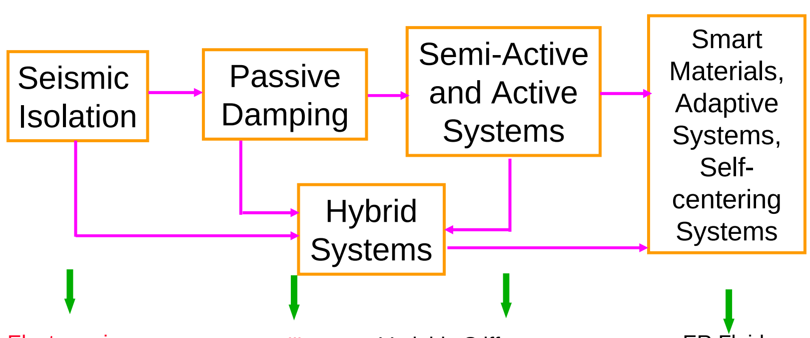
APPLICATIONS OF SEISMIC PROTECTIVE SYSTEMS IN OFFSHORE GAS AND OIL PLATFORMS

Michael C. Constantinou

Department of Civil, Structural, and Environmental Engineering

University at Buffalo, State University of New York

SEISMIC PROTECTIVE SYSTEMS



Elastomeric
Lead-rubber
Sliding (FP)
Constant restoring force
Elastoplastic

Metallic
Friction
Viscoelastic
Viscous
Magnetic

Variable Stiffness
Variable Damping
Active Bracing System

ER Fluid
MR Fluid
SMA
Adaptive Devices
Self-centering

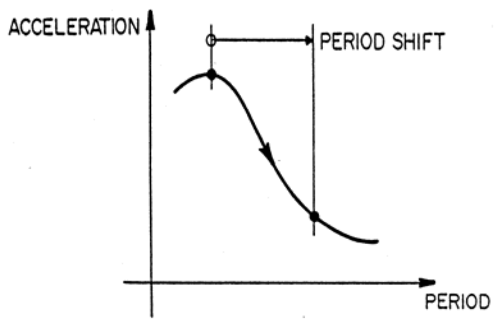
SCOPE OF PRESENTATION

- Description of seismic protective systems and hardware
- Presentation of selected implementations of seismic isolation and energy dissipation hardware with emphasis on applications of infrastructure and particularly offshore gas and oil platforms
- Mention of developmental work done at the University at Buffalo

ACKNOWLEDGMENTS

- Professors A.M. Reinhorn and A.S. Whittaker, Univ. at Buffalo
- M. Efthymiou, Shell/Sakhalin Energy Development
- C. Clarke, Mustang Engineering, formerly of AMEC, UK
- R. Buchanan, AMEC, UK
- Y. Rudolf, ExxonMobil (formerly of Sandwell, Vancouver, Canada)
- W. Turner, ExxonMobil
- Bora Tokyay, ExxonMobil
- Mark Chatten, Motioneering, Guelph, Canada
- Former doctoral and post-doctoral students: Prof. P. Tsopelas, Prof. O. Ramirez, Prof. P. Roussis, Dr. A.S. Mokha, Dr. A. Kasalanati, Dr. E.D. Wolff, Dr. Ani N. Sigaher, Dr. E. Pavlou, Dr. C. Chrysostomou
- Current students: Dan Fenz, Yiannis Kalpakidis
- Research Sponsors: NSF, NCEER, MCEER, FEMA, State of NY, Department of Commerce, Industry

SEISMIC ISOLATION

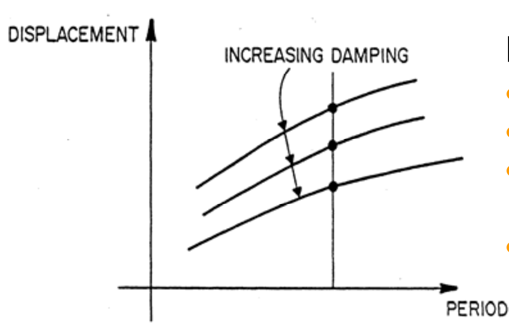


Period lengthening

- isolator flexibility
- force reduction
- displacement increase

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

SEISMIC ISOLATION

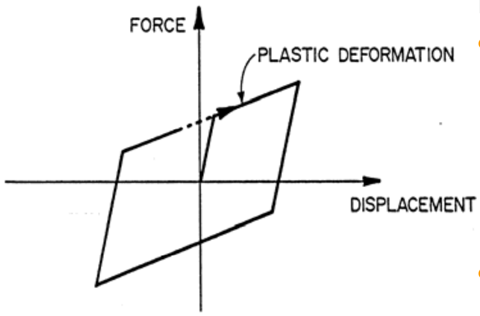


Displacements

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

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

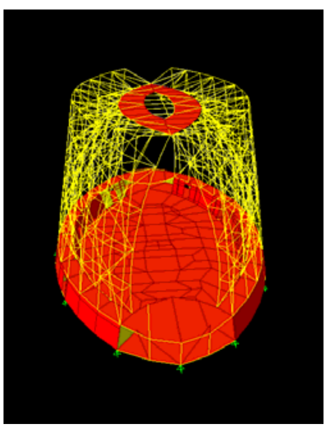
SEISMIC ISOLATION

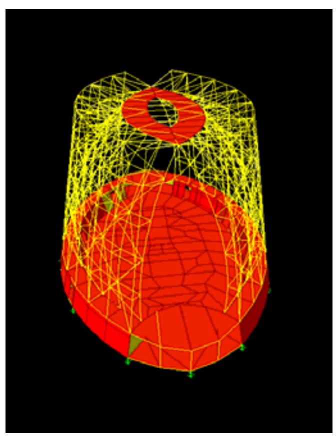


Energy dissipation

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

SEISMIC ISOLATION





CATHEDRAL CHRIST THE LIGHT, OAKLAND, CA (COURTESY SARAH DIEGNAN, SOM, SAN FRANCISCO)

ISOLATION HARDWARE

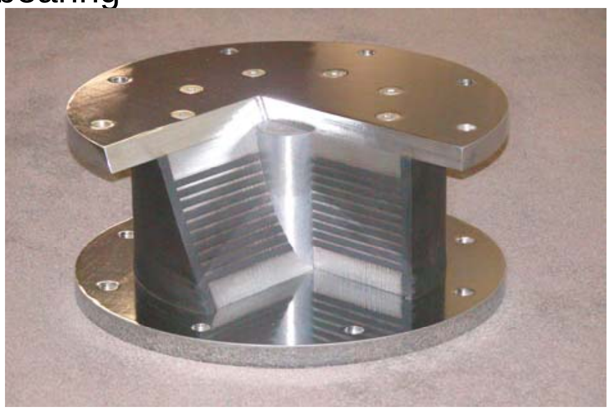
- Isolation bearings
  - Elastomeric
    - Low-damping rubber (NR)
    - High-damping rubber (HDR)
    - Lead-rubber (LR)
  - Sliding
    - Friction Pendulum (FP)
    - Sliding with Restoring Force
    - Sliding/Rolling with Constant Restoring Force
    - Sliding with Yielding Devices (Elastoplastic)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

ISOLATION HARDWARE

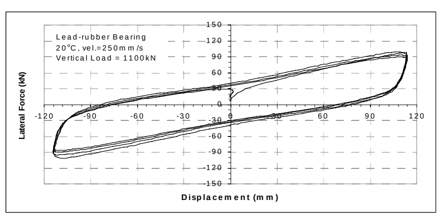
- Elastomeric Bearings for Sakhalin I Orlan Platform
- Tested at University at Buffalo

ISOLATION HARDWARE

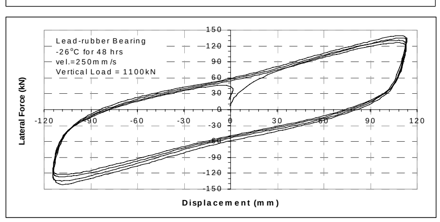
- LR bearing



LEAD-RUBBER BEARING



TEMP=20^{O}C

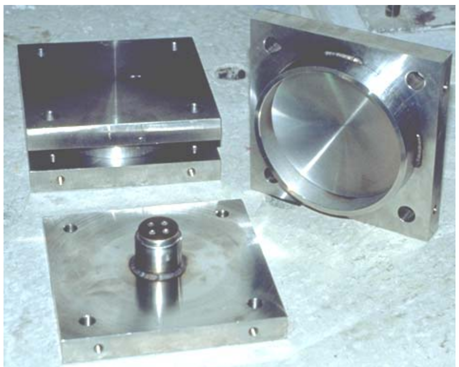


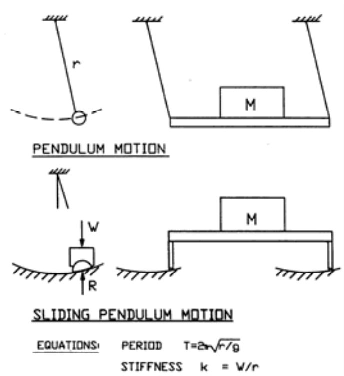
TEMP=-25^{O}C

LEAD-RUBBER BEARING, UNIVERSITY AT BUFFALO
LOAD=1100kN, DISPLACEMENT=100mm, VELOCITY=250mm/sec

ISOLATION HARDWARE

- FP bearing





FP BEARING

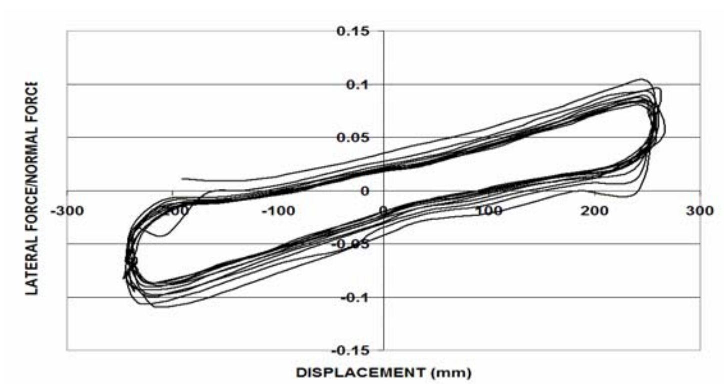
- Salkhalin II bearings
- Largest seismic isolators
- 700mm displacement
- 87,400kN vertical load
- Full-scale testing
- Reduced scale dynamic testing (load of up to 13,000kN, velocity of 1m/sec).

LARGE-SCALE DYNAMIC TESTING

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

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

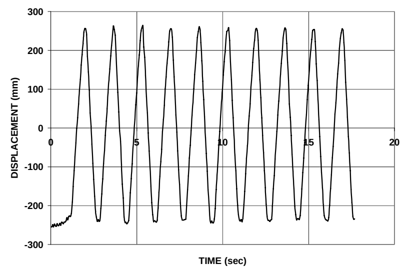
FP BEARING

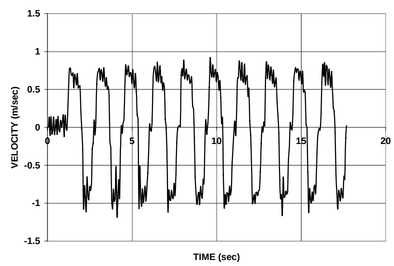


SAKHALIN II PLATFORMS PROTOTYPE BEARING PR1,
LOAD=6925kN, DISPLACEMENT=240mm, VELOCITY=0.9 m/sec
EPS BEARING TESTING MACHINE, OCTOBER 2005

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

FP BEARING



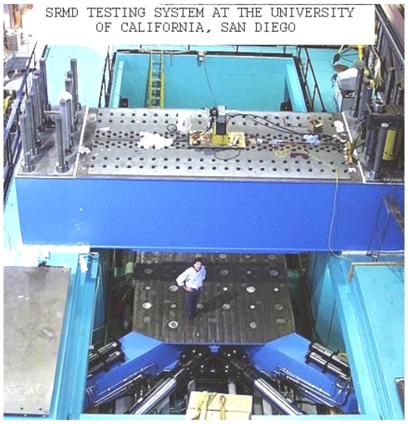


SAKHALIN II PLATFORMS PROTOTYPE BEARING PR1,
LOAD=6925kN, DISPLACEMENT=240mm, VELOCITY=0.9 m/sec
EPS BEARING TESTING MACHINE, OCTOBER 2005

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

FULL-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)



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF SEISMIC ISOLATORS IN OFFSHORE GAS PLATFORMS

SAKHALIN ISLAND, RUSSIA

OFFSHORE GAS PLATFORM WITH CONCRETE GRAVITY BASE

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF SEISMIC ISOLATORS IN OFFSHORE GAS AND OIL PLATFORMS

- Orlan Platform, Sakhalin, 2006
  - 100-ton Tuned Mass Damper to protect derrick
  - Contributions of University at Buffalo (peer review services, contributions in analysis of TMD, testing of rubber bearings used in TMD)
  - Engineering: Sandwell, Motioneering, Canada

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

ORLAN PLATFORM

CIDS (in Alaska-1984)

Orlan (in Russia-2005)

TMD

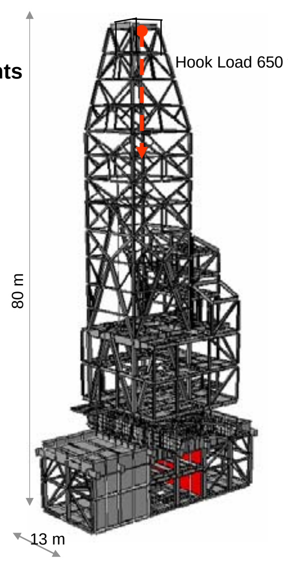
Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

ORLAN PLATFORM

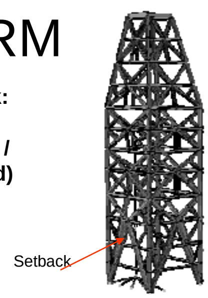
Drilling Stack Components

- 20 well positions
- Components sliding on each other
- Varying hook load
- Varying setback conditions

Drilling Stack: 4000 t

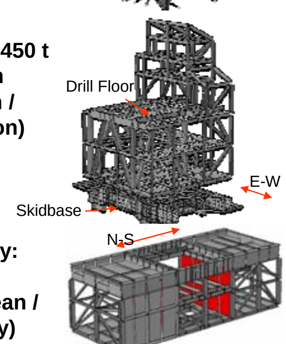


Derrick: 550 t (Bailey / Holland)



DES: 1450 t (Ocean Design / Houston)

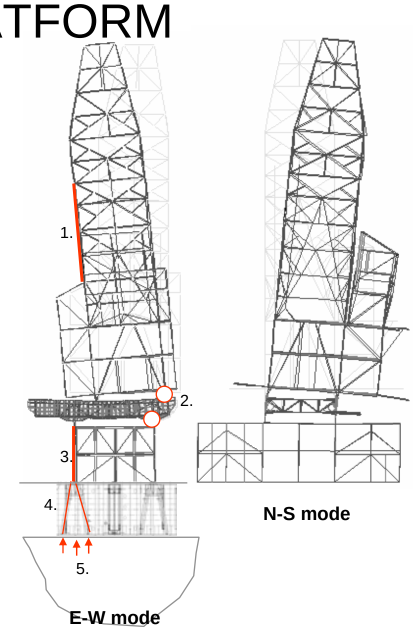
Wellbay: 2000 t (Triocean / Calgary)



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

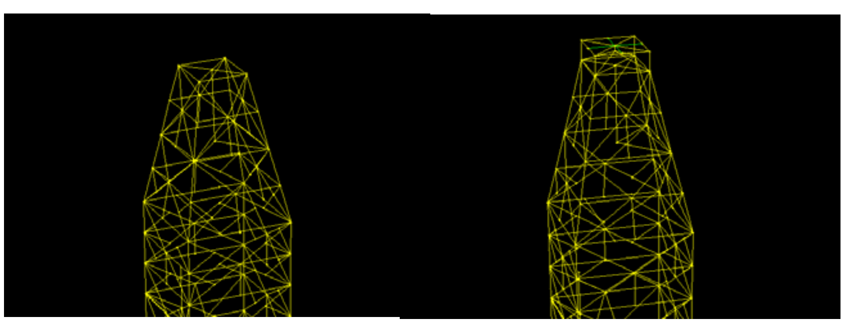
ORLAN PLATFORM

- **Dynamics**
  - First mode is rocking of a rigid DES/Derrick on flexible Skidbase
  - Period of around 1 second
  - The first mode has a modal mass participation of 40%, but it contributes 90% of overturning.
  - This mode dominates the overstressing of the structure and its foundation
- **Effect on Structure**
  - Structure is satisfactory in **SLE.**
  - In **DLE**:
  - 1. Derrick columns significantly overstressed with no ductility capacity
  - 2. Stack clamps overstressed in tension and at limits of casting size
  - 3. Wellbay module columns overstressed and at limit of plate thickness availability
  - 4. Deck strengthening at limit of feasibility
  - 5. Reactions transmitted to concrete structure exceeding capacity with no ability of retrofit



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

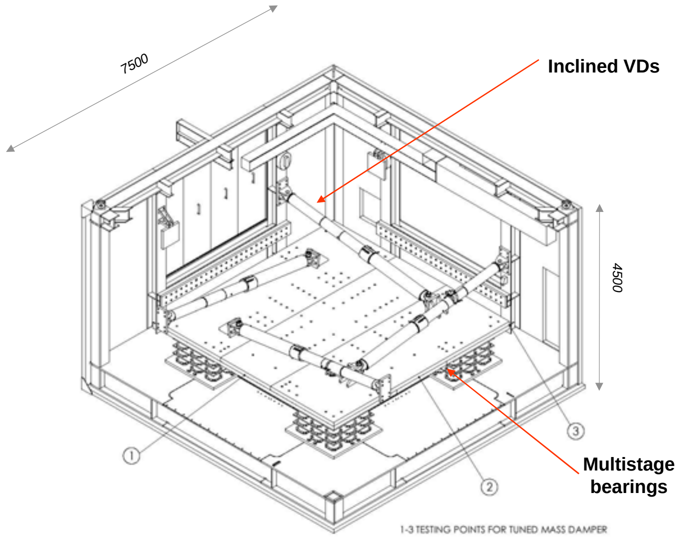
ORLAN PLATFORM



- General reduction in response of about 50%
- Elastic conditions, low-damped structure
- Heavy TMD, highly-damped TMD
- Considerable variability in properties due to foundation property uncertainty

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

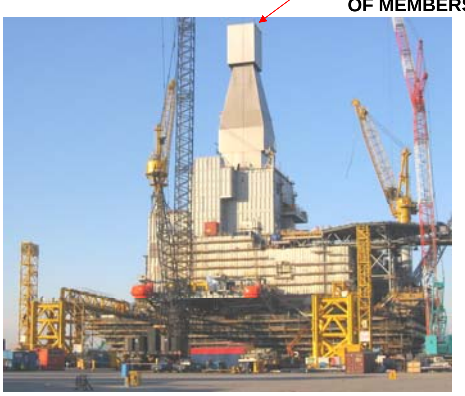
ORLAN PLATFORM



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

ORLAN PLATFORM

LOCATION OF TUNED MASS DAMPER IN ORLAN PLATFORM GOAL IS TO PREVENT FAILURE OF MEMBERS IN DERRICK



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

ORLAN PLATFORM

ORLAN PLATFORM

IMPLEMENTATION OF SEISMIC ISOLATORS IN OFFSHORE GAS 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 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 GAS PLATFORMS

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

LUNSKOYE/PILTUN GAS 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
    - -36^0C to 36^0C
  - Snow and ice accumulation
    - 100-year return period
    - 2500 m. tons per platform
  - Blast
    - Blast pressure greater than normal due to sealed compartments used to maintain minimum temperature $+5^0$C
  - Ice and wave
  - Seismic

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

LUNSKOYE/PILTUN GAS 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)
  - 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 GAS 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 GAS 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 GAS PLATFORMS

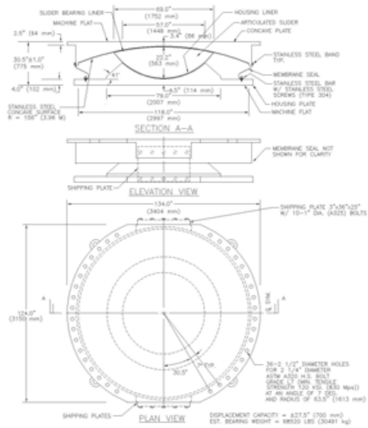
Isolation System Response			
	SLE nominal	DLE nominal	DLE Bounding analysis
Isolator displ. (mm)	118	550	630
Isolator shear force (MN)	13	22.3	24
Isolator axial force (MN)	123	146	149
Isolator travel (m)	1.5	9.0	10.4
Isolator velocity (m/sec)	0.45	1.24	1.48

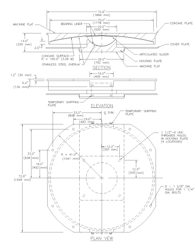
- Nominal properties of isolators and foundation were used for structural design
- Upper/lower bound isolator and foundation properties were used for isolator design and testing

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

LUNSKOYE/PILTUN GAS PLATFORMS

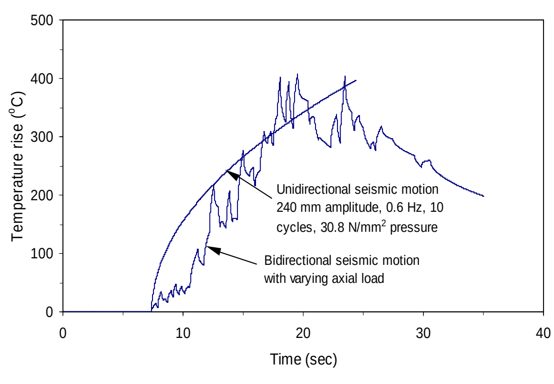
FULL SIZE PRDUCTION BEARING





REDUCED SIZE PROTOTYPE BEARING

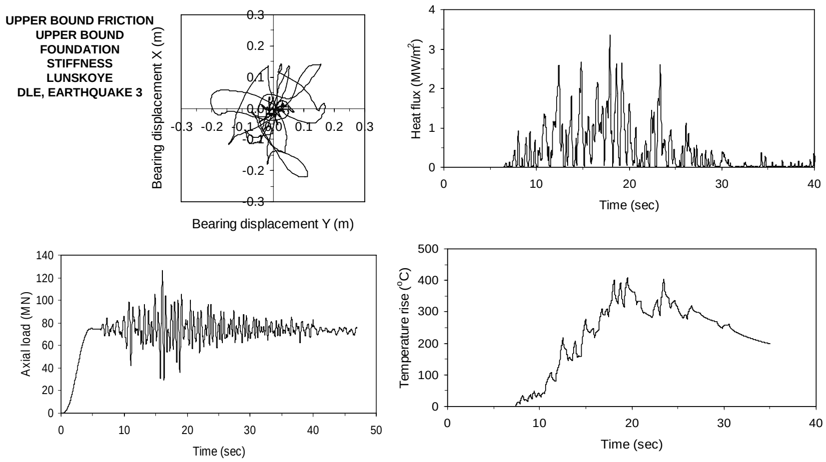
LUNSKOYE/PILTUN GAS PLATFORMS



SCALING PROCESS

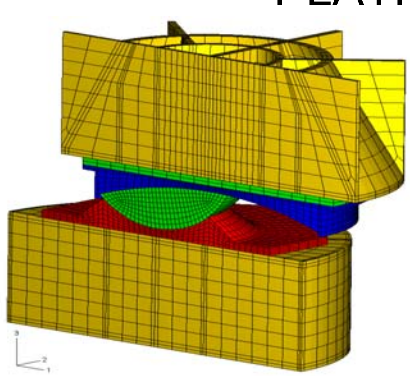
1. MAINTAIN AVERAGE PRESSURE
2. MAINTAIN EDGE PRESSURE
3. MAINTAIN THICKNESS OF LINER
4. SCALE OVERLAY THICKNESS
5. SELECT BEARING THICKNESSES TO MAINTAIN THERMODYNAMIC CONDITIONS
6. SELECT TESTING PROCEDURE TO SIMULATE TEMPERATURE RISE DUE TO FRICTIONAL HEATING AT SLIDING INTERFACE IN MOST CRITICAL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

LUNSKOYE/PILTUN GAS PLATFORMS- THERMODYNAMIC CALCULATIONS



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

LUNSKOYE/PILTUN GAS PLATFORMS



- Example of effort in the analysis and design of isolation system
- Entire structure modeled in ABAQUS, using analytical description of spherical sliding surfaces of FP bearings
- Detailed FE analysis of bearings

ANALYSIS OF FP BEARING AT MAXIMUM DISPLACEMENT
ANALYSIS BY AMEC, UK

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

LUN-A GBS TOW & INSTALLATION – JUNE 2005

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

LUN-A CONSTRUCTION OF TOPSIDES IN SHI, S. KOREA

- Heaviest Topsides ever to be installed by floatover
- Winterised facilities
  (fully winterised drilling rig)
- High consumables storage area
- Steel Material qualified to –40° C

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

LUN-A LOAD OUT – SHI YARD MAY 2006

LUN-A TOPSIDES ARRIVES AT LUNSKOYE FIELD JUNE 06

LUN-A FLOATOVER INSTALLATION JUNE 2006

LUN-A TOPSDES INSTALLED JUNE 2006

LUN-A ISOLATOR AT TOP OF LEG 2

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

WAVE PROTECTION SHIELD TO PROTECT FRICTION PENDULUM BEARINGS

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

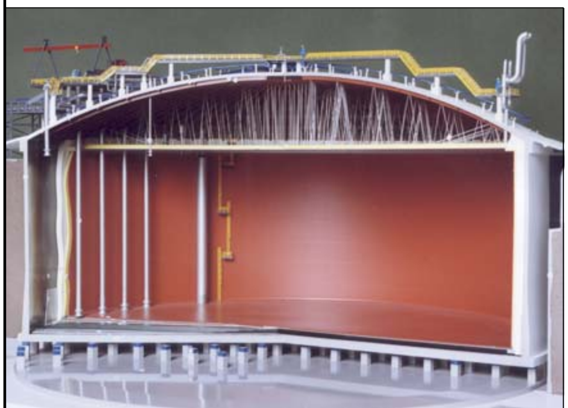
CHIRAG I OIL PLATFORM, AZERBAIJAN

- 1990's application
- Elastoplastic isolation system
- System does not have sufficient re-centering force capability per US or European seismic isolation specifications.

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

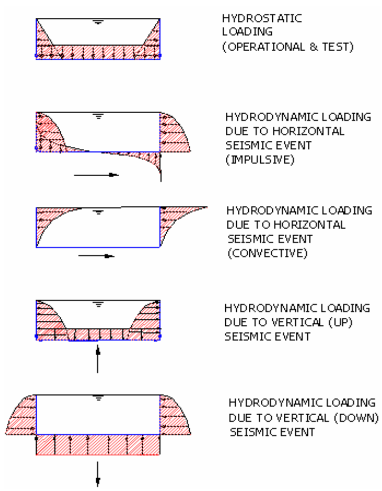
1m INSULATION AT BOTTOM
1m THICK CONCRETE SLAB

UNANCHORED INNER TANK

UNDERGROUND CONSTRUCTION FOR SAFETY REASONS (CONTAINMENT OF SPILLAGE, LOW PROFILE TARGET) AND AESTHETIC REASONS (DO NOT SIGNIFICANTLY ALTER VIEW OF ISLAND FROM MAINLAND)

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF SEISMIC ISOLATORS IN LNG TANKS



- **Hydrostatic and hydrodynamic loadings cause shell hoop tension**
- **Impulsive and convective liquid loading cause shell compression in the vertical direction**
- **Use of modification factors (R-factors) for shell hoop stress (e.g., API 620 utilizes a value 2.0) virtually guarantees shell elastoplastic buckling (elephant's foot buckling)**
- **LNG tanks are tested by filling with water. Since water has density twice that of LNG, tanks have extra shell thickness and ability to resist moderate earthquake forces**
- **Seismic isolation allows the use of standard LNG designs in strong seismicity areas without the need to anchor the tank or change the diameter to height ratio**

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF SEISMIC ISOLATORS IN LNG TANKS

Inspection, January 2002

LNG TANKS, REVITHOUSSA, GREECE, 1996

IMPLEMENTATION OF SEISMIC ISOLATORS IN CHEMICALS TANKS

- Case of chemicals 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
- Difficult construction

IMPLEMENTATION OF SEISMIC ISOLATORS IN CHEMICALS TANKS

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

IMPLEMENTATION OF SEISMIC ISOLATORS IN CHEMICALS TANKS

IMPLEMENTATION OF SEISMIC ISOLATORS IN CHEMICALS 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

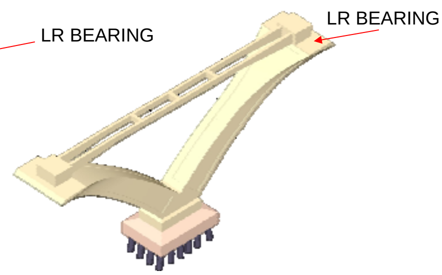
Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

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

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF SEISMIC ISOLATORS IN BRIDGES



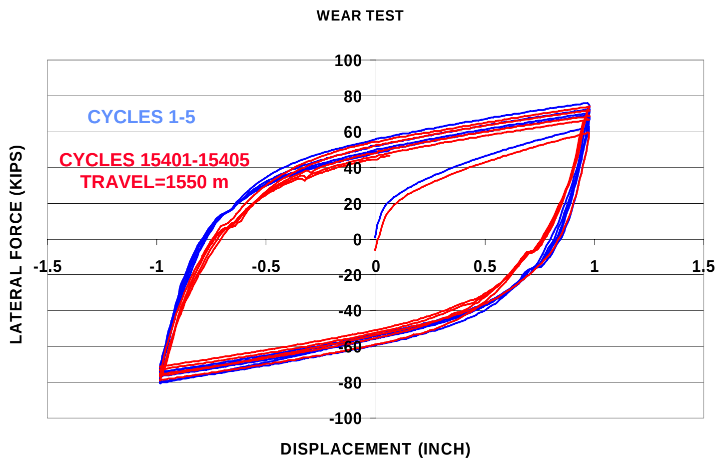
- Eastern US, small seismic displacements
- Seismic isolators most useful in seismic load distribution
- Behavior of bearings important in both service and seismic conditions
- Two bearings underwent wear testing (1.6km total movement, 16,000 cycles at 25mm amplitude with dynamic testing prior to and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

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

WEAR TESTING



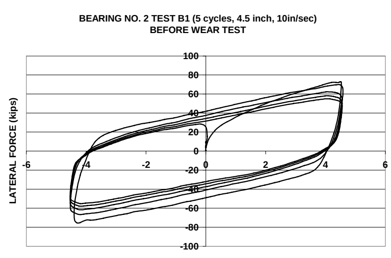
WOODROW WILSON BRIDGE

LR BEARINGS

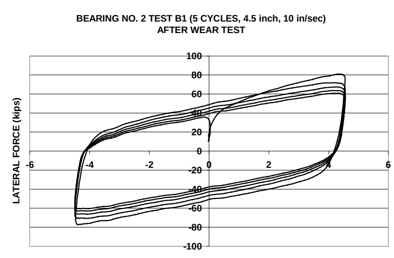
Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

WOODROW WILSON BRIDGE

BEFORE WEAR TEST (1600m TRAVEL)

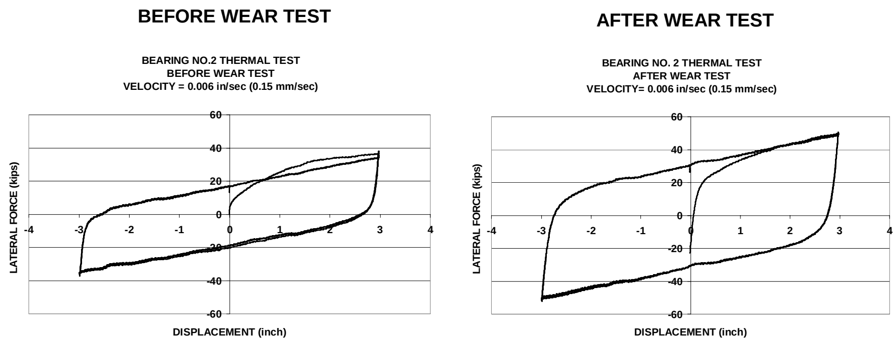


AFTER WEAR TEST



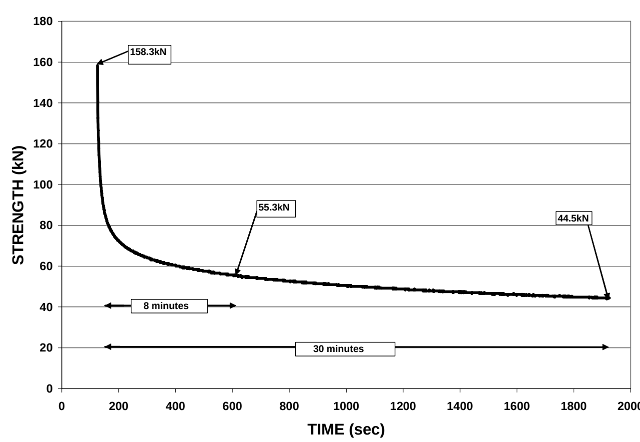
Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

WOODROW WILSON BRIDGE



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

WOODROW WILSON BRIDGE



RELAXATION OF LEAD RUBBER BEARING

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

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

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

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

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

IMPLEMENTATION OF HYBRID SEISMIC ISOLATION SYSTEMS

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

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

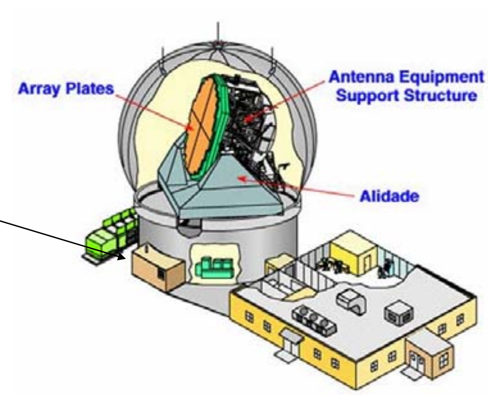
CASE OF AN ADVANCED HYBRID SEISMIC ISOLATION SYSTEM: SHEMYA RADAR FACILITY

- As part of the National Missile Defense system, an advanced X-band radar facility was planned for Shemya Island
- Radar featured a hybrid seismic isolation system with horizontal and vertical flexibilities using FP isolators, helical springs and fluid viscous dampers.
- Requirements for rigidity under service loads were met by use of a two-stage active system capable of activation within seconds. Precise repositioning of the system following an earthquake was possible within short interval.
- System components developed and tested.
- Construction postponed following 9/11 events.

Engineering: Black & Veach, Kircher & Assoc., USACE

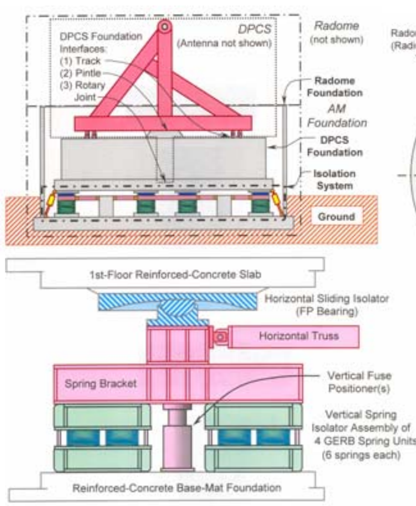
SHEMYA RADAR FACILITY

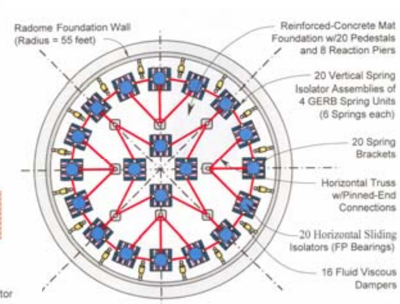
ISOLATION OF FOUNDATION OF XBR ANTENNA MOUNT
DISPLACEMENT CAPACITIES:
HORIZ. 24 INCH
VERT. 6 INCH



Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

SHEMYA RADAR FACILITY





Rocking/translational frequency ≈3.5 Hz

Radius of curvature of FP bearings 154in

Linear viscous dampers to minimize acceleration response

Dept. of Civil, Structural & Environmental Eng. , University at Buffalo

TOPICS FOR DISCUSSION

- Construction of offshore oil/gas platforms-problems and advantages of seismic isolation:
  - Lack of redundancy
  - Redistribution of non-seismic loads
  - Great loads on isolators
  - Testing of isolators
  - Could other types of isolators be used?
- TMD application in Orlan platform-any other options to protection of derrick?
- What is the most uncertain and yet very important part in the analysis and design of seismic protective systems?
- Is computer software capable of complex analysis required for such projects?
  - Modeling isolator behavior
  - Modeling soil-structure interaction
  - Verification