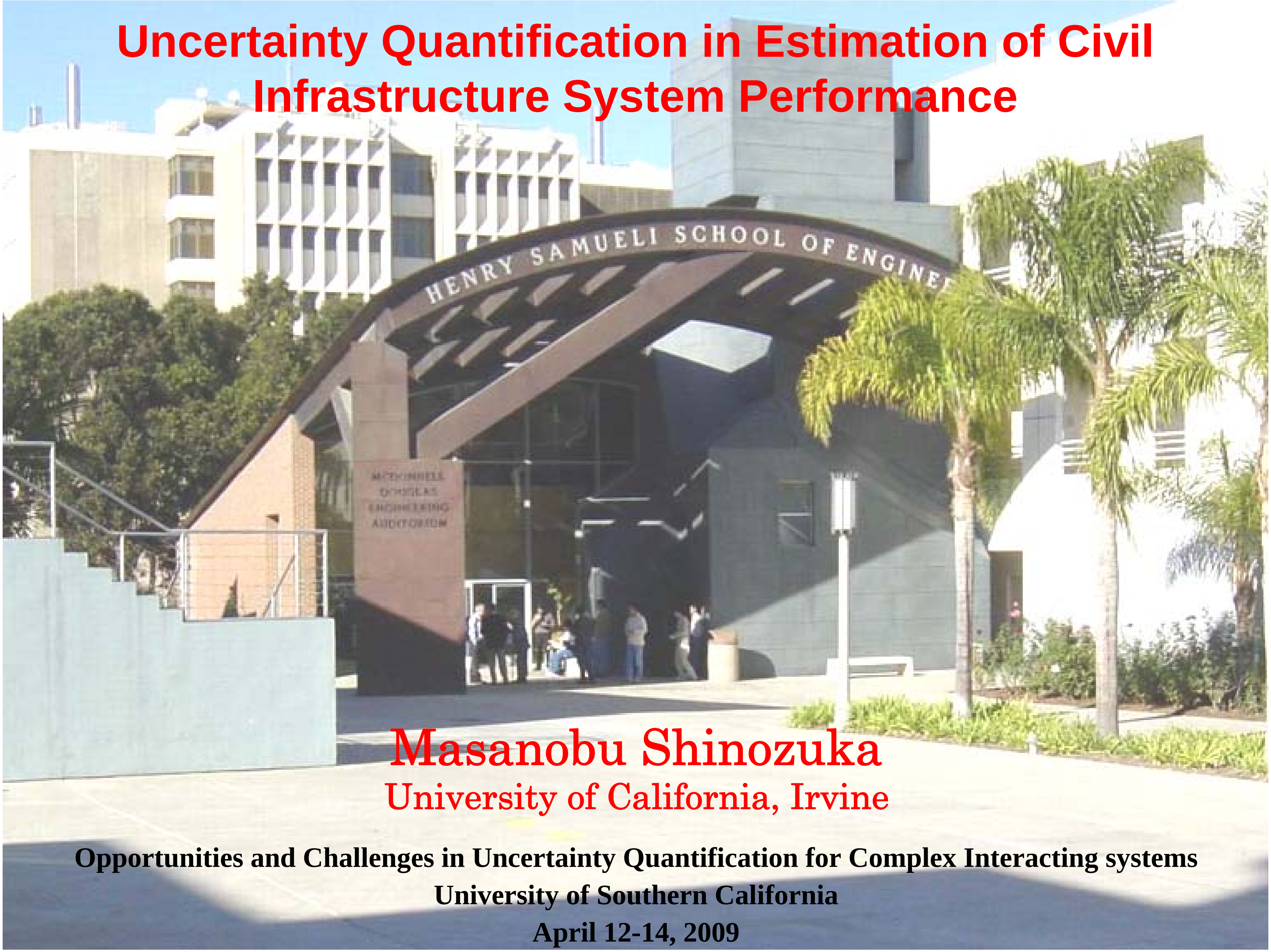
Uncertainty Quantification in Estimation of Civil Infrastructure System Performance



Masanobu Shinozuka
University of California, Irvine

Opportunities and Challenges in Uncertainty Quantification for Complex Interacting systems

University of Southern California

April 12-14, 2009

Sources of Uncertainty

Models of Infrastructure system

Hazard Models: Where, When, How

Natural Hazards

Earthquake, Tsunami, Flood, Scouring,
Hurricane, Wildfire, Drought

Technological Hazards

Industrial Accidents

Manmade Hazards

Terrorist attack

Pragmatic Objective

- Identify the contributing factors that influence the performance of infrastructure systems.
- Minimize the level of the uncertainty involved in these factors through the research,
- And maximize the system performance

System Performance

- Robustness
- Resilience
- Sustainability
- Complexity

System Interaction and Interdependency

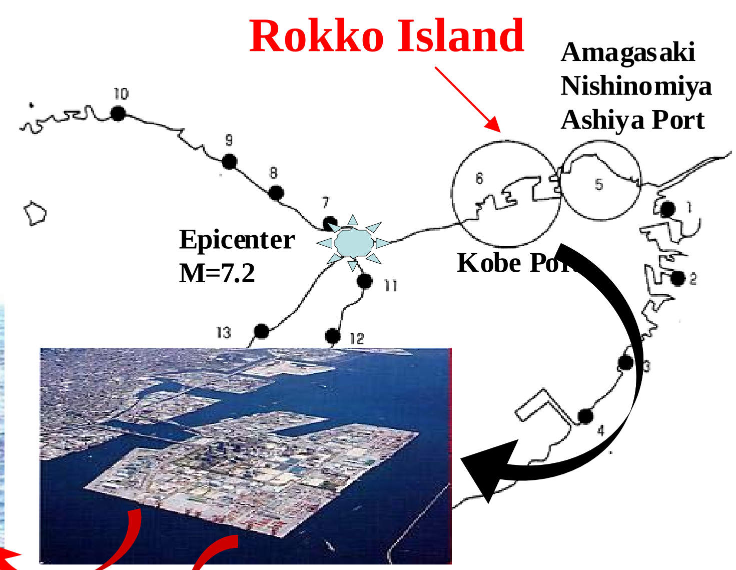
Definition depends on stake holders

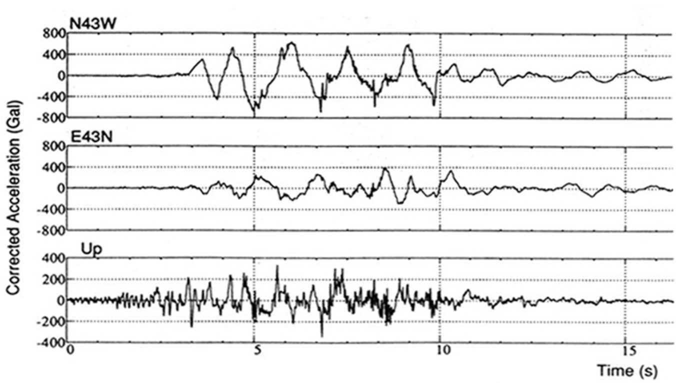
1995 Kobe Earthquake

Loss estimated at $150 billion

($100 billion in infrastructure and $50 billion in economic disruption”).

http://www.rms.com/Publications/KobeRetro.pdf

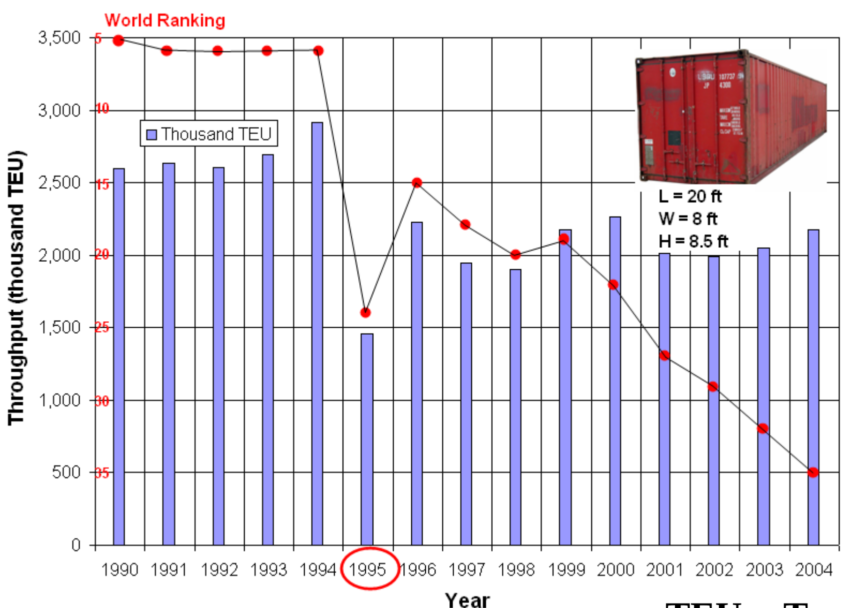




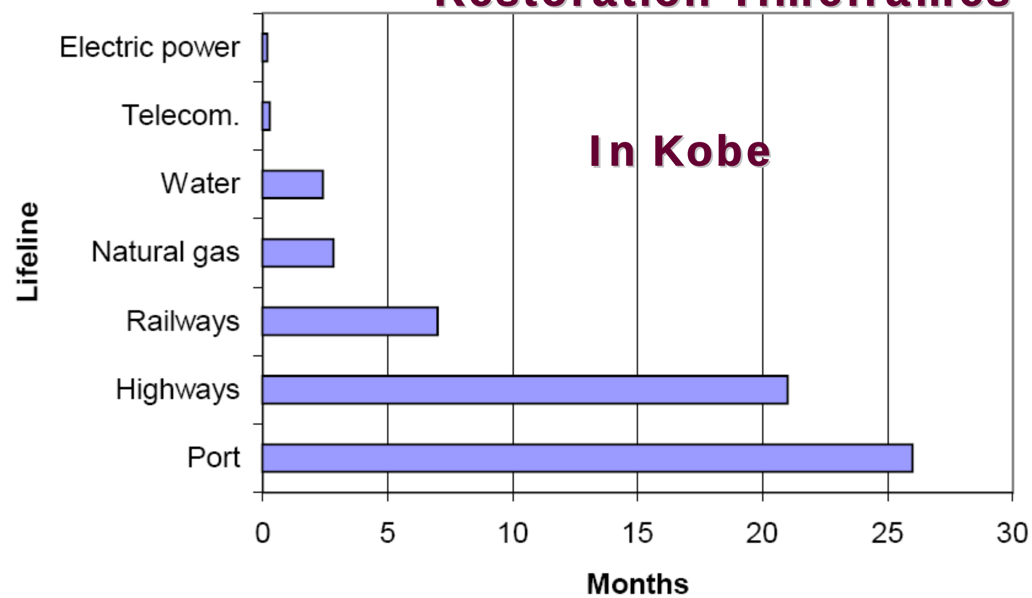
Resilience and Sustainability

of Kobe Port

Container traffic



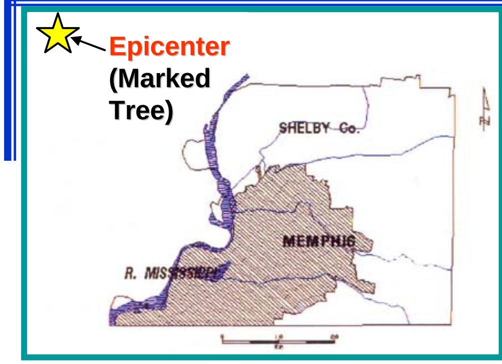
Restoration Timeframes



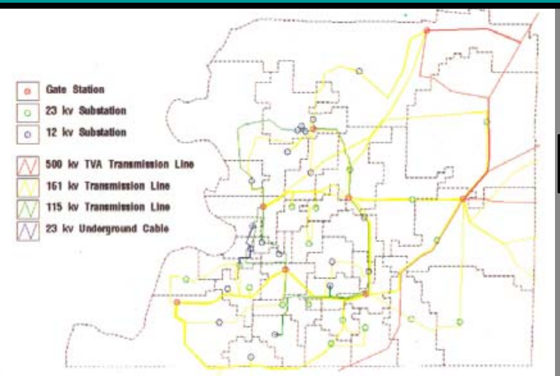
TEU = Twenty-foot Equivalent Unit

Source: Containerization International Yearbook

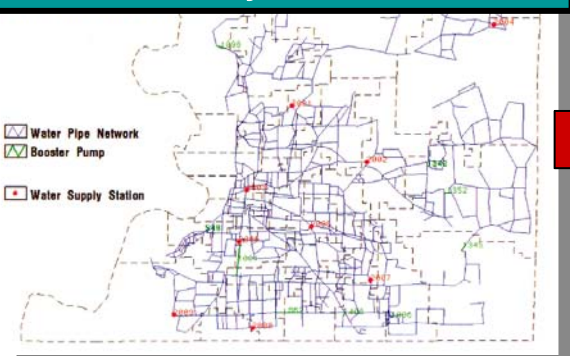
INTEGRATED WATER AND POWER SYSTEM



Electric Power Transmission Network

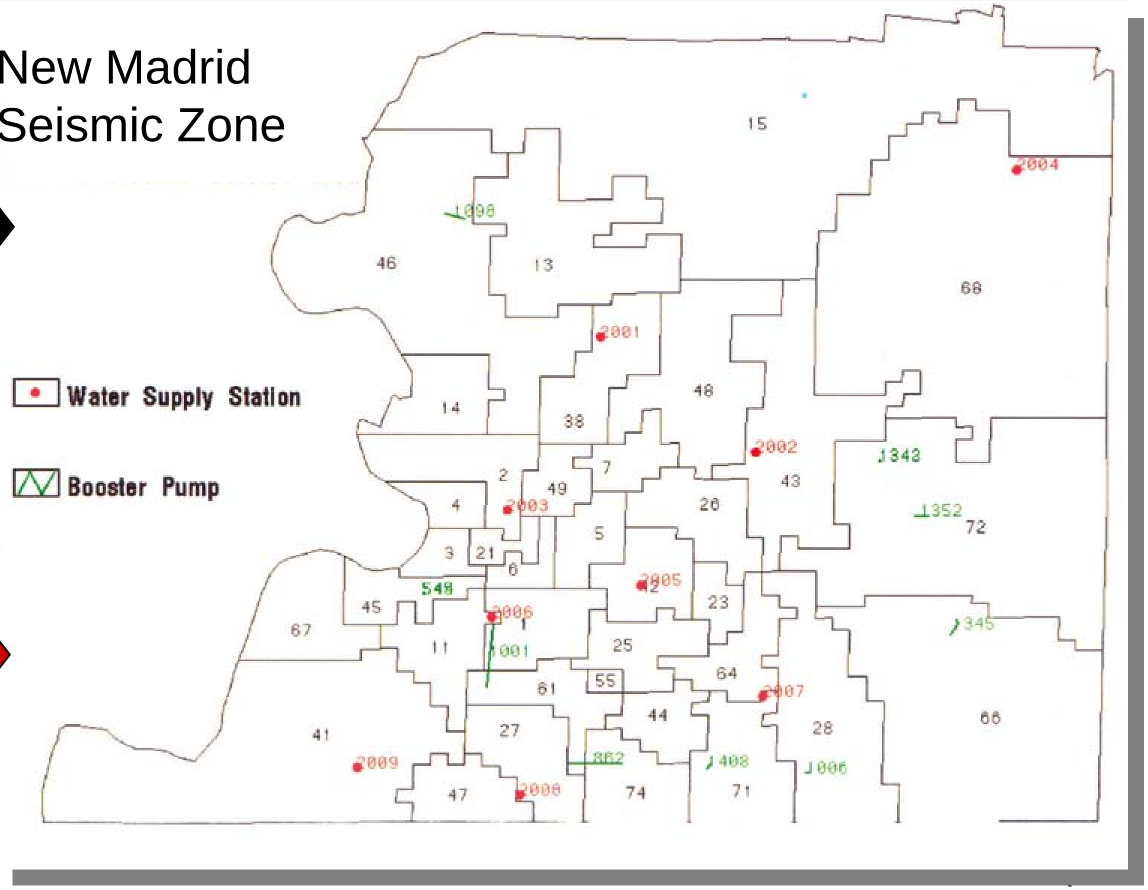


Water Delivery Network

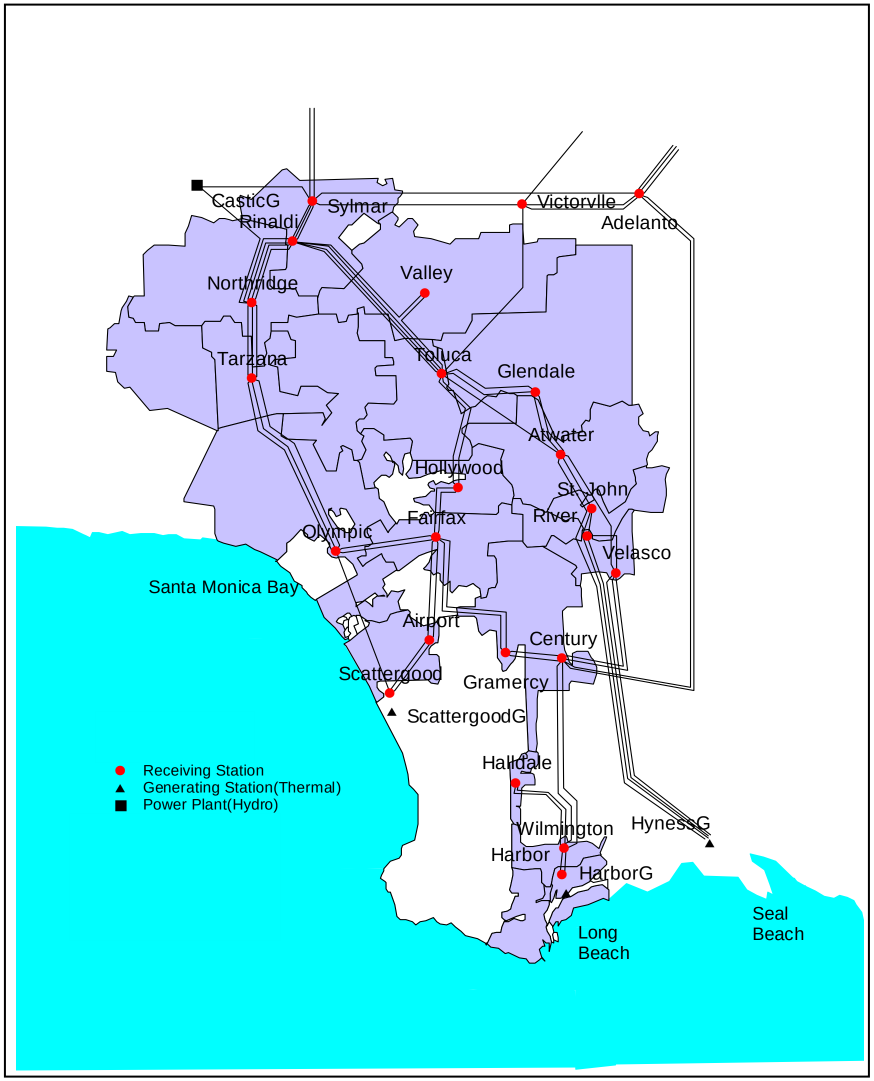


MLGW Water Supply Stations & Booster Pumps On the Electric Service Area

New Madrid Seismic Zone



Los Angeles Department of Water and Power's Electric Power Transmission system

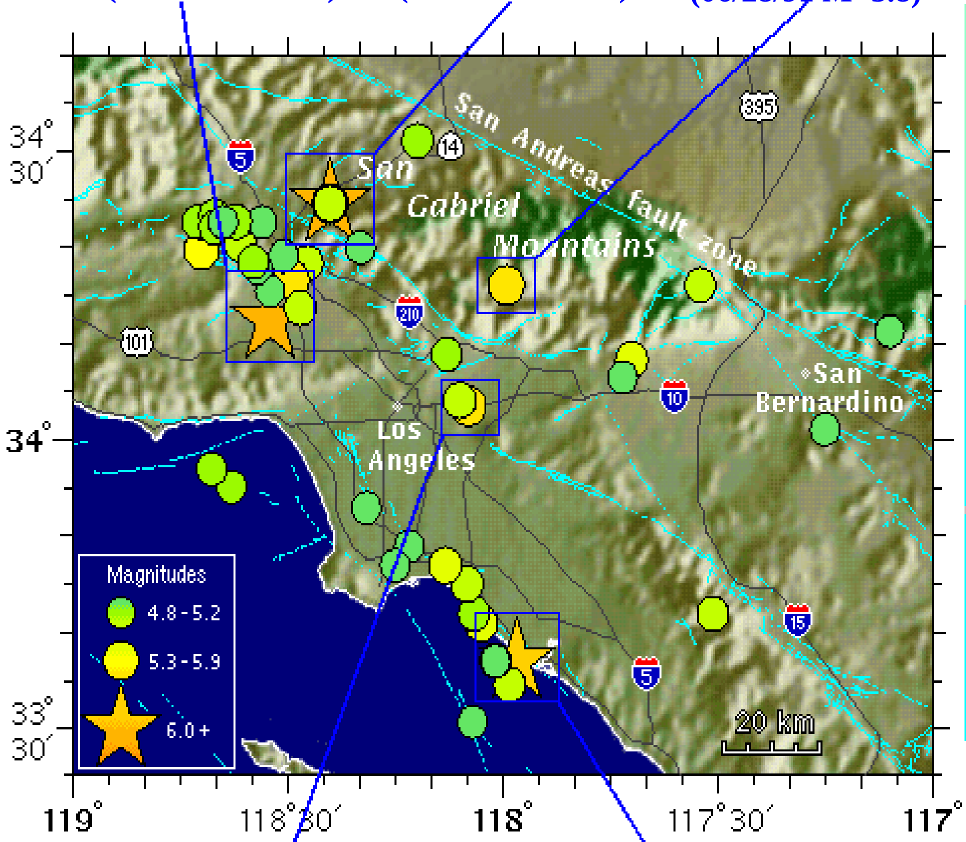


Part of Western Electricity Coordination Council's (WECC's) network covering 14 US western states, 2 Canadian provinces and northern part of Baja California

6,300 MW at a typical peak hour for a population of 3.7 million

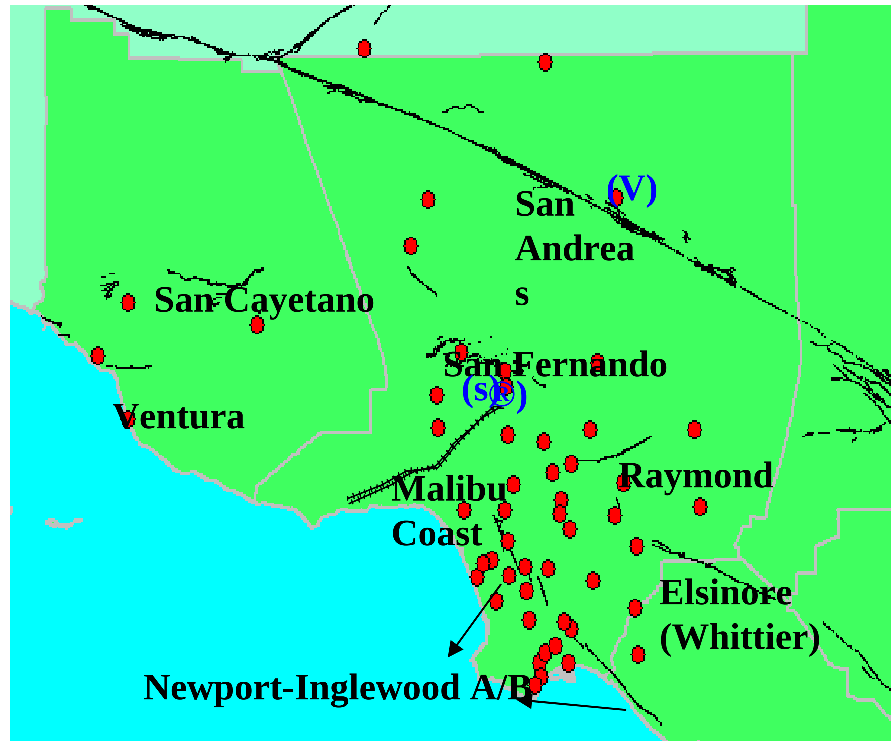
Seismic Hazard

Los Angeles Basin Seismicity (1932-1996)
To be represented by scenario earthquakes



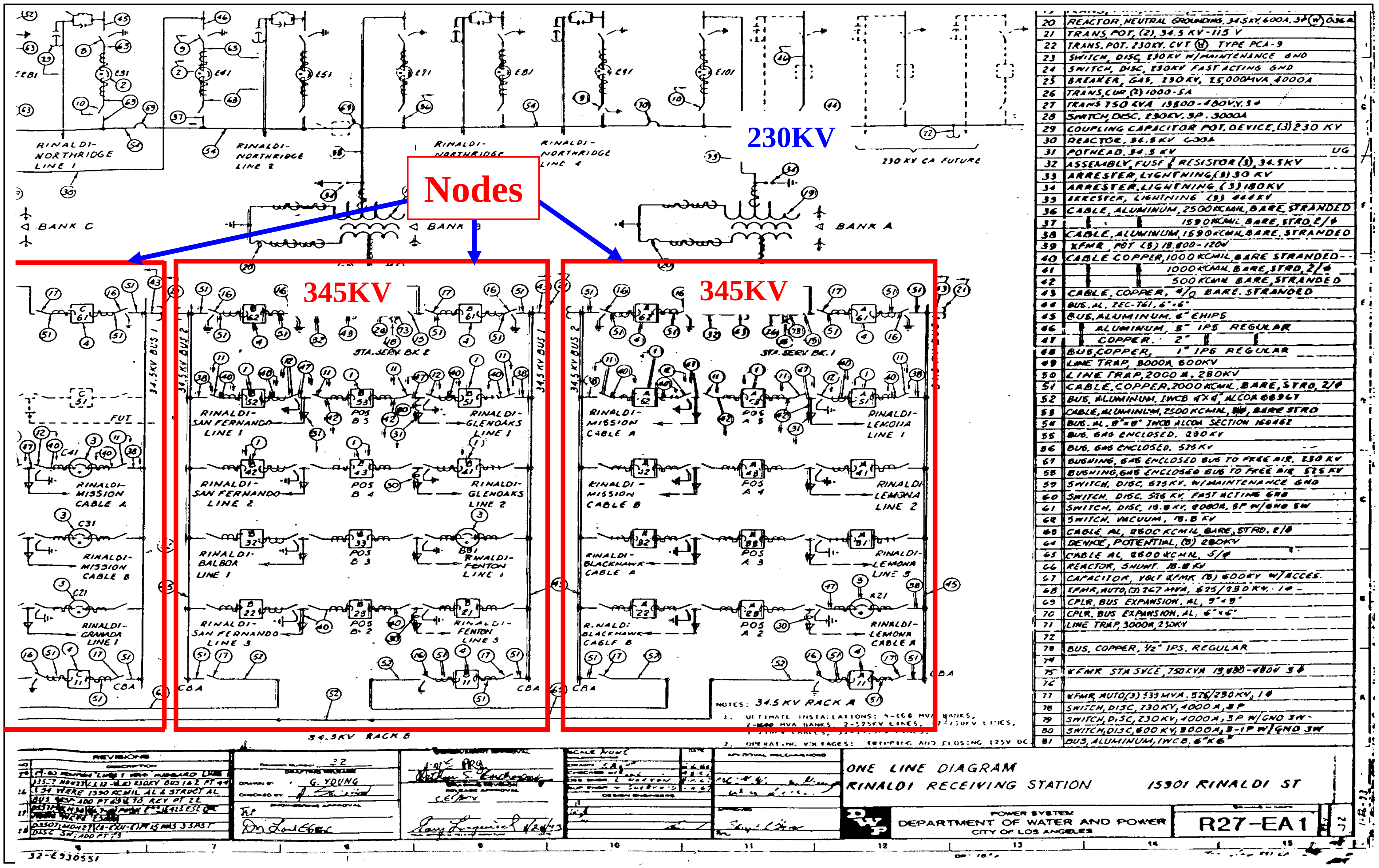
Seismic Exposure

Locations of Seismic Faults and 52 Receiving Stations in Study Area



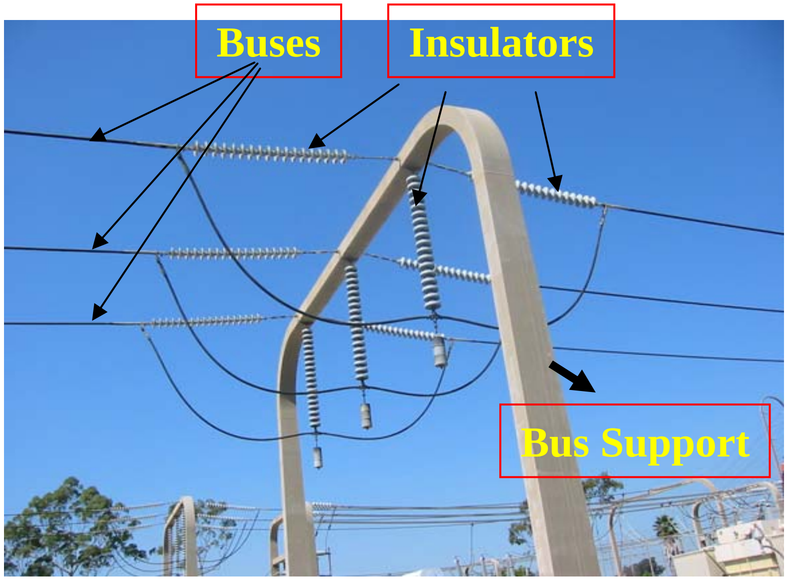
http://www.scecdc.scec.org/labasin.html

One line diagram of a receiving station



500kV/230kV Transformer

Bus

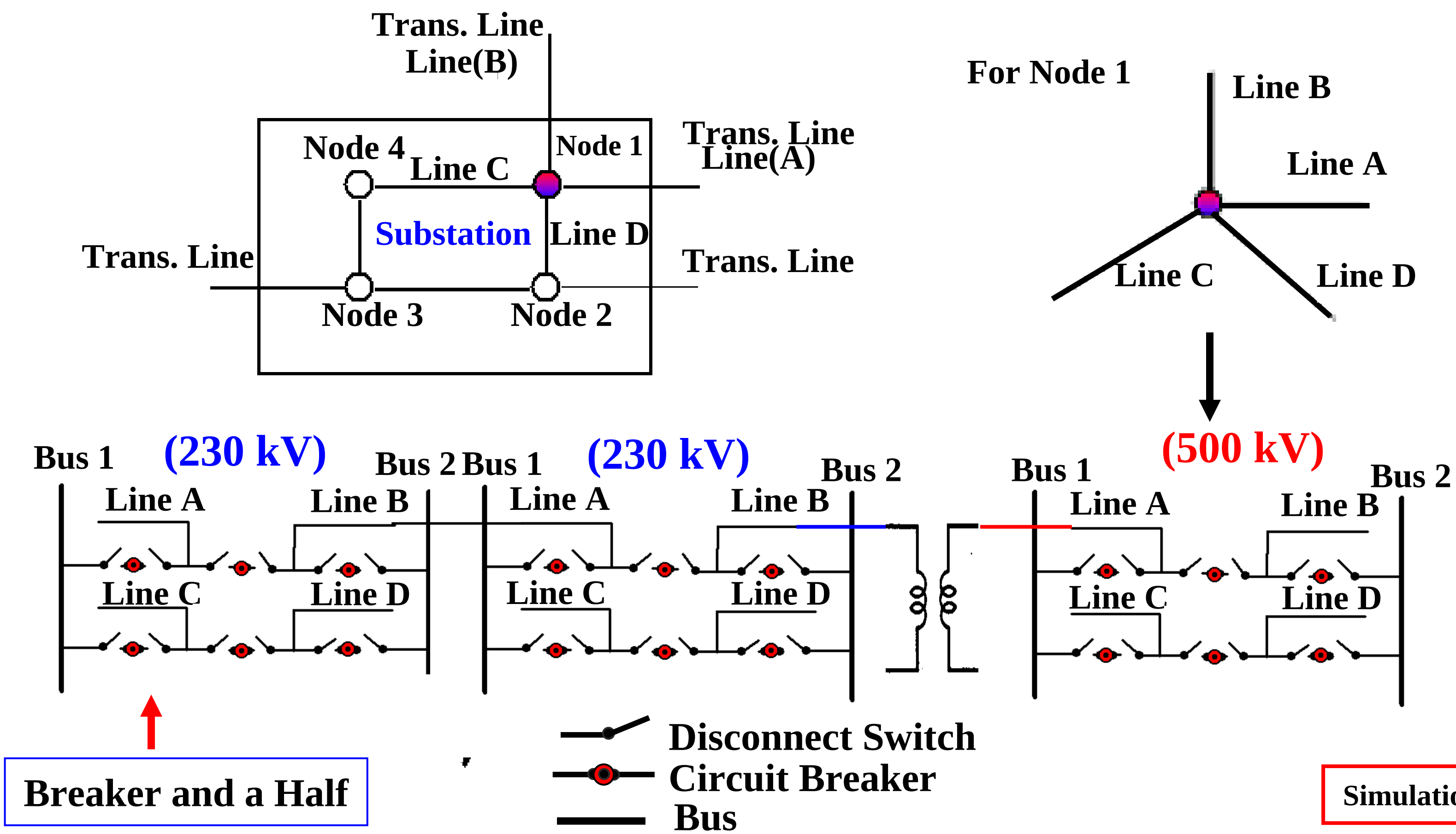


Circuit Breakers

Disconnect Switches

Models for Substation and Nodes

Substation and Nodes



Simulation #1

47 Scenario Earthquakes Representing Regional Seismic Hazard

Maximum Credible Earthquakes

EQ Scenario	Scenario EQ	Type a)	Magnitude	Annual PB	Lat.	Long.
1	Elysian Park	MCE	7.1	0.0007	34.165	-117.833
2	Malibu Coast	MCE	7.3	0.0001	34.007	-118.615
3	Newport-Inglewood(N.)	MCE	7.0	0.0005	33.975	-118.359
4	Newport-Inglewood(S.)	MCE	7.0	0.0005	33.660	-117.997
5	Palos Verdes	MCE	7.2	0.0015	33.618	-118.170
6	Raymond	MCE	6.7	0.0007	34.127	-118.120
7	San Andreas	MCE	8.0	0.0049	34.278	-117.477
8	San Jacinto	MCE	7.5	0.0008	33.882	-117.087
9	Santa Susana	MCE	6.9	0.0044	34.318	-118.599
10	Sierra Madre	MCE	7.4	0.0021	34.143	-117.936
11	Simi Santa Rosa	MCE	7.5	0.0002	34.282	-118.822
12	Verdugo	MCE	6.8	0.0006	34.184	-118.273
13	Whittier	MCE	7.5	0.0003	33.643	-117.348

Scenario Earthquakes Representing Regional Seismic Hazard (Cont'd)

User Defined Earthquakes

14	Malibu Coast	U/D	6.0	0.0003	34.140	-118.042
15	Malibu Coast	U/D	6.0	0.0005	34.116	-118.158
16	Malibu Coast	U/D	6.0	0.0003	34.094	-118.372
17	Newport-Inglewood	U/D	6.0	0.0010	33.896	-118.269
18	Newport-Inglewood	U/D	6.0	0.0010	34.008	-118.374
19	Newport-Inglewood	U/D	6.0	0.0010	33.817	-118.197
20	Newport-Inglewood	U/D	6.0	0.0010	33.737	-118.079
21	Newport-Inglewood	U/D	6.0	0.0010	33.645	-117.955
22	Palos Verdes	U/D	6.0	0.0016	33.778	-118.315
23	San Andreas	U/D	6.0	0.0200	34.431	-117.815
24	San Andreas	U/D	6.0	0.0200	34.627	-118.319
25	San Jacinto	U/D	6.0	0.0100	34.263	-117.499
26	Santa Susana	U/D	6.0	0.0100	34.328	-118.607
27	San Fernando	U/D	6.0	0.0050	34.294	-118.468
28	Sierra Madre	U/D	6.0	0.0100	34.256	-118.254
29	Sierra Madre	U/D	6.0	0.0100	34.161	-117.920
30	Whittier	U/D	6.0	0.0015	33.957	-117.907

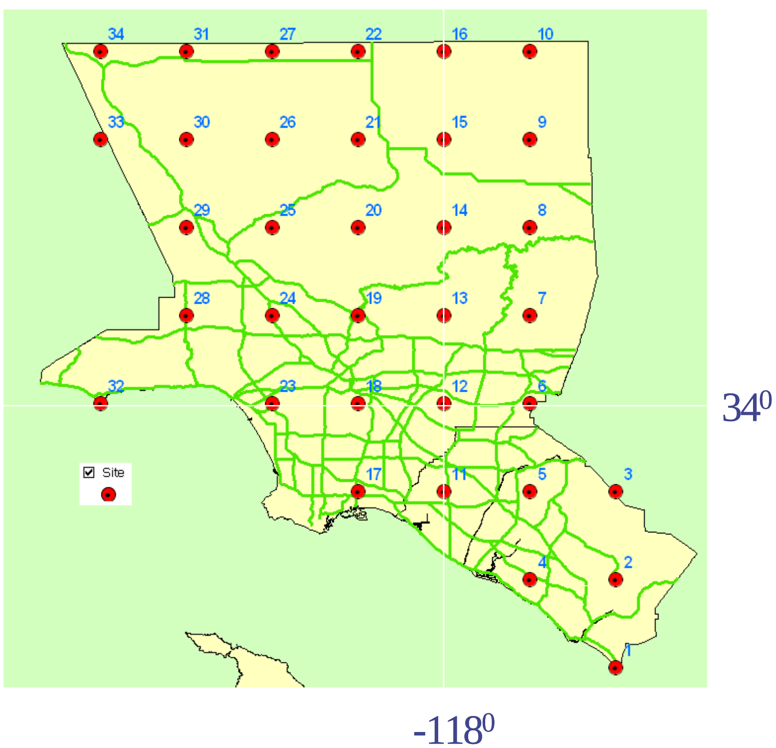
Scenario Earthquakes Representing Regional Seismic Hazard (Cont'd)

User Defined Earthquakes

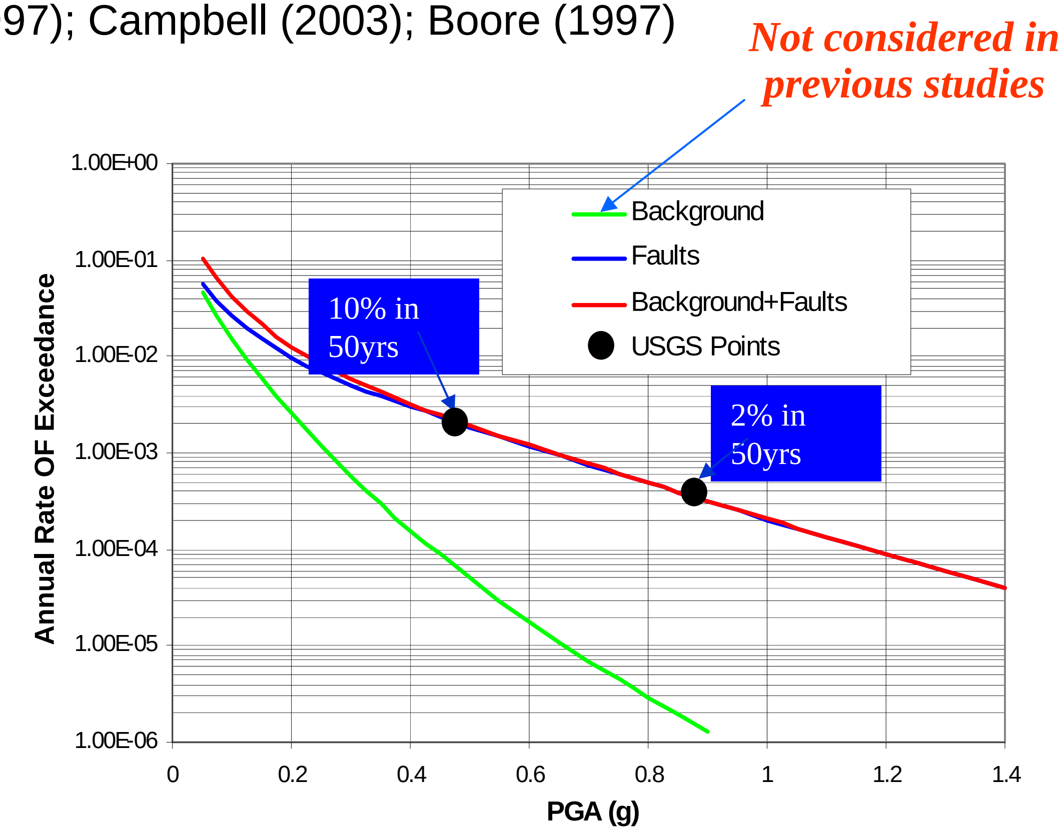
31	Malibu Coast	U/D	6.5	0.0002	34.143	-118.122
32	Malibu Coast	U/D	6.5	0.0002	34.109	-118.073
33	Malibu Coast	U/D	6.5	0.0001	34.092	-118.380
34	Newport-Inglewood	U/D	6.5	0.0005	33.940	-118.319
35	Newport-Inglewood	U/D	6.5	0.0005	33.790	-118.146
36	Newport-Inglewood	U/D	6.5	0.0005	33.656	-117.959
37	San Andreas	U/D	6.5	0.0080	34.594	-118.205
38	San Andreas	U/D	6.5	0.0080	34.439	-117.839
39	San Jacinto	U/D	6.5	0.0050	34.230	-117.454
40	Santa Susana	U/D	6.5	0.0011	34.297	-118.423
41	Whittier	U/D	6.5	0.0010	33.924	-117.841
42	Malibu Coast	U/D	7.0	0.0001	34.065	-118.456
43	Malibu Coast	U/D	7.0	0.0001	34.123	-118.157
44	San Jacinto	U/D	7.0	0.0015	34.237	-117.463
45	San Andreas	U/D	7.0	0.0030	34.573	-118.179
46	San Andreas	U/D	7.0	0.0030	34.403	-117.732
47	Whittier	U/D	7.0	0.0005	33.940	-117.884

Probabilistic scenario earthquakes are developed to represent regional seismic hazard consistent with USGS estimation

- Probabilistic Scenario Earthquake Set of 47 Earthquakes
- Hazard Curve is averaged over 4 empirical attenuation relationships
  Sadigh (1997); Abrahamson (1997); Campbell (2003); Boore (1997)



Grid Sites in Study Region



Hazard Comparison at Site 12

Newport-Inglewood (S) Earthquake (MCE=7.0)

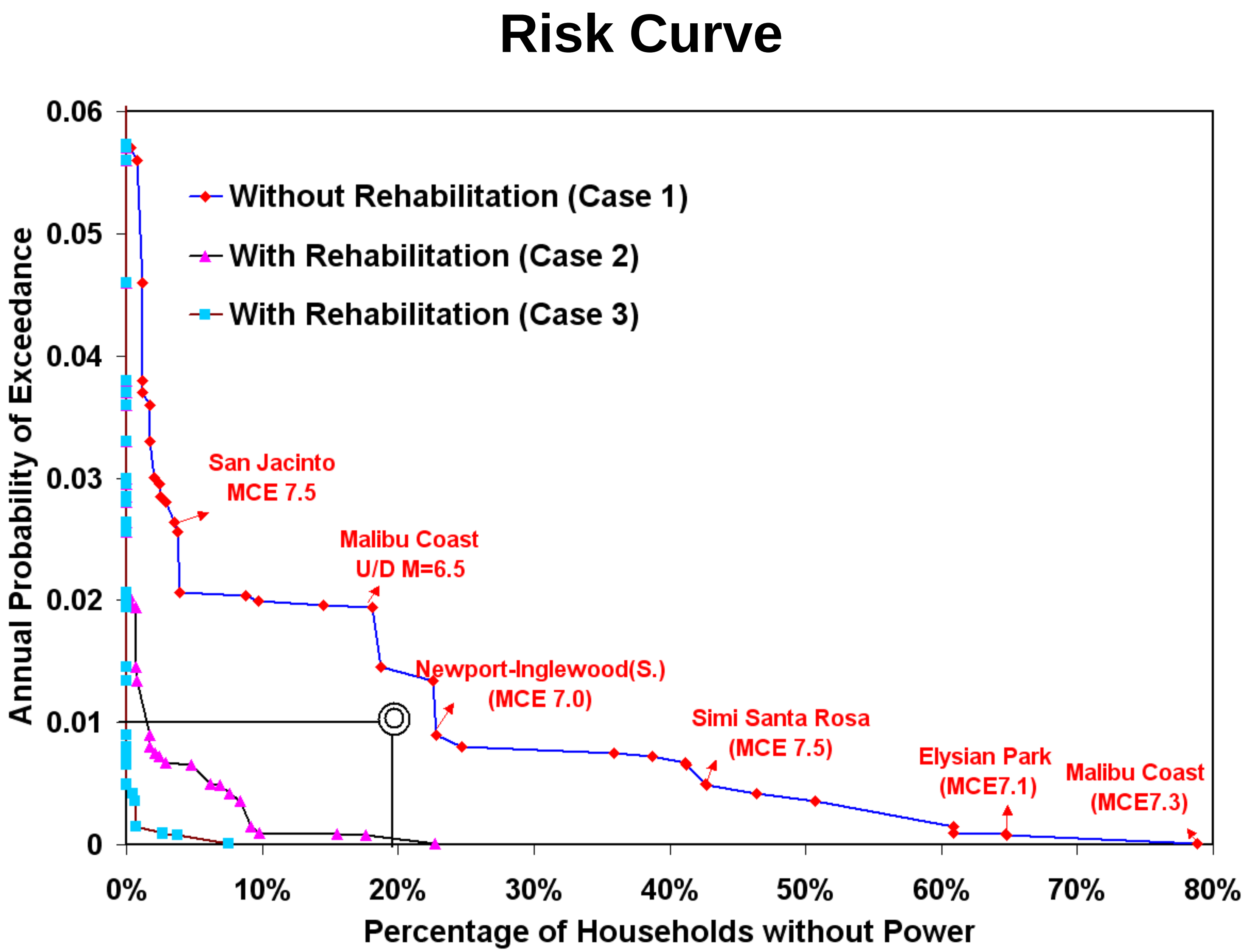
Equipment Damage Information

Substation Name	Xmers	CBs	DSs	Substation Name	Xmers	CBs	DSs
RINALDI	0	2	2	GOULD	0	2	2
SYLMAR	0	1	3	GOODRICH	0	2	2
NORTHRIDGE(STA_J)	0	3	3	MESA	0	3	2
TARZANA9STA_U)	0	2	6	LAGUNA_BELL	1	1	7
OLYMPIC(STA_K)	0	3	2	LIGHTHIPE	2	2	14
SCATTERGOOD	0	3	4	LA_FRESA	2	2	14
AIRPORT(STA_N)	0	3	2	REDONDO_BEACH	0	1	10
FAIRFAX(STA_D)	0	1	3	EL_NIDO	0	3	9
HOLLYWOOD(STA_H)	0	3	5	EL_SEGUNDO	0	2	6
TOLUCA(STA_E)	0	2	3	LA_CIENEGA	0	2	5
VALLEY	0	1	3	HILSON	2	5	29
GLENDALE(AIR_WAY)	0	2	2	ARCO	4	5	25
ATWATER(STA_G)	0	2	1	HORBORGEN	1	2	8
ST.JOHN(STA_A)	0	1	2	LONG_BEACH	7	10	45
RIVER	0	1	5	DEL_AMO	0	3	17
VELASCO(STA_F)	0	1	10	CENTER	0	2	5
CENTURY(STA_B)	0	2	7	ALAMITOS	5	2	22
GRAMERCY	0	2	9	WALNUT	0	2	4
TAP1&TAP2	0	2	6	RIO_HONDO	0	2	3
HALLADLE	0	1	3	VINCENT	0	1	1
WILLINGTON(STA_C)	0	1	14	ANTELOPE	0	3	2
HARBOR(STA_Q)	1	3	6	BALLEY	0	2	1
HARBOR5G	0	1	2	MOOR_PARK	0	2	2
EAGLE_ROCK	0	2	3	ORMOND_BEACH	0	1	2
PARDEE	0	1	2	SANTA_CLARA	0	1	2
SAUGUS	0	2	1	MANDALAY	0	1	2

Disabled Lines

FSubstation	TSubstation	FNode	Tnode
GRAMERCY	CENTURY	10014	10069
GRAMERCY	FAIRFAX	10014	10076
GRAMERCY	TAP1&TAP2	10014	10095
GRAMERCY	CENTURY	10015	10069
GRAMERCY	FAIRFAX	10015	10076
GRAMERCY	TAP1&TAP2	10015	10096
HALLADLE	TAP1&TAP2	10016	10095
HALLADLE	TAP1&TAP2	10016	10096
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
RIVER	ST.JOHN	10063	10068
RIVER	VELASCO	10063	10080
CENTURY	CENTURY	10070	10069
CENTURY	CENTURY	10071	10069
CENTURY	CENTURY	10072	10069
CENTURY	CENTURY	10072	10069
CENTURY	WILLINGTON	10069	10073
CENTURY	WILLINGTON	10069	10074
LAGUNA_BELL	LAGUNA_BELL	34117	34274
LONG_BEACH	LONG_BEACH	34119	34216
LONG_BEACH	LONG_BEACH	34119	34217
LONG_BEACH	LONG_BEACH	34119	34228
LONG_BEACH	LONG_BEACH	34119	34229
LONG_BEACH	LONG_BEACH	34119	34230
LONG_BEACH	LONG_BEACH	34119	34234
LONG_BEACH	LIGHTHIPE	34120	34126
LONG_BEACH	LONG_BEACH	34120	34231
LONG_BEACH	LONG_BEACH	34120	34232
LONG_BEACH	LONG_BEACH	34120	34233

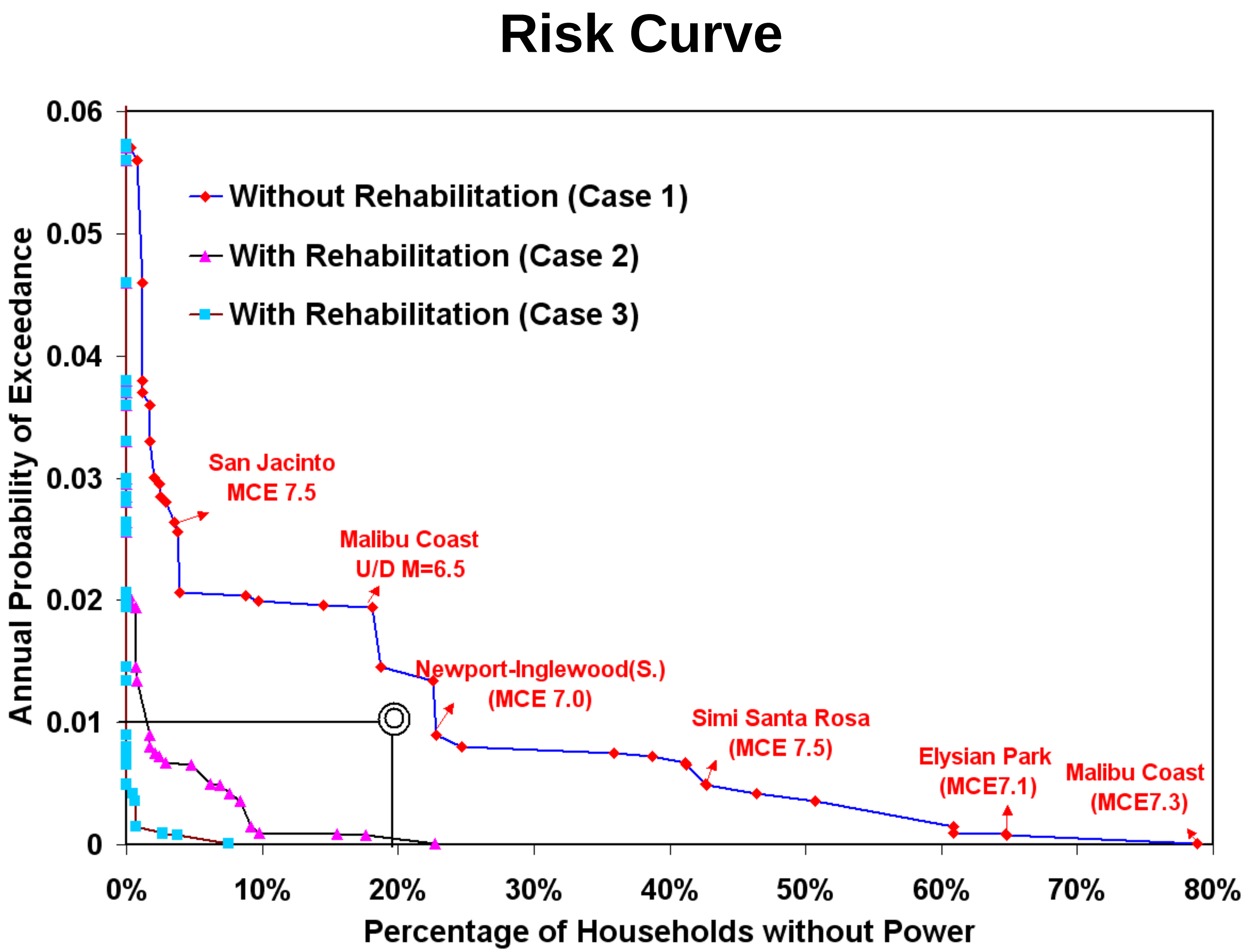
Annual Probability of Exceedance for Households without Power (enlarged view)



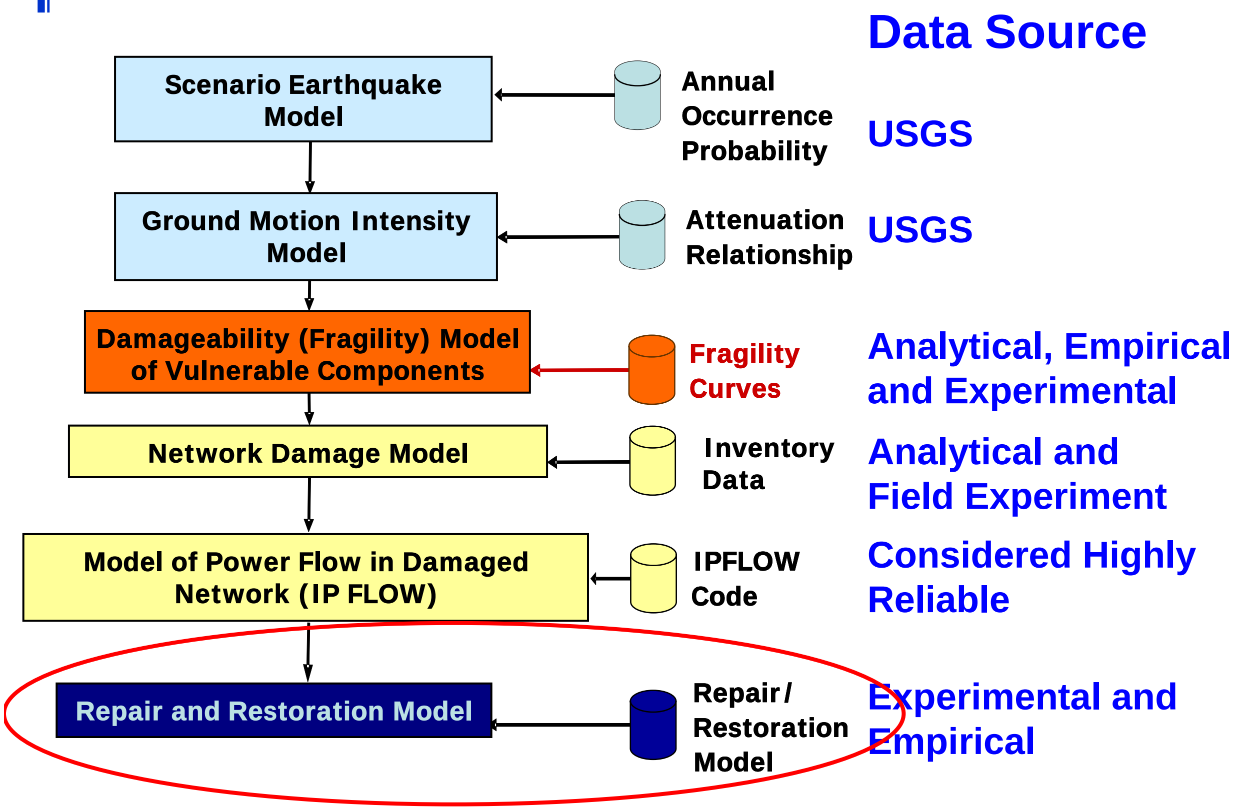
Fragility Curves for Transformers

Base Isolation System Utilized in NCREE/UCI/Bridgestone Tests

Annual Probability of Exceedance for Households without Power (enlarged view)



Simulation of Seismic Performance of Power Systems



Vulnerable components:
Transmission towers,
Transmission lines,
Substation equipments,
Power generation plants

Failure Criteria

- Loss of connectivity
- Imbalance of power

$$\frac{\text{total supply}}{\text{total demand}} > 1.05 \quad \text{or} \quad \frac{\text{total supply}}{\text{total demand}} < 1$$

- Abnormal voltage

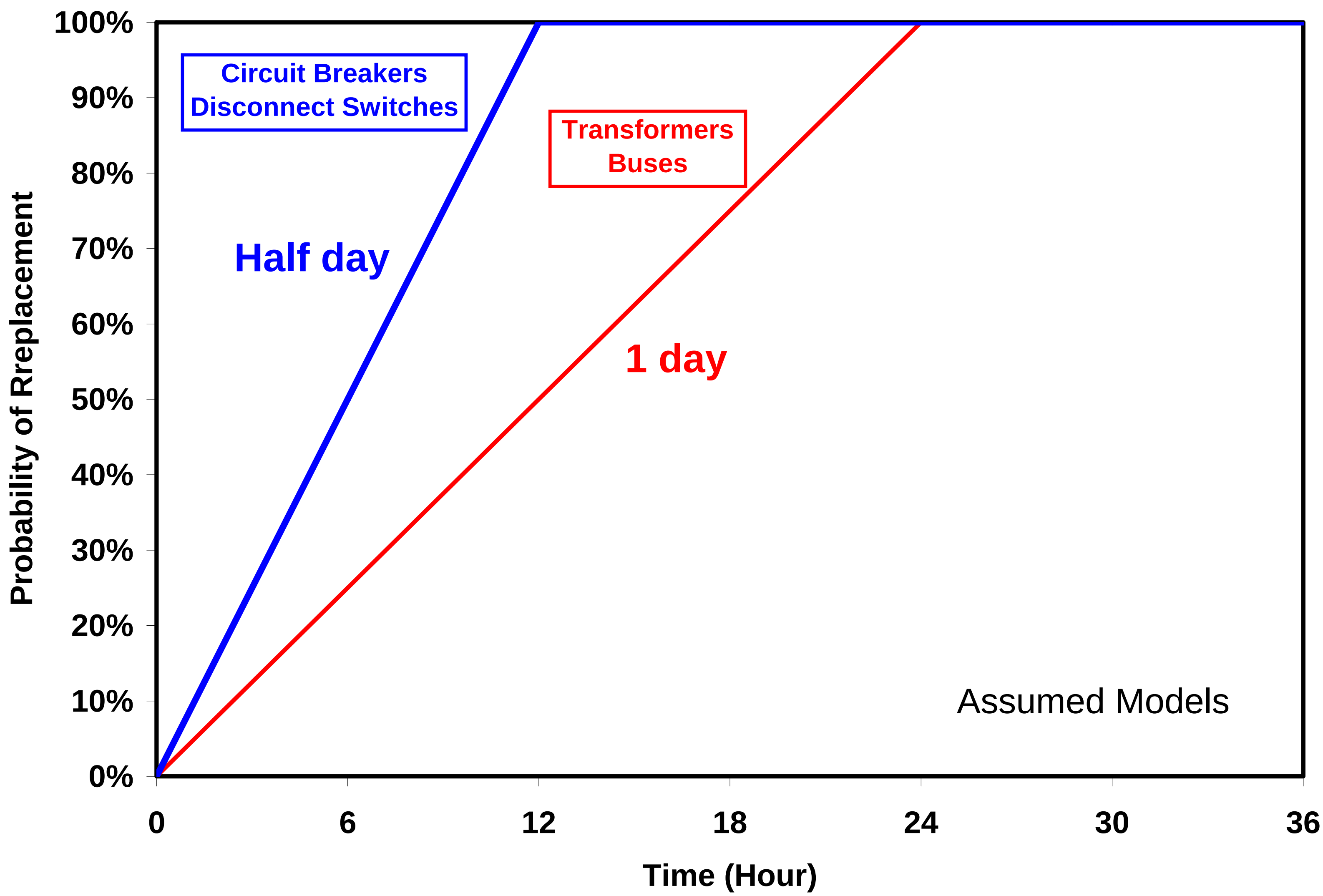
$$\left|\frac{V_{\text{intact}} - V_{\text{damaged}}}{V_{\text{intact}}}\right| > 0.1$$ (node by node)

- Frequency change

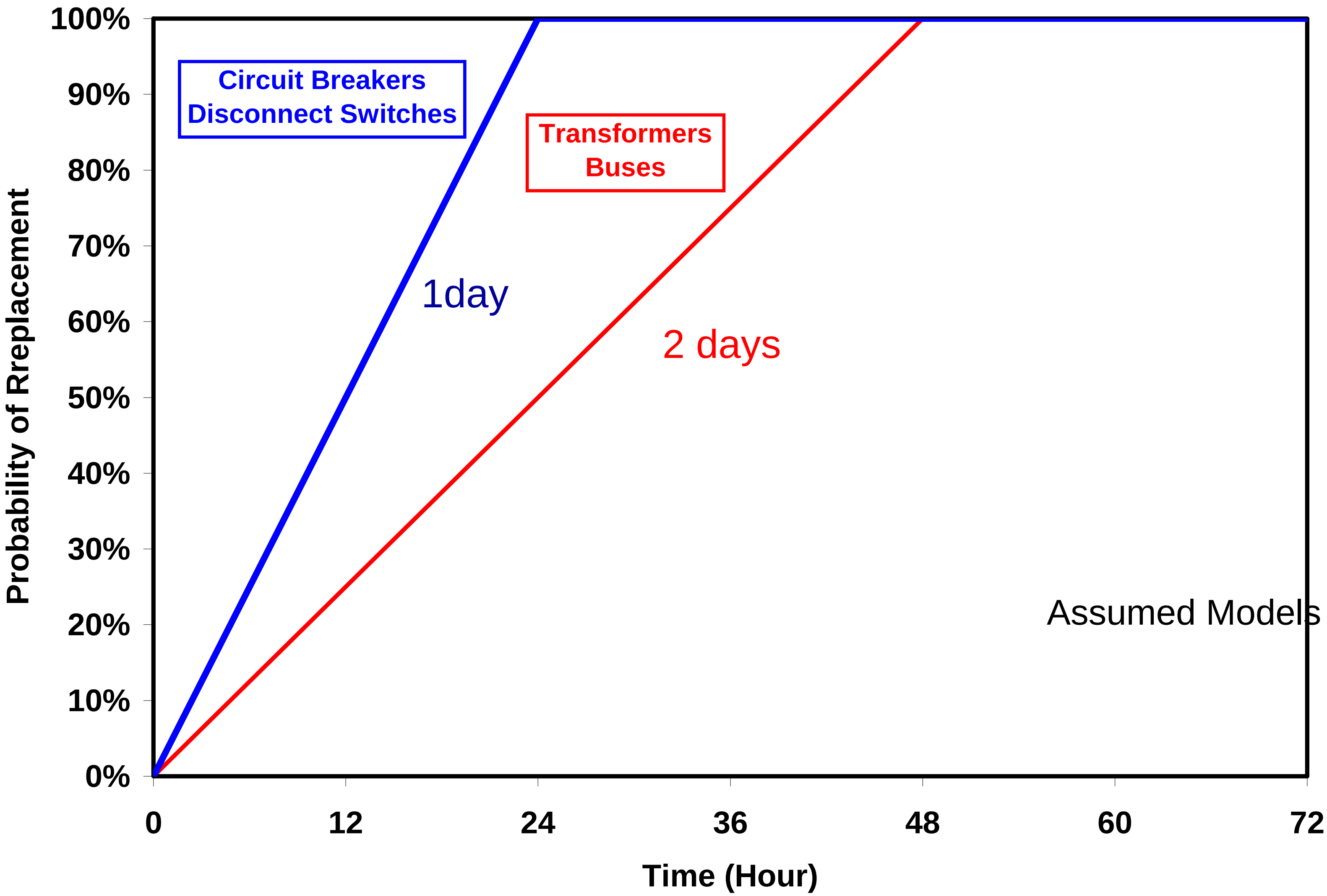
IPFLOW does not check

Sequential modular tasks

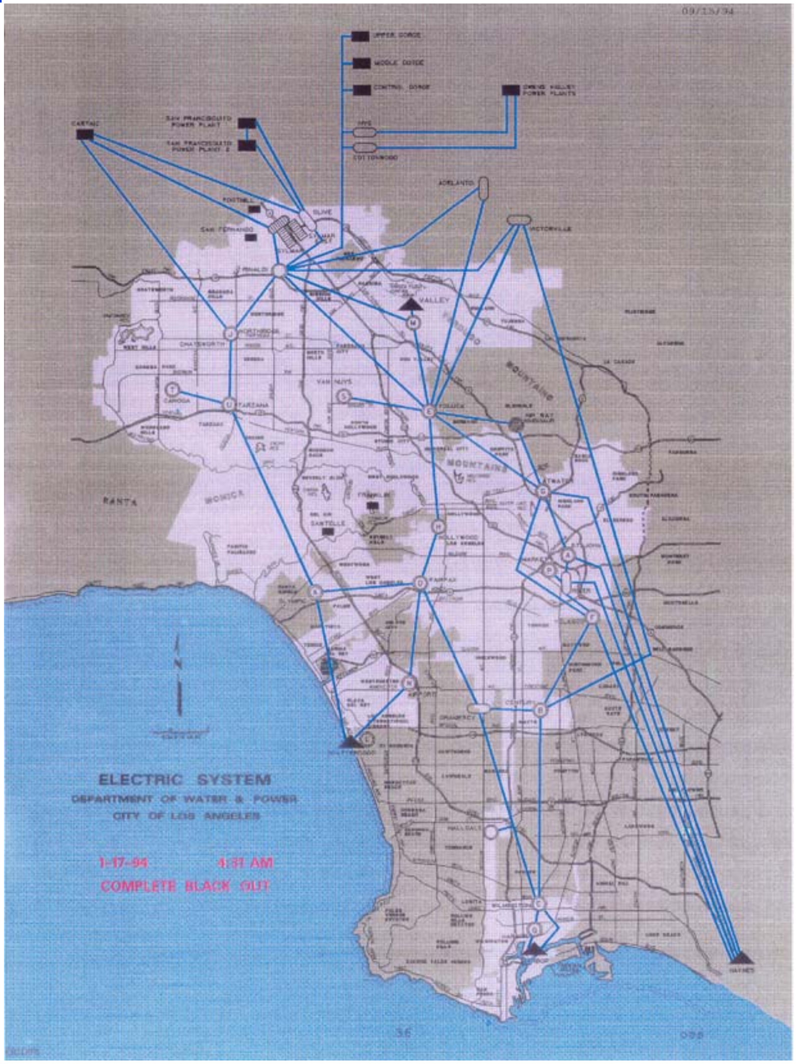
Repair/Replacement Curves



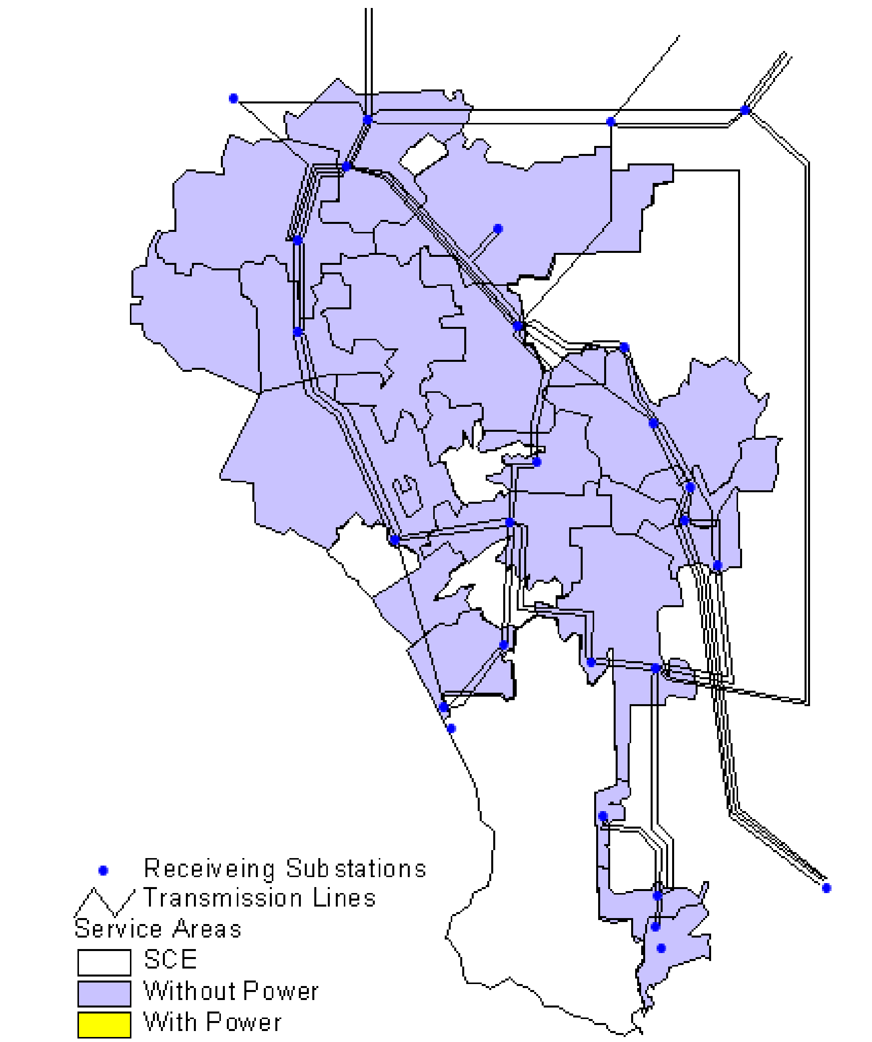
Repair/Replacement Curves



LADWP's Power Supply; Immediately after Earthquake

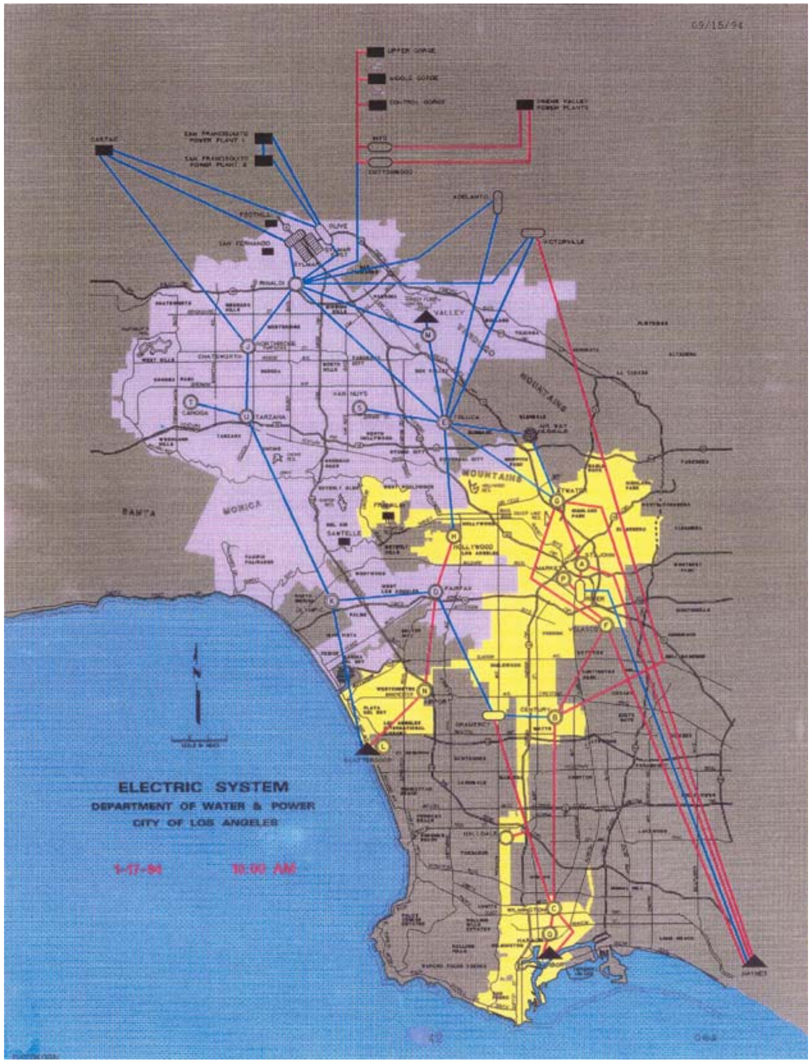


1-17-94 4:31AM

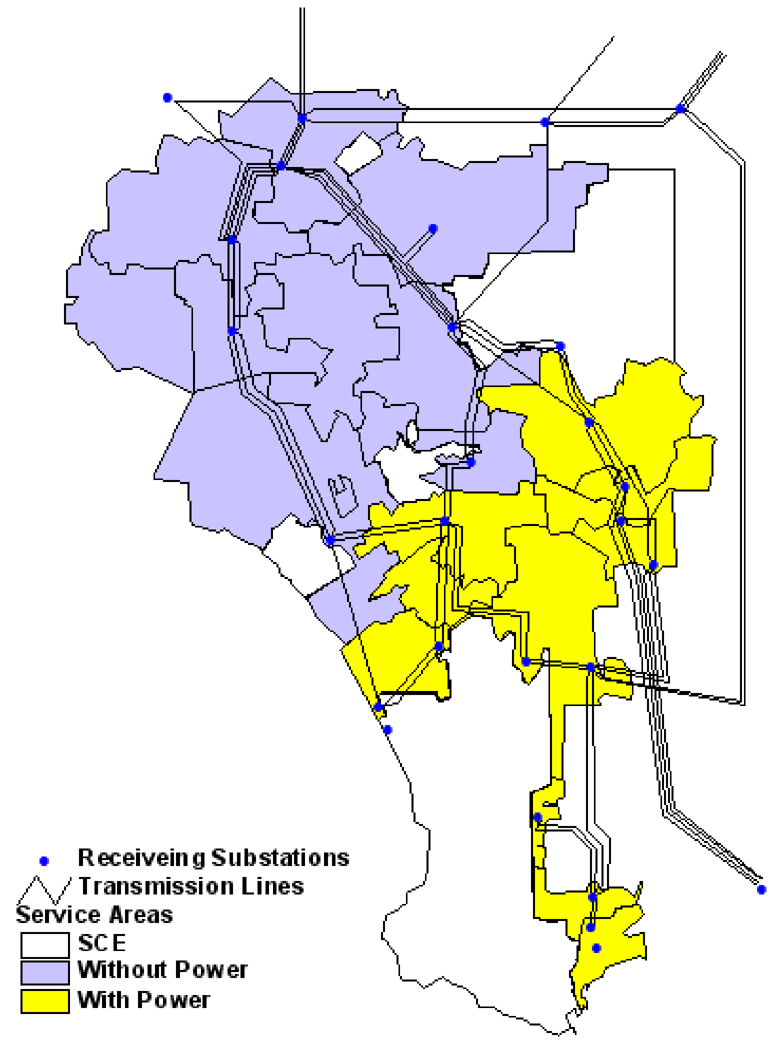


Northridge/N=20/Tr,CB,DS,Bus,T_1=12hrs T_2=24Hrs

LADWP's Power Restoration; 6 Hours after Earthquake

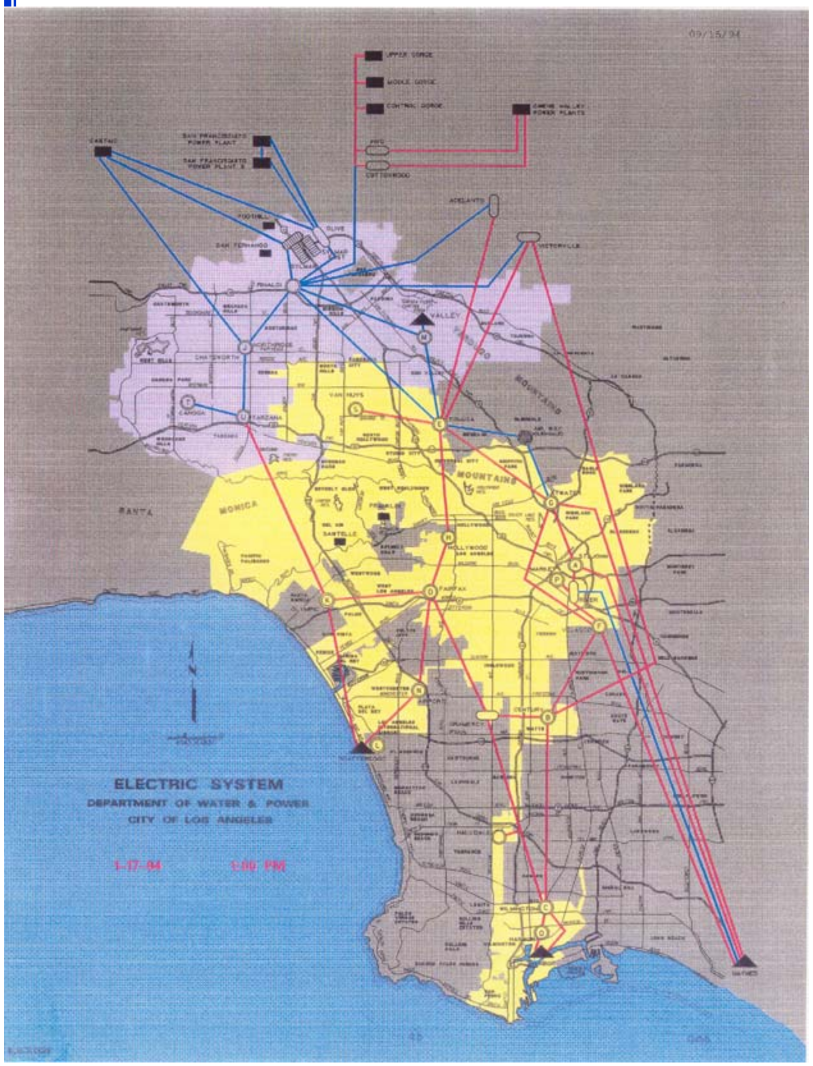


1-17-94 10:00 AM

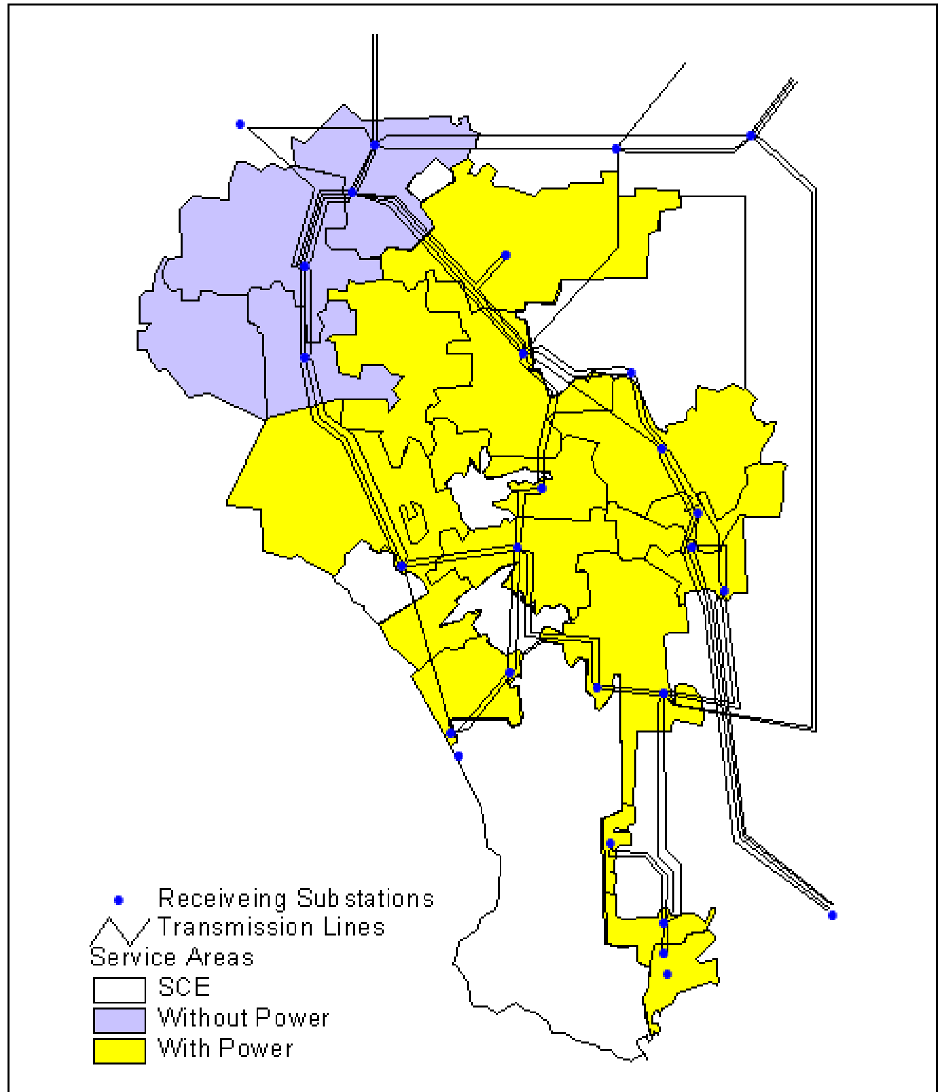


Northridge/N=20/Tr,CB,DS,Bus,T_1=12hrs T_2=24 Hrs

LADWP’s Power Restoration; 12 Hours after Earthquake

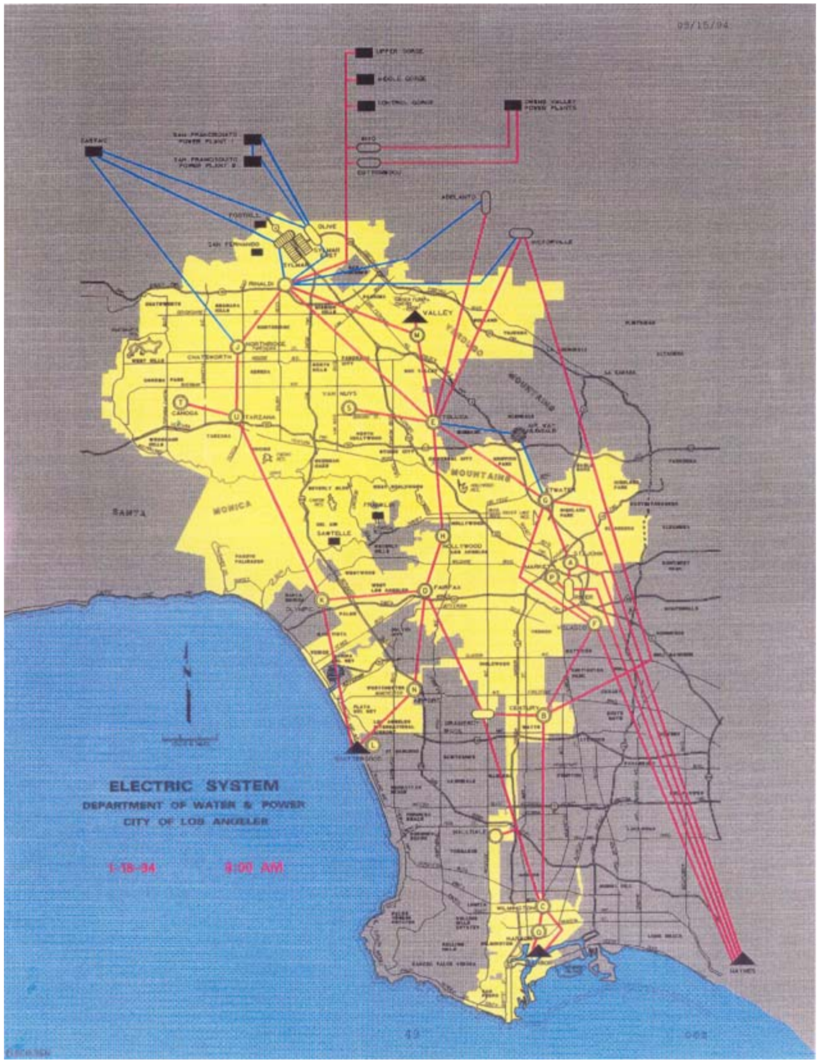


1-17-94 1:00 PM

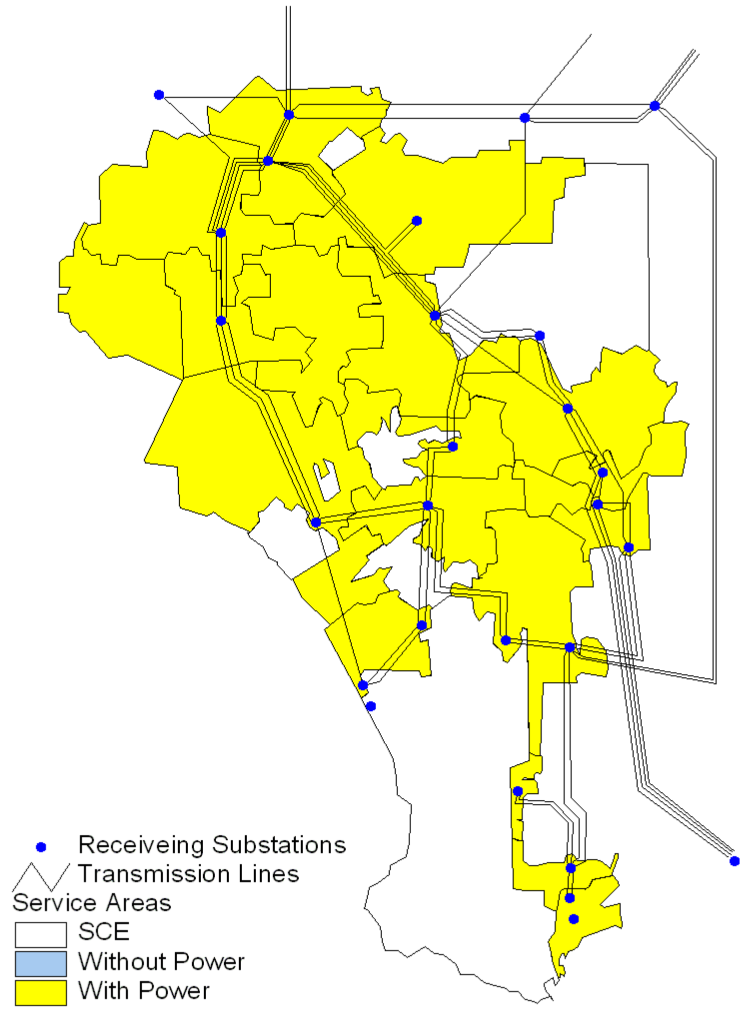


Northridge/N=20/Tr,CB,DS,Bus,T_1=12hrs T_2=24Hrs

LADWP's Power Restoration; 24 Hour after Earthquake

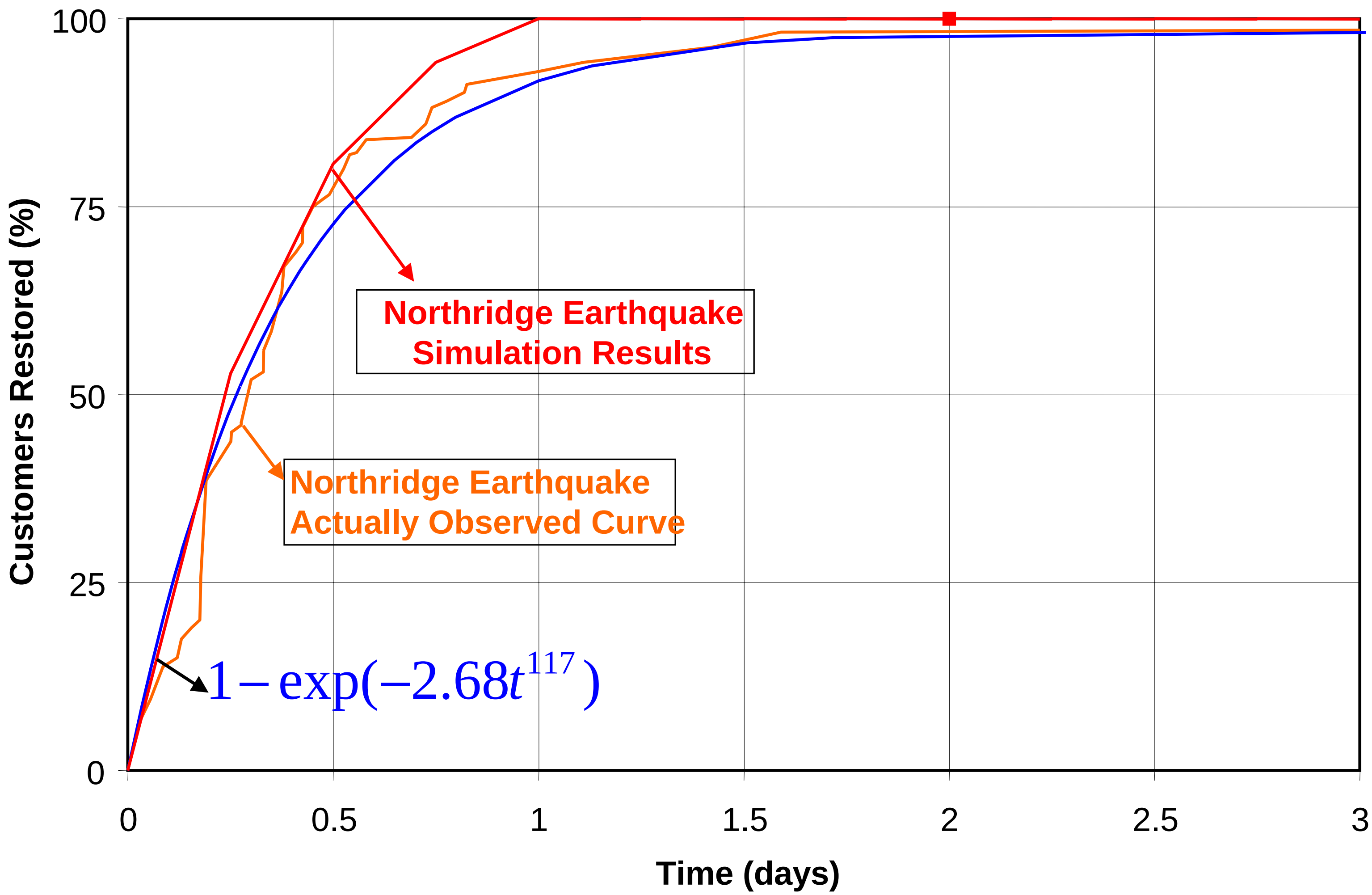


1-18-94 8:00 AM



Northridge/N=20/Tr,CB,DS,Bus,T_1=12hrs T_2=24 Hrs

LADWP's Power System Restoration

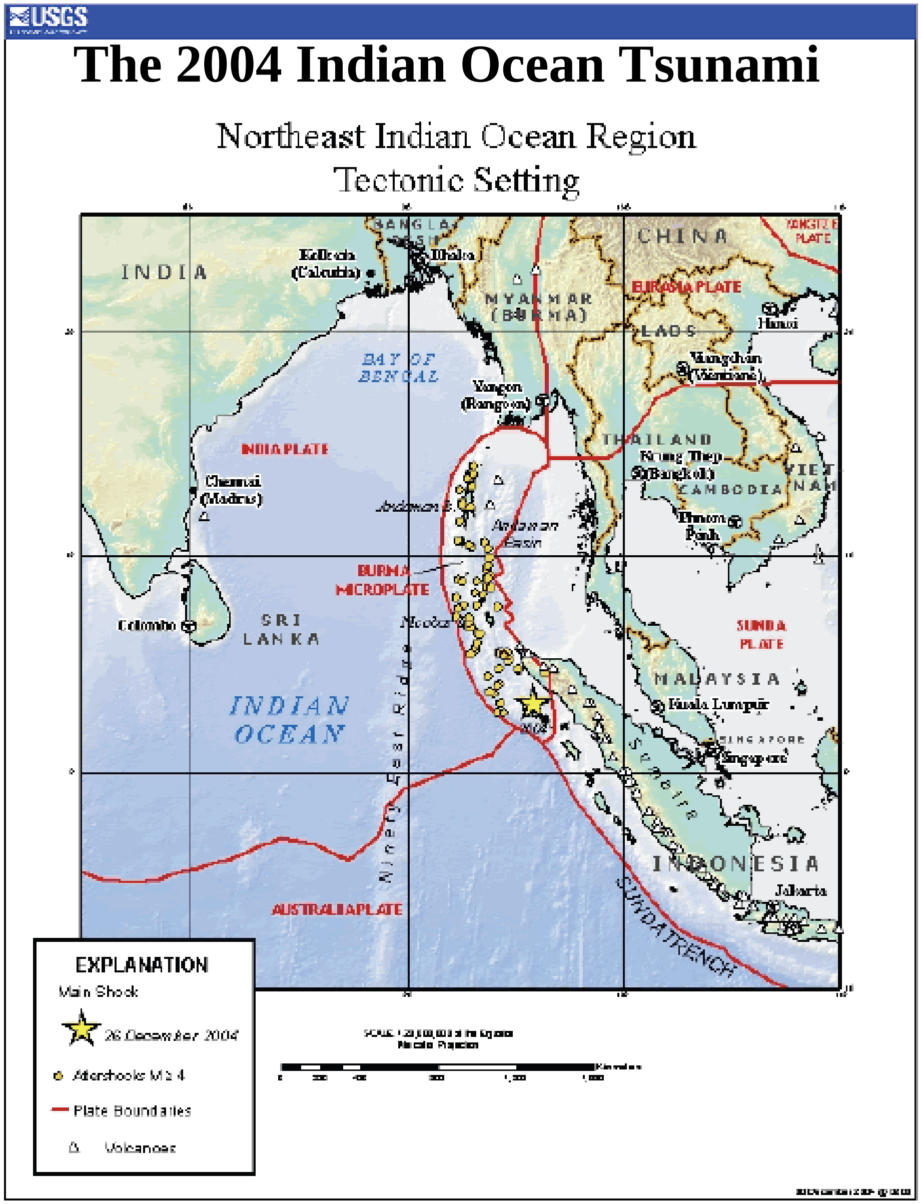


N=20/Tr,CB,DS,Bus,T_1=12hrs T_2=24Hrs

Simulation of Tsunamis and Their Consequences

The 2004 Indian Ocean Tsunami

Simulation of Tsunamis and Their Consequences



Off the west coast of northern Sumatra

Sunday, Dec.26 at 07:58AM , LT

Magnitude 9.0

Location : 3.3N, 95.9E

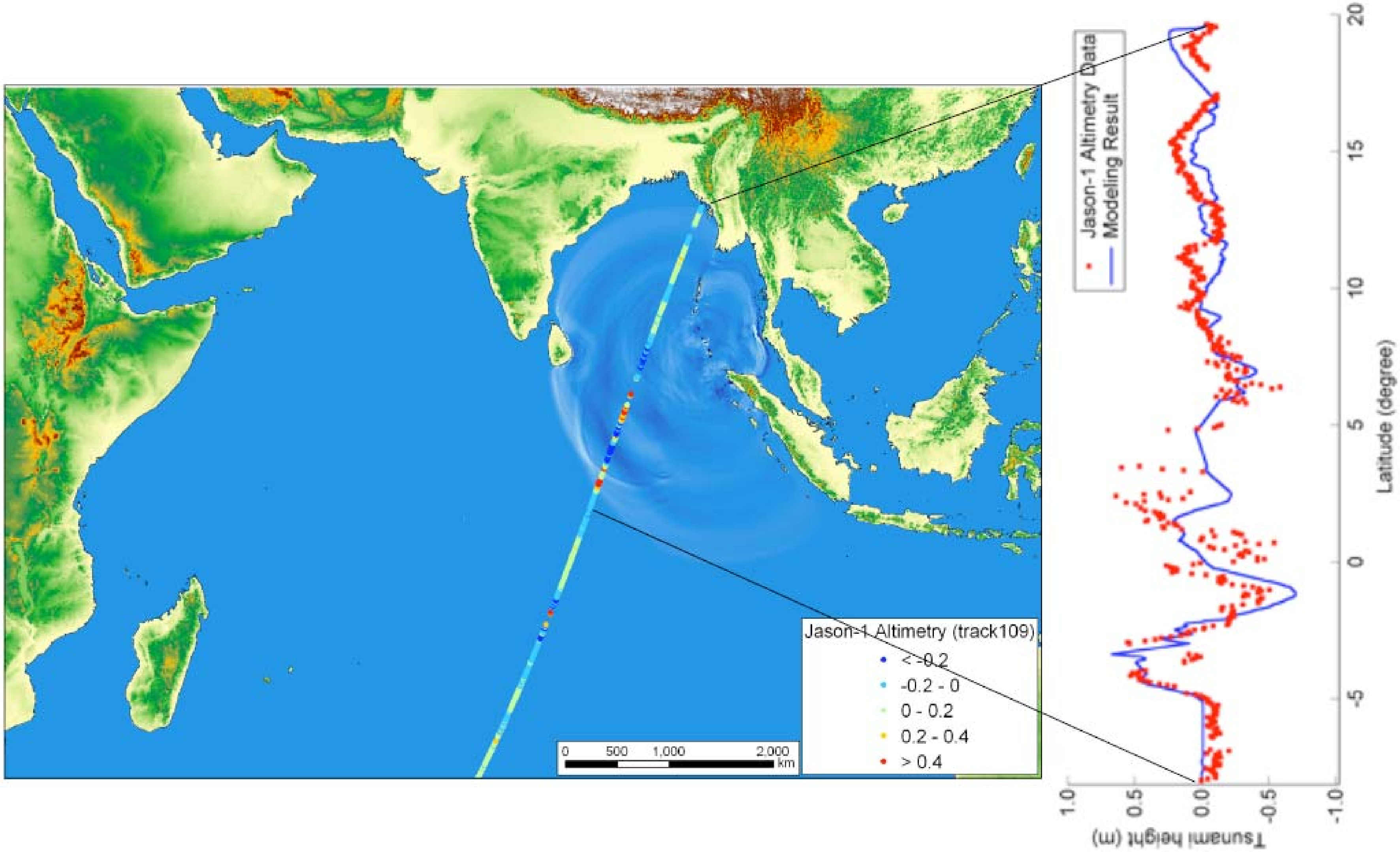
Depth : 30 Km

Simulation by Professor Koshimura,
Tohoku University, Japan

The forth largest earthquake in the world since 1900.

Almost 300,000 people were killed or still missing

Model Validation with Altimetry Data



1995 Kobe Earthquake

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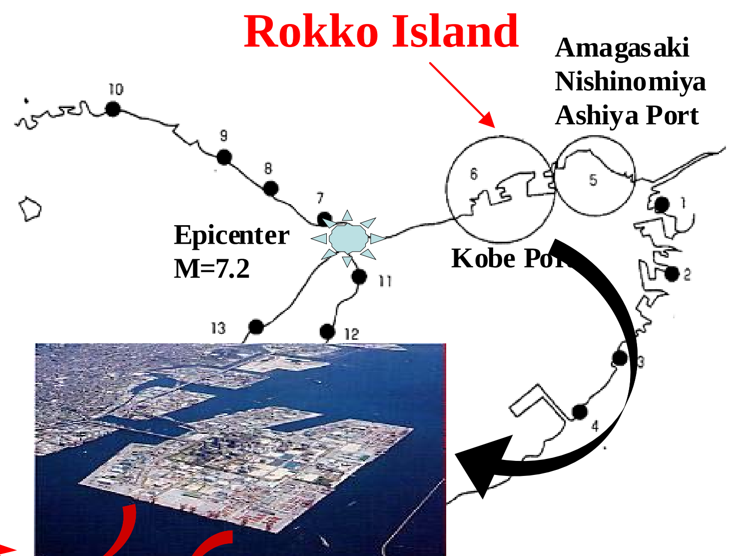
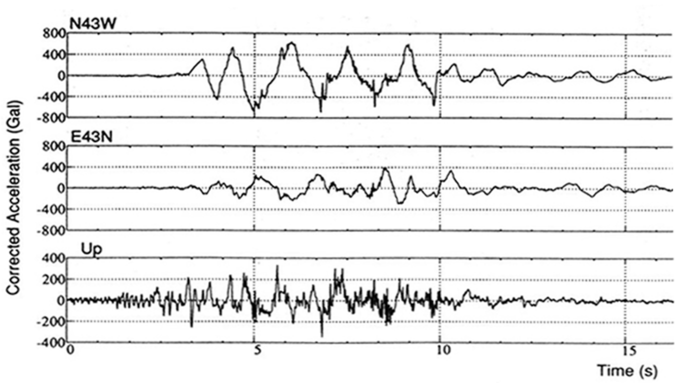
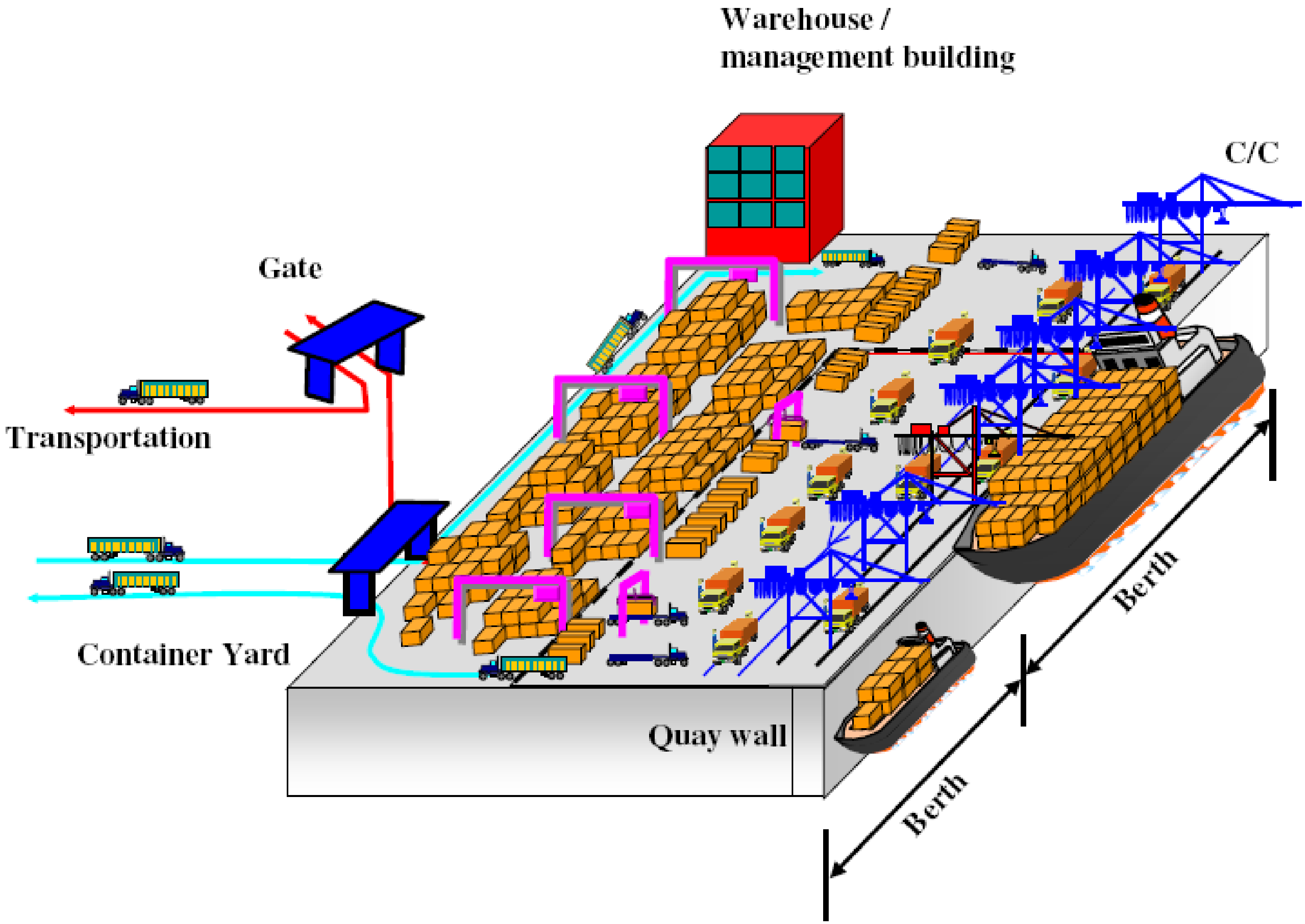


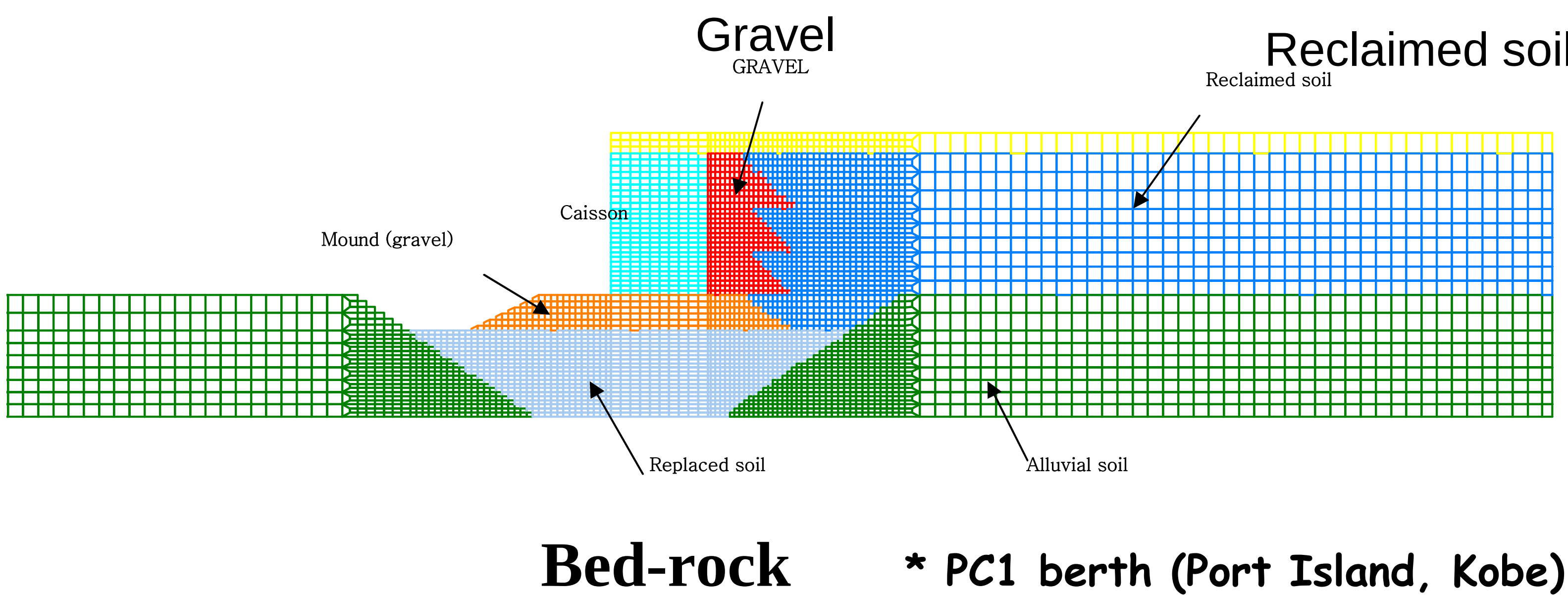


Container Terminal System



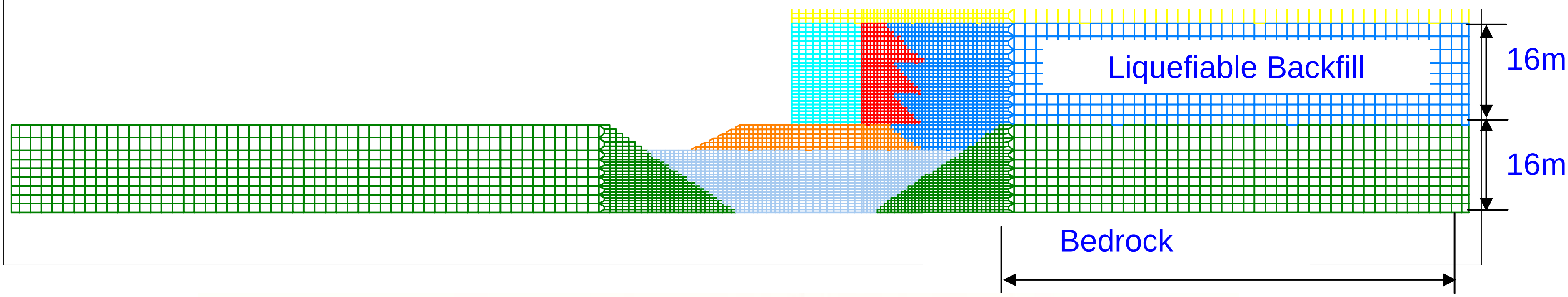
Numerical Simulation

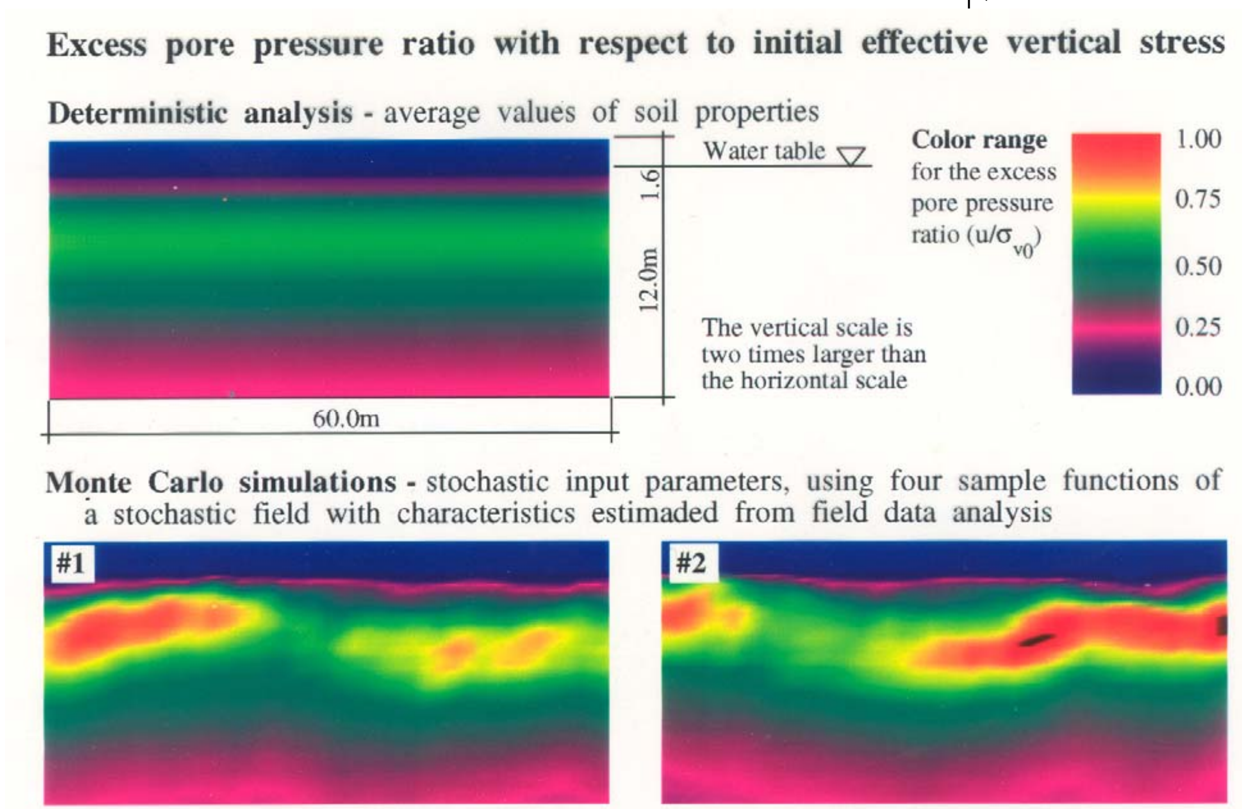
- Modeling of the quay wall
  - FLAC (Itasca, 2005)
  - Dynamic analysis for a reference structure (PC1, Kobe)



* PC1 berth (Port Island, Kobe)

Digital Simulation of Stochastic Field (Muti-Dimensional and Multi-Variate) by Spectral Representation Method

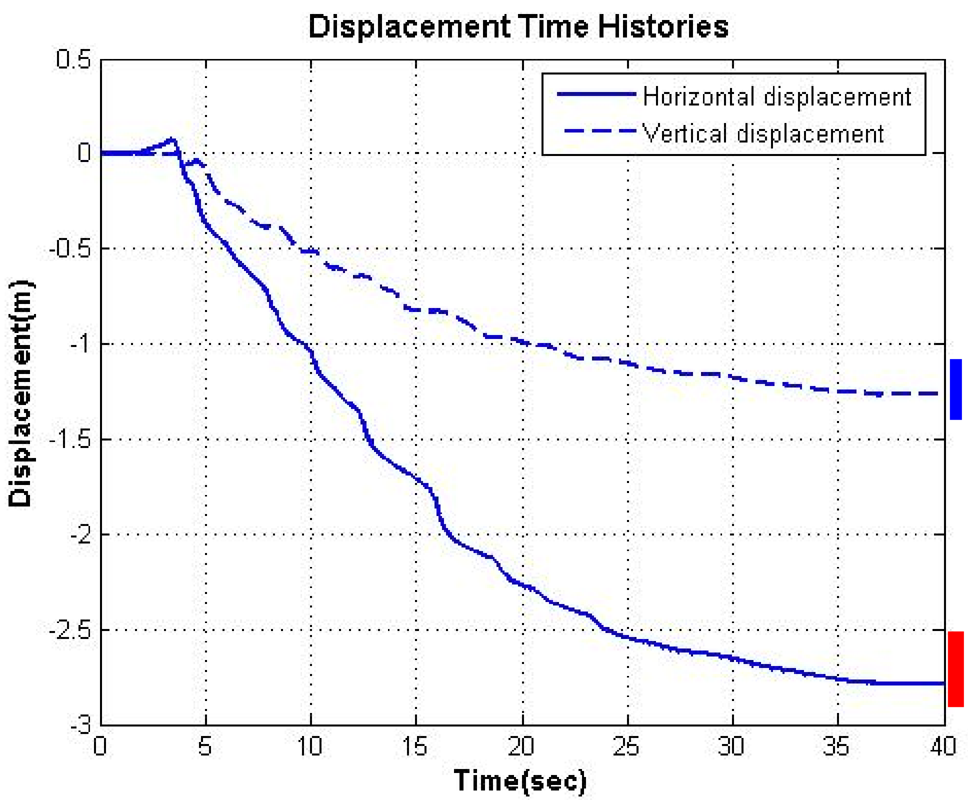




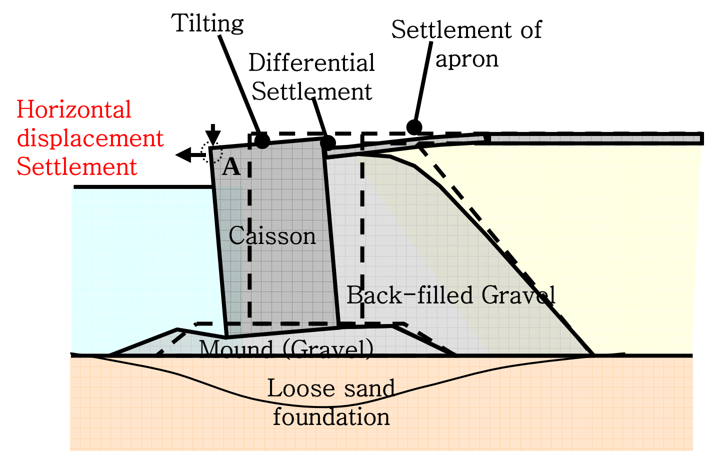
Prevost, Deodatis & Popescu

Numerical Simulation

* Displcement time histories of the upper seaside corner of the caisson



Under homogeneous soil property

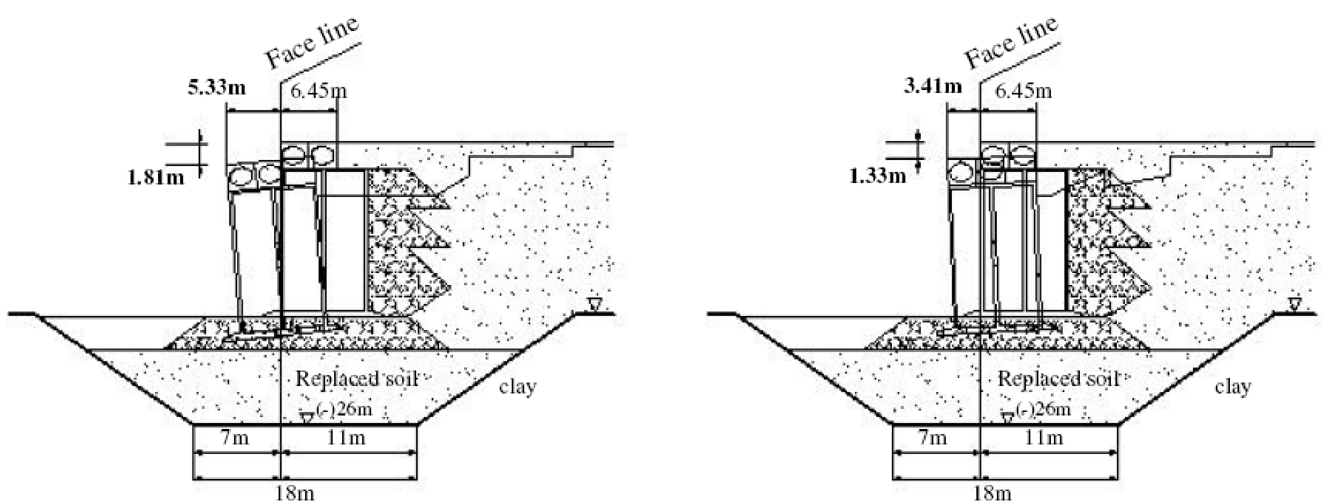


Problem in
Ship berthing
Crane Operation

Field observation 2.55 to 2.80m in the horizontal direction
1.13 to 1.41m vertical settlements

Effect of Soil Non-homogeneity

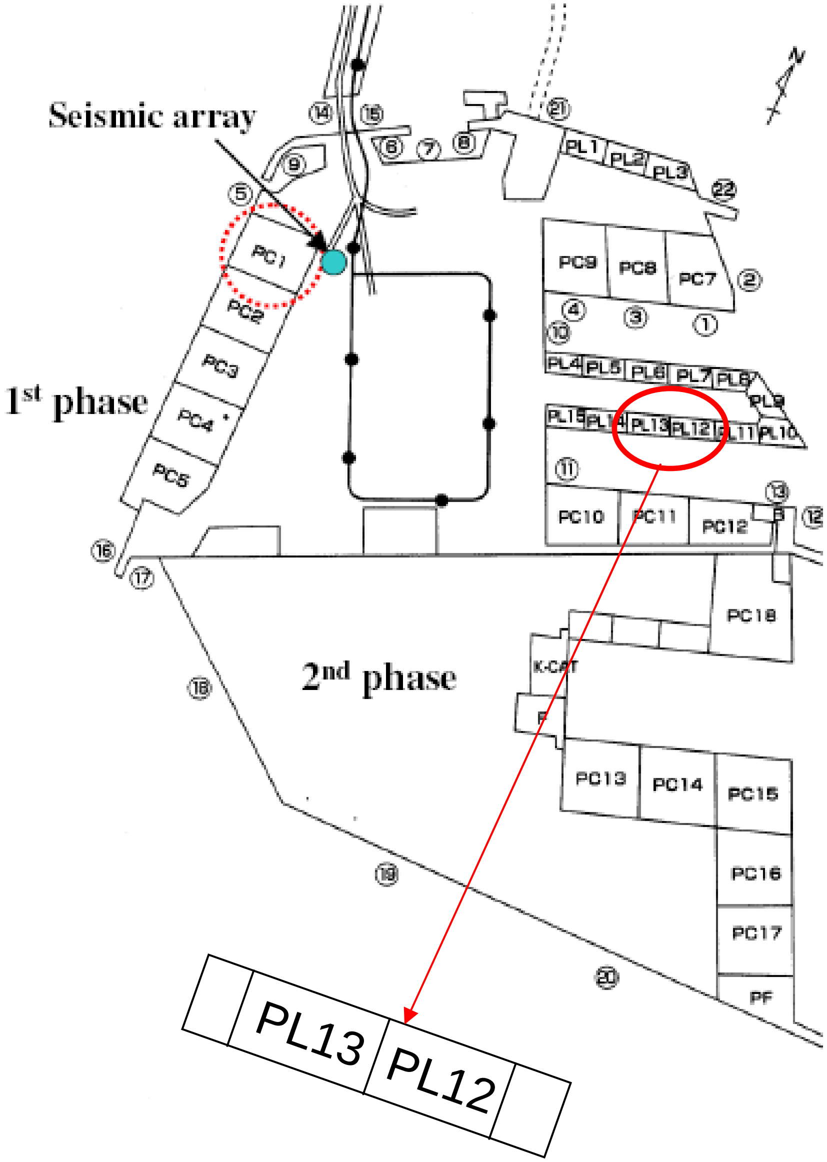
- Considerable variability in seismic response
  - Identical configuration, located at the same site, with similar seismic intensity and similar soil conditions
  - > experienced different degrees of damage

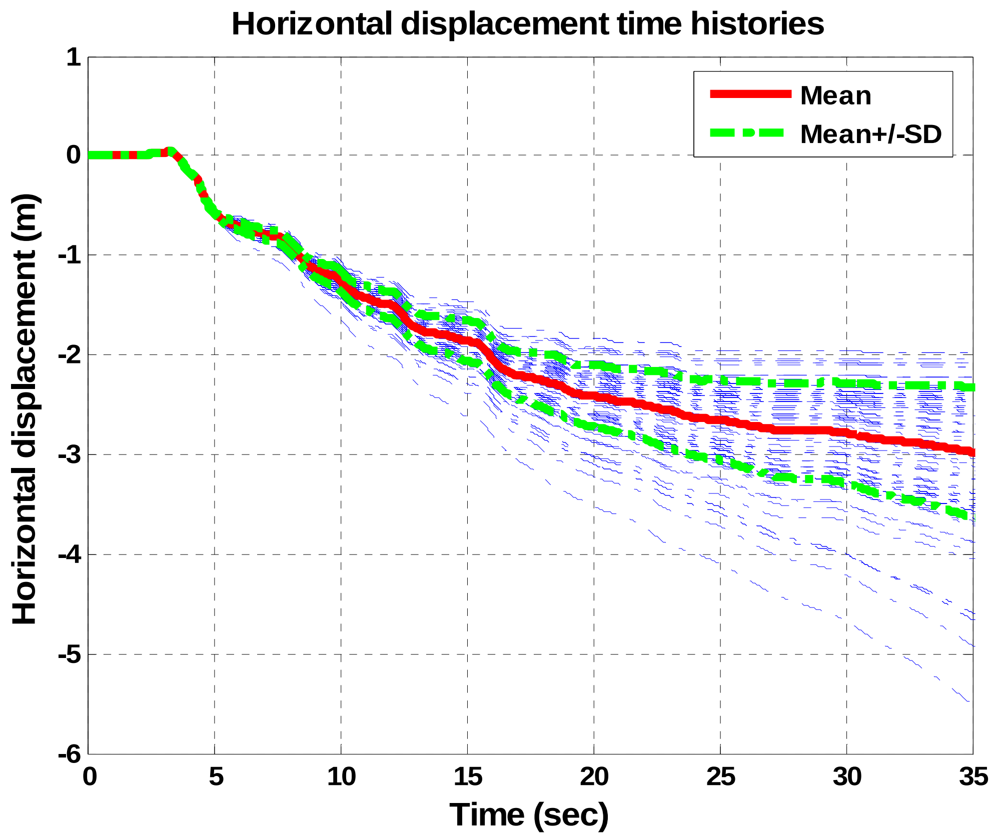


(a) PL 13 berth (b) PL 12 berth

Two identical caissons sitting next to each other showing different degrees of damage (Port Island, Kobe)

Time histories of horizontal displacement for 130 cases of backfill soil property realizations





Damage Level

- Damage state proposed by PIANC(2001)
  - **Based on Serviceability and Structural damage modes**

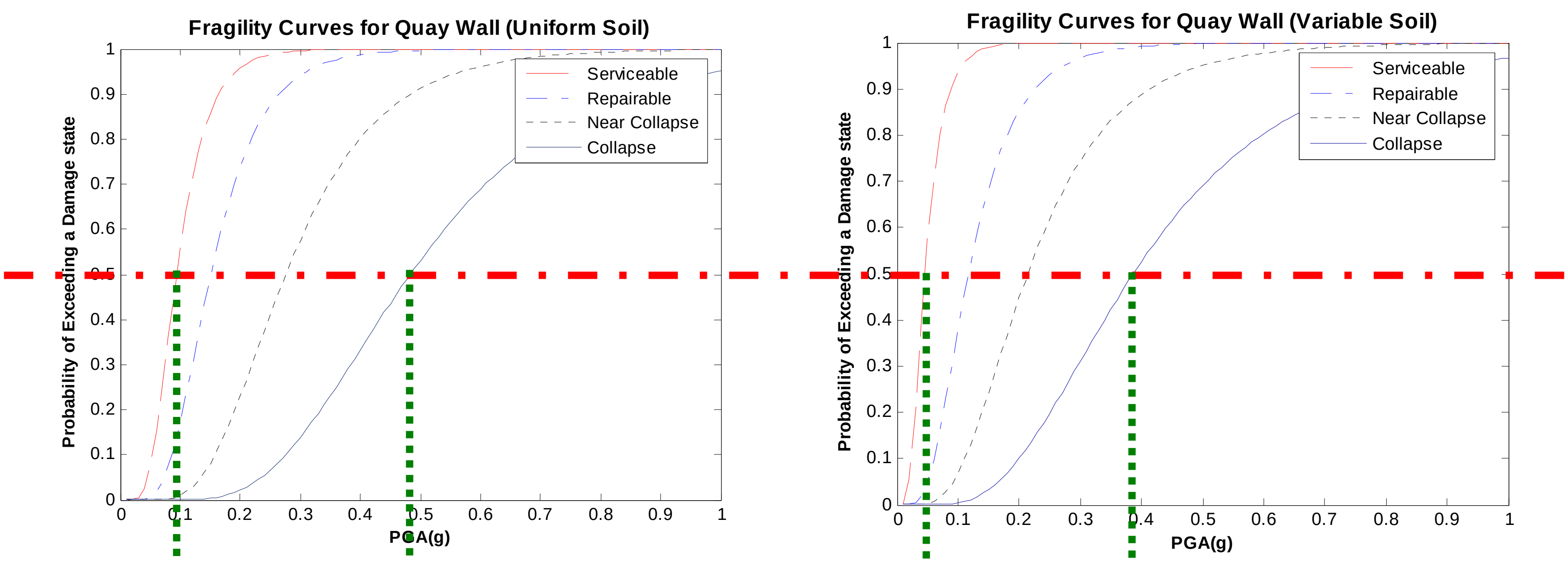
Table 1. Proposed damage criteria for gravity quay walls

Level of Damage		Degree I	Degree II	Degree III	Degree IV
Gravity Wall	Normalized Residual Horizontal displ.	~1.5%	1.5~5%	5~10%	10%~
	Residual tilting	~3°	3~5 °	5~8 °	8 °~
Apron	Differential settlement	~0.1m	N/A	N/A	N/A

Highest damage degree among different criteria is the final result of the evaluation.

Fragility Analysis

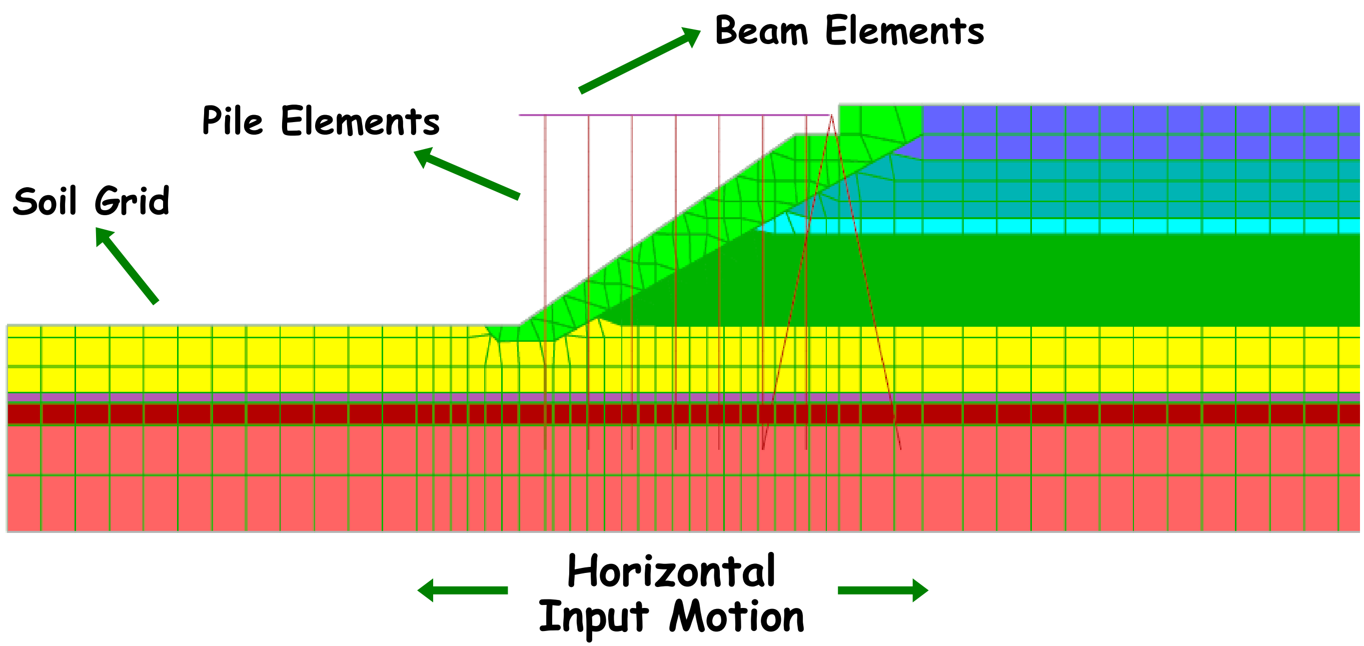
- Fragility curves obtained from analysis
  - Comparison between no-spatial variation / variation



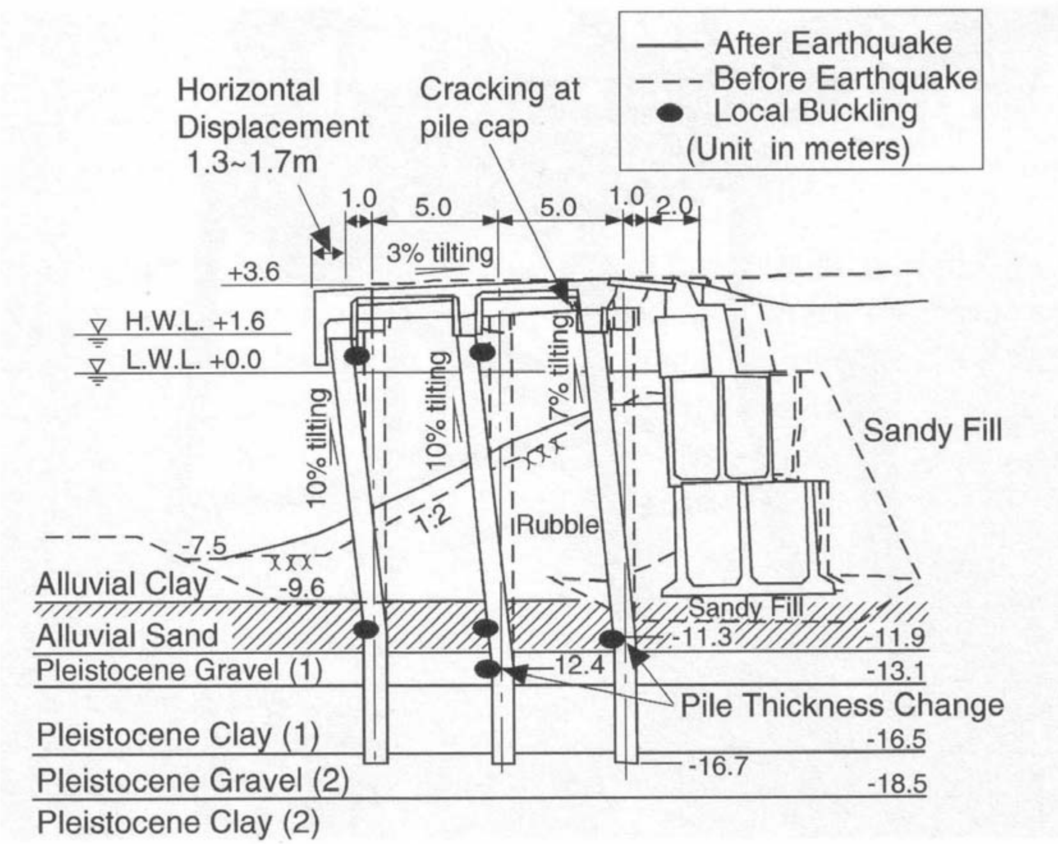
$$P(DM \geq d \mid IM = PGA)$$

Pile Supported Wharf

- Typical structure



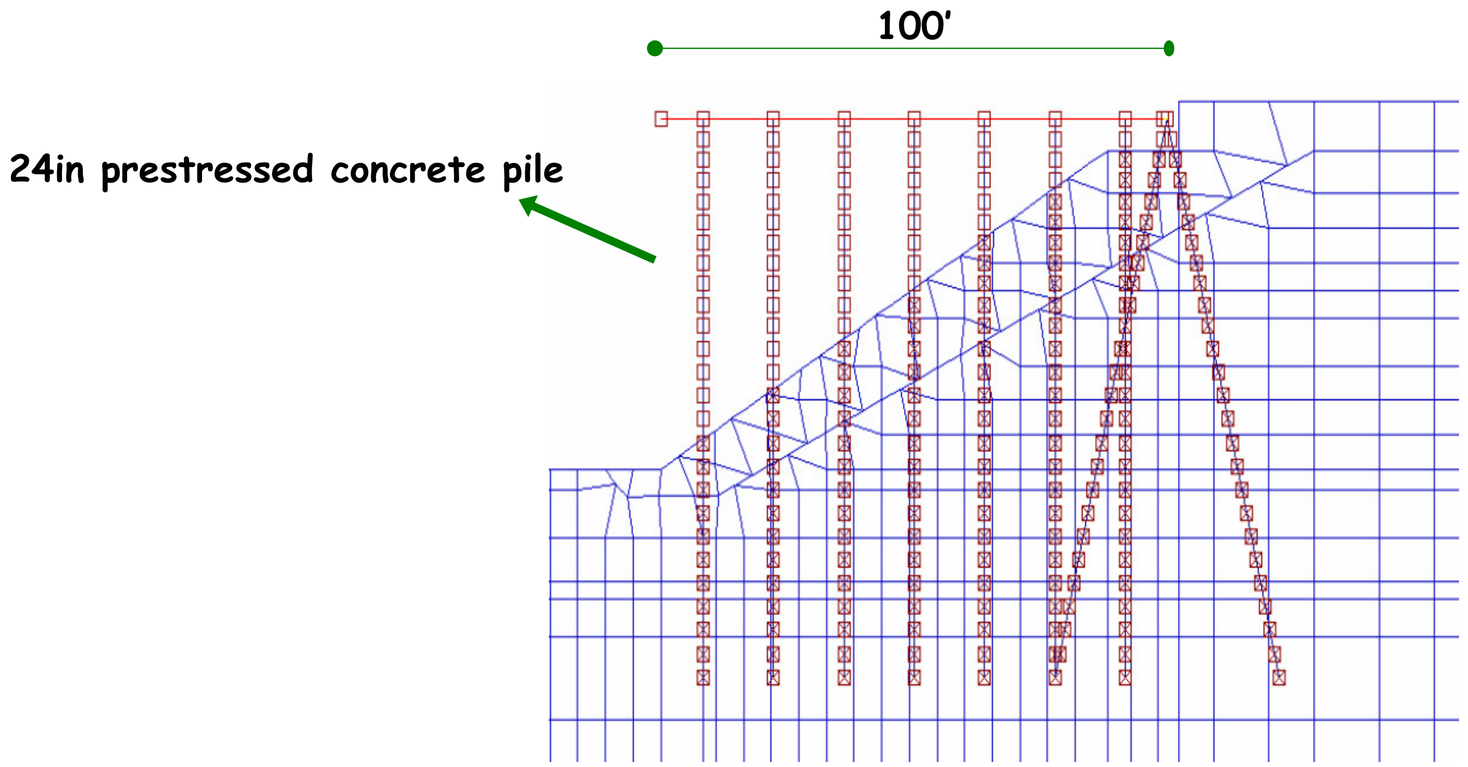
Pile supported wharf : damage state during Kobe EQ



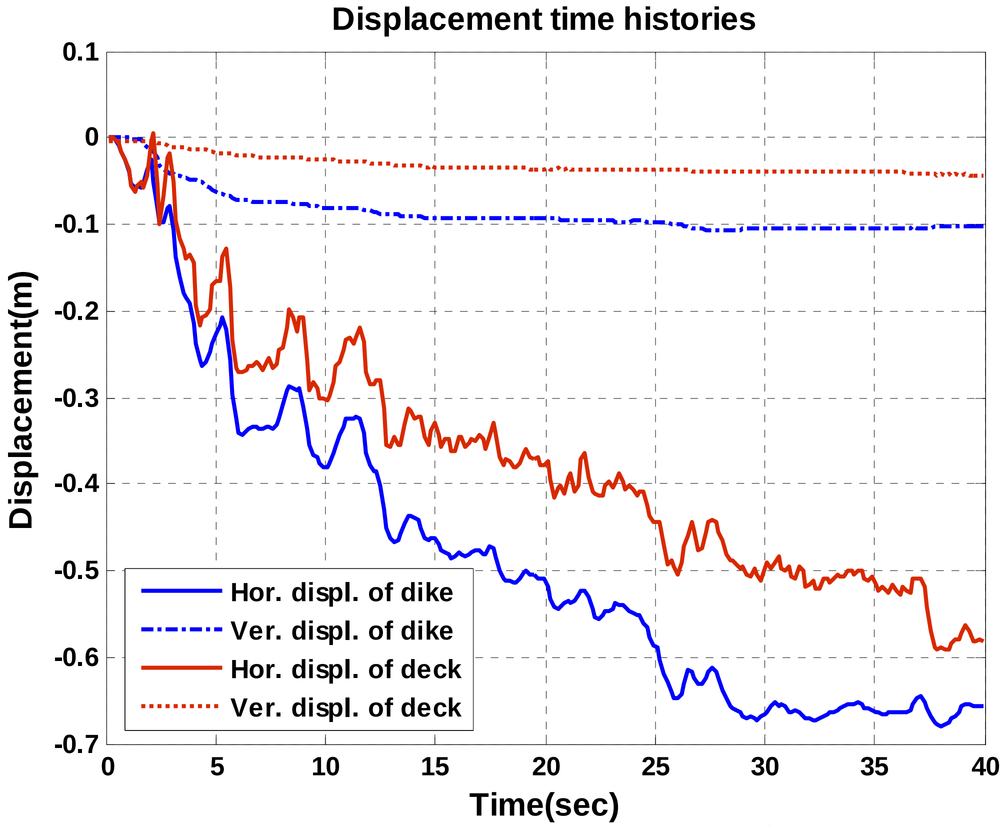
Cross section of a pile-supported wharf at Takahama Wharf, Kobe Port and damage during the Great Hanshin earthquake of 1995.

Pile Supported Wharf

- Structure Discretization

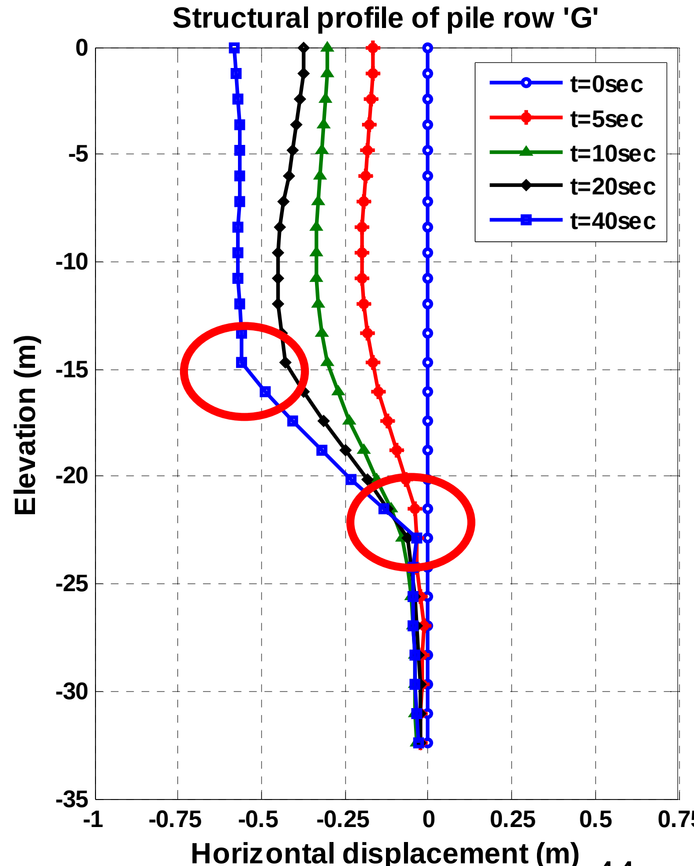


Analysis results



(Displacement of deck/dike)

(Displacement of pile)



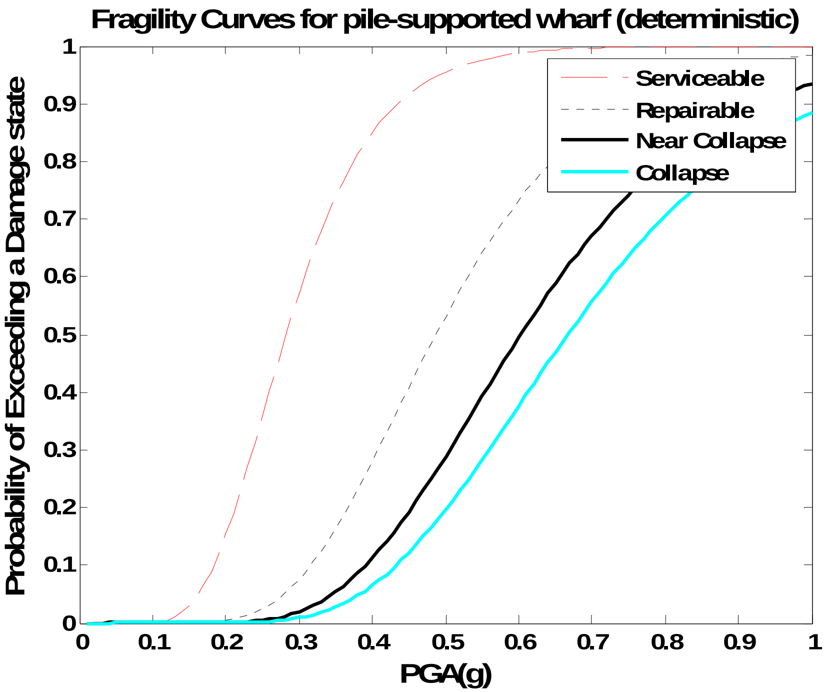
Damage Level

- Damage state proposed by PIANC(2001)
  - **Based on Serviceability and Structural damage modes**

Table. Proposed damage criteria for pile-supported wharf

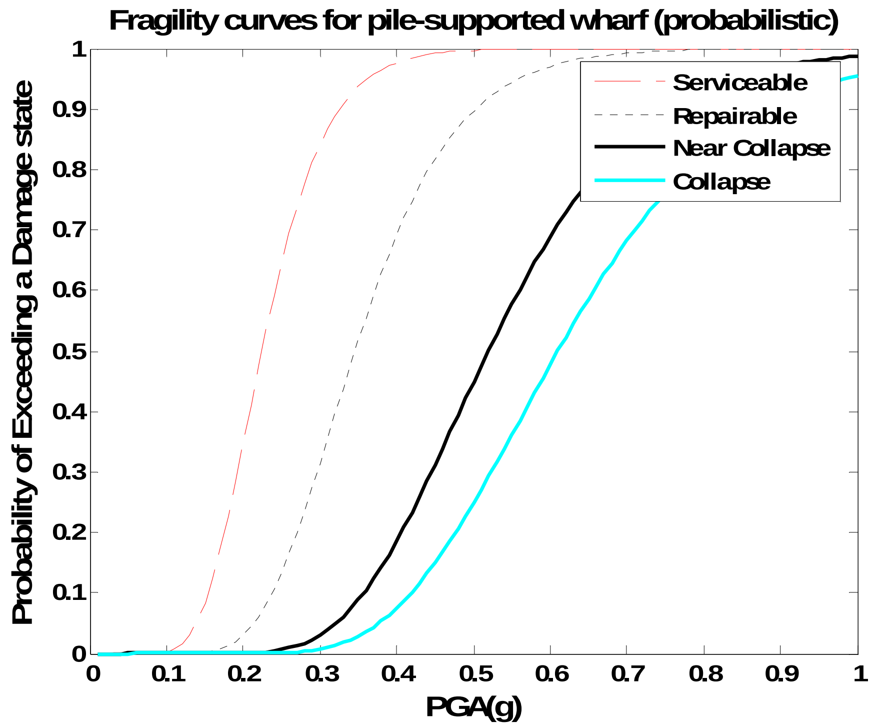
Level of Damage		Degree I	Degree II	Degree III	Degree IV
Pile & Deck	Differential Settlement	~0.1m	0.1-0.3m	N/A	N/A
	Peak response of pile	elastic	No residual deform	repairable	Plastic hinge
Dike/ slope	Normalized Residual Horizontal displ.	~1.5%	1.5~5%	5~10%	10%~

Fragility Curves



(Deterministic)

(Probabilistic)



FLAC

- FLAC is a two-dimensional explicit Finite difference program for engineering mechanics computation.
- FLAC simulates the behavior of structures built of soil, rock or other materials that may undergo plastic flow when their yield limits are reached.
- Materials are represented by elements, or zones, which form a grid that is adjusted by the user to fit the shape of the object to be modeled.
- Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints.
- The explicit, Lagrangian calculation scheme and the mixed-discretization zoning technique used in FLAC ensure that plastic collapse and flow are modeled very accurately.

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Conclusions and Future Study

- Improved models for each contributing factor, in particular, system restoration process is needed
- Better quantification of uncertainty associated with each contributing factor is needed
- Performance definitions depending on stakeholders

Contributors

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Acknowledgement for Support

- Multidisciplinary Center for Earthquake Engineering Research (MCEER)
- California Department of Transportation (Caltrans)
- National Science Foundation (NSF)
- Federal Highway Administration (FHWA)

Material parameters of the soil layers considered in this study

Parameters	Replaced soil	Reclaimed soil	Clay	Foundation gravel and Back-filled gravel
Density	1.6	1.6	1.7	1.8
Shear Modulus (KPa)	5.8E4	7.9E4	7.5E4	9.9E4
Poisson's ratio	0.3	0.3	0.3	0.3
Friction angle (°)	37	36	30	40
Void ratio	0.5	0.5	0.64	0.69

Annual Probability of Exceedance for Households without Power (enlarged view)