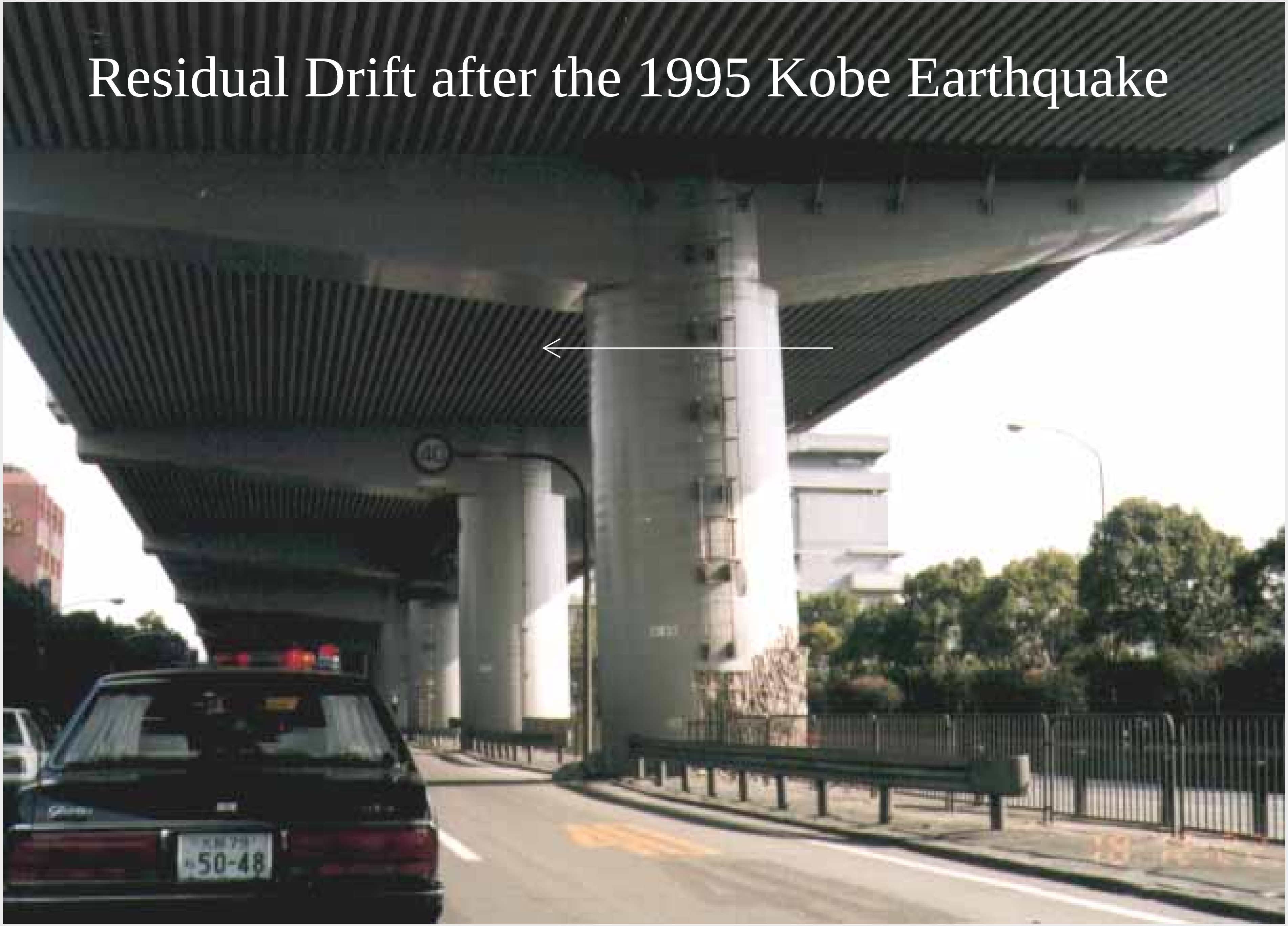
Damage of Unseating Prevention Devices

Damage of Unseating Prevention Devices

Damage of Unseating Prevention Devices

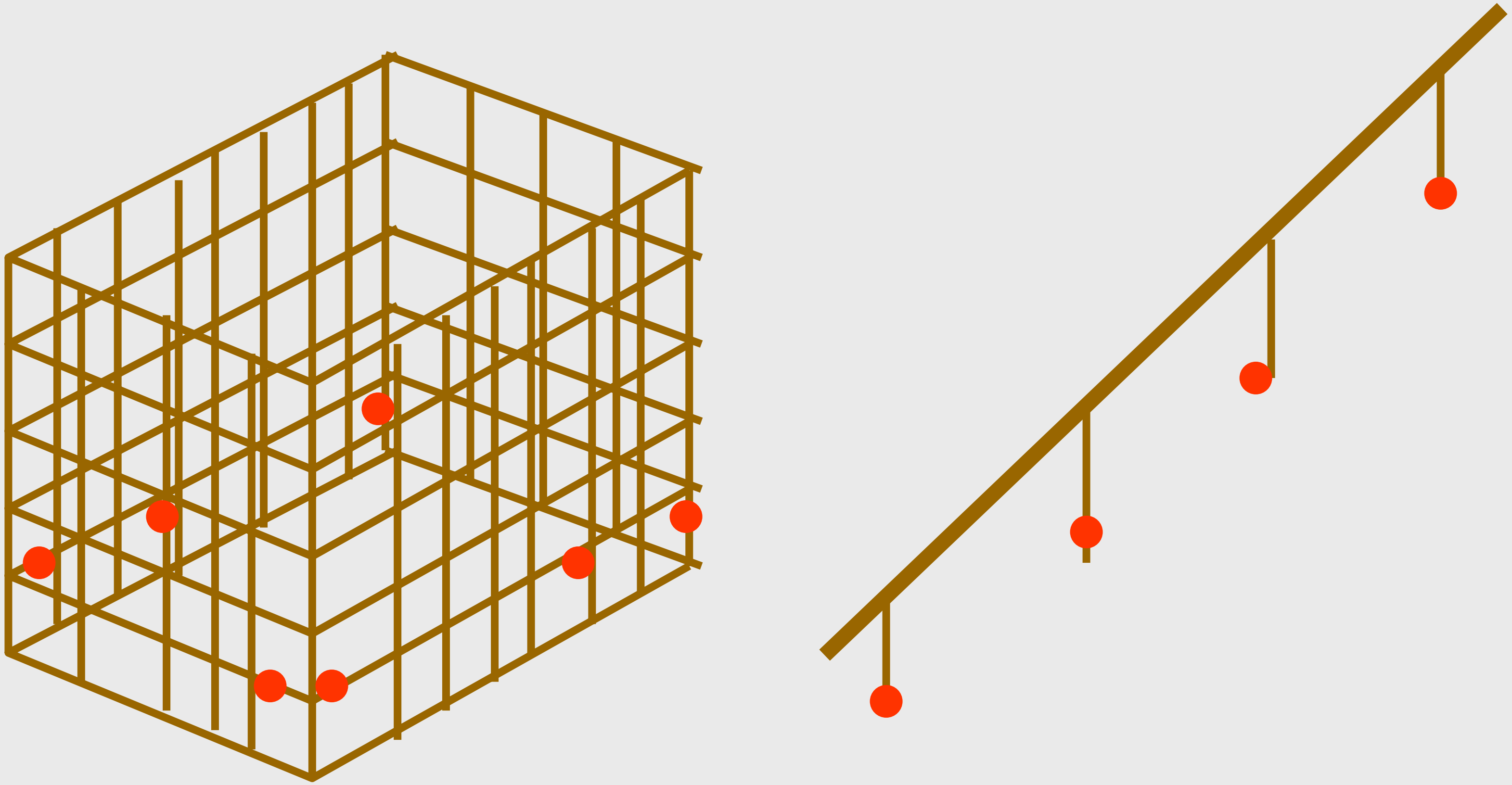
Residual Tilt of Columns

Residual Drift after the 1995 Kobe Earthquake



Residual Drift

Much Less Static Indeterminacy in Bridges than Buildings



Plastic Hinges

First Provision to Residual Tilt of Piers

- A new provision was introduced for limiting residual tilt of columns after the 1995 Kobe earthquake. This was the first provision for the residual tilt.

- Residual displacement response spectra were used to formulate the provision as:

$$u_R < u_{Ra}$$ ← Design residual displacement

$$u_R = c_R \cdot u_{R\max} = c_R(\mu_r - 1)(1 - r)u_y$$

$$u_{Ra} = \frac{1}{100}H$$ ← Column height

Summary of the 1995 Kobe Earthquake

What were lessons?

Experience of the 1995 Kobe Earthquake

Past damage occurred at foundations & Piers/Columns

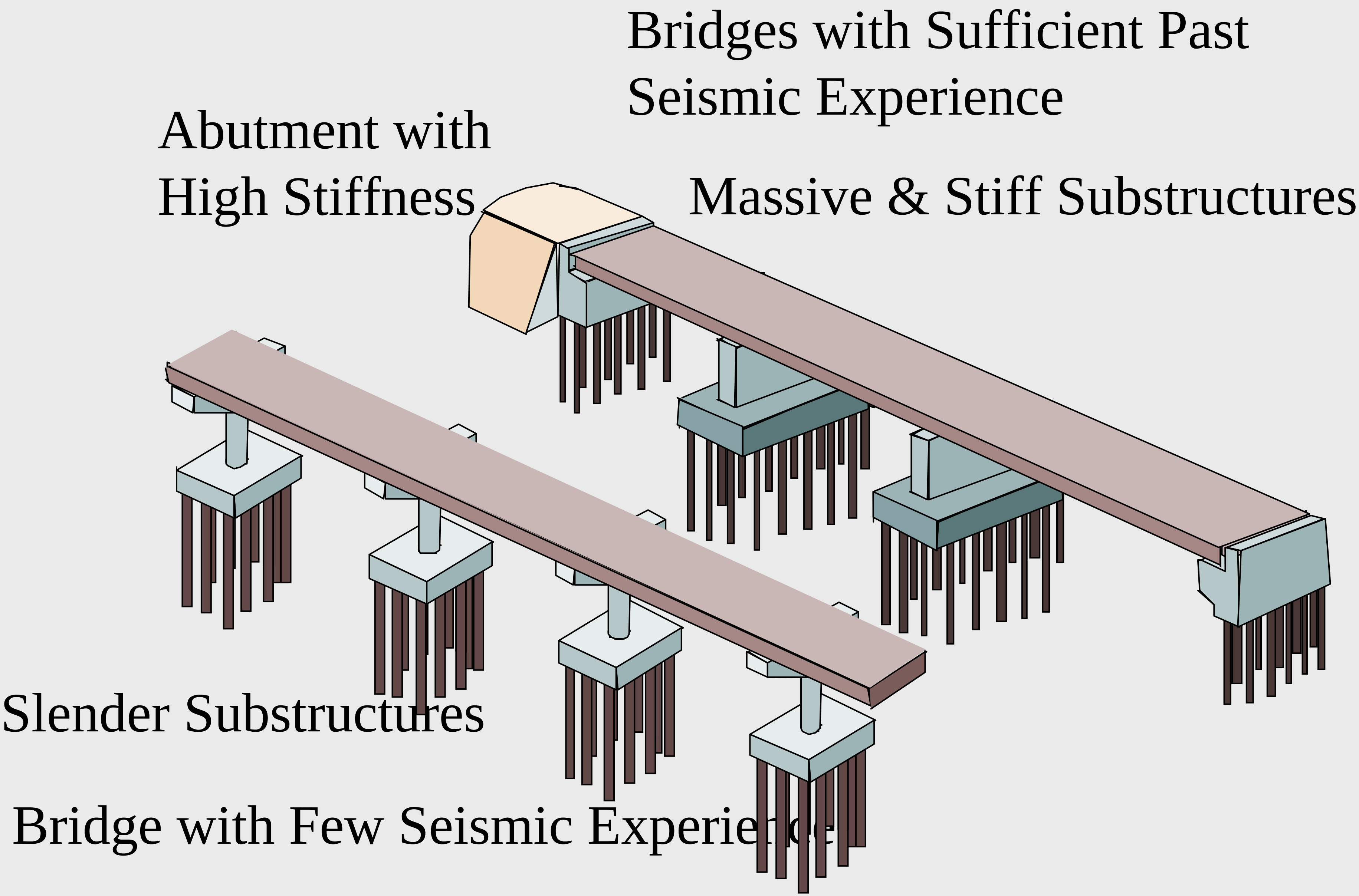
→ Construction of Massive & Stiff Foundations & Piers with Large Sections

↓ Restrictions of Space under Bridges

Construction of Slender RC and Steel Columns

Extended the Past Design Practice to Slender RC and Steel Columns

New experience on the column ductility



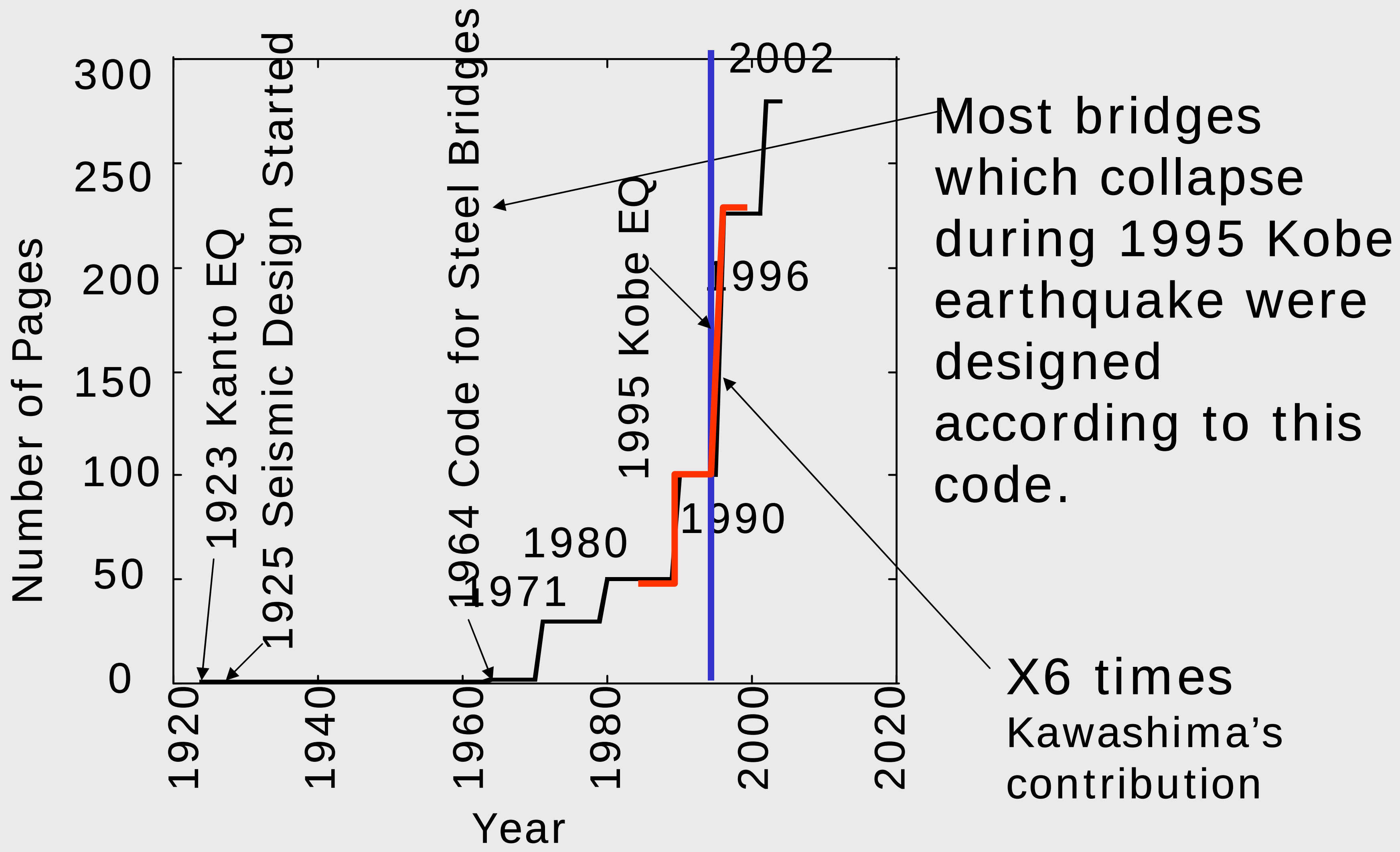
Cause of Damage of Bridges in 1995 Kobe Earthquake

- Destructive near field ground motions
- Insufficient strength & ductility of columns, bearings and unseating prevention devices.

Have good insight on the damage & bridge behavior under extensive ground motions

- Seeing is believing.
- We tend not to believe what we have not yet seen.
- We should have a good insight on what could happen.

Number of Pages related to Seismic Design of Highway Bridges in Japan



1971Code and the Latest Code (2002)

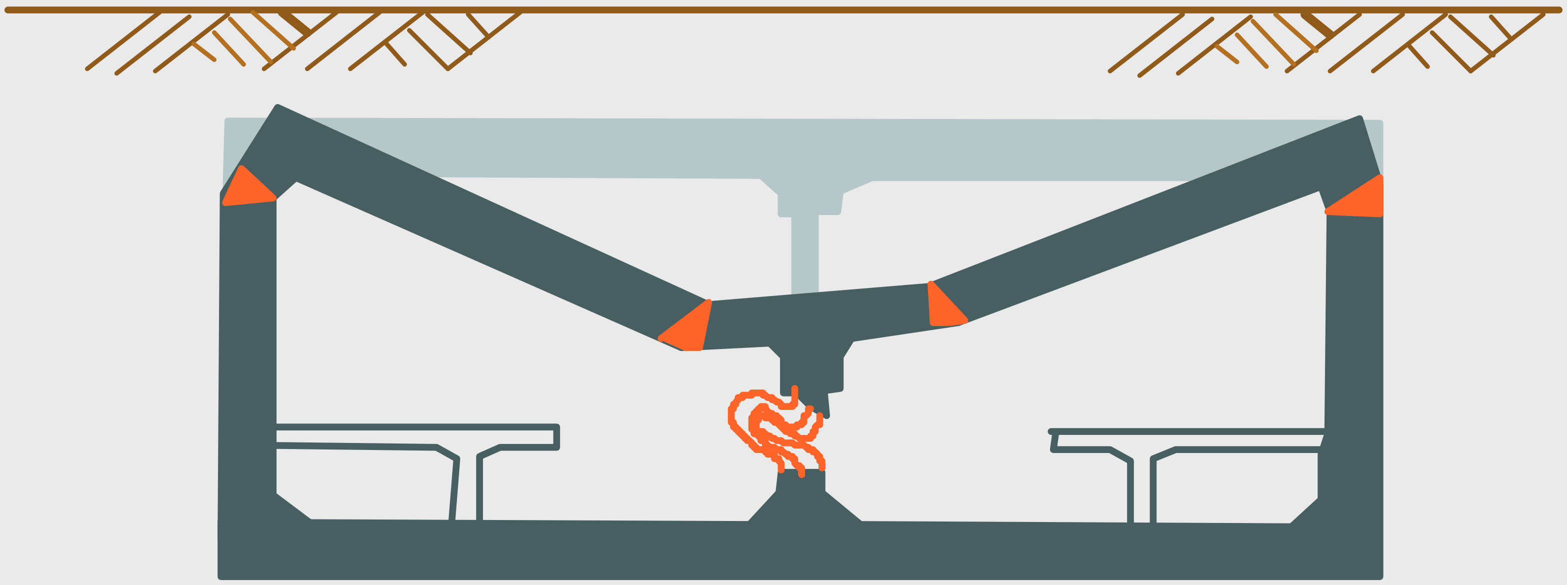
About a half pages was references

What are the research targets in the next 10 years?

What are the concern of the public?

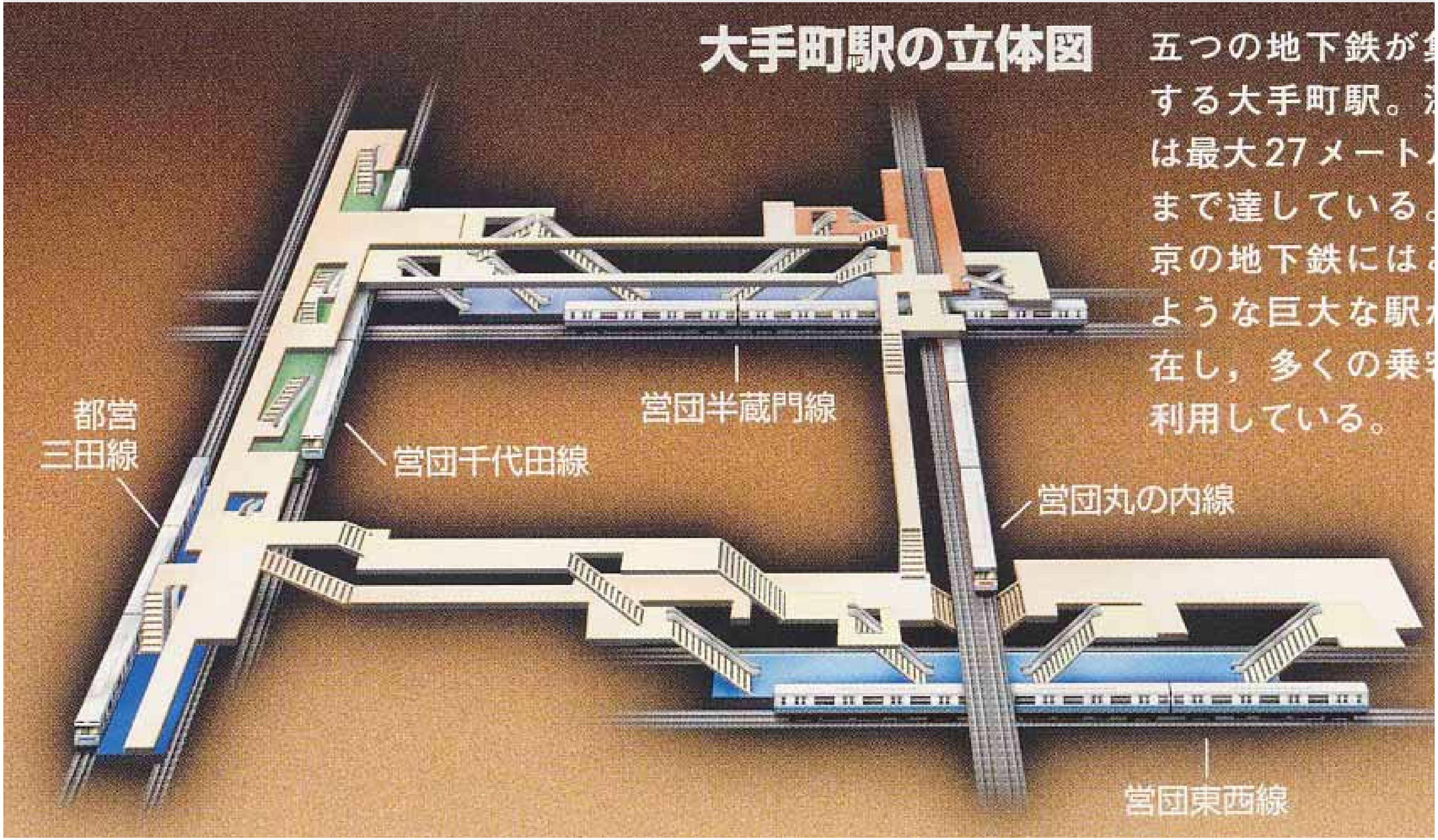
Failure of Subway Station

Failure Mechanism of Subway Station



Settlement of Road Surface

High Risk of Subway Stations with Complex Structures

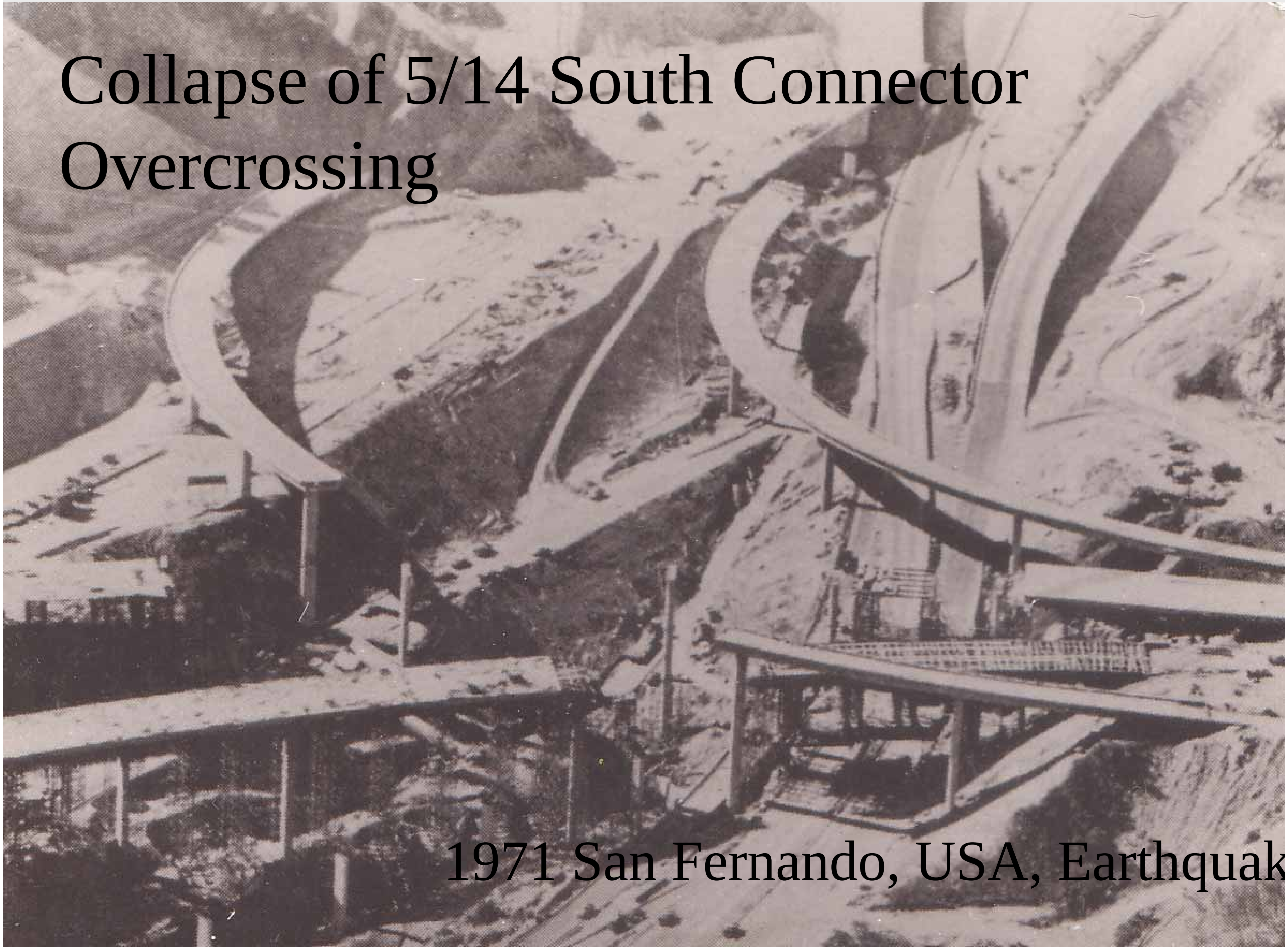


What are the research targets in the next 10 years?

- Are bridges safe as a system to ensure the safety of public in the urban areas?
- What are the next type damage?
- Are the current seismic performance goal that bridge should not collapse during an extensive earthquake acceptable to the public?

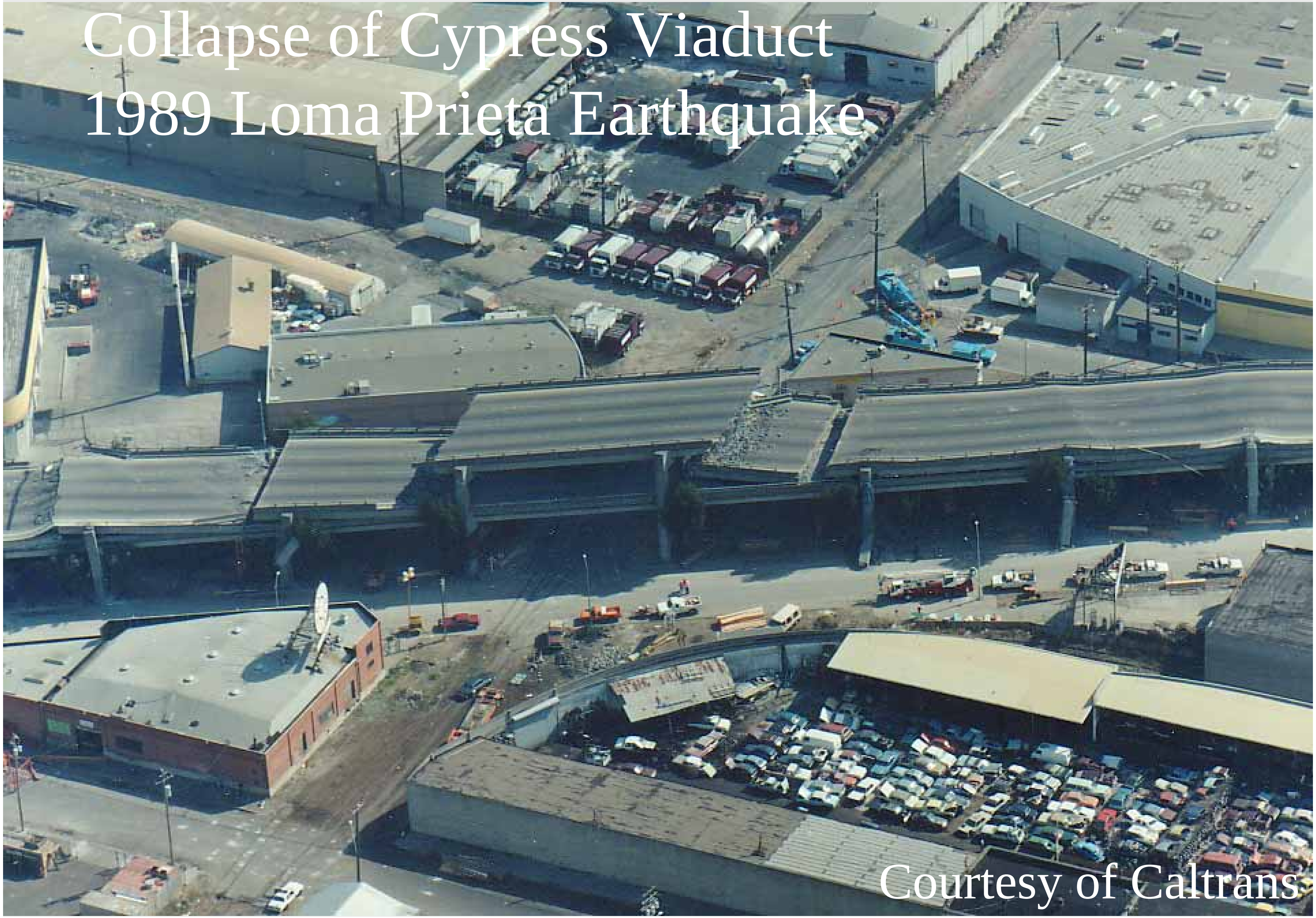
Seismic Damage of Bridges in USA

Collapse of 5/14 South Connector Overcrossing



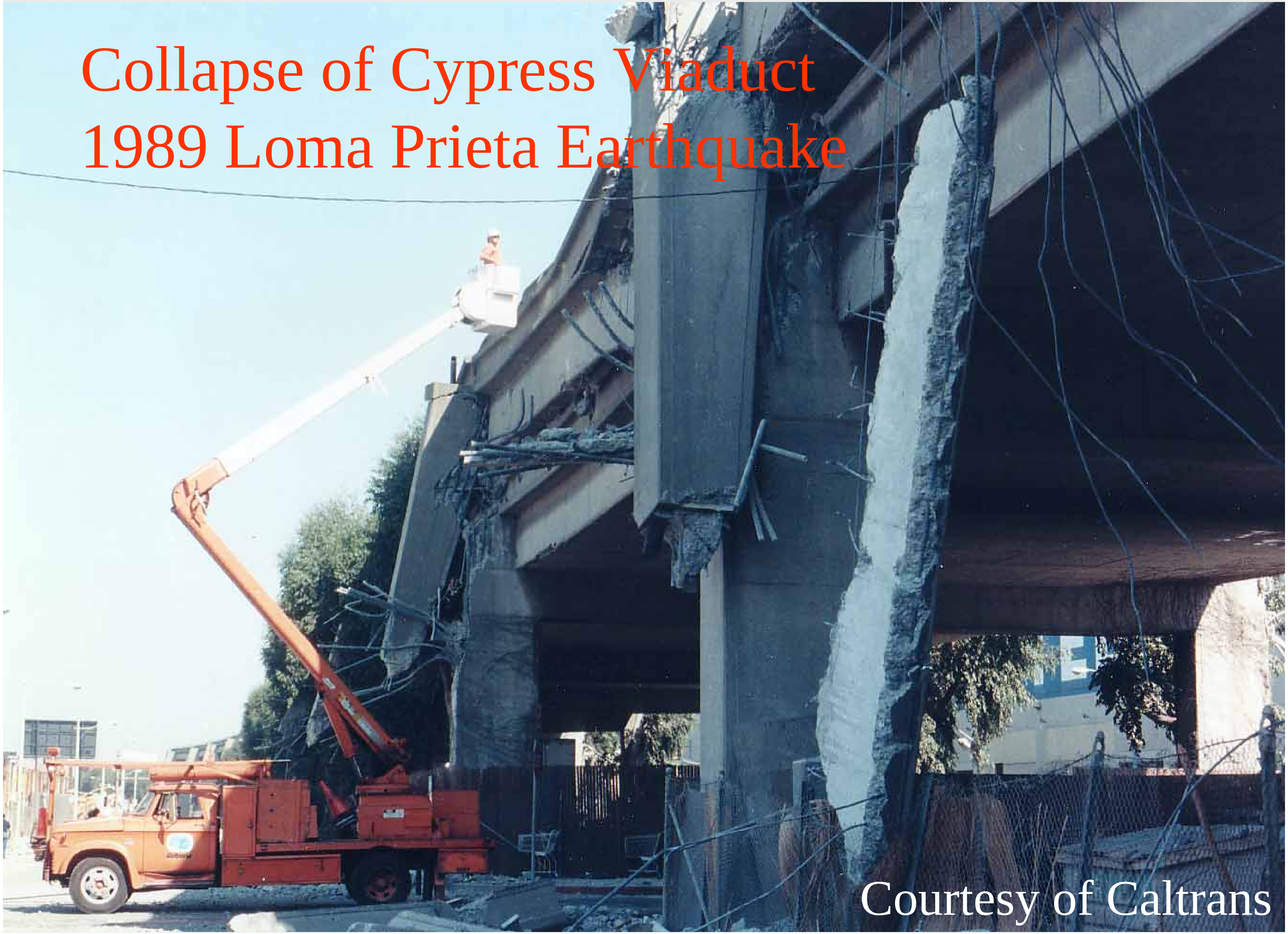
1971 San Fernando, USA, Earthquak

Collapse of Cypress Viaduct
1989 Loma Prieta Earthquake



Courtesy of Caltrans

Collapse of Cypress Viaduct
1989 Loma Prieta Earthquake



Courtesy of Caltrans

1989 Loma Prieta Earthquake

How Did Damage Progress?


3
1104


4


5


6

Pounding of Decks at Intermediate Hinge

History of Seismic Design of Bridges in USA

1776	Independence
1830-1840	Gold Rush
1850	California became a part of US territory
1906	San Francisco Earthquake
1933	Long Beach Earthquake
	Field Act (0.1 Seismic coefficient for school buildings, and 0.02-0.05 seismic coefficient or other structures) & Riley Act
1936	Construction of San Francisco Oakland Bay Bridge
1957	Construction of Cypress Viaduct
1961	First Stipulation for Seismic Effects in AASHO
1961	First Stipulation for Seismic Effect in California Department of Transportation

History of Seismic Design of Bridges in USA (continued)

1971	San Fernando Earthquake Damage of bridges during 11 earthquakes with magnitude of 5.4-7.7 between 1933 and 1971 was only $100,000
1973	New Caltrans Seismic Design (Incorporated into AASHTO in 1975)
1981	New FHWA Seismic Design Code
1989	Loma Prieta EQ
1994	Northridge EQ

History of Seismic Design of Bridges in Japan

1923 Kanto EQ

1925 First Design Code for Bridges including Seismic Effects

1964 Design Specifications (2 pages)
$kh=0.2$, $kv=0.1$

1971 First Independent Seismic Design Specifications (30 pages)
Unseating prevention devices, Evaluation for liquefaction potential

1980 Design Specifications (50 pages)
Updated Evaluation for Liquefaction

History of Seismic Design of Bridges in Japan (continued)

1990 Design Specifications (100 pages)

Check for Ductility, Lateral Force for Multi-span Bridges, Standard Ground Motions for Dynamic Analysis

1995 Kobe EQ

1996 Design Specifications (200 pages)

Ductility Design, Near-Field Ground Motions

2002 Design Specifications (240 pages)