Design of the SR 520 West Approach Bridge Using Seismic Isolation Bearings

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Washington State
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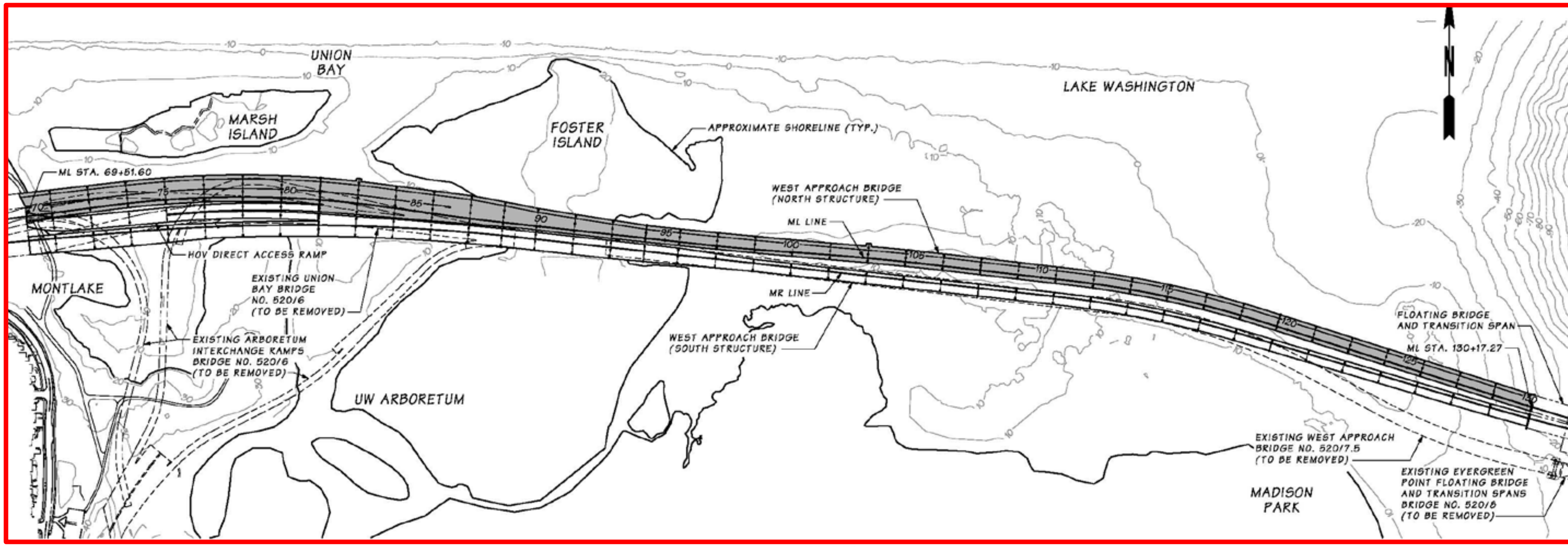
Objectives

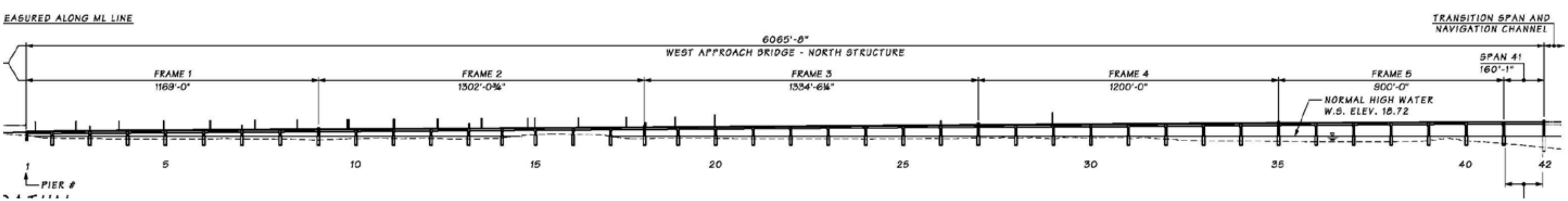
- Introduction to Project
- Basic Principles of Seismic Isolation
- Types of Isolation Systems Available
- Non – Linear Time History Analysis
- Benefits and Costs

West Approach Bridge – Location

West Approach Bridge – North



PLAN

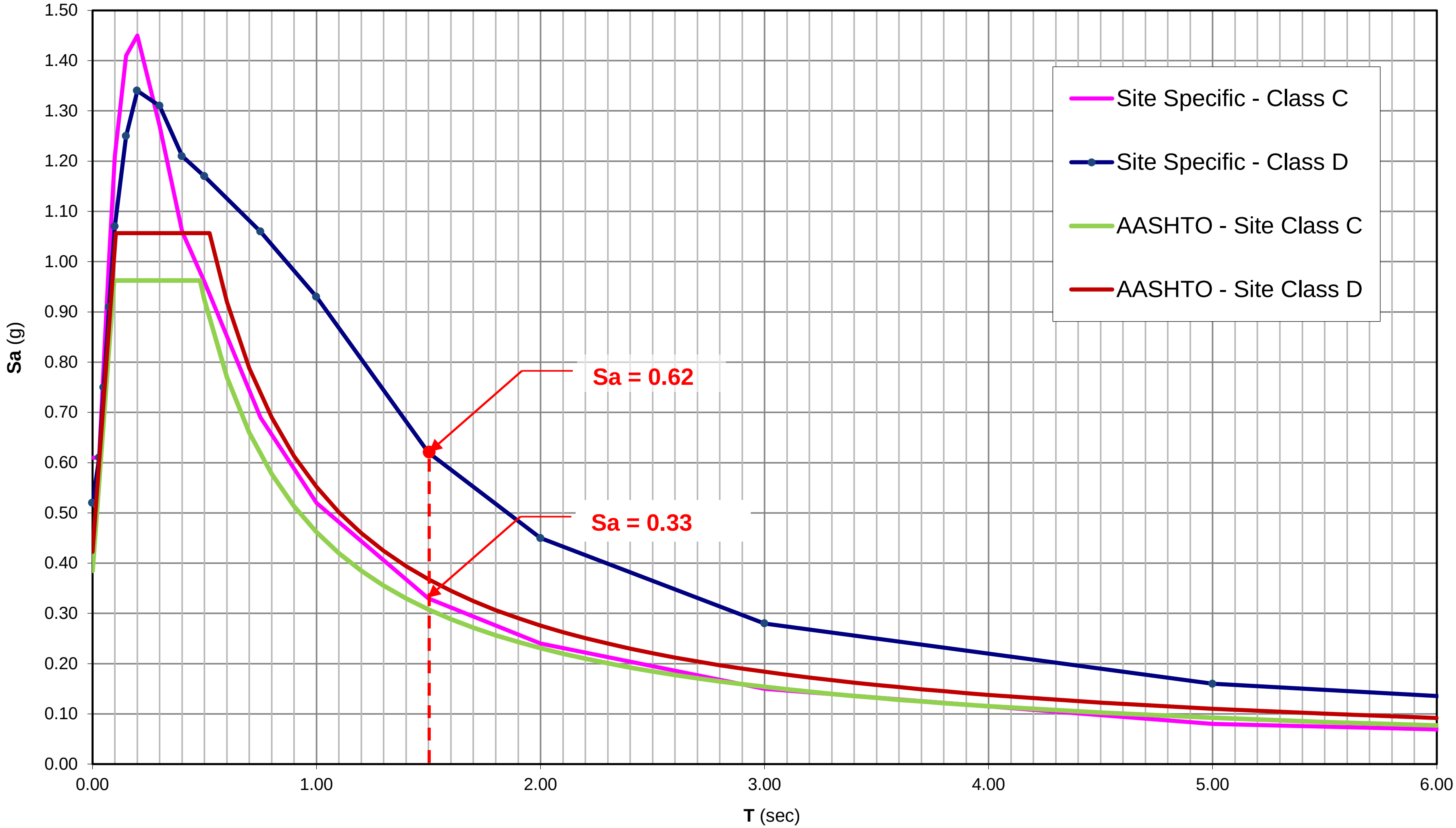


- Deck area = 500,000 sf (approx.)
- Average width = 81 ft (typical width = 65 .4 ft)
- Number of columns = 95
- Column heights vary from 4 ft to 40 ft.
- Prestressed girders : WF74G (TYP.), One span WF50G, and WF83G
- Typical span length = 150'
- Single column /single shaft foundations (8’ to 12’ dia. Shafts)
- Soft soils from 6 ft to 80 ft deep

UNIFORM HAZARD - SPECTRAL ACCELERATION - RESPONSE SPECTRUM COMPARISON

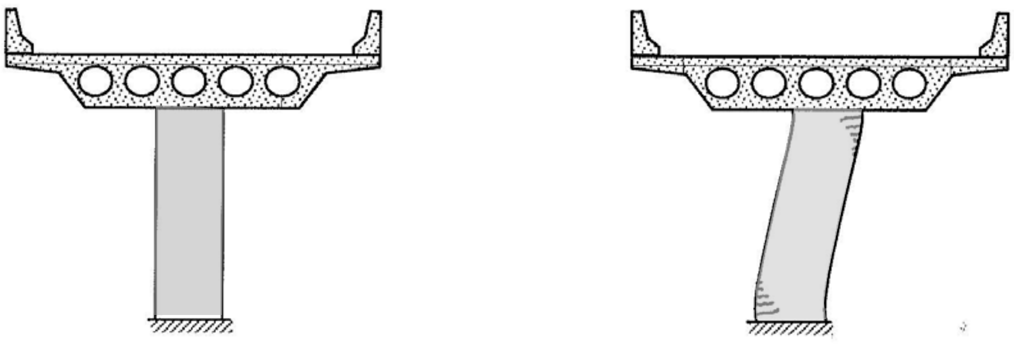
7% PROBABILITY OF EXCEDANCE IN 75 YEARS - 1000 YEAR ARP

5% DAMPING

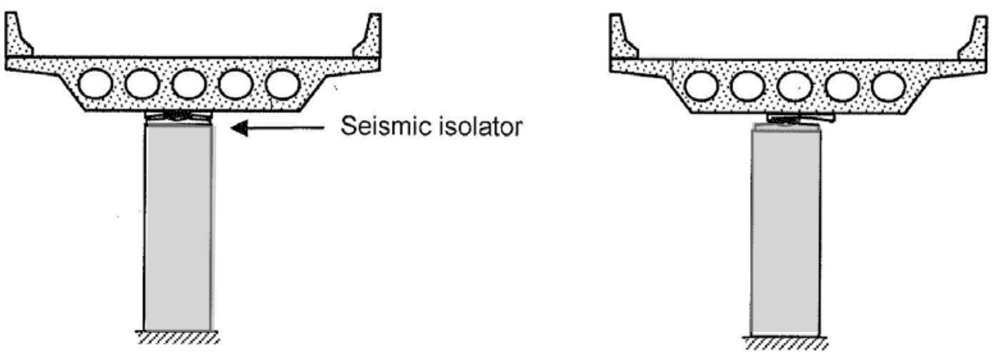


Basic Principles of Seismic Isolation

- Accommodates structure displacement in specially designed bearings
- Lengthens the structures fundamental period
- Adds damping to the system
- Reduces structure acceleration
- Reduces structure force demands
- Increases structure displacement demands

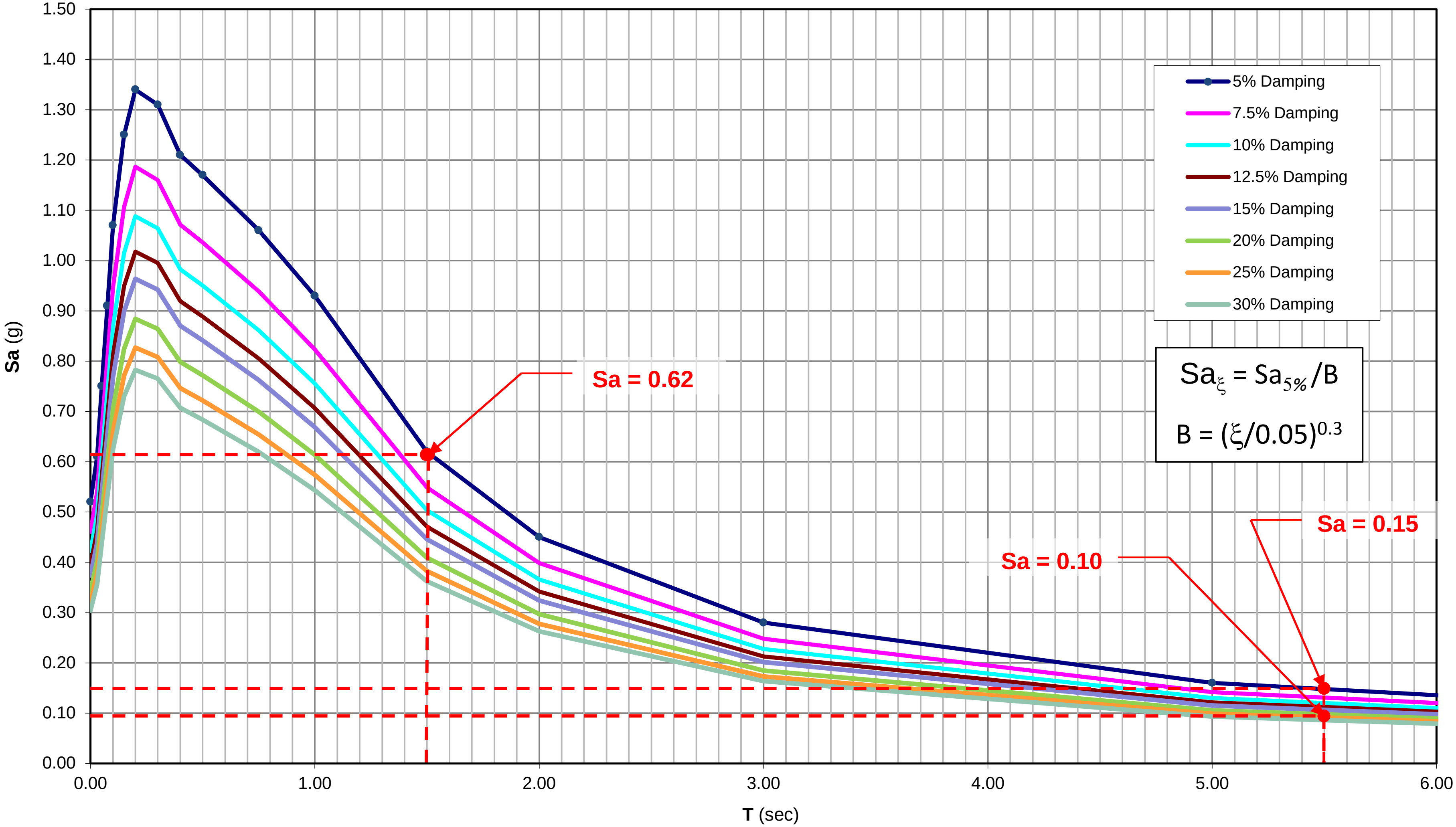


(a) Conventional bridge where deformation occurs in substructure.

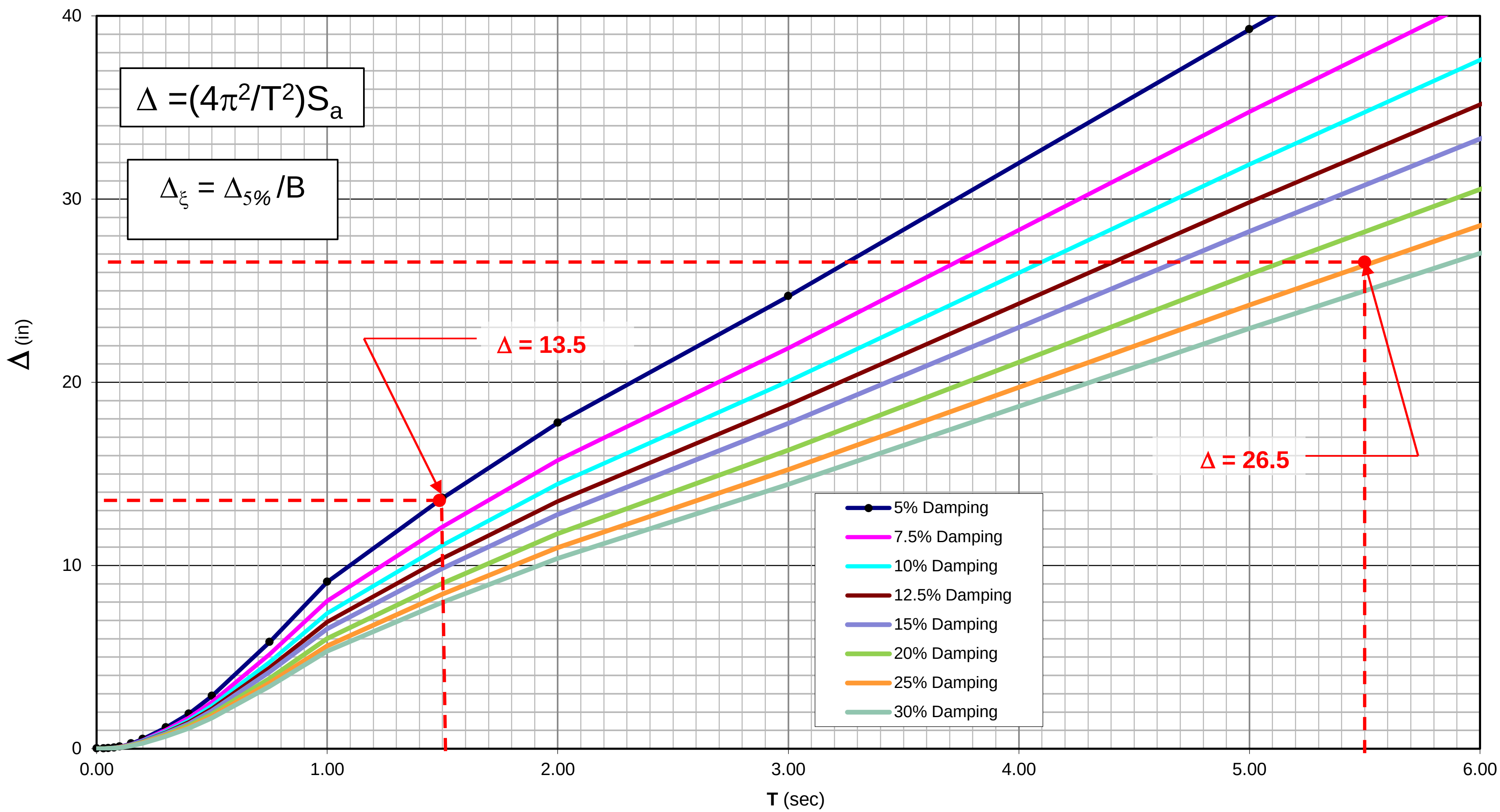


(b) Seismically isolated bridge where deformation occurs in the isolator.

SPECTRAL ACCELERATION RESPONSE SPECTRUM
Site Class D



DISPLACEMENT RESPONSE SPECTRUM
Site Class D

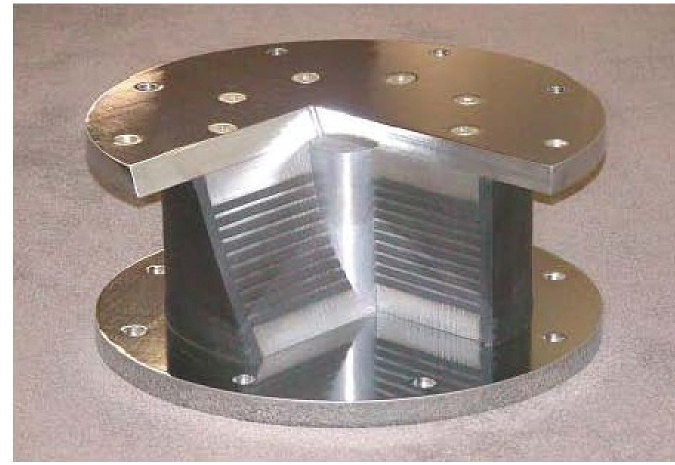


Types of Seismic Isolation Bearings

Elastomeric Bearings

- Low-damping natural or synthetic rubber bearing
- High-damping natural rubber bearing
- Lead-rubber bearing

(Low damping natural rubber with lead core)

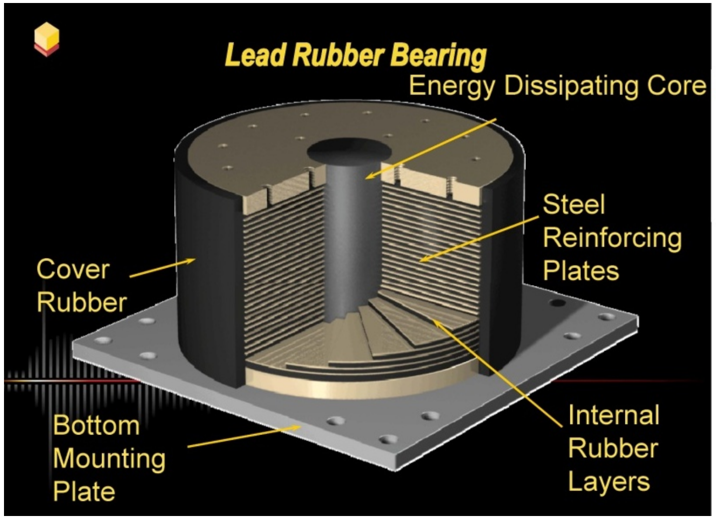


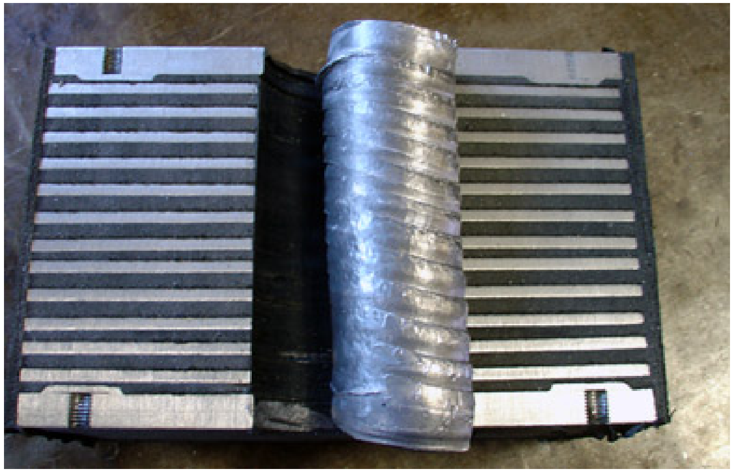
Sliding Bearings

- Flat sliding bearing (Eradiquake)
- Spherical sliding bearing (FPS)

Lead Rubber Bearing Isolation System

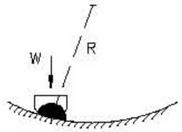
- Low damping rubber layers provide lateral flexibility.
- Lead core yields as it is pushed by steel reinforcing plates.
- Yielding produces permanent deformations and heat which accounts for the hysteretic energy dissipation.





Friction Pendulum Bearing Isolation System

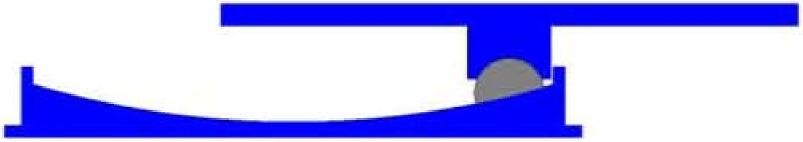
- Based on pendulum behavior.



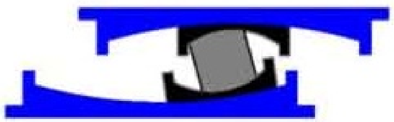
- Utilizes concave surface of constant radius to constrain motion.
- Friction coefficients of 2% to 12% possible.
- Dissipates energy through friction and heat.

$$T = 2\pi\sqrt{\frac{R}{G}}$$

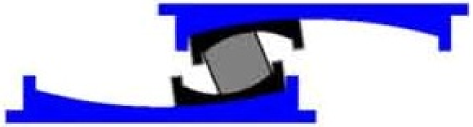
Period is independent of mass



SINGLE PENDULUM MOTION
MAXIMUM CREDIBLE EARTHQUAKE



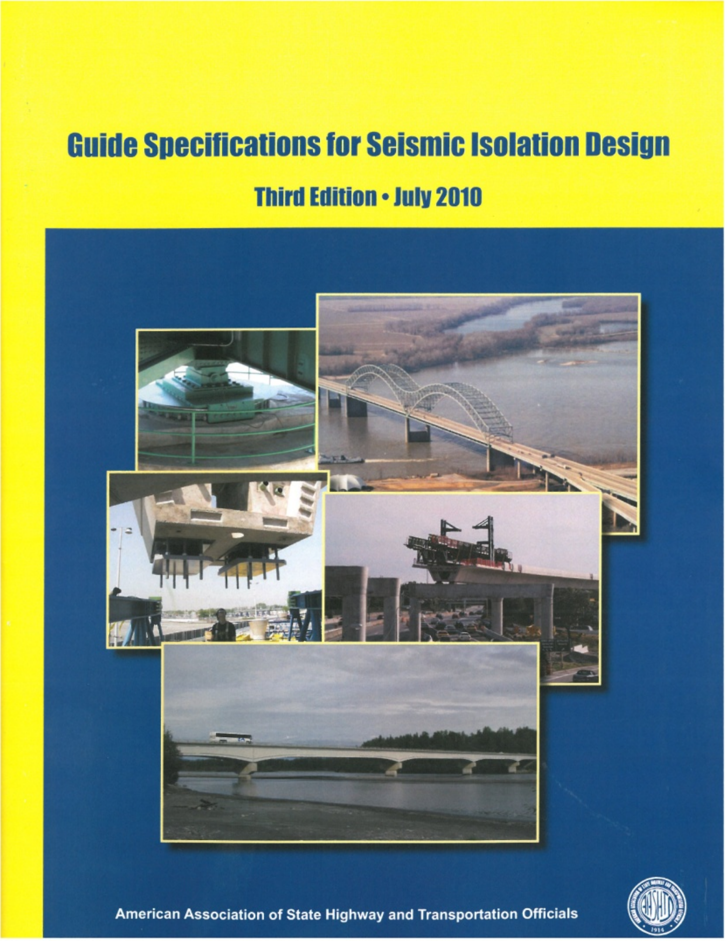
LOWER PENDULUM MOTION
DESIGN BASIS EARTHQUAKE



UPPER PENDULUM MOTION
MAXIMUM CREDIBLE EARTHQUAKE

Non-Linear Time History Analysis

- NTH analysis required by AASHTO for effective period greater than 3 seconds
- Peer review is not required by the AASHTO Guide Specifications, but was utilized.
- Peer group (SC Solutions) performed parallel NTH analysis.
- Entire 6100 ft. long bridge analyzed in one model.
- Input motions for 5 earthquakes and dynamic soil structure interaction (DSSI) analysis was provided by Shannon and Wilson.*



*See paper titled "*Dynamic Analysis of a Base-Isolated Bridge, Seattle, Washington*.", Jeremy Butkovich et al.

Model Differences

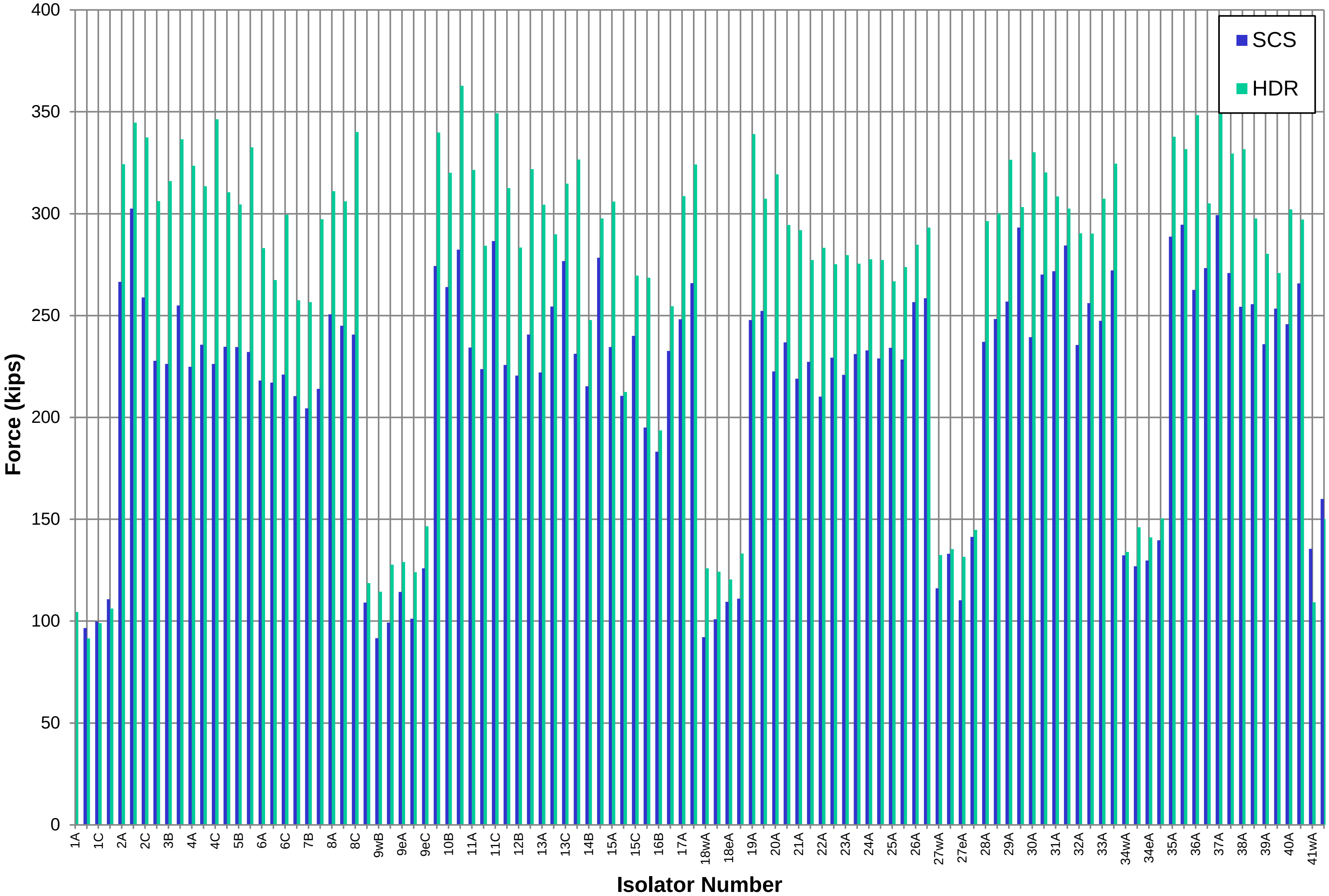
Modeling Parameter	HDR	SC Solutions
Software	CSI Bridge	Adina
Analysis Method	Fast Non-Linear Analysis (FNA)	Direct Integration (DI)
Viscous Damping	Linear Interpolated Modal	Raleigh
Superstructure Model	Grillage	Frame and Shell Elements
SSI	6x6 Coupled Linear Spring at Mudline	p-y and t-z spings Along Shaft Length
P-Delta	Post-Processed	Large P-Delta included in DI Execution
Triple Friction Pendulum	Flate Plate and Single Pendulum in Parallel *	Custom TFP Element

* From "*Modeling Triple Friction Pendulum Isolators in Program SAP2000*", Sarlis and Constantinou, June 27, 2010

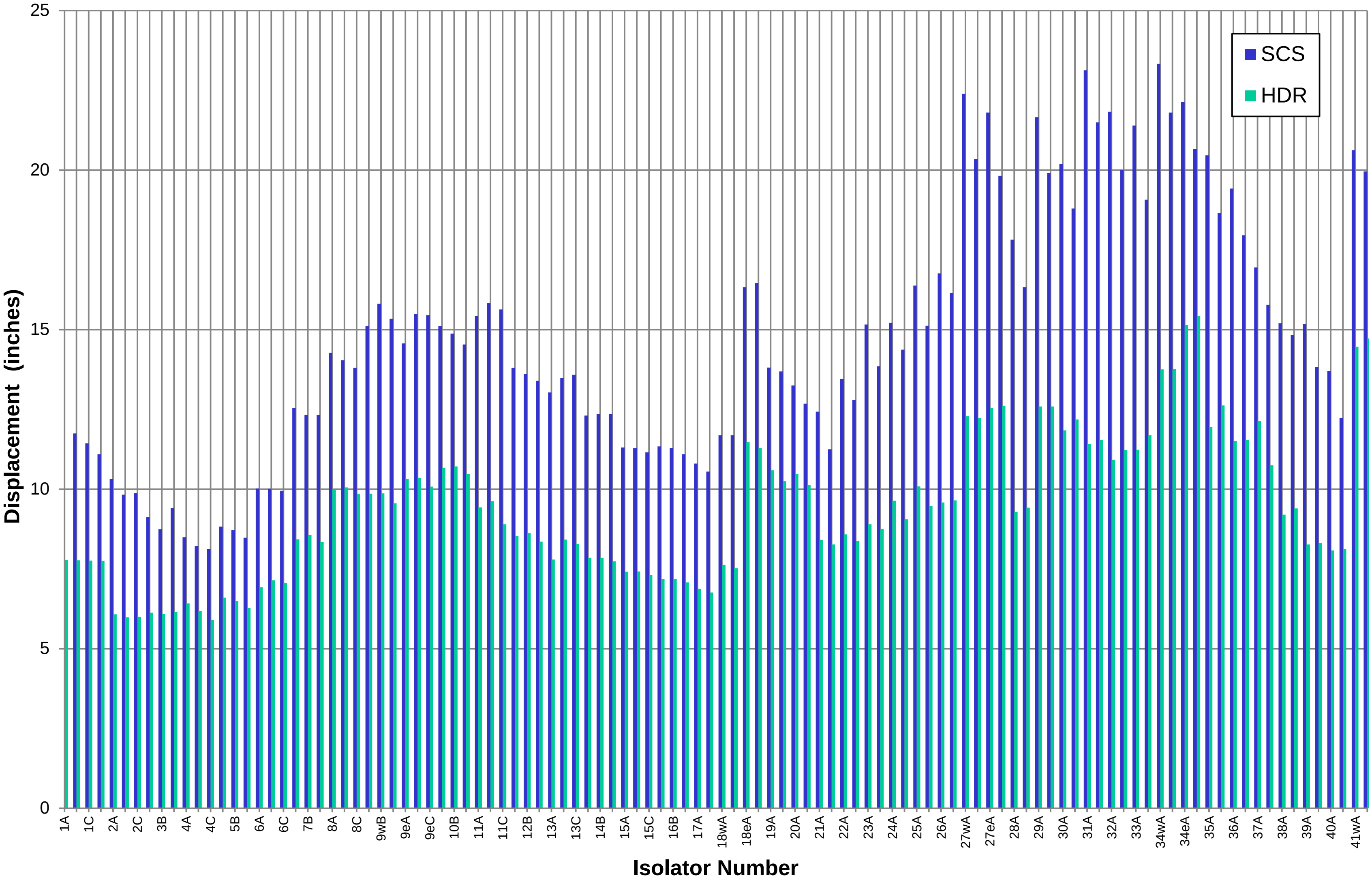
Analysis Matrix

Analysis #	Substructure Stiffness Variation		Isolation Bearing Properties Variation		Live Load Variation		# of Time Histories
	Stiff	Soft	Max	Min	With LL & LRT	No LL & No LRT	
1	X		X		X		5
2	X		X			X	5
3	X			X	X		5
4	X			X		X	5
5		X	X		X		5
6		X	X			X	5
7		X		X	X		5
8		X		X		X	5
Total Number of Analysis Cases							40

Maximum Isolator SRSS Shear

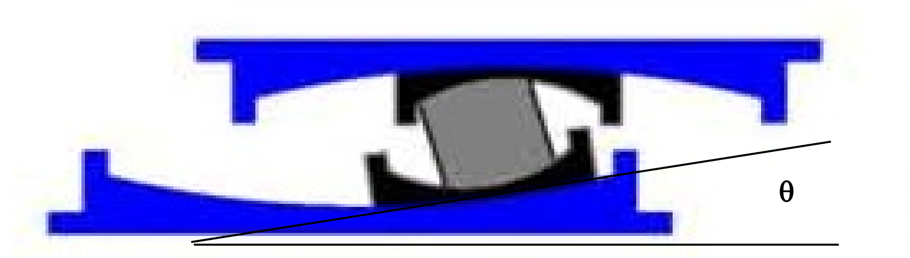


Maximum Isolator Displacement Demands

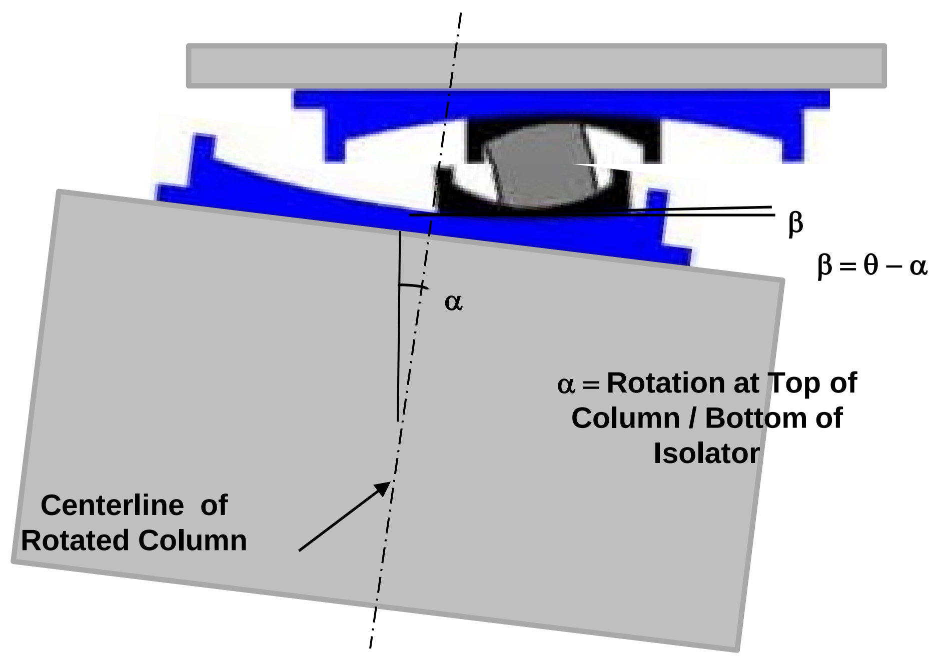


Column Rotational Effects on Isolator Stiffness

Non-Rotated System

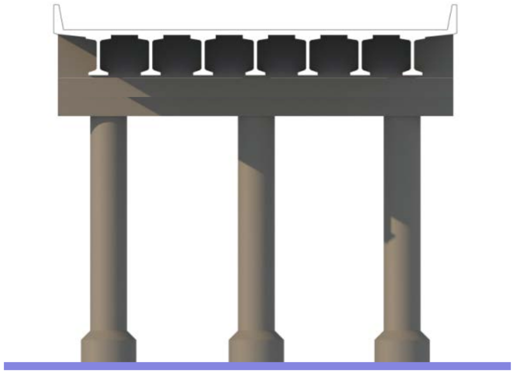


Rotated System at Top of Flexible Column

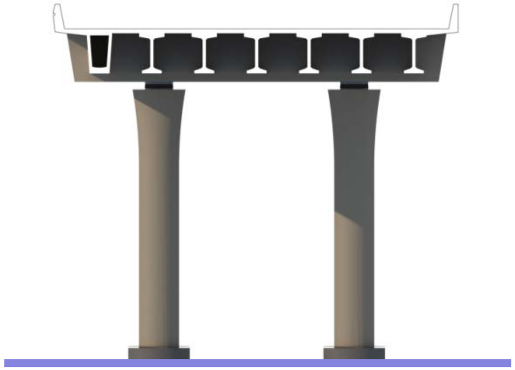


Benefits of Utilizing Seismic Isolation

- Reduces structural demands on substructure
- Simplifies use of precast column (ABC)
- Provides economical way to meet project specific Essential Bridge Criteria
- Provides improved performance
- Achieves balanced stiffness requirements
- Accommodates aesthetic enhancements
- Reduces project cost



Without

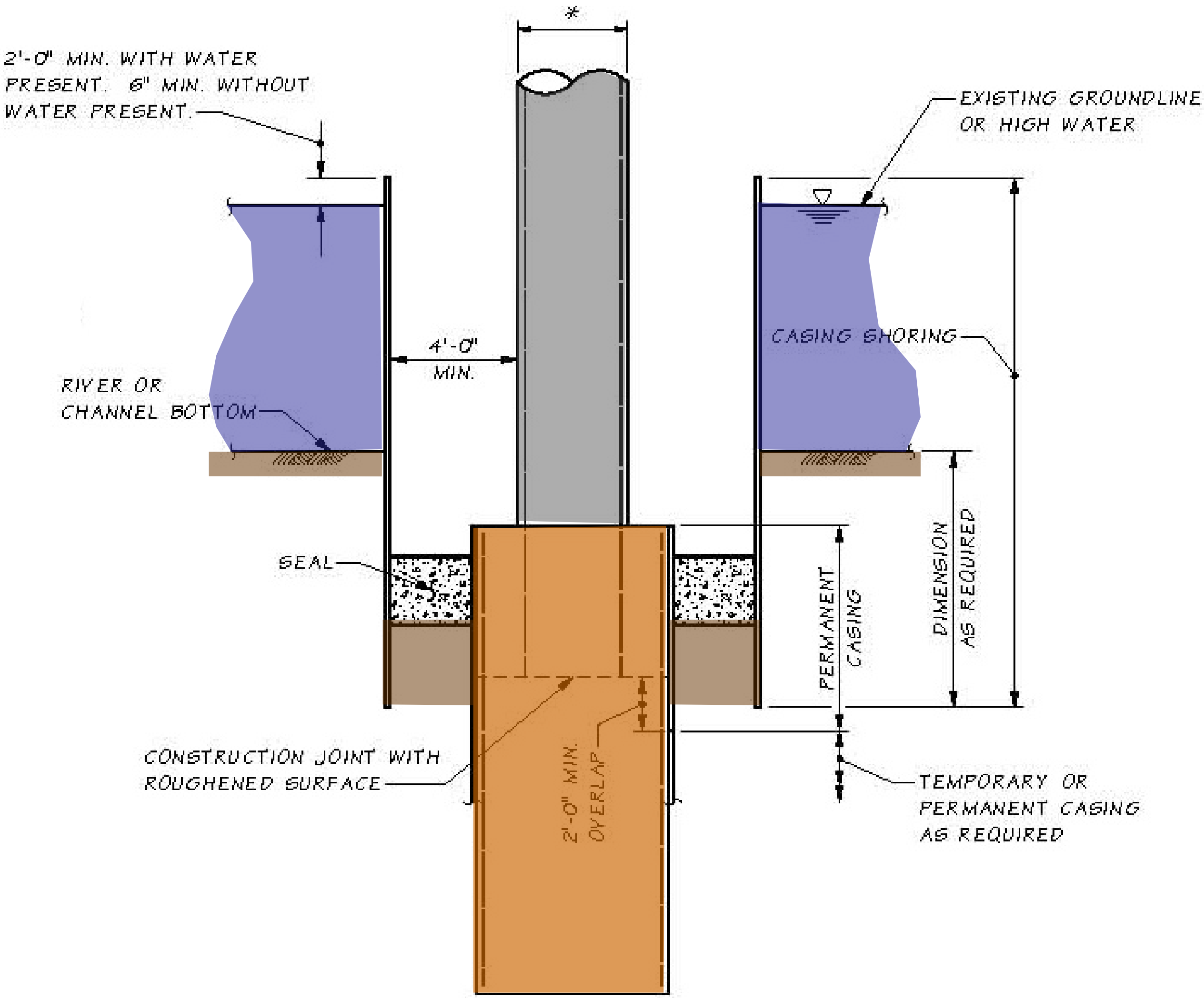


With

Costs of Utilizing Seismic Isolation

- Increases structure displacements
- Requires large expansion joints
- Requires specialized bearings
- May require additional effort for bearing selection and procurement.
- Requires additional analysis
- Increases design costs
- May increase maintenance cost

A Conventional Solution is Casing Shoring



West Approach Bridge (North) Construction Cost Savings

Item	Description	Quant. @ Unit Cost	Delta Cost
Reduced Size of Drilled Shafts	Size reduced for (95) shafts on average from 11' diameter to 9' diameter. Reinforcing volumetric ratio reduced by 1%	-10,200' @ $2,000	**-$20.3 M**
Eliminate Drilled Shafts	(39) - 11' diameter drilled shafts, average 103 LF per shaft	-4,000' @ $5,700	**-$22.8 M**
Eliminate Columns	(39) - 6.5' dia columns elimnated at 29 LF per Column	-1,100' @ $1,100	**-$1.2 M**
Eliminate Shoring Casing	Eliminated 76, 30 LF/Shaft (10' above mudline, 20' below)	-76 @ $22,000	**-$1.7 M**
Eliminate Crossbeams	(39) crossbeams Eliminated, 4' x 7' x 82' with 2% Reinf	-3,200' @ $800	**-$2.5 M**
Increase End Diaphragms	(45) end diaphragms incr by 8.2 'x 1' x 82' with 2% Reinf.	+3,700' @ $230	**$0.9 M**
Expansion Joints	Difference between expansion joint with and w/o isolation	+200' @ $2,000	**$0.4 M**
Isolation Bearings	(108) Seismic isolation bearings	+108 @ $30,000	**$3.2 M**
Falsework	Temp Falswork/ Shoring to support girders and deck		**$5.0 M**
Miscellaneous	Increased abutment size, additional detailing required for barriers, stormwater, and fire suppression systems		**$0.2 M**

Total Savings = -$39 M

Markups

Cost/Markup Type	Item	Markup	Markup Cost	Line Total
Construction	Base Cost			$38.8 M
	Mobilization	10.0%	$3.9 M	$42.7 M
	Sales Tax	9.5%	$4.1 M	$46.7 M
	Change Order Allowance	4.0%	$1.9 M	$48.6 M
	Subtotal for Construction Costs	**25%**	**$9.8 M**	**$48.6 M**
Engineering & Management	Design Engineering	6.0%	$2.9 M	$51.5 M
	CE/ Management	10.0%	$4.9 M	$56.4 M
	DPS - Direct Project Support	2.0%	$1.0 M	$57.3 M
	Subtotal for Eng. & Management Costs	**18%**	**$8.7 M**	**$57.3 M**
Risk & Inflation	Cumulative Risk Factor (CEVP)	15.0%	$8.6 M	$65.9 M
	Inflation (compounded annually)	3.0%	$8.3 M	$74.2 M
	Subtotal for Risk and Inflation	**29%**	**$16.9 M**	**$74.2 M**
	Total	**91%**	**$35 M**	**$74 M**

Note: Inflation assumed to be 3% compounded annually over 4 years

West Approach Bridge - North Benefit Summary

- Construction savings = $39 M
- Other savings = $35 M
- Total = $74 M
- Less other costs of $4 M
  - Additional structural engineering/analysis
  - Peer review
  - Additional geotechnical engineering/analysis
  - Additional contracting and review
- **Net Program Benefit of $70 M**
- **Program Cost Reduced from $270 M to $200 M**
- **Net Benefit of 25%**

Qualitative Benefits

Benefit	Description
Enhanced Safety	**Reduced probability of damage to the structure.**
Enhanced Reliability	**Increased probability the structure can remain in service after EQ.**
Reduced Environmental Impacts	**Group shaft caps avoided. Drilled shaft size reduced. Smaller footprint.**
Improved Sustainability	**Eliminates 12.5 million pounds of CO_2 emissions.**
Improved Construction Schedule	**Elimination of shoring casing reduces construction schedule.**

In Summary

- Seismic Isolation bearings lengthen the period of a structure and reduce acceleration and force demands.
- Modern isolation bearings incorporate energy dissipation mechanisms that further reduce demands.
- Peer review is recommended.
- SR 520 West Approach Bridge is using seismic isolation system that results in:
  - Significant cost savings
  - Better performance
  - Minimized environmental impacts

Questions?

Web Site:

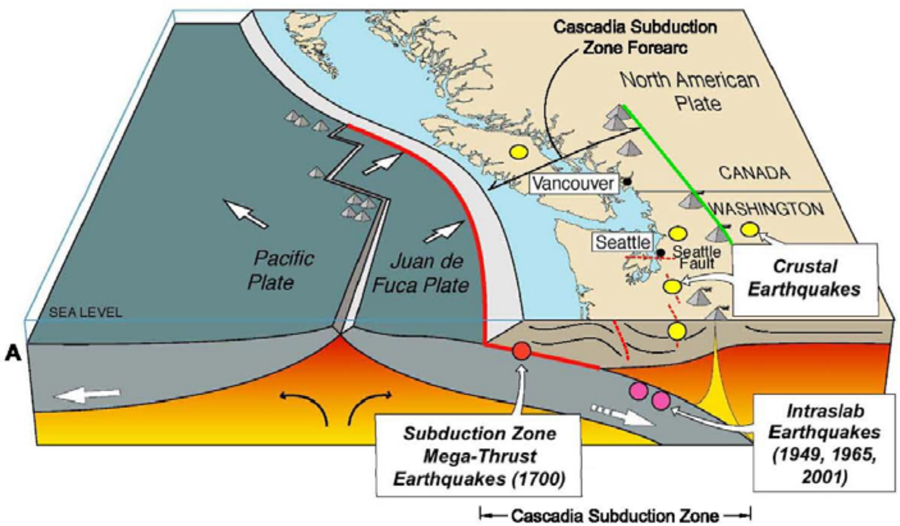
www.wsdot.wa.gov/projects/SR520Bridge

U.S. Department of Transportation
Federal Highway Administration

Washington State Department of Transportation

Northwest Region Seismic Setting

- Cascadia Subduction Zone
  - Interplate Mega-Thrust Earthquakes - M_{Max} = 9.2
  - Intraslab Earthquakes - M_{Max} = 7.5



TYPICAL GEOLOGIC CROSS SECTION

Not to Scale

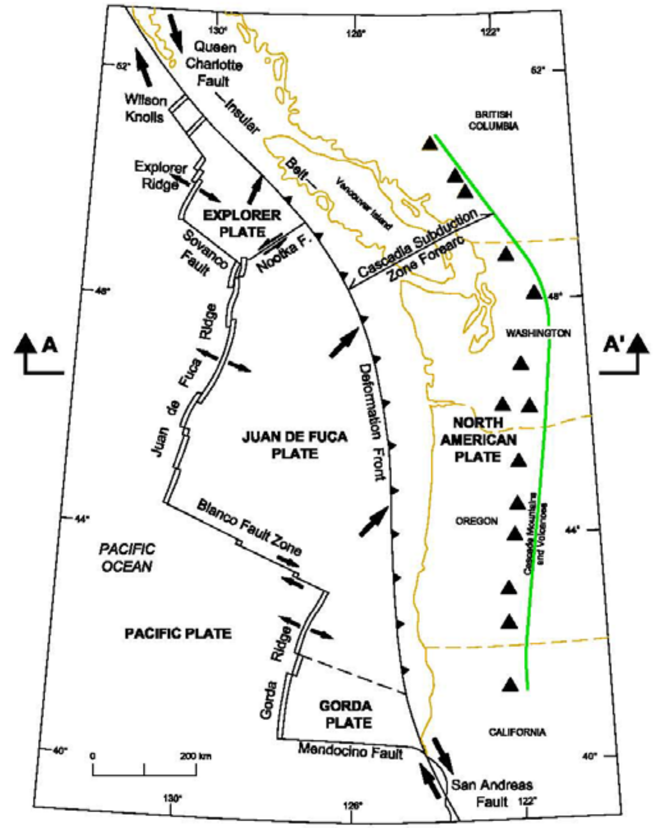


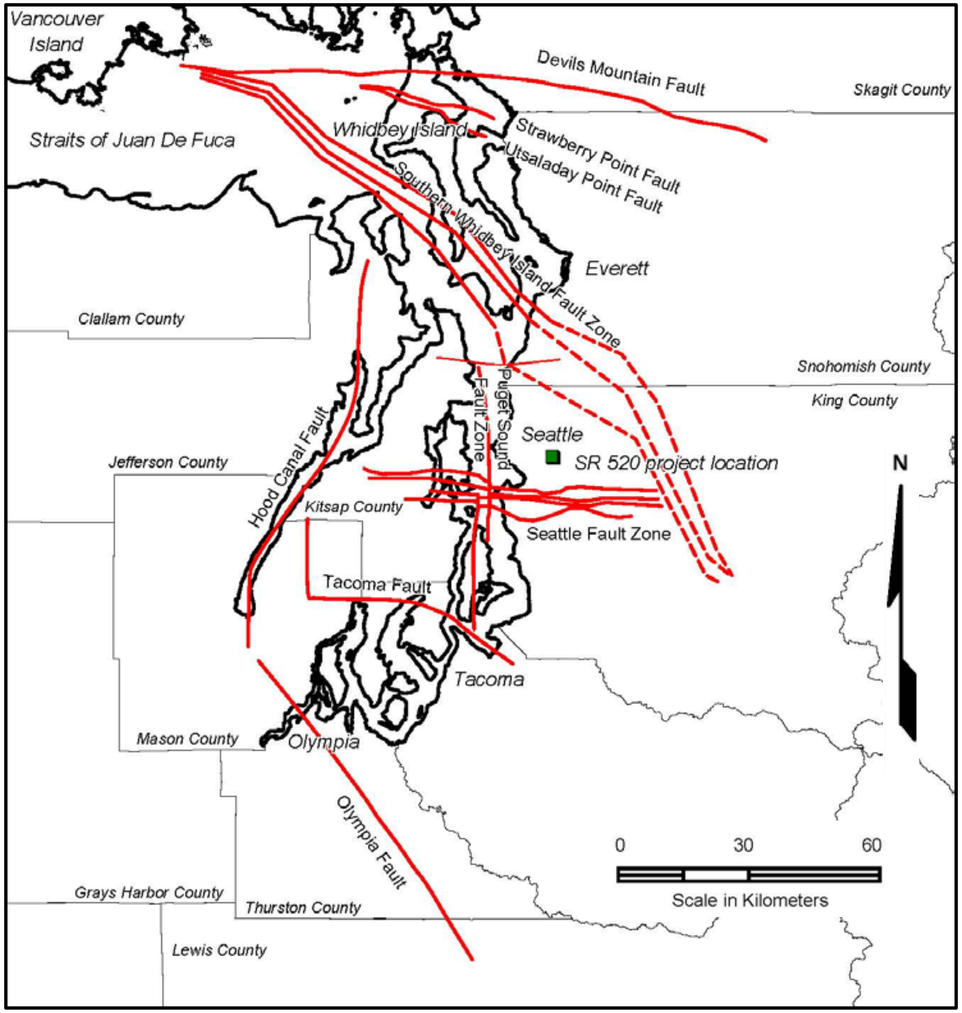
PLATE BOUNDARIES

LEGEND

A — Typical Geologic Cross Section Location

Puget Sound Region Seismic Setting

- Numerous crustal faults
- Significant sources:
  - Seattle Fault Zone (Less than 6 miles from the SR 520 Project)
  - South Whidbey Island Fault Zone
- These two sources are though to be capable of $M_{Max} = 7.5$.



Essential Bridge Designation

- In October 2009 WSDOT designated the mainline bridges on the SR 520 corridor as “essential” bridges.
- A reliable lake crossing is essential to the post – earthquake emergency mobility of the entire region.
- I-90 bridges across Lake Washington were not designed to current seismic standards
- Combined average daily traffic across the lake on I-90 and SR 520 is about 220,000.

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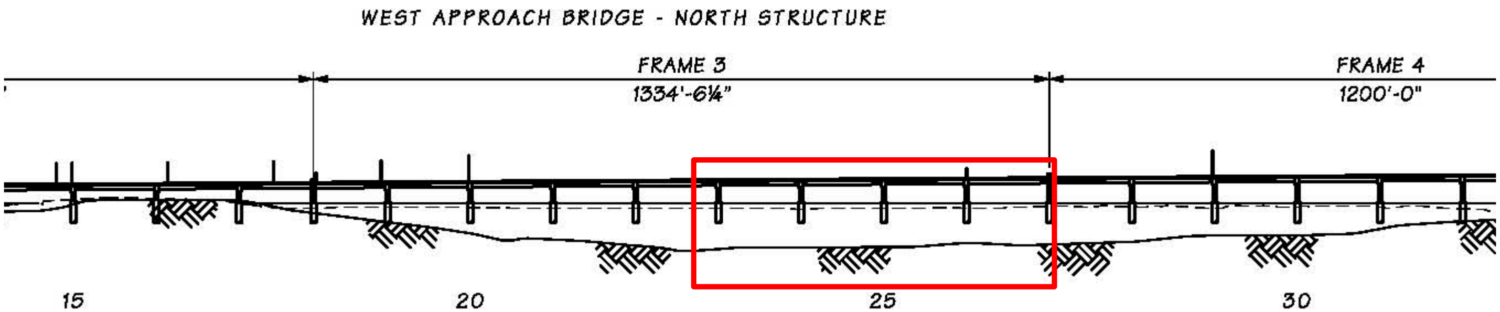
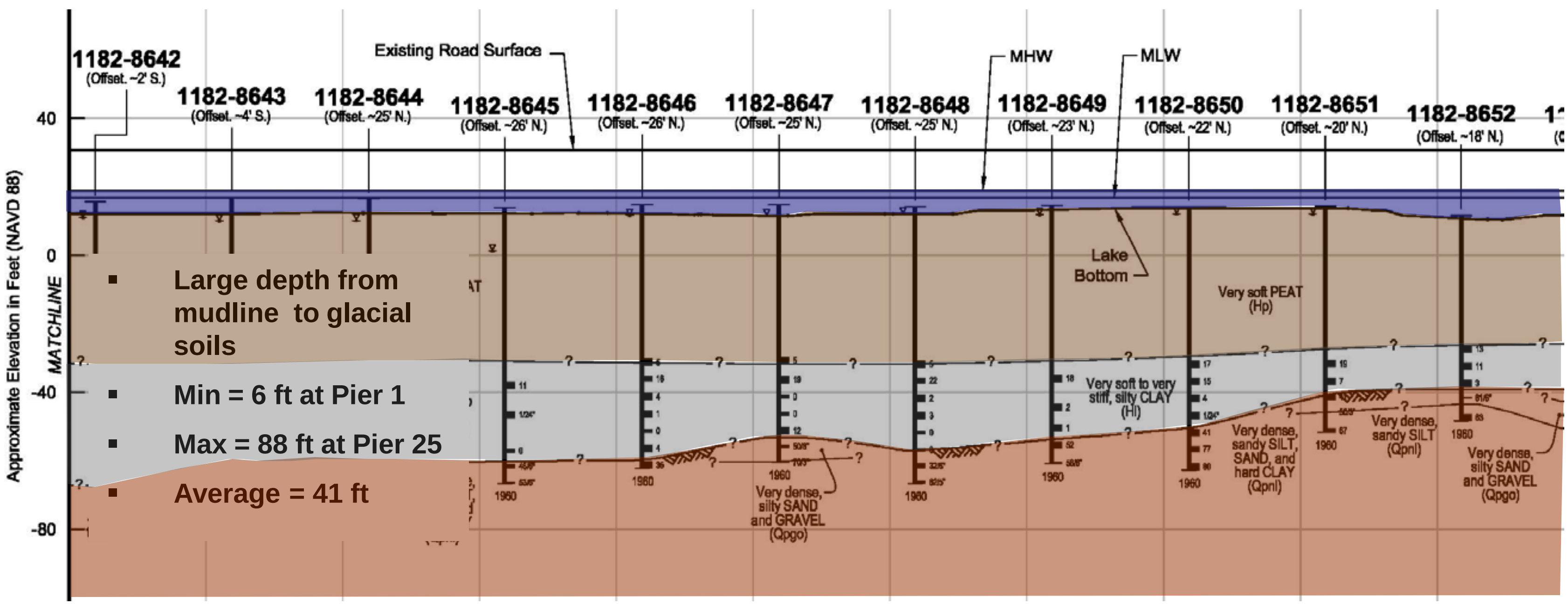
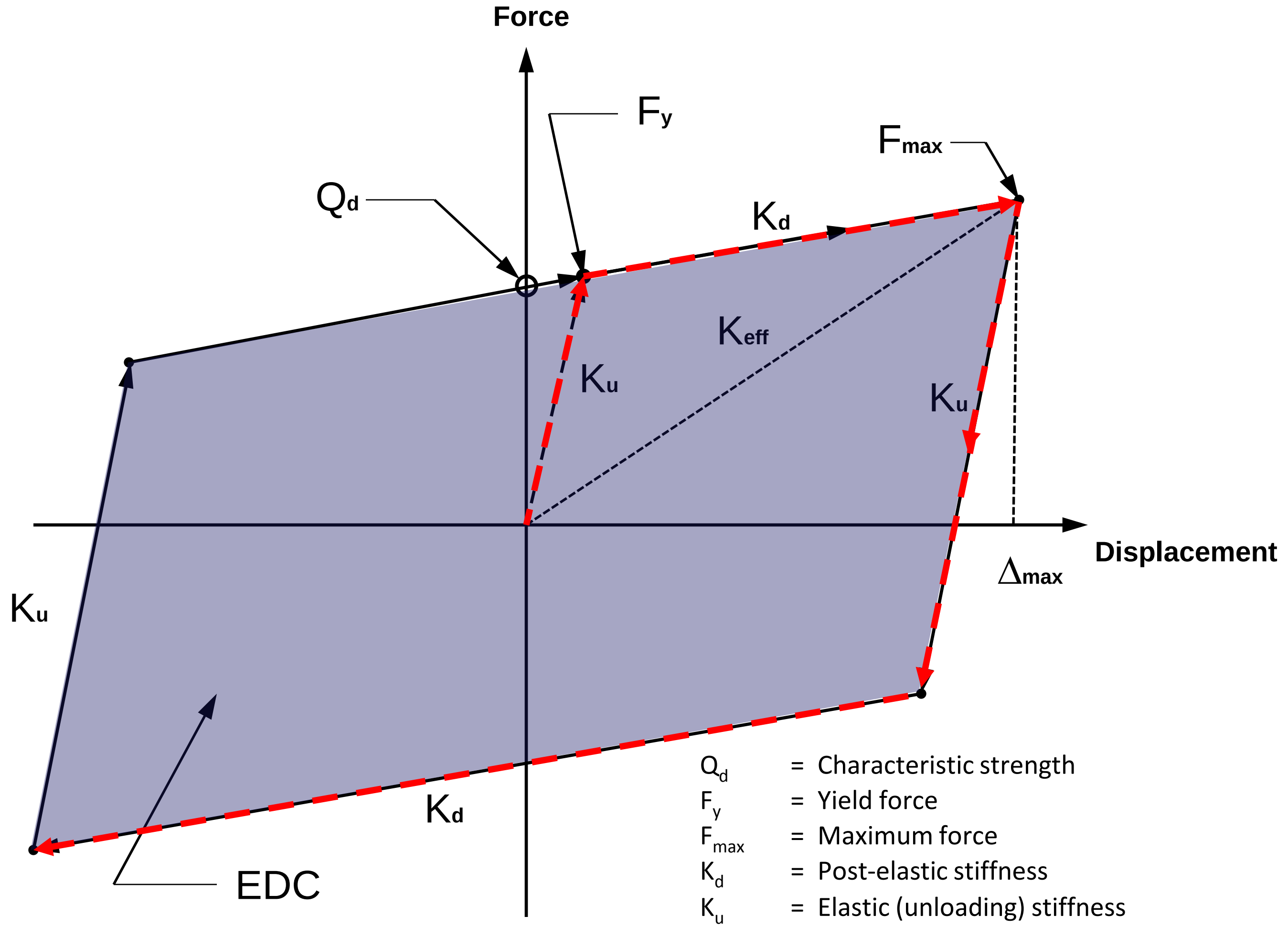
West Approach Bridge – Subsurface Soil Profile





- Large depth from mudline to glacial soils
- Min = 6 ft at Pier 1
- Max = 88 ft at Pier 25
- Average = 41 ft

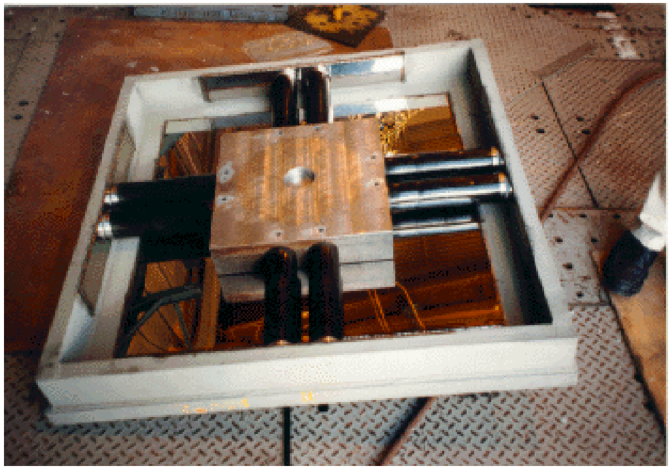
Typical Bilinear Hysteresis Loop



Q_d	=	Characteristic strength
F_y	=	Yield force
F_{max}	=	Maximum force
K_d	=	Post-elastic stiffness
K_u	=	Elastic (unloading) stiffness
K_{eff}	=	Effective Stiffness
Δ_{max}	=	Maximum Bearing Displacement
EDC	=	Energy Dissipation per cycle = Area of hysteresis loop (shaded)

Eradiquake Isolation Bearing

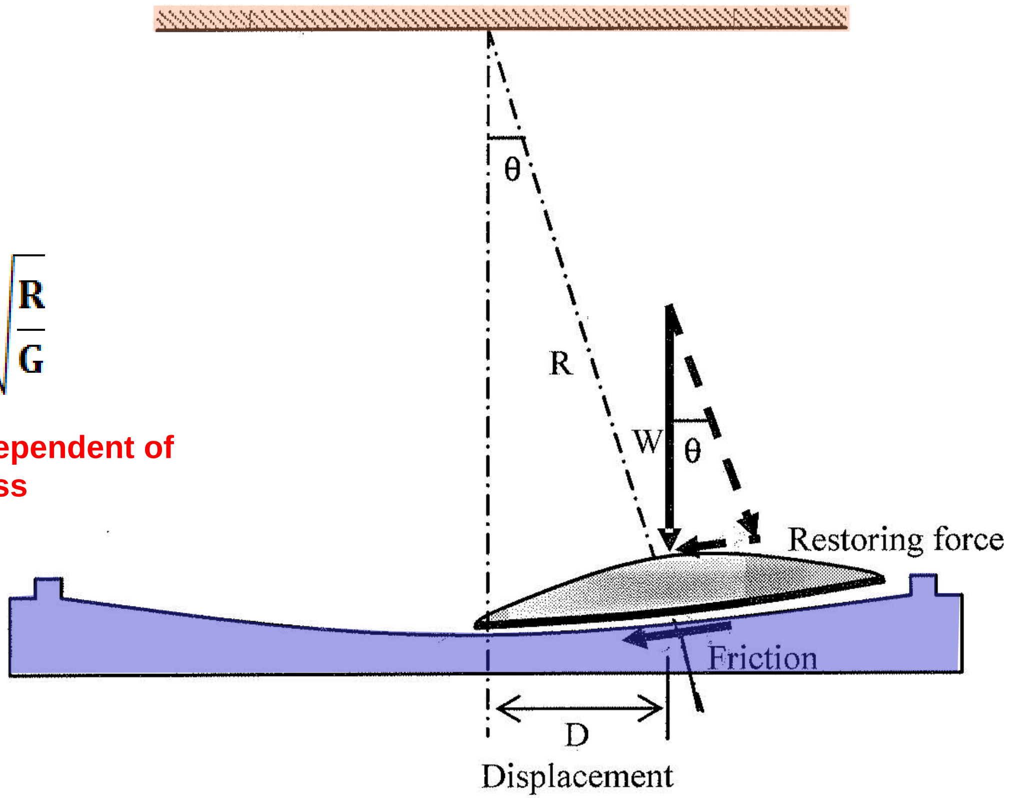
- Combines low friction sliding surface with a polyurethane disk bearing and polyurethane springs.
- Characteristic strength determined by the friction coefficient of the PTFE and polished mating surfaces.
- Post elastic stiffness is determined by the polyurethane springs.
- Polyurethane disk allows for structure rotations.
- Dissipates energy through friction and heat



Friction Pendulum Fundamentals

$$T = 2\pi\sqrt{\frac{R}{G}}$$

Period is independent of mass



$F_f = \mu W\cos\theta$

$F_r = W\sin\theta$

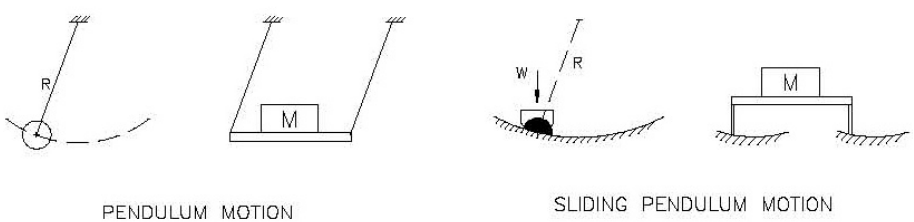
$\sin\theta = D/R$

$\cos\theta = 1$:
For small angles

$F = \mu W + WR/D$

or

$\mathbf{F = W(\mu + R/D)}$



Lateral force F is proportional to Weight.
This places the center of rigidity coincident with the center of gravity.

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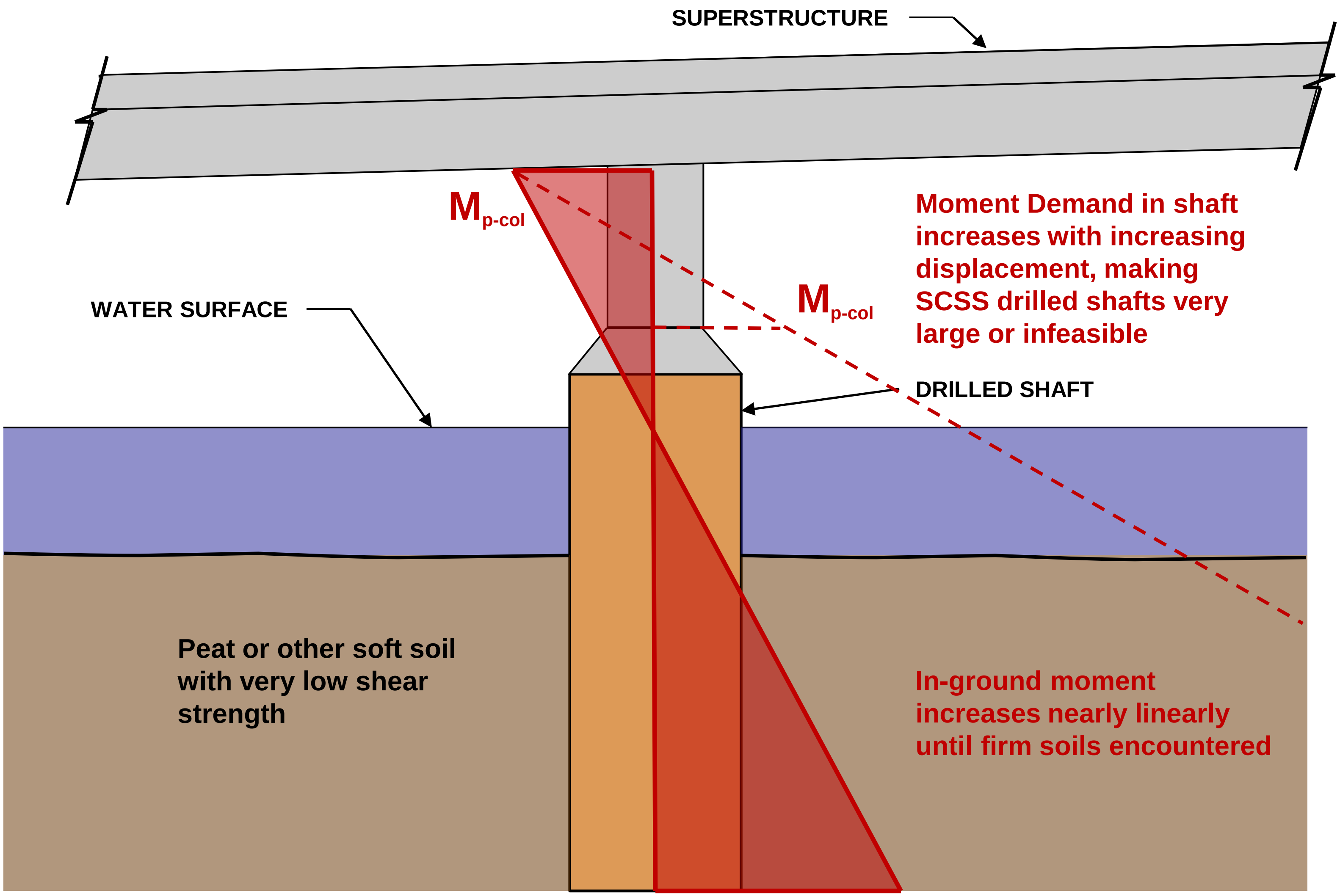
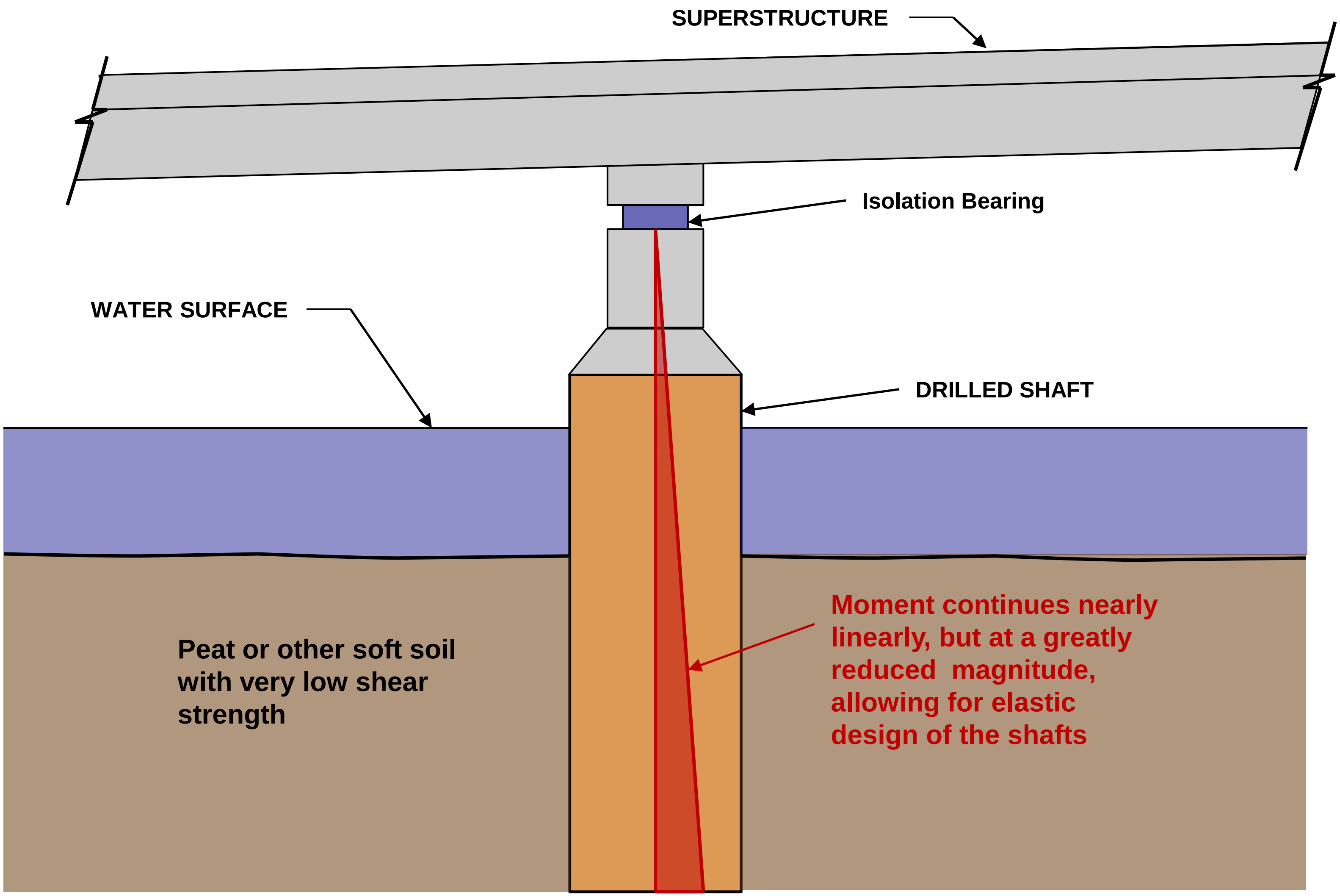
Short Columns and Soft Soils Pose Challenges for Conventional Seismic Design



Seismic Isolation Eliminates the Need for Casing Shoring



Model Parameters

Parameter	HDR	SC Solutions
Number of DOF	43,000	43,500
Number of Mode Shapes Required	1750	N/A
# of Unique Time History Input Files	705	2,541
# of Applied Time Histories	1515	22,995
Average Execution Time (per Analysis Case)	1 hour	4.5 hours
Post Processing Method	CSI Bridge API: Visual Basic / MS Excel	Adina AUI: Perl Script/ Visual Basic / MS Excel

Parallel Model for Triple FP

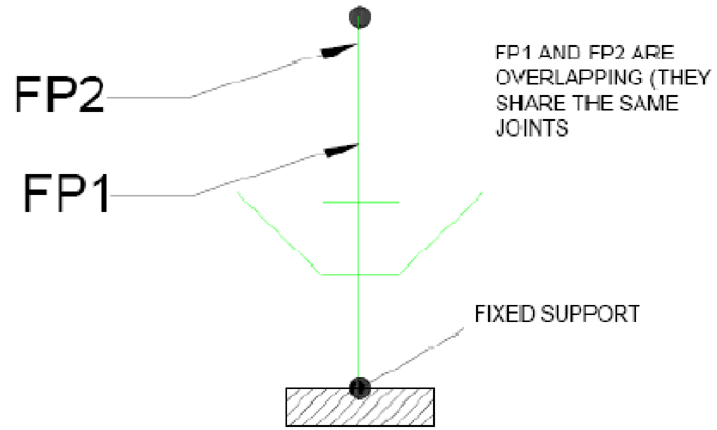


Figure 4 Parallel Model of Triple FP in SAP2000

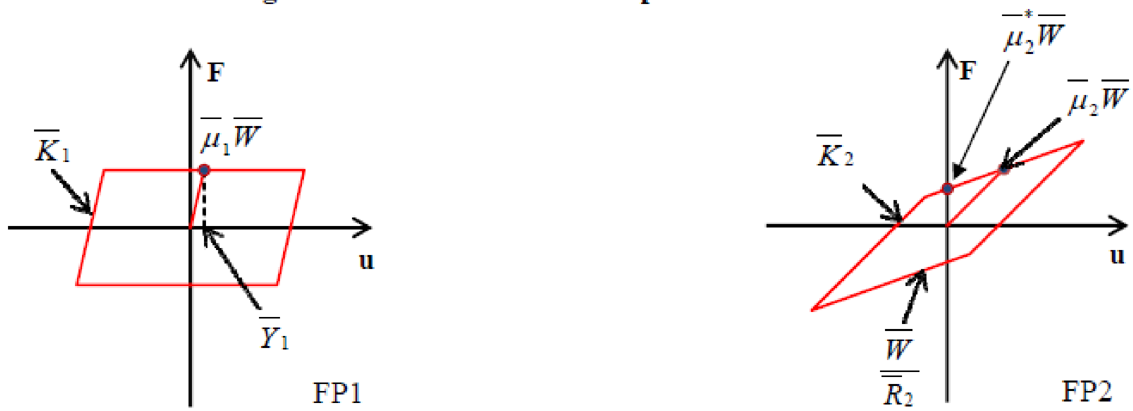


Figure 5 Force Displacement Loops of Elements FP1 and FP2 of the Parallel Model

From "Modeling Triple Friction Pendulum Isolators in Program SAP2000", Sarlis and Constantinou, June 27, 2010

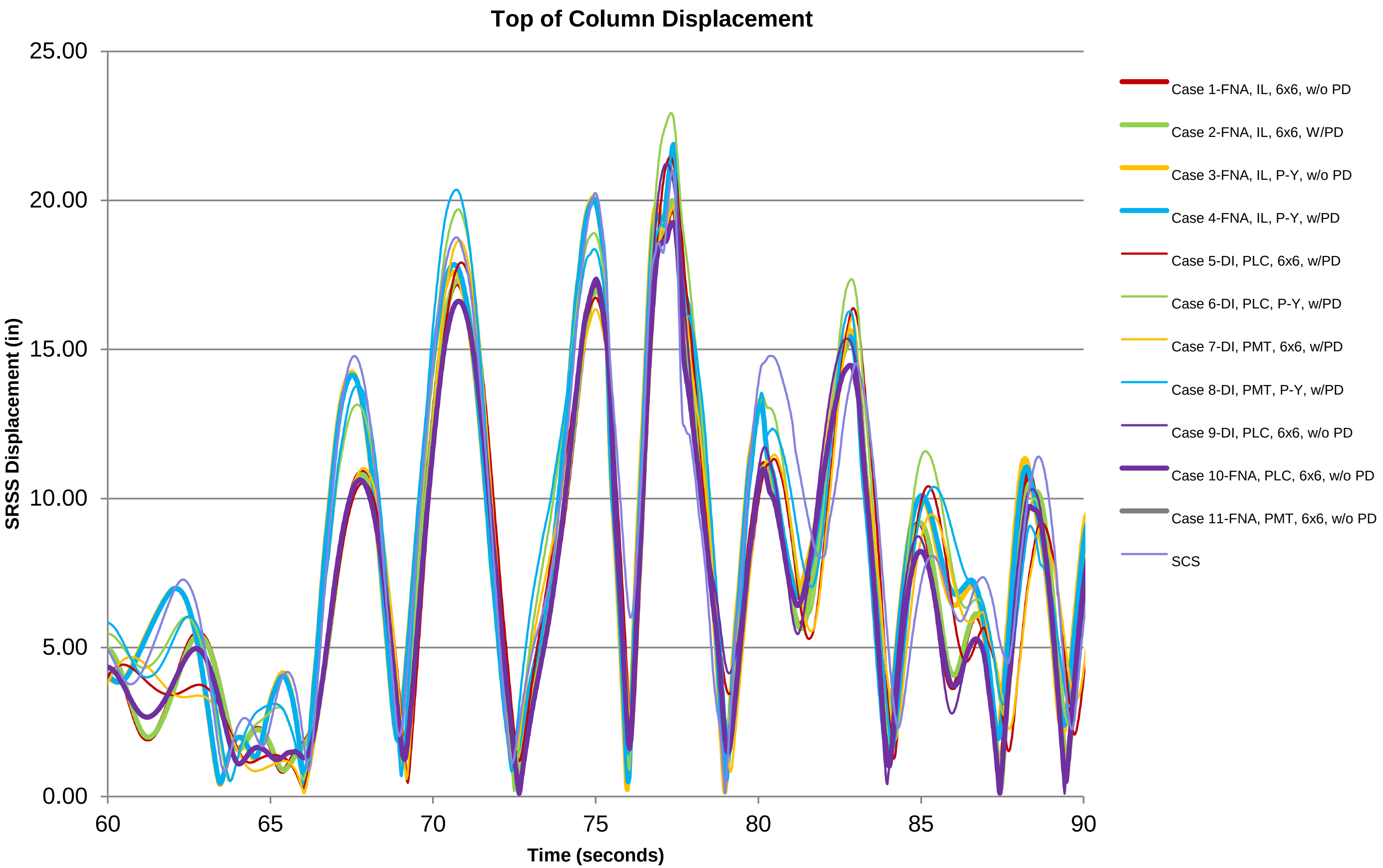
WABN Statistics

Parameter	Value	Notes
Length of Structure	6127 ft	Measured Along Survey Line
Number of Frames	5	Frame Lengths : 1198',1335',1335',1050',1050', Plus 1 Additional Simple span at 160'
Number of Spans	41	Typical span Length = 150 ft
Number of Piers	41	3 on Land, 38 in the Water
Number of Columns	95	
Number of Shafts	99	1 at each column + 4 at the abutment:
Number of Shafts in Water	89	99 Shafts - 4 at abutement - 6 at foster Island = 89
Average Diameter of Shafts	9 ft	8' Dia. Min, 12' Dia. Max
Number of Isolation Bearings	108	1 at each column = 95, + 4 at the abutment + additional 9 for the expansion joints = 108
Average Bridge Width	80.7 ft	Typical and Minimim = 65.9' , Maximum = 137.4' at the abutment (to exterior face of Barrier)
Approx. Plan Area of Bridge	500,000 SF	
Number of Shaft/Columns Eliminated by incorporating Seismic Isolation	39	

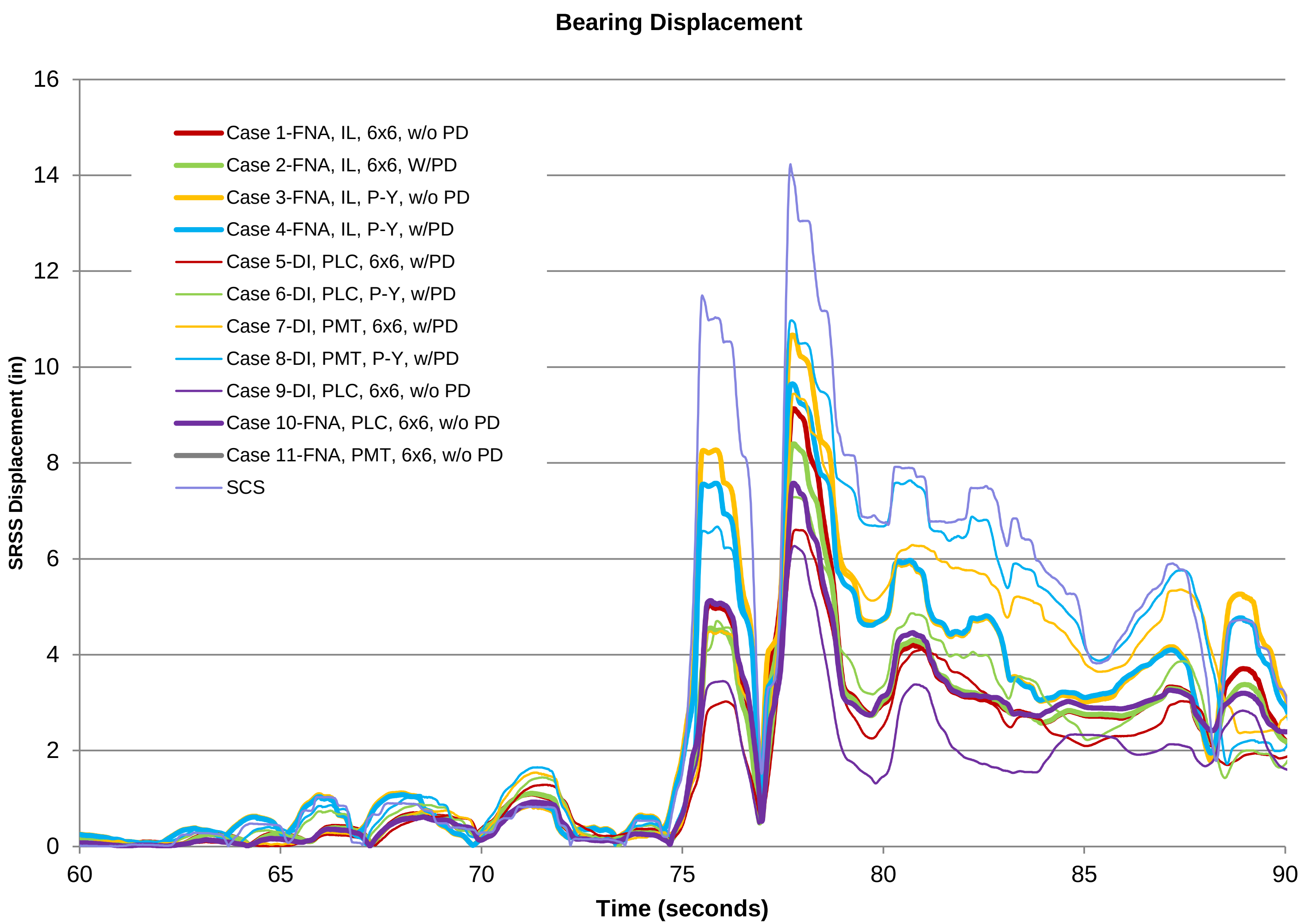
Parametric Study

Case	Analysis Method		Damping Method			Soil Structure Interaction		P Delta	
			Interp. Linear	Mass & Stiffness		6x6 Spring Matrix	P-Y Springs	w/o	With
	FNA	DI		On Load Case	On Materials				
1	X		X			X		X	
2	X		X			X			X
3	X		X				X	X	
4	X		X				X		X
5		X		X		X			X
6		X		X			X		X
7		X			X	X			X
8		X			X		X		X
9		X		X		X		X	
10	X			X		X		X	
11	X				X	X		X	
SCS		X			X		X		X

Parametric Study



Parametric Study



Column Results