TSRP Liquefaction Research

Steve Kramer

TSRP Research Committee

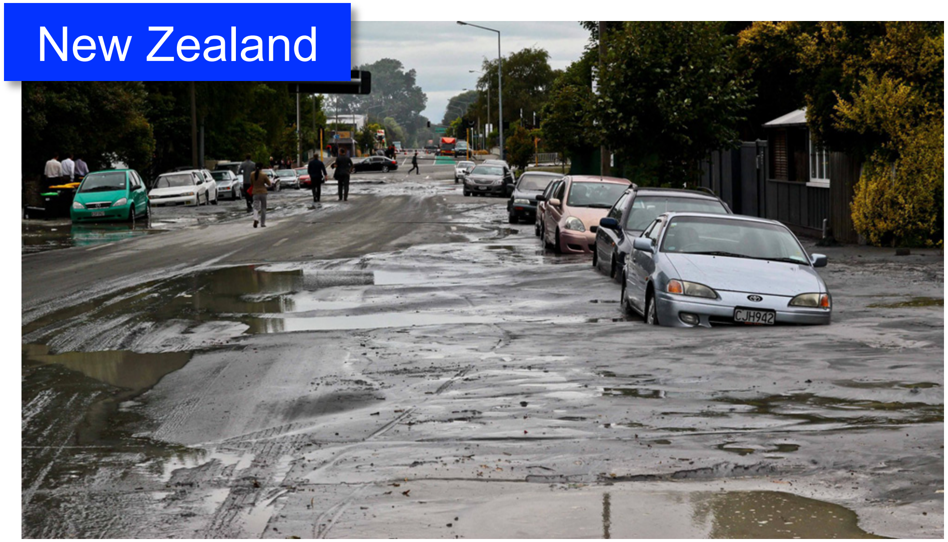
History of PEER Liquefaction Research

Turkey

Taiwan

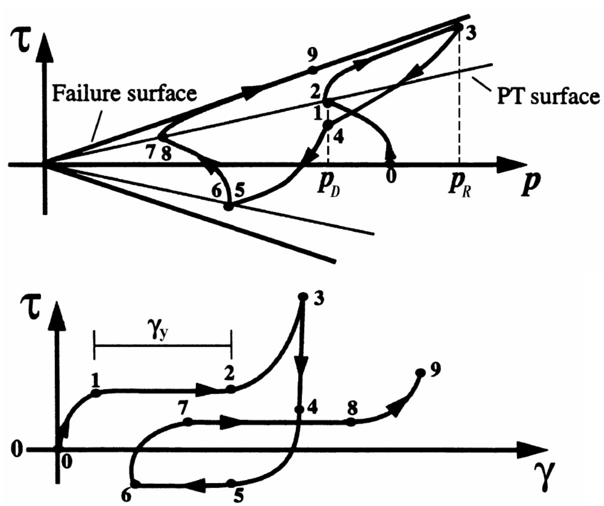
Japan

New Zealand



History of PEER Liquefaction Research

State-of-the-art reviews



PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Modeling Soil Liquefaction Hazards for Performance-Based Earthquake Engineering

Steven L. Kramer
University of Washington

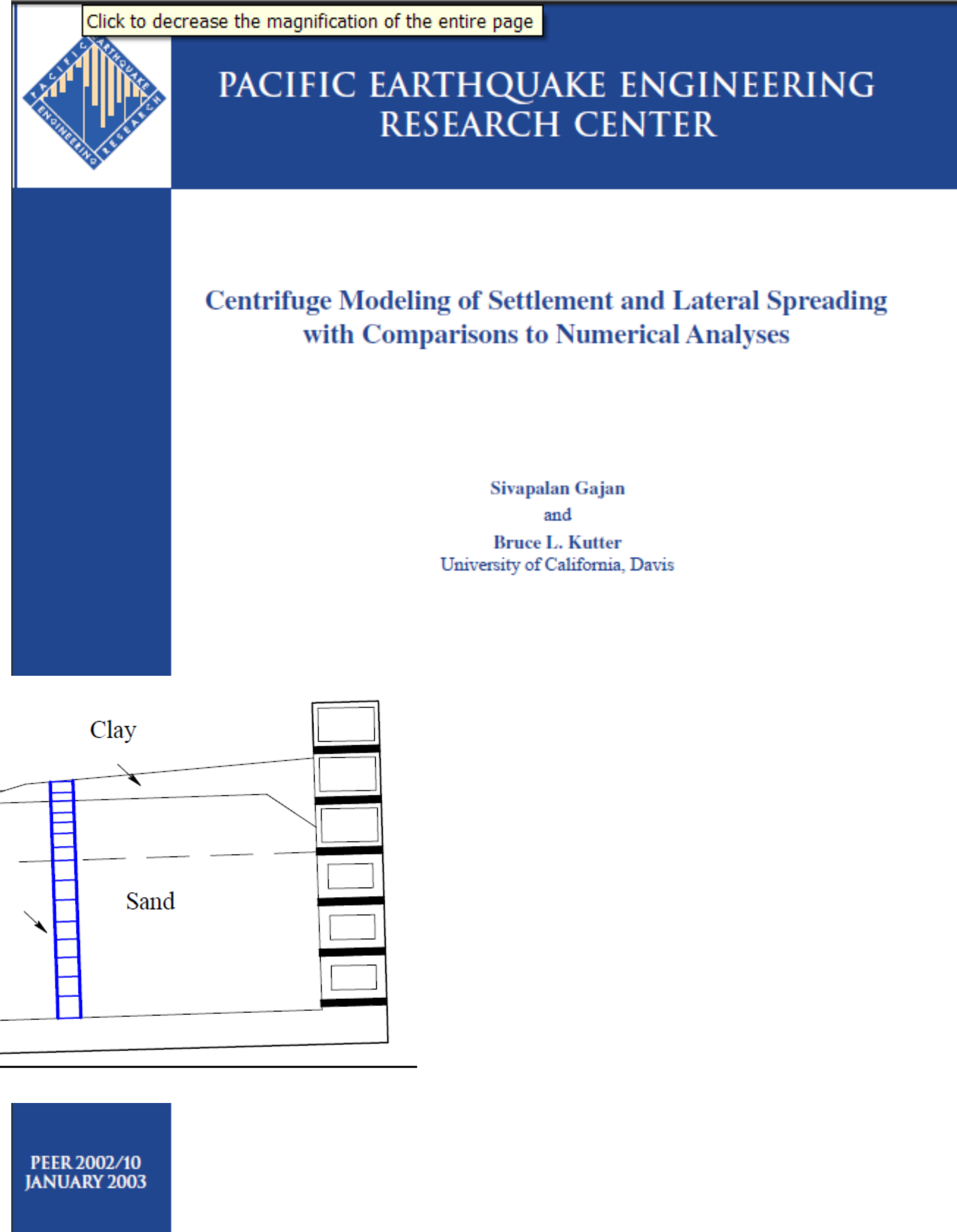
Ahmed-W. Elgamal
University of California, San Diego

A report on research conducted under
grant no. EEC-9701568 from the National Science Foundation

PEER 2001/13
FEBRUARY 2001

History of PEER Liquefaction Research

- State-of-the-art reviews
- Experimental studies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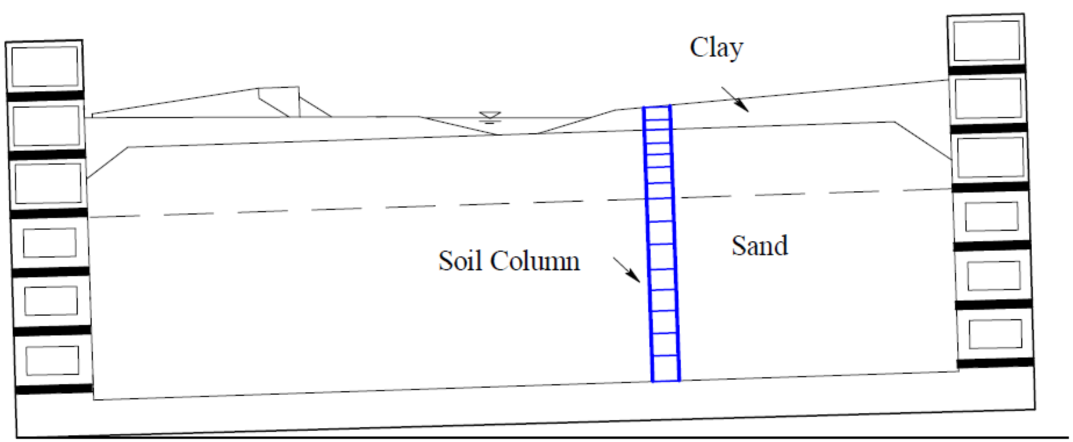
PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Centrifuge Modeling of Settlement and Lateral Spreading with Comparisons to Numerical Analyses

Sivapalan Gajan
and
Bruce L. Kutter
University of California, Davis

PEER 2002/10
JANUARY 2003



History of PEER Liquefaction Research

State-of-the-art reviews

Experimental studies

Analytical procedures

Simplified

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

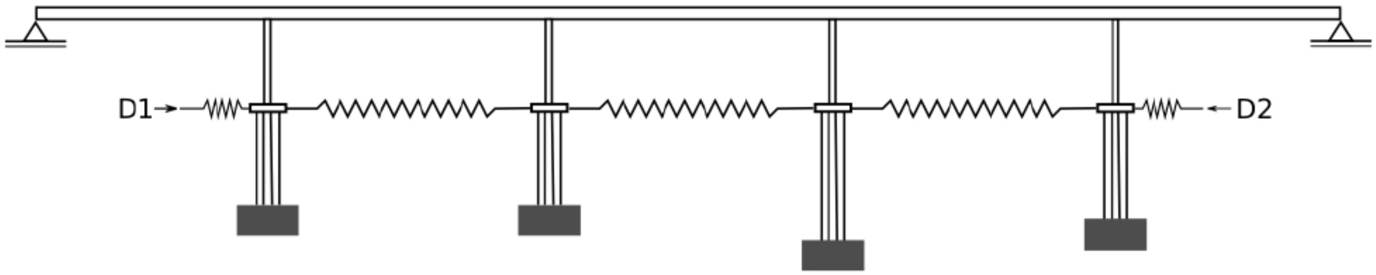
Performance-Based Earthquake Engineering Design Evaluation Procedure for Bridge Foundations Undergoing Liquefaction-Induced Lateral Ground Displacement

Christian A. Ledezma

and

Jonathan D. Bray

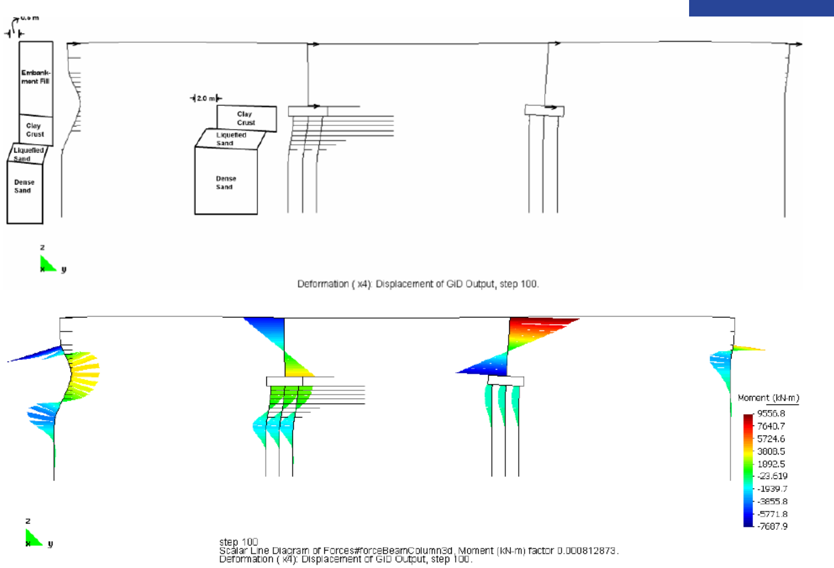
University of California, Berkeley



PEER 2008/05
AUGUST 2008

History of PEER Liquefaction Research

- State-of-the-art reviews
- Experimental studies
- Analytical procedures
  - Simplified
  - Intermediate



PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Demand Fragility Surfaces for Bridges in Liquefied and Laterally Spreading Ground

Scott J. Brandenberg
Department of Civil and Environmental Engineering
University of California, Los Angeles

Jian Zhang
Department of Civil and Environmental Engineering
University of California, Los Angeles

Pirooz Kashighandi
Department of Civil and Environmental Engineering
University of California, Los Angeles

Yili Huo
Department of Civil and Environmental Engineering
University of California, Los Angeles

Minxing Zhao
Department of Civil and Environmental Engineering
University of California, Los Angeles

PEER 2011/01
MARCH 2011

History of PEER Liquefaction Research

- State-of-the-art reviews
- Experimental studies
- Analytical procedures
  - Simplified
  - Intermediate
  - Complex

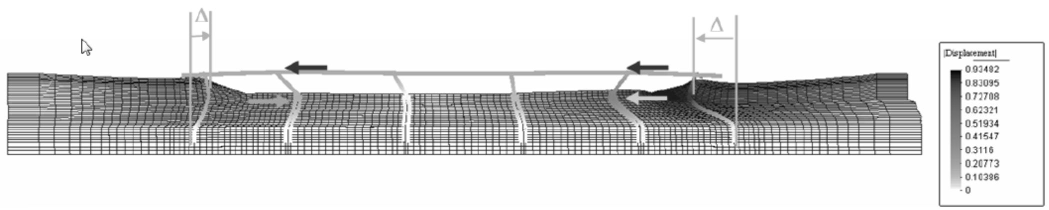
PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

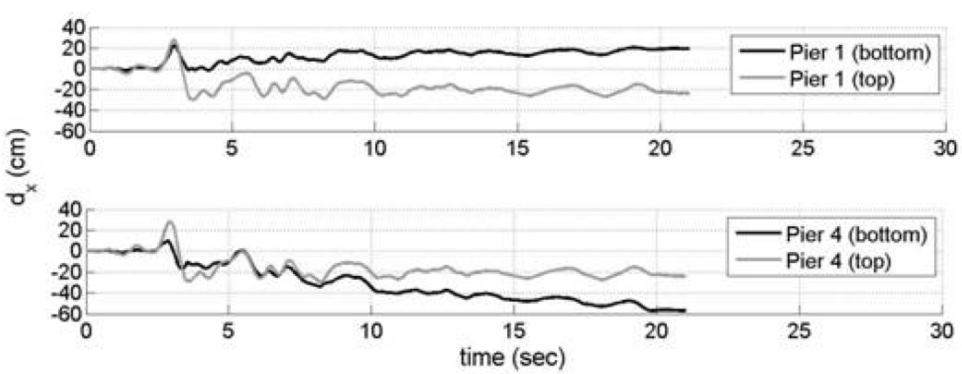
Using OpenSees for Performance-Based Evaluation of Bridges on Liquefiable Soils

Steven L. Kramer
University of Washington

Pedro Arduino
University of Washington

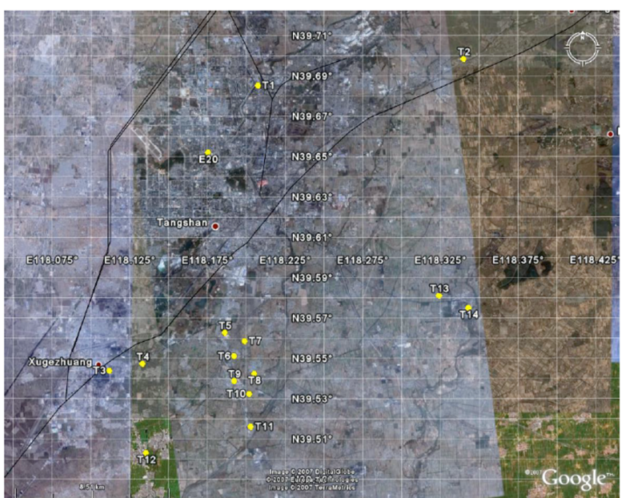
HyungSuk Shin
Kleinfelder, Inc.
Seattle, Washington





History of PEER Liquefaction Research

- State-of-the-art reviews
- Experimental studies
- Analytical procedures
  - Simplified
  - Intermediate
  - Complex
- Field investigations



PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Reinvestigation of Liquefaction and Nonliquefaction Case Histories from the 1976 Tangshan Earthquake

Robb Eric S. Moss
California Polytechnic State University
San Luis Obispo, California

Robert Kayen
U.S. Geological Survey

Liyuan Tong
Songyu Liu
Guojun Cai
Southeast University, Nanjing, People's Republic of China

Jiaer Wu
URS
Oakland, California

PEER 2009/102
AUGUST 2009

History of PEER Liquefaction Research

Kocaeli, Duzce
Turkey

Documenting Incidents of Ground Failure Resulting from the August 17, 1999 Kocaeli, Turkey Earthquake

Collaborative Research by U.C. Berkeley, Brigham Young Univ., and UCLA
with ZETAS, Sakarya Univ., and Middle East Technical Univ.

Sponsored by NSF, Caltrans, CEC, PG&E and the PEER Lifelines Program

Project Objectives: Significant occurrences of ground failure in the form of liquefaction, ground softening, and lateral spreading were documented by NSF-sponsored reconnaissance teams in several areas affected by the 1999 Kocaeli earthquake (M_w = 7.4). The primary goal of this project is to characterize the subsurface conditions at sites where ground deformations and/or building movements were well documented. Site characterization is being completed through the use of the cone penetration testing (some with pore pressure and shear wave velocity measurements) and rotary wash borings with primarily standard penetration testing (with energy measurements with the SPT Analyzer). The project is divided into 4 phases as shown below, with emphasis given to developing the data necessary to analyze the relationship between ground failure and building damage, to assess the threshold for liquefaction triggering for soils with significant fines (both non-plastic and plastic), and to document ground conditions and displacements at several sites of minor and significant lateral spreading. The data being collected through this research is being made available through this website as soon as possible to support the efforts of other investigators interested in these problems.

Project Benefits for California: The goal of California's Seismic Hazards Mapping Act is "to protect public safety from the effects of strong ground shaking, liquefaction, landslides, or other ground failure, and other hazards caused by earthquakes" (CDMG SP-117, 1997). The seismic hazards mapping effort is largely based on empirical methods that require re-evaluation and updating as important case histories emerge. Critical lessons can be learned from studying ground failure during the Turkey earthquake, because the soils and earthquake shaking represent one of the controlling earthquake hazards in California (i.e. poor soils close to large magnitude earthquakes). Ground failure incidents were widespread in Turkey, where hundreds of structures settled, tilted and collapsed due in part to liquefaction and ground softening. There were also observations of ground failure that have not been documented previously, such as horizontal translation of building founded on softened ground. An in-depth examination of these cases is required to ensure the profession is not ignoring an important earthquake hazard. Observations from design level earthquakes are invaluable to advancing the state-of-practice in earthquake engineering, and observations of ground failure in Turkey are transferable to California.

Phase 1	Phase 2	Phase 3	Phase 4
Ground Failure and Building Performance in Adapazari, Turkey	CPT Liquefaction Investigations, Adapazari, Turkey	Geotechnical Site Investigation at Electrical Sub-Stations	Geotechnical Site Investigation at Lateral Spread Sites
Jonathan D. Bray, University of California, Berkeley with A. Önalp of Sa. U., H. T. Durgunoglu of ZETAS, & J. Stewart of UCLA	T. Leslie Youd, Brigham Young University with J. D. Bray of UCB, A. Önalp of Sa. U., H. T. Durgunoglu of ZETAS, & J. Stewart of UCLA	Jonathan D. Bray, University of California, Berkeley with H. T. Durgunoglu of ZETAS, A. Önalp of Sa. U., & R. Seed of UCB	T. Leslie Youd, Brigham Young University, & K. Ö. Çetin of METU with J. D. Bray and R. Seed of UCB, H. T. Durgunoglu of ZETAS & A. Önalp of Sa. U.
Project Description	Project Description	Project Description	Project Description
Data & Site Location	Data & Site Location	Data & Site Location	Data & Site Location

Additional Information: This is an ongoing research project, so this website will be updated periodically as more information becomes available. Please contact

History of PEER Liquefaction Research

Kocaeli, Duzce
Turkey

Ground Failure and Building Performance in Adapazari...

Location: Tül and Yakin Streets, Cumhuriyet District, Adapazari.
GPS Coordinates: 40.77922°N 30.39487°E

TEST	TYPE	DEPTH (m)	SITE PHOTOS (click on photos for higher resolution images)
CPT-A1 click here for CPT log (.pdf) click here for CPT data file (.csv)	CPTU	8.96	
CPT-A2 click here for CPT log (.pdf) click here for CPT data file (.csv)	CPT	8.77	
CPT-A3 click here for CPT log (.pdf) click here for CPT data file (.csv) click here for shear wave velocity profile (.pdf)	SCPTU	8.99	Overview of building A1 during the Kocaeli event reconnaissance. Note settlement of 1.5 m at Northwestern corner. (Photo by Bora Baturay)
CPT-A4 click here for CPT log (.pdf) click here for CPT data file (.csv)	CPT	8.29	
CPT-A5 click here for CPT log (.pdf) click here for CPT data file (.csv)	CPTU	8.51	View of the Northeastern corner of a new construction

Internet 100%

History of PEER Liquefaction Research

Chi-Chi
Taiwan

Yuanlin - Taiwan Ground Failure Database

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- Bracing Berkeley Report
- Tools for Researchers
- Annual Report
- Lifelines Projects Prior to 2006
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- PEER Review newsletter

Other reports
- Taiwan Ground Failure Database
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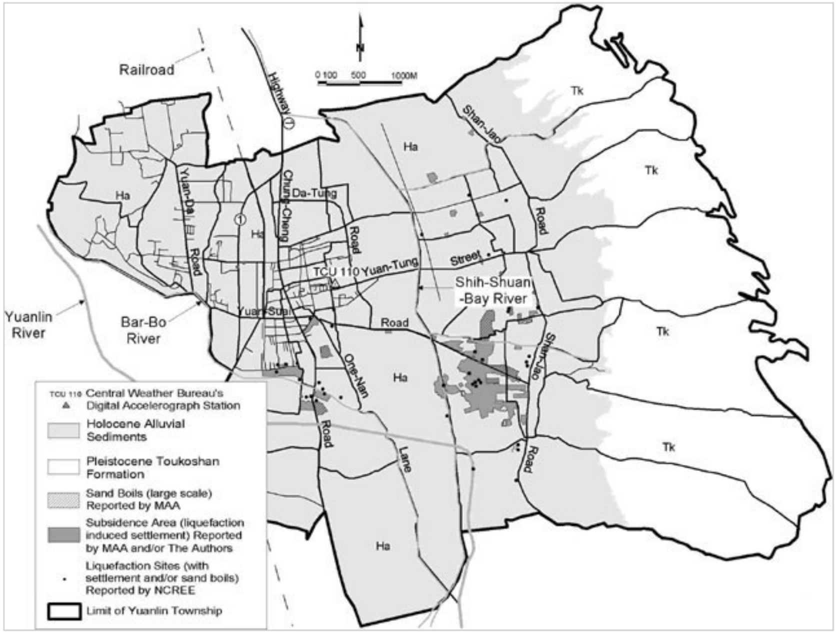
Yuanlin



Click on map to enlarge it

Summary of In-Situ Tests Performed at Sites

Site Name	Latitude (North)	Longitude (East)	CPT (Cone Penetration Test)	Boring & SPT (Standard Penetration Test)
NCREE/MAA Sites	24.05650°	120.69682°	Yes	Yes
PEER/USGS-SASW Site	23° 56.611'	120° 35.837'		

Done | Internet | 100%

History of PEER Liquefaction Research

Chi-Chi
Taiwan

History of PEER Liquefaction Research

State-of-the-art reviews

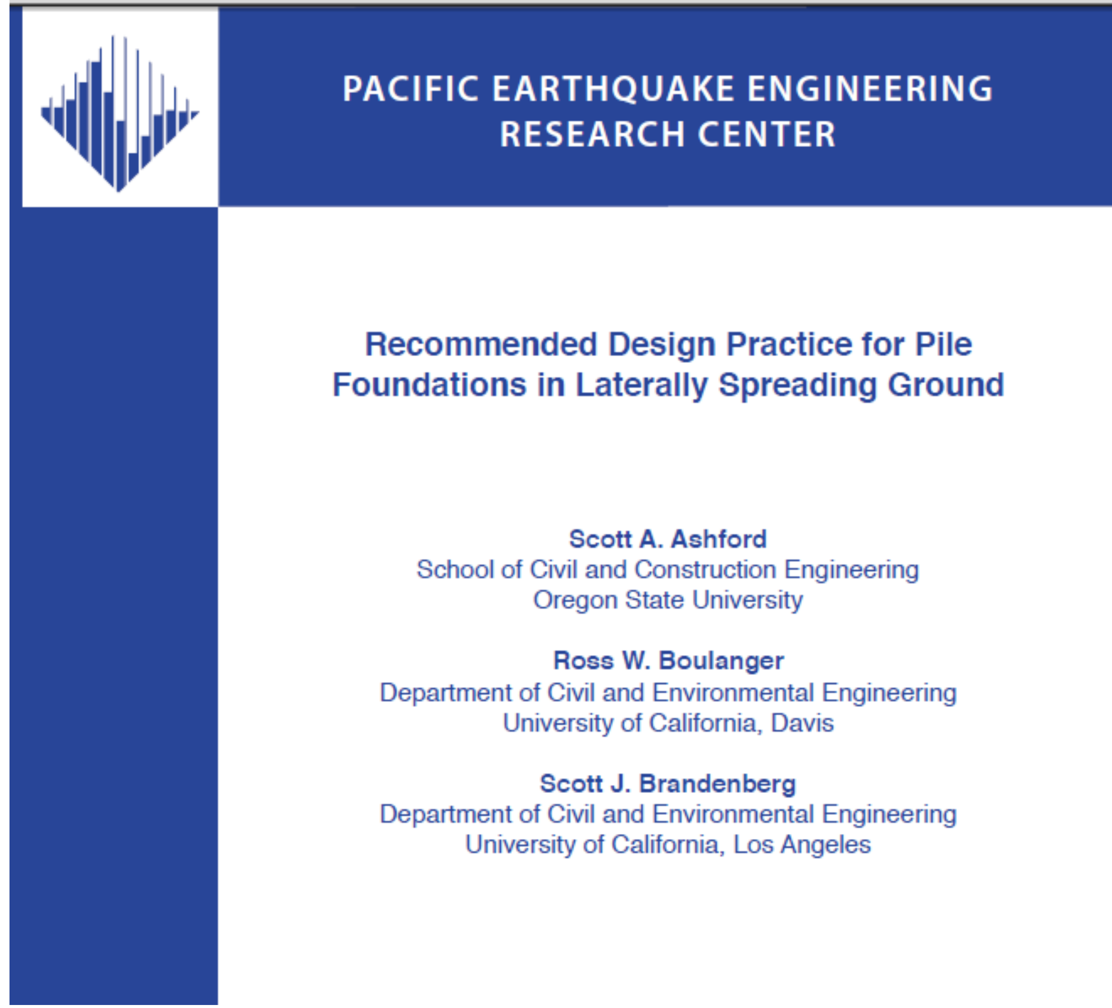
Experimental studies

Analytical procedures

- Simplified
- Intermediate
- Complex

Field investigations

Design guidelines



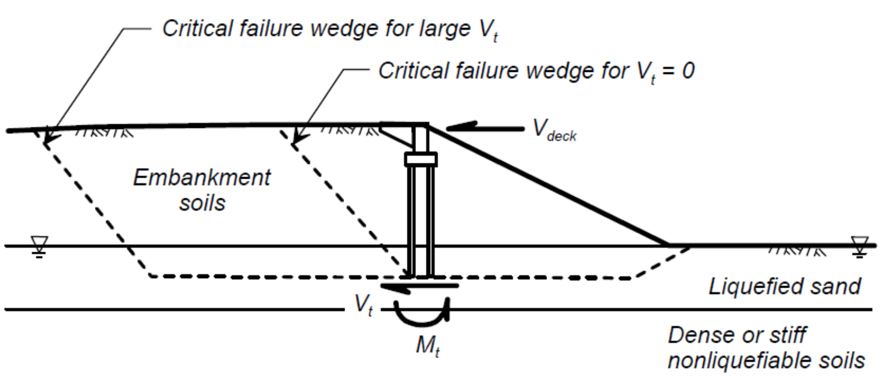
PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Recommended Design Practice for Pile Foundations in Laterally Spreading Ground

Scott A. Ashford
School of Civil and Construction Engineering
Oregon State University

Ross W. Boulanger
Department of Civil and Environmental Engineering
University of California, Davis

Scott J. Brandenberg
Department of Civil and Environmental Engineering
University of California, Los Angeles



History of PEER Liquefaction Research

Lifelines Program

Cetin et al. (2000) SPT - Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Initiation Hazard

Bardet et al. (2002) Liquefaction Ground Deformation Database

Moss et al. (2004) Retesting of Liquefaction and Non-Liquefaction Case Histories in the Imperial Valley using CPT

Ashford and Juirnarongrit (2004) Performance of Lifelines Subjected to Lateral Spreading: Japan Blast Test Results

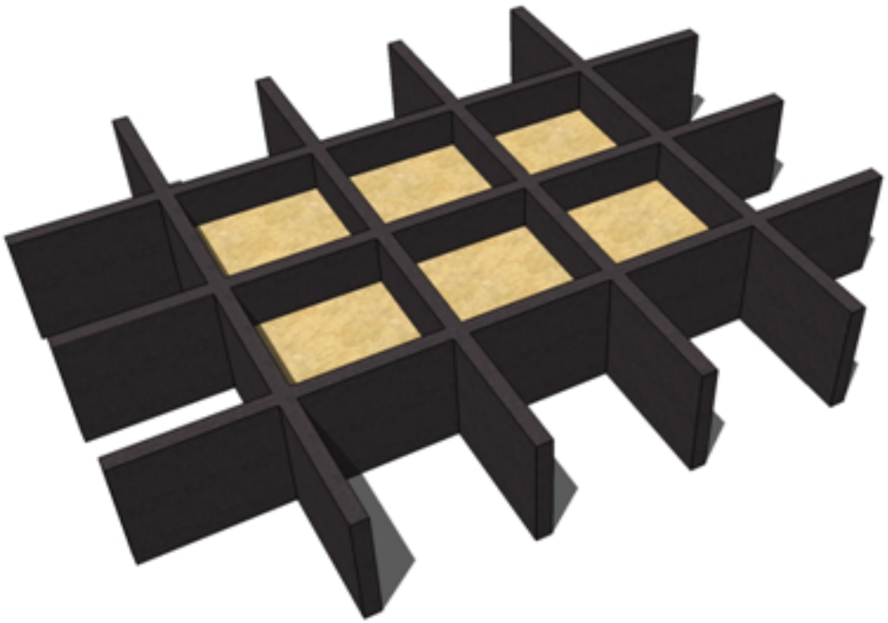
Current Liquefaction Research

Ross Boulanger Ahmed Elgamal	Mitigation of liquefaction hazards using shear reinforcement
Jon Bray Tara Hutchinson	Liquefaction-induced SFSI Damage in Maule, Chile earthquake
Steve Kramer	Geotechnical effects of long-duration motions

Mitigation of liquefaction hazards using shear reinforcement

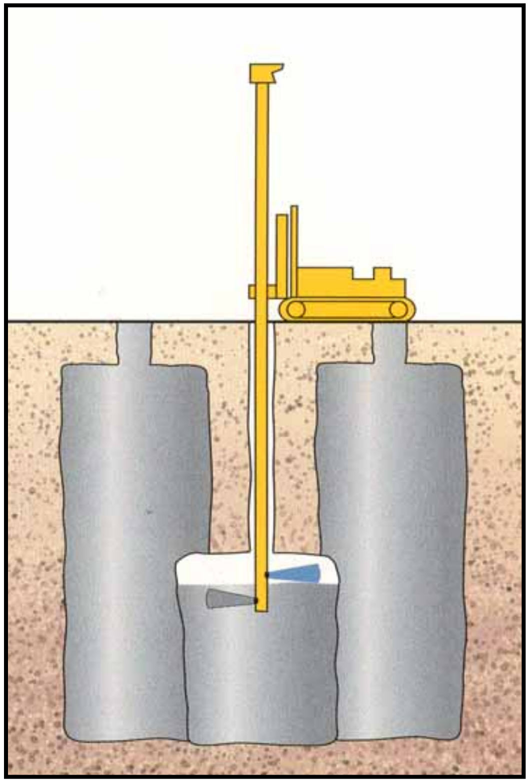
Investigate effectiveness of stiff inclusions on limiting strain and pore pressure in soil

Develop design procedures



Mitigation of liquefaction hazards using shear reinforcement

Investigate effectiveness of stiff inclusions on limiting strain and pore pressure in soil



Mitigation of liquefaction hazards using shear reinforcement

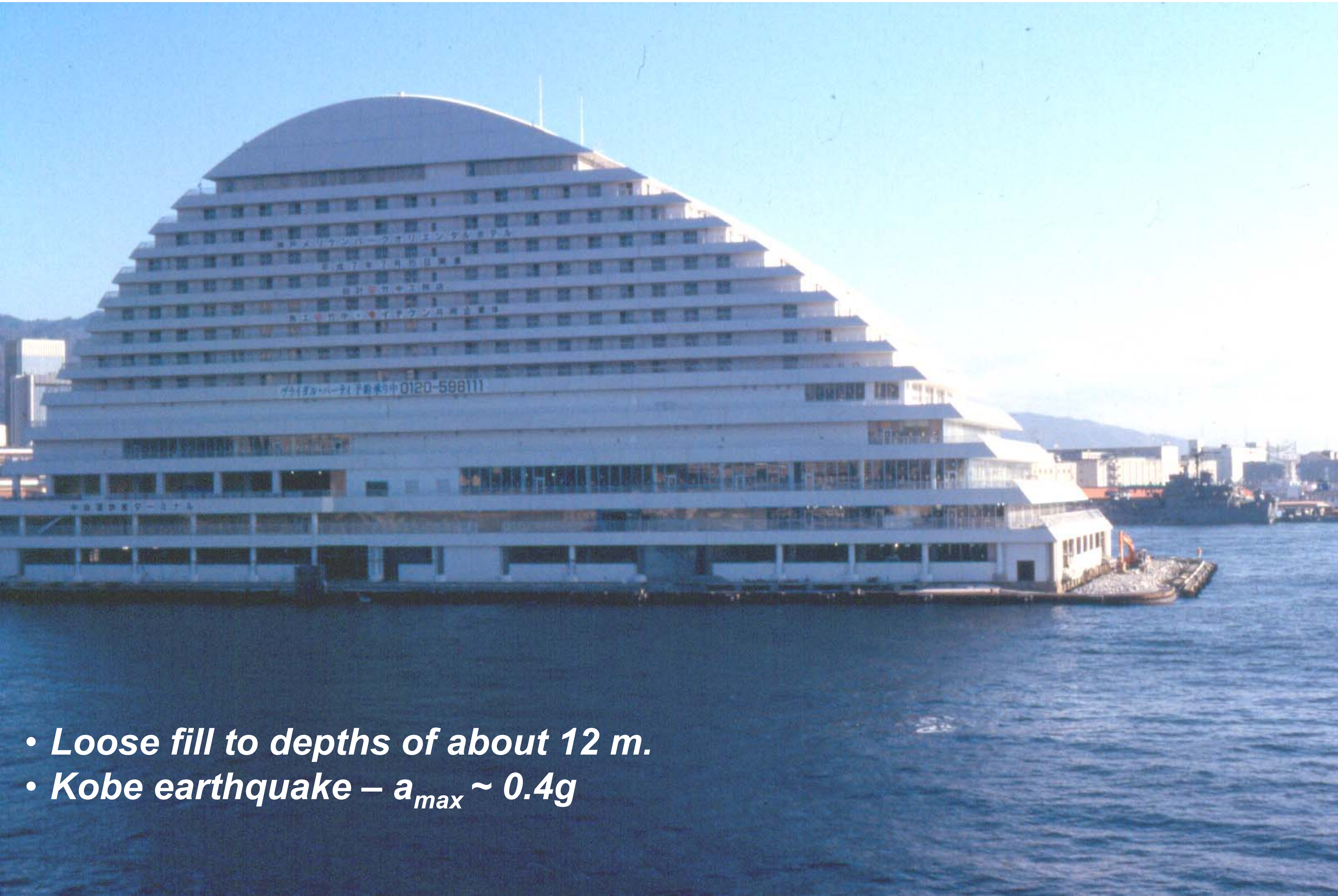
A grid of in-ground walls improves a liquefiable site by:

- Reducing earthquake-induced shear strains in the treatment zone, thereby limiting pore pressure generation.
- Containing the enclosed soil should it liquefy, and thus contributing to the composite strength.
- Acting as a barrier to the migration of excess pore pressures from the adjacent untreated zones into the treatment area.

Can be used in a wide variety of soils, including sensitive clays, silts, and sandy silts.

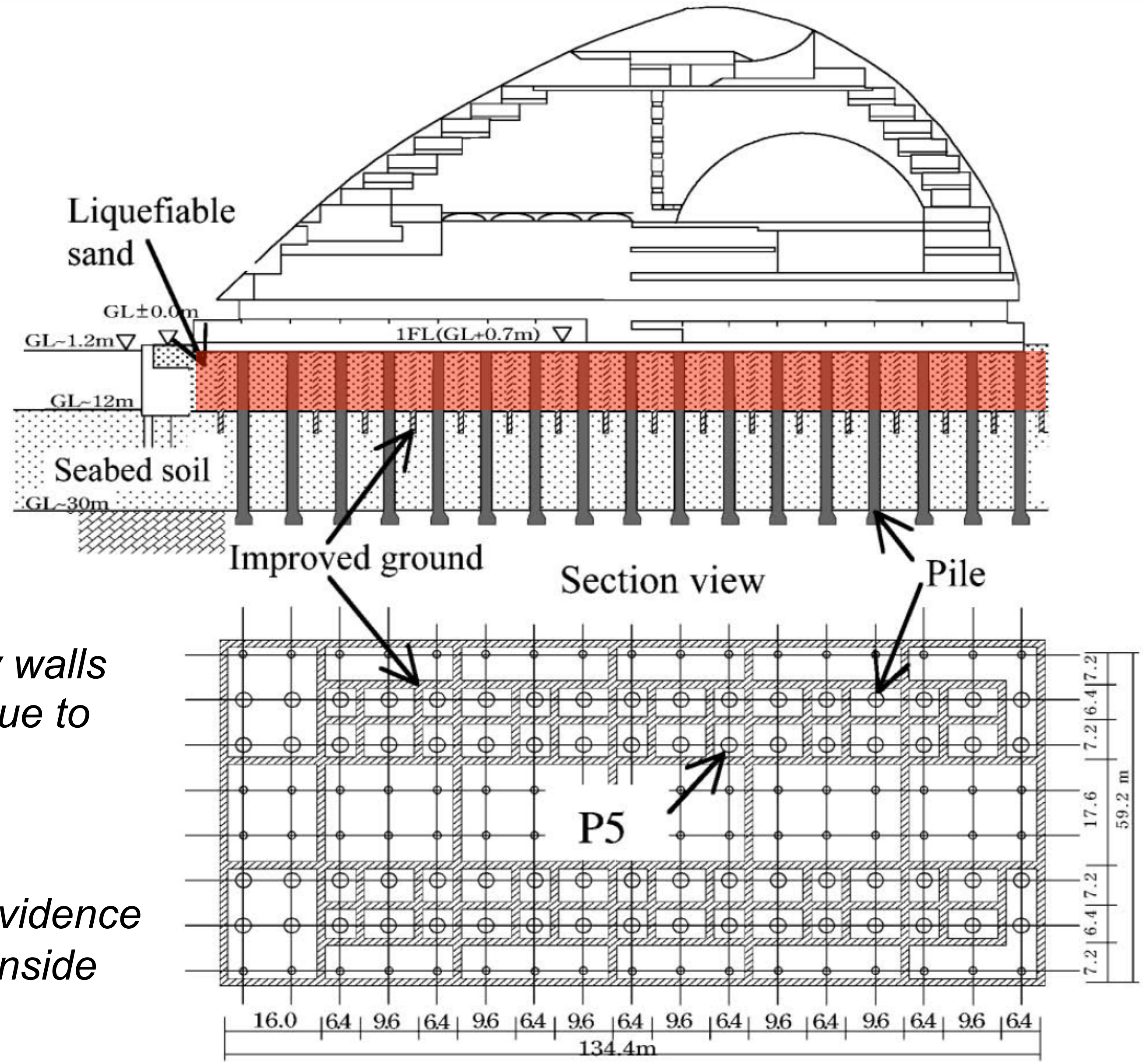
Cracking of soil-cement is a concern.

Mitigation of liquefaction hazards using shear reinforcement



- *Loose fill to depths of about 12 m.*
- *Kobe earthquake – a_{max} ~ 0.4g*

Mitigation of liquefaction hazards using shear reinforcement

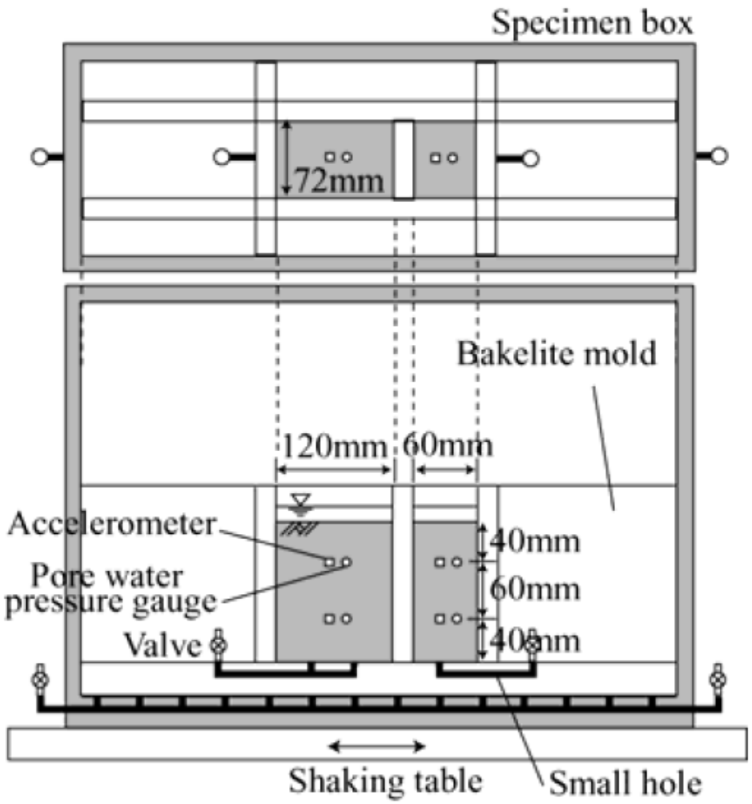


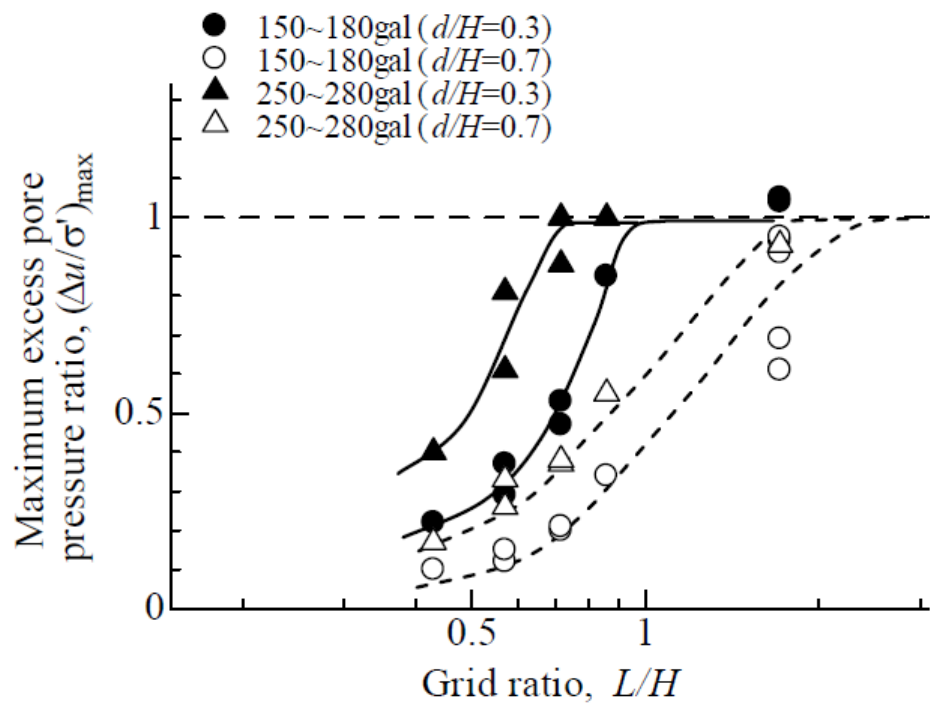
Perimeter quay walls moved 1-2 m due to liquefaction.

No damage to foundation or evidence of liquefaction inside DSM walls.

Mitigation of liquefaction hazards using shear reinforcement

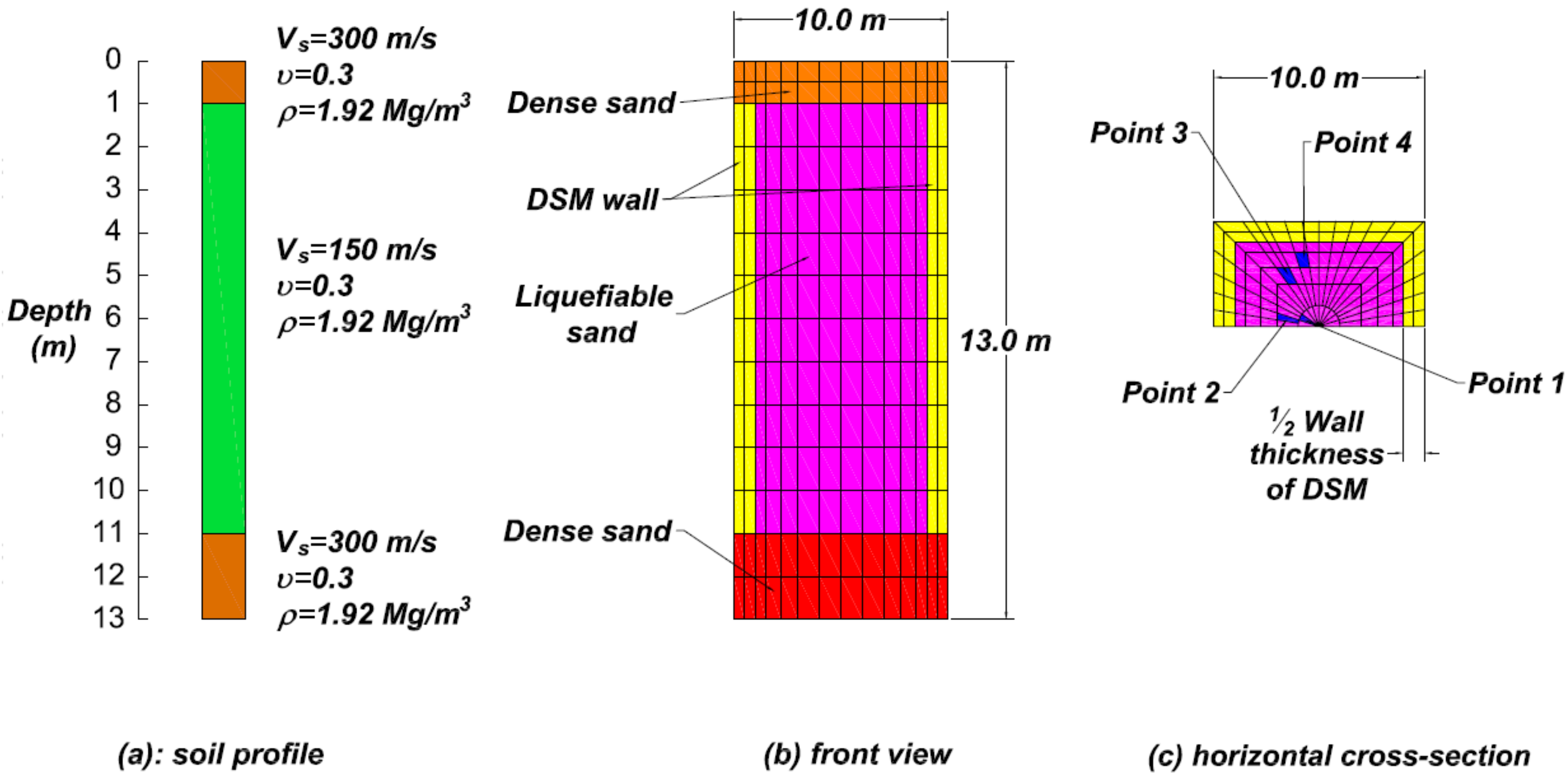
- *Tests by Kitazume and Takahashi (2010) showed beneficial effect of grids: L = grid spacing, H = grid height, d = depth.*





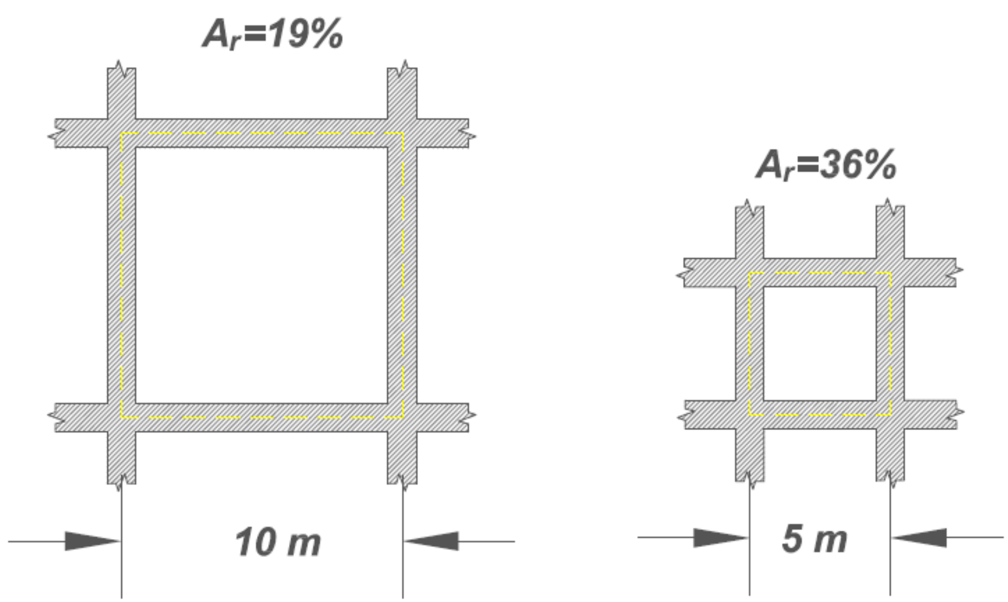
Mitigation of liquefaction hazards using shear reinforcement

- *3D analyses of unit cell (Nguyen et al. 2012) to explore a wider range of parameters to develop a design relationship.*



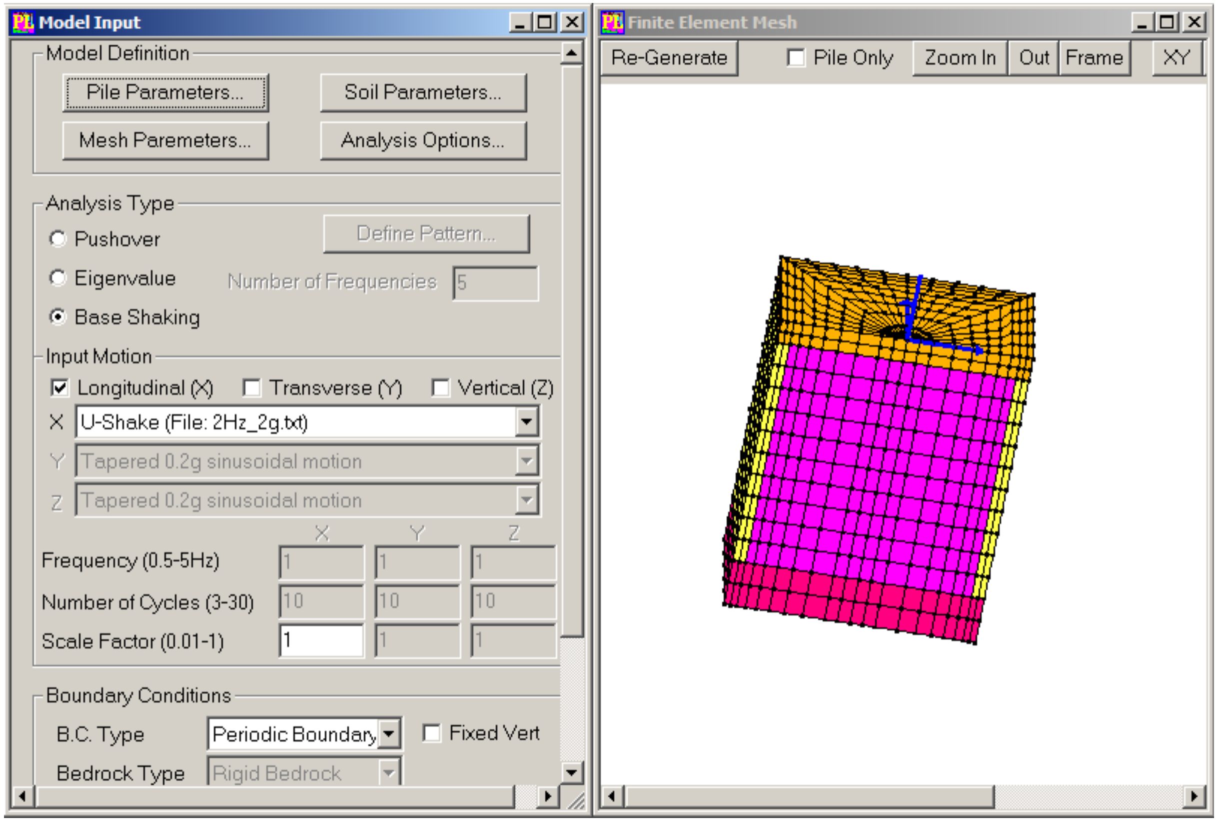
Mitigation of liquefaction hazards using shear reinforcement

- *Parameter variations:*
  - *G of wall material varied to give G_r = 13.5, 20, and 50.*
  - *Wall spacing varied to give A_r = 0.10, 0.19, 0.36 (plus others for special cases shown later).*
  - *Equivalent damping ratios of 2, 5, and 10%.*
  - *Pseudo-static, harmonic, and earthquake excitation.*



Mitigation of liquefaction hazards using shear reinforcement

- *OpenSeesPL platform:*
  - *User interface that builds on PEER's OpenSees platform; e.g., Elgamal, Lu, and Forcellini, D. (2009)*
  - *http://cyclic.ucsd.edu/openseespl*



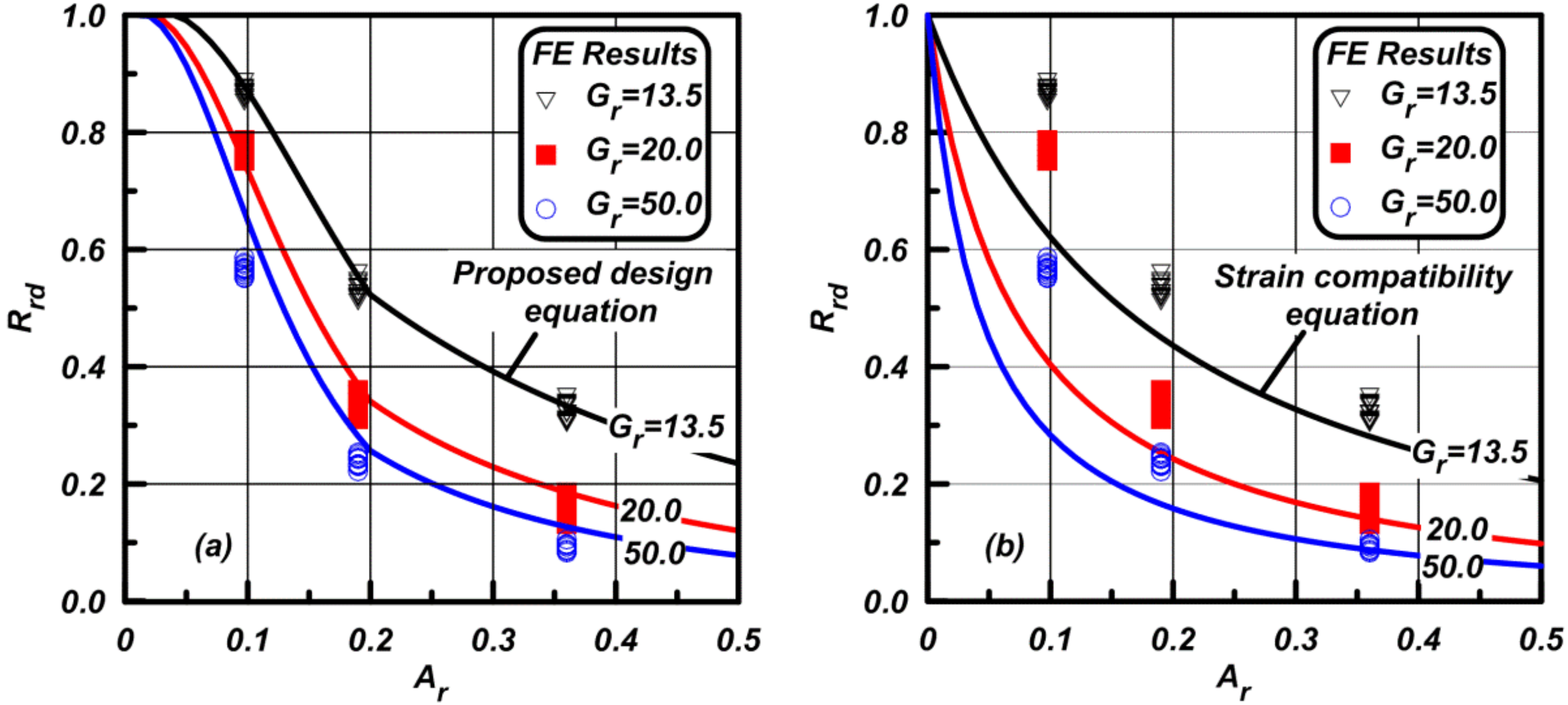
Mitigation of liquefaction hazards using shear reinforcement

Effect on triggering related to difference in CSR for improved case (CSR_I) and unimproved case (CSR_U)

Depends on changes in a_{max} and r_d

$$R_{CSR} = \frac{CSR_I}{CSR_U} = \frac{\tau_{s,I}}{\tau_{s,U}} = \left(\frac{a_{\max,I}}{a_{\max,U}}\right)\left(\frac{r_{d,I}}{r_{d,U}}\right) = R_{a\max}R_{rd}$$

Mitigation of liquefaction hazards using shear reinforcement

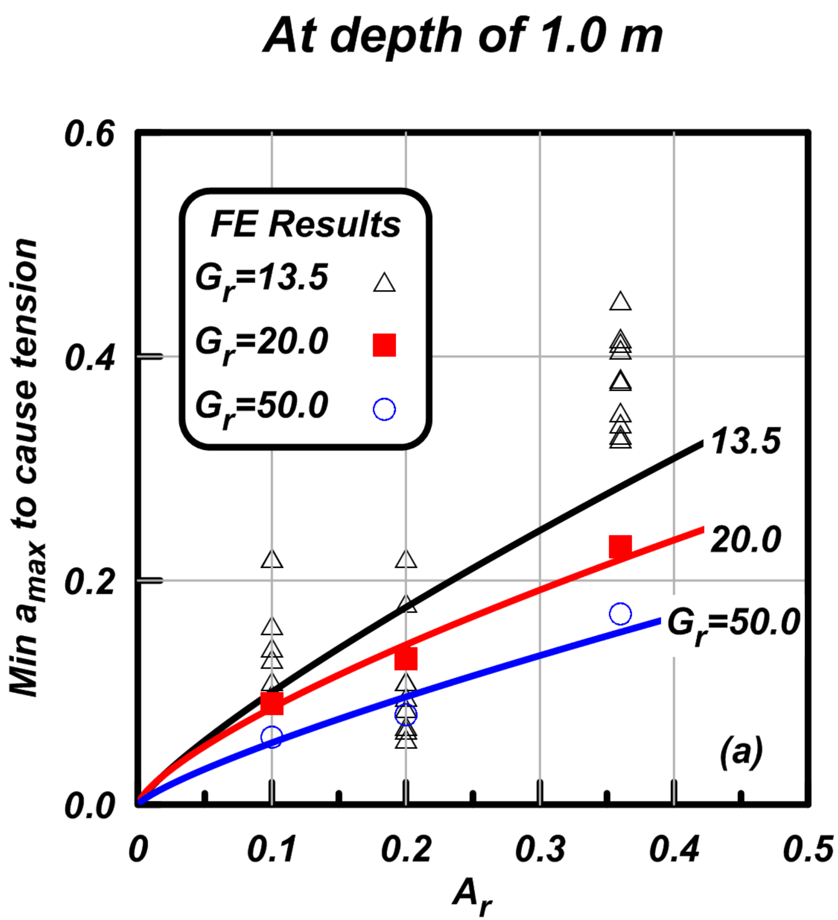


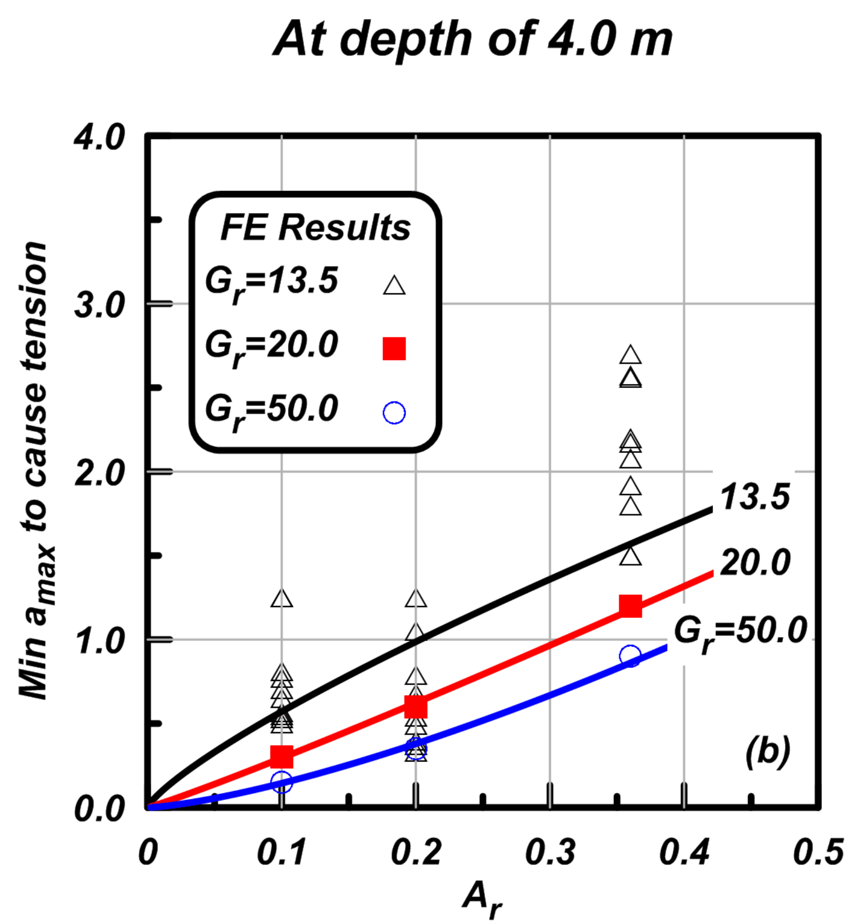
(a) Proposed γ_r *(b) Assume γ_r = 1*

$$R_{rd} = \frac{1}{\gamma_r G_r C_G A_r + (1 - A_r)}$$

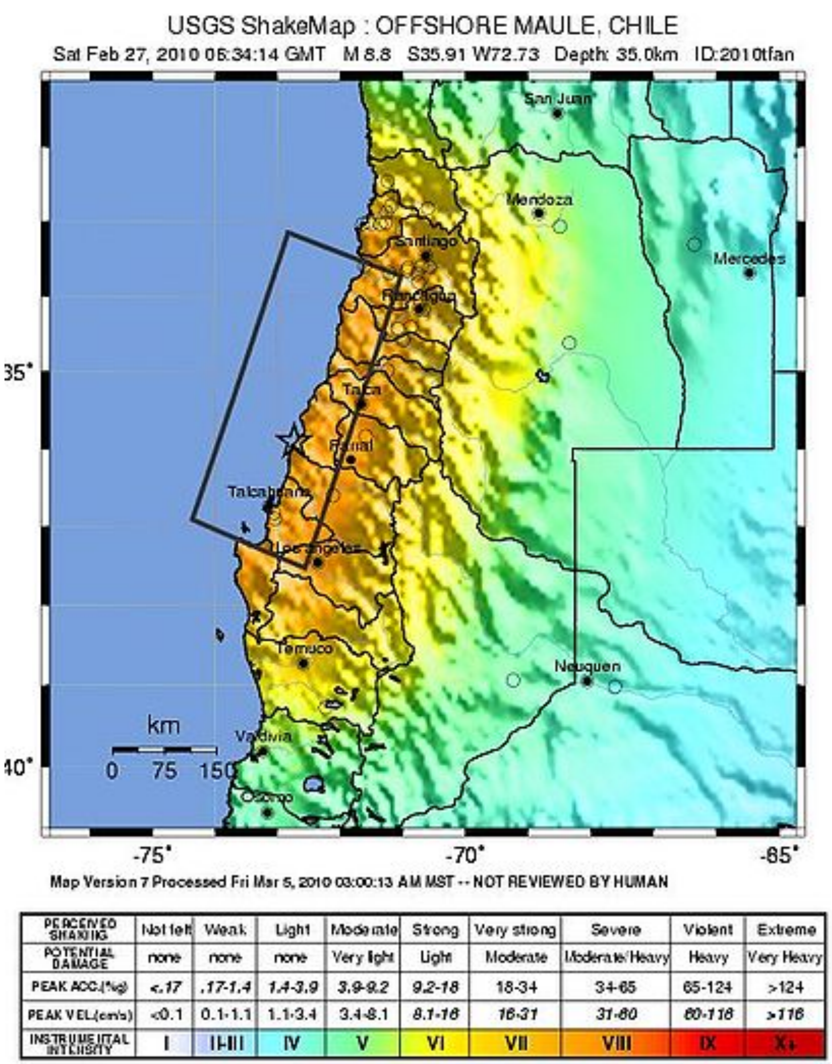
Mitigation of liquefaction hazards using shear reinforcement

Can estimate a_{max} value required to cause tension in panels





Liquefaction-induced SFSI Damage in Maule, Chile earthquake



Liquefaction-induced SFSI Damage in Maule, Chile earthquake

<u>Goals</u>:

Investigate several sites with structures damaged by liquefaction during the 2010 M=8.8 Chile EQ

Subsurface investigation with CPT and SPT

Additional documentation of structural damage

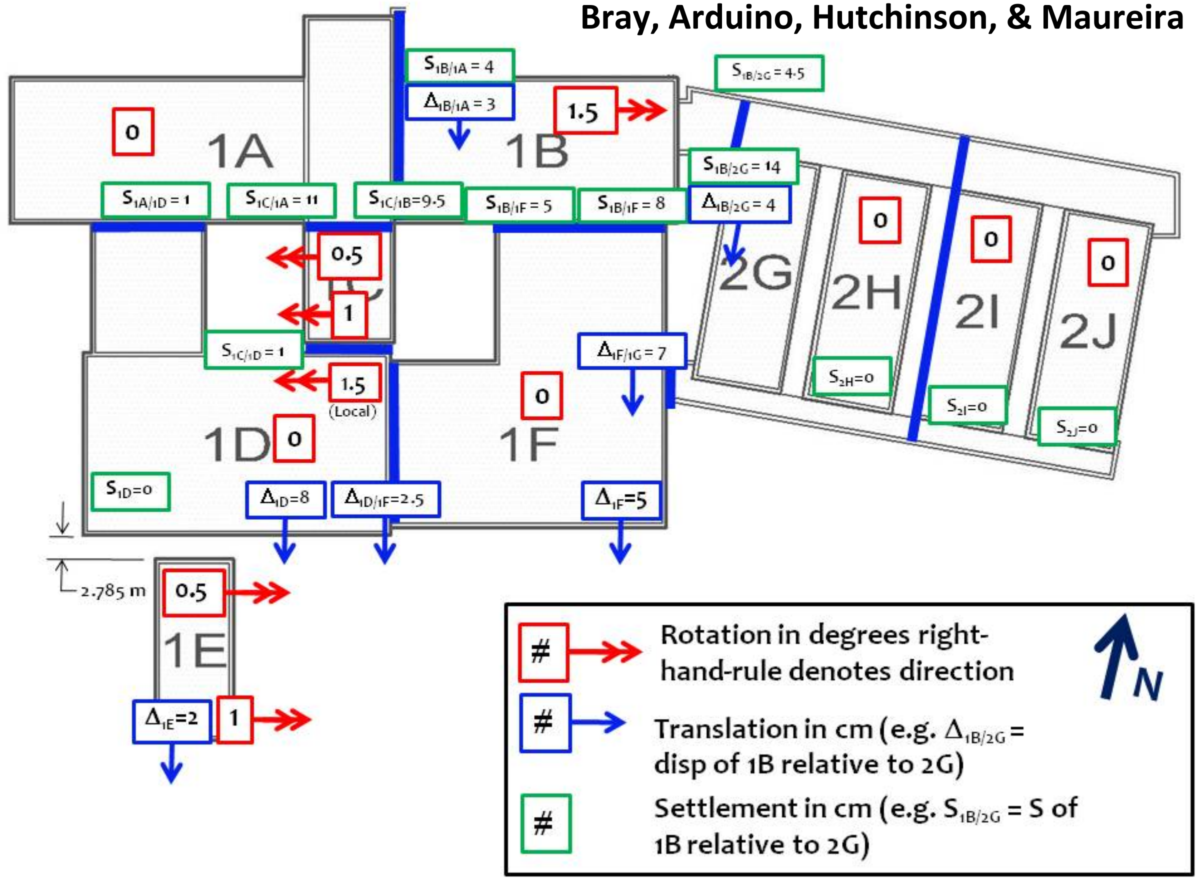
Use these case histories to study the effects of liquefaction on SFSI of bridges and buildings

Hospital Provincial, Curanilahue

10 isolated wings: 1 - 6 stories

Varying liquefaction damage

Bray, Arduino, Hutchinson, & Maureira

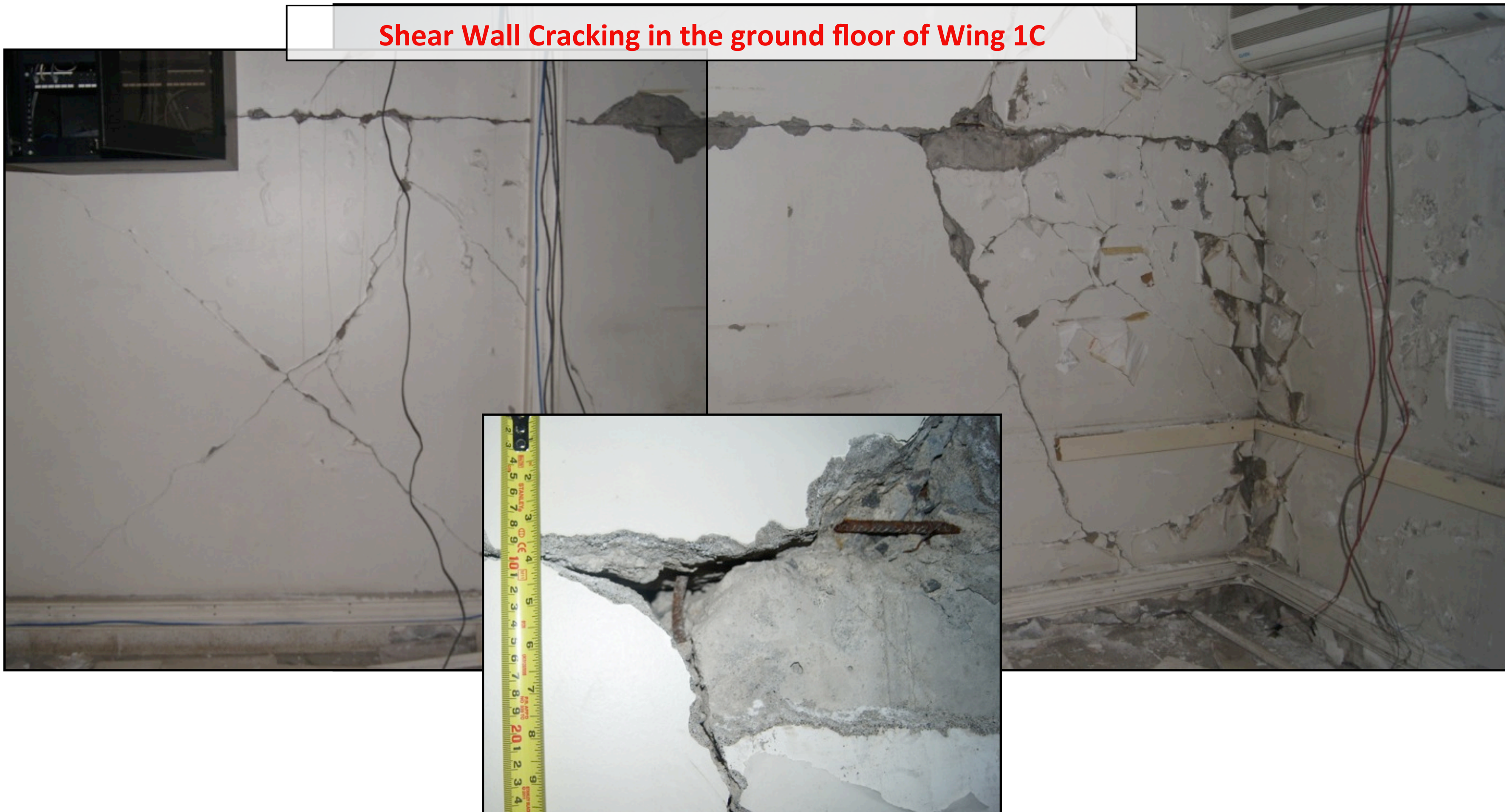


Hospital Provincial, Curanilahue

10 isolated wings: 1 - 6 stories

Varying liquefaction damage

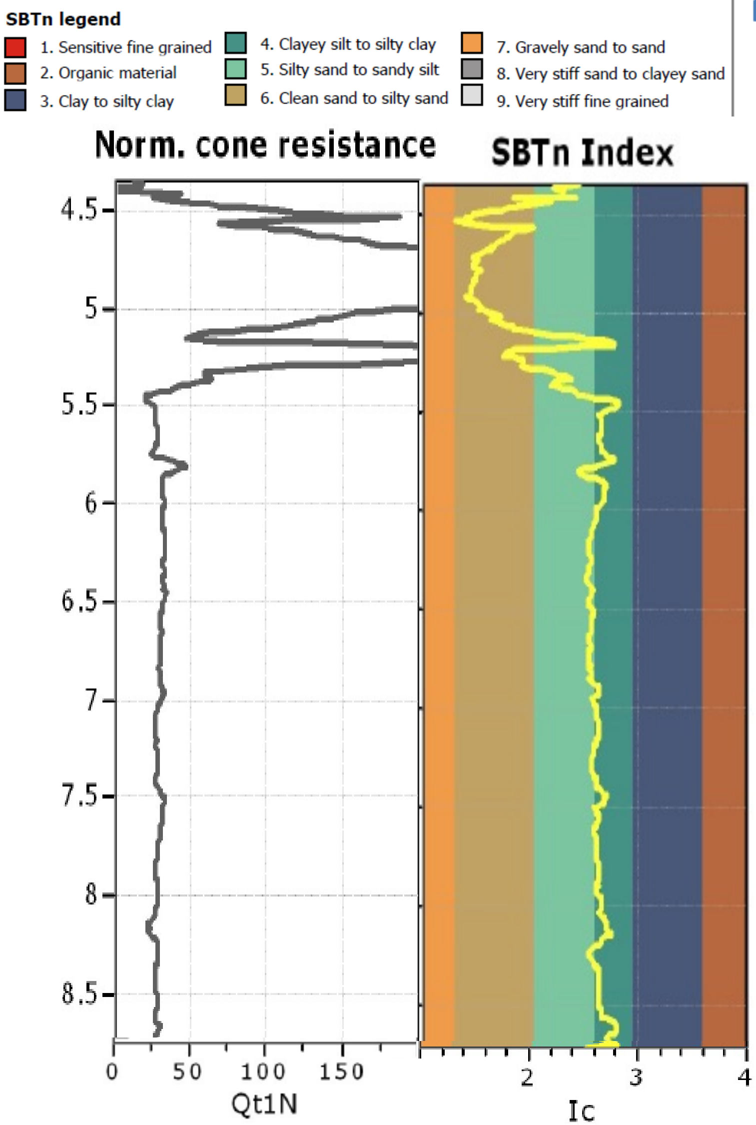
Differential settlement between wings observed at upper floors

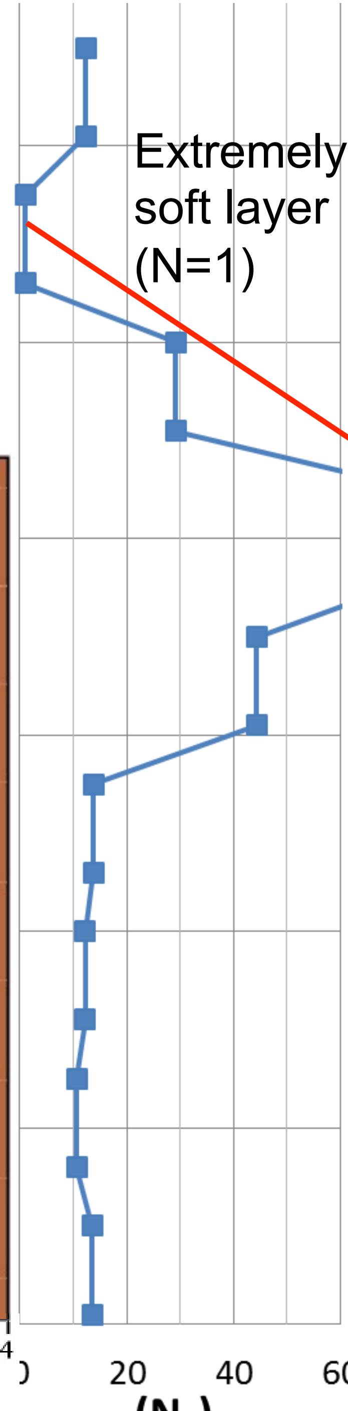


Shear Wall Cracking in the ground floor of Wing 1C

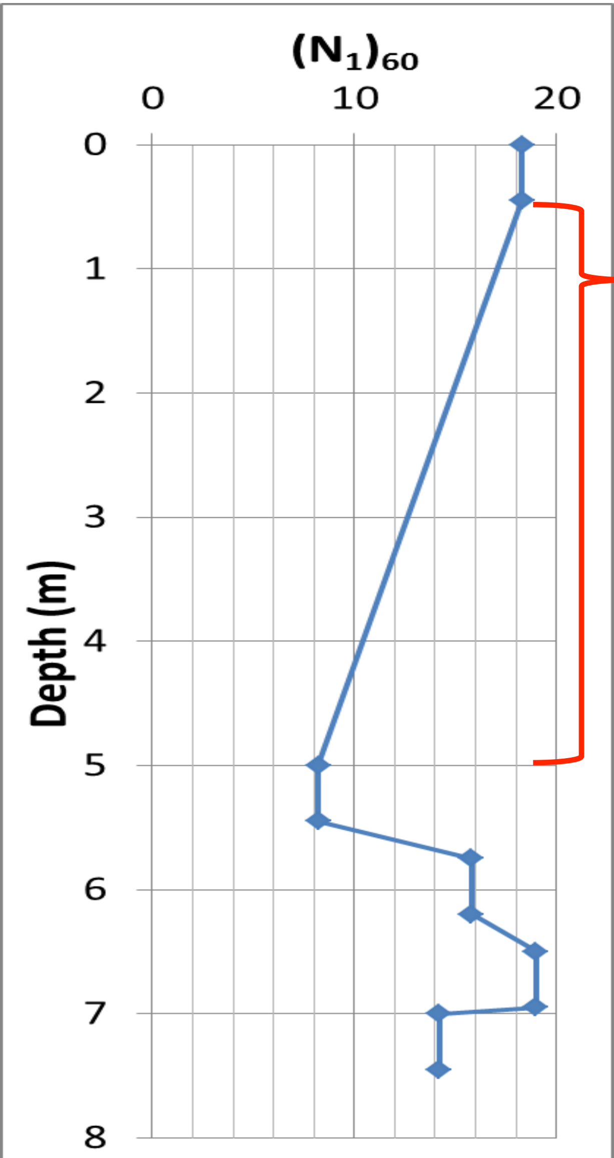
Hospital Provincial, Curanilahue

Predrilled first 4+ meters of CPT to pass fill

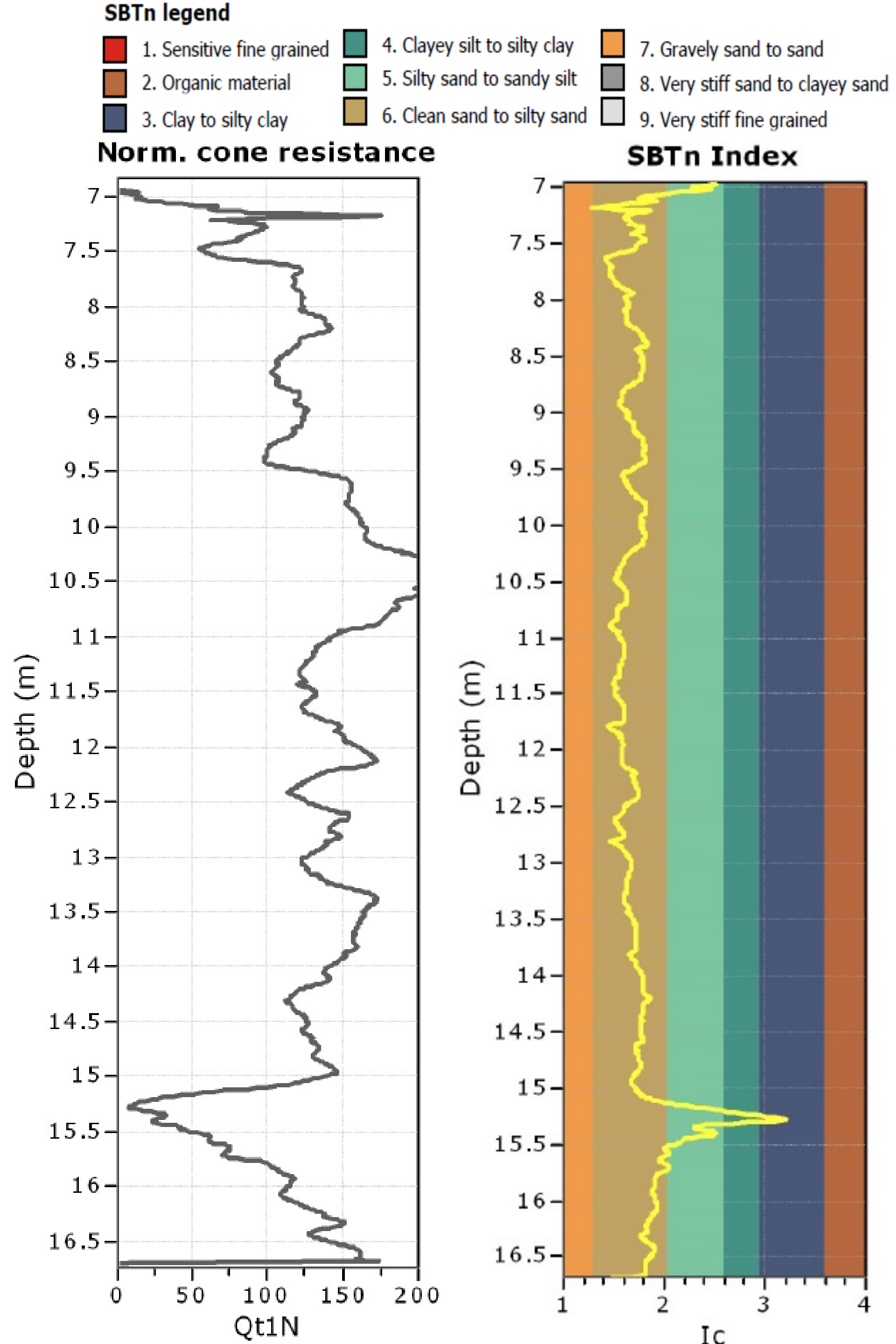




Juan Pablo II Bridge, Concepcion



Needed to drill through fill containing large debris (e.g., concrete shown below).



Liquefaction-induced SFSI Damage in Maule, Chile earthquake

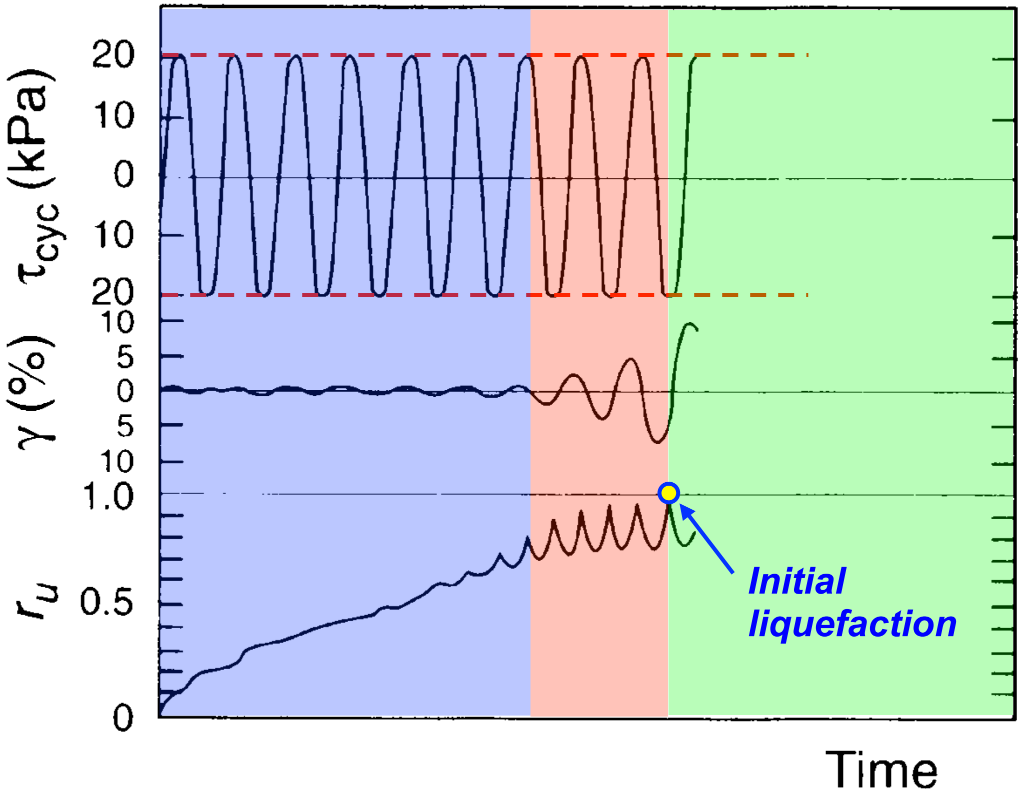
Preliminary findings:

- Provided energy-measured SPT data and CPT data at these sites which was previously lacking
- Bridge piers damaged by liquefaction-induced lateral spreading of medium dense sandy soils
- Spread footings with grade beam foundation at hospital settled differentially as well as underwent rigid-body tilt due to liquefaction of silty soils
- Permanent differential displacements and rotations damaged the hospital superstructure

Geotechnical Effects of Long Duration Motions

Number of equivalent cycles

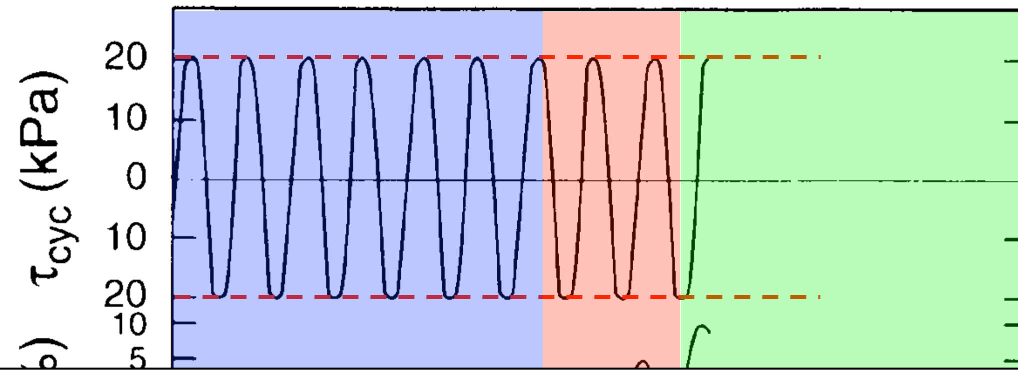
Developed for evaluation of liquefaction potential

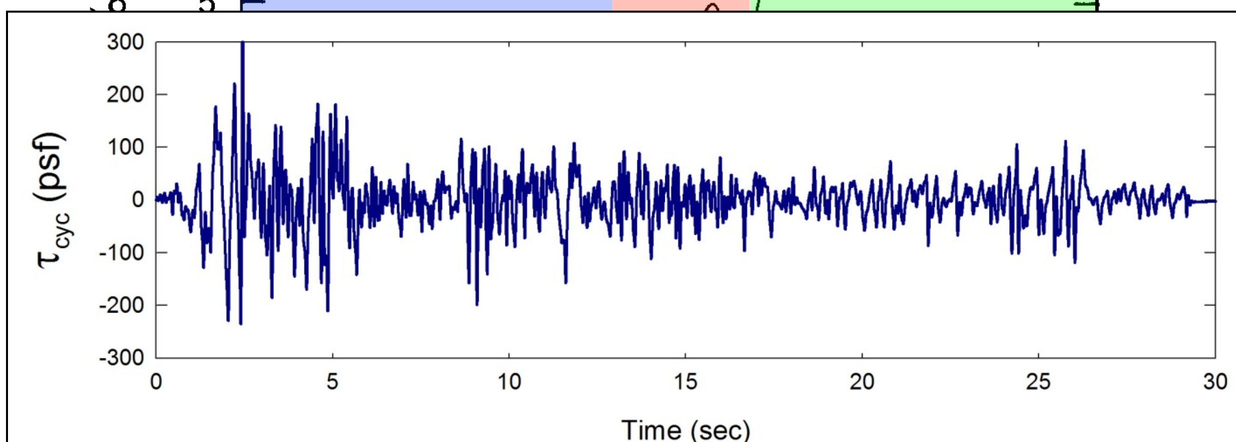


Geotechnical Effects of Long Duration Motions

Number of equivalent cycles

Developed for evaluation of liquefaction potential

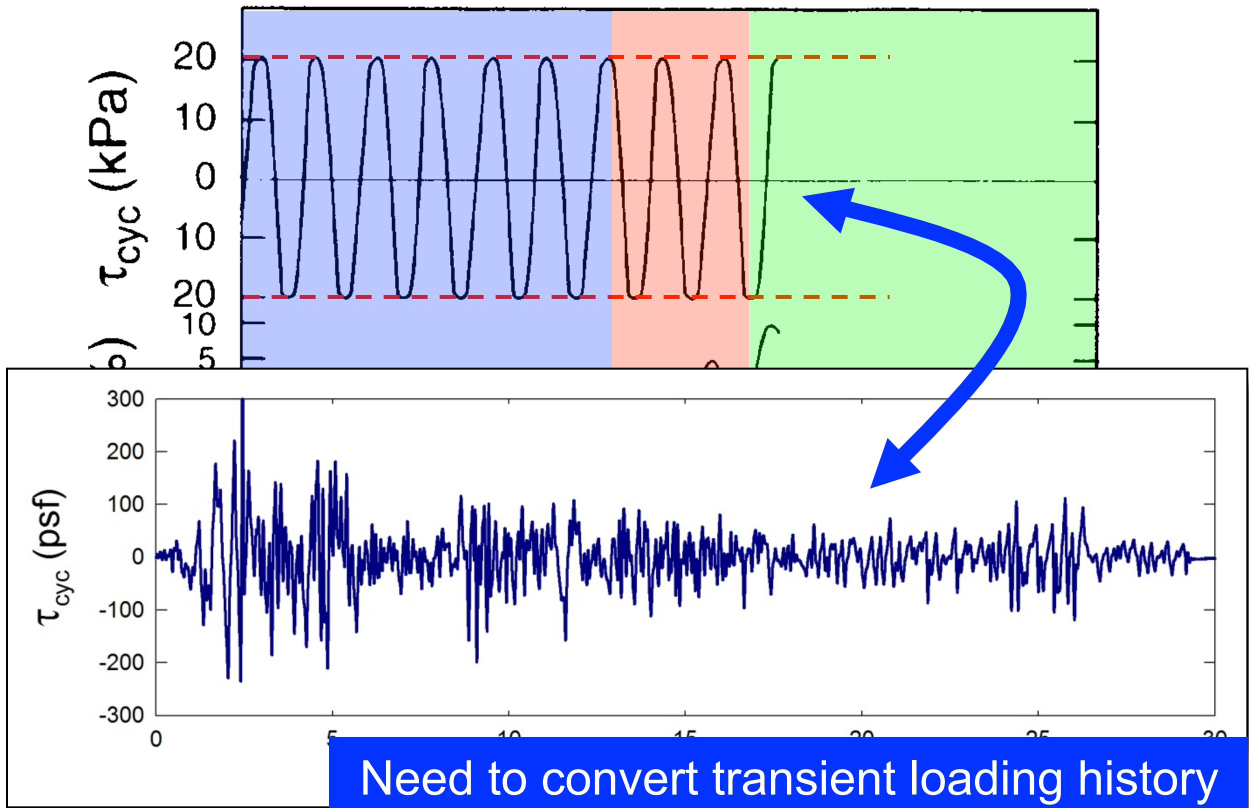




Geotechnical Effects of Long Duration Motions

Number of equivalent cycles

Developed for evaluation of liquefaction potential



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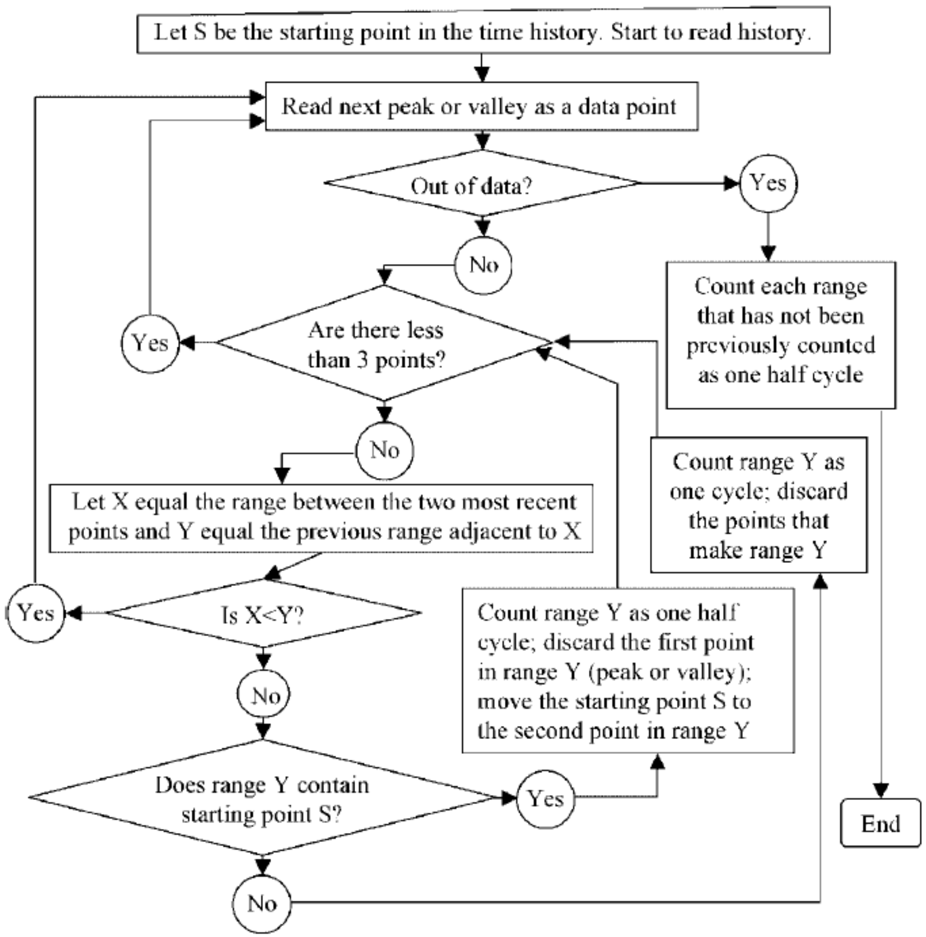
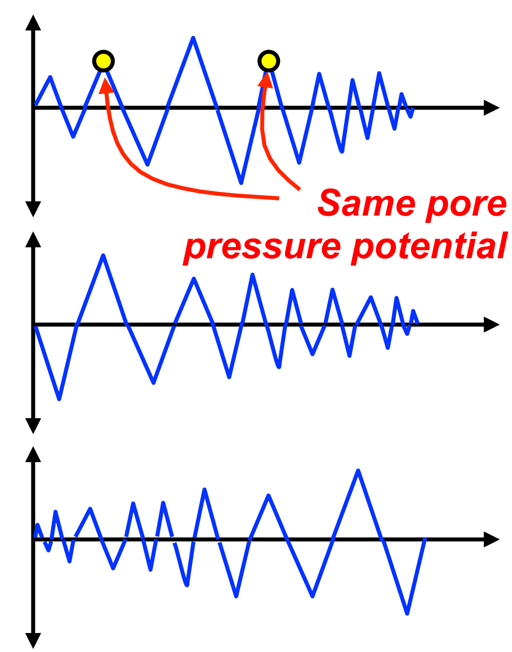
Geotechnical Effects of Long Duration Motions

Number of equivalent cycles

Developed for evaluation of liquefaction potential

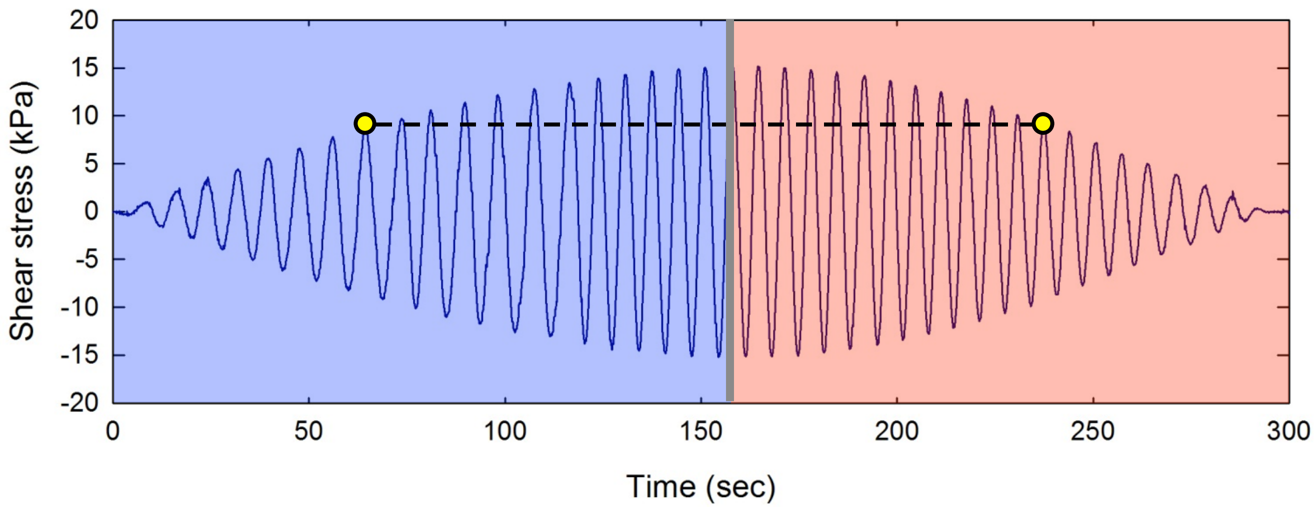


Counting procedures do not consider order of cycles



Geotechnical Effects of Long Duration Motions

How does liquefiable soil actually behave?



Modulated harmonic loading

Amplitudes increase, then decrease

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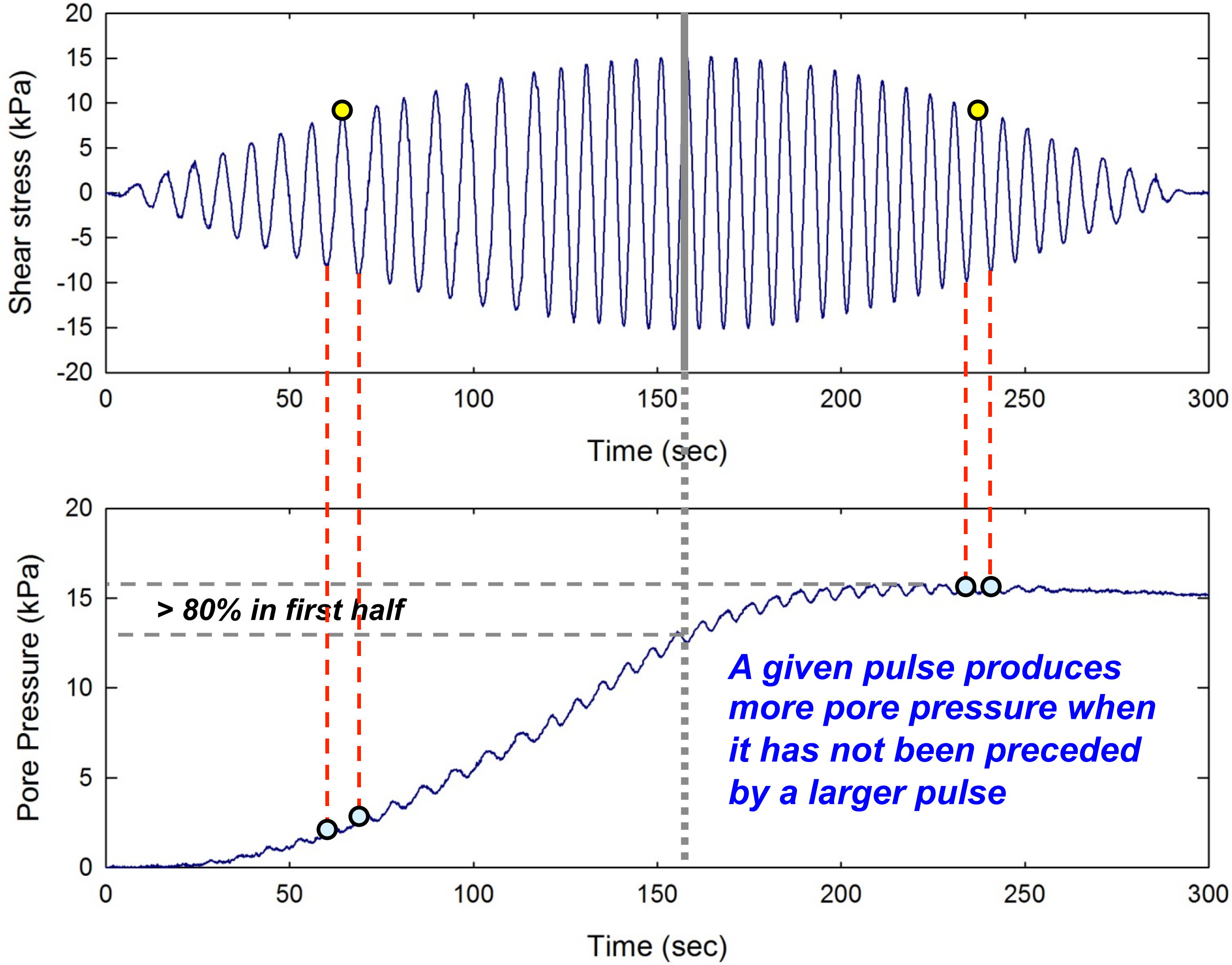

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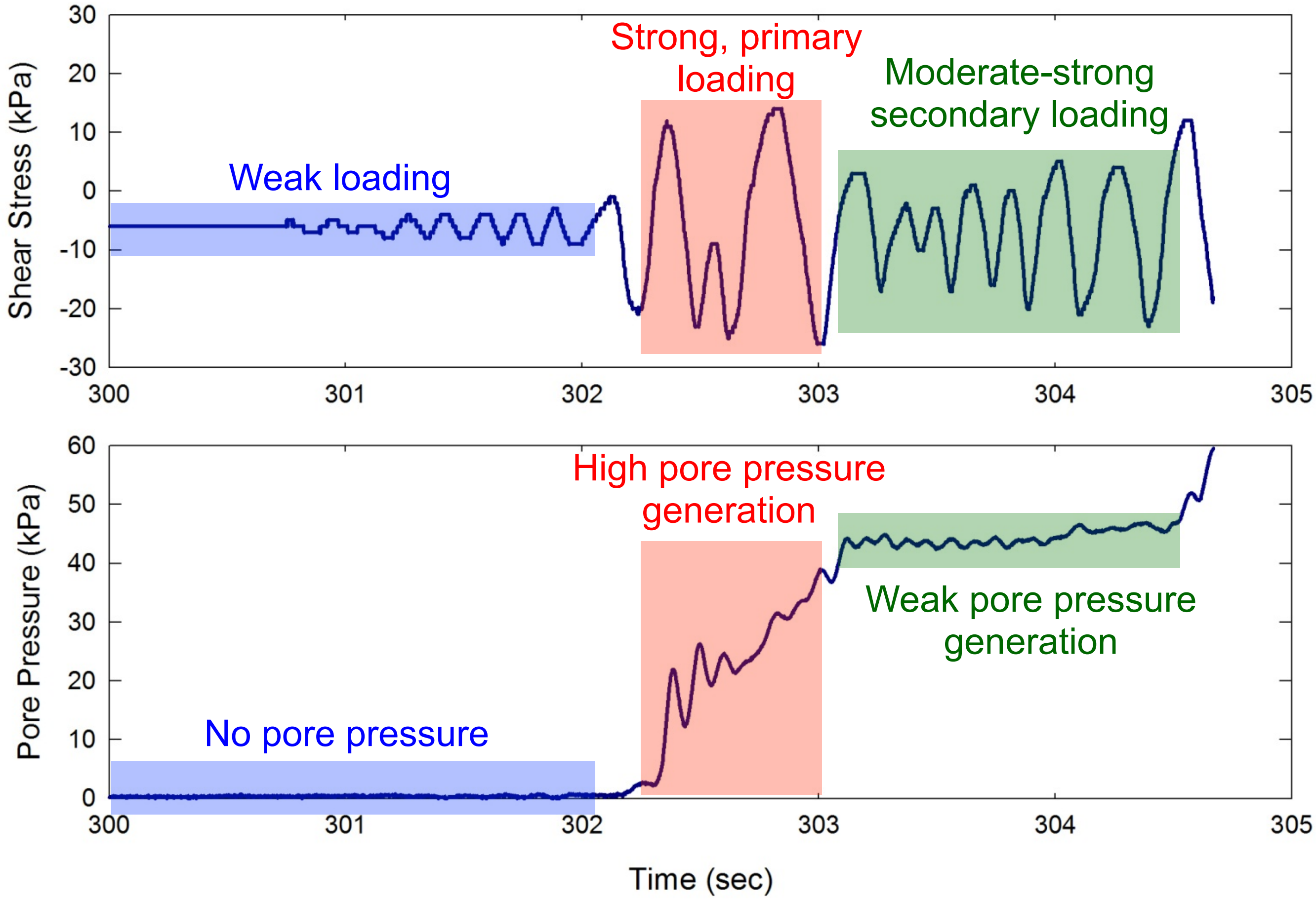
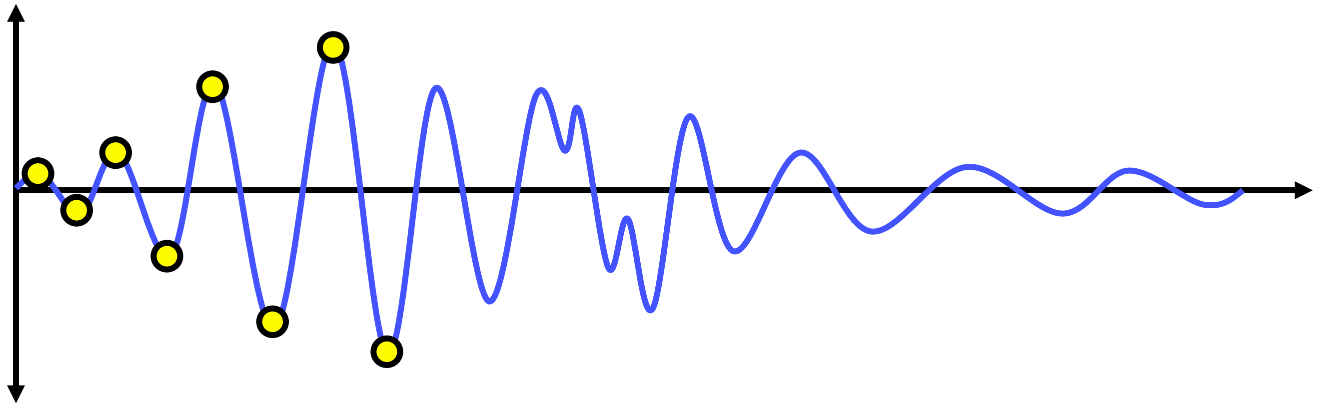


Geotechnical Effects of Long Duration Motions

Modified Cycle-Counting Procedure



Primary cycles – cycles whose amplitude has not been previously exceeded

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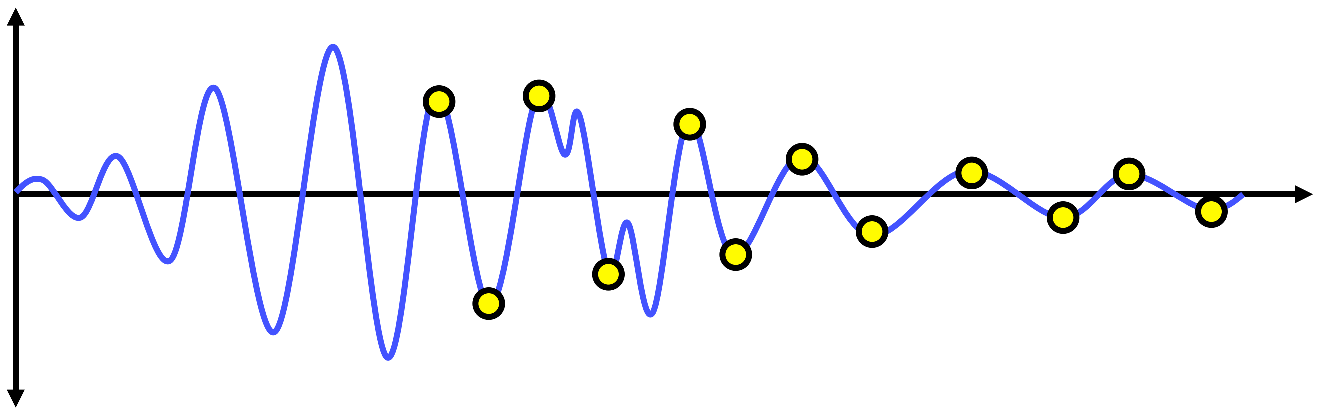
Modified Cycle-Counting Procedure



Primary cycles – cycles whose amplitude has not been previously exceeded

Secondary reversing cycles – cycles whose amplitude has previously been exceeded and that involve reversal of shear stress

Each treated differently

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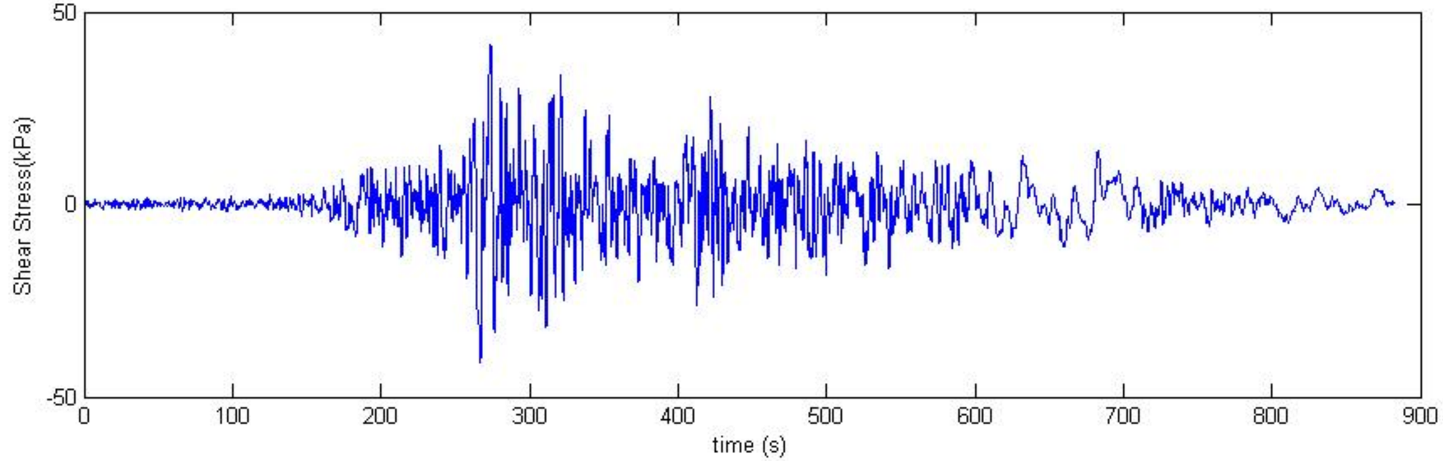

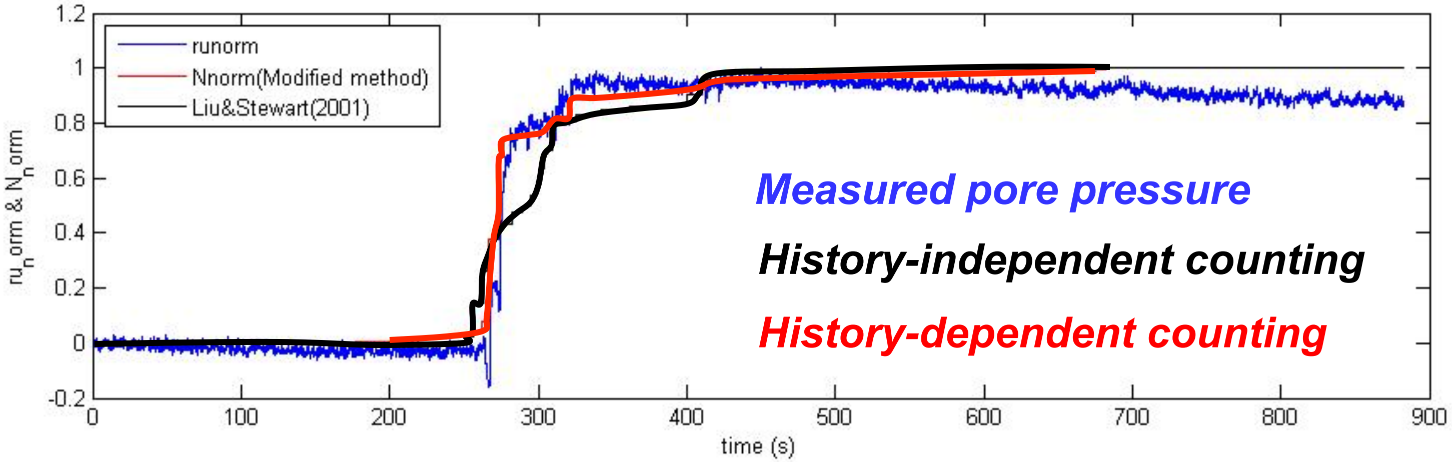

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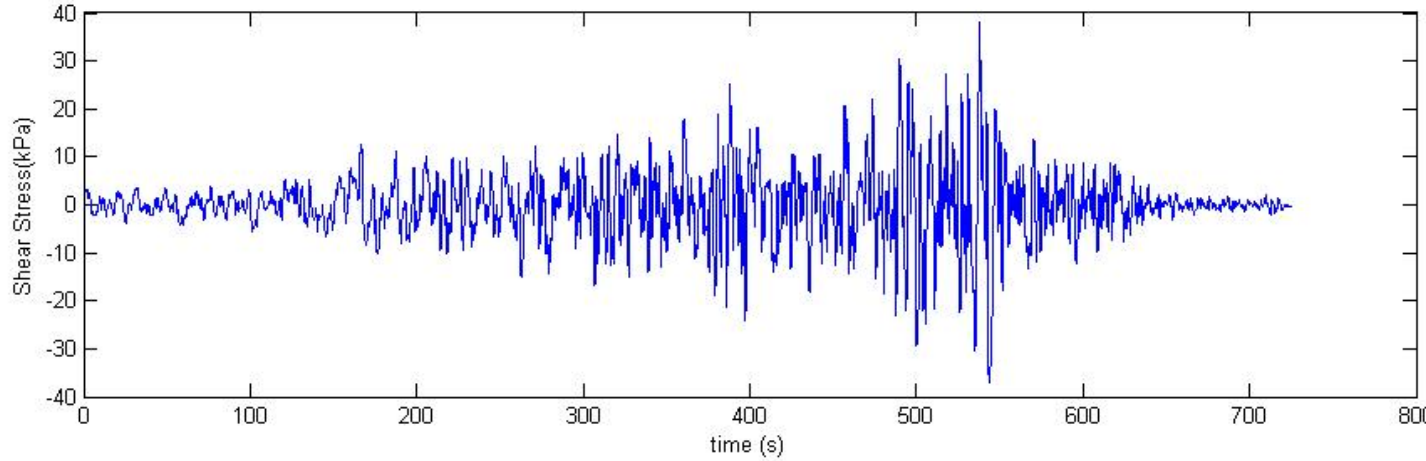

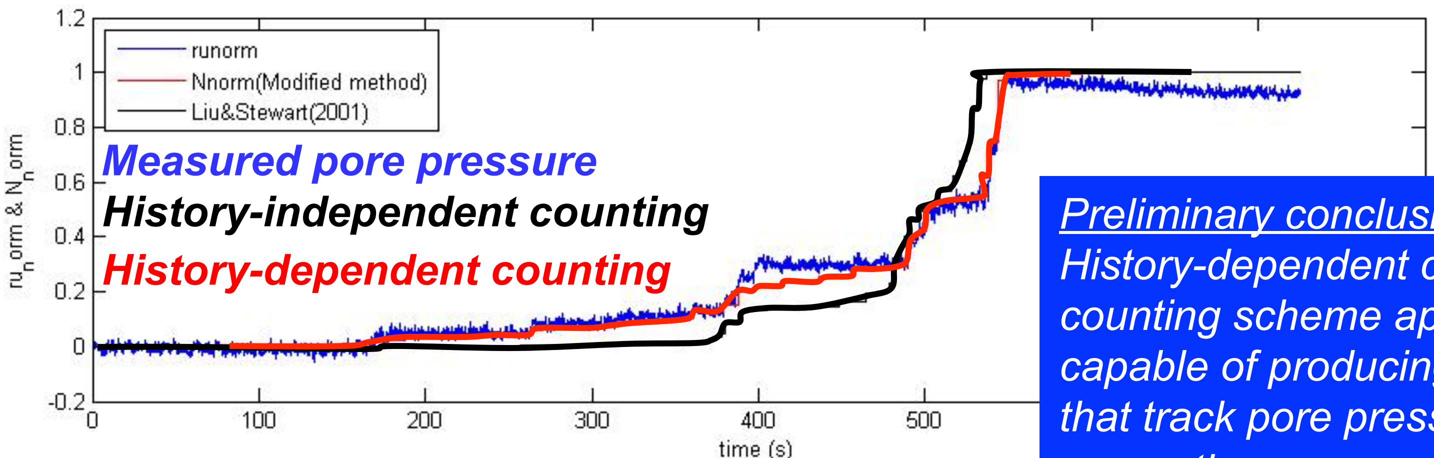

<u>Preliminary conclusion:</u>
History-dependent cycle-counting scheme appears capable of producing IMs that track pore pressure generation more accurately

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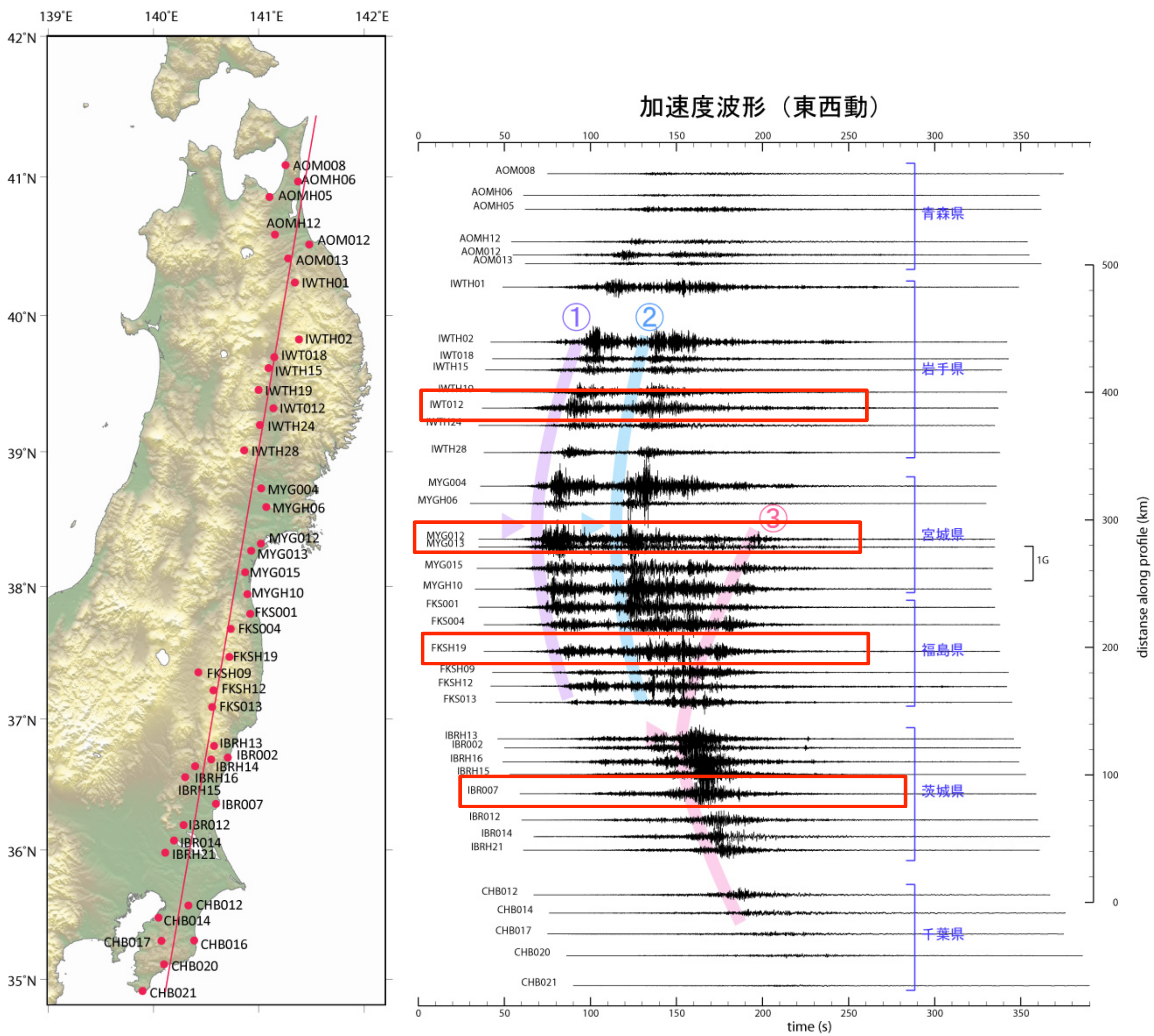

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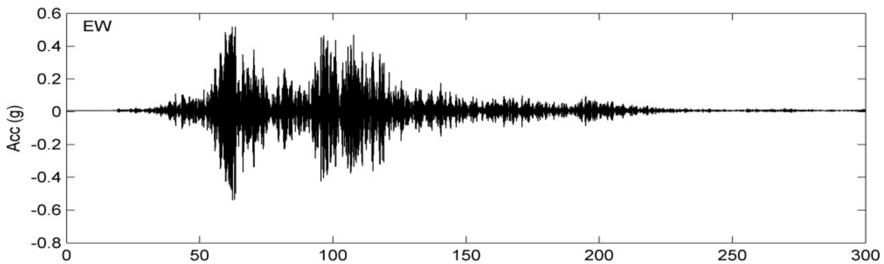

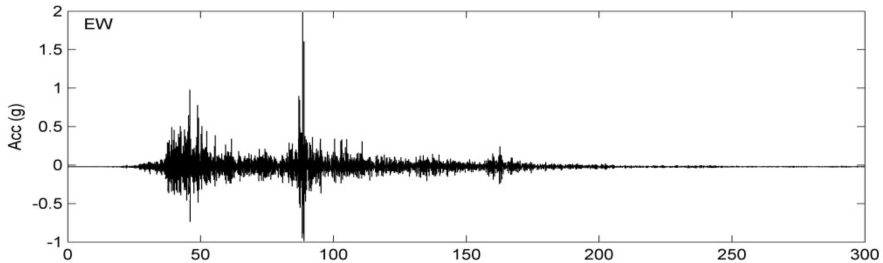

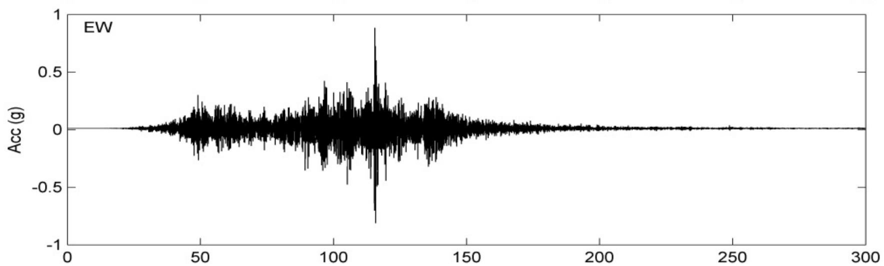

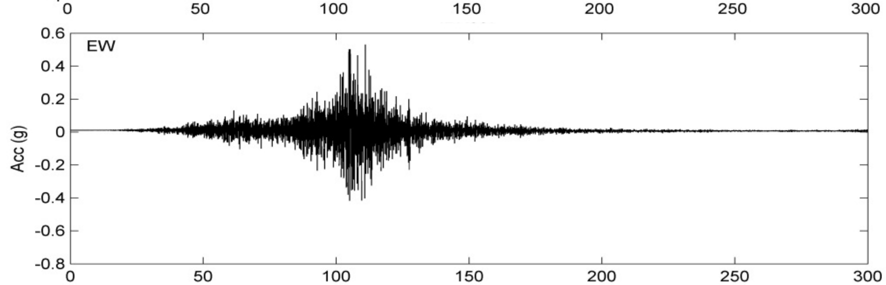

Number of equivalent cycles

Liu et al. (2001)	Modified
76.5	64.1
3.0	2.9
7.1	7.0
22.8	20.6

Summary

- Long history of successful and influential liquefaction research within PEER
- Still important issues to be addressed
  - Triggering
  - Effects
- Geotechnical challenges session will discuss tomorrow morning

Thank you