Bridge Seismic Design, Retrofitting and Loss Assessment

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Richmond, VA March 9, 2012

Outline

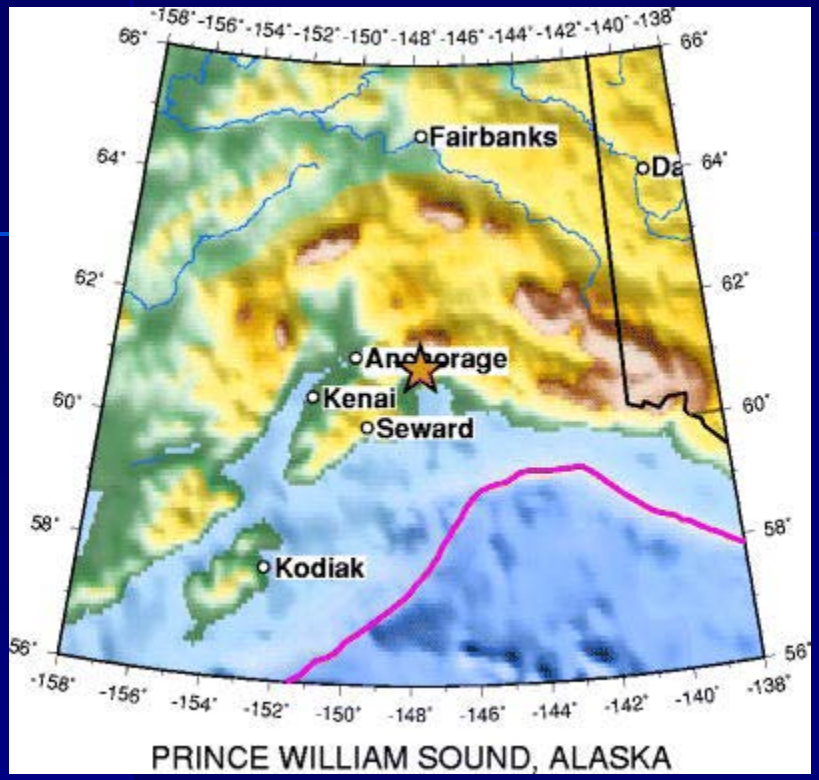
- Lessons Learned
- Seismic Design
- Seismic Retrofitting
- Risk Analysis / Loss Assessment
- Summary

The Bridges Lessons Learned from Devastated Large Earthquakes

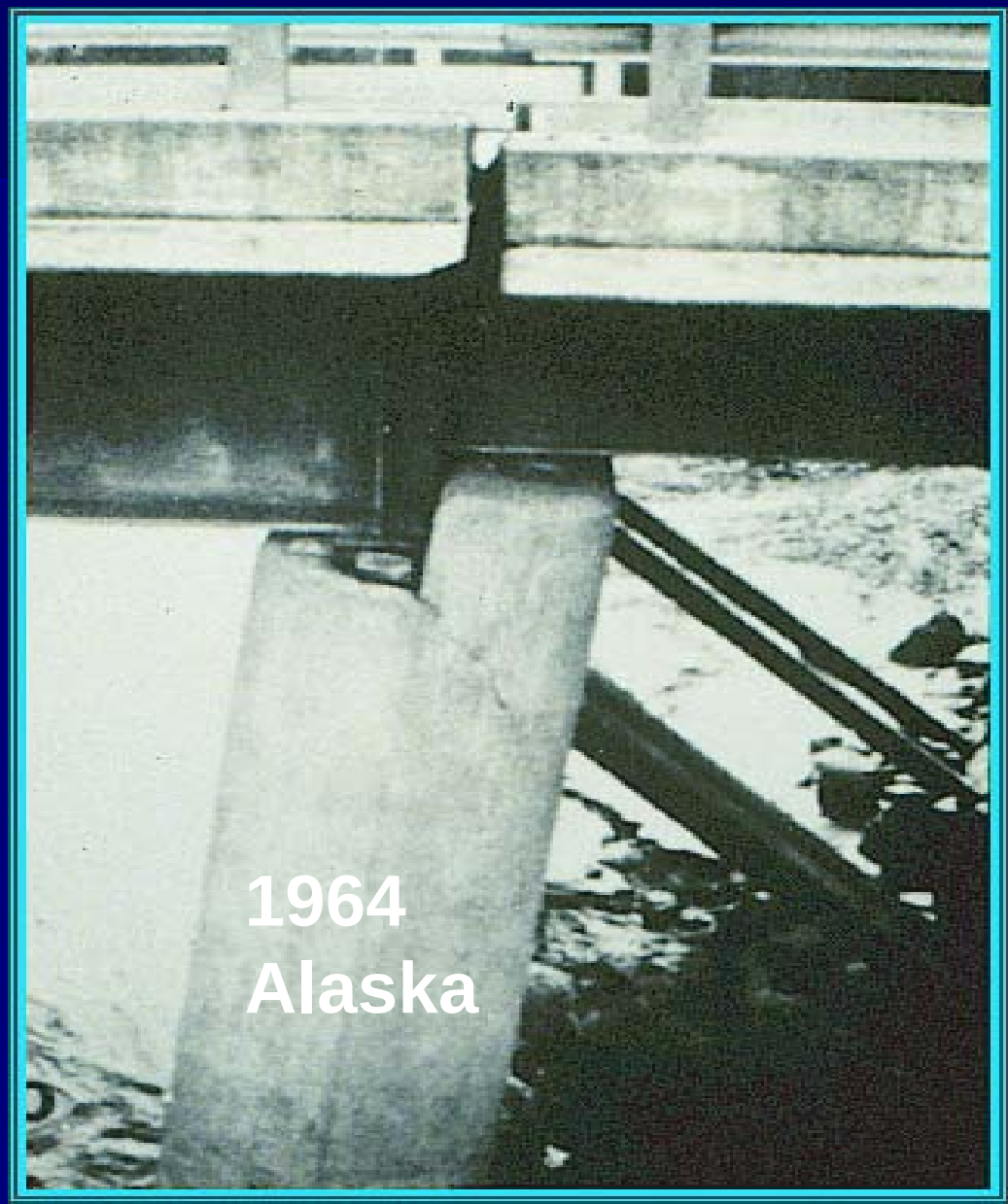
WHAT 47 YEARS DAMAGING EARTHQUAKES HAVE TAUGHT US

- 1964 Alaska (Prince William Sound), AK
- 1971 San Fernando, CA
- 1989 Loma Prieta, CA
- 1994 Northbridge, CA
- 1995 Kobe, Japan
- 1999 Kocaeli & Bolu,Turkey
- 1999 Chi-chi Taiwan
- 2001 Nishiqually, WA
- 2008 Wunchuan, China
- 2010 Maule Offshore, Chile
- 2011 Tohoku, Japan

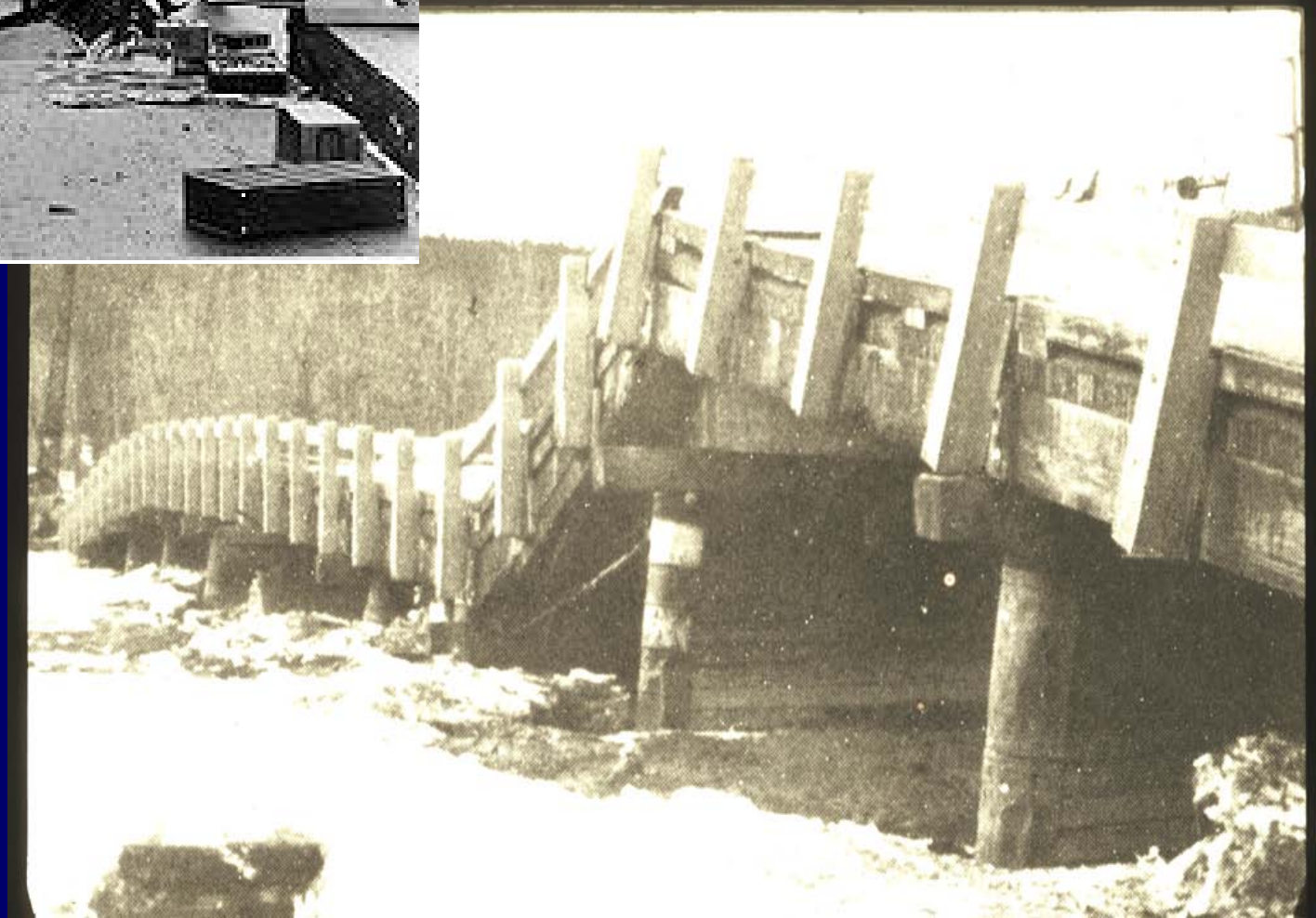
ALASKA



Earthquake parameters:
Prince William Sound, Alaska
1964 March 27 05:36 p.m. -- local time
Magnitude 9.2



ALASKA EQ. 13-15 M Vertical Displacement

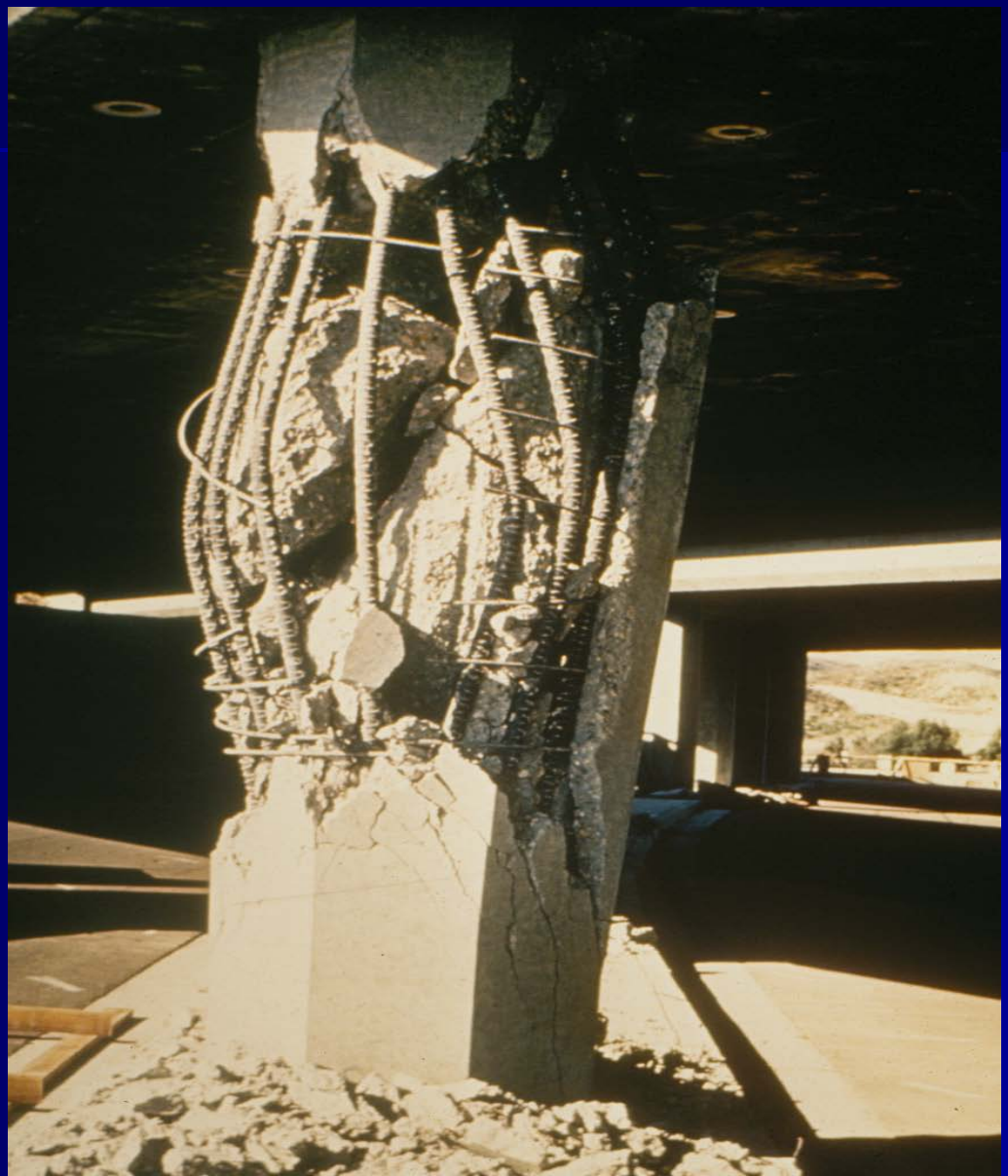


LESSONS LEARNED from 1964 ALASKA EARTHQUAKE

- Identify Liquefiable Soils
- Accommodate Relative Displacements

SAN FERNANDO, CA 1971

SAN FERNANDO



SAN FERNANDO

LESSONS LEARNED EARTHQUAKE DISASTERS 1971 SAN FERNANDO, CA

- Increase Seat Width
- Provide Continuity at Bearings and Joints
- Design Columns for Shear and Moment
- Develop Column to Footing/Cap Anchorage

LOMA PRIETA, 1989

LOMA PRIETA

LESSONS LEARNED EARTHQUAKE DISASTERS 1989 LOMA PRIETA

- Simple retrofit helps
- Evaluate Soil/Foundation Stability
- Account for Forces/Displacements
- Evaluate Existing Inventory

NORTHRIDGE,1994

Fault question -

- How many unknown faults that we still don’t know?

NORTHRIDGE

NORTHRIDGE

LESSONS LEARNED EARTHQUAKE DISASTERS 1994 NORTHRIDGE

- Complex Geometry Redistributes Forces
  - - Skew
  - - Varied Column Heights
- Accommodate Shear & Flexure
- Post ‘89 Designs Reduced Damage
- Retrofit Improves Resistance
- - Joint Restrainers
- - Column Jacketing
- Preparedness Facilitates Recovery

KOBE, Japan 1995

KOBE

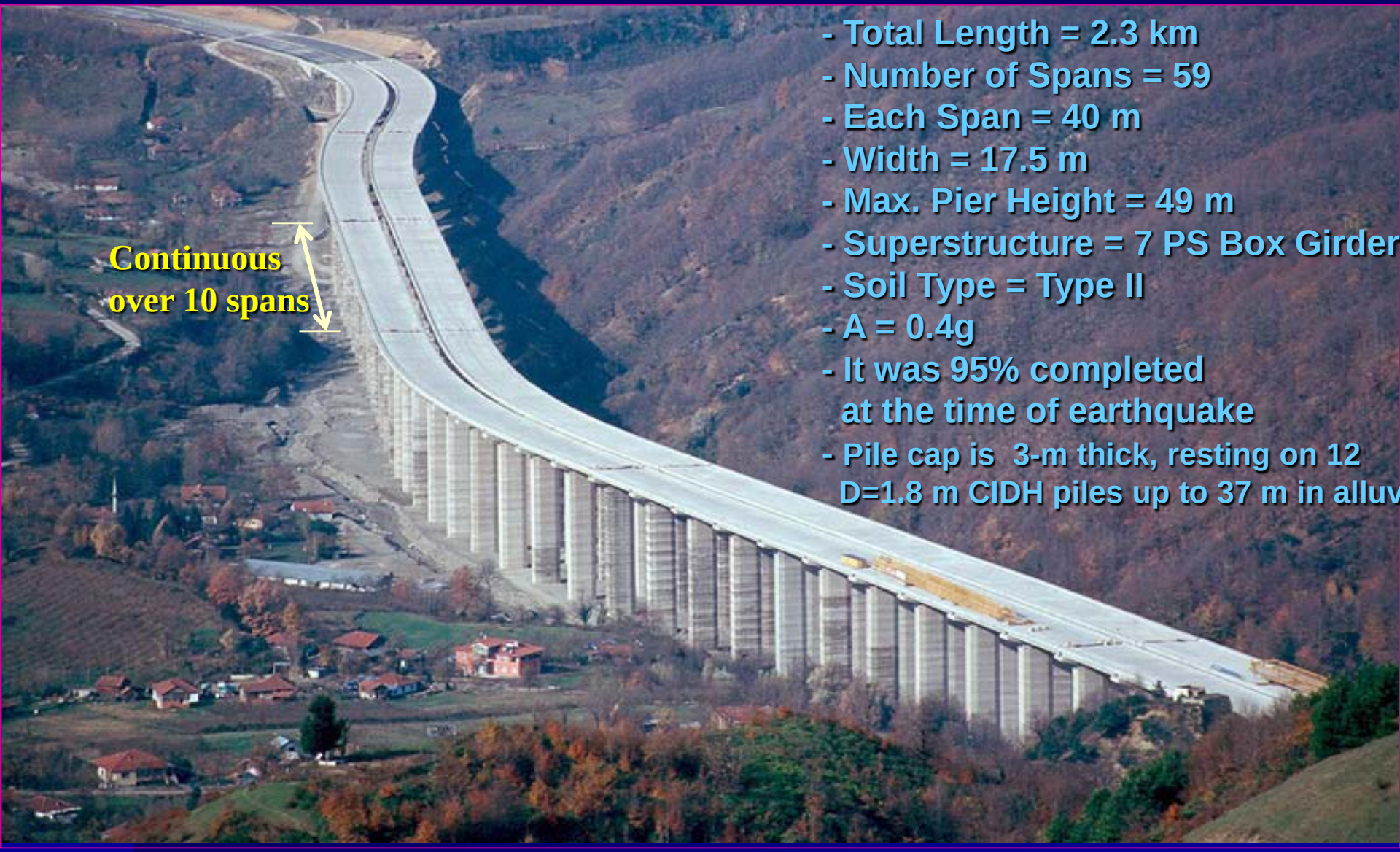
LESSONS LEARNED EARTHQUAKE DISASTERS 1995 HANSHIN AWAJI (KOBE)

- **Consider Structural Filters / Fuses**
  - **Isolation**
  - **Energy Dissipation**
  - **Displacement Control**

The 1999 Turkish Earthquakes: **Post-Earthquake Investigation**

Epicenters and PGAs

General View of the Viaduct # 1

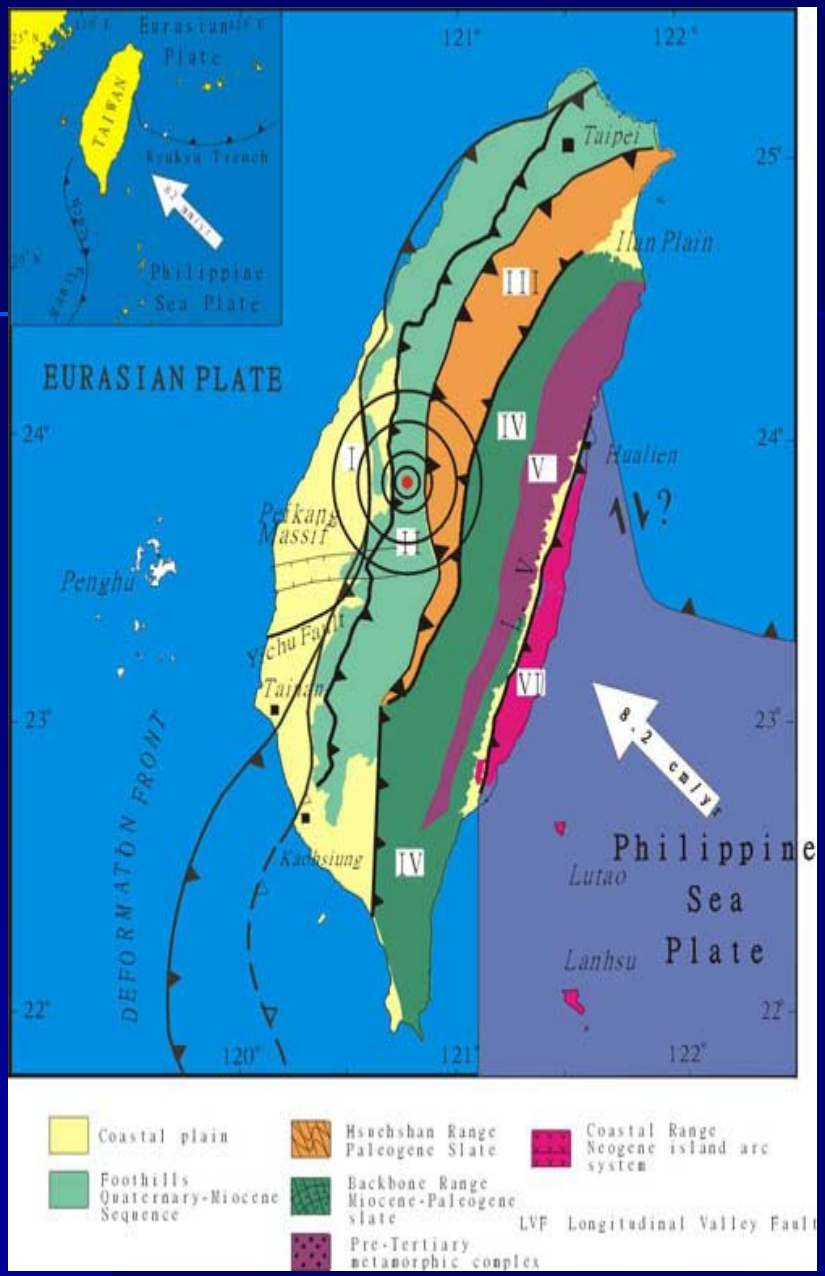


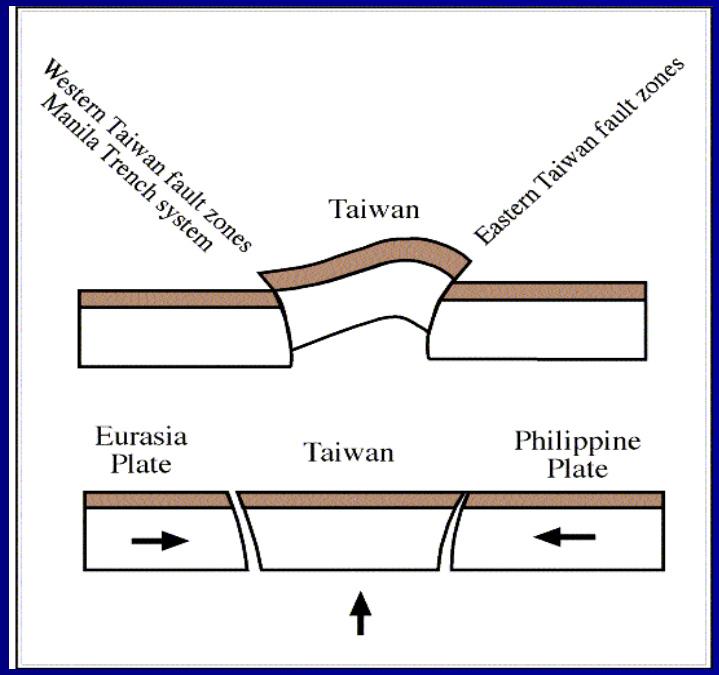
- Total Length = 2.3 km
- Number of Spans = 59
- Each Span = 40 m
- Width = 17.5 m
- Max. Pier Height = 49 m
- Superstructure = 7 PS Box Girder
- Soil Type = Type II
- A = 0.4g
- It was 95% completed at the time of earthquake
- Pile cap is 3-m thick, resting on 12 D=1.8 m CIDH piles up to 37 m in alluv

Excessive Movement in Longitudinal Direction

EDU Failure

Chi-Chi Earthquake, Taiwan, 9/21, 1999
Local Magnitude = 7.3





Reverse Fault

I-Jiang Bridge

Failure of shear-critical columns in Tong-tou bridge, Chi-chi Earthquake, Taiwan, September 1999

Wunchuan Earthquake 2008

USGS science for a changing world

GSN USAID FROM THE AMERICAN PEOPLE

M 7.9, EASTERN SICHUAN, CHINA

Origin Time: Mon 2008-05-12 06:28:01 UTC
Location: 31.02°N 103.37°E Depth: 19 km

PAGER Version 8
Created: 1 days, 8 hrs after earthquake

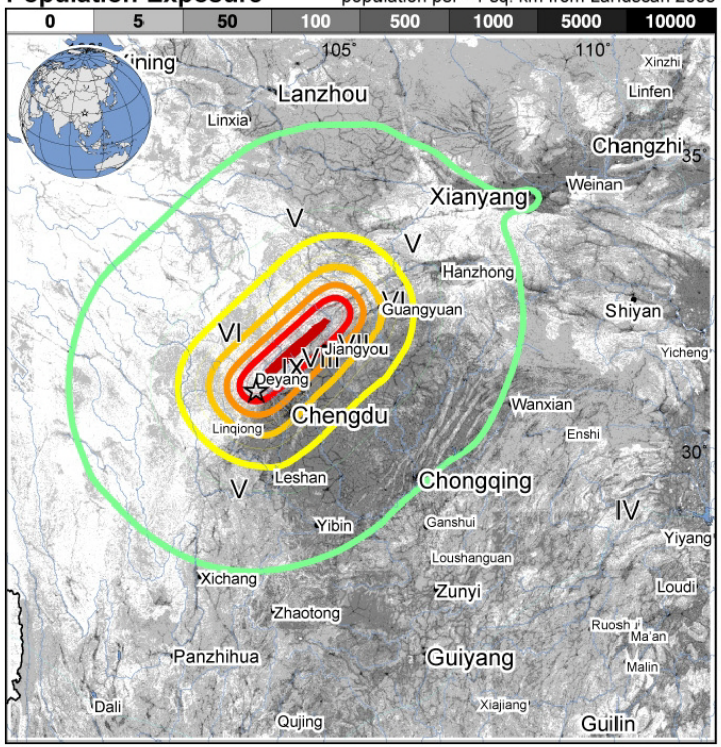
Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	- -*	188,523k*	89,143k	15,400k	12,673k	3,897k	707k	610k
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan 2005



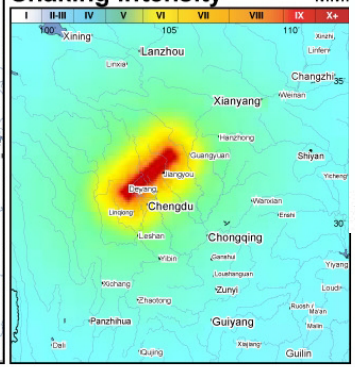
Selected City Exposure

MMI	City	Population
VIII	**Jiangyou**	**127k**
VIII	Tianpeng	60k
VII	**Deyang**	**152k**
VII	**Linqiong**	**55k**
VII	**Chengdu**	**3,950k**
VII	Mianyang	264k
VII	**Guangyuan**	**213k**
V	Nanchong	7,150k
V	**Chongqing**	**3,967k**
V	**Lanzhou**	**3,200k**
IV	Shiyan	3,460k

bold cities appear on map (k = x1000)

Shaking Intensity

MMI



Overall, structures in this region are vulnerable to earthquake shaking, though some resistant structures exist. A magnitude 6.4 earthquake struck the Sichuan, China region on August 23, 1976 (UTC), with estimated population exposures of 1,500 at intensity IX or greater and 5,700 at intensity VIII, resulting in 41 deaths. Additionally, a magnitude 7.3 struck this region in 1933 killing 6,800 people. Recent earthquakes in this area have also triggered landslide hazards that have contributed to losses. Users should consider the preliminary nature of this information and check for updates as additional data becomes available.

This information was automatically generated and has not been reviewed by a seismologist.

http://earthquake.usgs.gov/pager

Event ID: us2008ryan

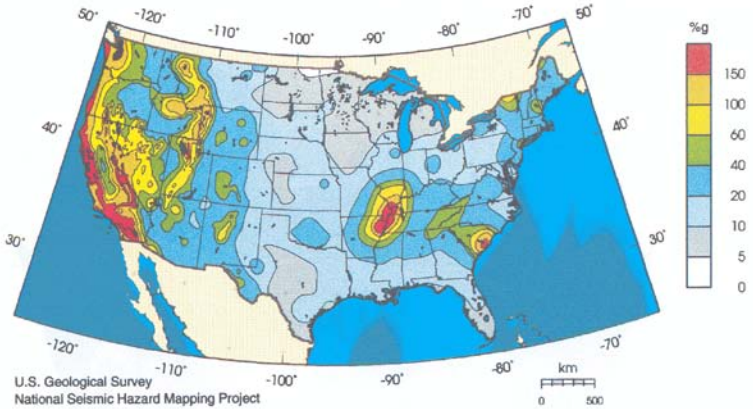
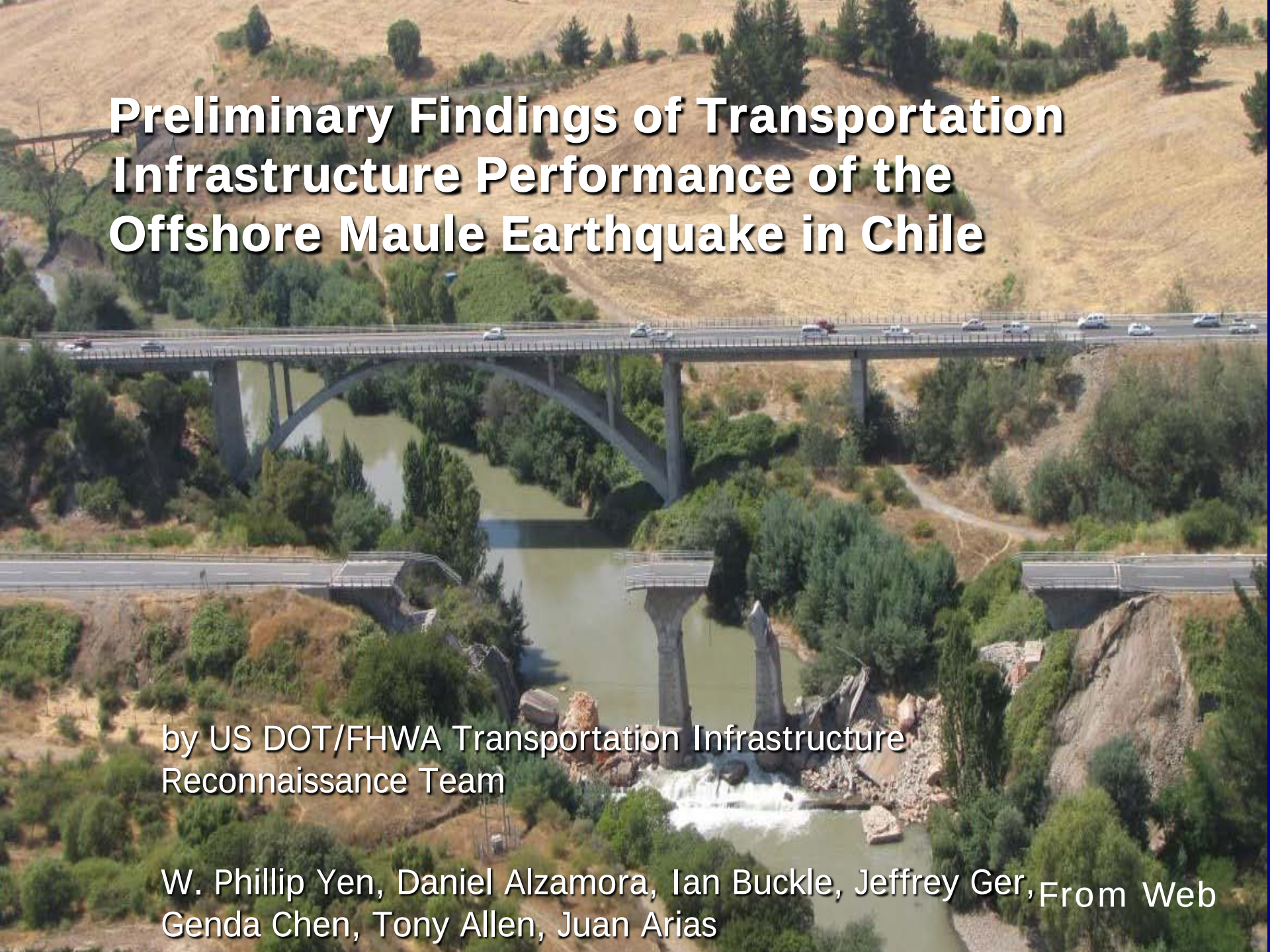


Figure 9a. MCE ground motion map of the 48 conterminous states for the 0.2 sec horizontal spectral response acceleration (%g), 5% of critical damping. Site Class B.

Wunchuan Earthquake, China on May 12, 2008

1. Constructed in 2004
2. 18 spans and L=450m
3. Piers, bearings and tie beams failures
4. 5 spans totally collapsed
5. Demolished after the earthquake



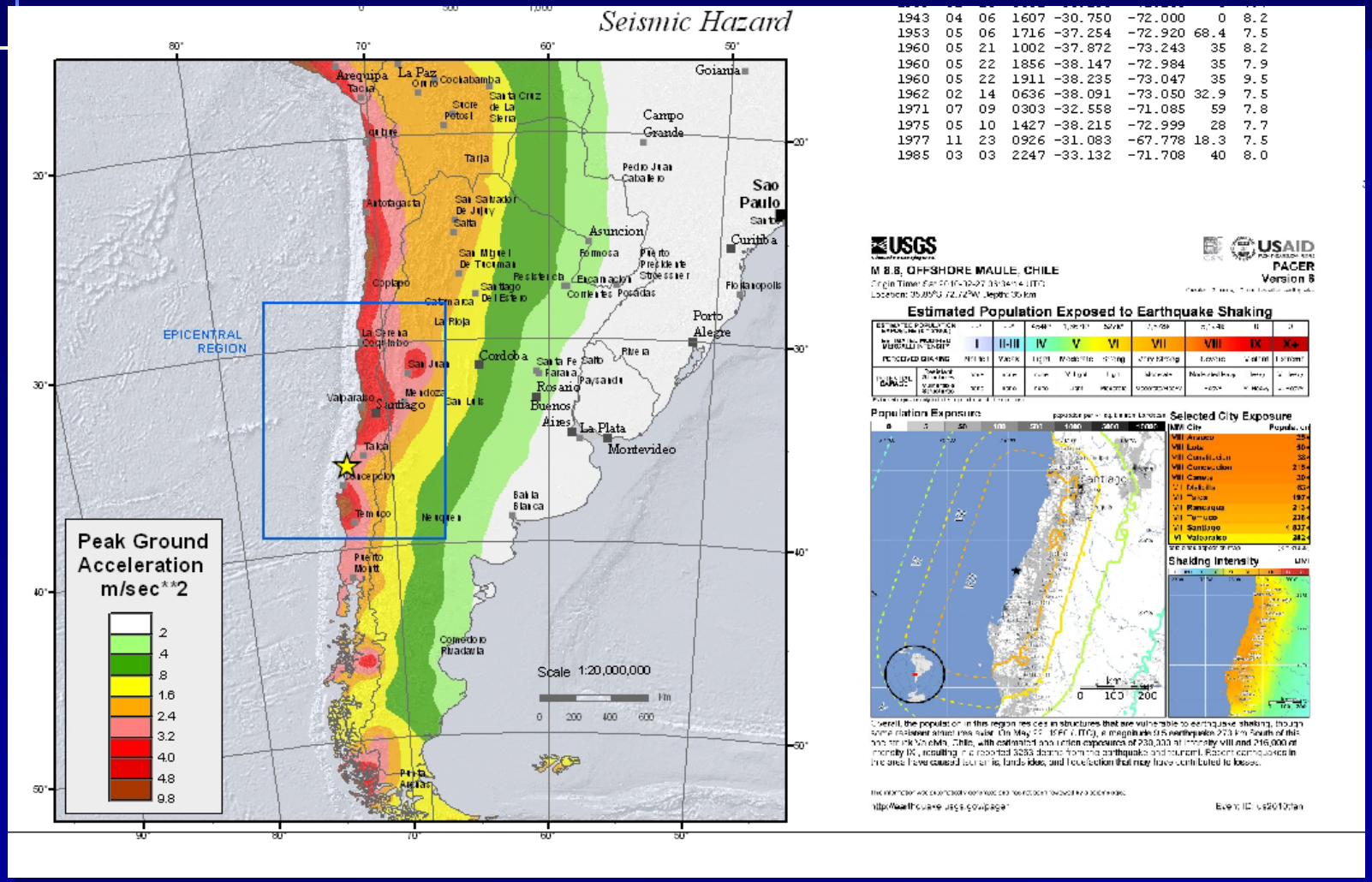
Preliminary Findings of Transportation Infrastructure Performance of the Offshore Maule Earthquake in Chile

by US DOT/FHWA Transportation Infrastructure Reconnaissance Team

W. Phillip Yen, Daniel Alzamora, Ian Buckle, Jeffrey Ger, Genda Chen, Tony Allen, Juan Arias

From Web

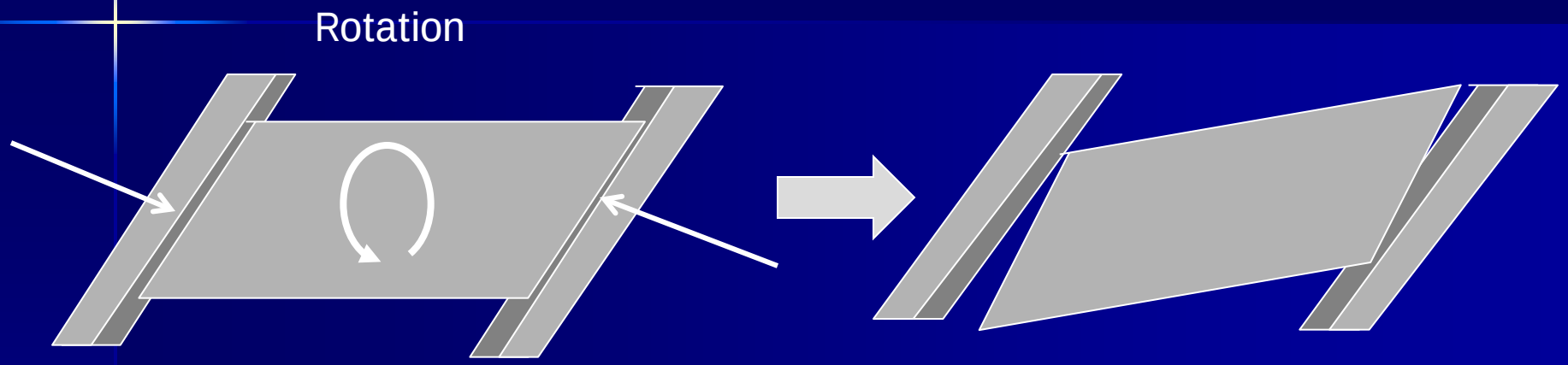
USGS Data


Seismic Hazard
EPICENTRAL REGION
Peak Ground Acceleration m/sec**2
.2
.4
.8
1.6
2.4
3.2
4.0
4.8
9.8
Scale 1:20,000,000
Arequipa
La Paz
Cochabamba
Santa Cruz de La Sierra
Goiania
Campo Grande
Tarija
Pedro Juan Caballero
Sao Paulo
Curitiba
Florianopolis
Asuncion
Formosa
Puerto Presidente Stroessner
Encarnacion
Corrientes
Posadas
Resistencia
Santiago Del Estero
San Miguel De Tucuman
San Salvador De Jujuy
Antofagasta
Copiapo
Catamarca
La Rioja
La Serena
Coquimbo
San Juan
Mendoza
Valparaiso
Santiago
San Luis
Cordoba
Santa Fe
Parana
Rosario
Paysandu
Buenos Aires
La Plata
Montevideo
Porto Alegre
Pelotas
Santa Rosa
Talca
Concepcion
Temuco
Neuquen
Bahia Blanca
Puerto Montt
Comodoro Rivadavia
Punta Arenas
1943 04 06 1607 -30.750 -72.000 0 8.2
1953 05 06 1716 -37.254 -72.920 68.4 7.5
1960 05 21 1002 -37.872 -73.243 35 8.2
1960 05 22 1856 -38.147 -72.984 35 7.9
1960 05 22 1911 -38.235 -73.047 35 9.5
1962 02 14 0636 -38.091 -73.050 32.9 7.5
1971 07 09 0303 -32.558 -71.085 59 7.8
1975 05 10 1427 -38.215 -72.999 28 7.7
1977 11 23 0926 -31.083 -67.778 18.3 7.5
1985 03 03 2247 -33.132 -71.708 40 8.0
USGS
USAID
M 8.8, OFFSHORE MAULE, CHILE
PAGER
Version 6
Estimated Population Exposed to Earthquake Shaking
Population Exposure
Selected City Exposure
Shaking Intensity

Skewed Vs Straight Bridges

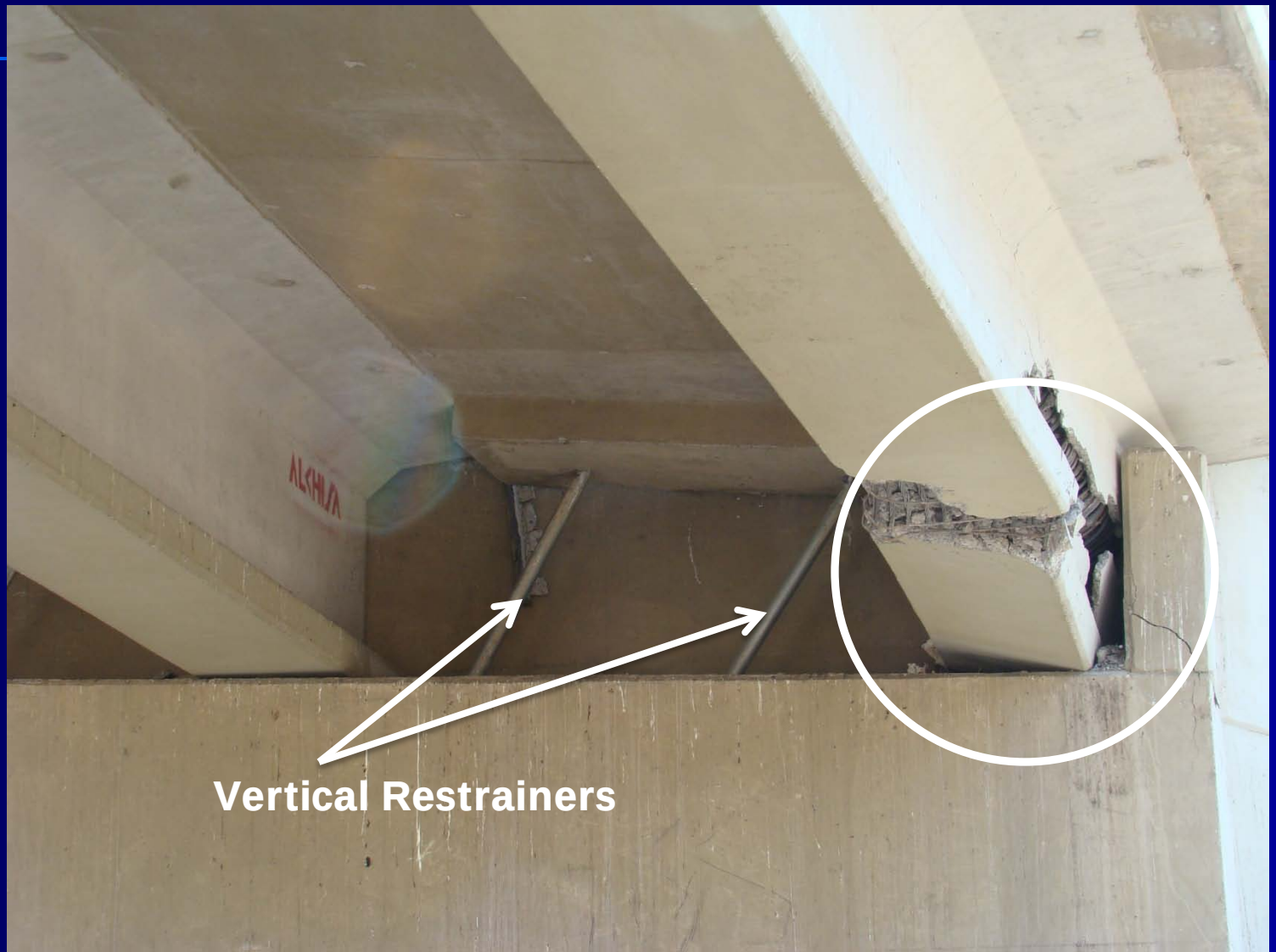
Two overpass bridges across a railway: one is skewed and the other is straight

Skewed Bridges



Performance w/ and w/o Concrete Diaphragm

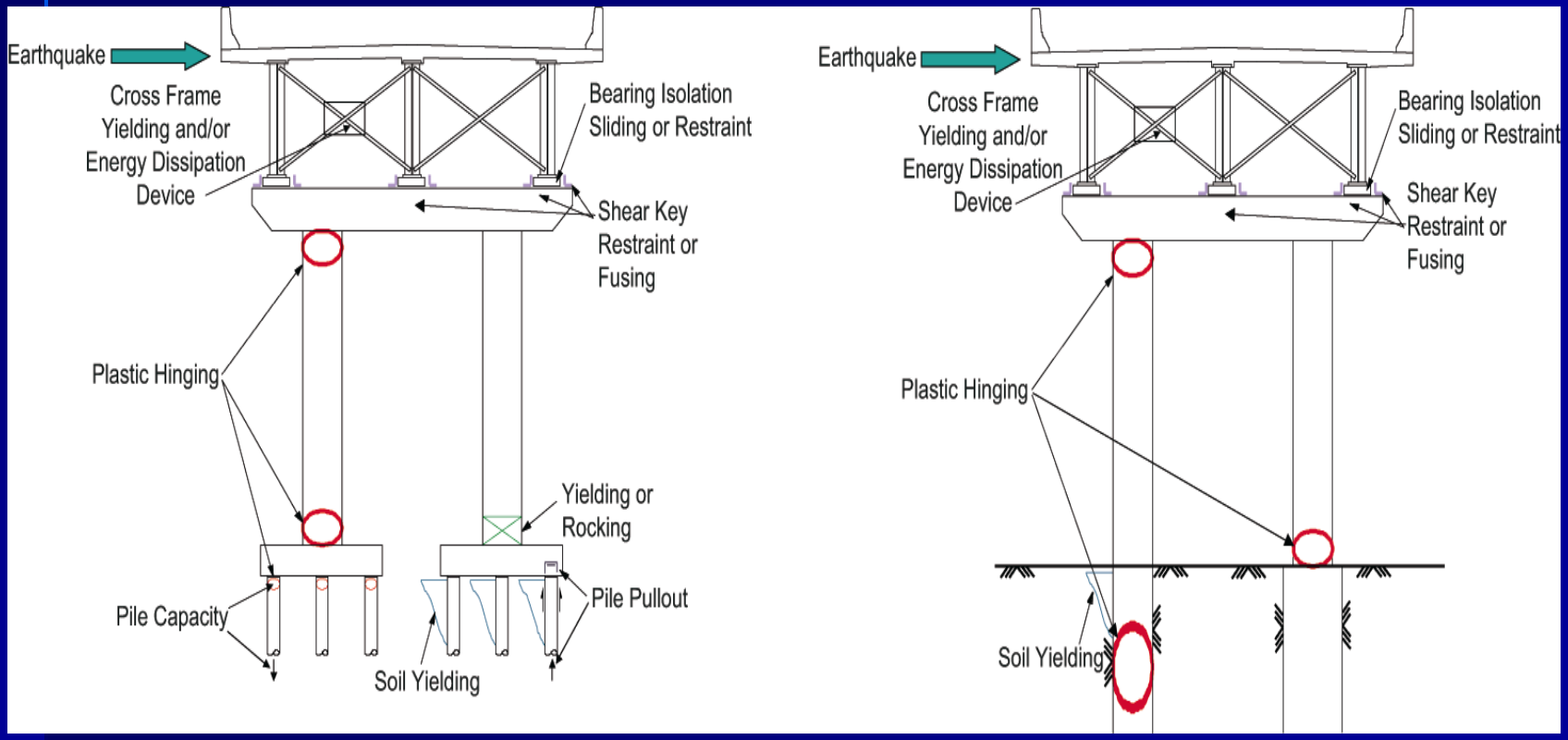
Girder Damaged



Performance Criteria -
Bridge Seismic Design Strategy

- **Type 1 -** Design a ductile substructure with an essentially elastic superstructure.
- **Type 2 -** Design an essentially elastic sub-structure with a ductile superstructure.
- **Type 3 -** Design an elastic superstructure and substructure with a fusing mechanism at the interface between the superstructure and the substructure.

Seismic Load Path and Affected Components



Steel Superstructure Design Option – Type 2

March 11, 2011
M 9.0 Tohoku Earthquake, Japan

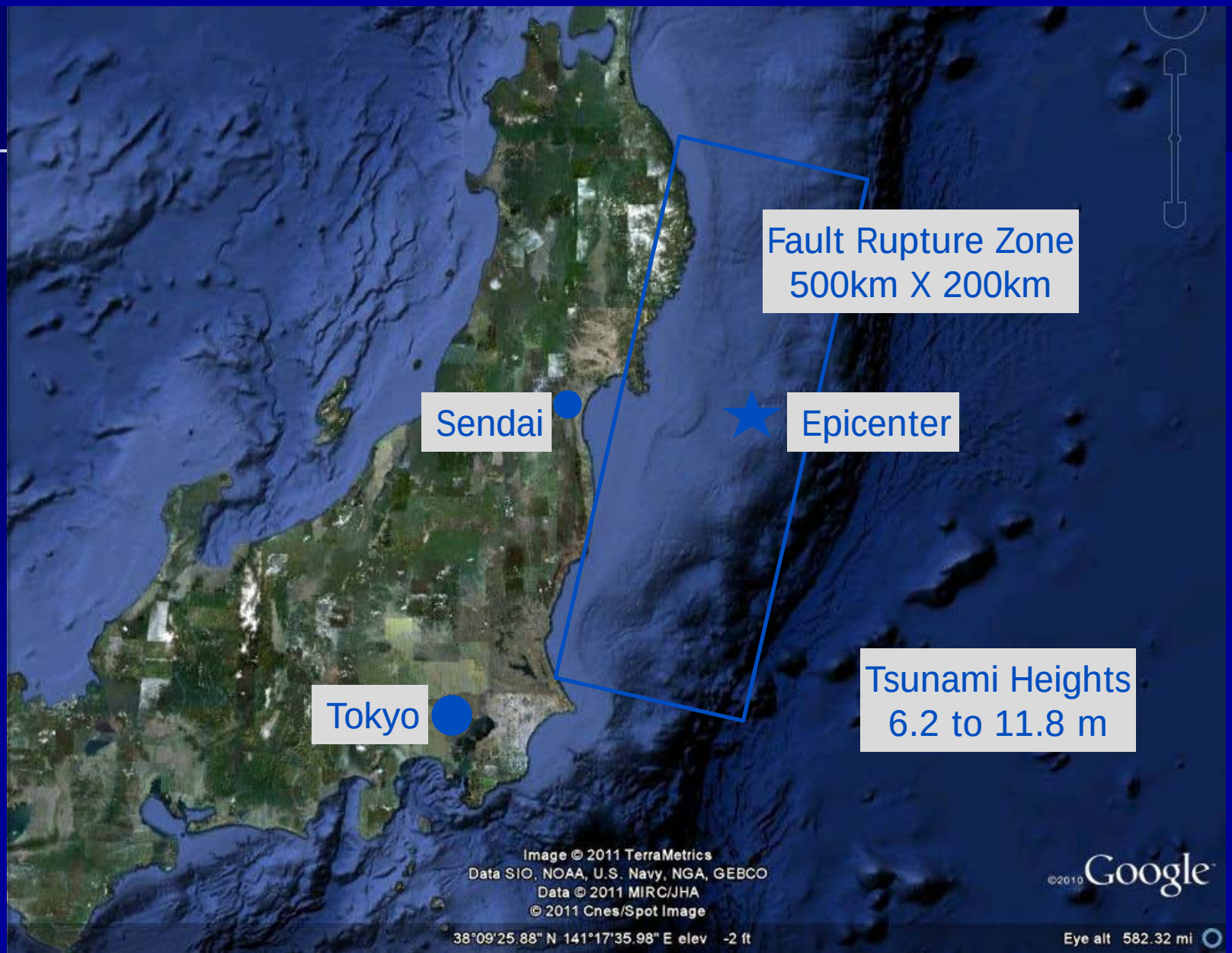
Bridge Damage Reconnaissance

June 2 – 6, 2011

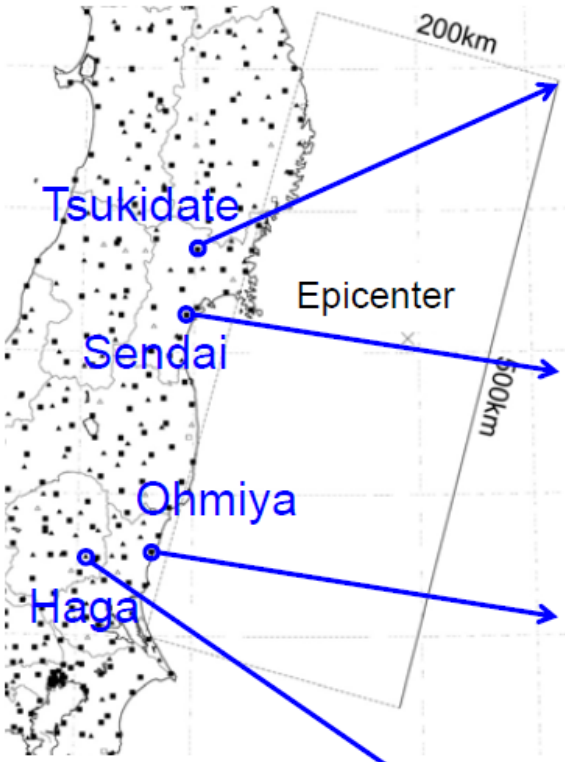
US - Federal Highway Administration
Bridge Reconnaissance Team

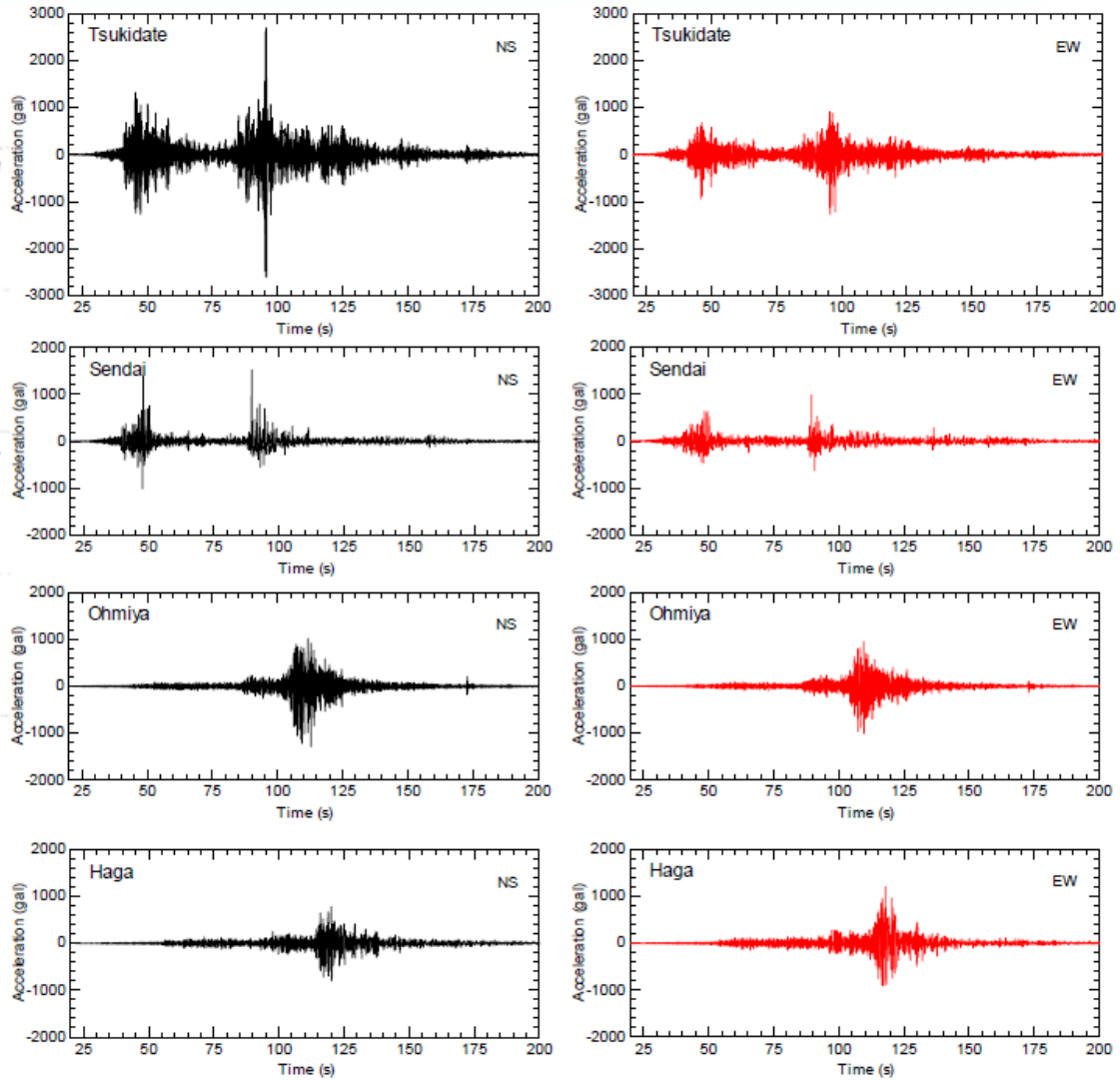
Hosted by Japan's Public Works Research Institute

March 11, 2011 Magnitude 9.0 Tohoku Subduction Earthquake



Strong Motion Acceleration Records

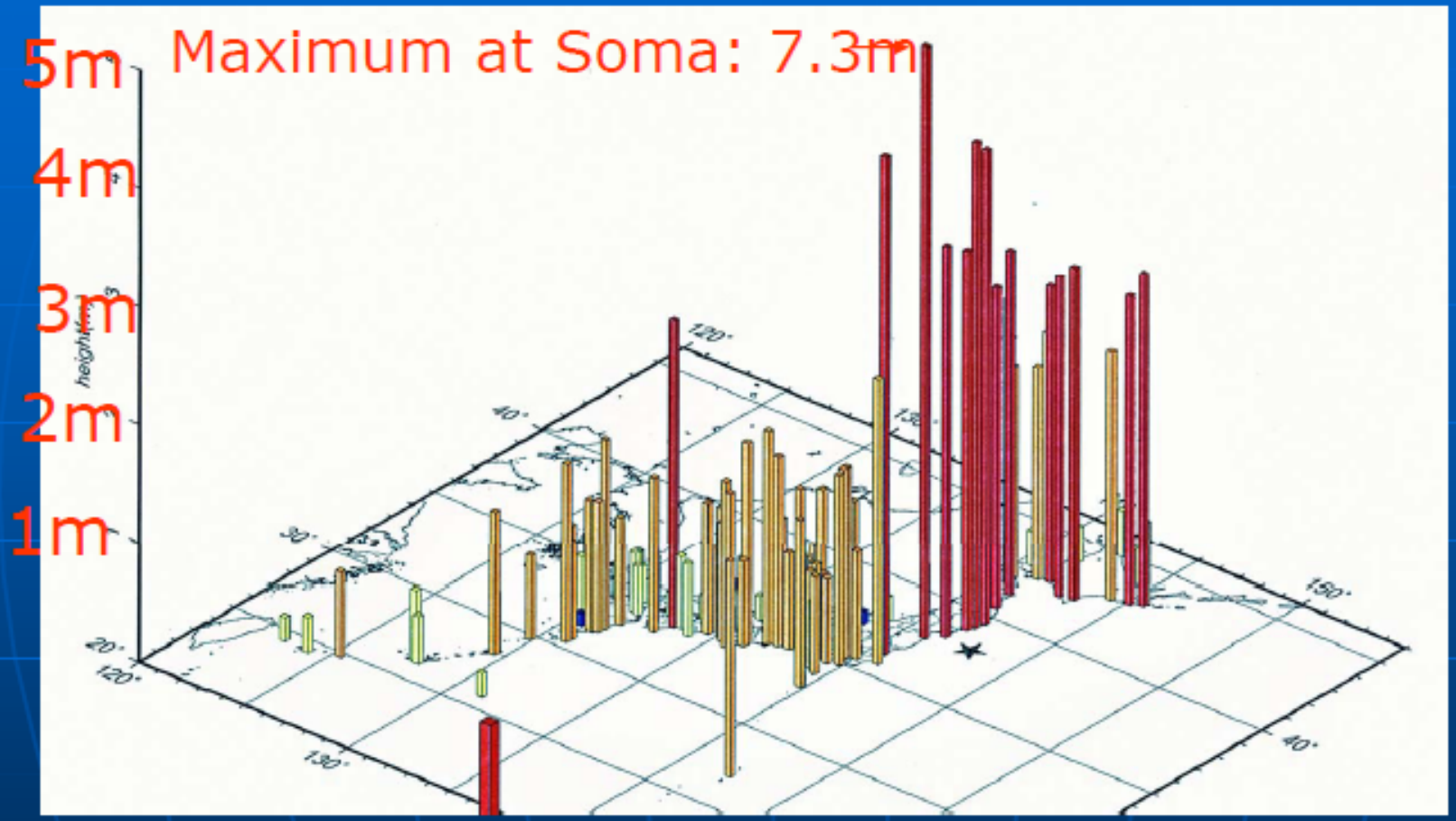




Source: National Research Institute for Earth Science and Disaster Prevention

Graphics Courtesy of PWRI Center for Advanced Engineering Structural Assessment and Research

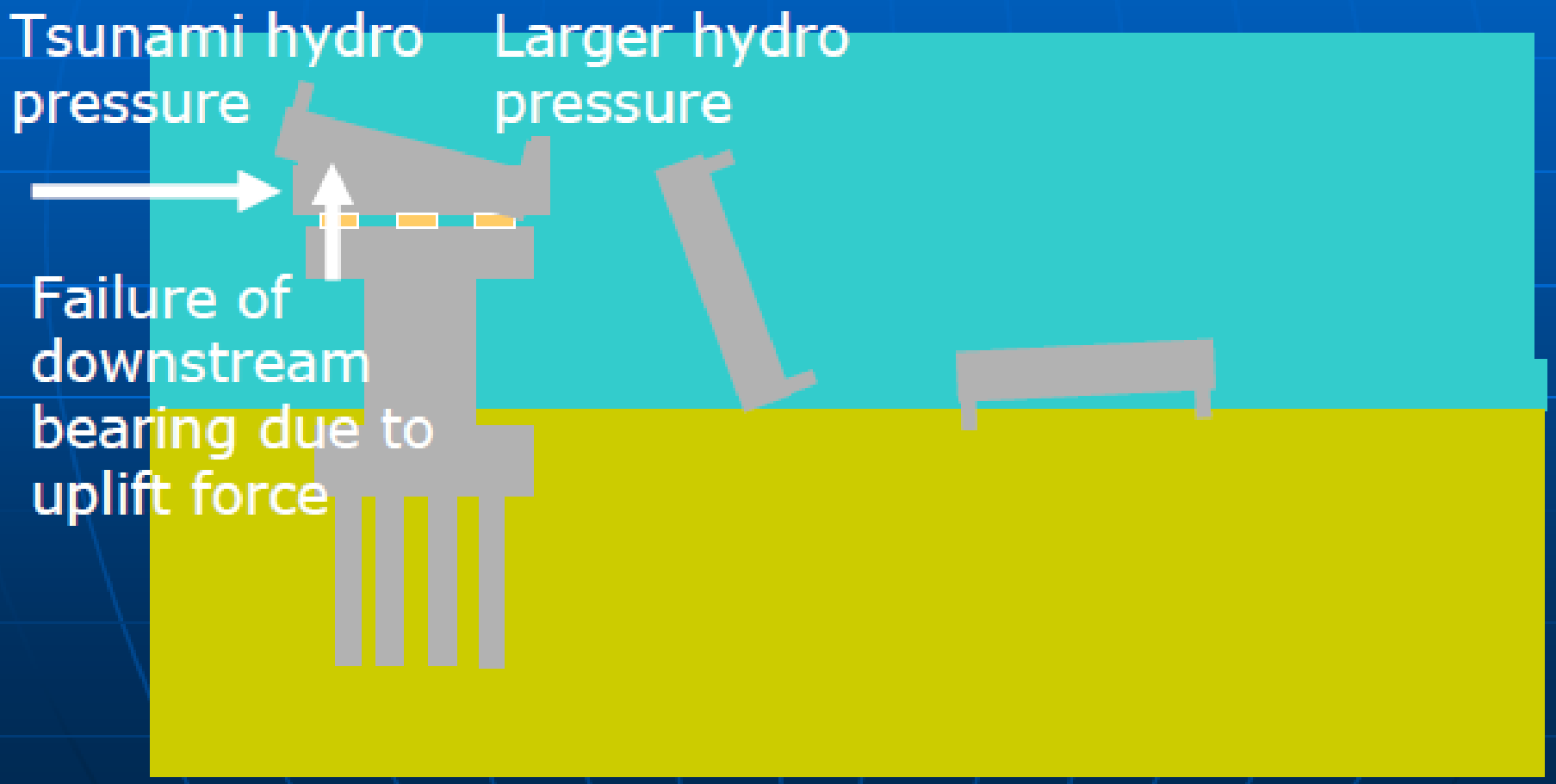
Tsunami Height measured by JMA



- Local tsunami height is being investigated. It is reported that tsunami run up 23 m at a site in Ofunato City.

Utatsu O-hashi Piers 3 to 10

Most Probable Failure Mechanism of Bridges due to Tsunami



LESSONS LEARNED EARTHQUAKE DISASTERS

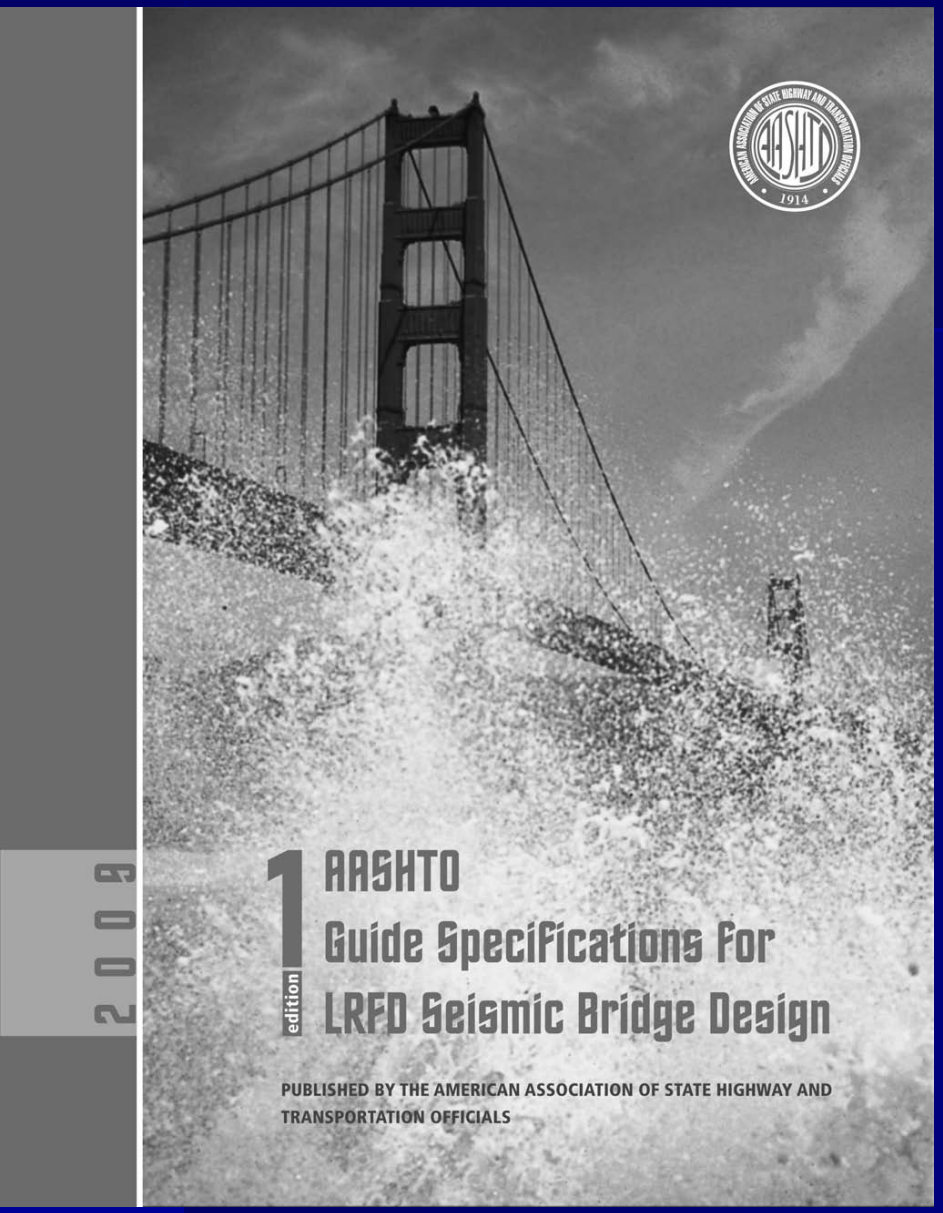
- Accommodate Forces & Displacements
- Evaluate Ground Motion Amplification/Attenuation & Long Duration
- Consider “Near Field” Effects
- Skew/ Curved Bridges
- Vertical Acceleration Component
- Identify Liquefaction Potential
- Retrofit Improves Performance
- Newer Designs Improve Seismic Resistance
- Preparedness Facilitates Recovery
- Nothing is “Earthquake Proof”

- Newer Designs Improve Performance
- Retrofit Helps…but……..
- US Seismicity is not well understood
- Cannot Reduce Natural Hazards
  - Natural Hazards Can Damage Transportation Infrastructure System Entirely Even Within Seconds
- Can Reduce the Loss if We Are WELL Prepared
  - Past Performance Experience
  - Advanced Research Experiments
  - IMPLEMENTATION the Preparations

Mitigation Seismic Hazard through Designing

- **Pre-San Fernando (1971)**
  - **0.06g Static Coefficient**
  - **No Consideration For**
    - » **Spectral Response**
    - » **Foundation Material**
    - » **Structural Ductility**

- **Today**
  - **Seismic Performance Criteria Identified**



ABBREVIATED TABLE OF CONTENTS

- SECTION 1: INTRODUCTION
- SECTION 2: DEFINITIONS AN D NOTATION
- SECTION 3: GENERAL REQUIREMENTS
- SECTION 4: ANALYSIS AND DESIGN REQUIREMENTS
- SECTION 5: ANALYTICAL MODELS AND PROCEDURES
- SECTION 6: FOUNDATION AND ABUTMENT DESIGN
- SECTION 7: STRUCTURAL STEEL COMPONENTS
- SECTION 8: REINFORCED CONCRETE COMPONENTS
- APPENDIX A: FOUNDATION-ROCKING ANALYSIS

PERFORMANCE CRITERIA

- Bridges shall be designed for the life safety performance objective considering a seismic hazard corresponding to a 7% probability of exceedance in 75 years. i.e. – 1000 Yr. for “Normal Bridges”.
- Higher levels of performance, such as the operational objective, may be established and authorized by of the bridge owner.

Life safety

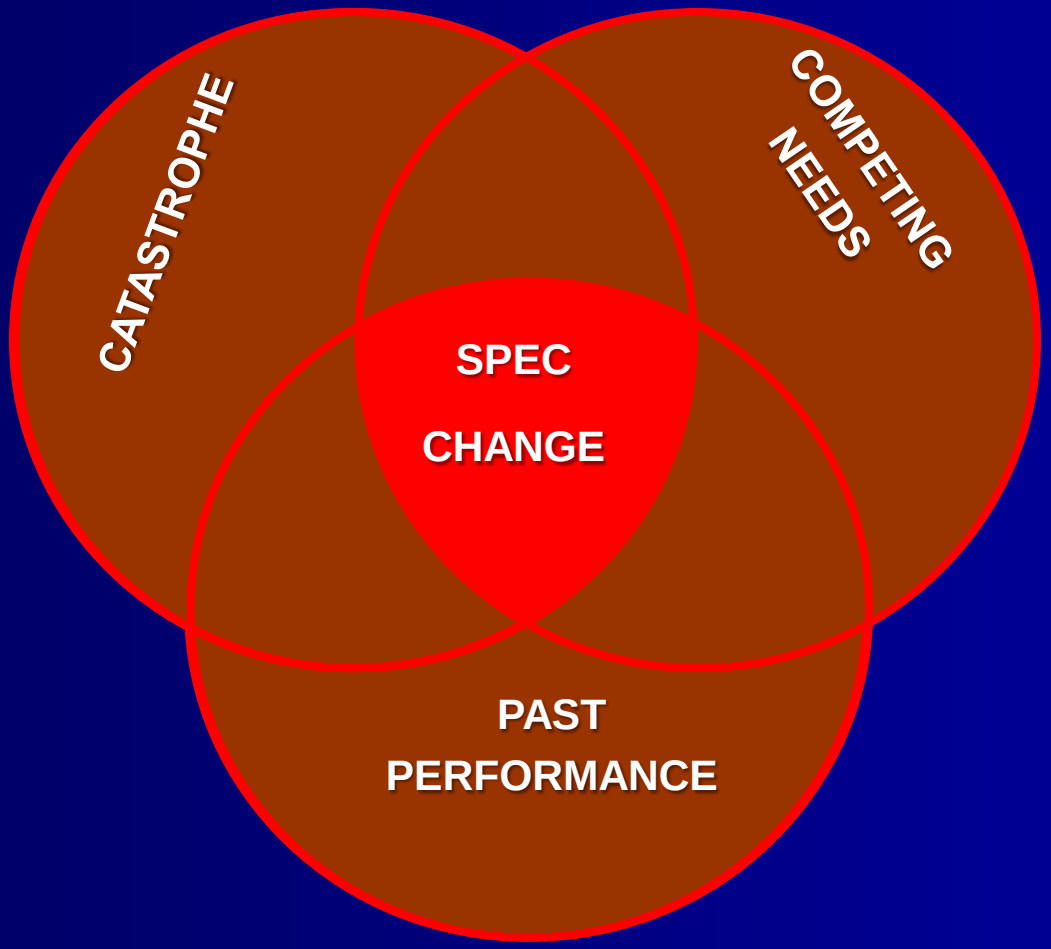
- **Low probability of collapse but, may suffer significant damage and significant disruption to service is possible.**
  - cracking,
  - reinforcement yielding,
  - major spalling of concrete
  - extensive yielding and local buckling of steel columns,
  - global and local buckling of steel braces, and
  - cracking in the bridge deck slab at shear studs.

SEISMIC DESIGN CATEGORY (SDC)

- Partitions for Seismic Design Categories A, B, C & D

Value of $SD_1 = F_V S_1$	SDC
$SD_1 < 0.15$	A
$0.15 \leq SD_1 < 0.30$	B
$0.30 \leq SD_1 < 0.50$	C
$0.50 \leq SD_1$	D

IMPLEMENTING SPECIFICATION CHANGE



No Detailed Analysis Required

- Bridges Located in SDC – A
  - Minimum horizontal connection force >0.25 W_g
- Single Span Bridges –
  - Minimum support length
  - Liquefaction – Geotech. Analysis by Owner

EARTHQUAKE RESISTING SYSTEMS (ERS)

- REQUIREMENTS FOR SDC C & D

- ERS and ERE
  - Permissible,
  - Permissible with Owner's Approval, and
  - Not Recommended for New Bridges.

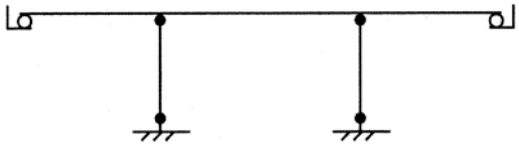
EARTHQUAKE RESISTING SYSTEMS (ERS)

- REQUIREMENTS FOR SDC C & D

- ERS and ERE
  - Permissible,
  - Permissible with Owner's Approval, and
  - Not Recommended for New Bridges.

Permissible ERS

Longitudinal

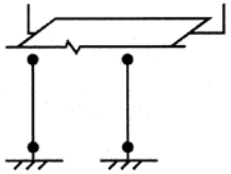


Abutment resistance not required as part of ERS

Plastic hinges in inspectable locations or elastic design of columns.

Knock-off backwalls permissible

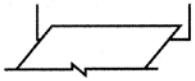
Transverse



Abutment not required in ERS, breakaway shear keys permissible

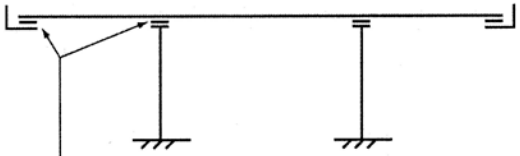
Plastic hinges in inspectable locations or elastic design of columns.

Transverse or Longitudinal



Abutment resistance required, but abutment able to resist 3% in 75-year earthquake elastically and passive soil pressure in longitudinal directiion is less than 0.70 x presumptive value given in 7.5.2

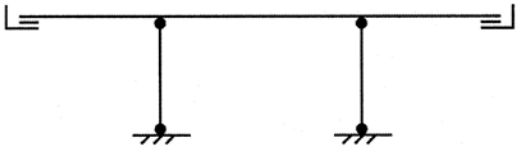
Longitudinal



Abutment not required as part of ERS

Isolation bearings accomodate full displacement

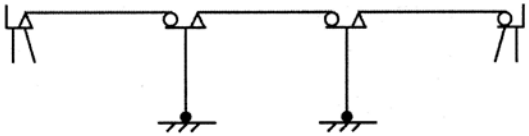
Longitudinal and Transverse



Isolation bearings with significant energy dissipation capacity or energy dissipators are used at the abutment to limit overall displacements.

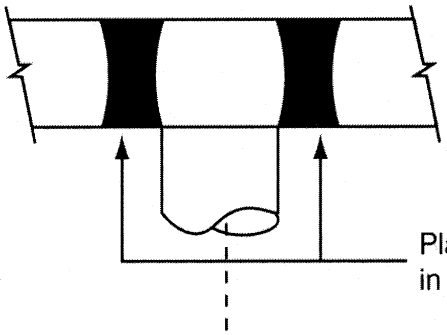
Plastic hinges in inspectable locations or elastic design of columns.

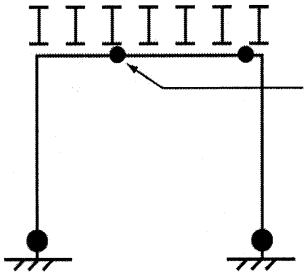
Longitudinal

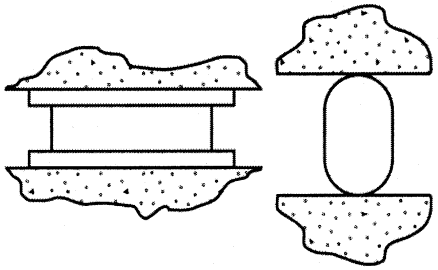


Multiple simply-supported spans with adequate seat widths. Plastic hinges in inspectable locations or elastic design of columns.

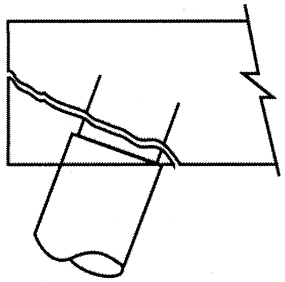
Not Permissible ERE







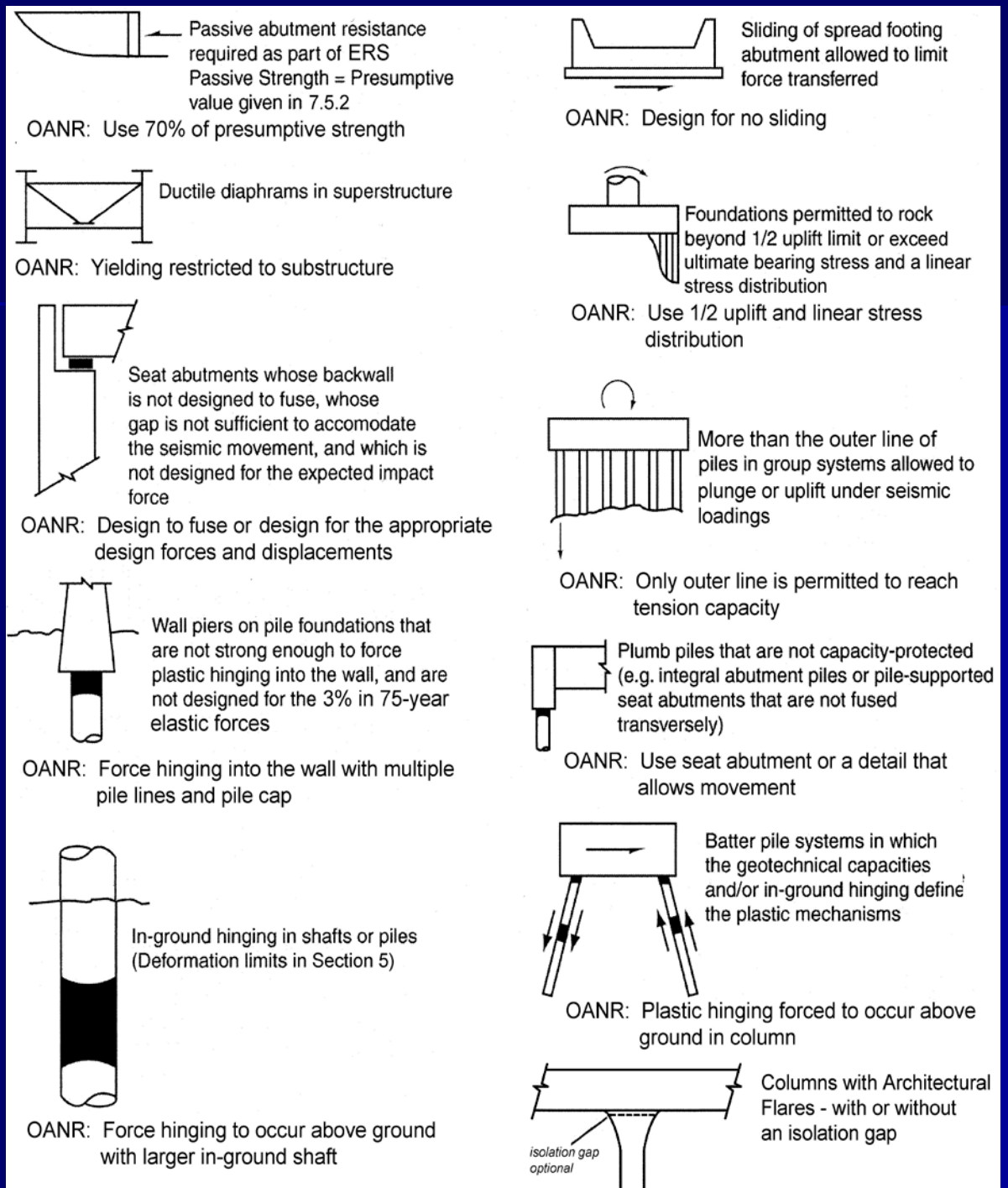
Bearing systems that do not provide for the expected displacements and/or forces (e.g. rocker bearings)



Battered-pile systems that are not designed to fuse geotechnically or structurally by elements with adequate ductility capacity

Permissible ERE –

Require Owner's Approval



Maps

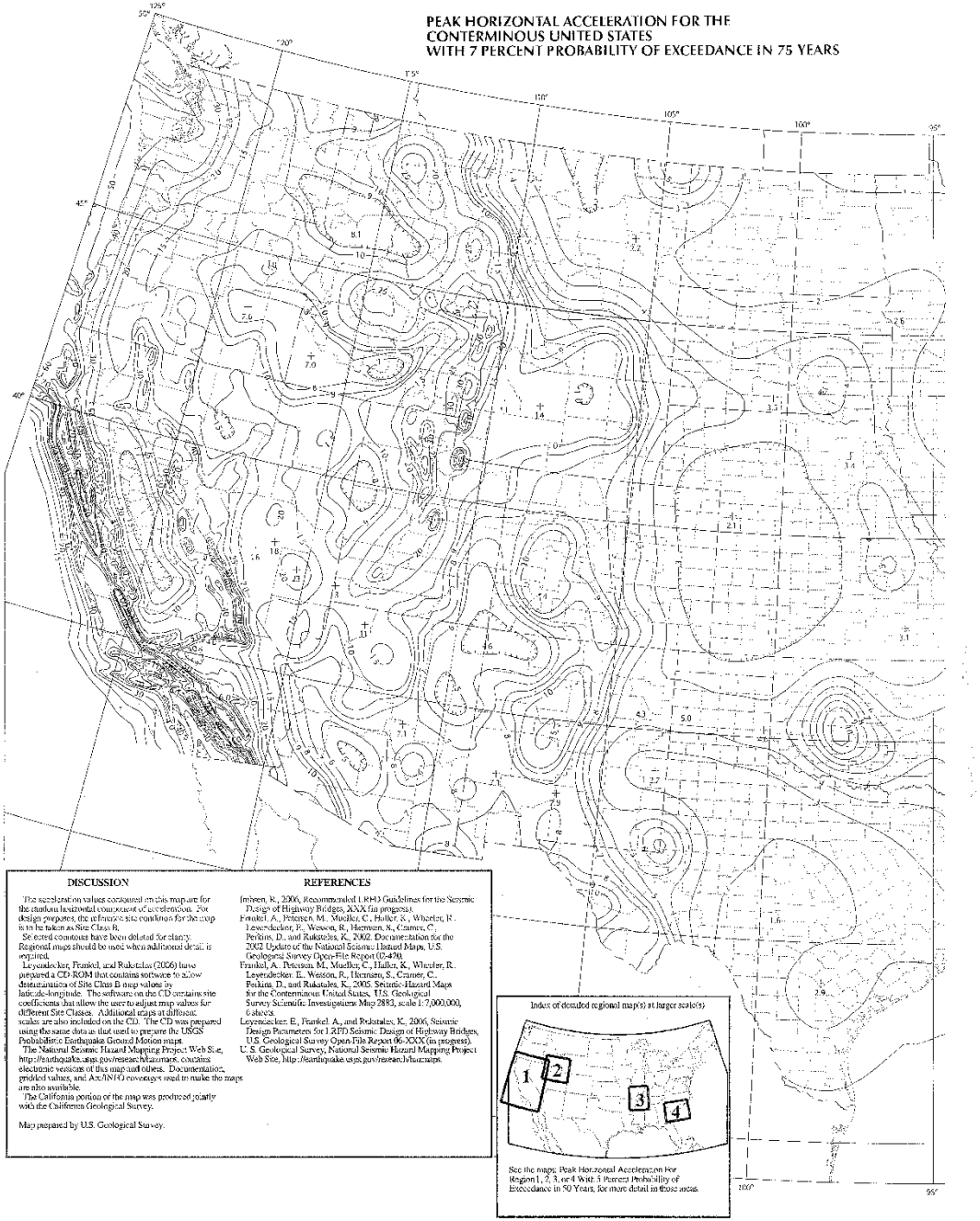
- The maps package included a series of maps that provide:
  - the peak horizontal ground acceleration coefficient, *PGA*
  - a short period (0.2 sec) value of spectral acceleration coefficient, *Ss*
  - a longer period (1.0 sec) value of spectral acceleration coefficient, *S1*

Maps

- Maps of the conterminous 48 states were based on USGS data used to prepare maps for a **2002 update**.
  - Alaska was based on USGS data used to prepare a map for a 2006 update.
  - Hawaii was based on USGS data used to prepare 1998 maps.
  - Puerto Rico was based on USGS data used to prepare 2003 maps.

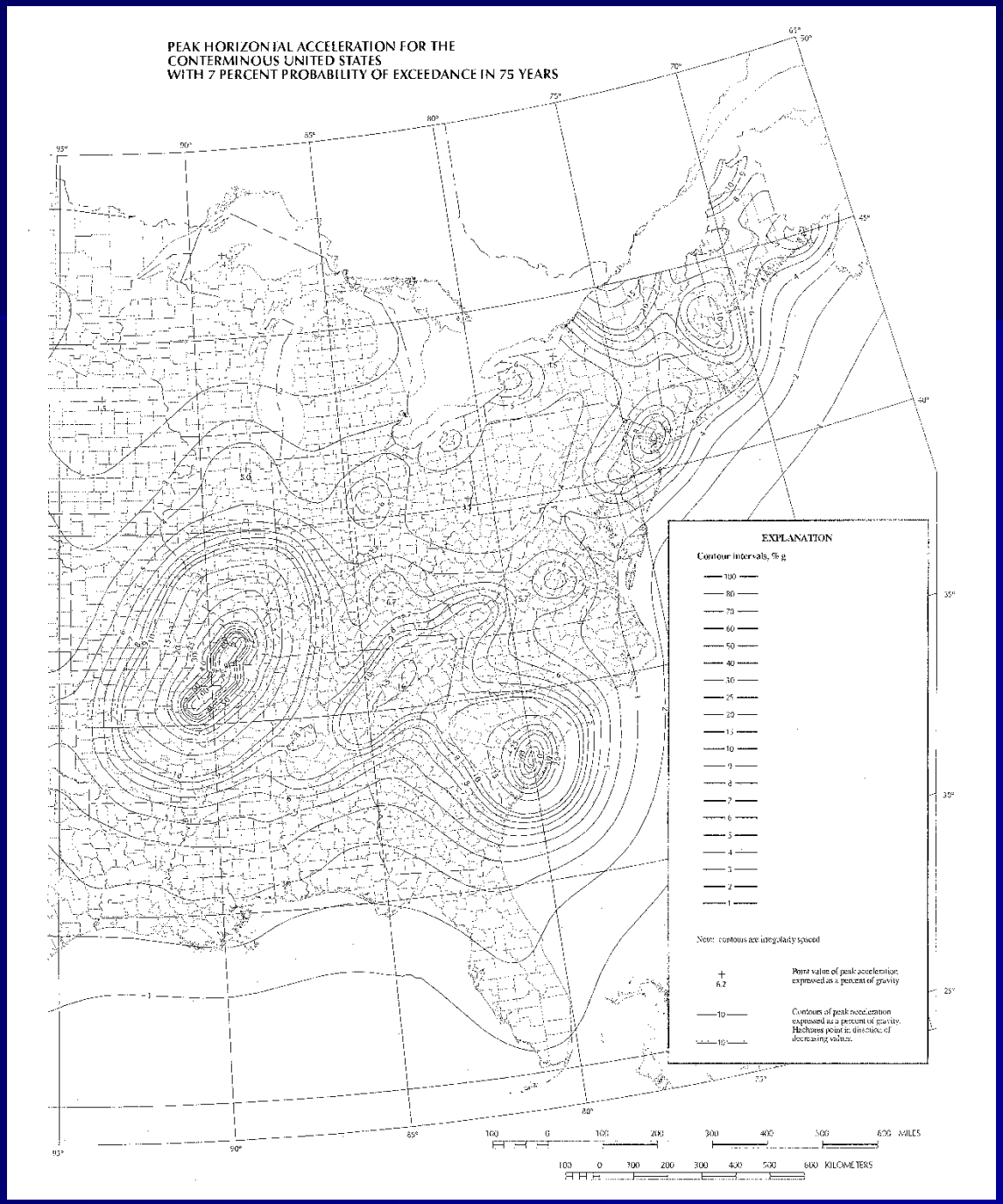
Peak Horizontal Ground Acceleration

- (Western) 7 Percent in 75 Years (Approx. 1000 Year Return Period).

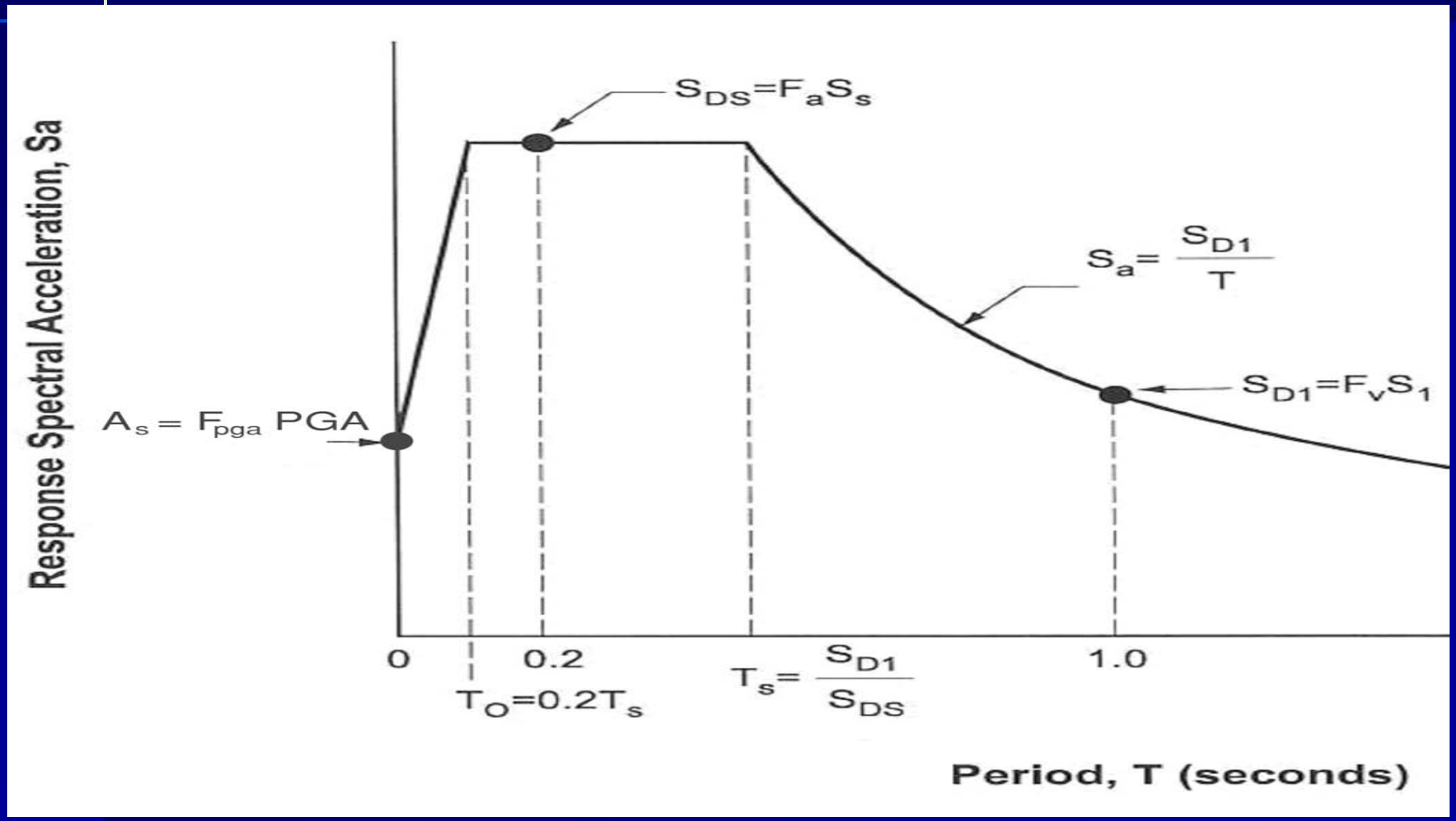


Peak Horizontal Ground Acceleration

- (Eastern) 7 Percent in 75 Years (Approx. 1000 Year Return Period).



Response Spectrum Construction – Two Point Method



Site Classification

Site Class	v_s	N	s_u
A	> 5000 ft/sec	–	–
B	2500 to 5000 ft/sec	–	–
C	1200 to 2500 ft/sec	> 50	> 2000 psf
D	600 to 1200 ft/sec	15 to 50	1000 to 2000 psf
E	<600 ft/sec	<15 blows/ft	<1000 psf
F	**Soils requiring site-specific evaluations**		

Table note: If the s_u method is used and the *Nch* and s_u criteria differ, select the category with the softer soils (for example, use Site Class E instead of D).

Site Coefficient Fa

Values of *Fa* as a Function of Site Class and Mapped Peak Ground Acceleration or Short-Period Spectral Acceleration Coefficient.

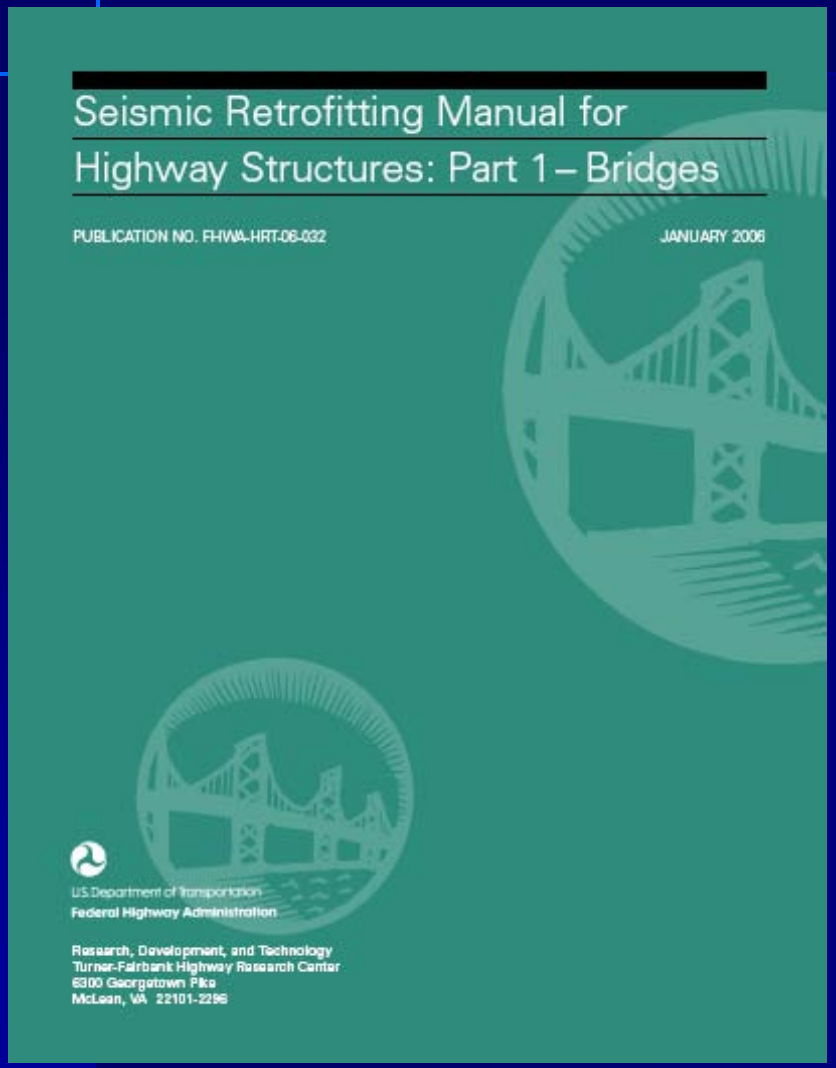
Site Class	Mapped Peak Ground Acceleration or Spectral Response Acceleration Coefficient at Short Periods				
	PGA≤ 0.10 $S_s \leq 0.25$	$PGA = 0.20$ $S_s = 0.50$	$PGA = 0.30$ $S_s = 0.75$	$PGA = 0.40$ $S_s = 1.00$	$PGA \geq 0.50$ $S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	*a*	*a*	*a*	*a*	*a*

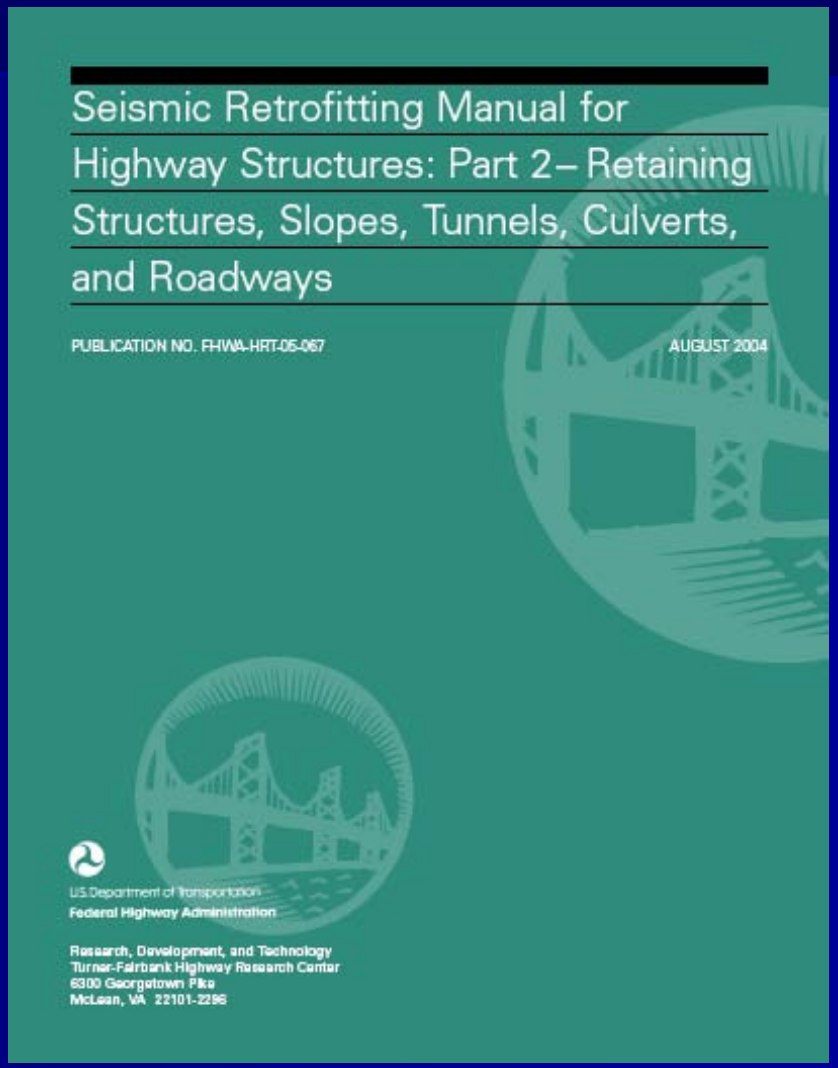
Table notes:Use straight line interpolation for intermediate values of *PGA* and S_s, where *PGA* is the peak ground acceleration and S_s is the spectral acceleration coefficient at 0.2 sec. obtained from the ground motion maps.

a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed

Mitigation Seismic Hazard through Retrofitting

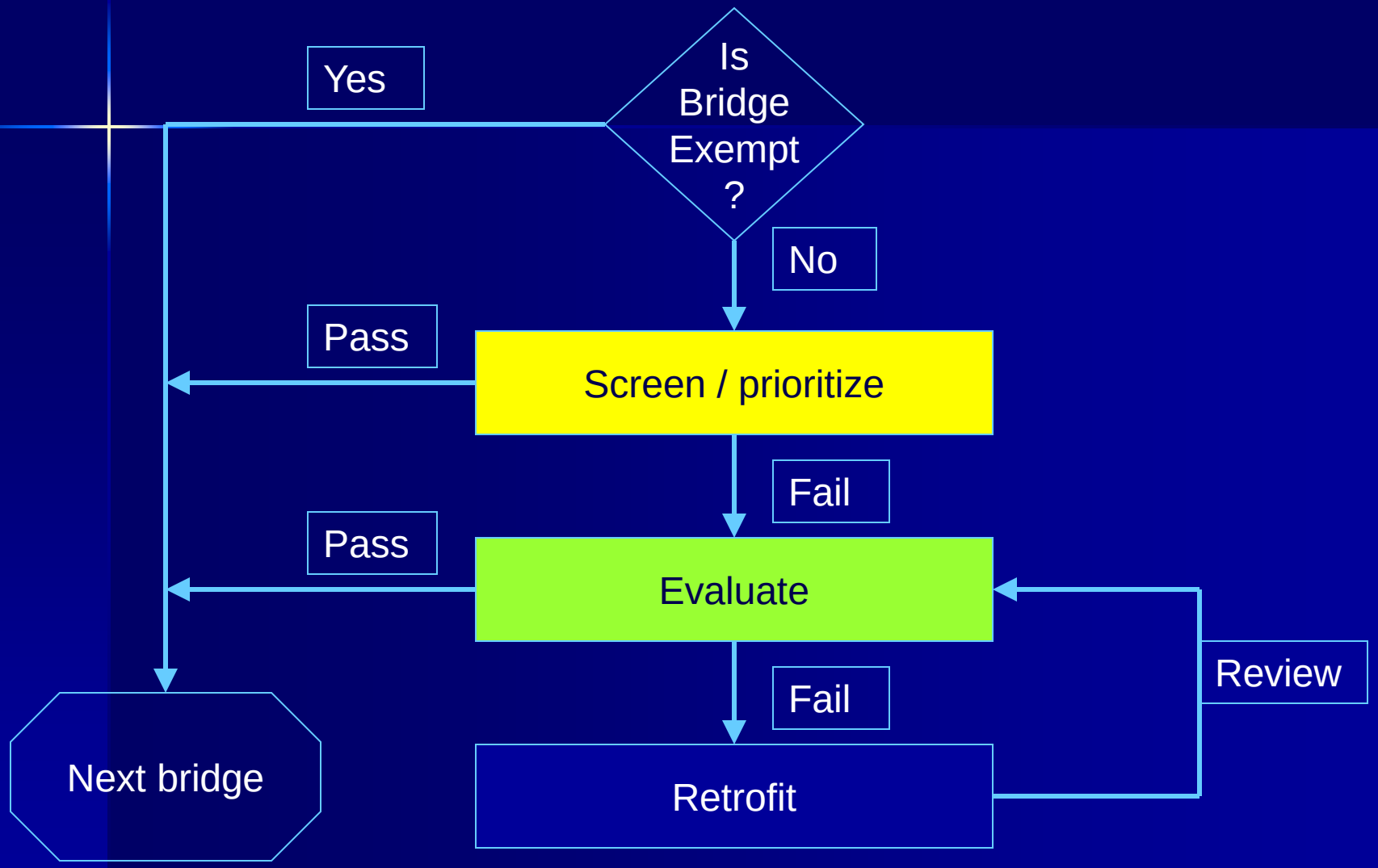
NEW FHWA Seismic Retrofitting Manuals





Content

- Philosophy and process
- Screening a bridge inventory
- Evaluation of bridge performance
- Retrofit strategies for deficient bridges


Is Bridge Exempt ?
Yes
No
Pass
Screen / prioritize
Fail
Pass
Evaluate
Review
Fail
Next bridge
Retrofit

Performance-based retrofit

Performance	Earthquake		
	Small	Intermediate	Large
No interruption	√	√	
Limited access		√	√
Closed for repairs			√

Performance-based retrofit

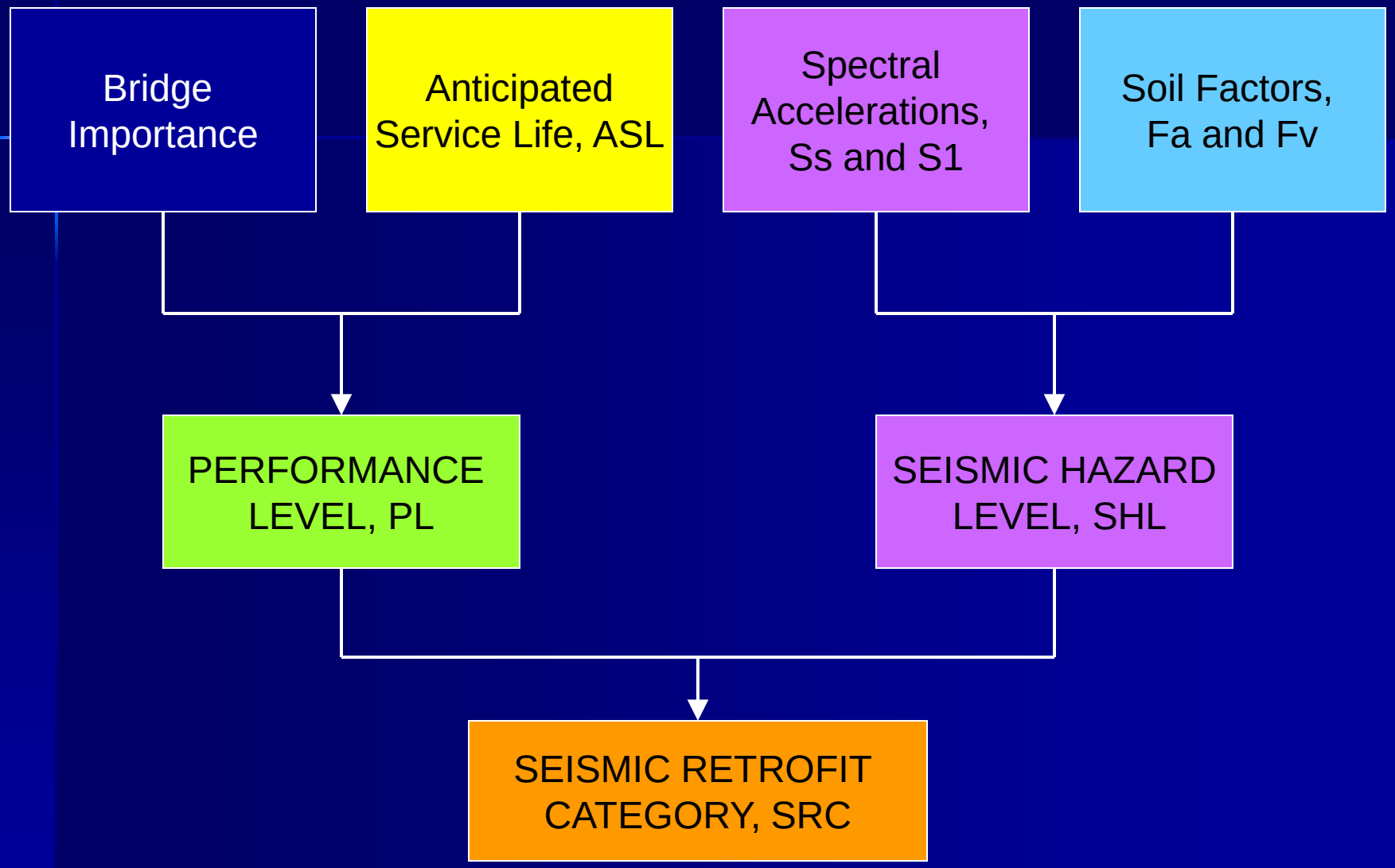
- Application of *performance-based design* to bridge retrofitting
  - two earthquake levels (Lower Level, Upper Level)
  - two bridge types (standard, essential)
  - three service life categories (ASL1,-2,-3)
  - two performance levels (life safety, operational)

Seismic retrofit categories

- *Seismic Retrofit Categories*, *SRC*, are used to recommend minimum levels of
  - screening
  - evaluation, and
  - retrofitting

  If these minima are satisfied, the required performance levels will be satisfied.

- SRCs are similar to *Seismic Performance Categories (SPC)* used in new design


Bridge Importance
Anticipated Service Life, ASL
Spectral Accelerations, Ss and S1
Soil Factors, Fa and Fv
PERFORMANCE LEVEL, PL
SEISMIC HAZARD LEVEL, SHL
SEISMIC RETROFIT CATEGORY, SRC

Upper and lower level earthquakes

- Lower Level earthquake (LL): 100-year return period (50% probability of exceedance in 75 years)
- Upper Level earthquake (UL): 1000-year return period (7% probability of exceedance in 75 years)

Seismic hazard levels: I - IV

HAZARD LEVEL	Using $S_{DI} = F_v S_I$	Using $S_{DS} = F_a S_s$
I	$S_{DI} \leq 0.15$	$S_{DS} \leq 0.15$
II	$0.15 < S_{DI} \leq 0.25$	$0.15 < S_{DS} \leq 0.35$
III	$0.25 < S_{DI} \leq 0.40$	$0.35 < S_{DS} \leq 0.60$
IV	$0.40 < S_{DI}$	$0.60 < S_{DS}$

Notes:

1. For the purposes of determining the Seismic Hazard Level for Site Class E soils, the value of F_v and F_a need not be taken larger than 2.4 and 1.6 respectively, when S_I is less than or equal to 0.10 and S_s is less than 0.25.
2. For the purposes of determining the Seismic Hazard Level for Site Class F soils, F_v and F_a values for Site Class E soils may be used with the adjustment described in Note 1 above.

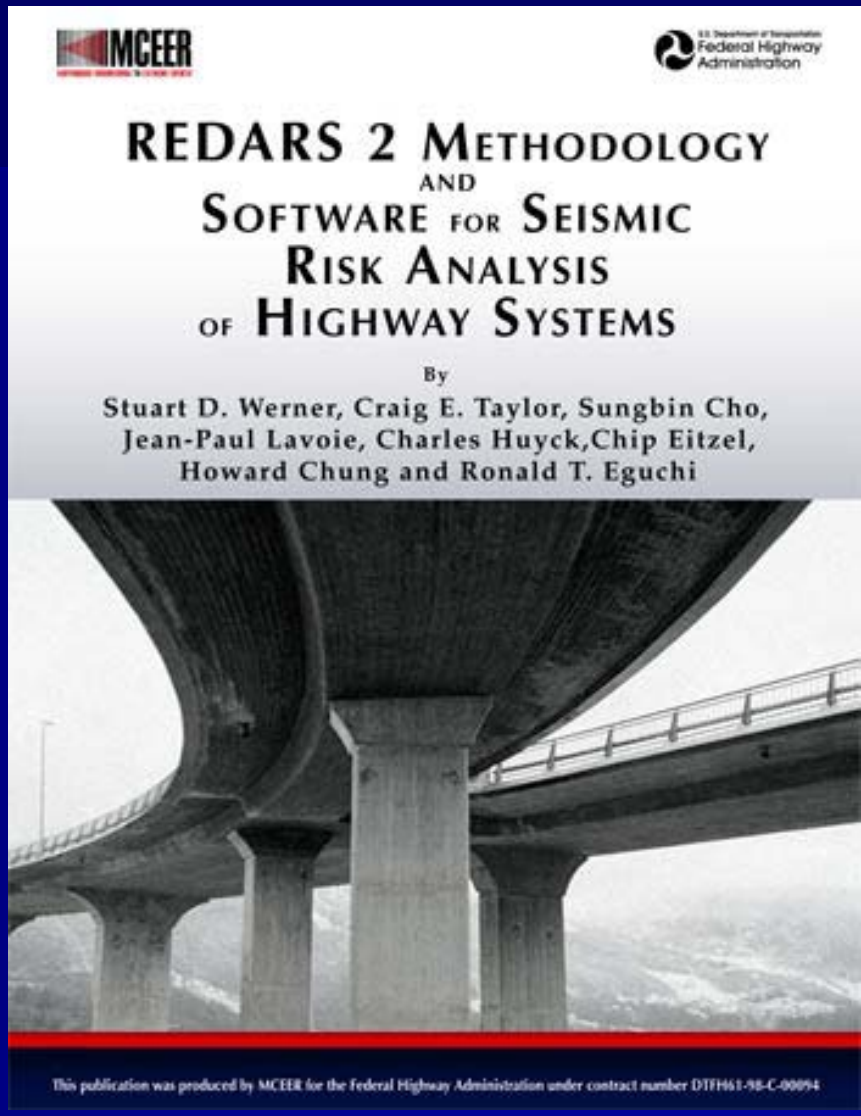
Seismic retrofit category

HAZARD LEVEL	PERFORMANCE LEVEL		
	PL0: No min.	PL1: Life-safety	PL2: Operational
I	A	A	B
II	A	B	B
III	A	B	C
IV	A	C	D

Mitigation Seismic Hazard through Planning/ Risk Analysis/ Loss Assessment

REDARS 2: Methodology and Software for Seismic Risk Analysis of Highway Systems

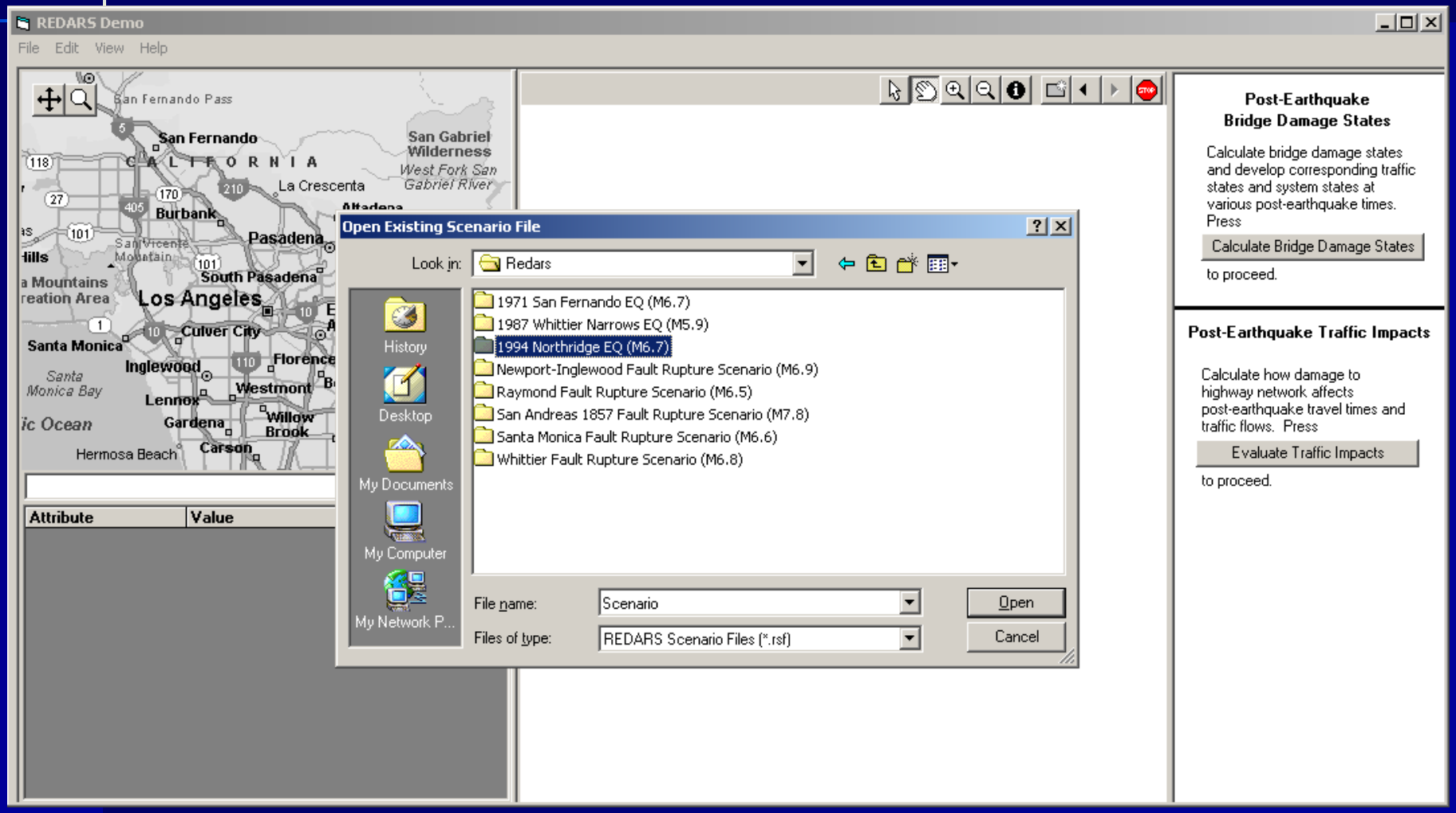
- S.D. Werner, C.E. Taylor, S. Cho, J-P. Lavoie, C. Huyck,
  C. Eitzel, H. Chung and R.T. Eguchi
- The REDARS 2 report provides the basic framework and a demonstration application of the Seismic Risk Analysis (SRA) methodology and its modules. The main modules of the REDARS 2 SRA methodology include hazards, components, system and economic. The northern Los Angeles, California highway system is used as a demonstration application of the SRA methodology.



REDARS SOFTWARE: DESCRIPTION

- A Systematic Approach based on Loss Estimation
- Pre-EQ.
  - Loss Estimation
  - Emergency Planning
- Post-EQ.
  - Emergency Dissemination

DIALOGUE BOX TO SELECT NORTHRIDGE EQ



NORTHRIDGE EQ: EPICENTER (SIGNATURE) VIEW

REDARS Demo - c:\Redars\1994 Northridge EQ (M6.7)\ScenarioA.rrs

File Edit View Help

San Fernando Pass
San Fernando
C A L I F O R N I A
San Gabriel Wilderness
West Fork San Gabriel River
La Crescenta
Altadena
Burbank
Pasadena
Monrovia
Azusa
San Vicente Mountain
Arcadia
South Pasadena
El Monte
Los Angeles
East Los Angeles
Valinda
Culver City
Walnut
Santa Monica
Montebello
Inglewood
Florence
Bell Gardens
Westmont
La Habra
Lennox
Willow Brook
Fullerton
Brea
Gardena
Carson
Bellflower
Hermosa Beach
Santa Monica Bay

Attribute	Value

Epicenter

Northridge 6.7

Post-Earthquake Bridge Damage States

Calculate bridge damage states and develop corresponding traffic states and system states at various post-earthquake times. Press

Calculate Bridge Damage States

to proceed.

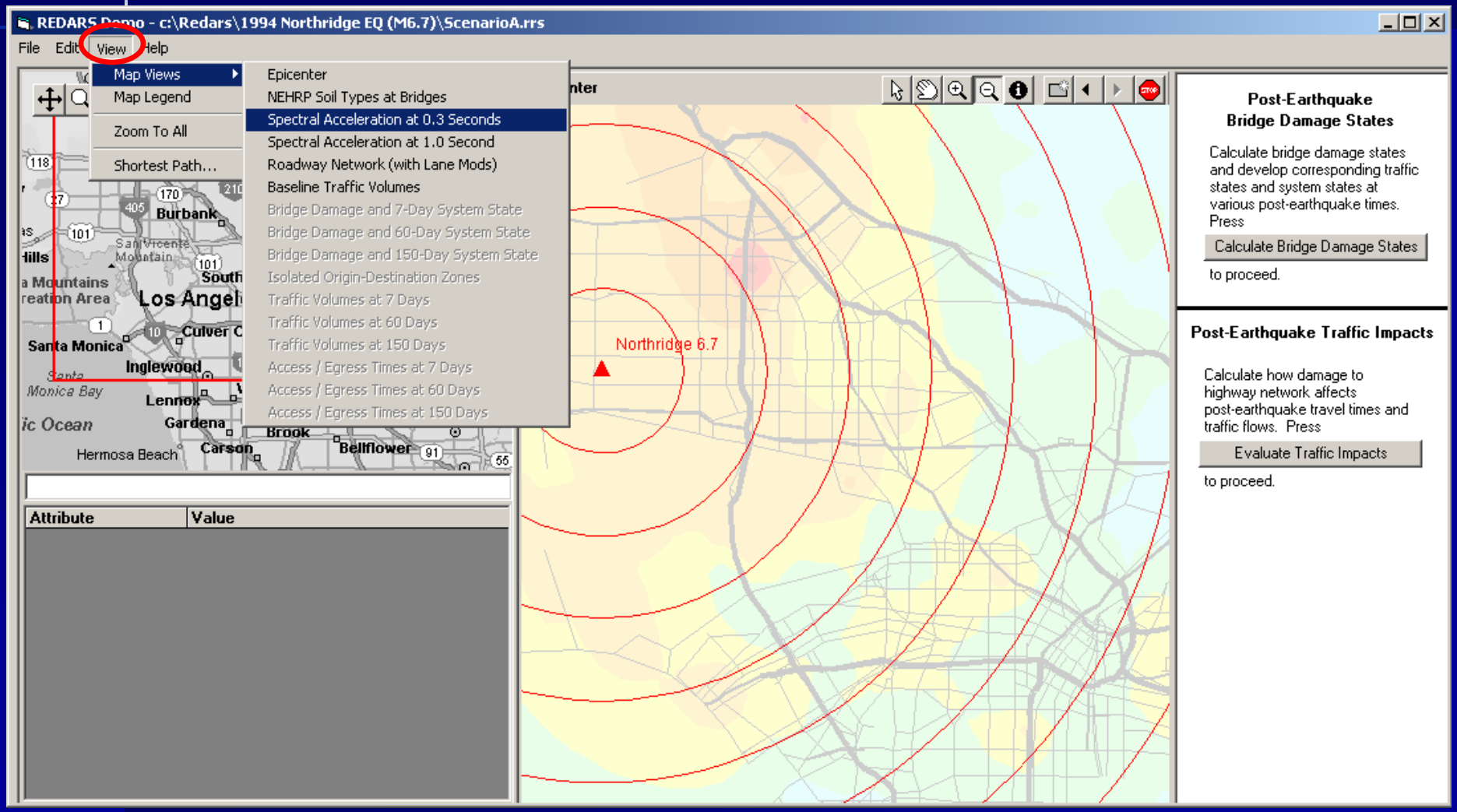
Post-Earthquake Traffic Impacts

Calculate how damage to highway network affects post-earthquake travel times and traffic flows. Press

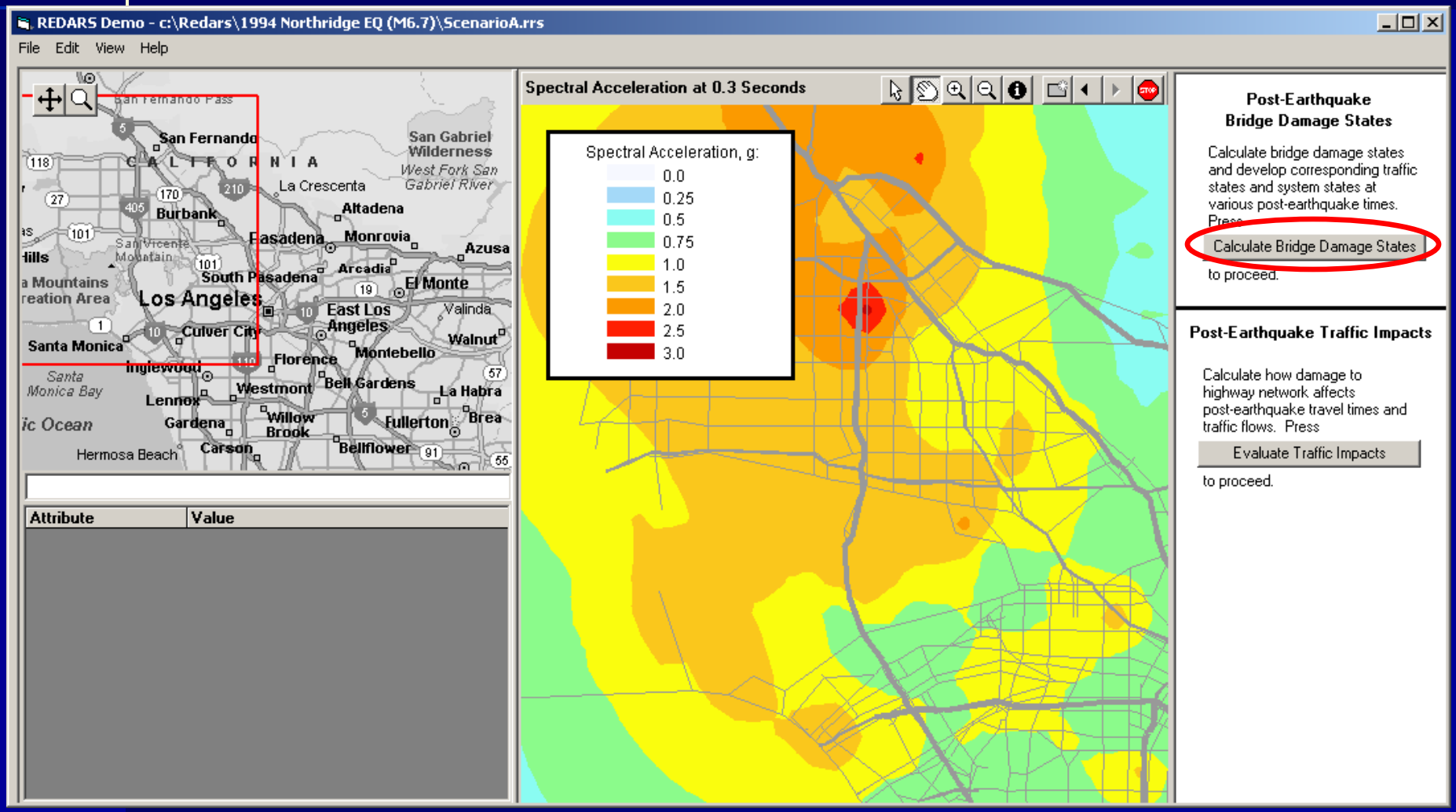
Evaluate Traffic Impacts

to proceed.

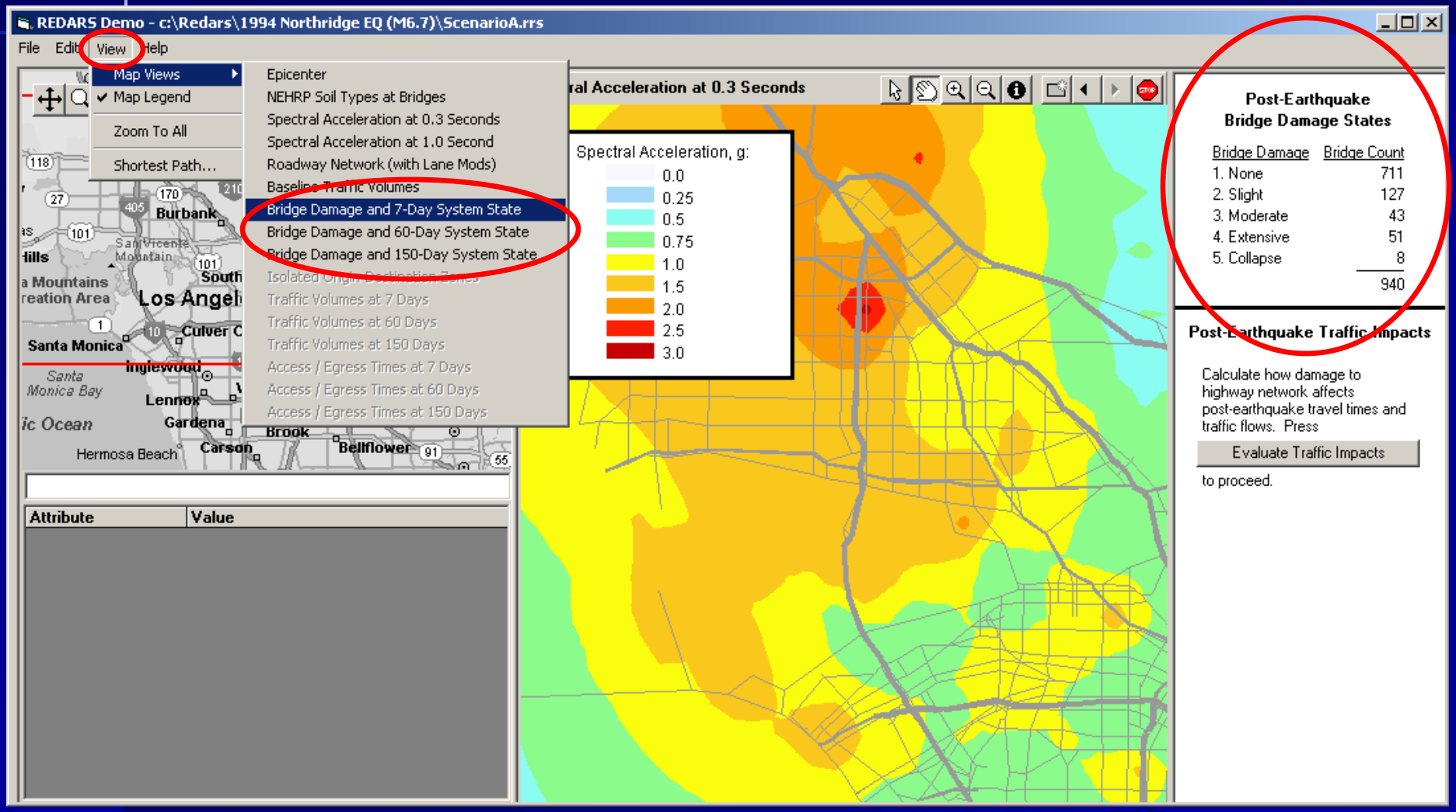
DROP-DOWN MENU:
ACCESS OF GROUND MOTION DATA



DISPLAY OF GROUND MOTIONS: SPECTRAL ACCELERATIONS AT T = 0.3 SEC.



DROP-DOWN MENU: ACCESS BRIDGE DAMAGE & SYSTEM STATE DISPLAYS



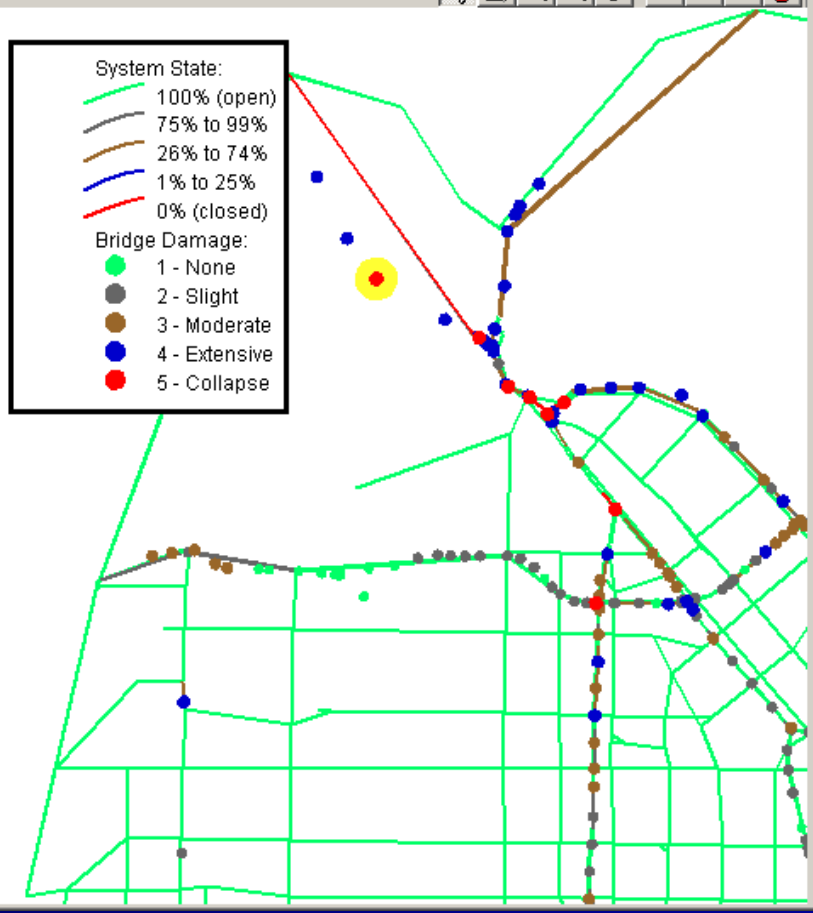
BRIDGE DAMAGE & SYSTEM STATES 7-DAYS AFTER EQ: (INDIVIDUAL BRIDGE DATA DISPLAY)

REDARS Demo - c:\Redars\1994 Northridge EQ (M6.7)\ScenarioA.rrs

File Edit View Help

Attribute	Value
DOT Ref	53 1797L
A Node Id	5027
B Node Id	5029
K3D Value	1
X Coordinate	357909.088307266
Y Coordinate	3802043.77790286
Year Built	1967
Bridge Group	CD_G1
Bridge Type	105
Total Length	225.8
Number of Main Spans	5
Soil Code	4
Fragility Code	1

Bridge Damage and 7-Day System State



Post-Earthquake Bridge Damage States

Bridge Damage	Bridge Count
1. None	711
2. Slight	127
3. Moderate	43
4. Extensive	51
5. Collapse	8
	940

Post-Earthquake Traffic Impacts

Calculate how damage to highway network affects post-earthquake travel times and traffic flows. Press

Evaluate Traffic Impacts

to proceed.

Summary

- Background
  - Natural Hazards & Transportation Infrastructure
  - FHWA Research Program
- Planning
  - REDARS Program
- Designing
  - New Design Spec
- Retrofitting
  - New Retrofitting Manuals

Better Design Code = Better Performance

Well Preparedness = Reduce Loss

Thank you!

For further information, please contact Dr. W. Phillip Yen at
Wen-huei.Yen@fhwa.dot.gov