ATLSS & NHERI Lehigh Seminar, December 6, 2016

#### Hybrid Simulation of a Seismically Isolated Nuclear Power Plant

Andreas Schellenberg, Ph.D., P.E. Alireza Sarebanha Matt Schoettler, Ph.D. Benshun Shao Gilberto Mosqueda, Ph.D. Stephen Mahin, Ph.D.

**PEER** (Pacific Earthquake Engineering Research Center)

## Outline

- 1. Motivation
- 2. Prototype Structure & Bearing Designs
- 3. Experimental Test Program
- 4. Hybrid Simulation Test Results
- 5. Characterization Test Results
- 6. Summary & Conclusions

# **Motivation**

#### HS of large isolated structure

- On a shaking table the testing of large structures such as NPPs is impractical due to the size, weight and strength limitations imposed by the simulator platform
- Using hybrid simulation
  - The linear-elastic plant superstructure can be modelled analytically
  - Only the nonlinear isolator behavior needs to be tested physically
  - Large axial loads due to gravity and axial load fluctuations caused by overturning and vertical input can be imposed in force control
- Need a testing facility that can be converted to perform real-time hybrid simulations on large full-scale isolators

# Hybrid Simulation Concept $\mathbf{M} \cdot \ddot{\mathbf{u}} + \mathbf{C} \cdot \dot{\mathbf{u}} + \mathbf{P}_{r}(\mathbf{u}, \dot{\mathbf{u}}, \ddot{\mathbf{u}}) = \mathbf{P}(t)$





#### Prototype Structure & Bearing Designs

#### Prototype Structure

#### Korean Advanced Power Reactor (APR1400)



# Three Bearing Designs

Isolation bearing	Design displacement, D <sub>d</sub> (mm)	Lateral force at D <sub>d</sub> (kN)	Q <sub>d</sub> (kN)	Plan dimension (mm)	Height (mm)
Unison eTech (LPRB)	210	1,900	1,010	1,520	533
ESCO RTS (EQSB)	152	2,920	1,090	2,900	607
Earthquake Protection Systems (TFPB)	584	1,510	730	1,980	711



ATLSS & NHERI Lehigh Semir

#### Unison eTech



∎HI TEN	S. VI Drawing No	E- 6 DESCRIPTION	에 접 NATERNAL	규칙및 섹수 DIVENSION	¢. 917	NET(KC)	H Z Remark
1.1		RUBBER	NR	#1520x533	1	417.2	
1.2		end plate	SS400	60Tx#1510	2	1657	828.7Kg/EA
1.3		INSERT PLATE	SS400	7Tx#1500	29	2767	95.4Kg/EA
1.4		END CAP	SS400	17.27##276	8	64	8Kg/EA
1.5		우각집시아리 문화님드(목격)	12.9	M16x30L	64	-	
1.6		LEAD CORE	Pb	#200x497	4	712	178Kg/EA

TOTAL WEIGHT : 5,200 Kg



	(EDIE)AL	DND	ISION TOLER	ANCE	(MACHINE	EB 730 STNDOLS	UCROMS)	3					
L	RANGE	TOL	RANGE	TOL.	✓	-	~	2					
L	3~6	±0,1	121~315	±0.5	₹∕	1005	V	1					
	7~30	±0.2	316~1000	±0.8	₹	255	₩	RE/	변경일자		월 계	검도	송 인
	31~120	±0.3	1001~2000	±1.2	₩	6.35	w	HO	DATE	REVISION	DESIGN	CHECKED	APPROVED
Γ	4 4 1 380 ANS PROJECT	ELE Min	SCALE			N 3	JATE SALAS		LRB (1520-533-200		0)		
ŀ	DRAW	E N	AL 2 DESIGN	<u> </u>	3 0-E083		PPROVED	,	B N			, NG	
								⊢	TITLE				L
┝				+		_		•	DWGNO	LBC15001	-01		
Γ	PROJEC	T&r IER	수출평 문 유니손이터	1전 연 1그(2	8 개발 1)기술인	구소			Ş	말 방미든이	비크	(주)	

#### **Unison eTech Bearing**

Table 2.2-1 LPRB desig	n properties.
Vertical stiffness (K <sub>v</sub> )	12,896 kN/mm
Initial stiffness (K1)	545 kN/mm
Second slope stiffness (K <sub>2</sub> )	4.2 kN/mm
Characteristic strength (Q <sub>d</sub> )	1,002 kN
Equivalent stiffness $(K_{eq})$	9.0 kN/mm
Equivalent damping ratio (H <sub>eq</sub> )	0.335





#### **ESCO RTS Bearing**



ATLSS & NHERI Lehigh Seminar, December 6, 2016

#### **ESCO RTS Bearing**

Table 2.3-1 EQSB desig	n properties.
Coefficient of friction	0.11
Second slope stiffness (K <sub>2</sub> )	11.6 kN/mm
Characteristic strength $(Q_d)$	1,092 kN
Equivalent stiffness $(K_{eq})$	18.8 kN/mm

WxL = 2400x2400 mm - H = 600 mm - P<sub>Gravity</sub> = 9.7 MN -  $\mu = 11 \%$ -  $k_2 = 11.6 \text{ kN/mm}$ 



#### **EPS Bearing**





ATLSS & NHERI Lehigh Seminar, December 6, 2016

#### **Experimental Test Program**

## Overview of SRMD @ UC San Diego

- Built by Caltrans, MTS and UCSD in 1999 to test
   Seismic Response
   Modification Devices at full scale
- Apply full-scale gravity loads, displacements and velocities to bearings and dampers



- Required significant adaptations to enable hybrid simulation while minimizing experimental errors
  - Receive and apply command displacement/forces
  - Return measured force feedback



### Overview of SRMD @ UC San Diego



#### Specifications of SRMD testing facility

**6 DOF platen** 

Component	Capacity				
Vertical Force	53,400 kN	12,000 kips			
Longitudinal Force	8,900 kN	2,000 kips			
Lateral Force	4,450 kN	1,000 kips			
Vertical Displacement	± 0.127 m	± 5 in			
Longitudinal Displacement	± 1.219 m	± 48 in			
Lateral Displacement	± 0.610 m	± 24 in			
Vertical Velocity	± 254 mm/s	± 10 in/s			
Longitudinal Velocity	± 1,800 mm/s	± 70 in/s			
Lateral Velocity	± 760mm/s	± 30 in/s			
Relative Platen Rotation (Roll, Pitch, & Yaw)	± 2 degrees				
Maximum Specimen Height	1.524 m	60 in			

ATLSS & NHERI Lehigh Seminar, December 6, 2016



18

#### **Implementation of Hybrid Simulation**

 Requires fast, accurate and reliable communication between computer simulation and experimental setup to solve hybrid model

# $\mathbf{M} \cdot \ddot{\mathbf{u}} + \mathbf{C} \cdot \dot{\mathbf{u}} + \mathbf{P}_{\mathbf{r}} (\mathbf{u}, \dot{\mathbf{u}}, \ddot{\mathbf{u}}) = \mathbf{P}(t)$



#### **Communication Details** OpenSees **OpenSees Finite** ExpElement **Element Model** LocalExpSite ExperimentalSetup **OpenFresco** ExperimentalControl **Middleware** Client 으 요 | 🕨 = inf 🛛 Normal 🖃 🔛 🔛 😵 🖽 🔰 🖼 🔳 🏵 Server SCRAMNet+ Target SFlag Control System File Scope Id: 1 in Laboratory xPC-Target real+time zeros(1,nAct) 멉 File Scope Id: 4 File Scope **Predictor-Corrector** File Scope Id: 5 File Scope Id: 3 tFlag File Scope •= Signal Offset SCRAMNet+ →∃ File Scope Id: 7 MTS SRMD realtime Controller **Physical Specimen** in Laboratory

## **OpenSees and OpenFresco Details**

- Hybrid models with several thousand DOF can be tested in real-time
  - First-time use of OpenSeesSP for HS
  - All integrators specialized for HS are now available in OpenSeesSP
  - Execution on high performance overclocked 8-core analysis machine
  - If system is linear command "algorithm Linear –factorOnce" can be used
- Added new command "partition \$eleTag"
  Added new element EEBearing

## Time Delay Compensation Methods

- + SRMD has delay of 60 msec
- Feedforward Gain
  - used last time, limited benefit for displ. control, did not work for vertical force control
- Polynomial Extrapolation
  - used last time, works for constant delays only, limited in how much delay it can compensate for
- Inverse Models
  - does not work well, relies on accurate system ID
- + Adaptive Time Series (ATS) method
  - developed at Lehigh by Y. Chae, based on least squares method, self-adapting to changes

#### **Horizontal Force Measurements**









#### **Three-Loop Hardware Architecture**



#### **Ground Motions**

#### **NRC Set: Motion Parameters**

NGA # Earthquake	Station	Mag	Dist (km)	Vs30 (m/s)	Scale Factor	NPTS	dt (s)	Duration (s)
68 San Fernando	LA - Hollywood Stor FF	6.6	22.8	316	3.7	2800	0.01	28
93 San Fernando	Whittier Narrows Dam	6.6	39.5	299	7.5	7997	0.005	39.985
186 Imperial Valley-06	Niland Fire Station	6.5	36.9	207	7.8	7997	0.005	39.985
285 Irpinia, Italy-01	Bagnoli Irpinio	6.9	8.2	1000	4.0	12712	0.0029	36.8648
718 Superstition Hills-01	Wildlife Liquef. Array	6.2	17.6	207	5.2	5961	0.005	29.805
730 Spitak, Armenia	Gukasian	6.8	36.2	275	4.4	1990	0.01	19.9
748 Loma Prieta	Belmont - Envirotech	6.9	44.1	628	6.9	7989	0.005	39.945
855 Landers	Fort Irwin	7.3	63.0	345	6.8	2000	0.02	40
862 Landers	Indio - Coachella Canal	7.3	54.3	345	6.5	3000	0.02	60
882 Landers	North Palm Springs	7.3	26.8	345	4.8	14000	0.005	70
1165 Kocaeli, Turkey	Izmit	7.5	7.2	811	3.3	6000	0.005	30
1487 Chi-Chi, Taiwan	TCU047	7.6	35.0	520	2.1	18000	0.005	90
1491 Chi-Chi, Taiwan	TCU051	7.6	7.7	273	3.0	18000	0.005	90
1602 Duzce, Turkey	Bolu	7.1	12.0	326	1.3	5590	0.01	55.9
1605 Duzce, Turkey	Duzce	7.1	6.6	276	1.4	5177	0.005	25.885
1611 Duzce, Turkey	Lamont 1058	7.1	0.2	425	7.7	3901	0.01	39.01
1762 Hector Mine	Amboy	7.1	43.1	271	3.5	3000	0.02	60
2113 Denali, Alaska	TAPS Pump Station #09	7.9	54.8	383	8.0	32895	0.005	164.475
2744 Chi-Chi, Taiwan-04	CHY088	6.2	48.4	273	7.4	12800	0.005	64
3264 Chi-Chi, Taiwan-06	CHY024	6.3	31.1	428	5.0	13204	0.005	66.02
	NGA #       Earthquake         68       San Fernando         93       San Fernando         93       San Fernando         186       Imperial Valley-06         285       Irpinia, Italy-01         285       Irpinia, Italy-01         718       Superstition Hills-01         730       Spitak, Armenia         748       Loma Prieta         855       Landers         862       Landers         882       Landers         882       Landers         1165       Kocaeli, Turkey         1487       Chi-Chi, Taiwan         1491       Chi-Chi, Taiwan         1602       Duzce, Turkey         1611       Duzce, Turkey         1762       Hector Mine         2113       Denali, Alaska         2744       Chi-Chi, Taiwan-04         3264       Chi-Chi, Taiwan-04	NGA #         Earthquake         Station           68 San Fernando         LA - Hollywood Stor FF           93 San Fernando         Whittier Narrows Dam           186 Imperial Valley-06         Niland Fire Station           285 Irpinia, Italy-01         Bagnoli Irpinio           718 Superstition Hills-01         Wildlife Liquef. Array           730 Spitak, Armenia         Gukasian           748 Loma Prieta         Belmont - Envirotech           855 Landers         Fort Irwin           862 Landers         Indio - Coachella Canal           882 Landers         North Palm Springs           1165 Kocaeli, Turkey         Izmit           1487 Chi-Chi, Taiwan         TCU047           1491 Chi-Chi, Taiwan         TCU051           1602 Duzce, Turkey         Bolu           1605 Duzce, Turkey         Duzce           1762 Hector Mine         Amboy           2113 Denali, Alaska         TAPS Pump Station #09           2744 Chi-Chi, Taiwan-O4         CHY024	NGA #         Earthquake         Station         Mag           68 San Fernando         LA - Hollywood Stor FF         6.6           93 San Fernando         Whittier Narrows Dam         6.6           93 San Fernando         Niland Fire Station         6.6           186 Imperial Valley-06         Niland Fire Station         6.6           285 Irpinia, Italy-01         Bagnoli Irpinio         6.9           718 Superstition Hills-01         Wildlife Liquef. Array         6.2           730 Spitak, Armenia         Gukasian         6.8           748 Loma Prieta         Belmont - Envirotech         6.9           855 Landers         Fort Irwin         7.3           862 Landers         Indio - Coachella Canal         7.3           1165 Kocaeli, Turkey         Izmit         7.6           1487 Chi-Chi, Taiwan         TCU047         7.6           1491 Chi-Chi, Taiwan         TCU051         7.1           1605 Duzce, Turkey         Bolu         7.1           1611 Duzce, Turkey         Lamont 1058         7.1           1762 Hector Mine         Amboy         7.1           1762 Hector Mine         CHY088         6.2           2744 Chi-Chi, Taiwan-04         CHY024         6.2	NGA #         Earthquake         Station         Mag         Dist (km)           68 San Fernando         LA - Hollywood Stor FF         6.6         22.8           93 San Fernando         Whittier Narrows Dam         6.6         39.5           186 Imperial Valley-06         Niland Fire Station         6.6         39.5           285 Irpinia, Italy-01         Bagnoli Irpinio         6.9         8.2           718 Superstition Hills-01         Wildlife Liquef. Array         6.2         17.6           730 Spitak, Armenia         Gukasian         6.8         36.2           748 Loma Prieta         Belmont - Envirotech         6.9         44.1           855 Landers         Fort Irwin         7.3         54.3           882 Landers         Indio - Coachella Canal         7.3         26.8           1165 Kocaeli, Turkey         Izmit         7.5         37.0           1487 Chi-Chi, Taiwan         TCU047         7.6         35.0           1491 Chi-Chi, Taiwan         TCU051         7.1         6.6           1605 Duzce, Turkey         Bolu         7.1         6.6           1611 Duzce, Turkey         Lamont 1058         7.1         6.6           1762 Hector Mine         Amboy         7.1	NGA #EarthquakeStationMagDist (km)V330 (m/s)68 San FernandoLA - Hollywood Stor FF6.622.831693 San FernandoWhittier Narrows Dam6.639.5299186 Imperial Valley-06Niland Fire Station6.536.9207285 Irpinia, Italy-01Bagnoli Irpinio6.98.21000718 Superstition Hills-01Wildlife Liquef. Array6.217.6207730 Spitak, ArmeniaGukasian6.836.2275748 Loma PrietaBelmont - Envirotech6.944.1628855 LandersFort Irwin7.363.0345862 LandersIndio - Coachella Canal7.354.3345882 LandersNorth Palm Springs7.335.05201487 Chi-Chi, TaiwanTCUO477.635.05201491 Chi-Chi, TaiwanTCUO517.67.72731602 Duzce, TurkeyBolu7.112.03261605 Duzce, TurkeyLamont 10587.10.24251762 Hector MineAmboy7.143.12712113 Denali, AlaskaTAPS Pump Station #097.954.83832744 Chi-Chi, Taiwan-O6CHY0246.331.14283264 Chi-Chi, Taiwan-O6CHY0246.331.14283264 Chi-Chi, Taiwan-O6CHY0246.331.14283264 Chi-Chi, Taiwan-O6CHY0246.331.14283264 Chi-Chi, Taiwan-O6	NGA #EarthquakeStationMagDist (km)Vs30 (m)Scale Facuation68 San FernandoLA - Hollywood Stor FF6.622.83163.739 San FernandoWhittier Narrows Dam6.639.52097.5186 Imperial Valley-O6Niland Fire Station6.636.92077.8285 Irpinia, Italy-O1Bagnoli Irpinio6.98.210004.0718 Superstition Hills-01Wildlife Liquef. Array6.23.622.0753.44730 Spitak, ArmeniaGukasian6.83.622.0754.44748 Loma PrietaBelmont - Envirotech6.94.416286.69855 LandersFort Irwin7.363.03.456.65882 LandersIndio - Coachella Canal7.326.83.454.861165 Kocaeli, TurkeyIzmit7.63.503.202.131487 Chi-Chi, TaiwanTCU0477.63.503.202.131602 Duzce, TurkeyBolu7.11.203.261.311605 Duzce, TurkeyBolu7.11.602.773.631605 Duzce, TurkeyBolu7.14.312.713.511762 Hector MineAmboy7.14.312.713.511713 Denail, AlaskaTAPS Pump Station #097.95.483.838.02744 Chi-Chi, Taiwan-0CHY0246.24.82.737.4	NGA #EarthquakeStationMagDisk (m)v30 (m)Scale PointNPT68 San FernandoLA Hollywood Stor FF6.622.83.053.073.0793 San FernandoWhittier Narrows Dam6.63.052.097.53.097186 Imperial Valley-O6Niland Fire Station6.63.682.0007.53.097285 Irpinia, Italy-O1Bagnoli Irpinio6.63.622.0104.0103.012718 Superstition Hills-O1Wildlife Liquef. Array6.83.622.0254.041.090730 Spitak, ArmeniaGukasian6.94.416.683.063.0913.091748 Lomar PrietaBelmont - Envirotech6.94.416.683.0013.0013.001855 LandersFort Irwin7.35.633.453.0603.0013.0013.001862 LandersIndio - Coachella Canal7.35.743.0453.0013.001815 Kocaeli, TurkeyIzmit7.57.28.113.0013.0011487 Chi-Chi, TaiwanTCUO517.67.72.033.0013.0011493 Chi-Chi, TaiwanDuzce7.16.62.763.013.0011602 Duzce, TurkeyBanon 1.0587.16.27.13.013.013.0011603 Loce, TurkeyDuzce7.16.27.23.013.0013.0011604 Loce, TurkeyBanon 1.0587.16.27.23.01	NG4 #EarthquakeStationMagDist (km)v30 (m)Scale FermNPTSDist (km)68 San FernandoLA - Hollywood Stor FF6.22.83.163.7.92.00093 San FernandoWhitier Narrows Dam6.63.9.52.097.7.87.900.000186 Imperial Valley-CoMand Fire Station6.63.6.92.0007.8.87.900.000285 Irpinia, Italy-O1Bagnoli Irpinio6.23.7.02.0003.7.89.0000.001718 Superstition Hills-O1Wildife Liquer, Array6.27.0.72.0.003.7.90.001730 Spitak, ArmeniaGukasian6.83.6.22.0255.4.41.9090.010748 Loma PrietaBelmont - Envirotech6.94.4.16.286.6.97.9.00.001855 LandersFort Irwin7.35.4.33.455.6.93.0000.001862 LandersIndio - Coachella Canal7.32.6.83.454.6.93.0000.0011615 Kocaeli, TurkyIzmit7.57.28.113.0003.0013.0000.0011614 Chi-fi, TaiwanTCUO377.67.72.7.33.0003.0013.0000.0011615 Ducce, TurkyBalum Lings7.14.17.13.0.13.0003.0013.0013.0013.0013.0013.0013.0013.0013.0013.0013.0013.0013.0013.0013.0013.001 <t< td=""></t<>

#### NRC Set: Response Spectra



#### NRC RG1.60: Spectral Matching



ATL



Time [sec]



Figure NRC-REC03-A: Spectral Matching and Time Series, NRC RG1.60 Ground Motion: REC03 Component: 1

Figure NRC-REC03-B: Spectral Matching and Time Series, NRC RG1.60 Ground Motion: REC03 Component: 2

30

30

30

seed

30

matched

#### Hybrid Simulation Test Results

#### **Result output locations**



## 2D Hybrid Simulation (LPRB)



#### 1D vs. 2D real time (LPRB)



#### 1D vs. 2D 2x-slower (LPRB)



## 1D vs. 2D (LPRB)













ATLSS & NHERI Lehigh Seminar, December 6, 2016

#### 2D 2x-slower vs. 3D 10x-slower (LPRB)



#### 2D vs. 3D (LPRB)











## Conclusions wrt LPRB isolator

- Need analytical model that can capture
   v-h force interaction correctly
- Need analytical model that can capture v-h displacement coupling
- Need analytical isolator model that can account for the reduction in the lead yield strength with increasing bearing temperature

## 1D vs. 2D real time (EQSB)



#### 1D vs. 2D 2x-slower (EQSB)



# 1D vs. 2D (EQSB)











Frequency (Hz)



ATLSS & NHERI Lehigh Seminar, December 6, 2016

#### 2D 2x-slower vs. 3D 10x-slower (EQSB)





## Conclusions wrt EQSB isolator

- Need analytical model that can capture v-h force interaction correctly
- Need analytical isolator model that can capture adhesion (break-away) effects on COF
- Need analytical isolator model that can capture temperature effects on COF

#### 1D vs. 2D 2x-slower (TFPB)





# 1D vs. 2D (TFPB)











ATLSS & NHERI Lehigh Seminar, December 6, 2016







## Conclusions wrt TFPB isolator

- Need analytical model that can capture v-h force interaction correctly
- Need analytical model that can capture v-h displacement coupling
- Need analytical isolator model that can capture adhesion (break-away) effects on COF
- Need analytical isolator model that can capture temperature effects on COF

## Average Delay Assessment (Long)

#### real time -> 6 msec

#### 2x slower -> 0 msec



## Normalized RMS Error (Long)

real time

#### 2x slower



## Average Delay Assessment (Lat)

#### real time -> 4 msec

#### 2x slower -> 1 msec



## Normalized RMS Error (Lat)

real time

#### 2x slower



#### **Characterization Tests**

#### **Axial Response under Compression**



# Failure Tests (LPRB and EQSB)



#### Rupture due to delamination

Bolt slip at peak load

# Failure Test (LPRB)



# Failure Tests (LPRB and EQSB)

#### LPRB by Unison eTech





Rupture due to delamination





Bolt slip at peak load

## Failure Tests (TFPB)



Stage 5-6 yielding of slider lip

#### Failure Tests (TFPB)



## Failure Tests (TFPB)

#### TFPB by EPS



#### Stage 5-6 yielding of slider lip

# Summary & Conclusions

## **Conclusions RTHS**

- Real-time hybrid simulation is possible in 2D and is a viable testing method to experimentally assess the behavior of large isolators at full-scale.
- The SRMD bearing test machine was successfully converted to perform rapid and real-time hybrid simulation tests for large hybrid models.
- Despite the lack of a load cell to directly measure the experimental bearing forces, reliable results were obtained using a real-time correction model.
- To achieve acceptable performance and accuracy in the force controlled vertical DOF a hybrid simulation should be performed at a minimum 10x-slower than real time.
- It was demonstrated that it is possible to use a high-performance computing platform with parallel processing capabilities (OpenSees*SP*) to perform real-time hybrid simulations of large structures with many DOFs, such as nuclear power plants.

#### **Conclusions Bearing Behavior**

- Overall, the seismically isolated plant facilities behaved as expected. Base shears and floor accelerations were generally reduced substantially compared to what might be expected for a fixed-base structure. However, the tests were able to identify specific differences associated with different bearings, loading conditions, and earthquake excitations.
- Heat generation in the LPRB was larger during 2D testing than during 1D testing, causing the yield strength of the lead cores to decrease faster, and leading to larger displacement demands in the hybrid tests.
- The real-time execution of the hybrid simulations had a moderate effect on the hysteresis loops of the LPRB.
- The LPRB showed substantial vertical—horizontal coupling behavior.
- In terms of overturning effects, net tension was not recorded in any of the bearings.

## **Conclusions Bearing Behavior**

- For the hybrid simulations on the EQSB, breakaway, static and dynamic friction values influence the response of the system.
- The EQSB isolator showed substantial vertical—horizontal coupling behavior.
- For the TFPB shear forces are significantly lower than the ones that were seen in the LPRB and EQSB. Lower isolator shear forces mean that less force is transmitted into the power plant superstructure; hence, the superstructure is better protected during seismic shaking.
- The TFPB isolator showed substantial vertical—horizontal coupling behavior.
- For the hybrid simulations on the TFPB, adhesion and static friction influence the response of the system. For modeling purposes a simple velocity dependent friction model is not sufficient. A friction model that can include adhesion, static, and dynamic friction needs to be developed and implemented.

# Questions? Discussion



**PEER** (Pacific Earthquake Engineering Research Center)