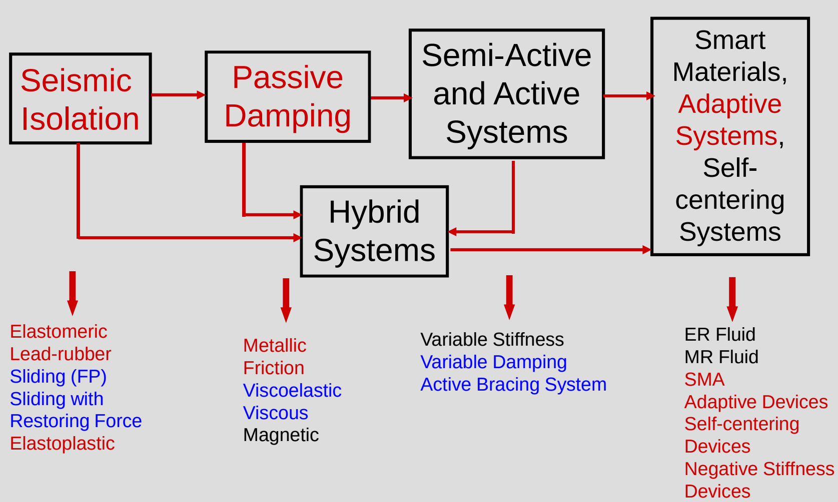
SEISMIC PROTECTIVE SYSTEMS

OVERVIEW OF STATE OF THE ART AND PRACTICE

Michael C. Constantinou
Professor
Department of Civil, Structural, and Environmental Engineering
University at Buffalo, State University of New York

SEISMIC PROTECTIVE SYSTEMS



SCOPE OF PRESENTATION

- Description of seismic protective systems and hardware
- Presentation of selected implementations of seismic isolation and energy dissipation hardware with emphasis on applications in bridges, buildings and the infrastructure
- Emphasis is placed on developmental work done at the University at Buffalo and projects in which the speaker was involved
- Scope is to demonstrate the maturity of the technology and the range of its application

ACKNOWLEDGMENTS

- Professors A. M. Reinhorn and A.S. Whittaker, Univ. at Buffalo
- Doctoral and post-doctoral students:

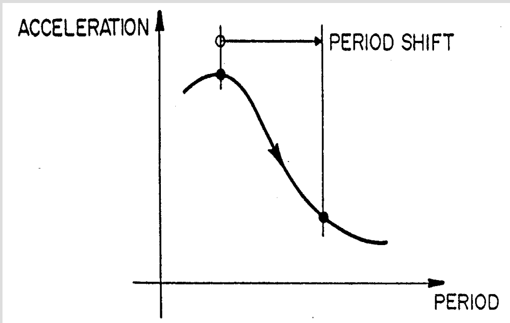
  Prof. N. Makris, Prof. P. Tsopelas, Prof. M.Symans,

  Prof. O. Ramirez, Prof. P. Roussis, Dr. A.S. Mokha,

  Dr. A. Kasalanati, Dr. J. Quarshie, Dr. E.D. Wolff, Dr. Ani N. Sigaher, Dr. E. Pavlou, Dr. C. Chrysostomou, Dr. D. Fenz, Dr. Y. Kalpakidis
- Current students:

  A. Sarlis, D. Basu, F. Fadi
- Research Sponsors: NSF, NCEER, MCEER, FEMA, State of NY, Department of Commerce, California Department of Transportation, Industry

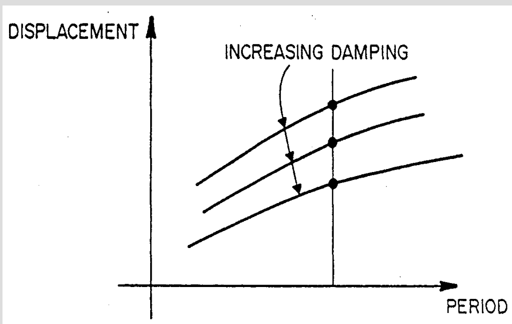
SEISMIC ISOLATION



A method of construction and a technology in which a system is used to provide period lengthening and ability to absorb energy

- isolator flexibility
- force reduction
- displacement increase

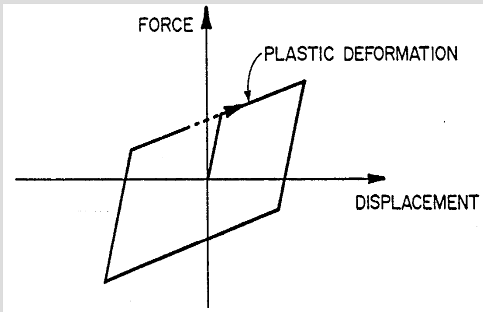
SEISMIC ISOLATION



Displacements

- isolator flexibility
- period shift
- isolator displacement
  - energy dissipation
- building displacement
  - damage reduction

SEISMIC ISOLATION

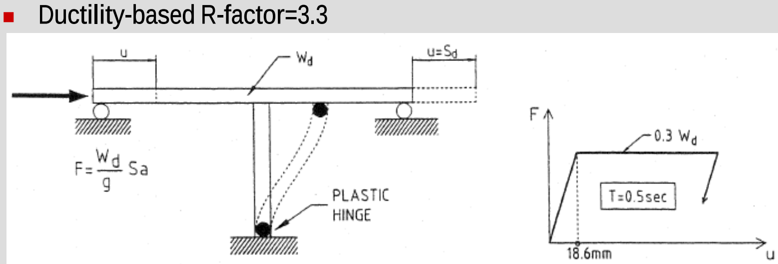


Energy dissipation

- hysteretic
  - high-damping rubber
  - yielding of lead
  - friction
  - external hardware
    - hybrid systems
- viscous
  - external hardware

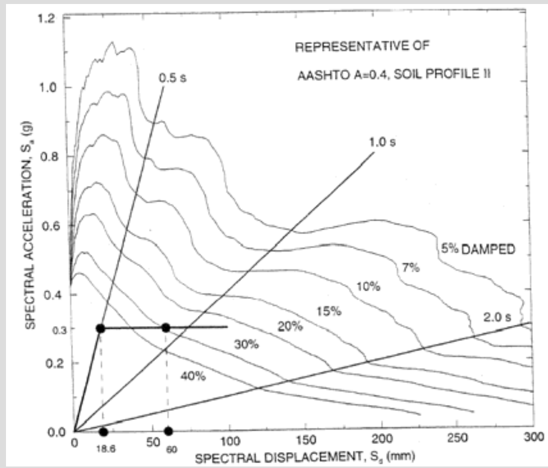
BENEFITS OF SEISMIC ISOLATION

- Consider a conventional bridge is AASHTO A=0.4, Soil Profile II (design-basis earthquake, 475-year return period)
- Expansion bearings are used at abutments-lateral resistance provided by a single multiple column bent
- Longitudinal direction elastic period is 0.5sec-elastic response is 1.0g
- R=5, Design Strength=0.2W, Yield (Actual) Strength=0.3W
- Over-strength=1.5 (primarily due to material over-strength)
- Ductility-based R-factor=3.3



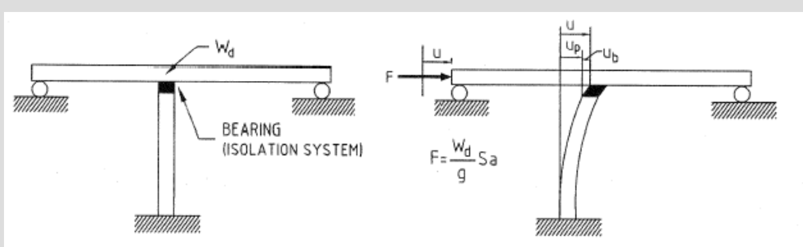
BENEFITS OF SEISMIC ISOLATION

- Performed simplified nonlinear static analysis (efficiency factor=0.7)
- Used FEMA 356 Method II
- Displacement=60mm
- T_{eff}=0.9sec
- Effective damp=0.30
- Ductility ratio=3.2



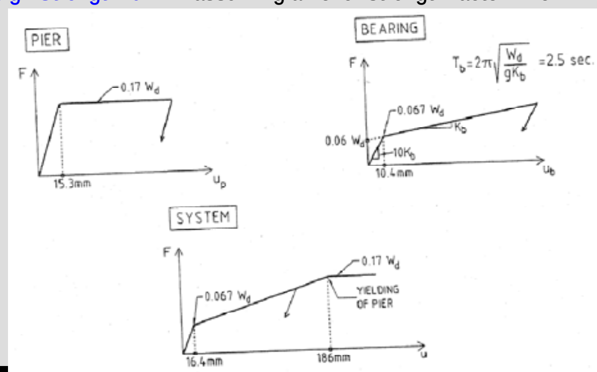
BENEFITS OF SEISMIC ISOLATION

- Consider a seismically-isolated bridge in which isolators are used only at the pier
- Expansion bearings are used at the abutment locations so that there are no benefits of re-distribution of the seismic force to all elements of the substructure
- Isolation system has 0.06W strength and period based on the post-elastic stiffness equal to 2.5sec (could be a lead-rubber system)



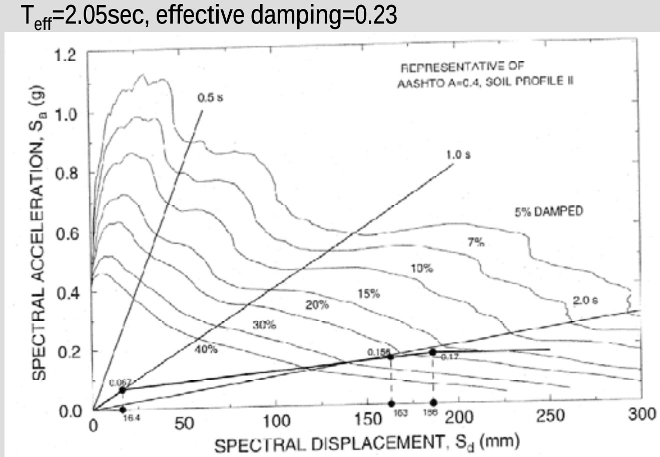
BENEFITS OF SEISMIC ISOLATION

- AASHTO would have allowed the use of R=2.5 but that is too large for the longitudinal direction for which the pier lacks redundancy and its over-strength cannot be larger than about 1.5. Rather, we select
  Yield Strength=0.17W, which is about 10% larger that the peak shear force calculated in the isolation system. This corresponds to
  Design Strength=0.11W assuming an over-strength factor =1.5



BENEFITS OF SEISMIC ISOLATION

- Displacement=163mm (149mm in the isolator, 14mm in the pier)
- Base shear=0.156W, elastic substructure
- T_{eff}=2.05sec, effective damping=0.23

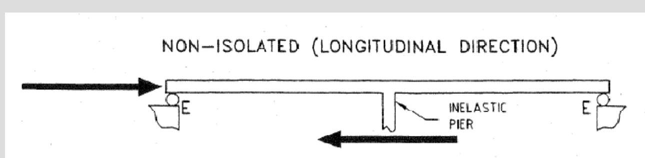


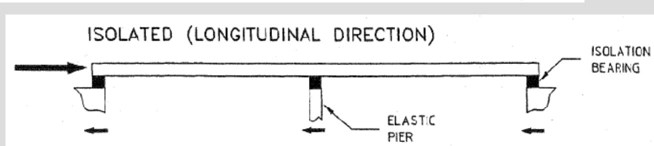
BENEFITS OF SEISMIC ISOLATION

- The isolated bridge has a pier Design Strength (0.11W) about half that of the conventional bridge (0.20W). Similarly, its Yield Strength (0.17W) is about half that of the conventional bridge (0.30W). This is the ultimate force for the design of the foundation.
- Elastic substructure of the isolated bridge and substantial inelastic action in the substructure of the conventional bridge
- Is this good enough for the isolated bridge?
- What happens in the Maximum Earthquake? Will the bridge fulfill the intent of Bridge Specifications for Collapse Prevention?
- Analysis for the Maximum Earthquake (approximately 1.5 times the Design-basis Earthquake) resulted in displacement of about 250mm and isolation base shear of about 0.21W. If the Yield Strength is 0.17W, a collapse mechanism will develop (cantilever column) and accounting for P-Δ effects, collapse could occur. To prevent collapse, the Yield Strength should exceed this amount, say it should be 0.25W.
- This corresponds to a Design Strength of 0.17W (but without the need for ductile detailing-although is a good practice to do so). Benefit of seismic isolation is seen as small in terms of the Design Strength (0.17 vs 0.20W) but there is damage prevention.

BENEFITS OF SEISMIC ISOLATION

- EFFECT OF RE-DISTRIBUTION
  - Seismic isolators will be placed at each support location, not just the pier
  - Base shear force will be near equally divided among the supports.





BENEFITS OF SEISMIC ISOLATION

- Conventional
  - Pier Design Strength=0.2W
  - Pier Yield Strength=0.3W
  - Substantial inelastic action in Design-basis Earthquake
  - Bearing displacement in Design Earthquake=60mm
  - Unknown performance in Maximum Earthquake
- Seismic Isolated (with re-distribution)
  - Pier Design Strength~0.06W
  - Pier Yield Strength~0.09W
  - Elastic substructure in Maximum Earthquake
  - Isolator displacement demand in Maximum Earthquake~250mm

ISOLATION HARDWARE

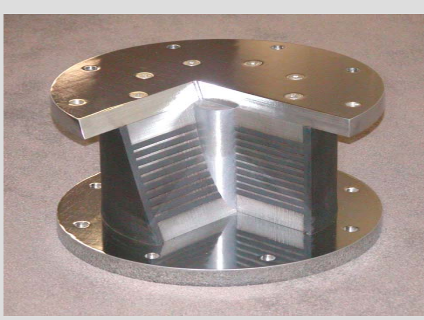
- Isolation bearings
  - Elastomeric
    - Low-damping rubber (NR)
    - High-damping rubber (HDR)
    - Lead-rubber (LR)
  - Sliding
    - Friction Pendulum (FP)
    - Sliding with Restoring Force
    - Sliding with Yielding Devices (Elastoplastic)
- Energy dissipation devices
  - Viscous dampers

ISOLATION HARDWARE

- Elastomeric Bearings for Sakhalin I Orlan Platform
- Tested at University at Buffalo, 2004

ISOLATION HARDWARE

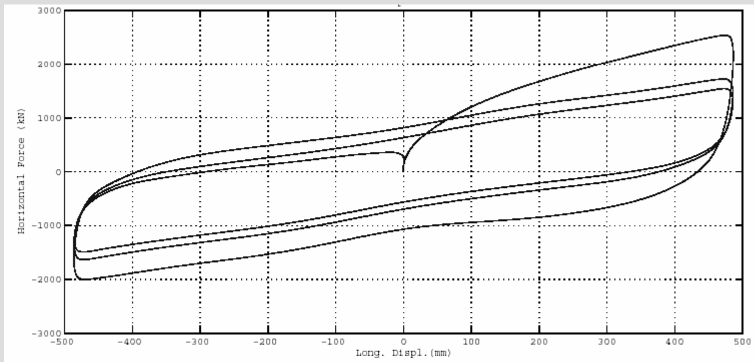
- LR bearing




ERZURUM HOSPITAL, TURKEY, 2007

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

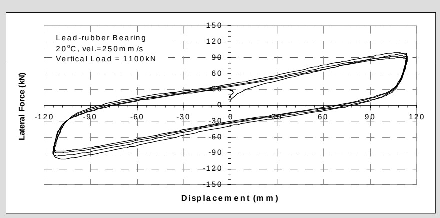
LEAD-RUBBER BEARING



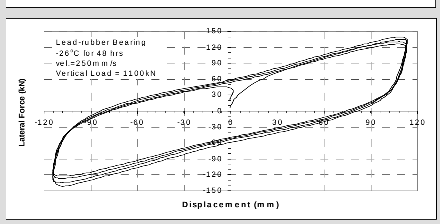
ERZURUM HOSPITAL, TURKEY, 2007
SRMD TEST MACHINE, UC SAN DIEGO
LOAD=10260kN, DISPLACEMENT=480mm, VELOCITY=1m/sec

CIE 500, 2009 **Civil, Structural & Environmental Eng. , University at Buffalo**

LEAD-RUBBER BEARING



TEMP=20^{O}C



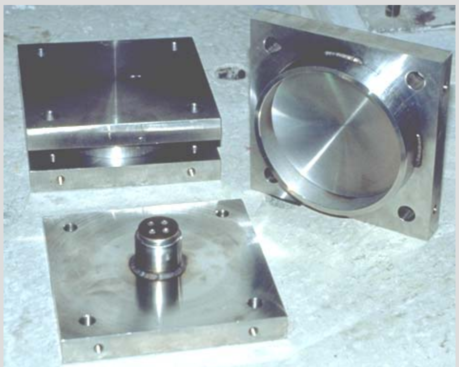
TEMP=-25^{O}C

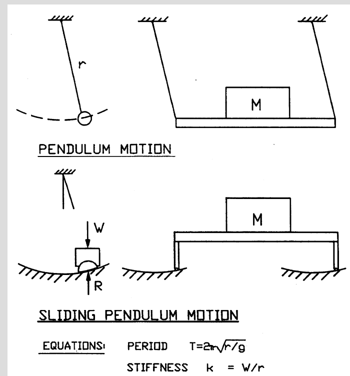
ROUTE 9W OVER WASHINGTON STREET, ROCKLAND COUNTY, NY
LEAD-RUBBER BEARING, UNIVERSITY AT BUFFALO
LOAD=1100kN, DISPLACEMENT=100mm, VELOCITY=250mm/sec

CIE 500, 2009 **Civil, Structural & Environmental Eng. , University at Buffalo**

ISOLATION HARDWARE

- FP bearing





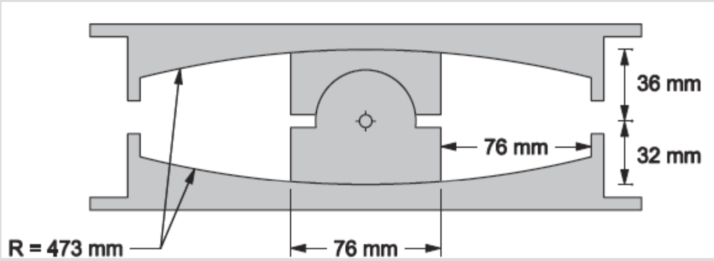
UNIVERSITY AT BUFFALO, 1988

FP BEARING

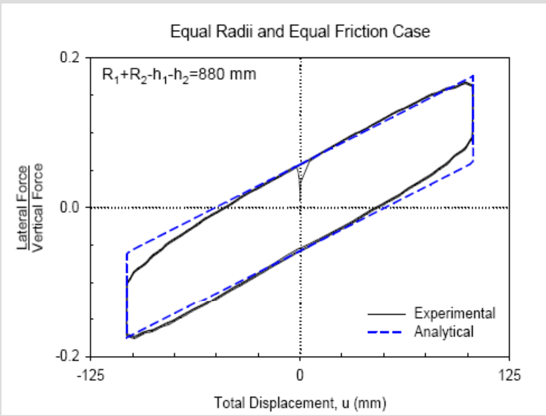
- Salkhalin II bearings
- Largest seismic isolators
- 700mm displacement
- 87,400kN gravity load
- 130,000kN max load
- Full-scale testing
- Reduced scale dynamic testing (load of up to 13,000kN, velocity of 1m/sec).

ADAPTIVE ISOLATORS

DOUBLE FP BEARING: A SYSTEM CAPABLE OF ADAPTIVE BEHAVIOR
RESULTS FROM TESTING AT UB



ADAPTIVE ISOLATORS
DOUBLE FP BEARING

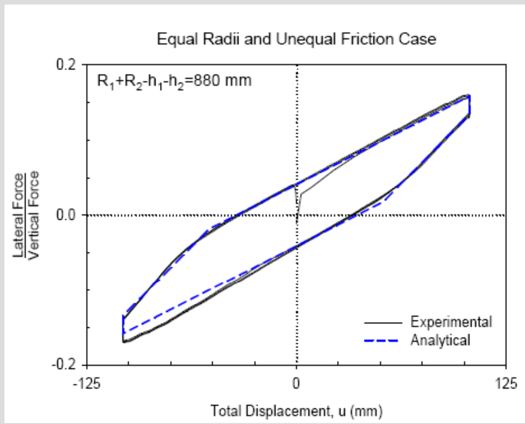


TWO CONCAVE PLATES, EACH WITH EQUAL RADII OF CURVATURE AND EQUAL COEFFICIENTS OF FRICTION

BEHAVIOR NEARLY IDENTICAL TO SINGLE CONCAVE FP BEARING- RIGID-LINEAR HYSTERETIC BUT OFFERS ADVANTAGES OF LARGE DISPLACEMENT CAPACITY AND SMALL PLAN DIMENSIONS

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

ADAPTIVE ISOLATORS
DOUBLE FP BEARING



TWO CONCAVE PLATES, EACH WITH EQUAL RADII OF CURVATURE AND UNEQUAL COEFFICIENTS OF FRICTION

RIGID-BILINEAR HYSTERETIC BEHAVIOR OFFERS ADVANTAGE OF REDUCTION OF SECONDARY SYSTEM RESPONSE

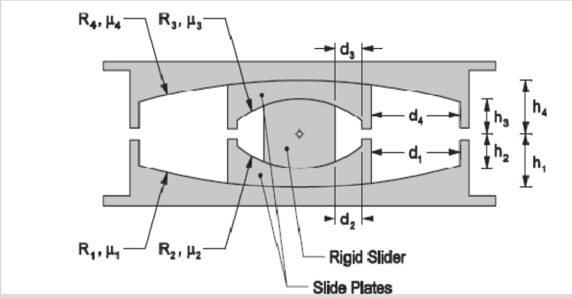
ADAPTIVE ISOLATORS
DOUBLE FP BEARING

Shake Table Testing
Univ. at Buffalo, 2004
Pacoima Record, San Fernando 1971
PGA=1.17g, PGV=0.57m/sec, PGD=0.91m

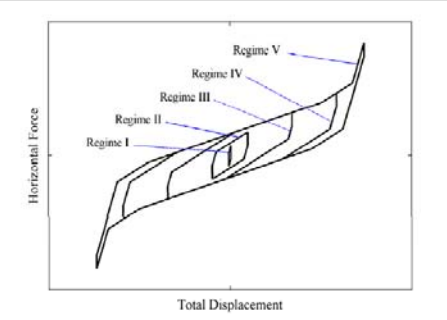
CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

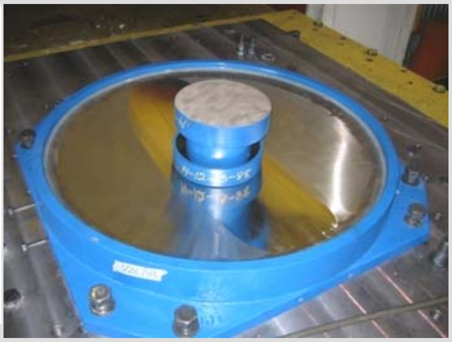
ADAPTIVE ISOLATORS
TRIPLE FP BEARING

TRIPLE FP BEARING: AN ADAPTIVE SYSTEM
RESULTS FROM TESTING AT UB

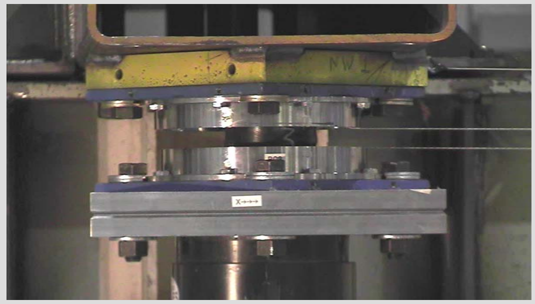


ADAPTIVE ISOLATORS
TRIPLE FP BEARING



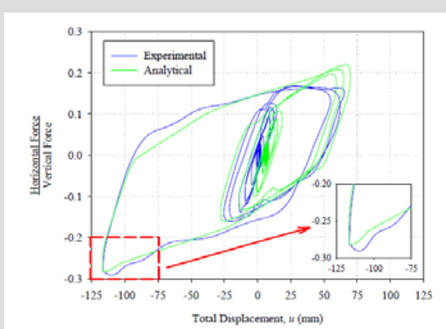


ADAPTIVE ISOLATORS
TRIPLE FP BEARING

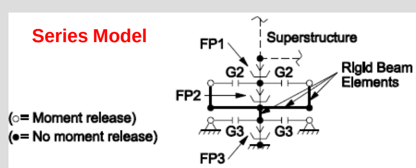


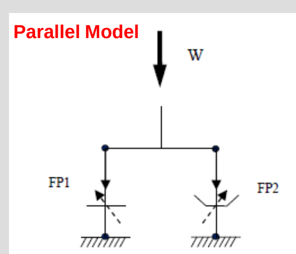
Shake Table Testing
Univ. at Buffalo, 2007
Sylmar Record, Northridge 1994
PGA=0.84g, PGV=0.65m/sec, PGD=0.8m

ADAPTIVE ISOLATORS
TRIPLE FP BEARING



Comparison of Experimental and Analytical Results



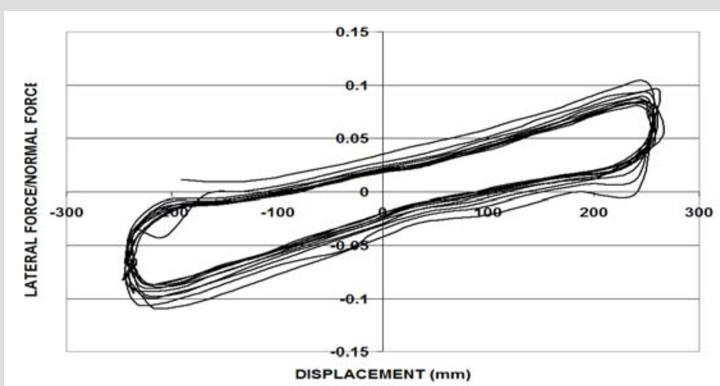


CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

LARGE-SCALE DYNAMIC TESTING

LARGE-SCALE TESTING MACHINE OF EPS
67,000 kN
1 meter/sec
2500mm STROKE

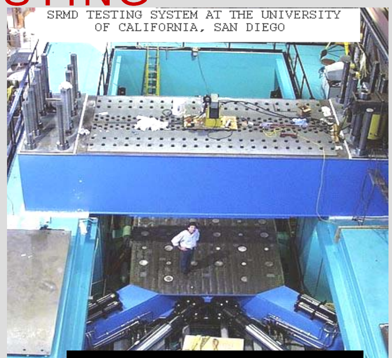
FP BEARING

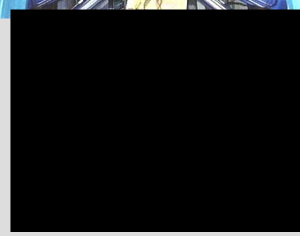


SAKHALIN II PLATFORMS PROTOTYPE BEARING PR1, LOAD=6925kN, DISPLACEMENT=240mm, VELOCITY=0.9 m/sec
EPS BEARING TESTING MACHINE, OCTOBER 2005

LARGE-SCALE DYNAMIC TESTING

- SRMD Test Machine
  - Horizontal capacity
    - 4500 kN per actuator
    - 2500 mm stroke
    - 1.8 meters/sec
    - 19.3m^3/min servovalves
  - Vertical capacity
    - 72 MN
- Used for testing of bearings for
  - Benicia Martinez bridge (FP)
  - Coronado bridge (LRB)
  - I-40 bridge (FP)
  - Erzurum Hospital (LRB)

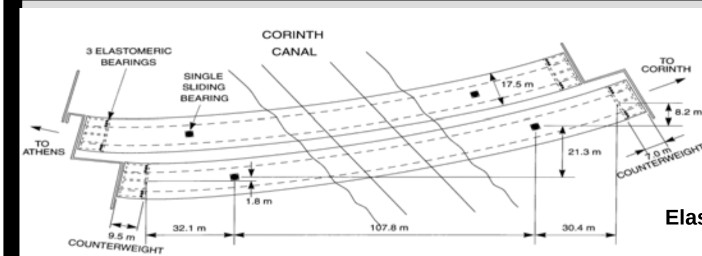




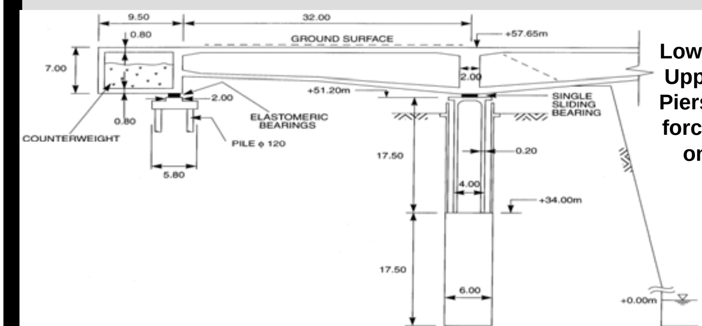
IMPLEMENTATION OF SEISMIC ISOLATORS IN BRIDGES

Corinth Canal Bridges, Greece, 1996

Twin, prestressed concrete box girder bridges.
Elastomeric and
flat sliding bearings.



Elastomeric (HDR) and flat sliding (DU metal in contact with stainless steel) bearings

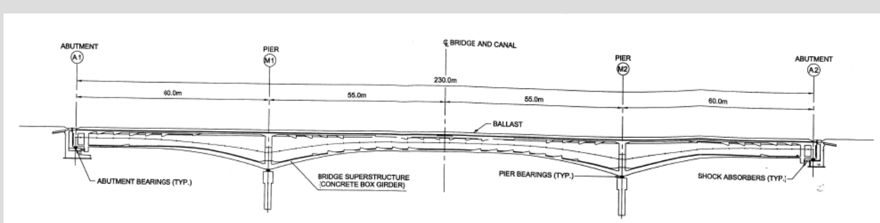


Lower bound friction 0.032
Upper bound friction 0.111
Piers designed for lateral force of 0.13 times load on sliding bearings

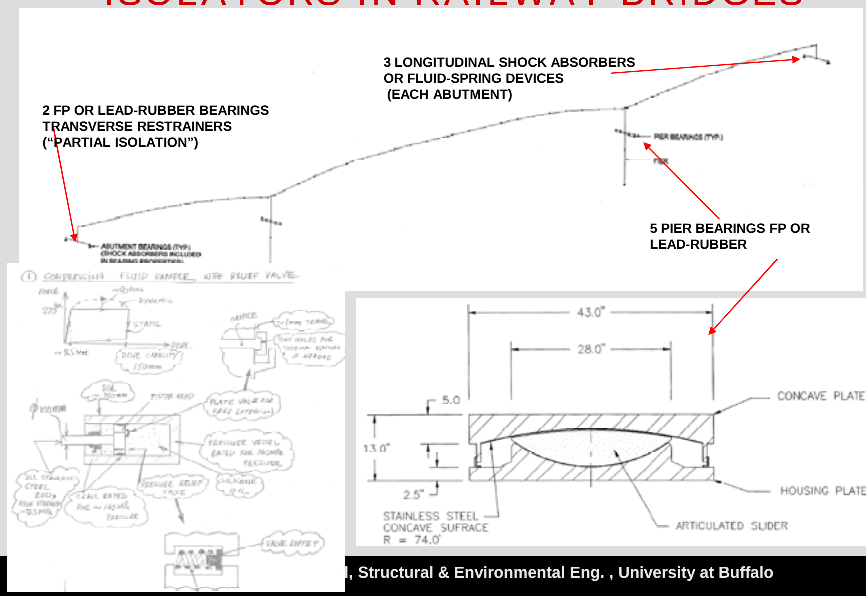
IMPLEMENTATION OF SEISMIC ISOLATORS IN RAILWAY BRIDGES

Corinth Canal Railway Bridge
Preliminary Design ,
Greece, 1996

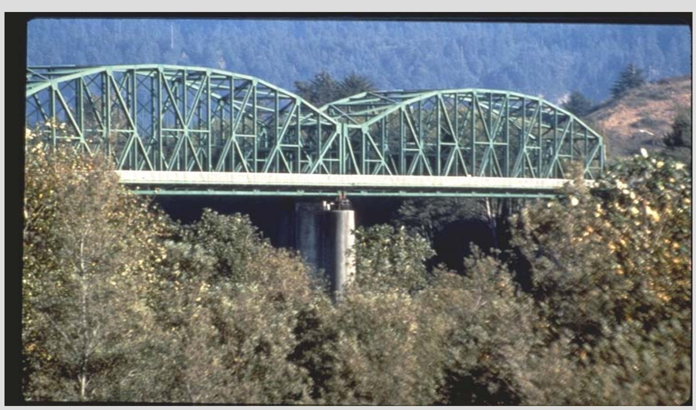
Prestressed concrete box girder bridge.



IMPLEMENTATION OF SEISMIC ISOLATORS IN RAILWAY BRIDGES



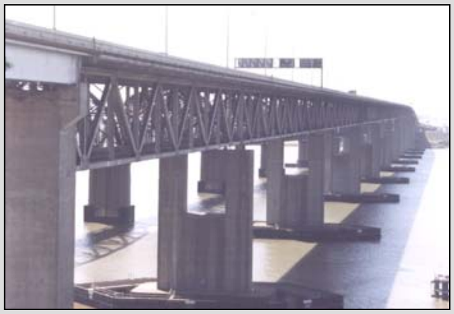
IMPLEMENTATION OF SEISMIC ISOLATORS IN BRIDGES



EEL RIVER BRIDGE
CALIFORNIA
RETROFIT, 1987

MOVED ABOUT 200mm IN PETROLIA EARTHQUAKE AND RE-CENTERED

IMPLEMENTATION OF SEISMIC ISOLATORS IN BRIDGES

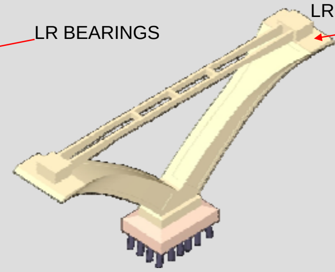


BENECIA-MARTINEZ BRIDGE
SAN FRANCISCO BAY AREA, RETROFIT 2000
OVER 1200mm DISPLACEMENT CAPACITY

IMPLEMENTATION OF SEISMIC ISOLATORS IN BRIDGES

- Woodrow Wilson Bridge, 2004
- Arch bridge
- Open lines of vision
- Bascule and fixed spans look the same
- Seismically isolated

IMPLEMENTATION OF SEISMIC ISOLATORS IN BRIDGES



- Eastern US, small seismic displacements
- Seismic isolators most useful in seismic load distribution
- Behavior of bearings important in both service and seismic conditions
- Two bearings underwent wear testing (1.6km total movement, 16,000 cycles at 25mm amplitude with dynamic testing prior to and after the wear test) at UB

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

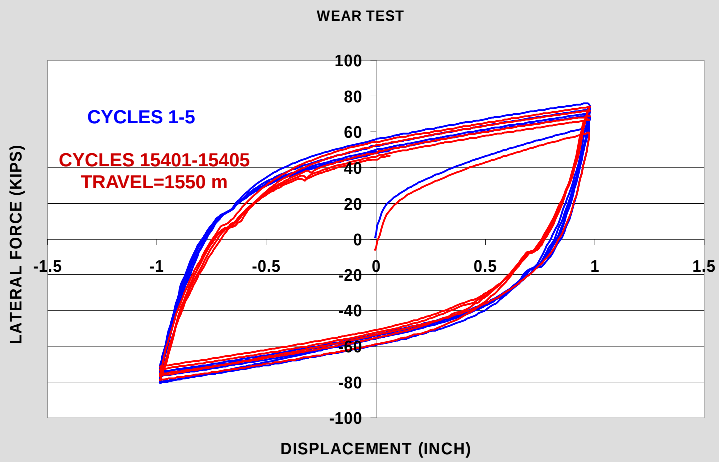
WOODROW WILSON BRIDGE

LEAD RUBBER BEARING
DYNAMIC TESTING
AT VELOCITY OF 250mm/sec, LOAD=1500kN

LEAD RUBBER BEARING
WEAR TESTING
AT VELOCITY OF 3mm/sec, LOAD=2000kN
16,000 CYCLES, TOTAL TRAVEL 1600m

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

CUMULATIVE TRAVEL (WEAR) TESTING



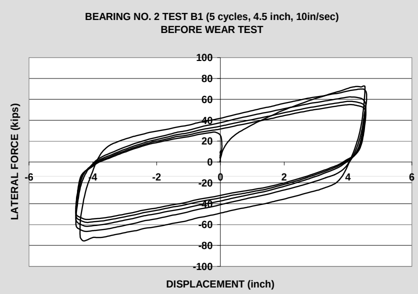
WOODROW WILSON BRIDGE

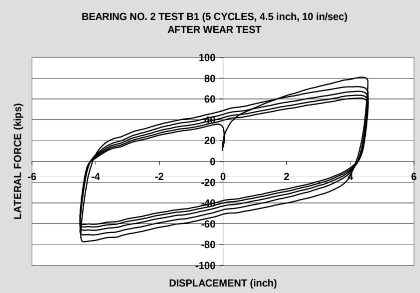
LR BEARINGS

WOODROW WILSON BRIDGE

BEFORE WEAR TEST (1600m TRAVEL)

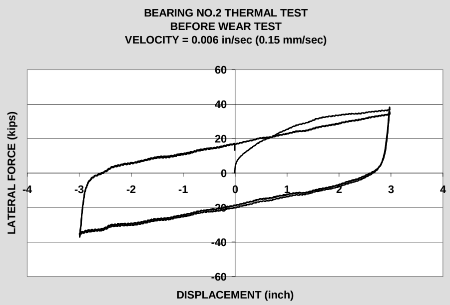
AFTER WEAR TEST



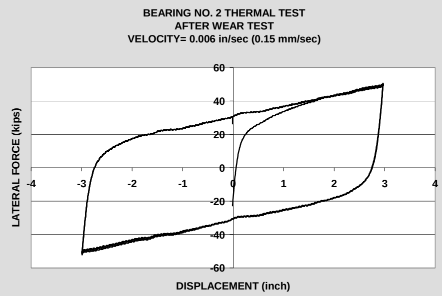


WOODROW WILSON BRIDGE

BEFORE WEAR TEST



AFTER WEAR TEST



IMPLEMENTATION OF SEISMIC ISOLATORS IN BRIDGES BOLU VIADUCT

BOLU VIADUCT, TURKEY
2.3 km LONG
DAMAGED IN DUCZE EARTHQUAKE OF NOV. 1999
CROSSED BY ANATOLIAN FAULT
BEARING DISPL. CAPACITY 210 mm
REQUIRED CAPACITY PER AASHTO OVER 1000 mm
LIKELY DEMAND IN EARTHQUAKE ≤1400mm

BOLU VIADUCT: DESCRIPTION OF DAMAGE

ALL 1638 BEARINGS FAILED

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

BOLU VIADUCT: DESCRIPTION OF DAMAGE

FAILED YIELDING STEEL DEVICES AT EXPANSION JOINT

LARGE LONGITUDINAL PERMANENT DISPLACEMENT

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

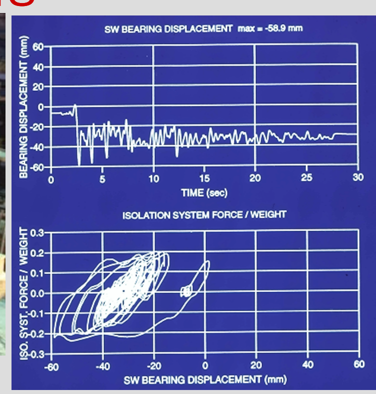
BOLU VIADUCT: CONCLUSIONS

- ISOLATION SYSTEM OF BOLU VIADUCT UNACCEPTABLE PER 1999 AASHTO GUIDE SPECIFICATIONS DUE TO LACK OF **SUFFICIENT RESTORING FORCE** (ALSO PER 2006 EUROPEAN prEN 1998)

- ISOLATION SYSTEM UNDER-DESIGNED PER 1991 AASHTO GUIDE SPECIFICATIONS (applicable at the time)
  - CAPACITY= 210 TO 480 mm, PLUS RESTRAINERS AND KEYS
  - DEMAND BASED ON AASHTO SPECTRUM=820 mm OR MORE
  - CAPACITY SHOULD HAVE BEEN 1.25X820= 1025 mm OR MORE

- PRINCIPAL PROBLEM: LACK OF PEER REVIEW

EXPERIMENTAL STUDY OF ELASTOPLASTIC ISOLATION SYSTEMS

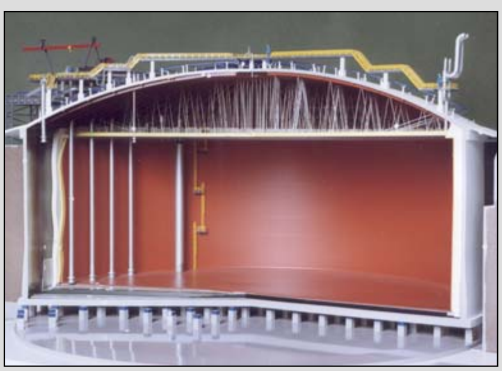


SHAKE TABLE TESTING OF ELASTOPLASTIC SYSTEM AT UNIVERSITY AT BUFFALO, 1993
SHOWN EXPERIMENTAL RESPONSE WITH LARGE PERMANENT DISPLACEMENT IS FOR 1952 TAFT N21E MOTION, SCALED TO 0.6 g (MOTION HAD A "HIGH" VELOCITY PULSE)

IMPLEMENTATION OF SEISMIC ISOLATORS IN INFRASTRUCTURE

- LNG Tanks, Greece, 1996
  - 430 Friction-pendulum bearings
  - Development work at University at Buffalo (development of computer code 3D-BASIS-ME, development of simplified procedures for analysis and design of inner tank under uplift conditions, development and implementation of quality control program for isolators, peer review services, inspection of isolators in 2002)
  - Tested by manufacturer (EPS)
  - Engineering: Whessoe, UK

IMPLEMENTATION OF SEISMIC ISOLATORS IN LNG TANKS



LNG TANKS, REVITHOUSSA, GREECE, 1996

65,000 m^3 CAPACITY, 75m DIAMETER, 35m HEIGHT (ISOLATOR TO ROOF)

9% NICKEL INNER TANK

PRESTRESSED CONCRETE OUTER TANK

1m PERLITE INSULATION WITH CURTAIN TO ALLOW THERMAL BREATHING

1m INSULATION AT BOTTOM
1m THICK CONCRETE SLAB

UNANCHORED INNER TANK

UNDERGROUND CONSTRUCTION FOR SAFETY REASONS (CONTAINMENT OF SPILLAGE, LOW PROFILE TARGET) AND AESTHETIC REASONS

ISOLATION ALLOWED CONSTRUCTION OF “SLENDER” TANK WITH REDUCED FOOTPRINT AND SMALLER SIZE FOUNDATION

IMPLEMENTATION OF SEISMIC ISOLATORS IN LNG TANKS

LNG TANKS, REVITHOUSSA, GREECE, 1996

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF SEISMIC ISOLATORS IN OFFSHORE GAS AND OIL PLATFORMS

SAKHALIN ISLAND, RUSSIA

OFFSHORE GAS PLATFORM WITH CONCRETE GRAVITY BASE

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF SEISMIC ISOLATORS IN OFFSHORE PLATFORMS

- Lunskoye and Piltun Platforms, Sakhalin, 2006
  - Seismic isolation of platforms
  - Contributions of University at Buffalo (development of procedures for scaling and testing seismic isolators, development of technical basis for design of isolators, simplified analysis of platforms)
  - Engineering: AMEC, UK

SAKHALIN ISLAND GAS/OIL PLATFORMS PILTUN AND LUNSKOYE PLATFORMS

SAKHALIN II PROJECT
LOCATION OF SEISMIC ISOLATION SYSTEM ON TOP OF CONCRETE GRAVITY BASE IN PILTUN AND LUNSKOYE PLATFORMS
GOAL IS TO PROTECT ENTIRE STRUCTURE ABOVE CONCRETE GRAVITY BASE

LUNSKOYE/PILTUN PLATFORMS

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

LUNSKOYE/PILTUN PLATFORMS

	Lunskoye	Piltun
Design Life (years)	30	30
Topsides Dry Weight (m. tons)	21 000	27 500
Topsides Operating Weight (m. tons)	27 000	33 500
Approximate Topsides Plan Dimensions (m)	100 x 50	100 x 70
Water Depth (m)	49	30
Number of Conductors	27	45
Facilities	Drilling Production Utilities Living Quarters	Drilling Production Utilities Living Quarters
Gas Production	1850 MMSCFD	100 MMSCFD
Oil/ Condensate Production	50000 BPD	70000 BPD
GBS Caisson Size LxBxD (m)	105x88x13.5	105x88x13.5
Number of GBS columns	4	4

- LOADINGS
  - Temperature
    - -36^{0}C to 36^{0}C
  - Snow and ice accumulation
    - 100-year return period
    - 2000 to 2500 m. tons per platform (~80psf)
  - Blast
    - Blast pressure greater than normal due to sealed compartments used to maintain minimum temperature of +5^{0}C
  - Ice and wave
  - Seismic

CIE 500, 2009 Civil, Structural & Environmental Eng. , University at Buffalo

LUNSKOYE/PILTUN PLATFORMS-ICE LOADING

- Ice present for 6 months, up to 2m thick
- Horizontal loads per platform
  - 260MN (103MN per leg) for 1-year return period (operational)
  - 324MN (124MN per leg) for 100-year return period (frequent event) (~18% of weight on each leg)
  - 435MN (155MN per leg) for 10,000-year return period
- Necessitated all services to be within legs
- Design criteria
  - No damage to topsides for 100-year wave/ice effects
  - Survival criteria for 10,000-year return period wave/ice

LUNSKOYE/PILTUN PLATFORMS-SEISMIC LOADING

Strength Level (SLE)

- 200-year return period
- No loss of life
- Essentially elastic behavior (some local limited yielding allowed)
- Equipment functional
- Shutdown and inspection likely

Ductility Level (DLE)

- 3000-year return period
- Structural damage acceptable
- Collapse prevention
- Safety critical equipment fully functional
- Means of escape intact
- No major environmental damage

LUNSKOYE/PILTUN PLATFORMS-ISOLATORS

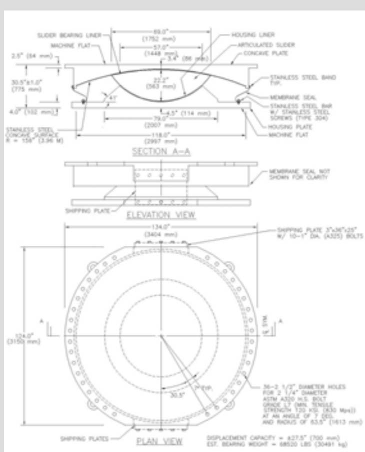
SLE Response		
Calculations based on nominal properties	Without isolation	With isolation
Deck Accel. (0 to +47m)	0.65 to 0.85 g	0.24 to 0.31g
Equipment Accel. (cranes, flare, etc.)	1.2 to 4.4 g	0.6 to 2.0 g

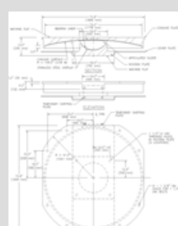
Isolators

- Single concave FP
- Cast steel suitable for low temperatures
- Radius of curvature 3962mm
- Displacement capacity 700mm
- Contact diameter 1752mm
- Pendulum period 4.0 sec
- Lower bound friction 0.040
- Upper bound friction 0.095
- Range of nominal friction 0.04 to 0.06
- λ-factors
  - 1.2 aging
  - 1.1 travel of 2900m
  - 1.4 temperature of -40^0C
- Adjustment factor 0.75, so that λ_{max}=1.60

LUNSKOYE/PILTUN PLATFORMS

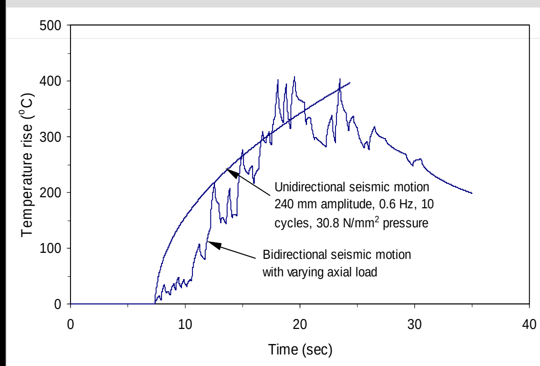
FULL SIZE PRDUCTION BEARING





REDUCED SIZE PROTOTYPE BEARING

LUNSKOYE/PILTUN PLATFORMS



SCALING PROCESS

1. MAINTAIN AVERAGE PRESSURE
2. MAINTAIN EDGE PRESSURE
3. MAINTAIN THICKNESS OF LINER
4. SCALE OVERLAY THICKNESS
5. SELECT BEARING THICKNESSES TO MAINTAIN THERMODYNAMIC CONDITIONS
6. SELECT TESTING PROCEDURE TO SIMULATE TEMPERATURE RISE DUE TO FRICTIONAL HEATING AT SLIDING INTERFACE IN MOST CRITICAL LOADING CASE (RELATED TO WEAR OF LINER)

IMPLEMENTATION OF SEISMIC ISOLATORS IN STORAGE TANKS

- Case of cryogenic storage tanks near populated seismically active area (Sicily, Italy)
- Demolition and rebuilding not an option-cannot build anything new in that area
- Seismic isolation retrofit an attractive option
- Concept applicable to refineries near populated areas

SICILY, 2005, COURTESY OF ANDREA SANTAGELO

IMPLEMENTATION OF SEISMIC ISOLATORS IN STORAGE TANKS

- Soft first story construction
- Strengthening of columns would transfer problem to tank above and would require strengthening of foundation
- Seismic isolation (reduction of force) an attractive option
- Strengthening of columns still needed

IMPLEMENTATION OF SEISMIC ISOLATORS IN STORAGE TANKS

IMPLEMENTATION OF SEISMIC ISOLATORS IN STORAGE TANKS

- Due to close spacing of columns, temporary transfer of load not needed (but support system provided)
- Isolators inserted without need to preload (no use of flat jacks)
- Use of FP bearings with transfer of P-Δ moment on strengthened column below

IMPLEMENTATION OF SEISMIC ISOLATORS IN BUILDINGS

Salt Lake City Hall

- 208 LR bearings
- 239 Rubber bearings

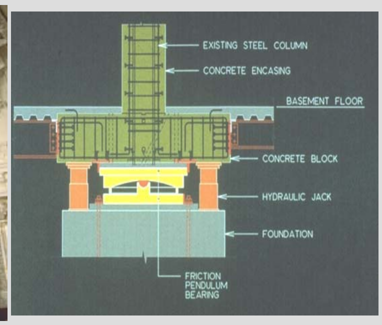
BUILT IN 1894, UNREINFORCED BRICK AND STONE, 5-STORY WITH 12-STORY TOWER, 80m BY 40m. BEARINGS 450mm IN PLAN, 400mm TALL. SEISMIC ISOLATION RETROFIT COMPLETED IN 1987. FIRST RETROFIT WITH ELASTOMERIC BEARINGS.

IMPLEMENTATION OF SEISMIC ISOLATORS IN BUILDINGS

- US Court of Appeals Building, San Francisco
  - 256 FP bearings
  - 100m by 81m, 32500sm

IMPLEMENTATION OF SEISMIC ISOLATORS IN BUILDINGS

US COURT OF APPEALS, SAN FRANCISCO FIRST SEISMIC ISOLATION RETROFIT WITH SLIDING BEARINGS. COMPLETED IN 1995.



BUILT IN 1905, SURVIVED 1906 E'QUAKE, STEEL FRAME WITH GRANITE WALLS.

IMPLEMENTATION OF SEISMIC ISOLATORS IN BUILDINGS

- AboveNet Building, 2001
  - San Francisco, 13000 sm
  - 98 FP bearings
  - Seismic rehabilitation

IMPLEMENTATION OF HYBRID SEISMIC ISOLATION SYSTEMS

SAN BERNANDINO HOSPITAL, CALIFORNIA, 1993
400 HIGH DAMPING RUBBER BEARINGS AND
186 NONLINEAR VISCOUS DAMPING DEVICES
600mm DISPLACEMENT CAPACITY

IMPLEMENTATION OF HYBRID SEISMIC ISOLATION SYSTEMS

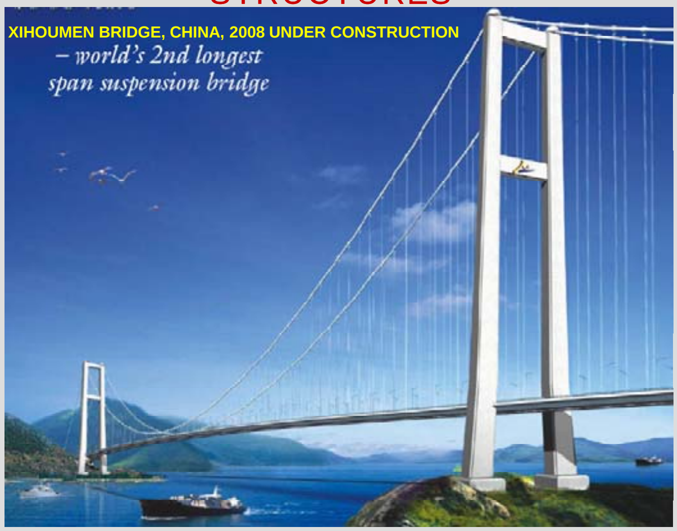
HAYWARD CITY HALL, CALIFORNIA
NEXT TO HAYWARD FAULT
53 FP BEARINGS AND 15 NONLINEAR VISCOUS DAMPING DEVICES
600 mm DISPLACEMENT CAPACITY

IMPLEMENTATION OF HYBRID SEISMIC ISOLATION SYSTEMS

SHAKE TABLE TESTING OF SEISMICALLY ISOLATED STRUCTURE WITH HYBRID SYSTEMS AT UNIV. AT BUFFALO, 2002

EMPHASIS ON SECONDARY SYSTEM RESPONSE AND VERIFICATION OF ACCURACY OF ANALYSIS TOOLS

IMPLEMENTATION OF DAMPERS IN STRUCTURES



XIHOUMEN BRIDGE, CHINA

DAMPERS, 8.8m LONG WHEN EXTENDED
+/-1.2m DISPLACEMENT CAPACITY
1000kN RATED LOAD CAPACITY

IMPLEMENTATION OF DAMPERS IN STRUCTURES

MILLENIUM BRIDGE, LONDON.
SUSPENSION BRIDGE WITH LATERAL CABLES.
OPENED JUNE 10, 2000, CLOSED IN TWO DAYS.
EXCEESSIVE BRIDGE SWAY WITH MORE THAN 1000 PEOPLE ON BRIDGE.

37 HERMETICALLY-SEALED VISCOUS DAMPERS, 1.3 BILLION CYCLES.
50 TUNED MASS DAMPERS.
OPENED TO PUBLIC JANUARY 2002

CONCLUSIONS

- Seismic isolation is a relatively mature technology with a significant range of applications
- Technology may provide significant benefits provided that is properly applied
  - Use of proper isolator for structure and seismic hazard.
  - Proper selection of seismic hazard.
  - Proper interpretation of seismic hazard.
- Yet several problems in seismic protective systems technologies exist and require understanding
  - Lifetime behavior of hardware (effects of time, history of loading and environment).
  - Procedures for analysis and design to account for lifetime behavior, uncertainty and variability in properties and uncertainty in seismic excitation.
  - Modeling of hardware to describe instantaneous behavior (heating effects, deterioration of strength and stiffness).
  - Scaling, similarity and testing.