Ground Failure and Geotechnical Impacts on Lifeline Performance, Northridge and Beyond

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20th Anniversary of Northridge Earthquake
January 17, 2014

Outline

1. Earthquake Ground Deformation
2. Ground Deformation Models
3. Lifelines Performance

Liquefaction-induced Ground Deformation

Liquefaction-induced ground deformations are permanent displacements resulting from earthquakes

- Areas as large as a few square kilometers
- Amplitudes ranging from few centimeters to several meters.

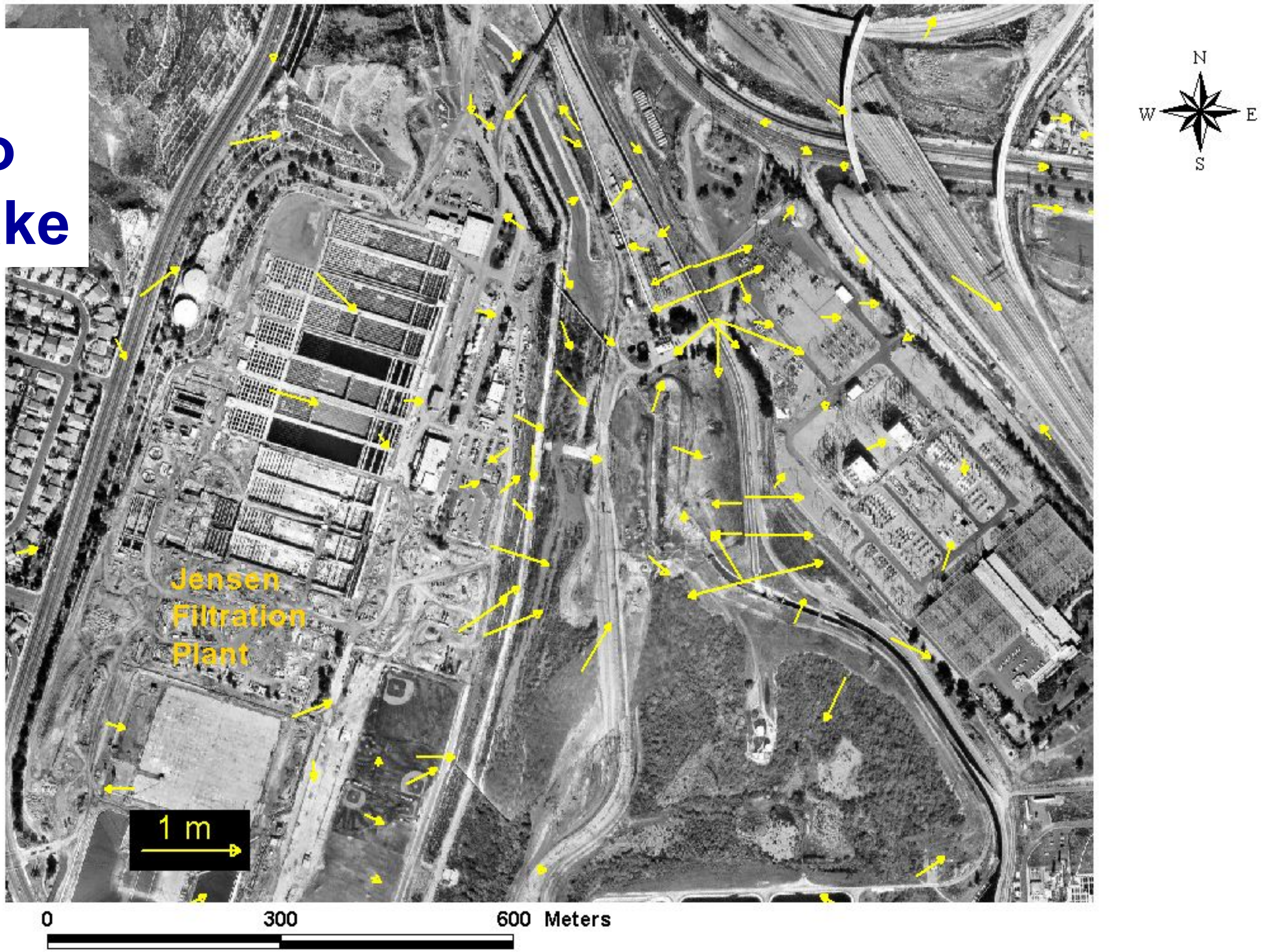
Liquefaction-induced ground deformations have systematically caused extensive damage to lifelines

Liquefaction-induced ground deformation from past earthquakes:

- 1999 Koceali, Turkey
- 1999 Chichi, Taiwan
- 1995 Hyogoken-Nanbu, Japan
- 1994 Northridge, California
- 1971 San Fernando, California
- 1964 Niigata, Japan

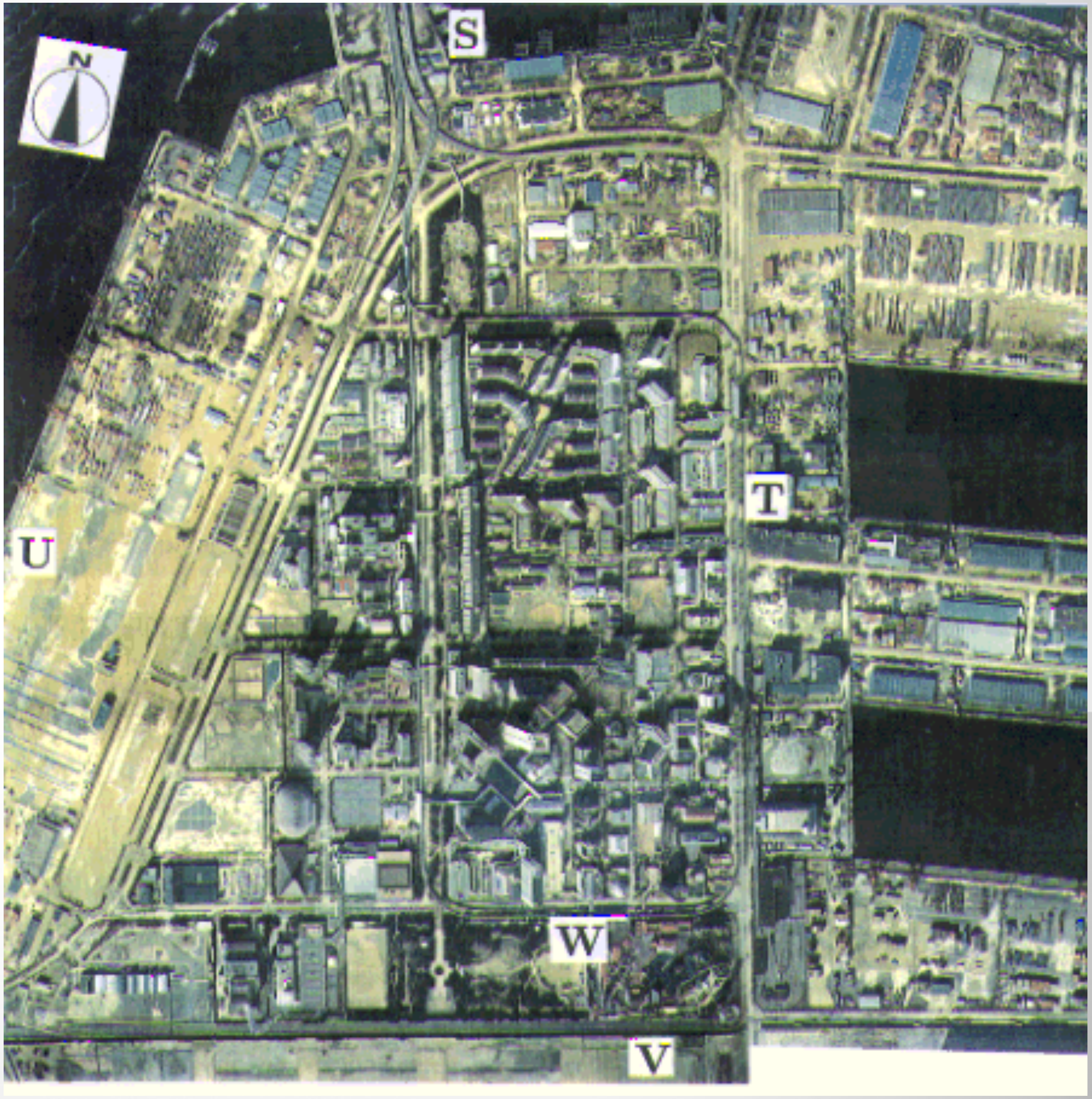
1964 Niigata Earthquake

1971 San Fernando Earthquake



Van Norman Complex 1994 Northridge Earthquake

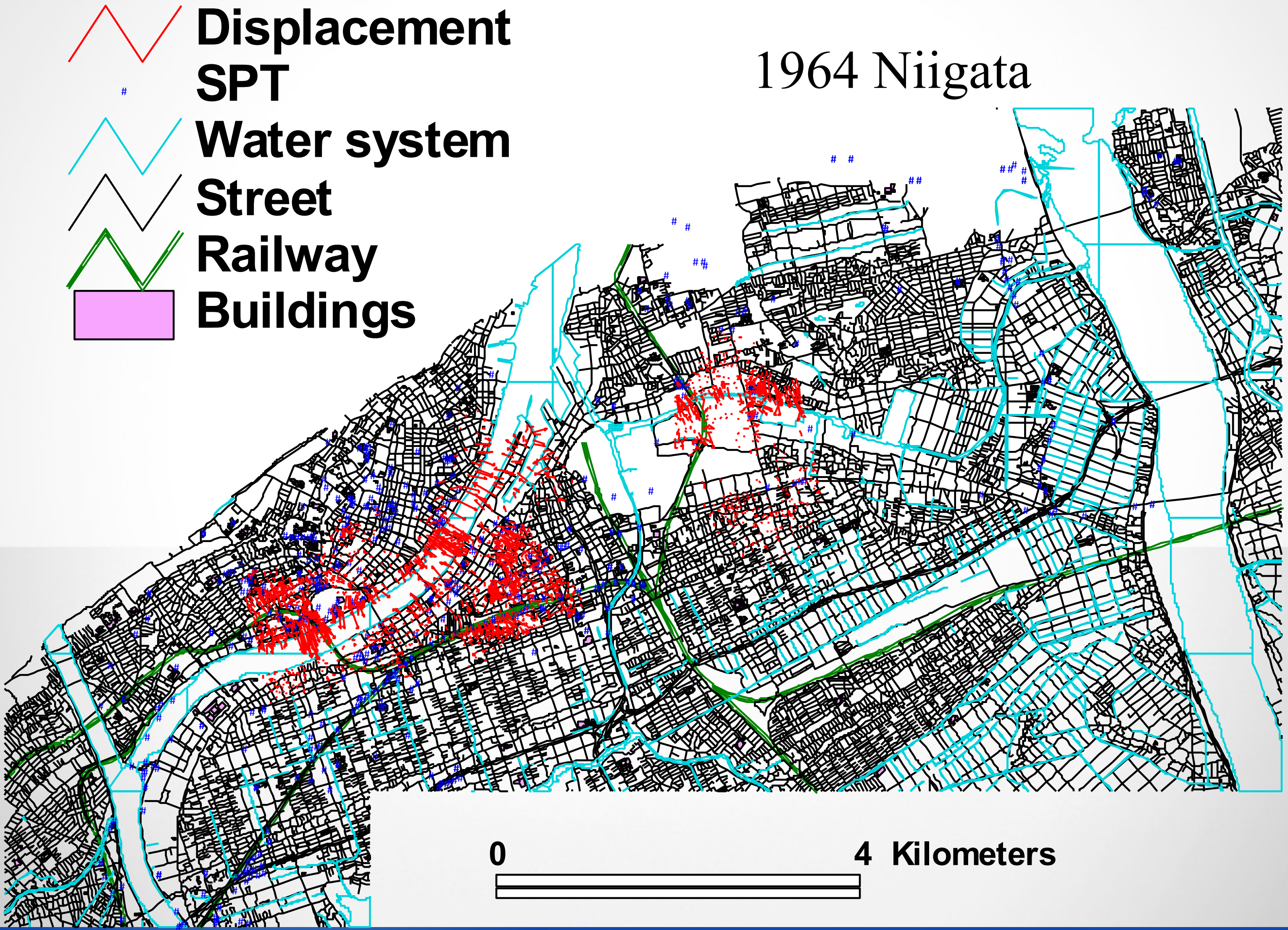
1995 Kobe Earthquake, Port Island



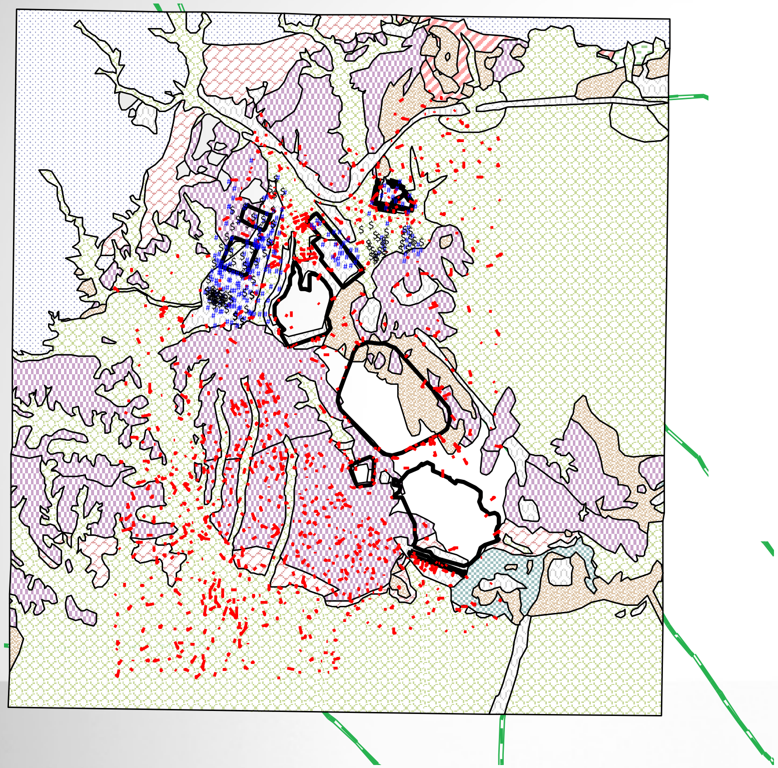
Ground Deformation Database

Earthquake	Displacements	Boreholes
1964 Niigata	2498	645
1964 Alaska		
1971 San Fernando/ 19994 Northridge	864	567
1983 Nihonkai-Chubu,Japan	2954	142
1987 Superstition Hills	4	108
1979 Imperial Valley		14
1989 Loma Prieta		223
1994 Northridge	1011	
1995 Hyogoken Nanbu	8894	5000
1999 Chichi Taiwan		
1999 Kocaeli Turkey		
Total	**16225**	**6699**

Ground Deformation Database

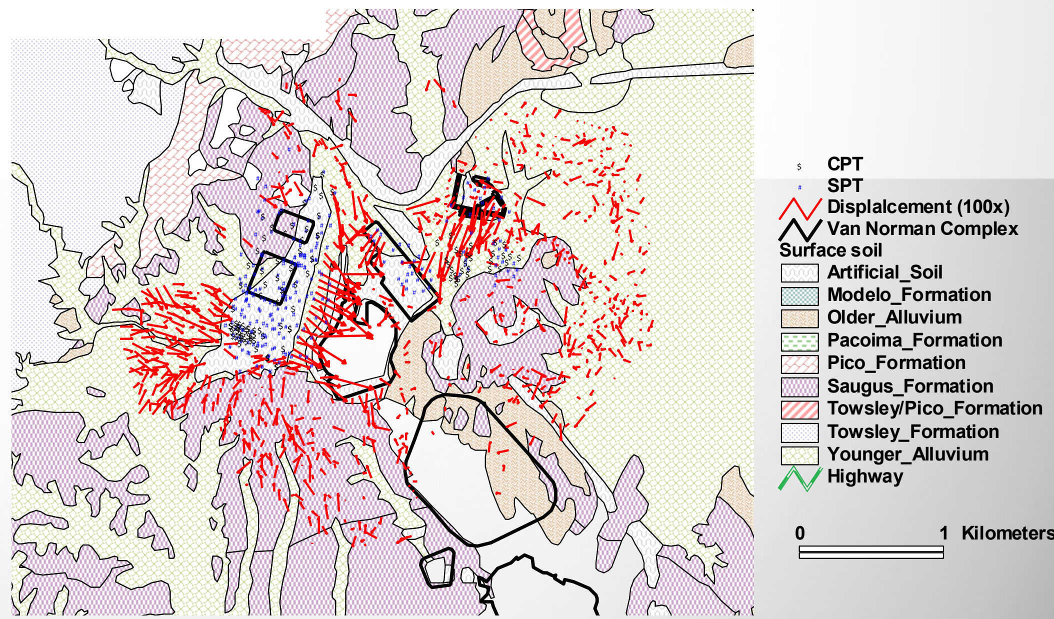


Ground Deformation Database

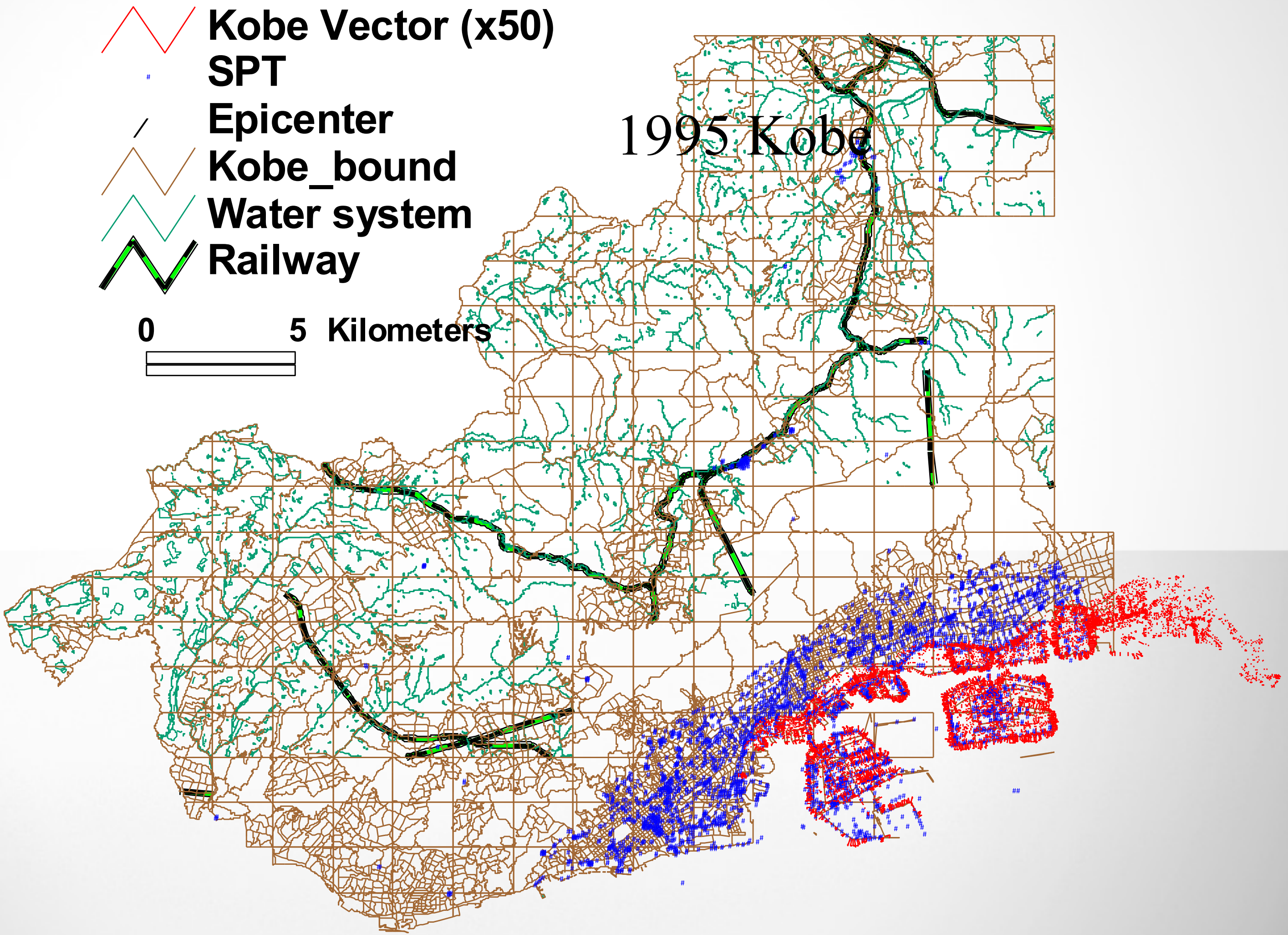


1994 Northridge

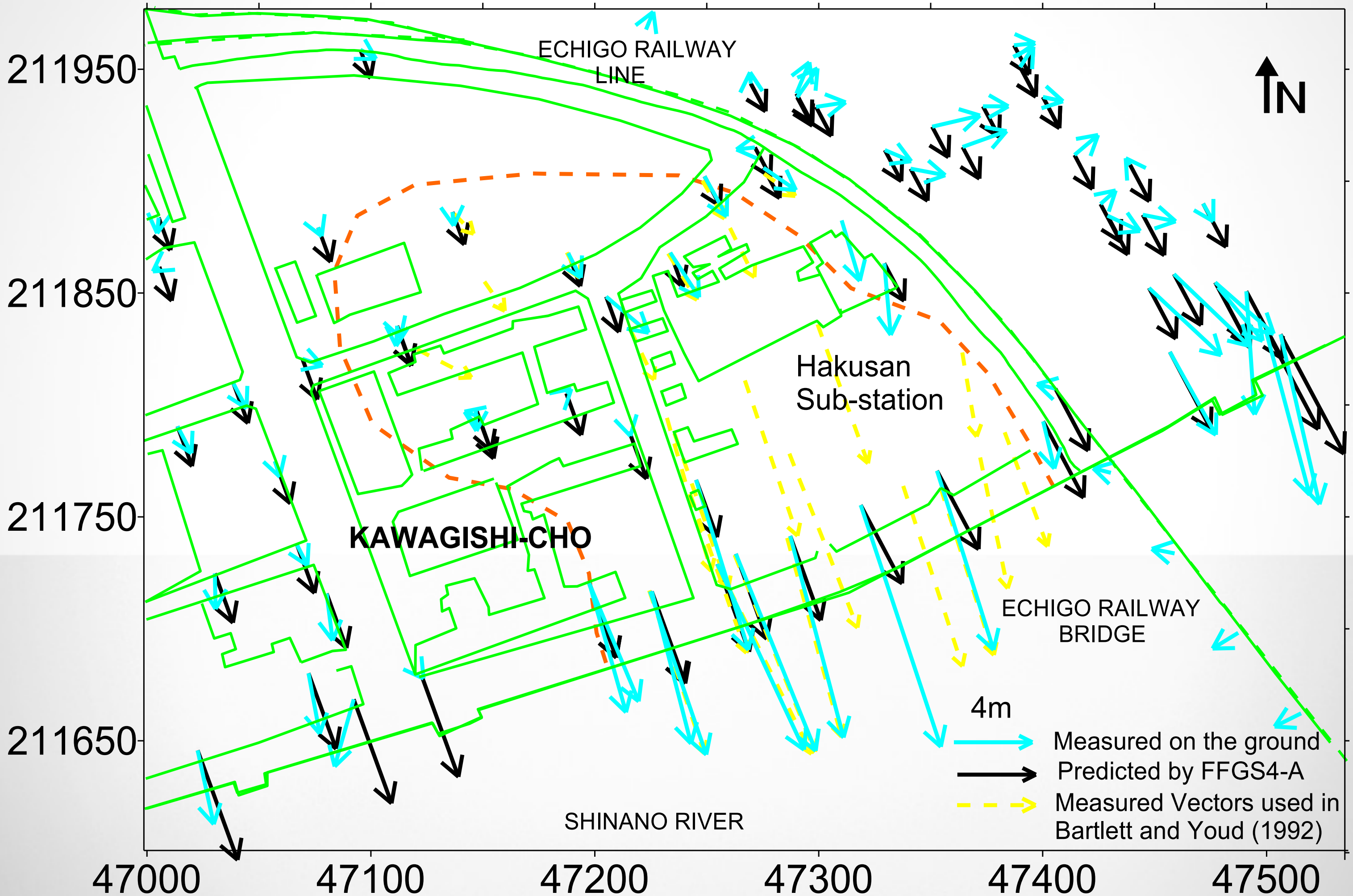
1971 San Fernando



Ground Deformation Database

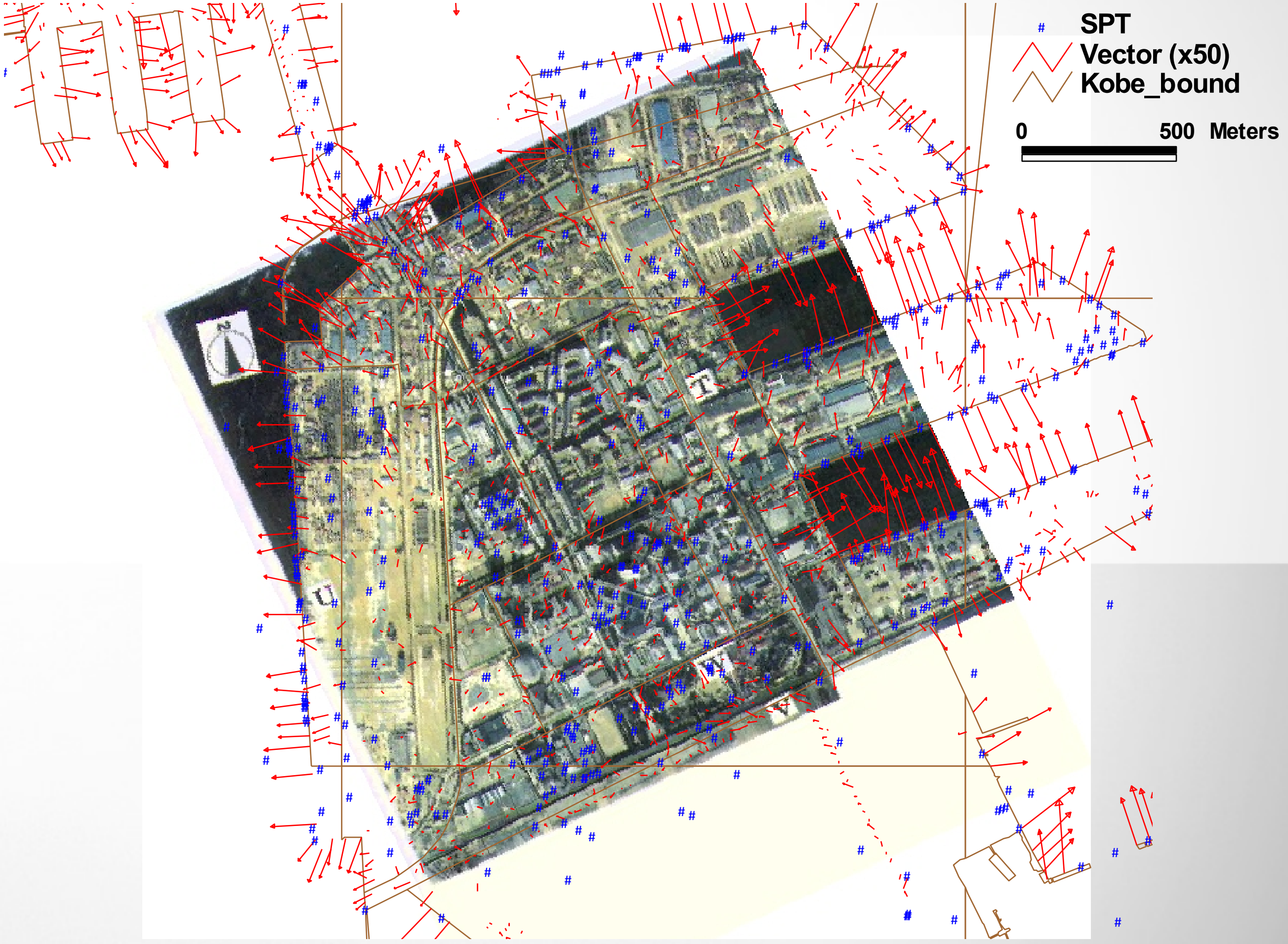


Spatial Analysis of 1964 Niigata

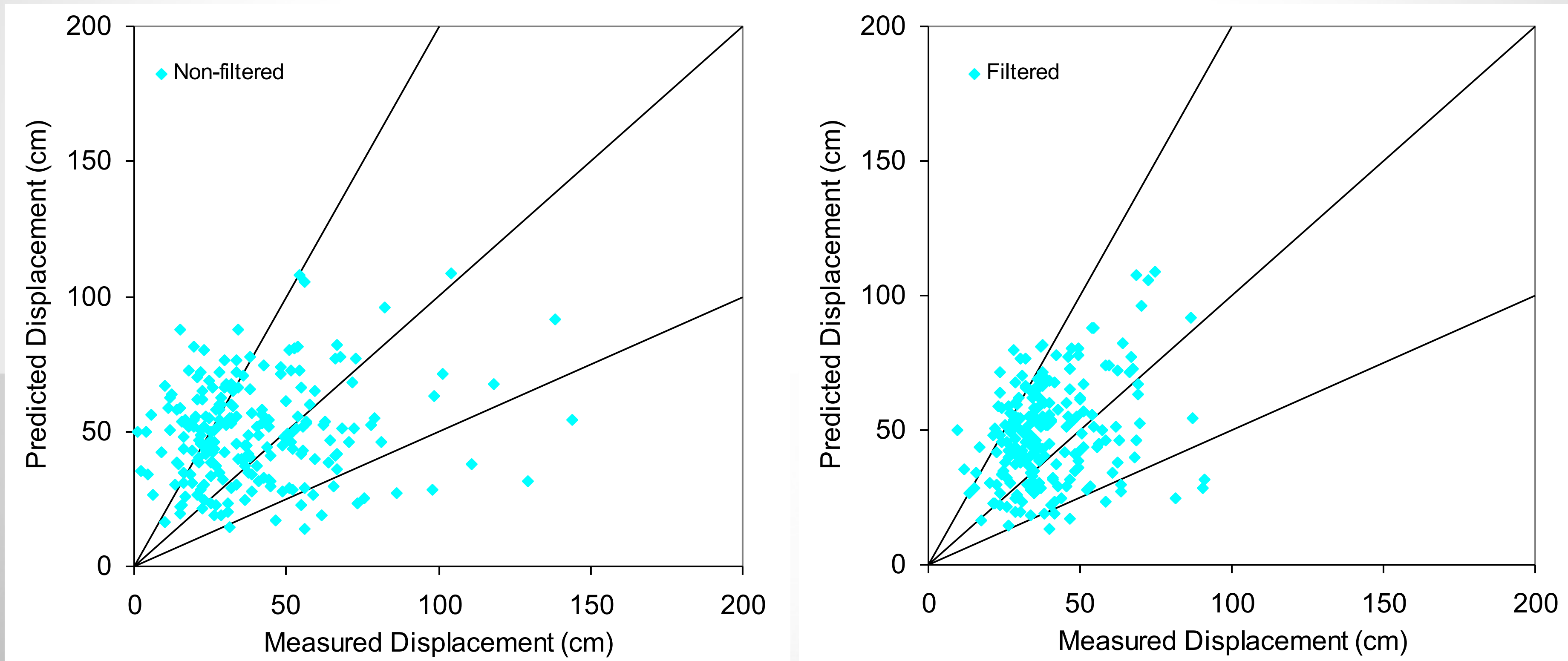


Spatial Analysis in Port Island, Japan

Location of measured displacement and SPT borehole test



Spatial Analysis in Port Island, Japan



Regression Models

Models \ Parameters	M	R	H	S	W	T_{15}	F_{15}	D_{5015}	LDI	a_{max}	T_d	L_{slide}	S_{top}	H_{face}	Z_{FSmin}	Z_{liq}
Hamada et al. (1986)			☑	☑												
Youd and Perkins (1987)	☑	☑														
Bartlett & Youd (1995); Youd et al. (2002)	☑	☑		☑	☑	☑	☑	☑								
Rauch (1997)	☑	☑								☑	☑	☑	☑	☑	☑	☑
Bardet et al. (2002)	☑	☑		☑	☑	☑										
Zhang et al. (2004)				☑	☑				☑							

Definitions:

- M Moment magnitude of earthquake
- R Epicentral distance (km)
- S Slope (%) of ground surface
- H Thickness (m) of liquefied soil
- W Free-face ratio (%)
- T_{15} Thickness (m) of saturated cohesionless soils (excluding depth>20m and > 15% clay content) with $N_{1\,60}$<15
- F_{15} Average fine content (% finer than 75 μm)
- D_{5015} Average D_{50} grain size (mm) in T_{15}
- LDI Lateral displacement index
- a_{max} Peak horizontal acceleration (g) at ground surface of site
- T_d Duration of strong earthquake motions at site (surface acceleration ?0.05 g)
- L_{slide} Maximum horizontal length (m) from head to toe of lateral spread
- S_{top} Average slope (%) across surface of lateral spread
- H_{face} Height (m) of free face, measured vertically from toe to crest of free face
- Z_{FSmin} Average depth (m) to minimum factor of safety in potentially liquefiable soil
- Z_{liq} Average depth (m) to top of liquefied soil.

MLR Models

- Bartlett and Youd (1995) and Youd et al. (2002)

Free-face conditions:

$$\log D = -16.213 + 1.532M - 1.406\log R^{*} - 0.012R + 0.338\log S$$
$$+0.540\log T_{15} + 3.413\log(100 - F_{15}) - 0.795\log(D50_{15} + 0.1mm)$$

Gently sloping ground conditions:

$$\log D = -16.713 + 1.532M - 1.406\log R^{*} - 0.012R + 0.592\log W$$
$$+0.540\log T_{15} + 3.413\log(100 - F_{15}) - 0.795\log(D50_{15} + 0.1mm)$$

where $R^{*} = 10^{0.89M - 5.64} + R$

- Bardet et al. (2002)

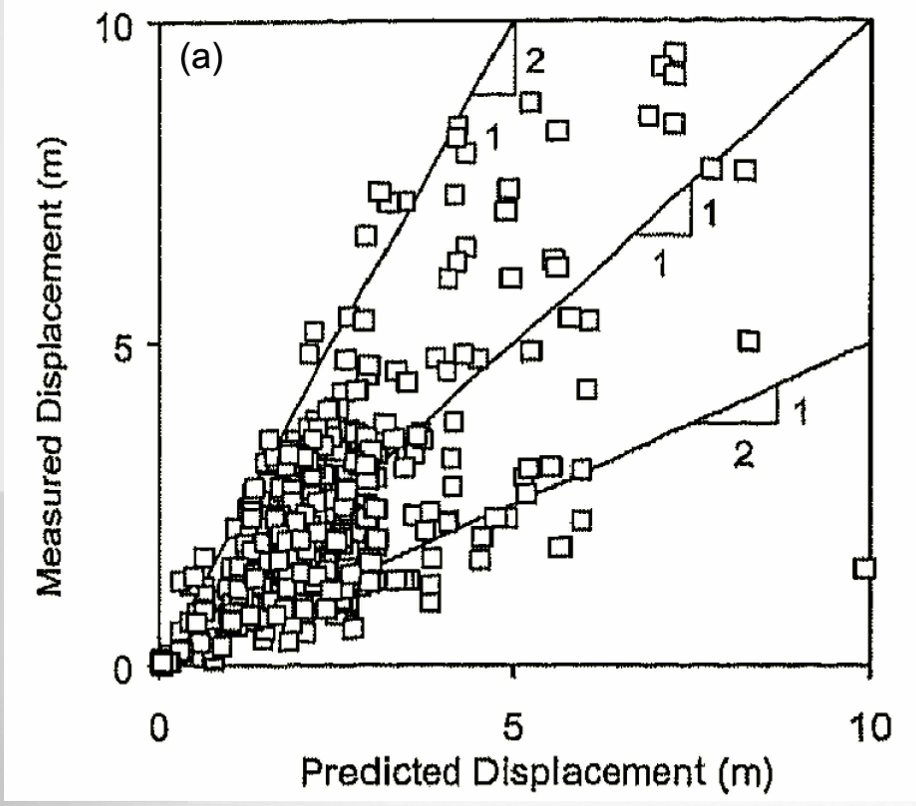
Free-face conditions

$$\log(D + 0.01) = -7.280 + 1.017M - 0.278\log R - 0.026R + 0.497\log W + 0.558\log T_{15}$$

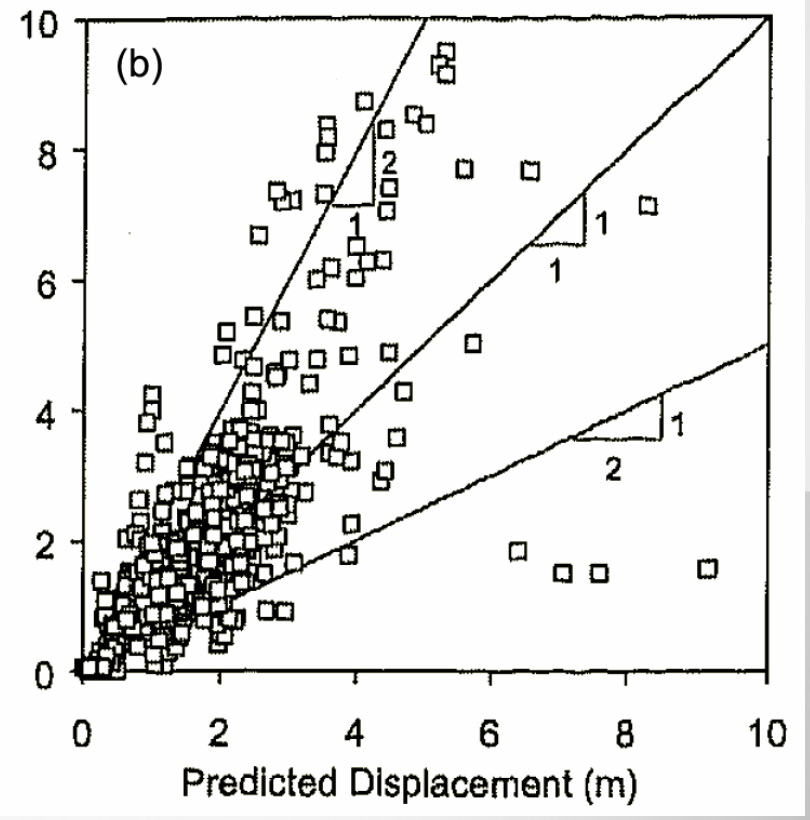
Gently sloping ground conditions:

$$\log(D + 0.01) = -6.815 + 1.017M - 0.278\log R - 0.026R + 0.454\log S + 0.558\log T_{15}$$

MLR Models



Bartlett and Youd (1995)



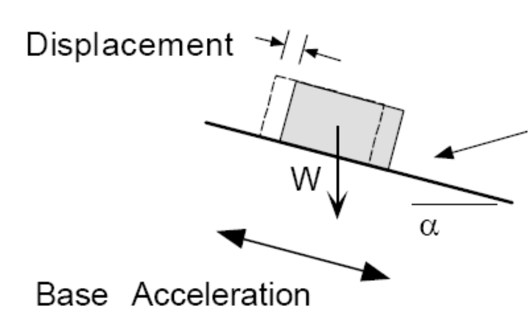
Bardet et al. (2002)

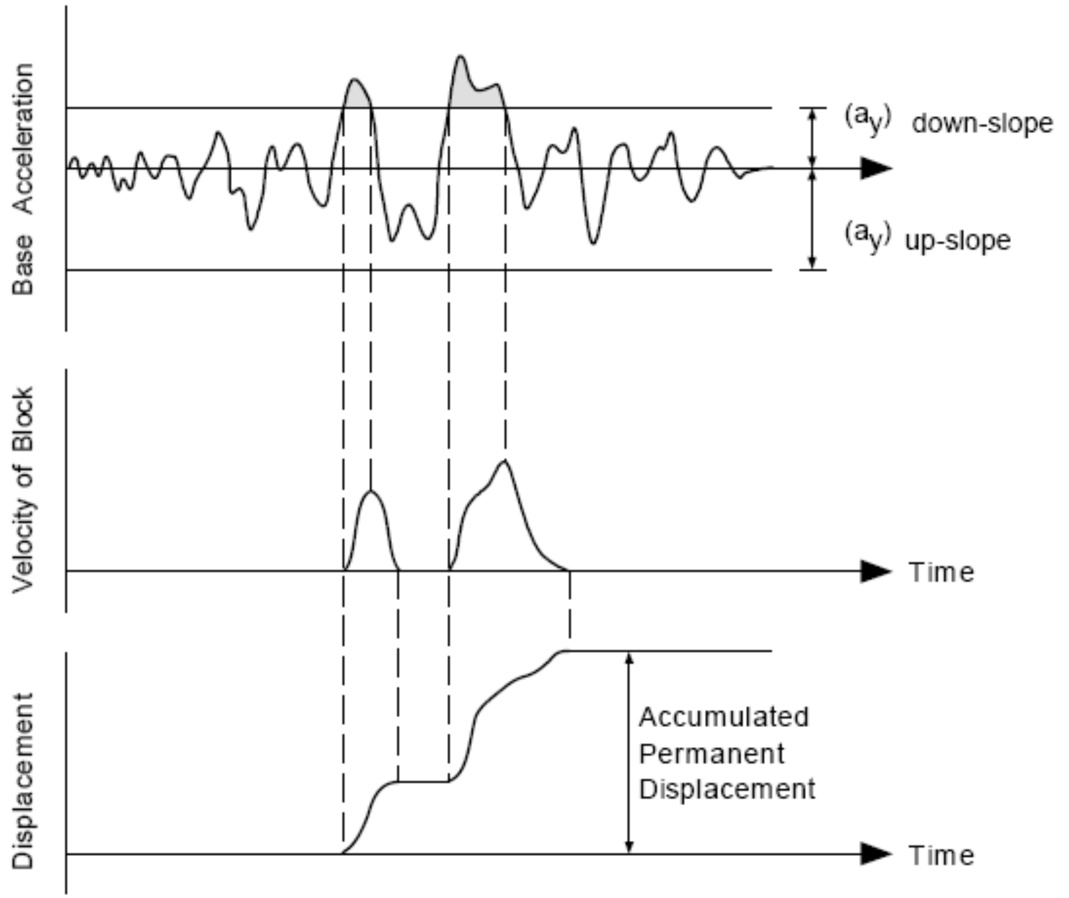
Outline

1. Earthquake Ground Deformation
2. **Ground Deformation Models**
3. Lifelines Performance

Newmark's Sliding Block Model

- *Newmark, 1965*

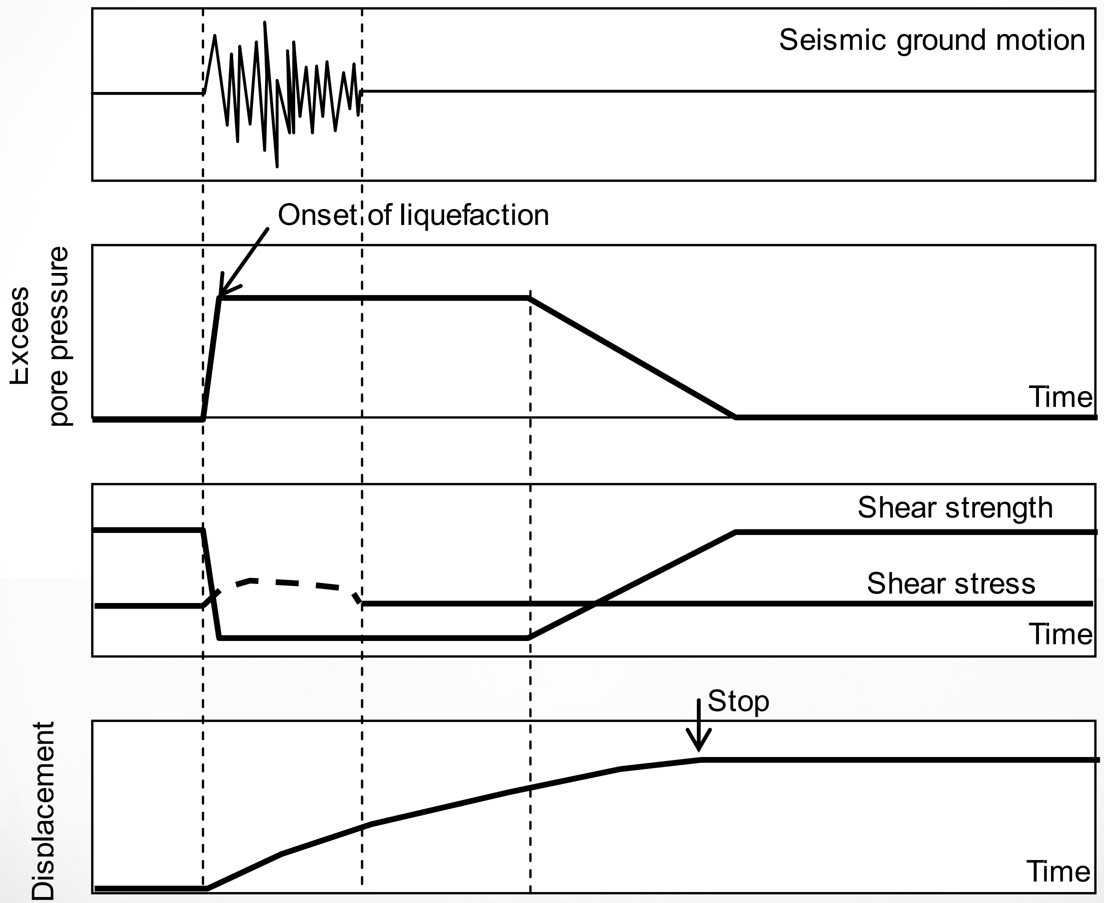




- *Jibson, 1993; Yegian et al., 1991*
- *Makdisi and Seed, 1978; Kramer and Smith, 1997*

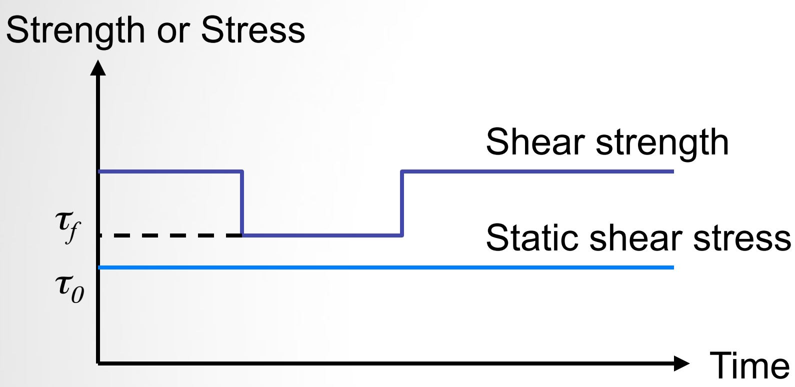
(Rauch 1997)

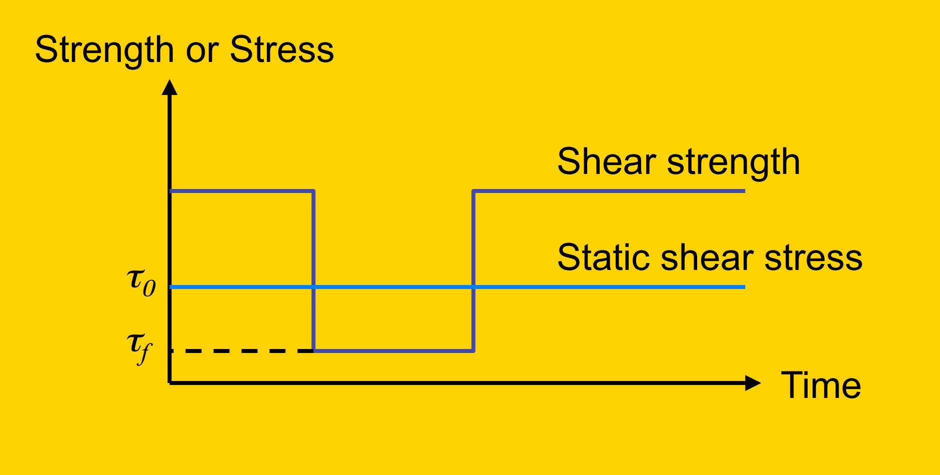
Physical Explanation for Liquefaction-Induced Deformation



After Towhata et al. 1999

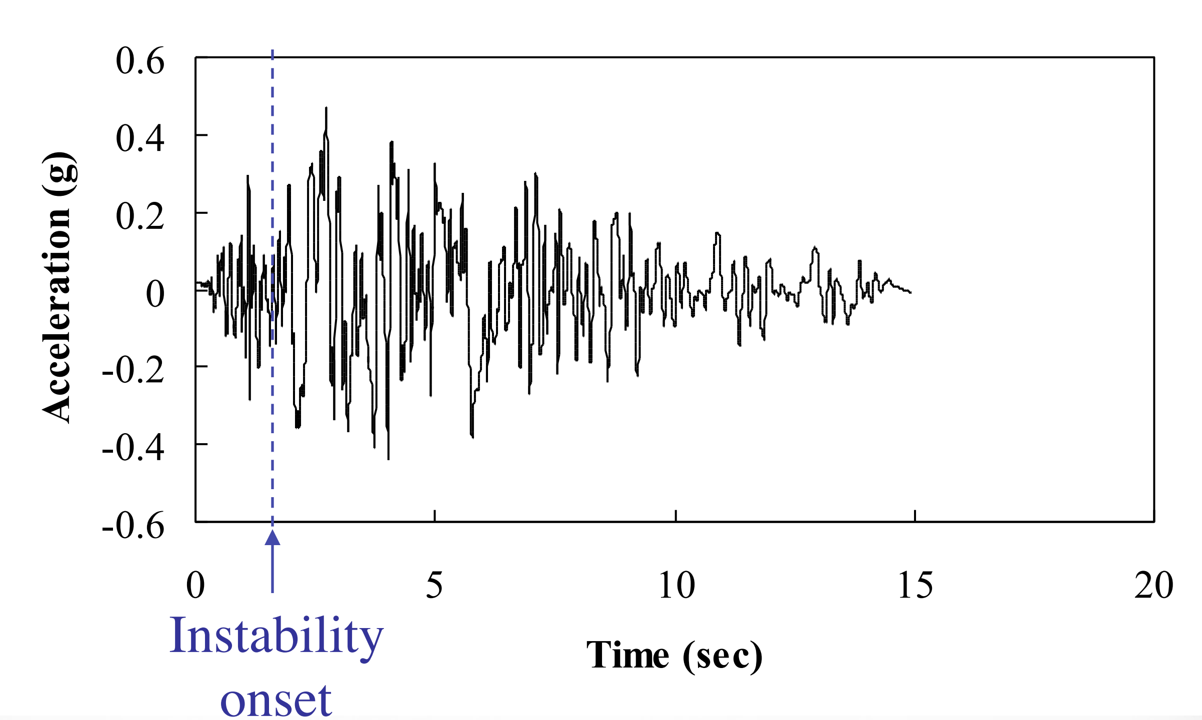
Simplified Model of Strength Loss





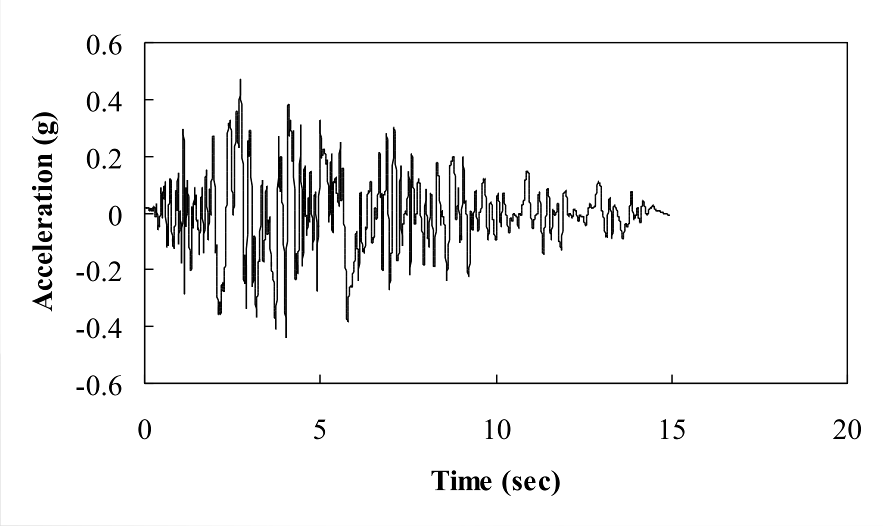
Statically unstable slopes, F_i<1 (where $F_i = \tau_f/\tau_0$)

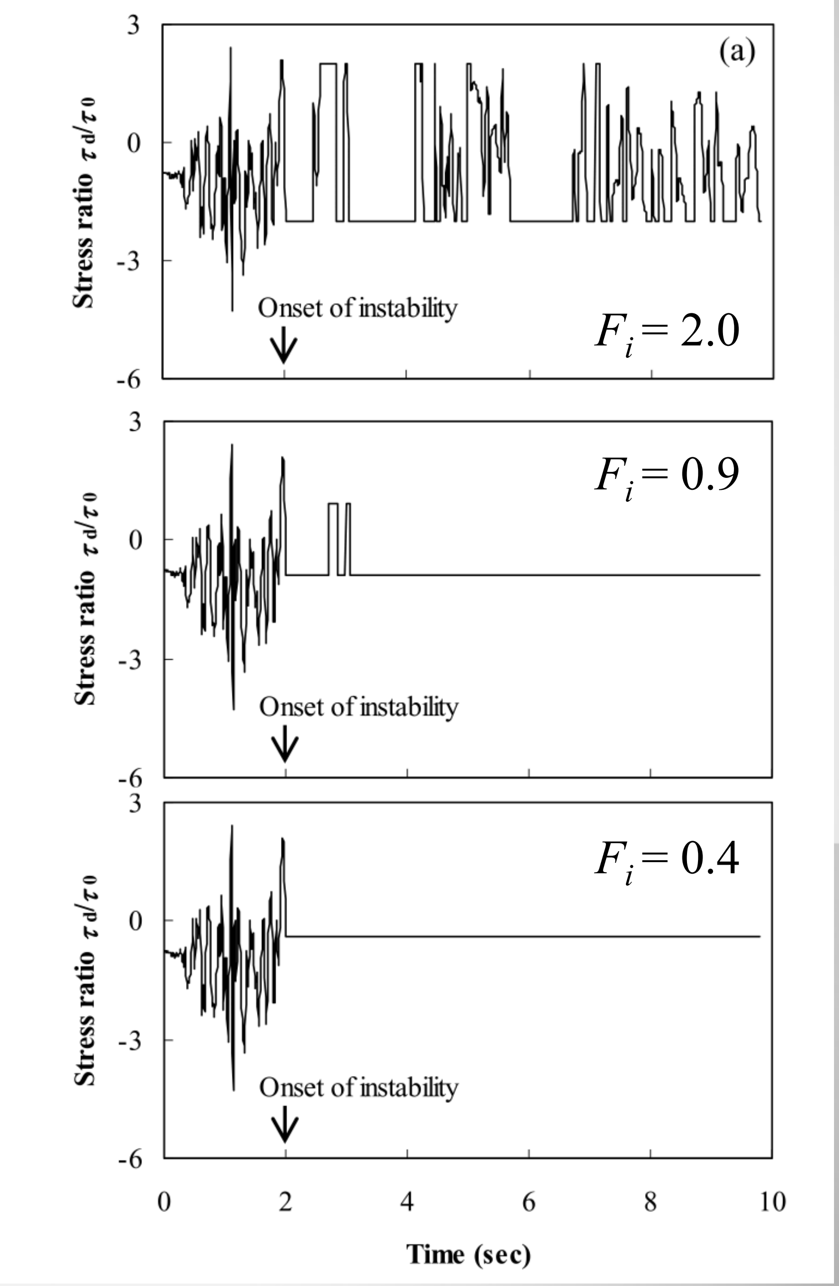
Example of Unstable Deformation



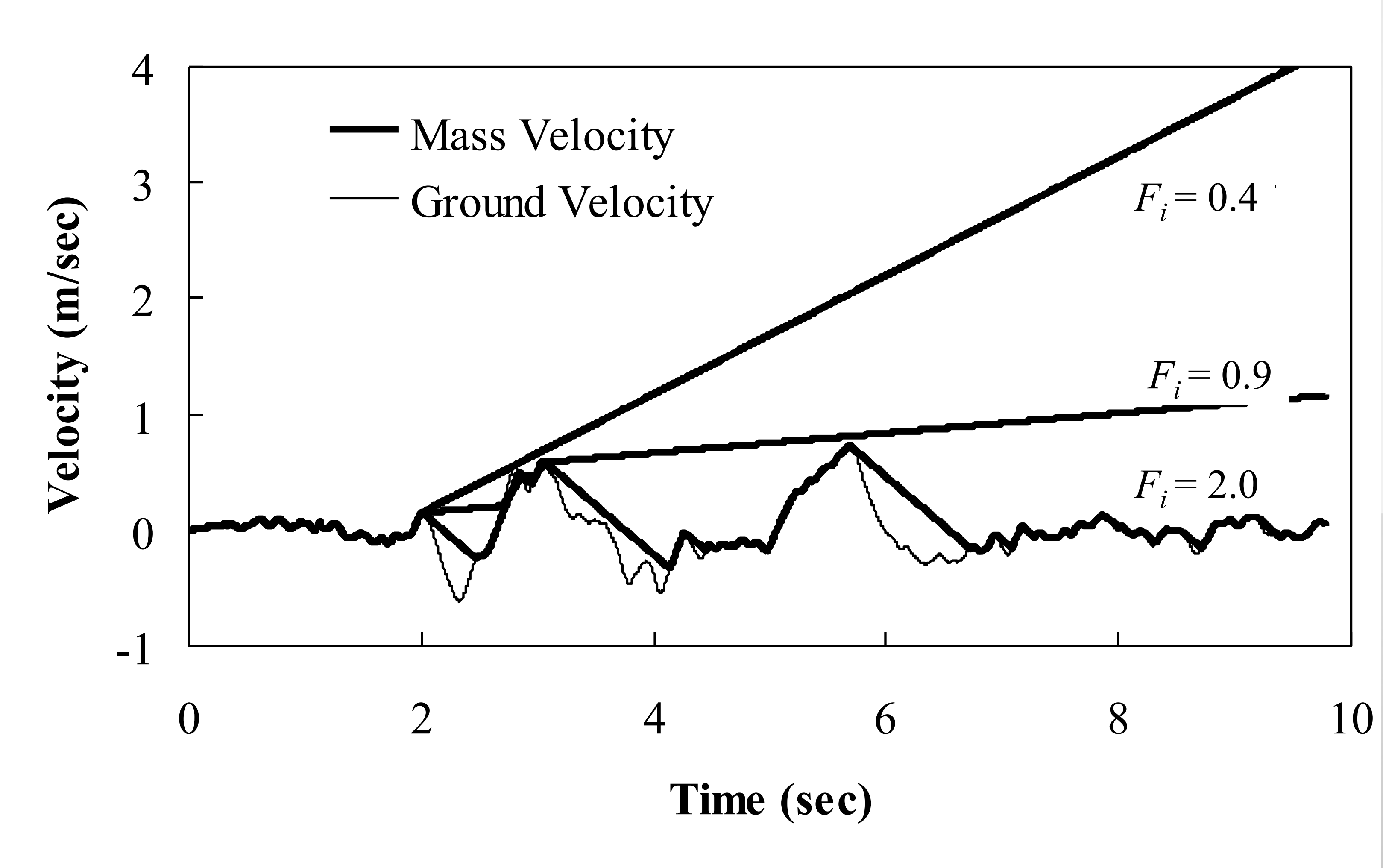
- Ground acceleration recorded at Rinaldi Receiving Station during the 1994 Northridge, California, earthquake
- Shear strength reduction takes place at $t_i = 2$ sec
- Slope inclination angle = 5°
- Initial Factor of Safety $F_i = 0.4, 0.9, 2.0$

Time histories of stress ratio of a 5° slope

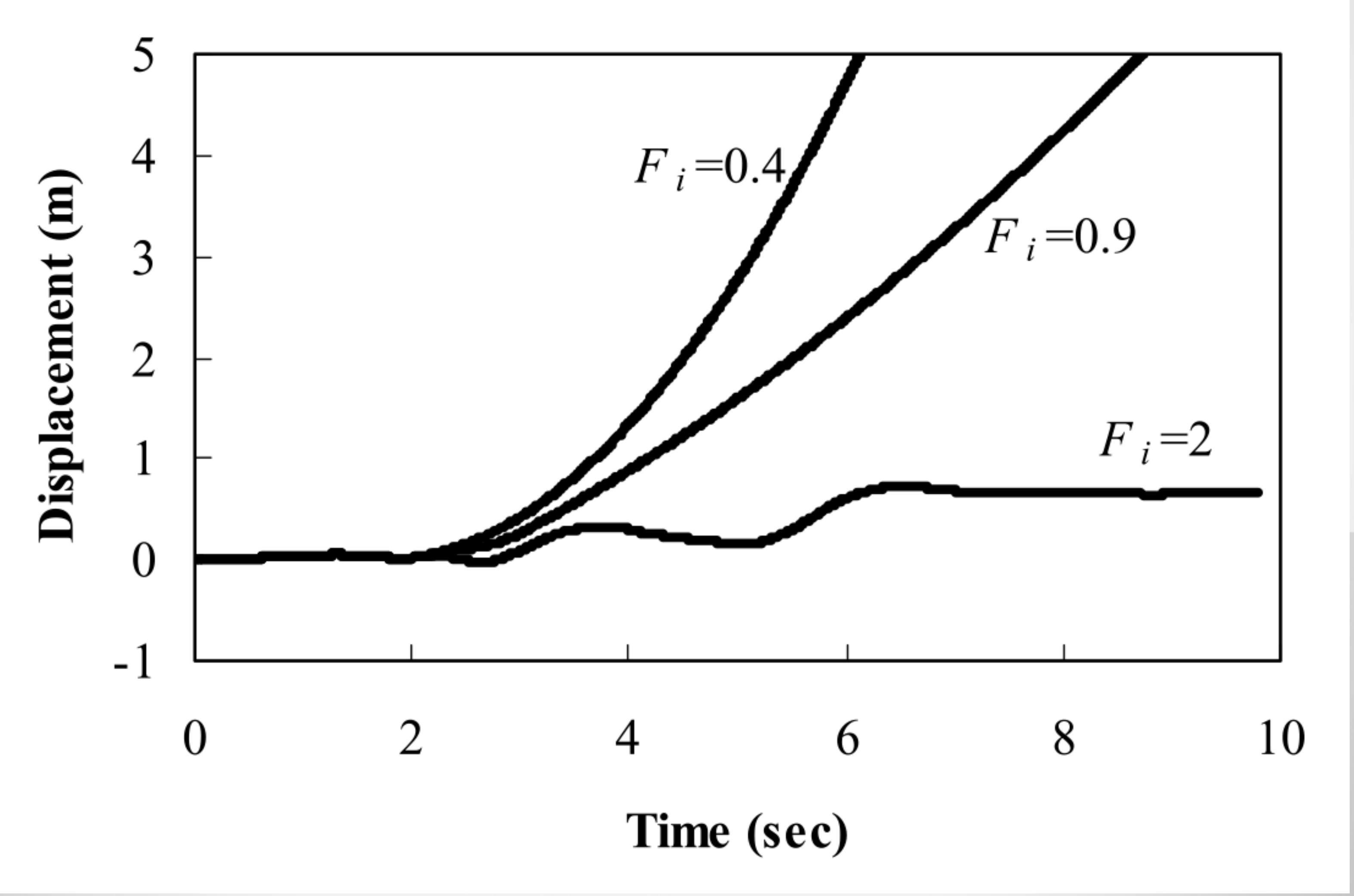




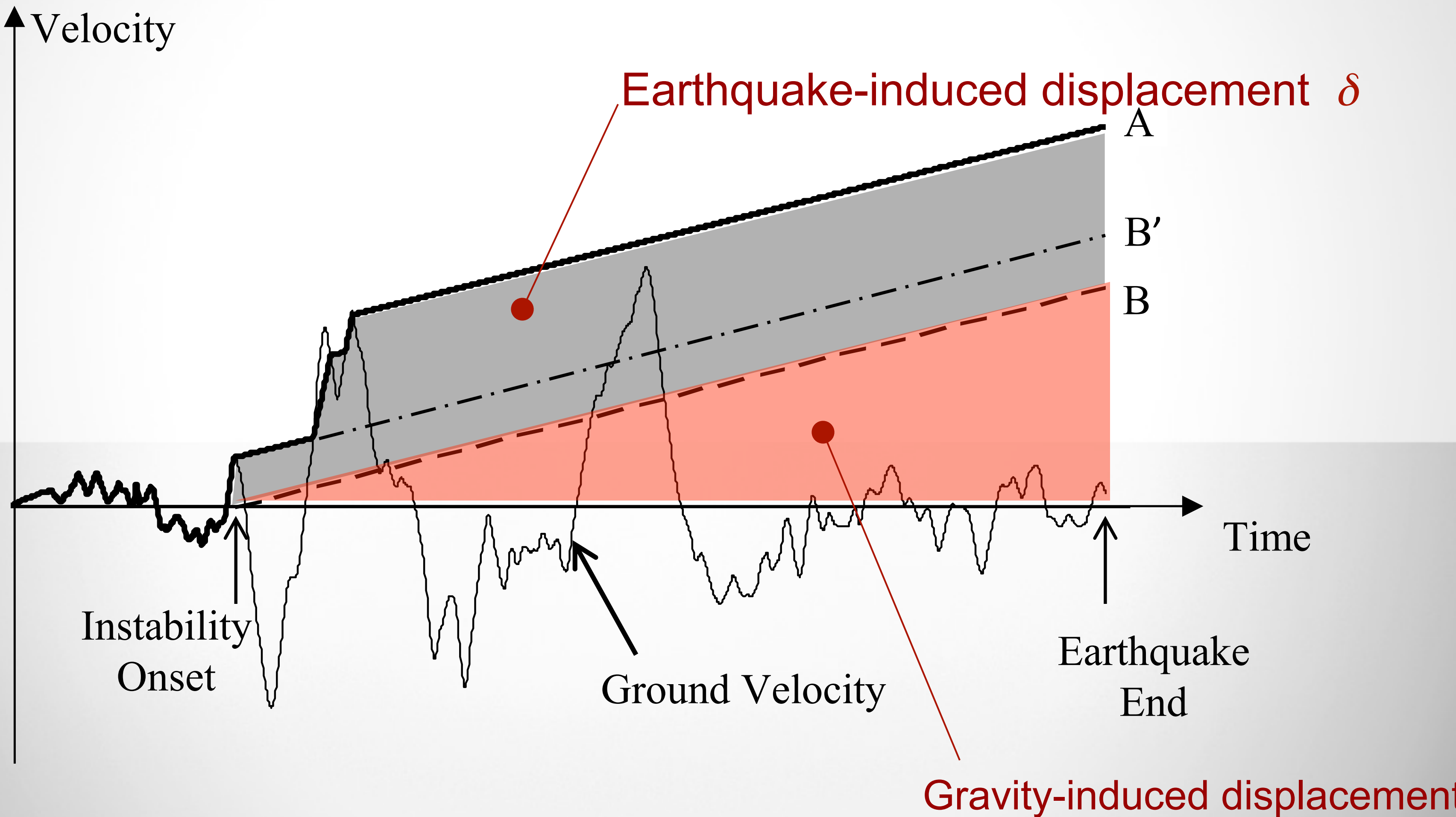
Time histories of mass velocity and ground velocity



Time histories of mass displacement



Earthquake contributions to unstable ground motions



Statistical Model of Unstable Deformation

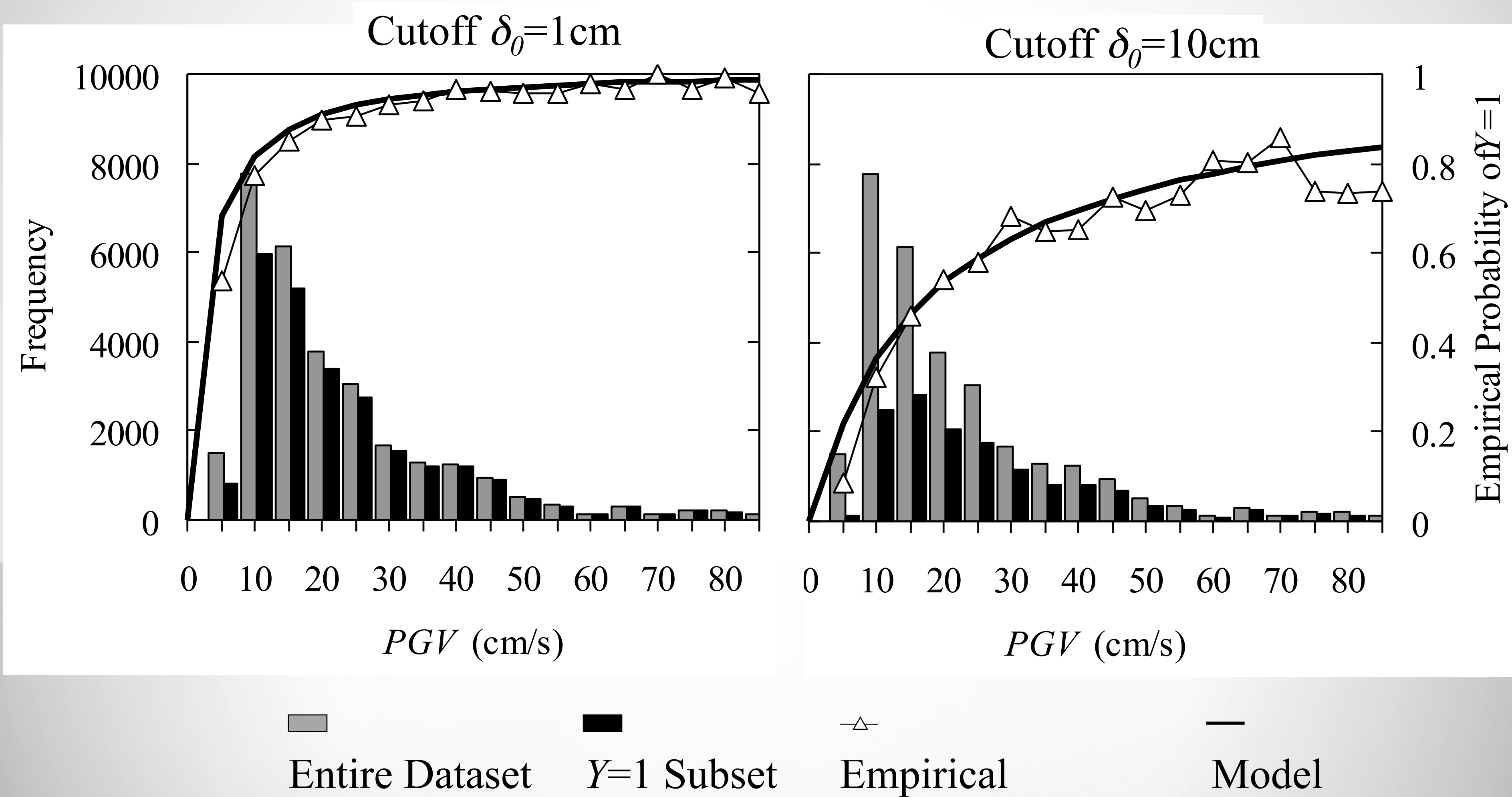
Monte Carlo Simulations

- 1,062 ground acceleration records
  (data from PEER strong-motion database, $PGA > 0.1g$)
- θ ranges from 0 to 5°, uniform distributed
- F_i ranges from 0 to 1, uniform distributed
- Onset of instability randomly takes place during the duration of strong motion

⇩

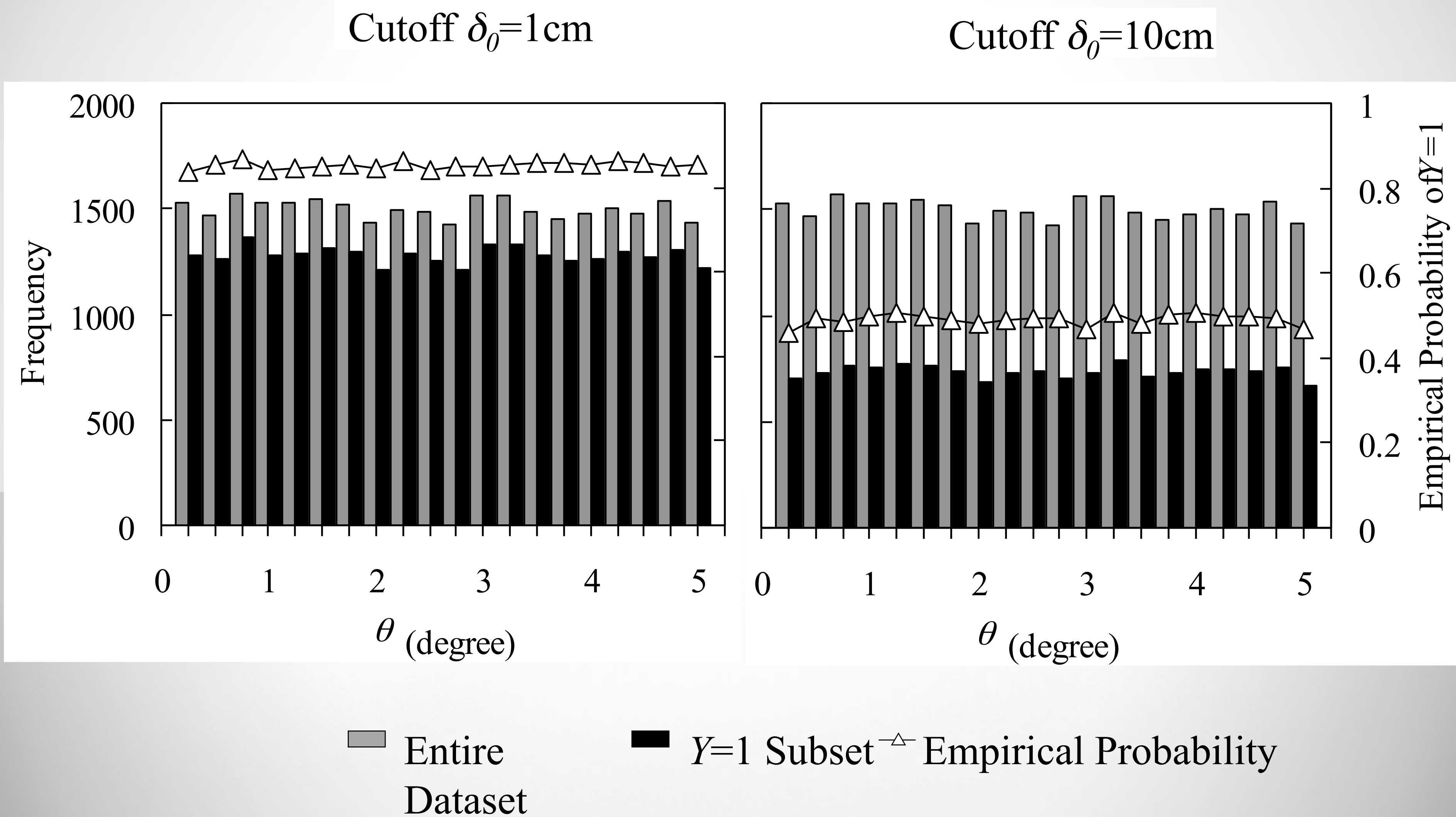
30,000 realizations

Empirical Probability

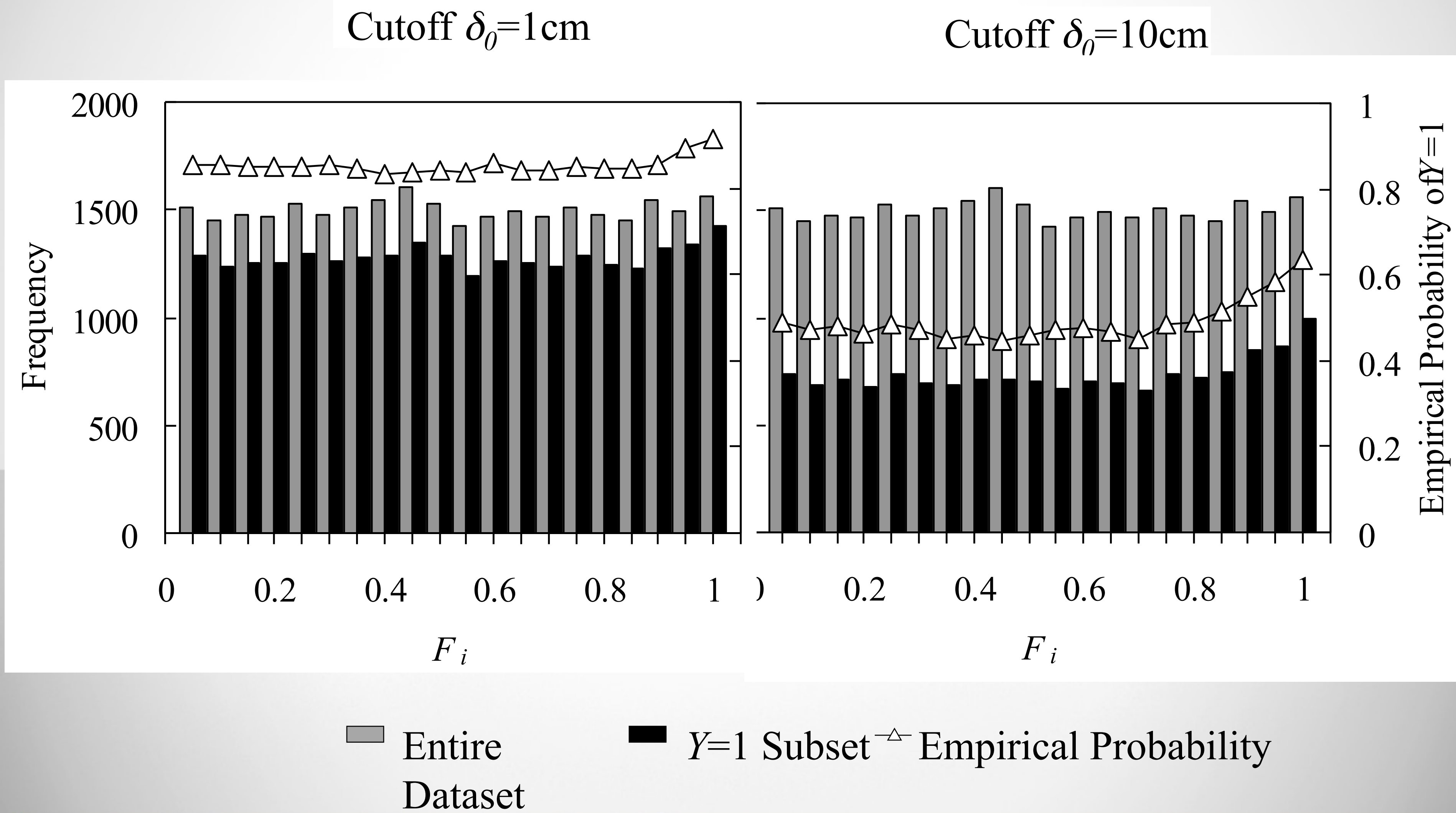


$$F(PGV, \delta_0) = \Phi\left(1.43\log_{10}(PGV) - 1.25\ \log_{10}(\delta_0) - 0.524\right)$$

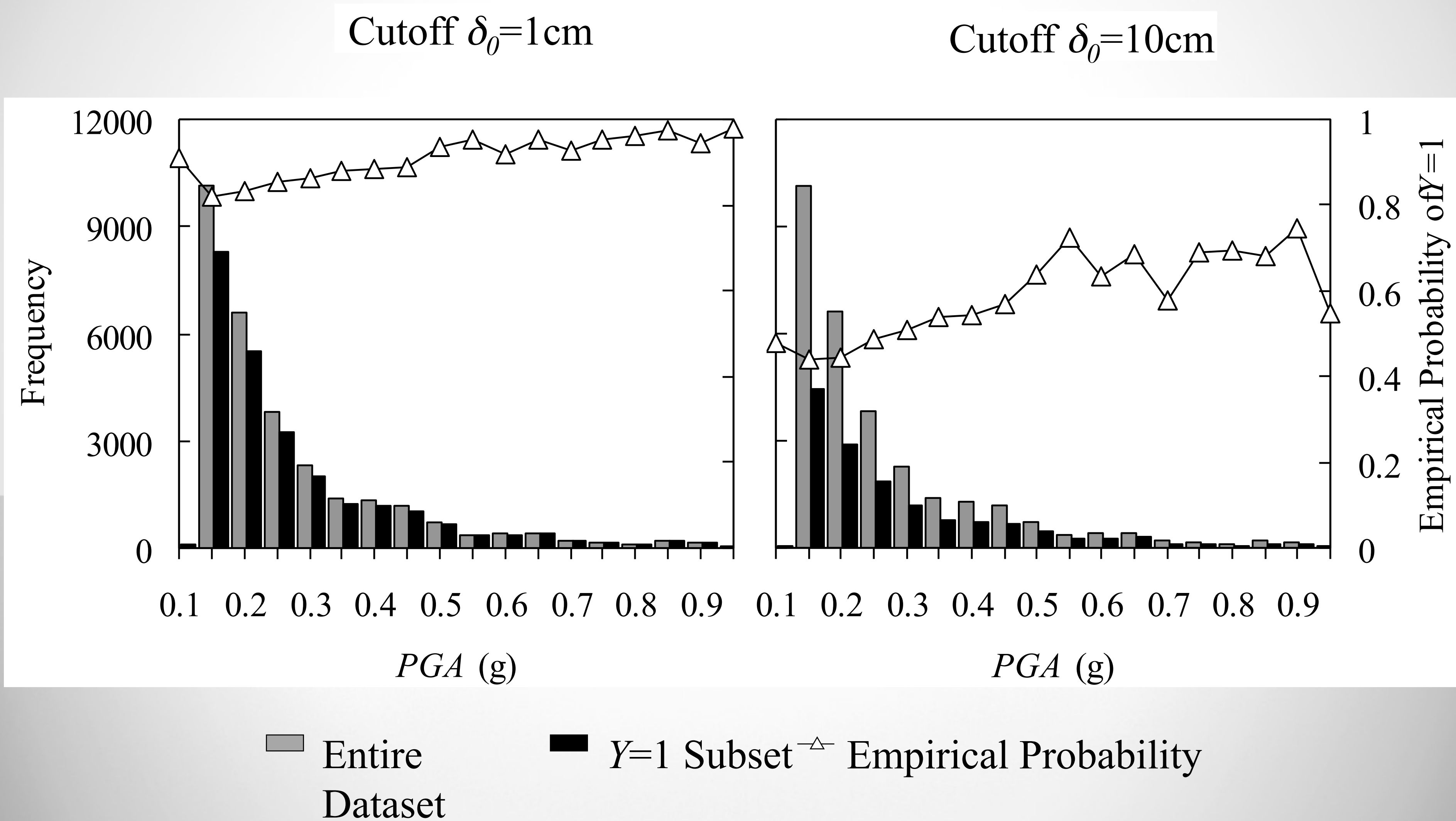
Empirical Probability



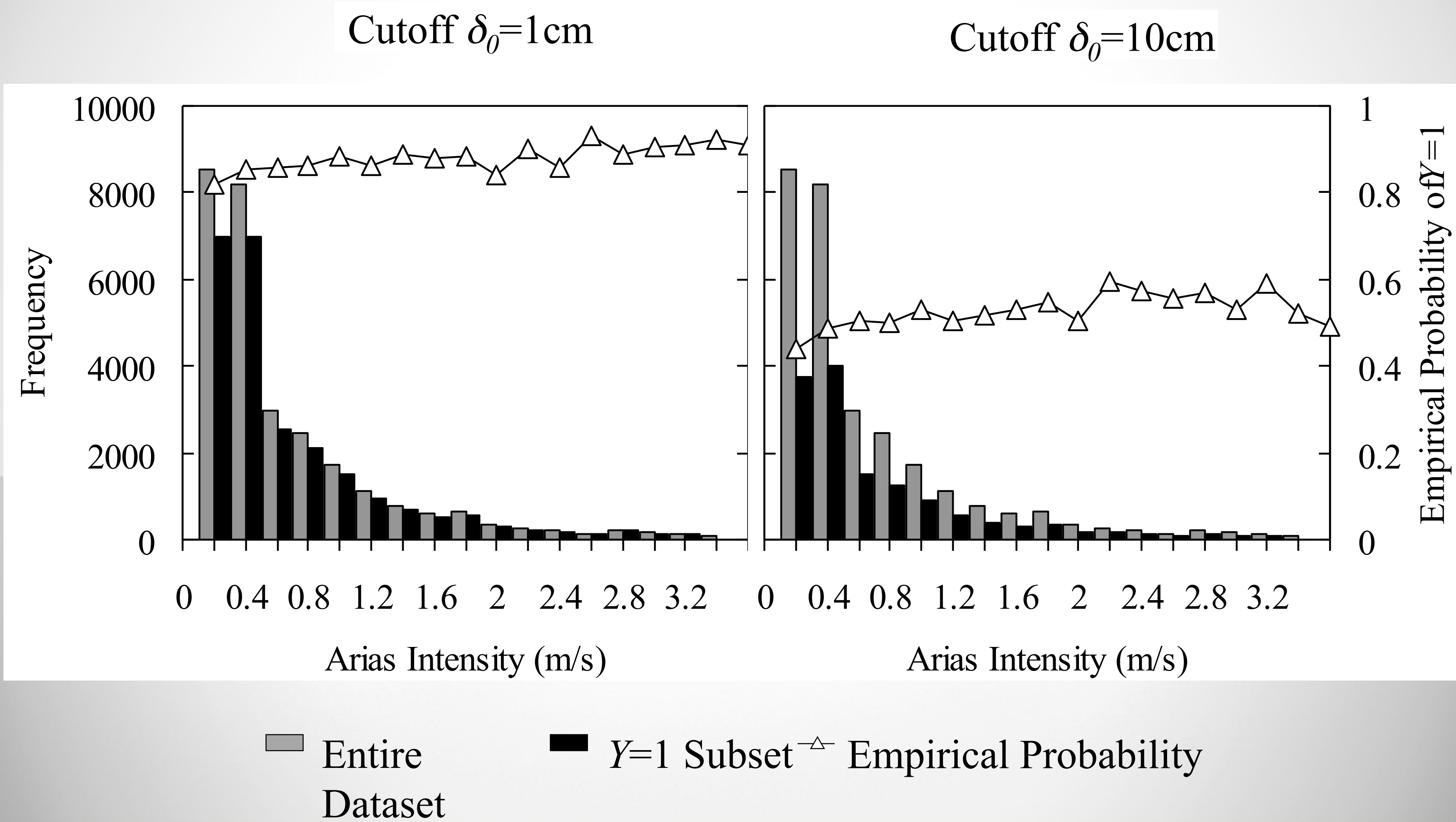
Empirical Probability



Empirical Probability



Empirical Probability



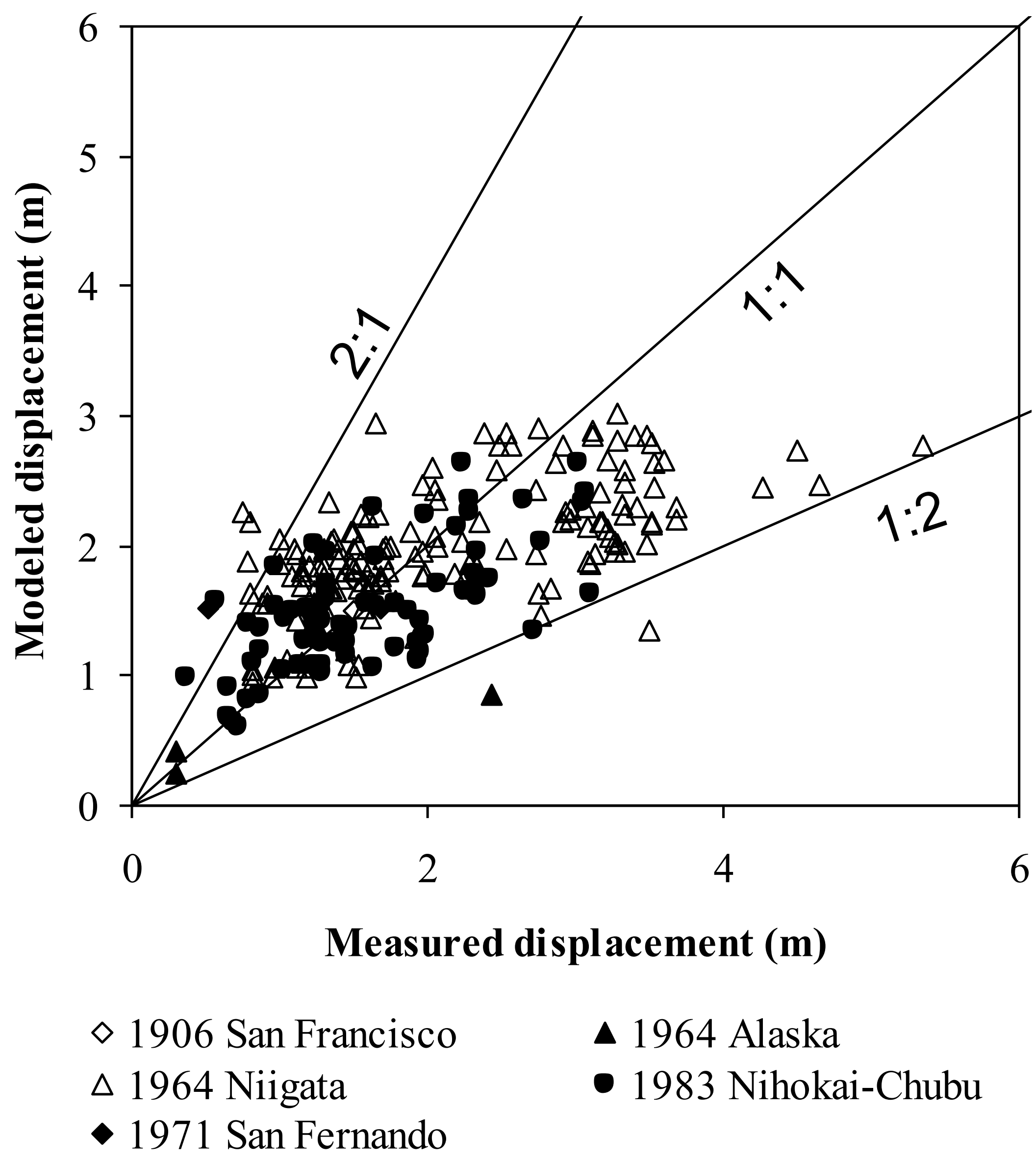
PGV-based model for liquefaction-induced deformation

Earthquake	Number of Cases	M_w	Focal Depth (km)	Epicentral Distance (km)	*PGV* (cm/s)	Note
1906 San Francisco	2	7.9	8	13, 14	56, 55	Campbell 1997
1964 Alaska	3	9.2	25	35, 100	48, 23	Campbell 1997
1964 Niigata	160	7.5	40	21	58	Kanno et al. 2006
1971 San Fernando	5	6.6	8.4	14	56	Liu and Heaton 1984
1983 Nihokai-Chubu	72	7.7	15	27	60	Kanno et al. 2006

Regression analysis

$$\log_{10}(D + 0.01m) = 0.364\log_{10}(S) + 1.461\log_{10}(PGV) + 0.456\log_{10}(T) - 2.590$$

PGV-based model for regional lateral deformation induced by liquefaction



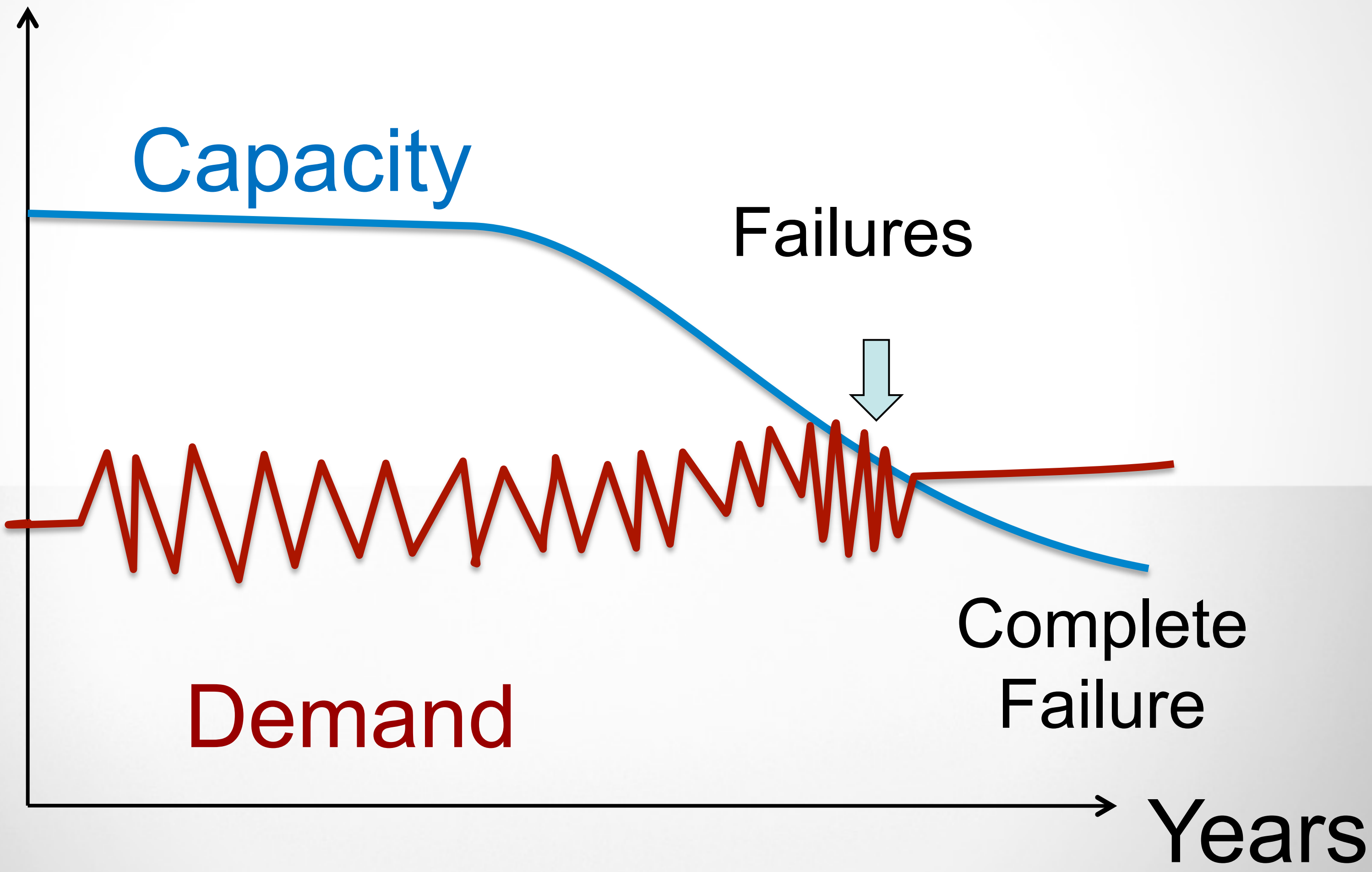
Summary (Part 1)

- A physical model was developed to distinguish the circumstances for which earthquakes impact the motions of gently sloping grounds
- Gently sloping grounds
  - Move largely unaffected by earthquake shakings in case of severe loss in shear strength,
  - Are influenced by pulses of earthquake ground velocity in case moderate reduction in shear strength
- The PGV-based model predicts reasonably well case histories of liquefaction-induced deformation.

Outline

1. Earthquake Ground Deformation
2. Ground Deformation Models
3. **Lifelines Performance**

Capacity and Demand



2013 Report Card for America's Infrastructure

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AMERICA'S INFRASTRUCTURE G.P.A. D+

Each category was evaluated on the basis of capacity, condition, funding, future need, operation and maintenance, public safety and resilience.

METHODOLOGY >

AVIATION	D	PORTS	C
BRIDGES	C+	PUBLIC PARKS AND RECREATION	C-
DAMS	D	RAIL	C+
DRINKING WATER	D	ROADS	D
ENERGY	D+	SCHOOLS	D
HAZARDOUS WASTE	D	SOLID WASTE	B-
INLAND WATERWAYS	D-	TRANSIT	D
LEVEES	D-	WASTEWATER	D

A = Exceptional
B = Good
C = Mediocre
D = Poor
F = Failing

ESTIMATED INVESTMENT NEEDED BY 2020:

$3.6 TRILLION

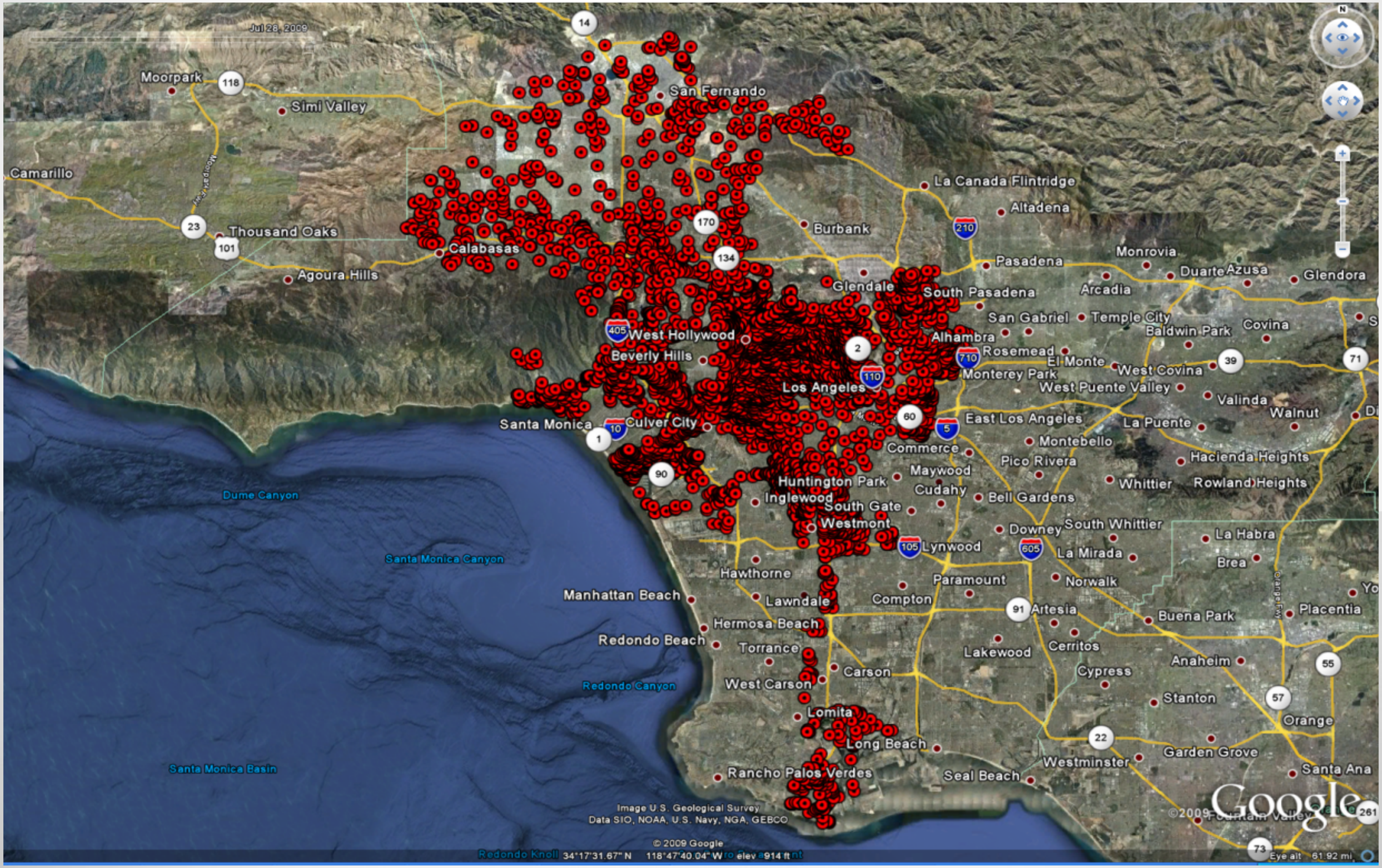
LEARN MORE >


Hartsook St
Corbin & Kittridge

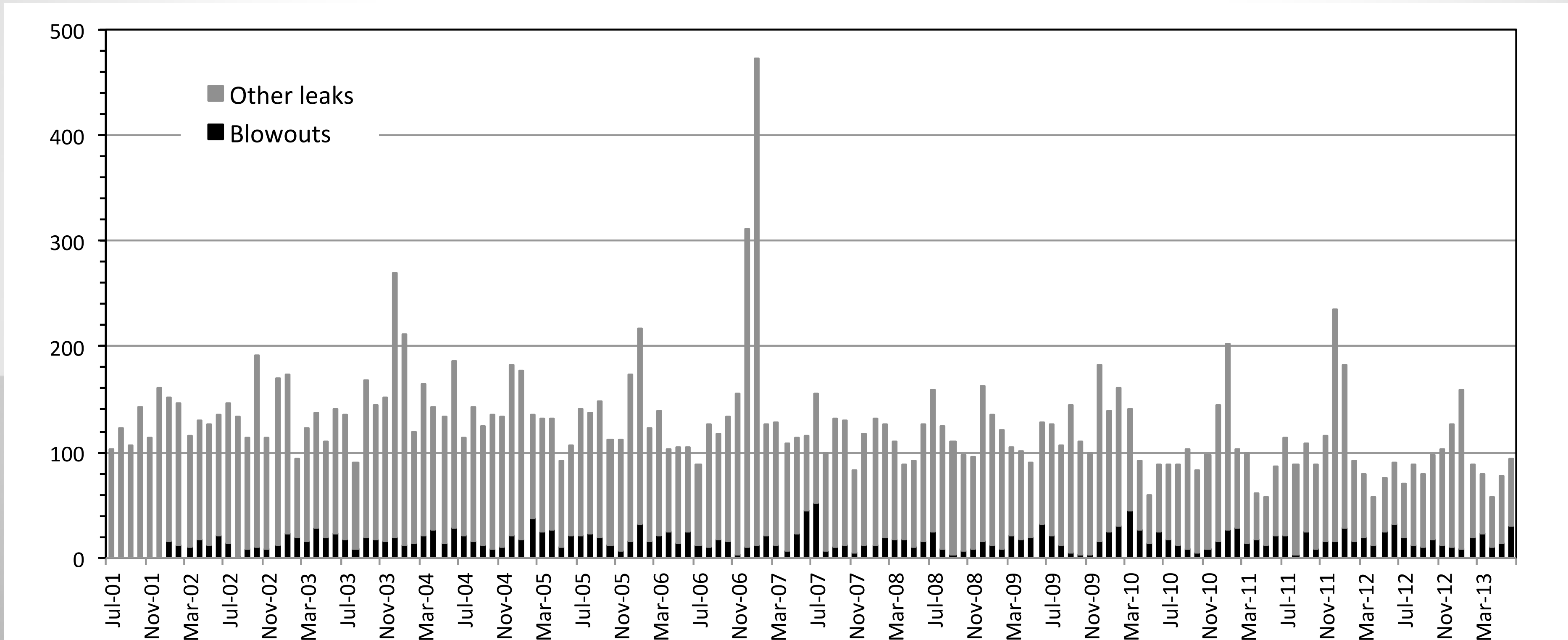

Coldwater Cyn
Burbank Blvd
LADWP WATER
CAUTION
CAUTION
LADWP WATER

Patch Blowouts of Cast Iron

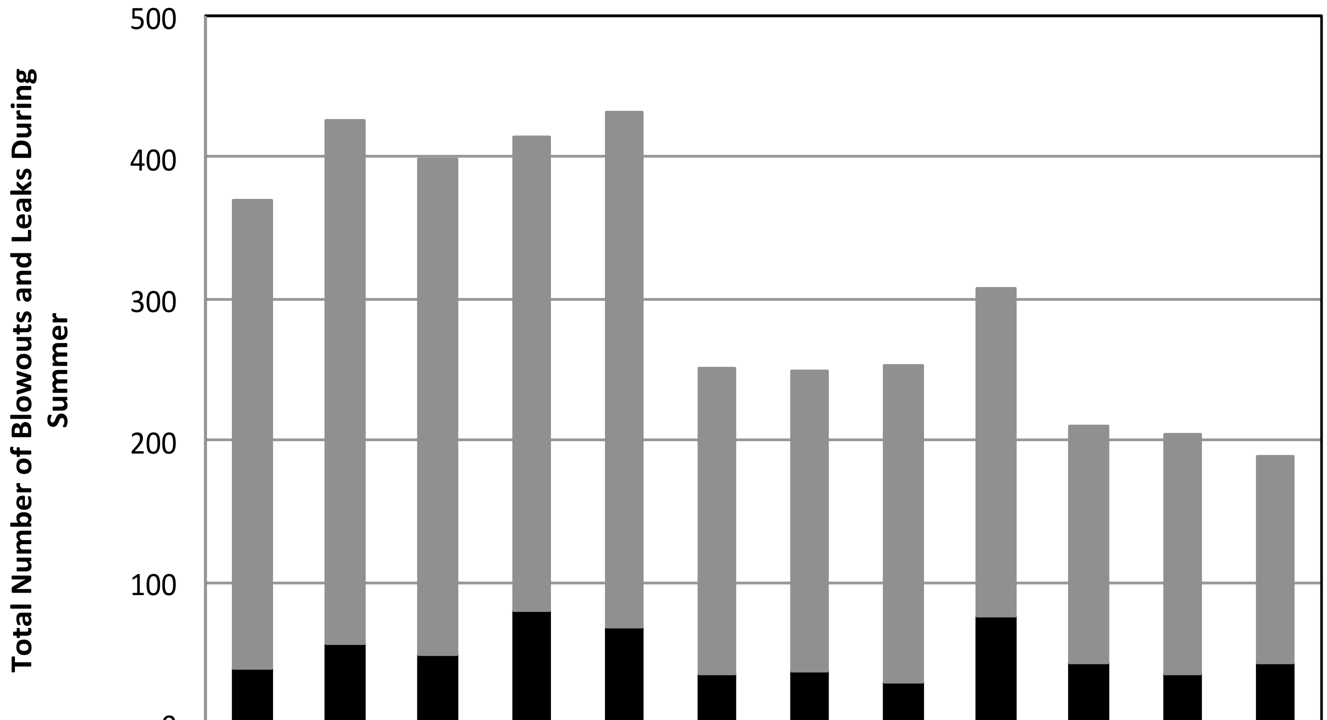
Leaks and Blowouts since 2001



Monthly number of blowouts and leaks in LADWP

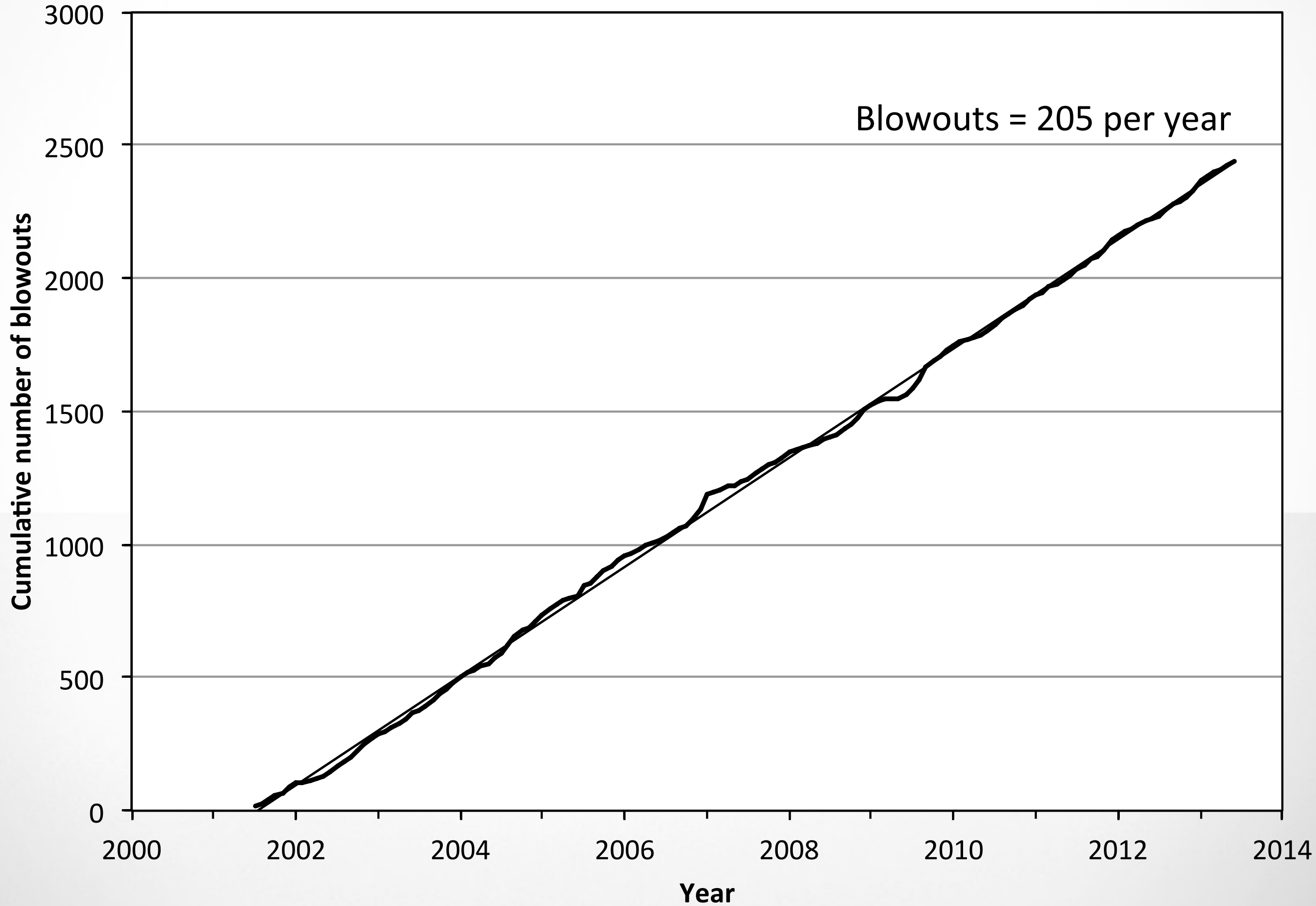


Blowouts and leaks in Los Angeles during summers 2001-2012

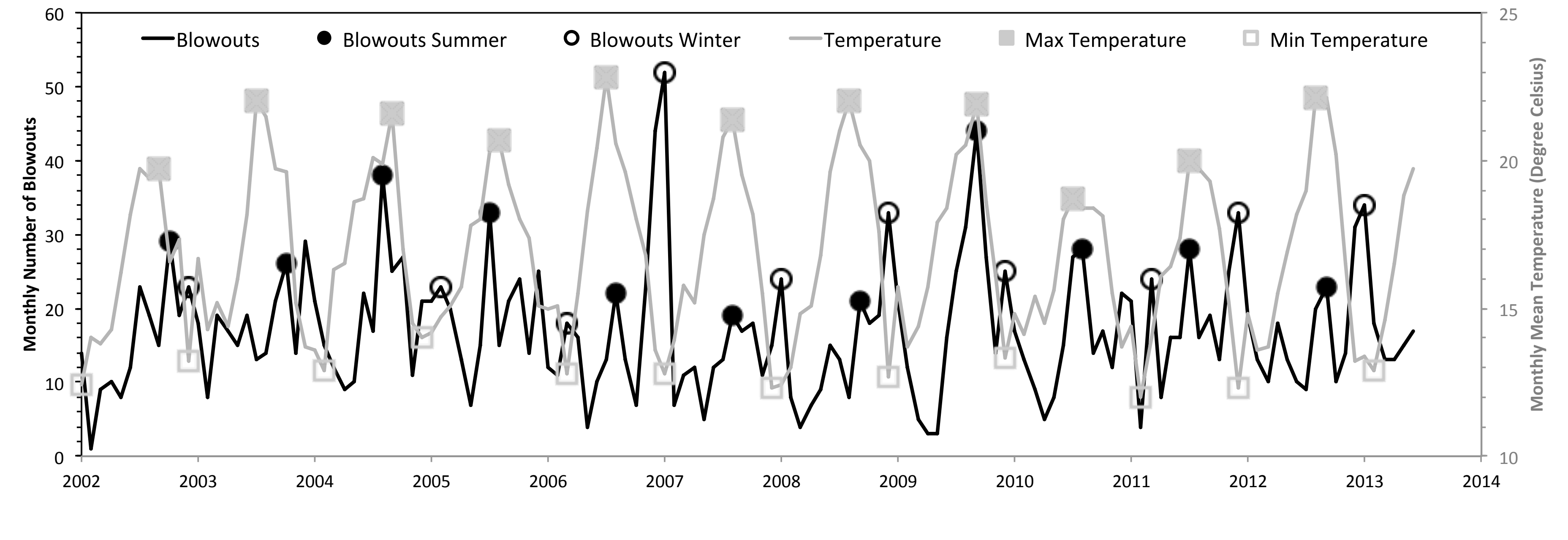


	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Other leaks	332	369	350	334	362	216	213	223	233	169	169	146
Blowouts	38	57	48	80	69	35	36	29	75	42	35	43

Cumulative numbers of blowouts between 2001 and 2013.



Monthly pipe blowouts and ambient temperatures in LA



Pipe length distribution in terms of years in service and material types in LADWP

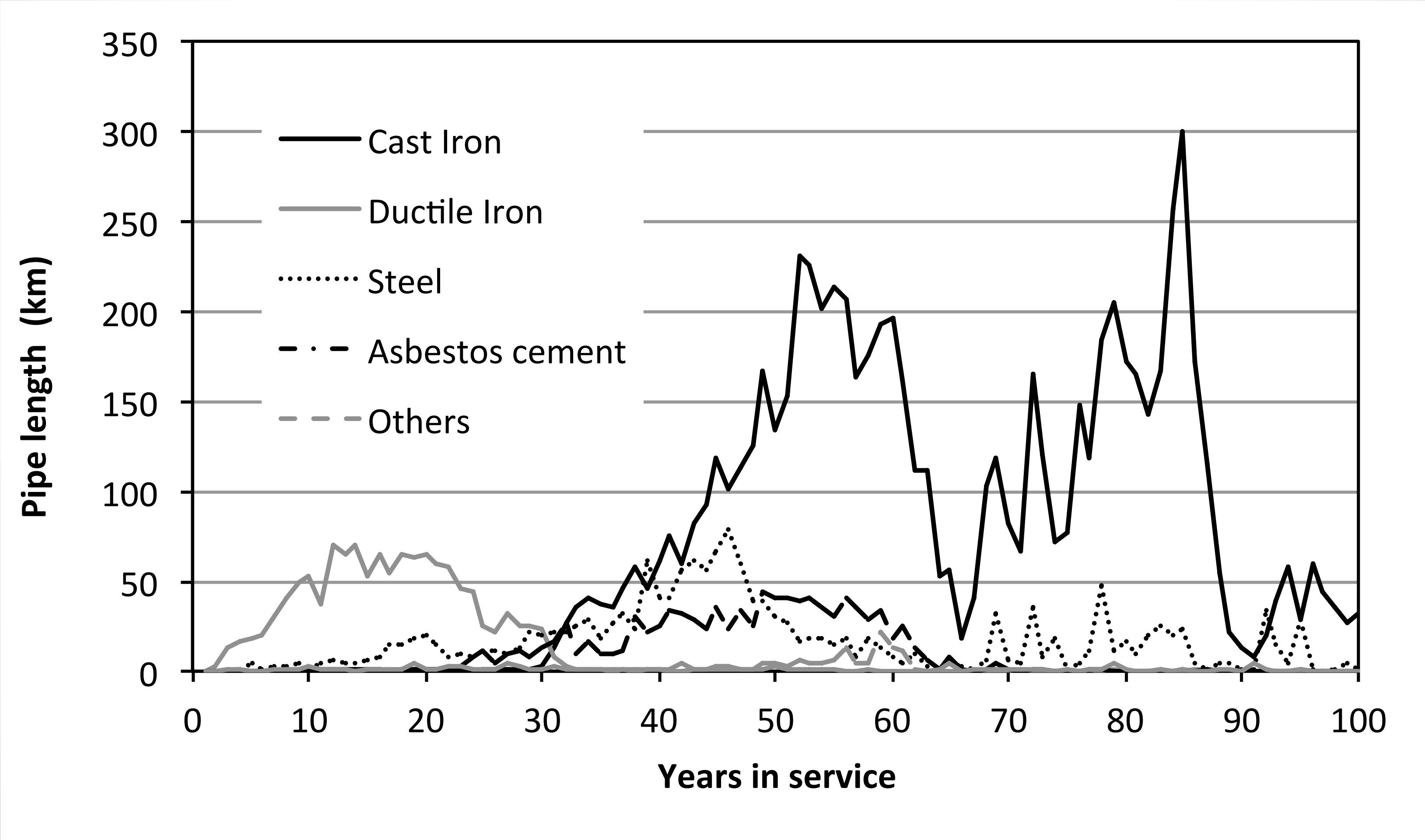
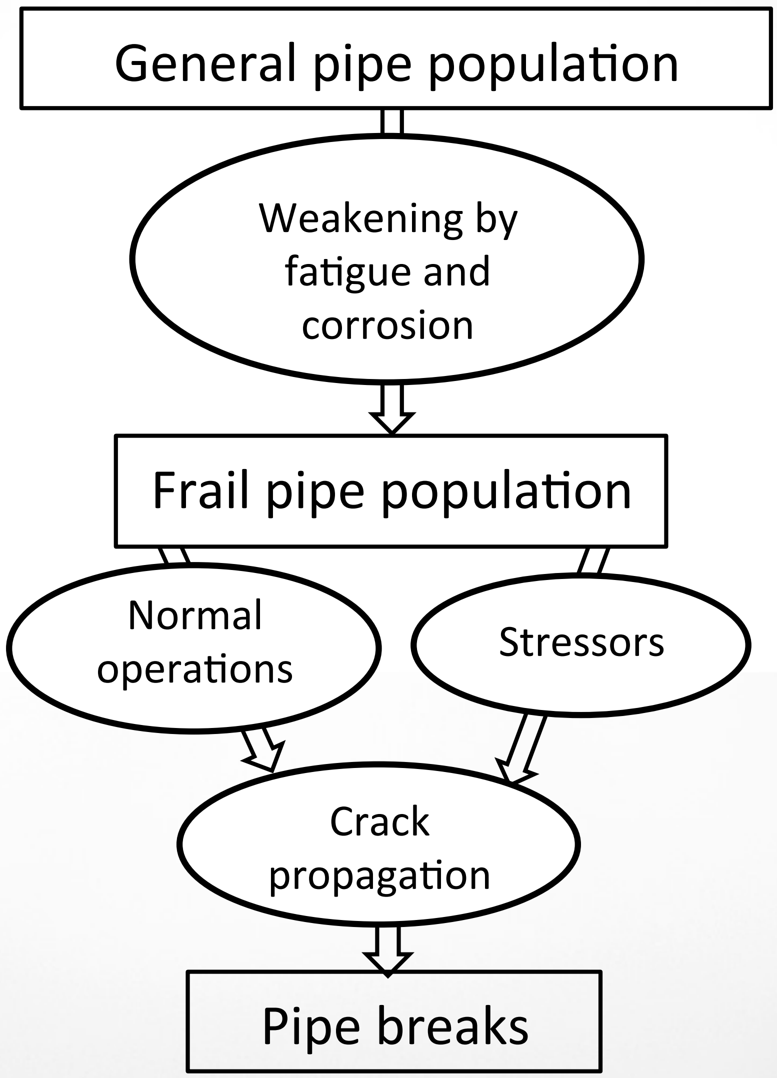
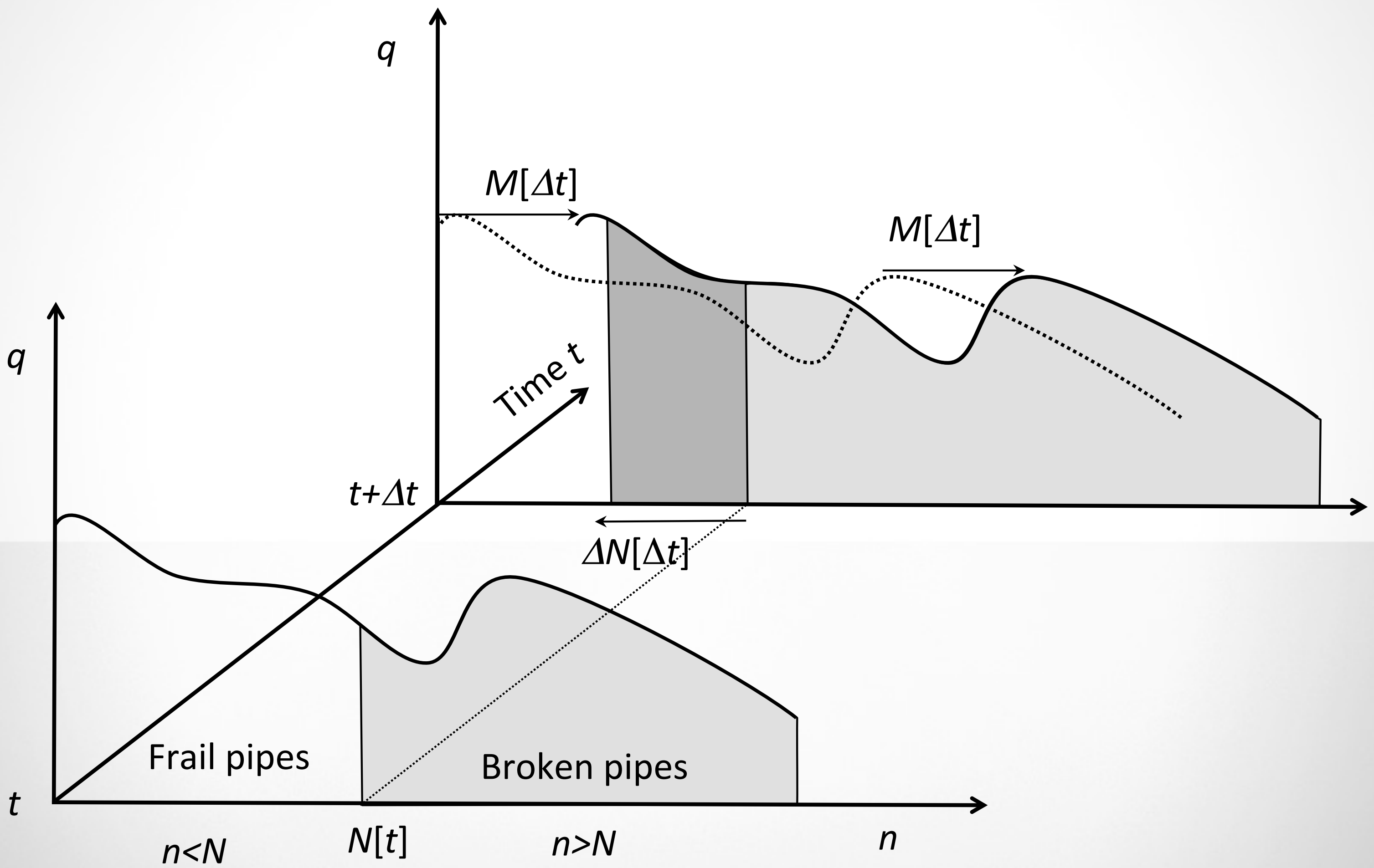


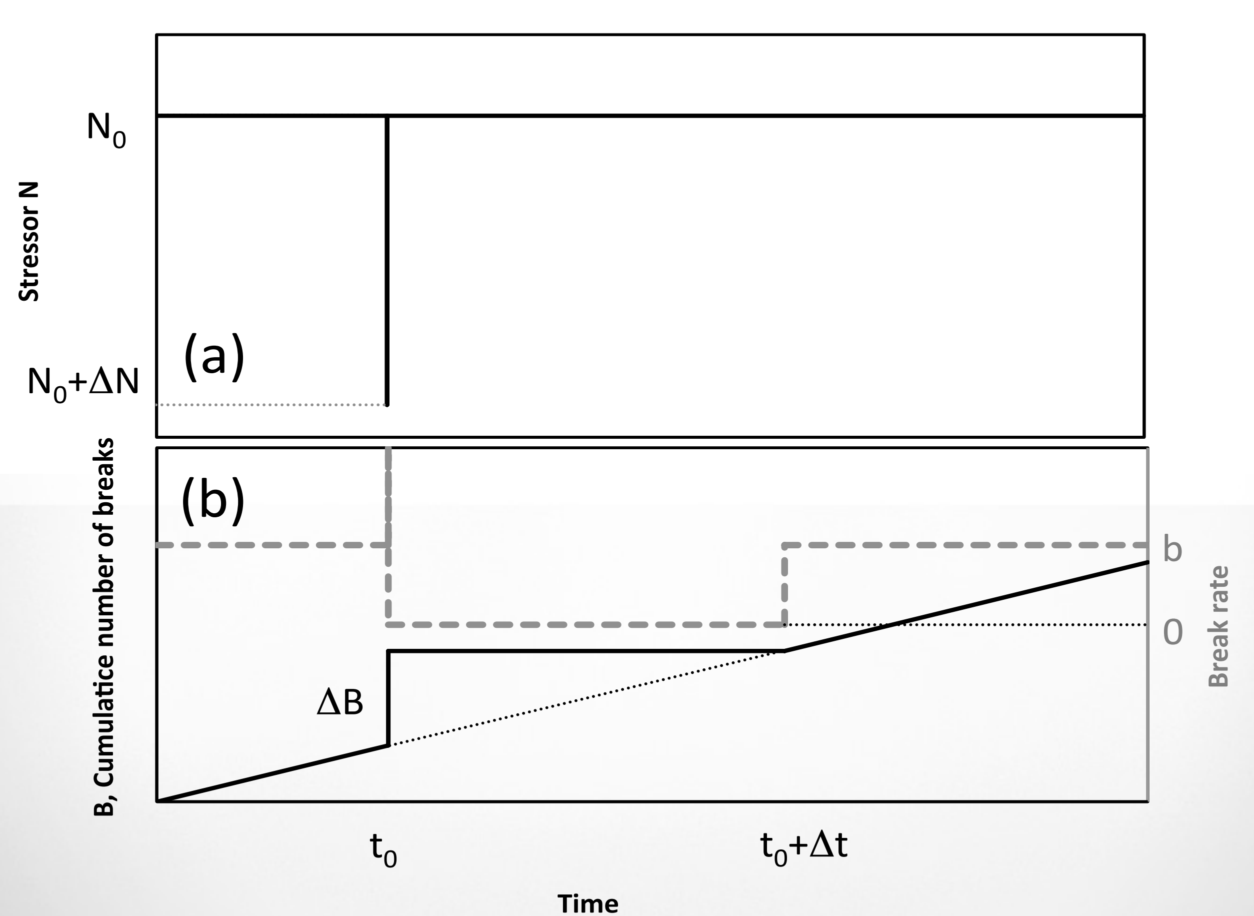
Illustration of harvesting framework



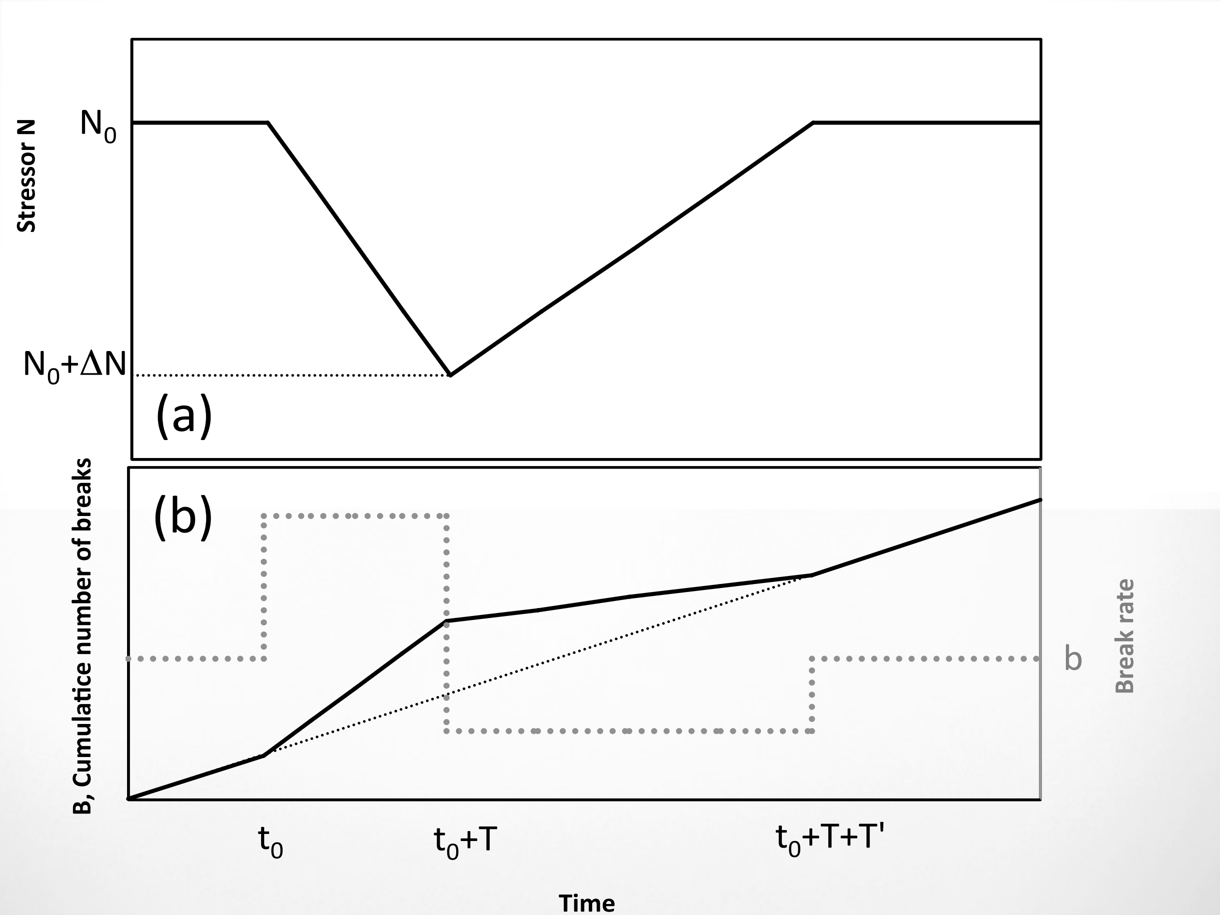
Distributions q[n] at times t and t + Δt.



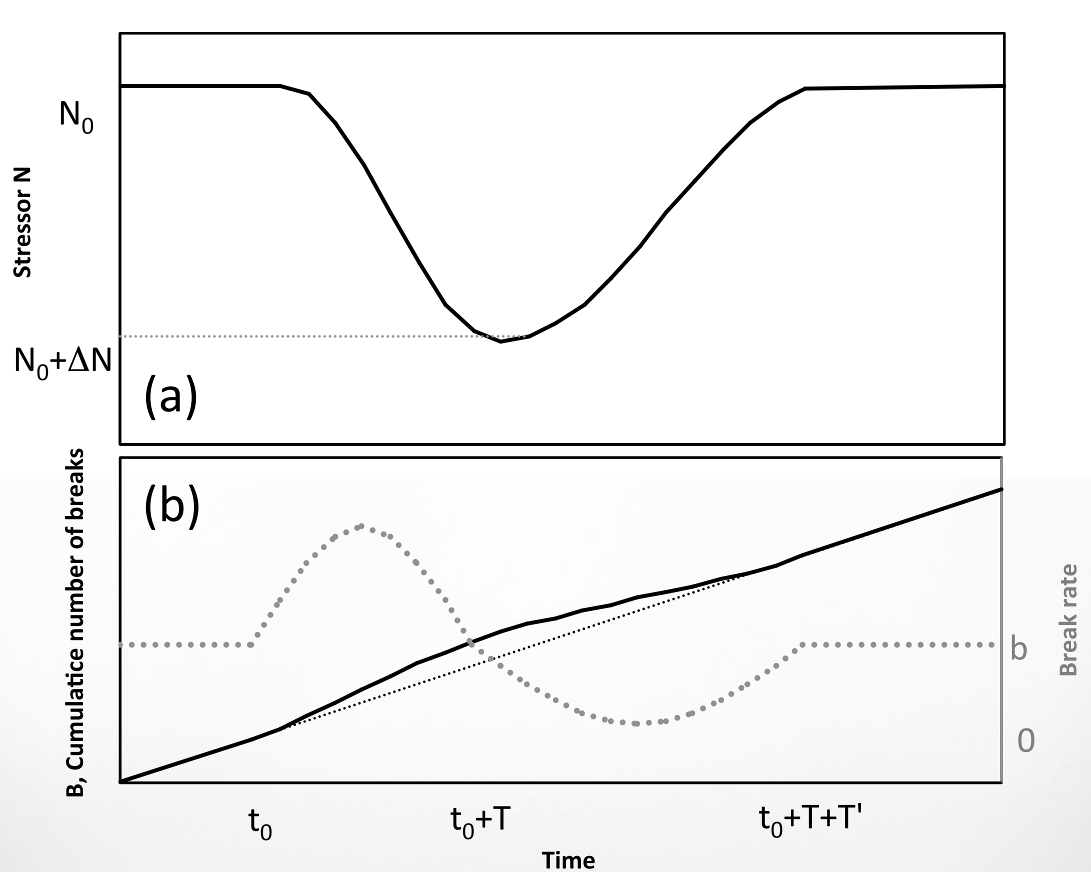
Impulse stressor: (a) Variation of stressor N, and (b) resulting variation of cumulative number of breaks B and break rate



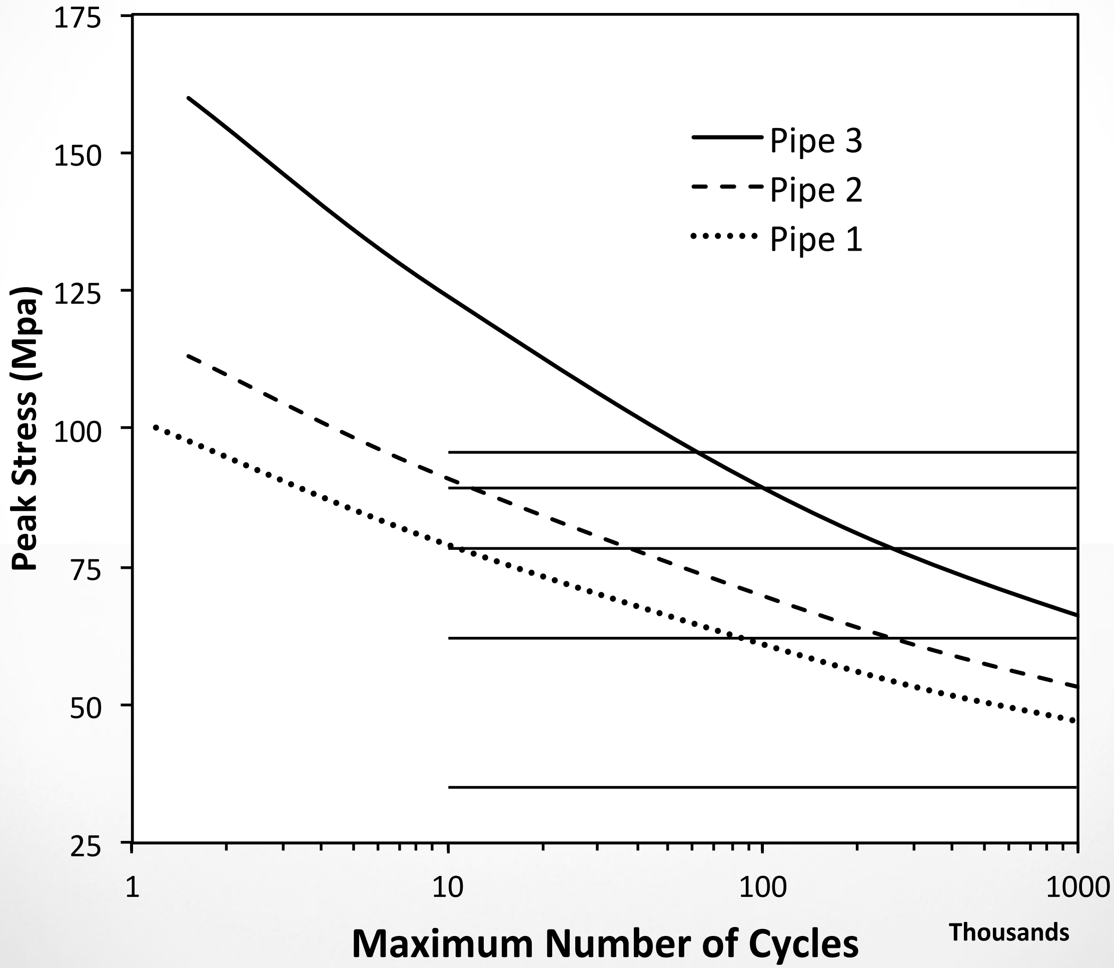
Triangular pulse: (a) variation of stressor N, and (b) resulting variation of cumulative number of breaks B and break rate



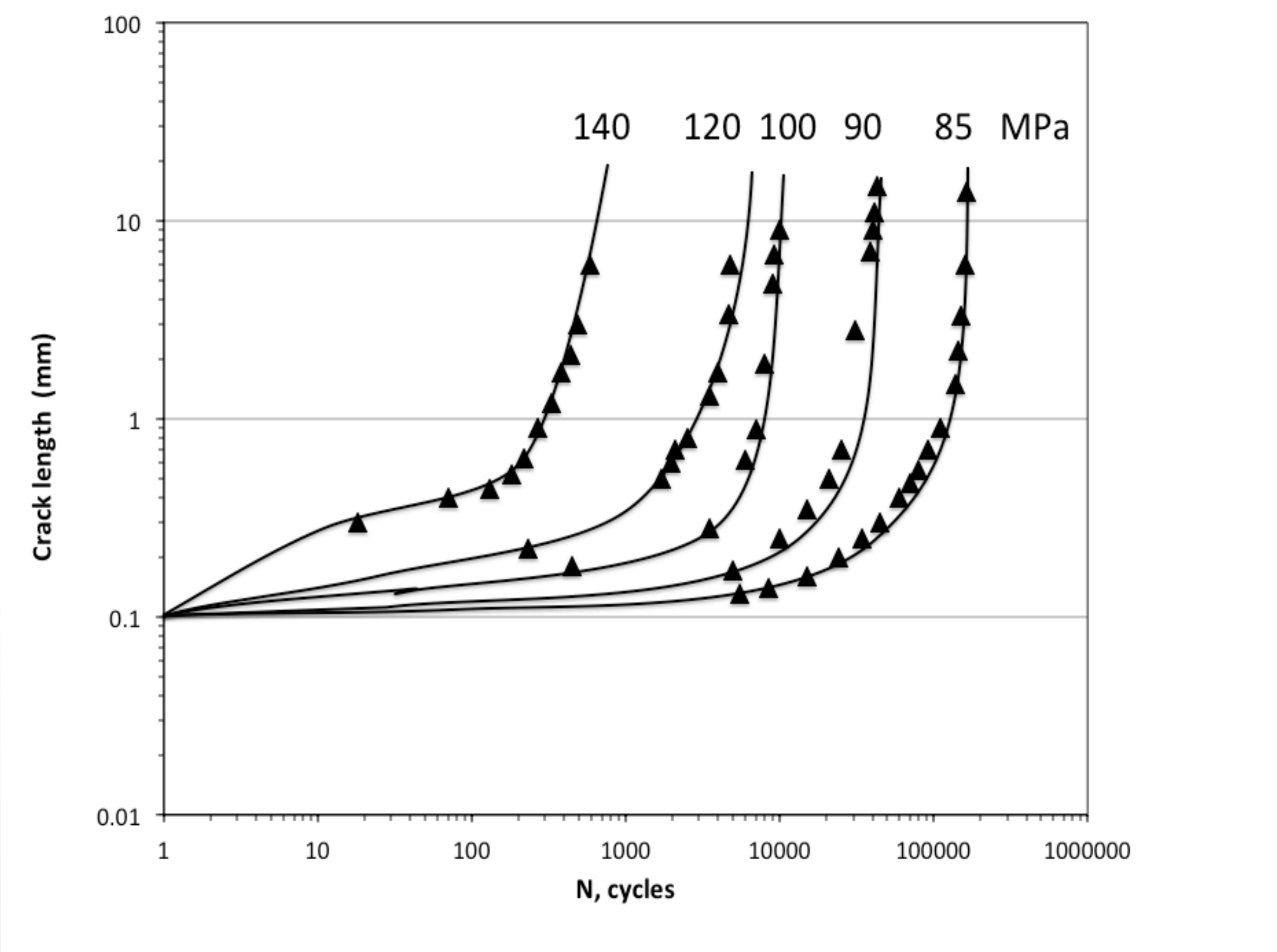
Unsymmetrical cosine pulse: (a) variation of stressor N, and (b) resulting variation of cumulative number of breaks B and break rate



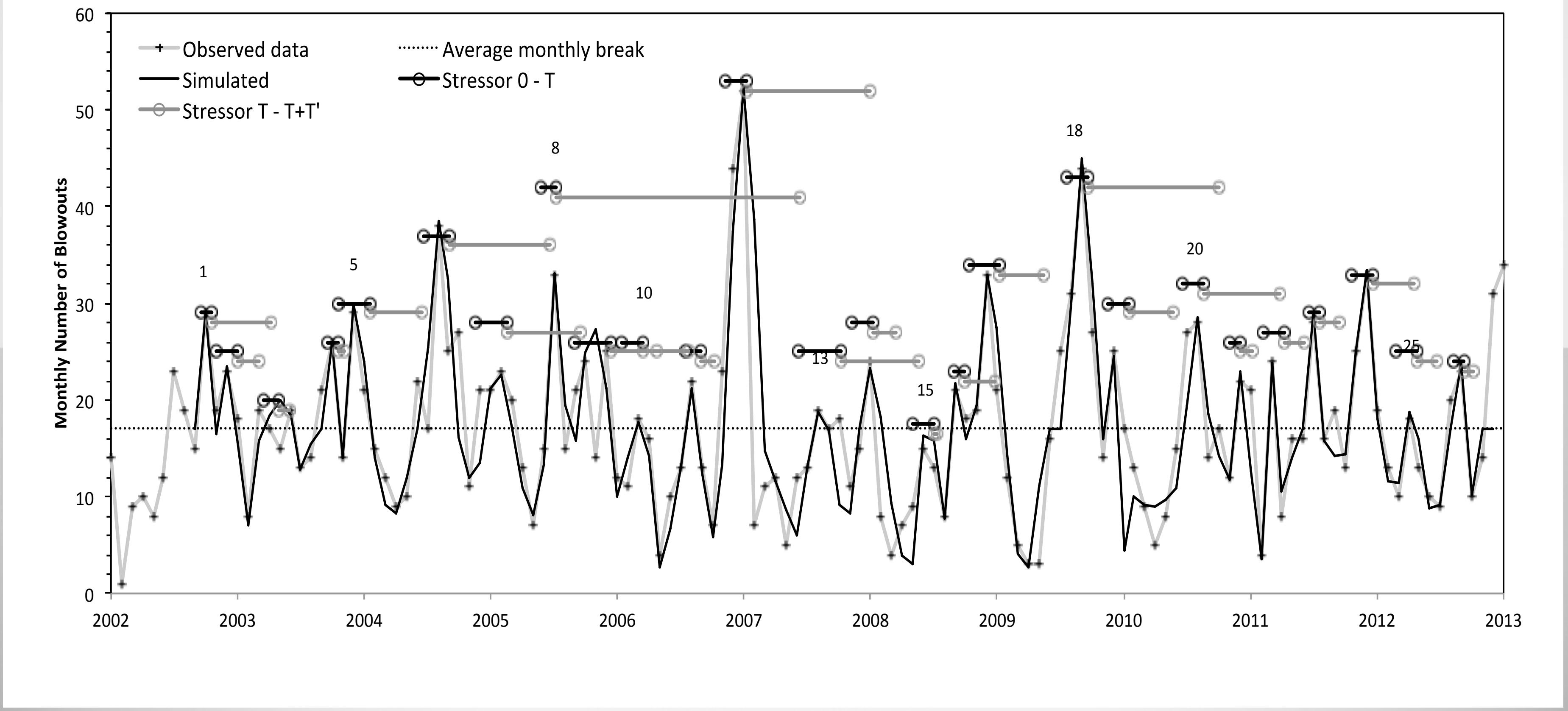
Fatigue curves for grey cast iron pipes
(data after Mohebbi et al., 2009)



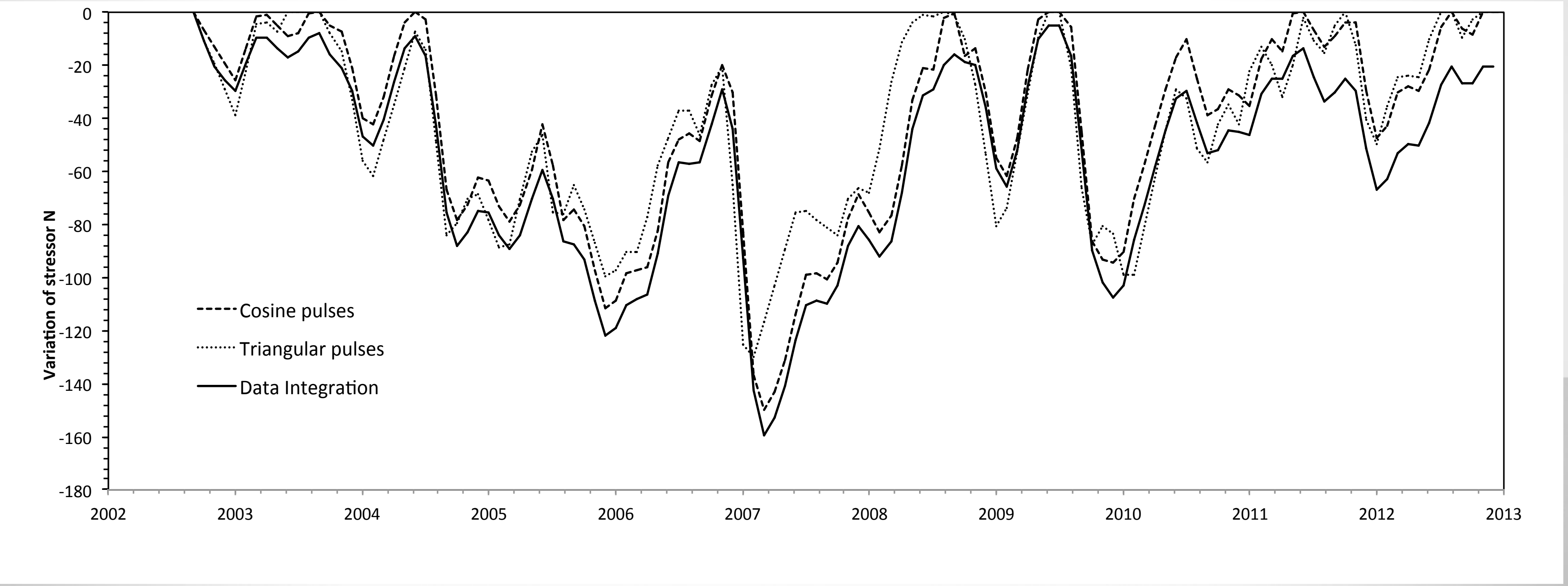
Variation of crack length with fatigue cycles in grey cast iron
(Data after Socie and Fash, 1982)



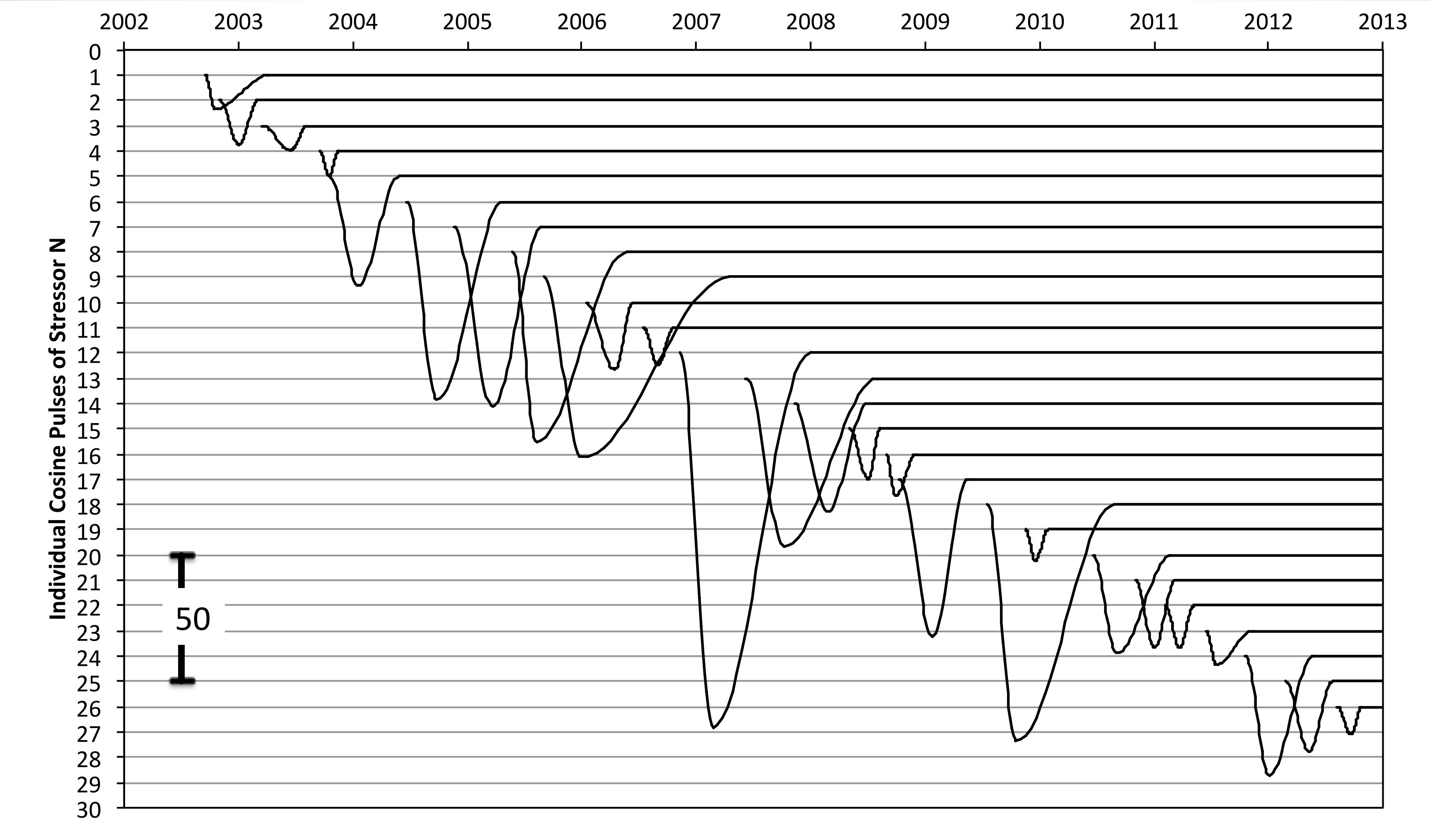
Observed and simulated variations of monthly number of blowouts in LADWP



Observed and simulated variations of stressor N from 2002 till 2013.



Individual cosine pulses of stressor N



Conclusion (Part 2)

- Urban water systems worldwide harbor numerous old and fragile pipes that often break dramatically in temporal clusters.
- A harvesting framework is introduced to analyze the time variations of disruptive pipe breaks that can help water agencies better understand clustered pipe failures.
- It assumes a cohort of pipes weakened state due to fatigue and corrosion.
- The harvesting model simulates an observed time series of monthly pipe breaks and has both explanatory and predictive power.

Conclusion

- Ground deformation is certainly one of the main causes of lifeline failures during earthquakes
- Ground deformation although complex when associated with reduction in shear strength and liquefaction correlates best with PGV
- Lifelines performance during earthquakes is not only influenced by earthquake shaking intensity but also by their pre-earthquake conditions