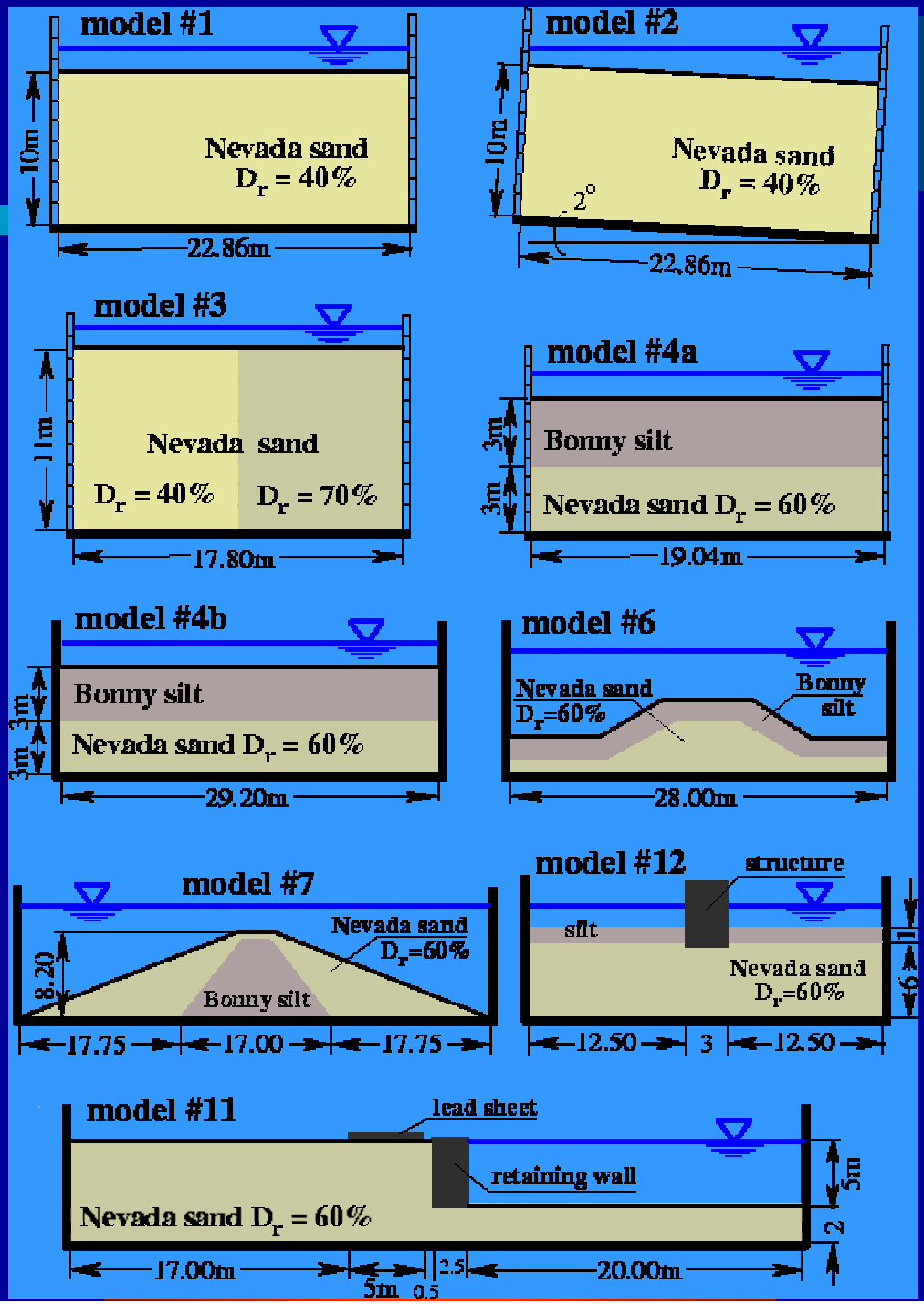
CENTRIFUGE EARTHQUAKE MODELING

R. Dobry

Rensselaer Polytechnic Institute



VERIFICATION OF LIQUEFACTION ANALYSIS BY CENTRIFUGE STUDIES

VELACS

NSF sponsored project

9 centrifuge models

6 centrifuge centres

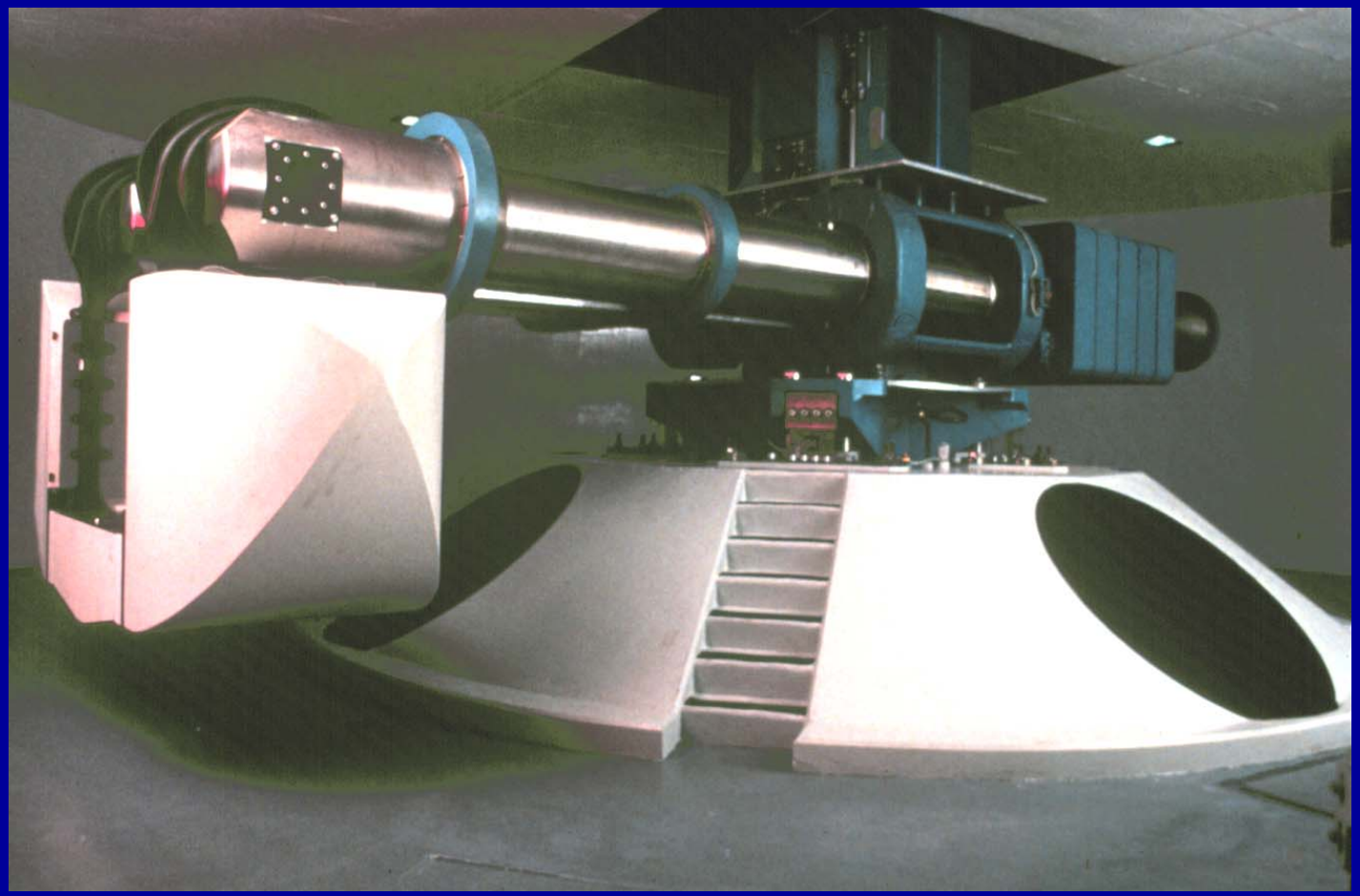
20 numerical modellers

http://ceor.princeton.edu/~radu/soil/velacs/

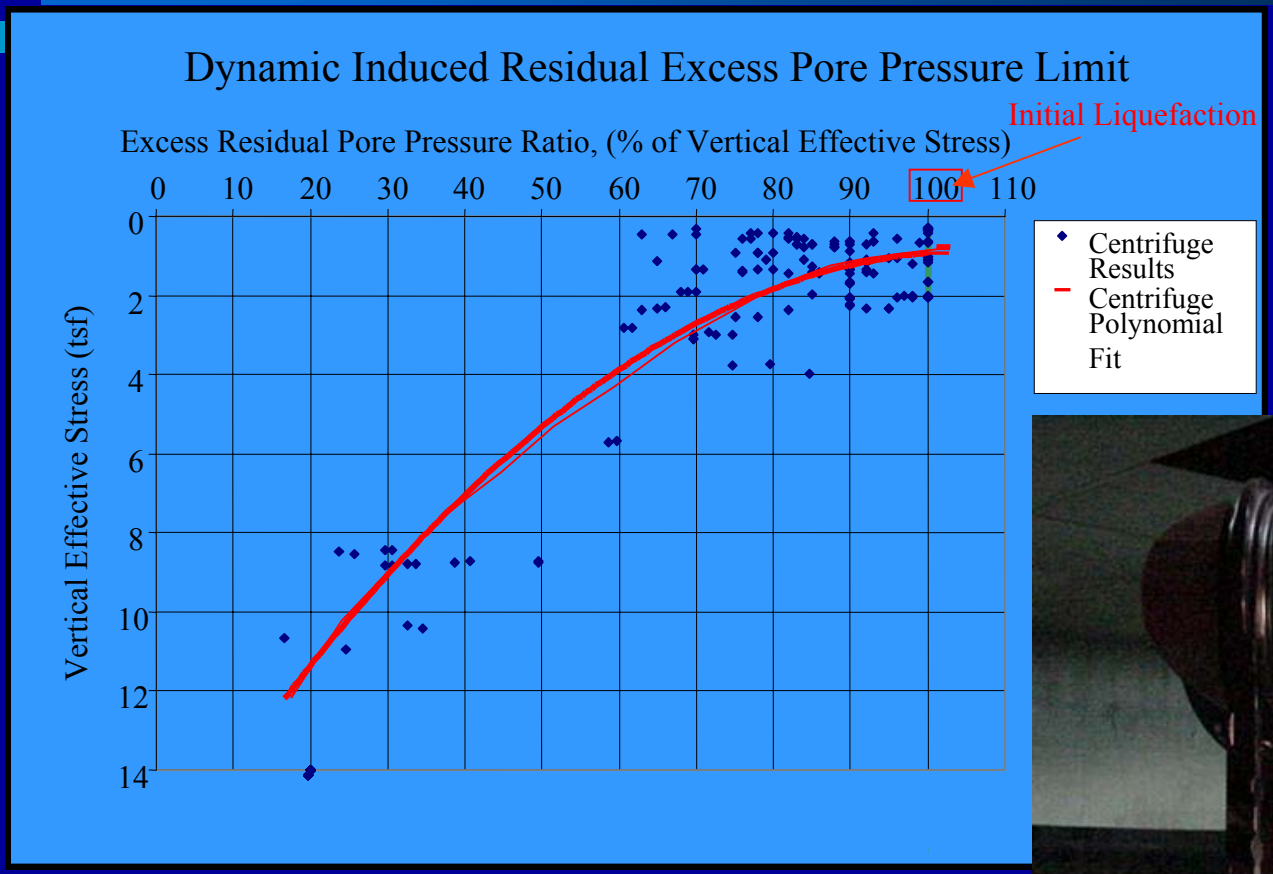
GENERAL

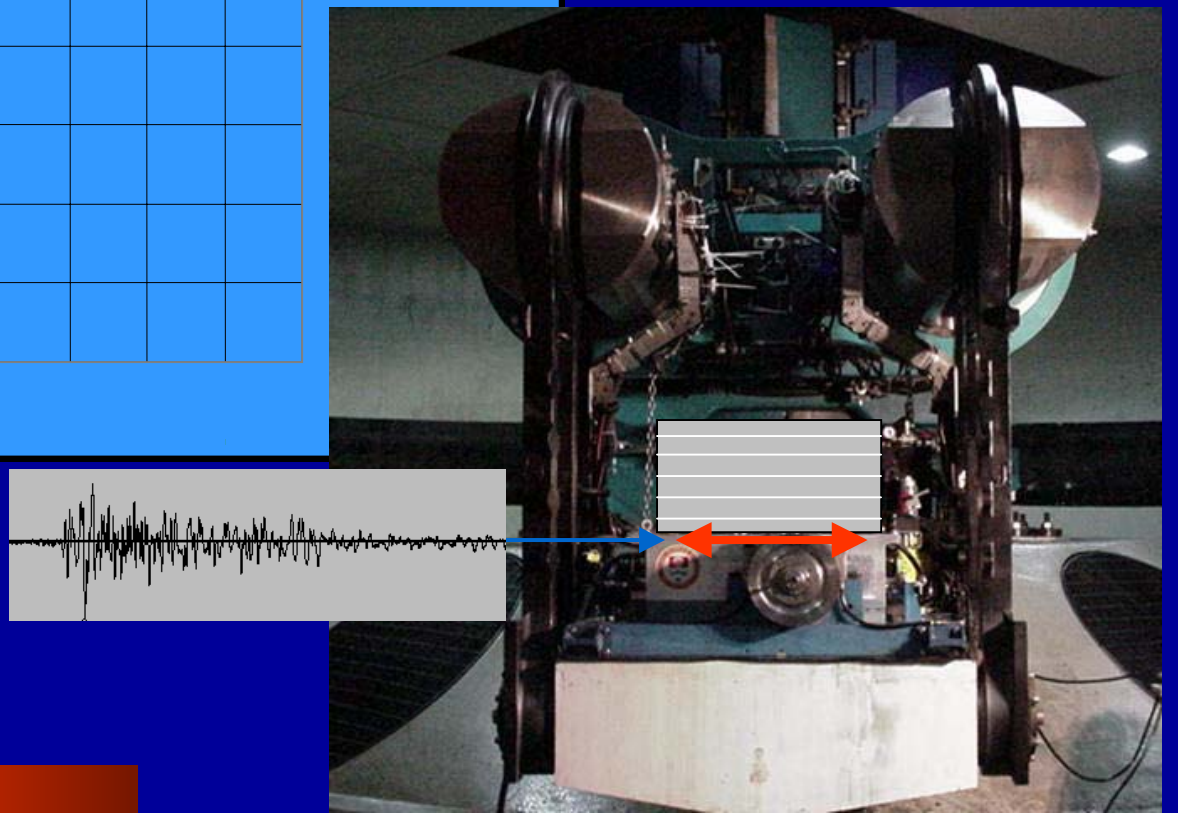
- Much work going on, mainly in the U.S., Japan and Europe
- Will present liquefaction results involving CoE, UC-Davis, Cambridge (UK), RPI, and Nat. Central U. (Taiwan)
- Three main subjects;
  - Liquefaction and lateral spreading
  - Effects on pile foundations
  - Effects on dykes and dams

Earthquake Engineering Research and Development Center (US Army CoE)



Effect of Depth on Liquefaction (CoE)



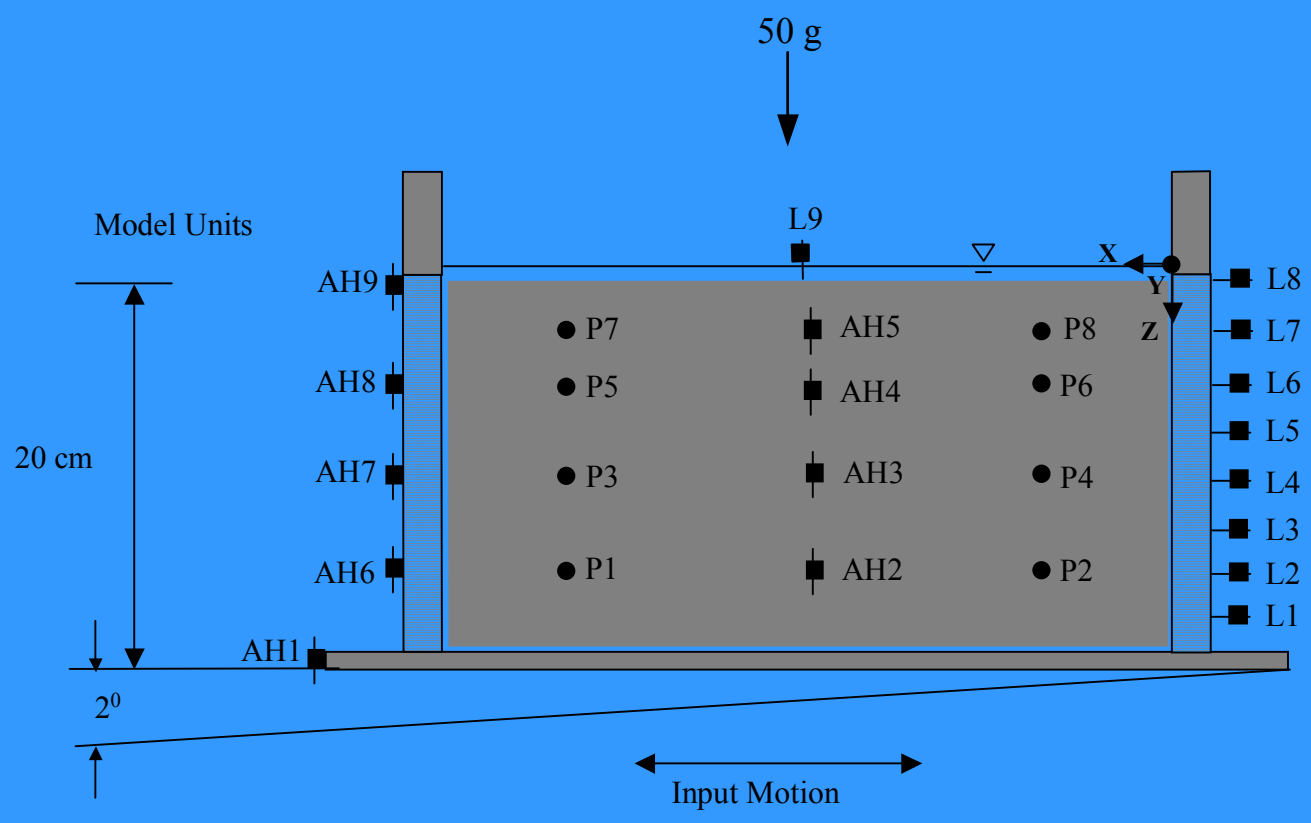


Steedman et al. (2000)

RPI 100 g-ton Centrifuge

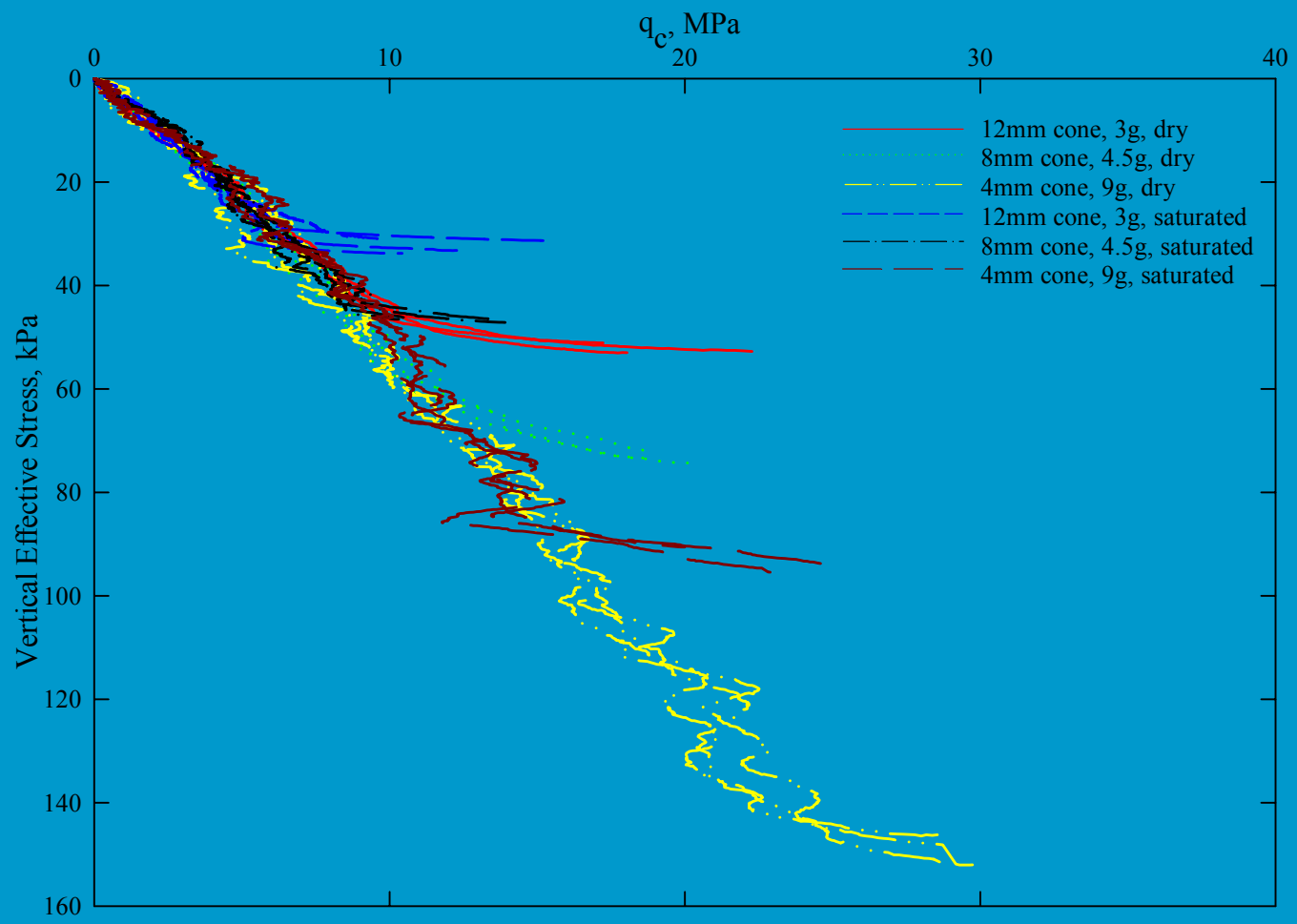
www.ce.rpi.edu/centrifuge

RPI Laminar Box and Instrumentation



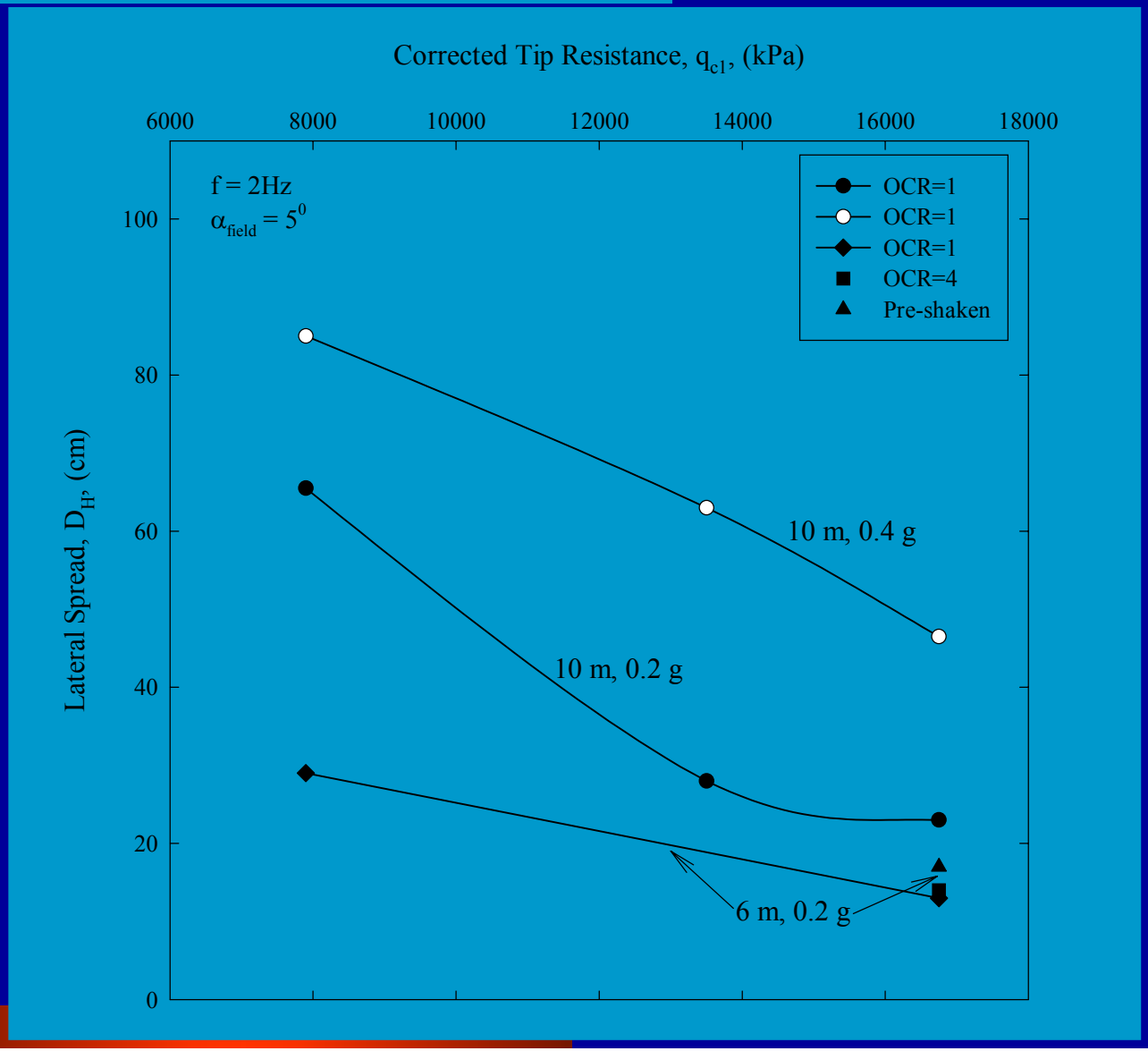
Linear variable displacement transformer Accelerometer Pore pressure transducer

D_r = 75% Results



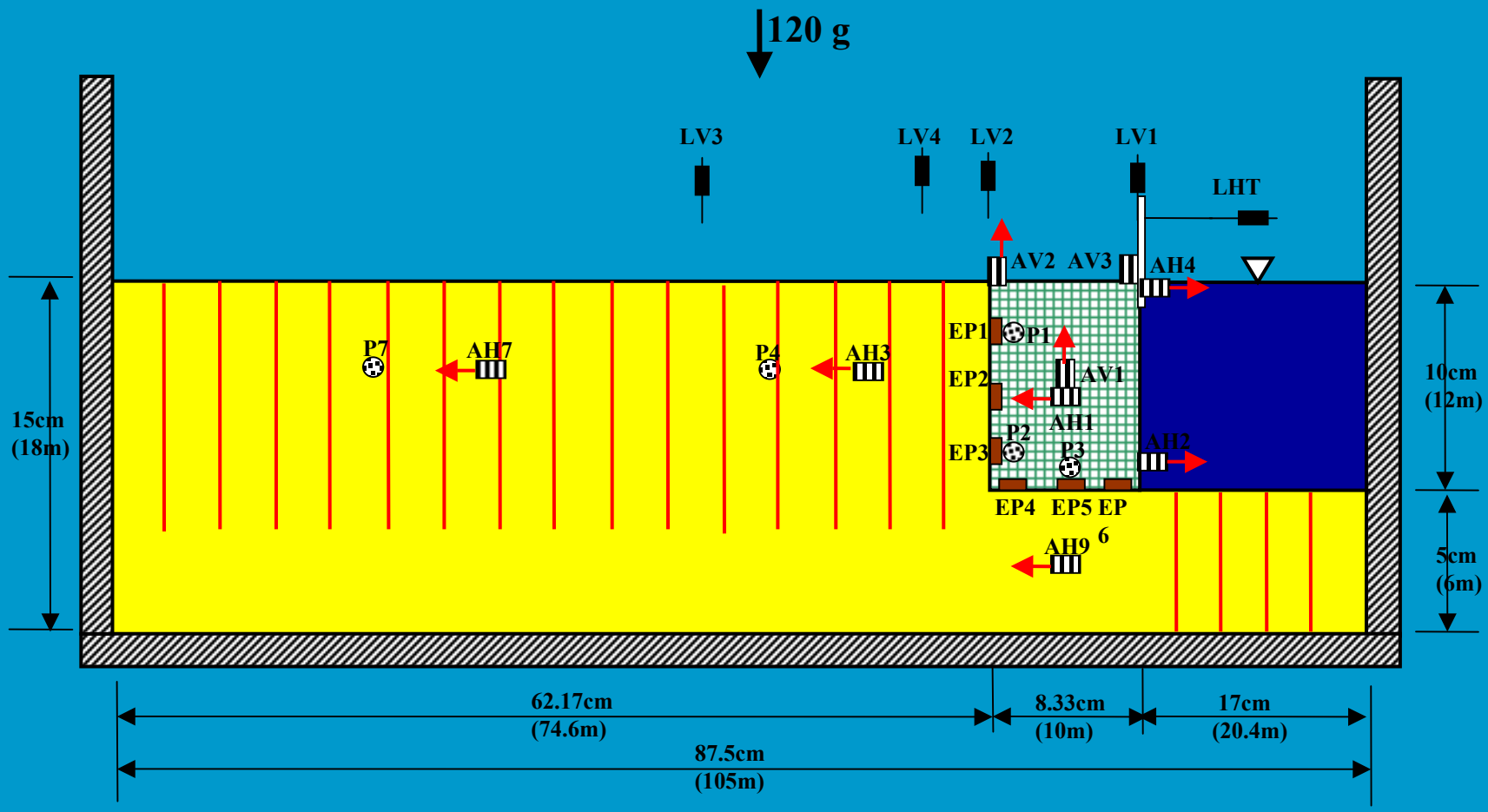
Sharp (1999)

Ground Surface Lateral Deformation Versus q_{c1} for 10m and 6m Deposits



Sharp (1999)

Quay Wall Model (Kobe 1995)



Earth pressure

Pore Pressure Transducer

LVDT

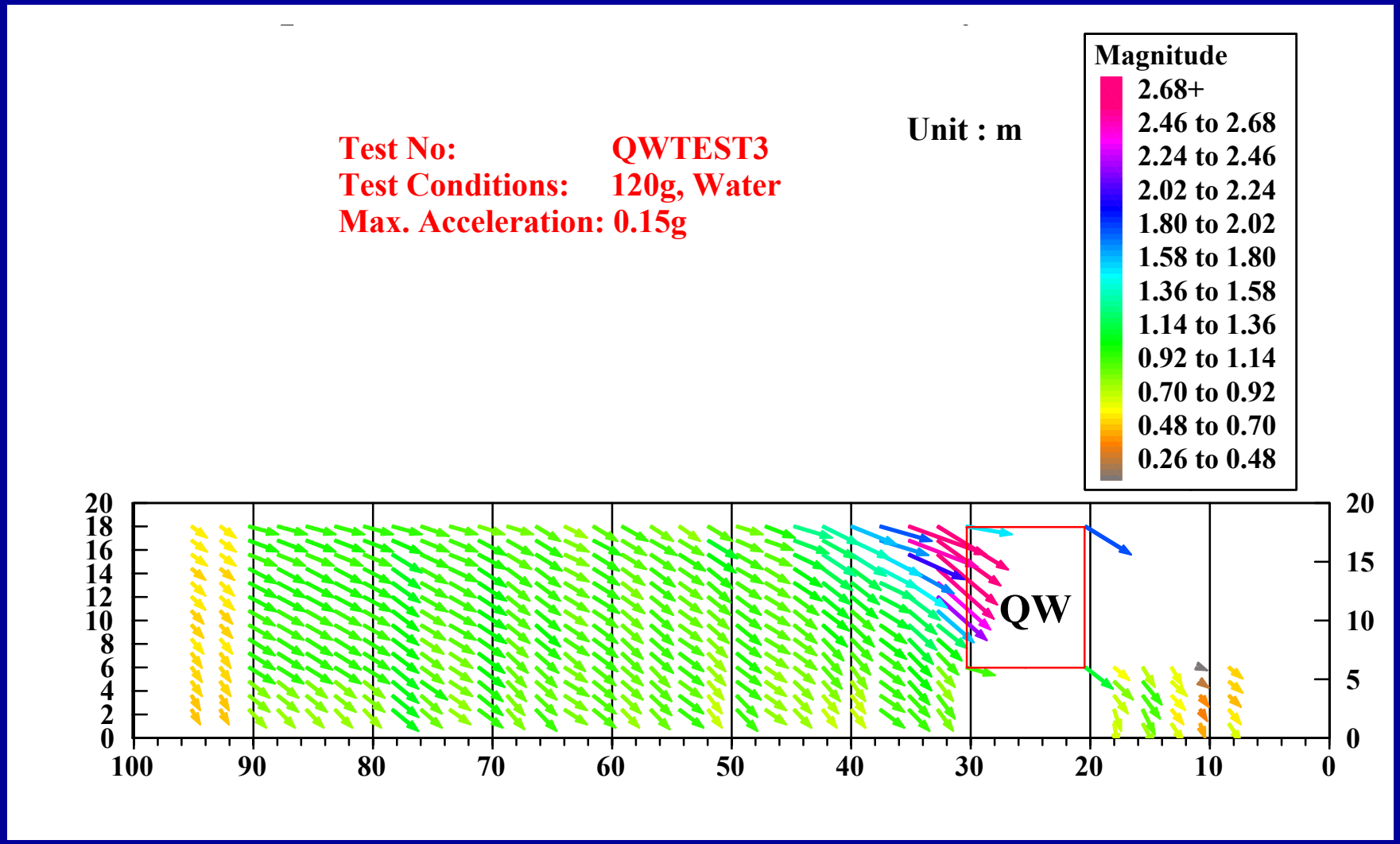
Accelerometer

Lee et al. (1999)

Ground Deformations Behind Quay Wall

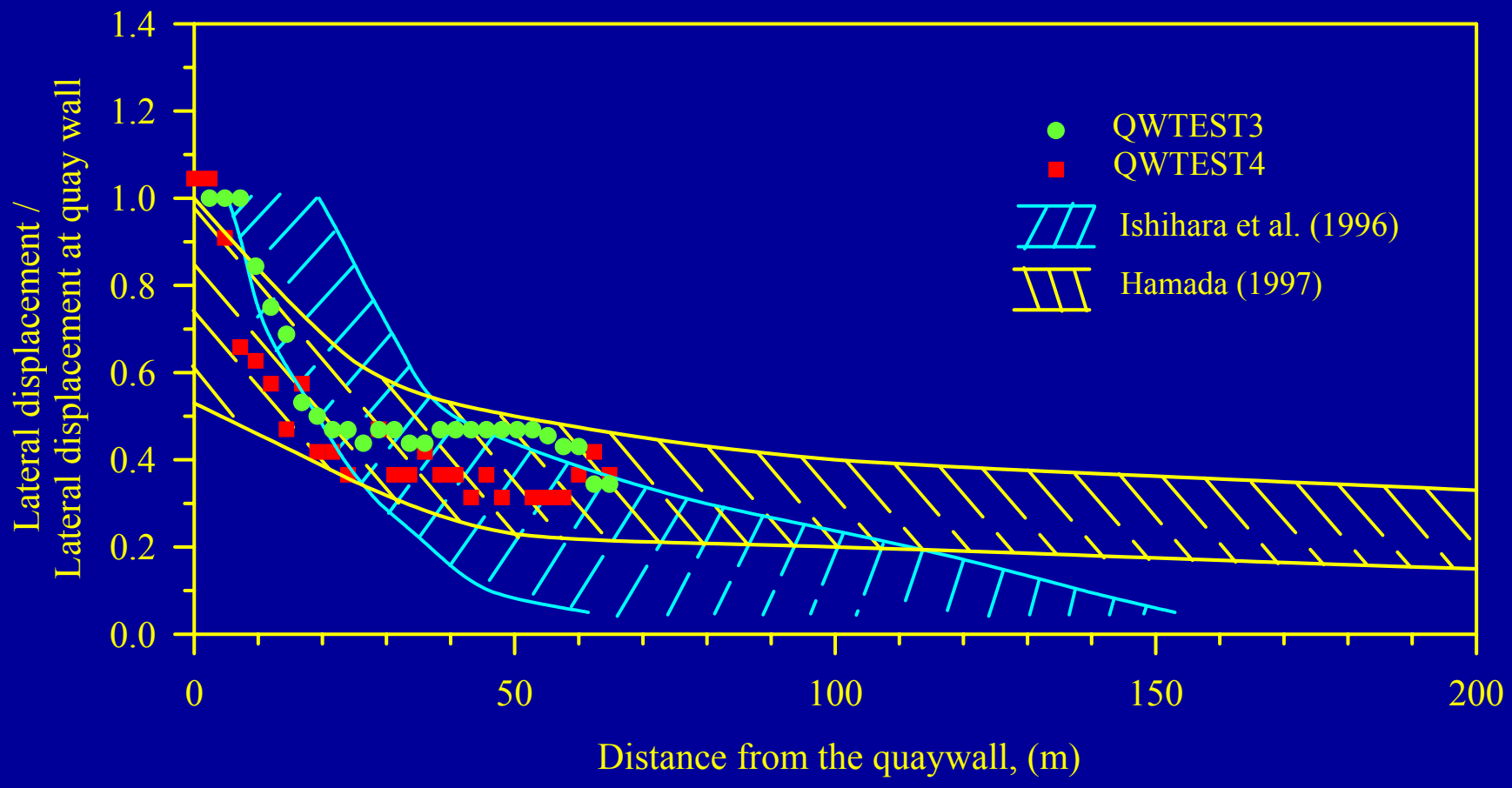
Lee et al. (1999)

Ground Displacement Vectors Behind Quay Wall

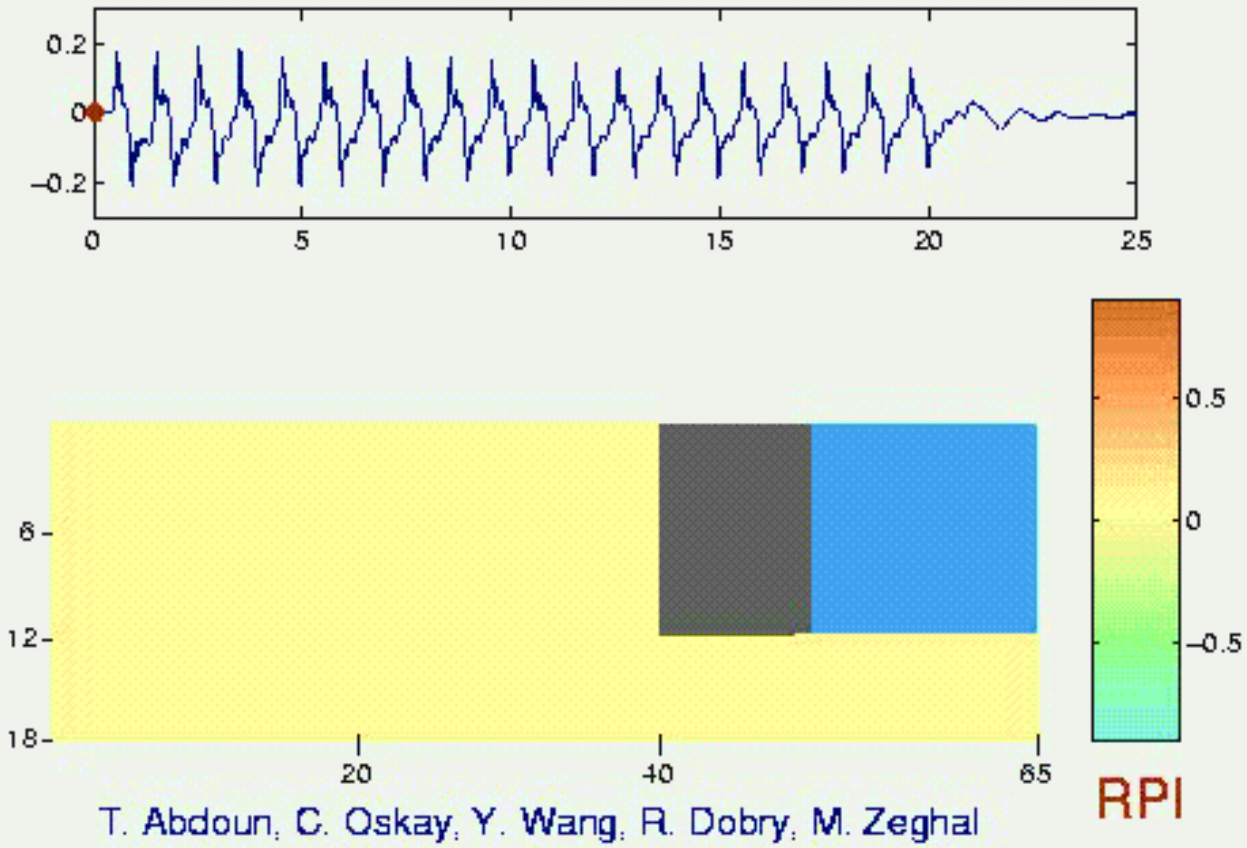


Lee et al. (1999)

Lateral Ground Displacement Spatial Variation



Excess Pore Pressure Distribution

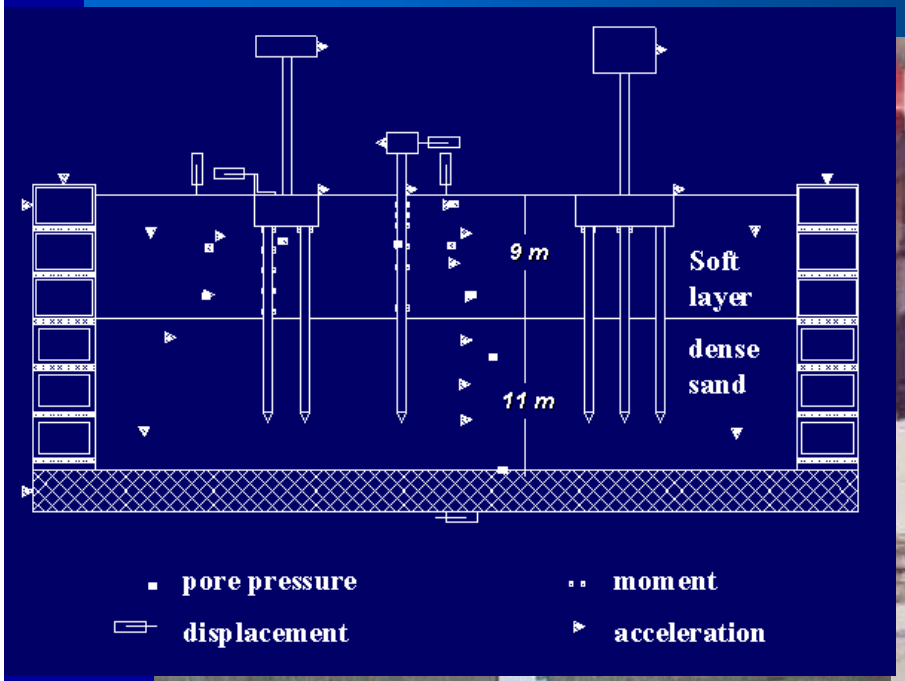


T. Abdoun, C. Oskay, Y. Wang, R. Dobry, M. Zeghal

Pile Damage due to Soil Liquefaction, Kobe 1995

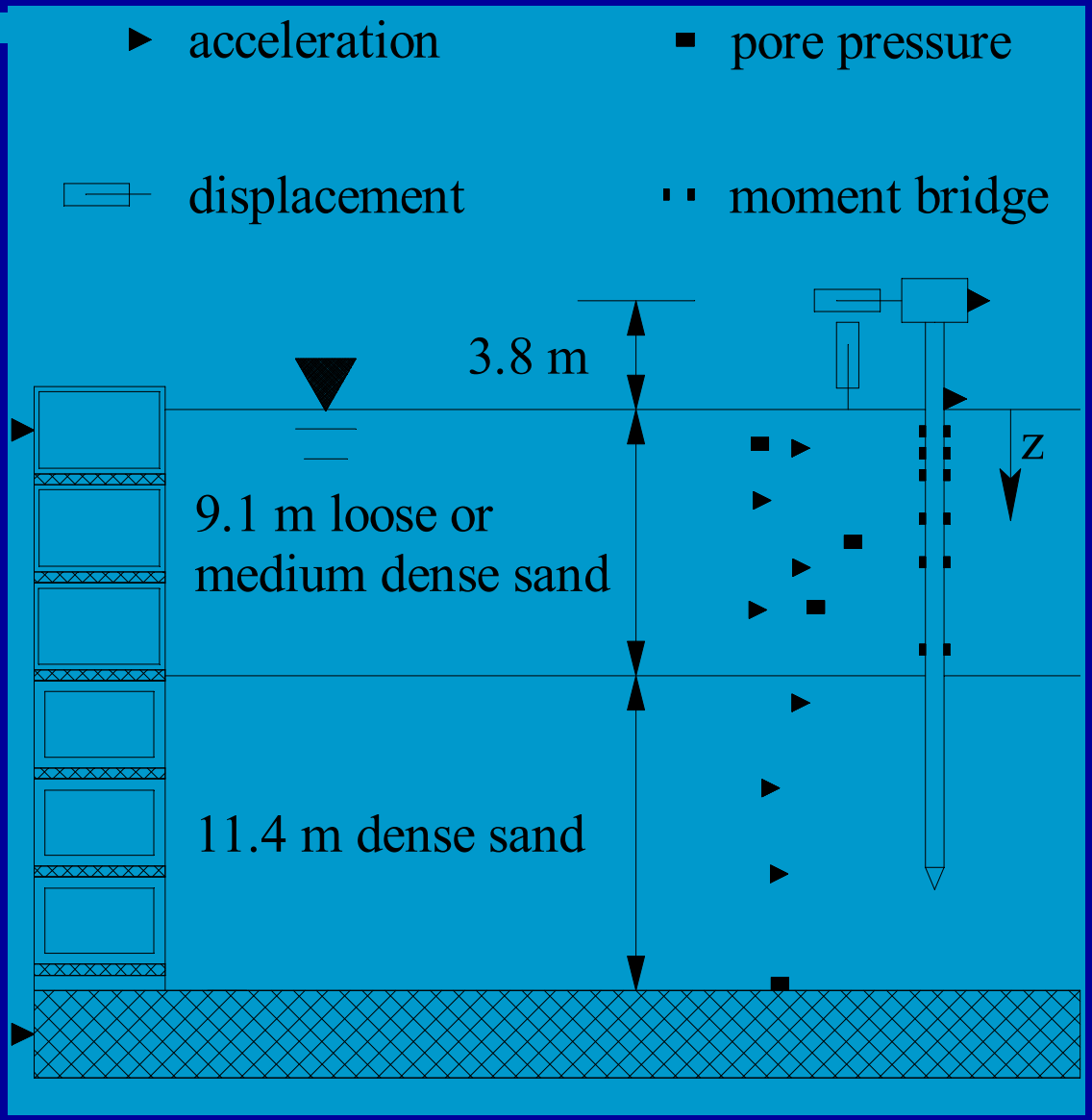
EARTHQUAKE DAMAGE

University of California, Davis



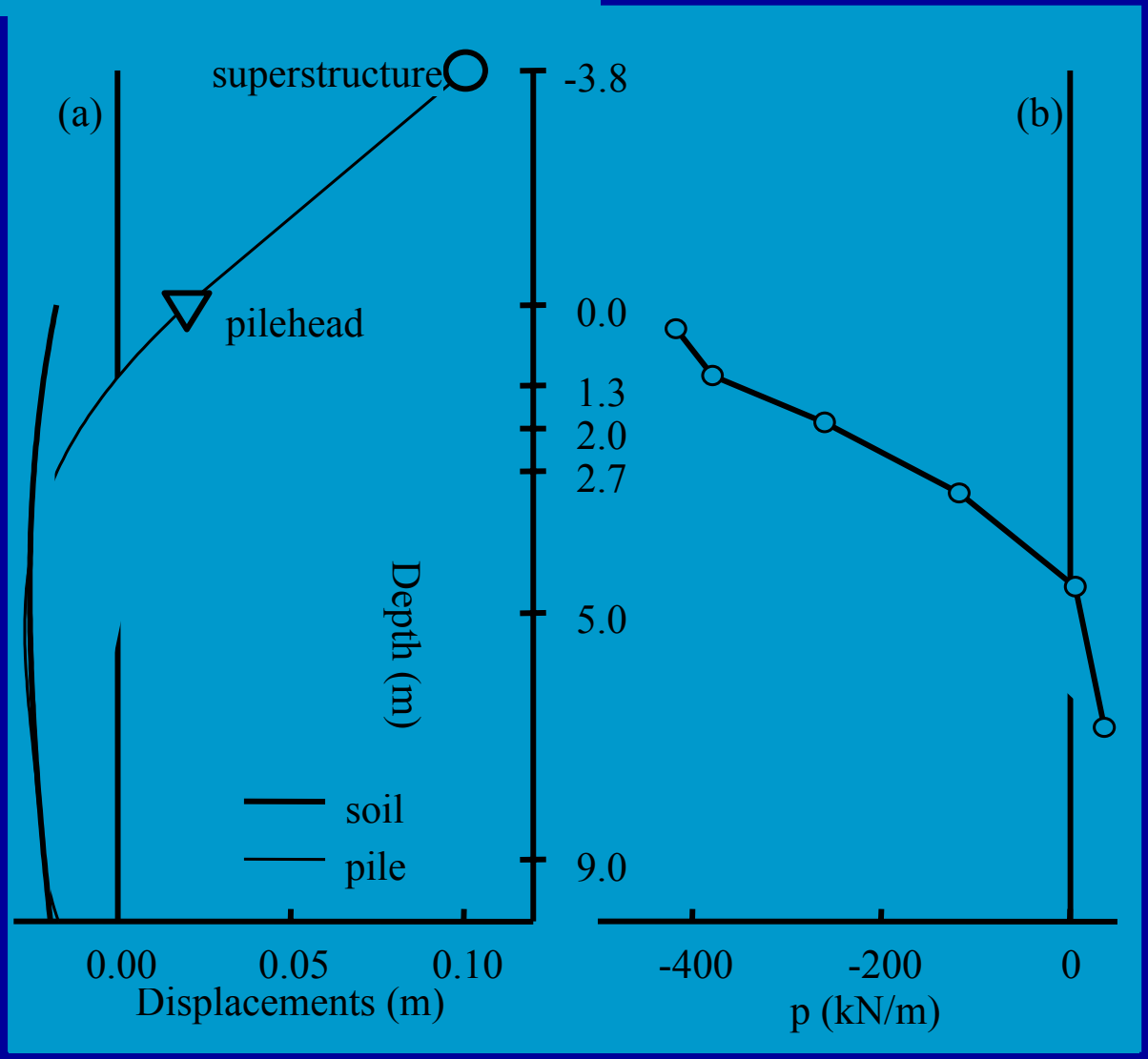
http://cgm.engr.ucdavis.edu/presentations/otrc99/

Lateral Resistance Between Pile and Liquefying Sand



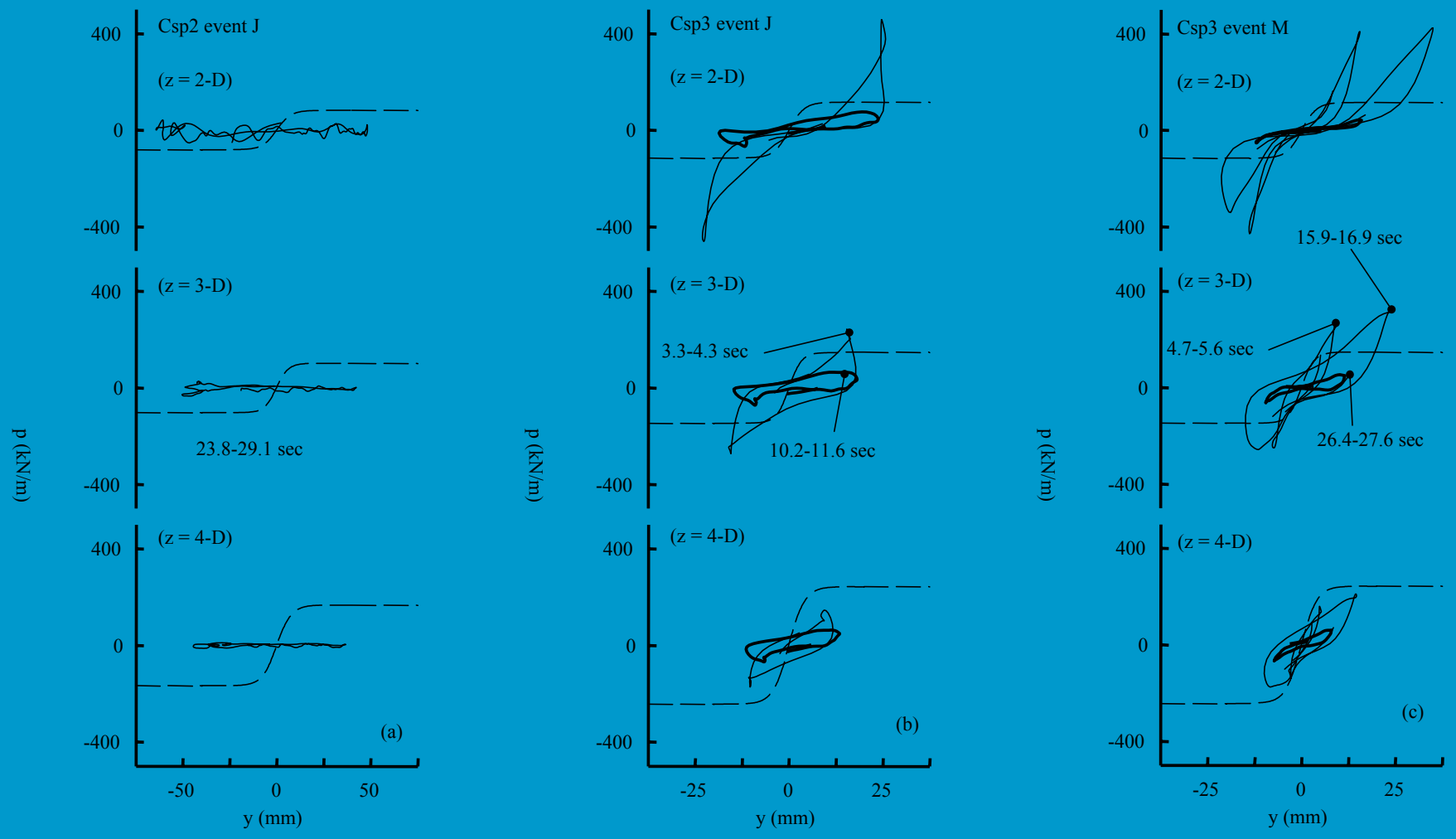
Wilson, Boulanger and Kutter (2000)

Lateral Resistance Between Pile and Liquefying Sand



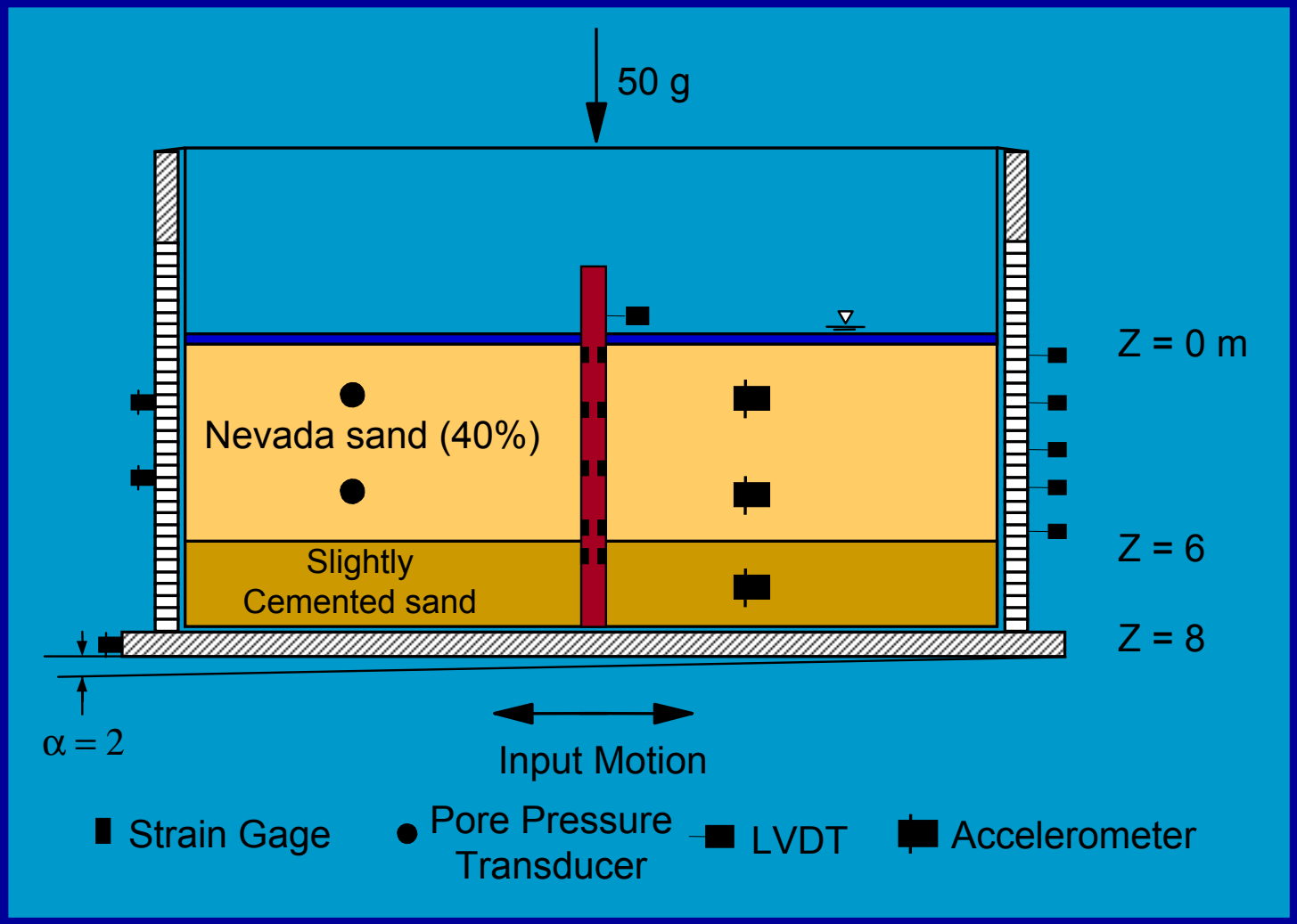
Wilson, Boulanger and Kutter (2000)

Lateral Resistance Between Pile and Liquefying Sand



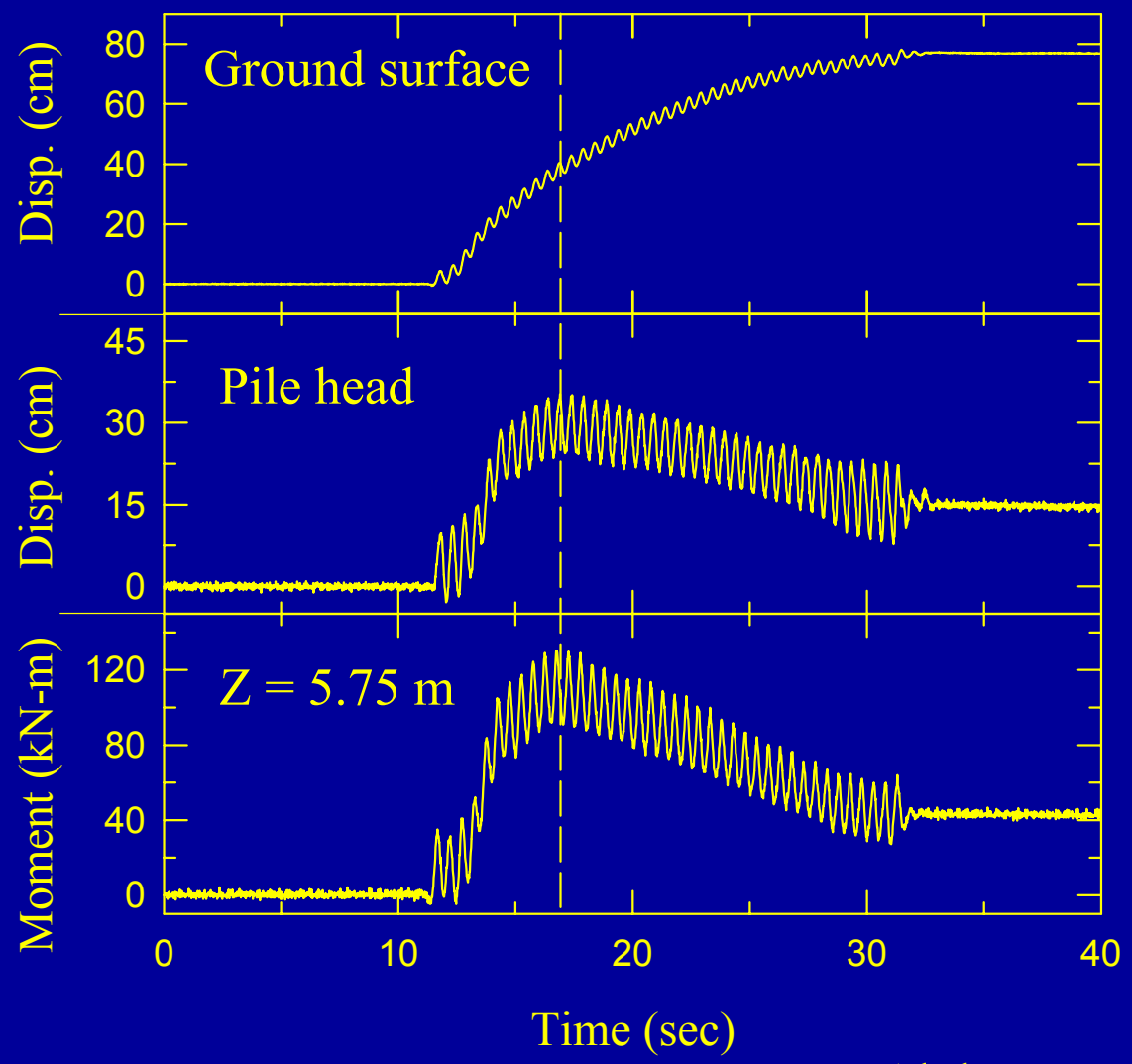
Wilson, Boulanger and Kutter (2000)

Effect of Lateral Spreading on Pile in Two-Layer Soil Profile



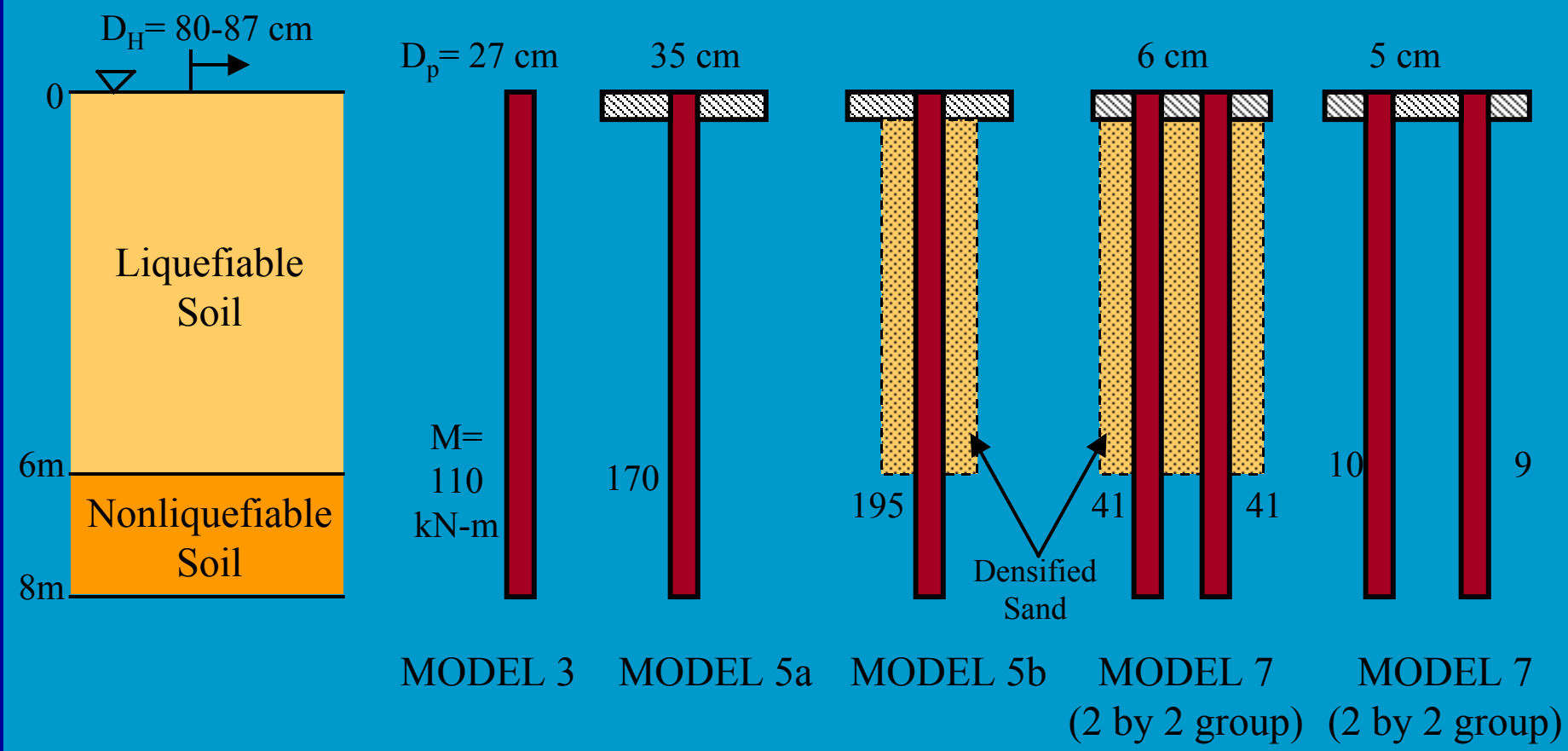
Abdoun (1997)

Effect of Lateral Spreading on Pile in Two-Layer Soil Profile



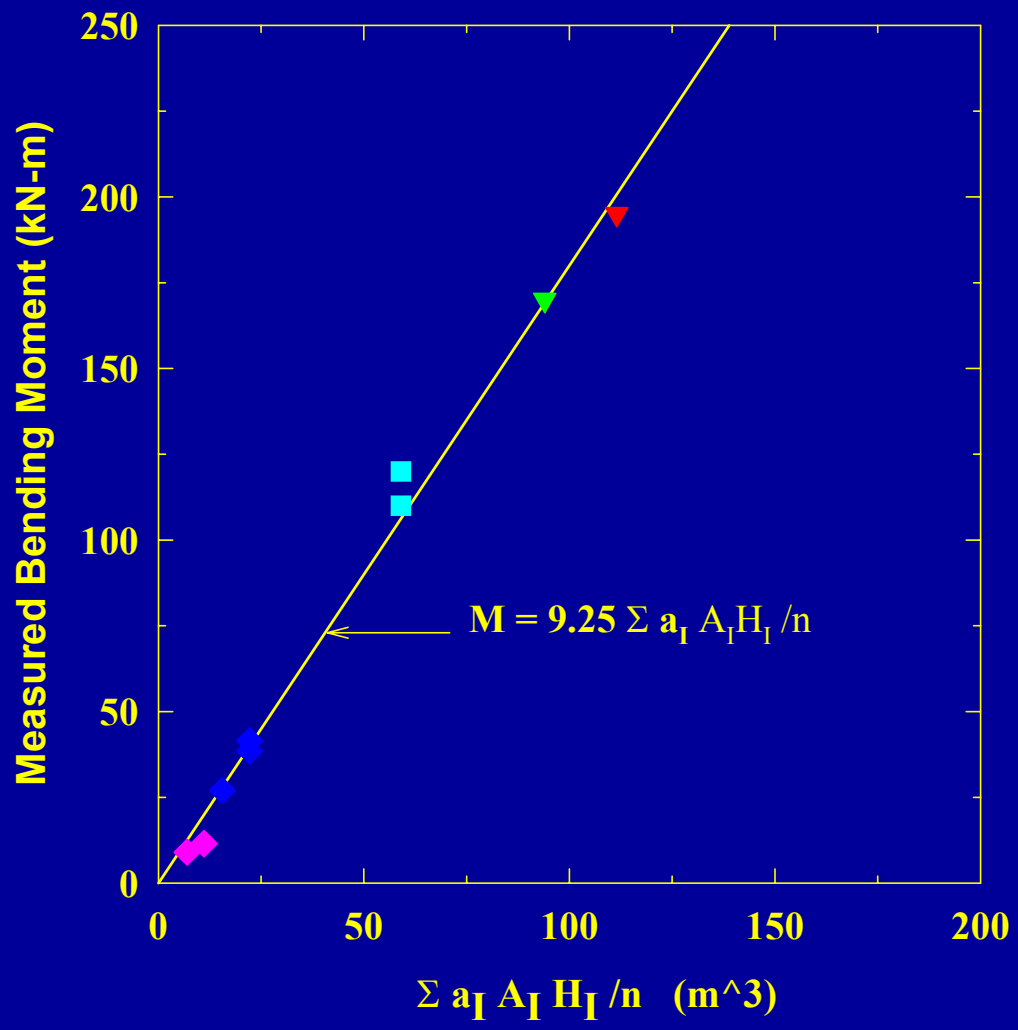
Abdoun and Dobry (1998)

Different Pile Models in Two-Layer Soil Profile



Abdoun (1997)

Limit Equilibrium Results



Drilled	Driven	
■		Single pile with no cap
▼	▼	Single pile with cap
◆	◆	2 by 2 pile group (both front and rear piles)

Abdoun (1997)

EARTHQUAKE DAMAGE

♦ *INTEVEP*

Oil Production, Venezula

Steedman and Habibian (1987)

Bolivar Coastal Dyke

EARTHQUAKE DAMAGE

♦ *INTEVEP*

Cambridge University

Centrifuge Model Test

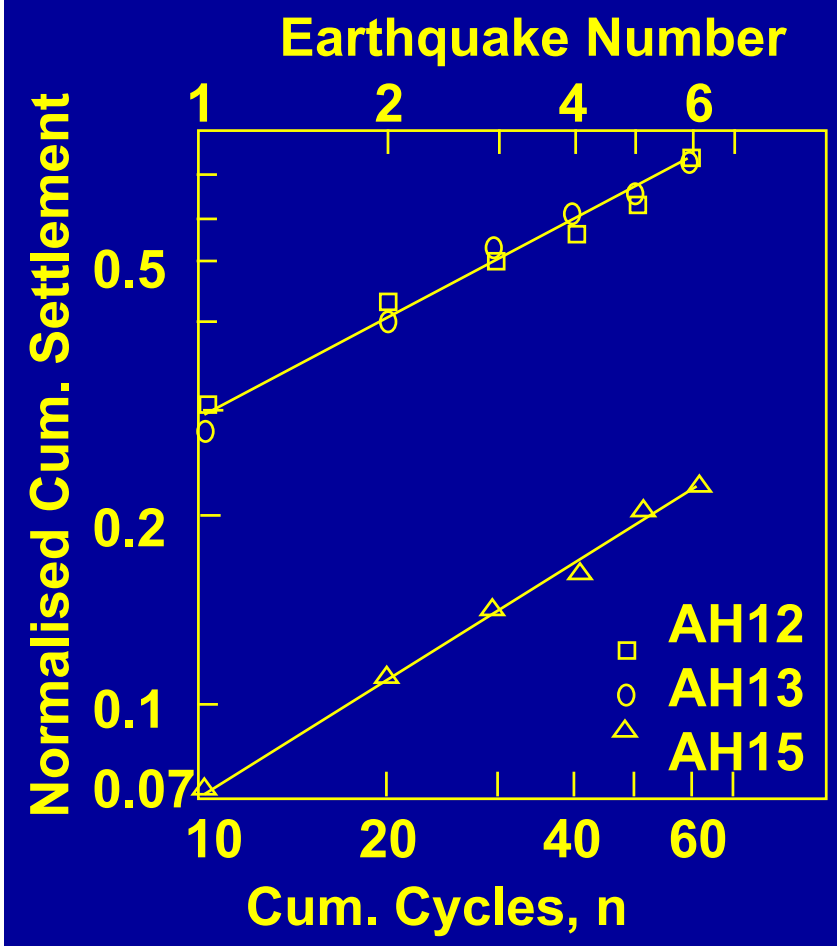
Typical Damage

Loose Sand

EARTHQUAKE DAMAGE

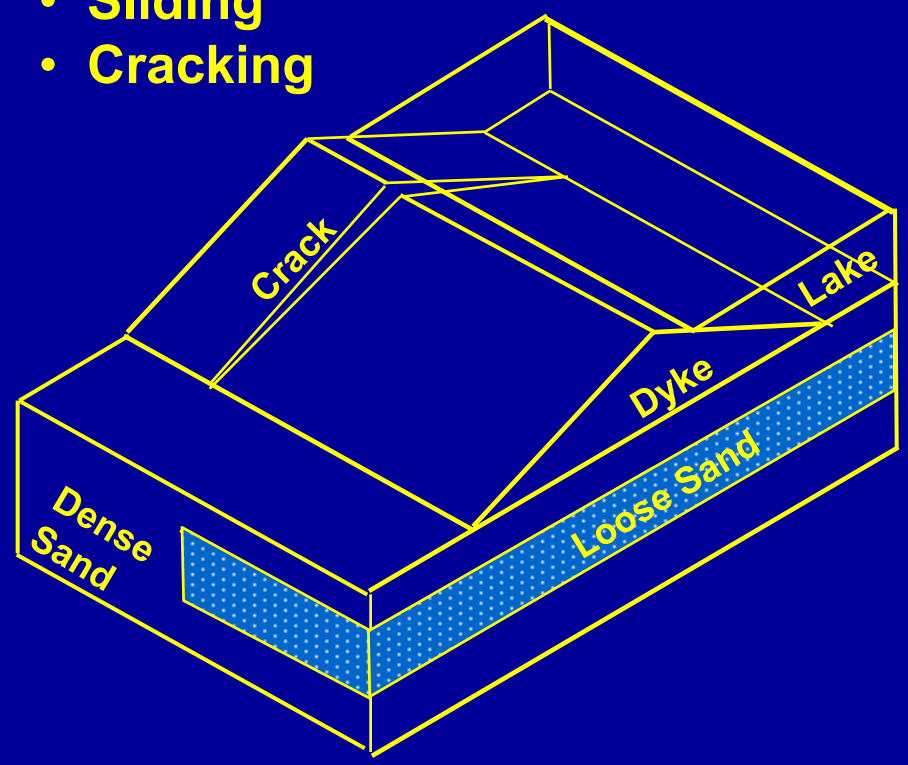
♦ *INTEVEP*

Cambridge University

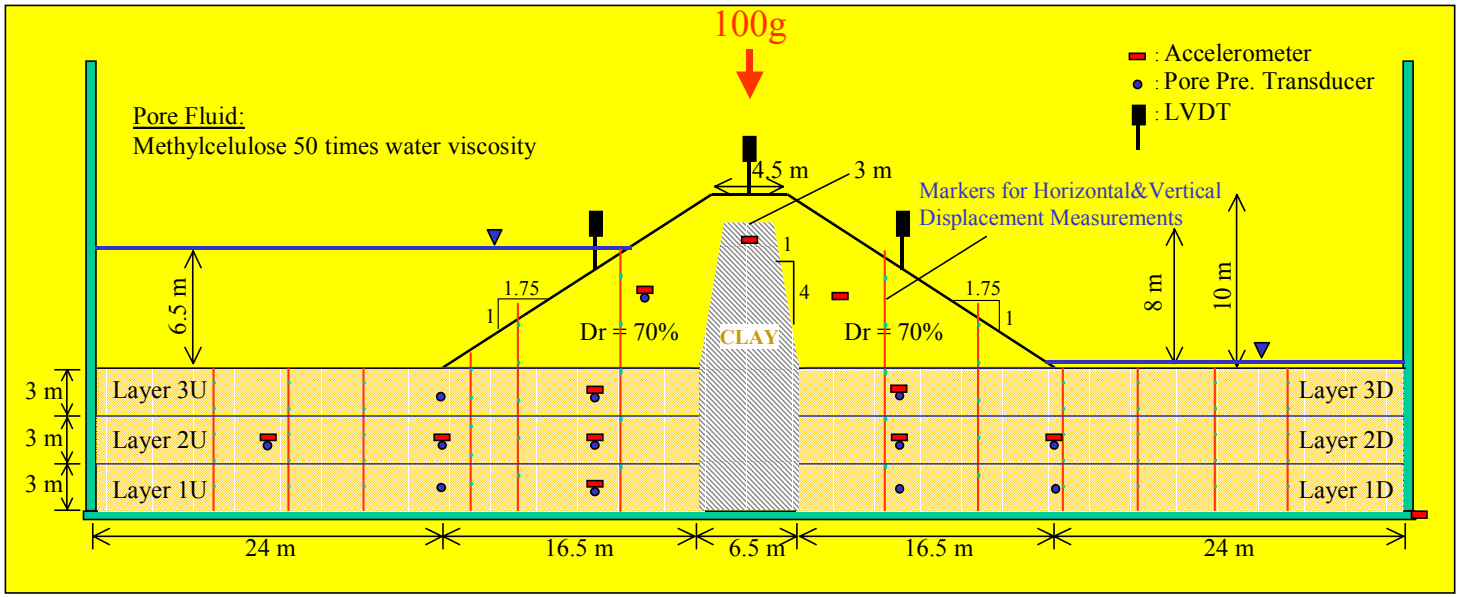


Guidelines for Dyke Evaluation

- Soil Profile
- Settlement
- Sliding
- Cracking



Embankments on Liquefiable Soil



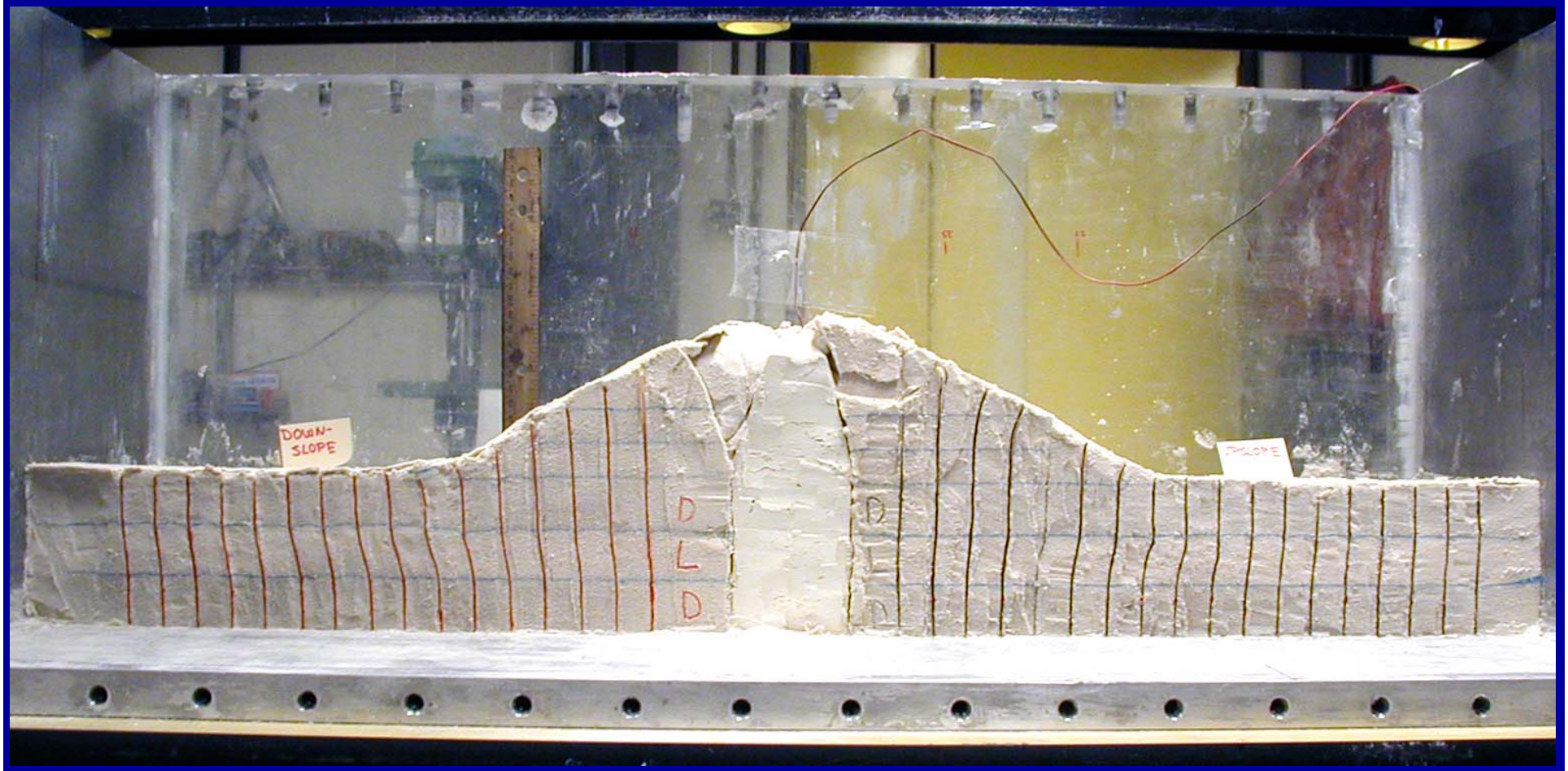
Tests:

SERIES 1	Vary ***depth*** of loose layer in foundation
SERIES 2	Vary ***thickness*** of loose layer in foundation
SERIES 3	Vary ***location*** of loose layer in foundation

Loose: Dr=35%, Dense: Dr= 70%

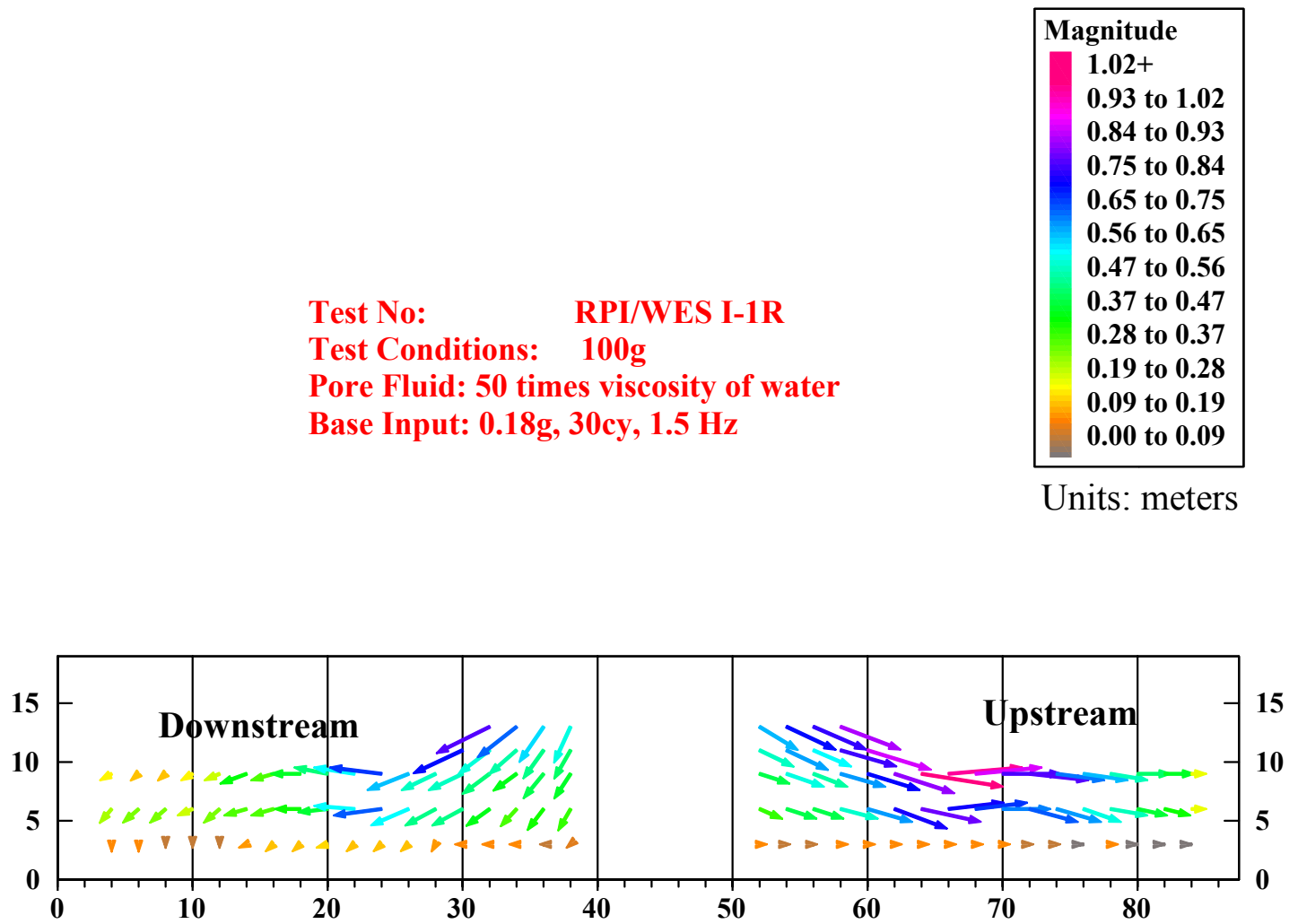
Adalier et al. (2001)

Embankments on Liquefiable Soil



Adalier et al. (2001)

Measured Displacement Vector Field



Adalier et al. (2001)

CONCLUSIONS

- Liquefaction and effects on foundations and embankments important and complicated; very difficult to model analytically
- Centrifuge ideal tool to clarify mechanics, develop engineering procedures, calibrate analysis tools
- Centrifuge results agree pretty well with field case histories when available
- Examples: CPT, quay walls Kobe 1995, pile dynamic response, liquefied soil pressure on piles, earth embankments on liquefiable soil

Recent Developments on Physical and Centrifuge Modeling of Liquefaction, Lateral Spreading and Their Effects on Deep Foundations
(Dobry and Abdoun, 2001)

Item	Explanation	References
1. SOA Reviews	Publication of several SOA reviews, general discussions and physical model test compilations relevant to liquefaction, seismic centrifuge testing, and effects of liquefaction on foundations	Schofield and Steedman (1988) Steedman (1991) Finn (1991) Ishihara and Takeuchi (1991) Dobry and Liu (1992) Ko (1994) Dobry (1995) Kutter (1995) Dobry et al. (1995) Dobry and Abdoun (1998) Ishihara and Cubrinovski (1998) Kutter and Balakrishnan (1998) Ko and Dewoolkar (1999)
2. Piles in Level Ground	Centrifuge and 1g shaking table model tests of instrumented deep foundations in level soil profiles including liquefiable soil (C = centrifuge tests; 1g = shaking table or other tests at 1g; PG = tests included pile groups)	Sato et al. (1995) C, PG Liu and Dobry (1995, 2001) C Kagawa et al. (1995) 1g, PG Sakajo et al. (1995) 1g, PG Boulanger et al. (1997) C, PG Wilson (1998) C, PG Wilson et al. (1998, 1999, 2000) C Koseki et al. (1998) C Taji et al. (1998) C, PG Adachi et al. (1998) C, PG Cubrinovski et al. (1999) 1g, PG
3. Piles in Sloping Ground or Behind Retaining Structure (effect of lateral spreading on deep foundation)	Centrifuge and 1g (mostly shaking table) model tests of instrumented deep foundations in sloping ground or behind retaining structure, with soil profile including liquefiable soil (C = centrifuge tests; 1g = shaking table or other tests at 1g; RS = tests included retaining structure; PG = tests included pile groups)	Tokida et al. (1992) 1g, PG Towhata (1995) 1g Abdoun et al. (1996) C Dobry et al. (1996) C Yasuda et al. (1996) 1g, RS Ohtomo (1996) 1g, PG Abdoun (1997) C, PG Tamura and Azuma (1997) 1g, RS Abdoun and Dobry (1998) C Satoh et al. (1998) C, RS Fujiwara et al. (1998) C, RS Takahashi et al. (1998) C, RS, PG Sato and Zhang (1998) C, RS, PG Horikoshi et al. (1998a,b) C, RS Ramos (1999) C Ramos et al. (1999, 2000) C Hamada (2000) 1g

LIST OF REFERENCES

Abdoun, T. H. [1997]. *Modeling of Seismically Induced Lateral Spreading of Multi-Layer Soil Deposit and Its Effect on Pile Foundations*, Ph.D. Thesis, Dept. of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Abdoun, T. H., R. Dobry, T. D. O'Rourke and D. Chaudhuri. [1996]. *Centrifuge Modeling of Seismically-induced Lateral deformation During Liquefaction and its Effect on a Pile Foundation*, Proc. Sixth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Technical Report NCEER-96-0012, NCEER, SUNY-Buffalo, NY, pp. 525-539.

Abdoun, T. H. and R. Dobry. [1998]. *Seismically Induced Lateral Spreading of Two-layer Sand deposit and its Effect on Pile Foundations,* Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp.321-326.

Abdoun T., C. Oskay, Y. Wang, C.-J. Lee and M. Zeghal. [2001]. *Visualization of Measured Quay Wall Seismic Response,* Proc. XV Int. Conf. on Soil Mechanics and Geotechnical Engineering, Istanbul, Turkey, August (accepted).

Adachi, N., Y. Miyamoto and K. Koyamada. [1998]. *Shaking Table Test and lateral Loading Test for Pile Foundation in Sturated Sand*, Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp.289-294.

Adalier, K. et al. [2001]. In preparation.

American Petroleum Institute (API). [1993]. *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms*, API RP 2A-WSD, 20th Ed., Washington, D.C.

Arulanandan, K. and R. F. Scott (eds.). [1993]. *Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, A. A. Balkema, Rotterdam, Vol. 1.

Arulanandan, K. and R. F. Scott (eds.). [1994]. *Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, A. A. Balkema, Rotterdam, Vol. 2,

Boulanger, R. W., W. W. Wilson, B. L. Kutter and A. Abghari. [1997]. *Soil-pile-superstructure Interaction in Liquefiable Sand*, Transportation Research Record 1569.

Cubrinovski, M., K. Ishihara and K. Furukawazono. [1999]. *Analysis of Full-scale Tests on Piles in Deposits Subjected to Liquefaction*, Proc. 2nd Intl. Conf on Earthquake Geotechnical Engineering (P. Seco e Pinto, ed.), Lisbon, Portugal, June 21-25, Vol. 2, pp. 567-572.

Dobry, R. [1995]. *Liquefaction and Deformation of Soils and Foundations under Seismic Conditions*, State-of-the-art paper, Proc. Third Intl. Conf on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (S. Prakash, ed.), St. Louis, MO, April 2-7, Vol. III, pp. 1465-1490.

Dobry, R. and L. Liu. [1992]. *Centrifuge Modeling of Soil Liquefaction*, Proc. 10th World Conf. on Earthquake Engng., Madrid, Spain, Vol. 11, pp. 6801-6809.

Dobry, R., V. Taboada and L. Liu [1995]. *Centrifuge Modeling of Liquefaction Effects During Earthquakes*, Keynote lecture, Proc. 1st Intl. Conf on Earthquake Geotechnical Engineering (K. Ishihara, ed.), Tokyo, Japan, Nov. 14-16, Vol. 3, pp. 1291-1324.

Dobry, R. and T. H. Abdoun. [1998]. *Post-Triggering Response of Liquefied Soil in The Free Field and Near Foundations*, State-of-the-art paper, Proc. ASCE 1998 Specialty Conference on Geotechnical Earthquake Engineering and Soil Dynamics (P. Dakoulas, M. Yegian and R. D. Holtz, eds.), University of Washington, Seattle, Washington, August 3-6, Vol. 1, pp. 270 – 300.

Dobry, R., P. Van Laak, A.-W. Elgamal, T. F. Zimmie and K Adalier. [1997]. *The RPI Geotechnical Centrifuge Facility*, NCEER Bulletin, April, pp. 12-17.

Dobry, R. and T. Abdoun. [2001]. *Recent Studies on Centrifuge Modeling of Liquefaction and its Effects on Deep Foundations*, State-of-the-art paper, Proc Fourth Intl. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (S Prakash, ed.), San Diego, CA, March 26-31 (submitted).

Elgamal, A.-W., R. Dobry, P. Van Laak and J. Nicolas-Font. [1991]. *Design, Construction and Operation of 100 g-ton Centrifuge at RPI*, Proc. Intl. Conf. Centrifuge'91 (H.-Y. Ko and F. G. McLean, eds.), pp. 27-34.

Finn, W. D. L. [1991]. *Assessment of Liquefaction Potential and Post Liquefaction Behavior of Earth Structures, Developments 1981-1991*, State-of-the-art paper, Proc. Second Intl. Conf on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (S. Prakash, ed.), St. Louis, MO, March 11-15, Vol. II, pp. 1833-1850.

Fujiwara, T., K. Horikoshi, and T. Sueoka. [1998]. *Dynamic Behavior of Gravity Type Quay Wall and Surrounding Soil During Earthquake*, Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp. 359-364.

Hamada, M. [2000]. *Performances of Foundations Against Liquefaction-Induced Permanent Ground Displacement*, Proc. 12th World Conf. On Earthquake Engineering, Paper 1754.

Horikoshi, P., T. Fujiwara and A. Tateishi. [1998a]. *Pile behavior During Seismically-induced Lateral Spreading of Liquefied Sand,* Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp. 377-382.

Horikoshi, P., A. Takeishi and T. Fujiwara. [1998b]. *Centrifuge Modeling of a Single Pile Subjected to Liquefaction-induced Lateral Spreading*, Soils and Foundations, Special Issue No. 2, pp. 193-208.

Ishihara, K. and M. Takeuchi. [1991]. *Flow Failure of Liquefied Sand in Large-Scale Shaking Tables*, State-of-the-art paper, Proc. Second Intl. Conf on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (S. Prakash, ed.), St. Louis, MO, March 11-15, Vol. II, pp. 1753-1766.

Ishihara, K. and M. Cubrinovski. [1998]. *Problems Associated with Liquefaction and Lateral Spreading During Earthquakes*, State-of-the-art paper, Proc. ASCE 1998 Specialty Conference on Geotechnical Earthquake Engineering and Soil Dynamics (P. Dakoulas, M. Yegian and R. D. Holtz, eds.), University of Washington, Seattle, Washington, August 3-6, Vol. 1, pp. 301-312.

Japan Road Association. [1996]. *Specifications for Highway Bridges, Part V Seismic Design*, (in Japanese).

Kagawa, T., C. Minowa, A. Abe and S. Oda. [1995]. *Shaking-table Tests on and Analyses of Piles in Liquefying Sand*, Proc. 1st Intl. Conf on Earthquake Geotechnical Engineering (K. Ishihara, ed.), Tokyo, Japan, Nov. 14-16, Vol. 2, pp. 699-704.

Ko, H.-Y. [1994]. *Modeling Seismic Problems in Centrifuges*, Proc. Intl. Conference Centrifuge'94, Singapore, August 31-Sept. 2, (C.F. Leung, F.H. Lee and T.S. Tan, eds.), A.A. Balkema, Rotterdam, pp. 3-12.

Ko, H.-Y. and M. M. Dewoolkar. [1999]. *Modeling Liquefaction in Centrifuges*, Physics and Mechanics of Liquefaction (P. V. Lade and J. A. Yamamuro, eds.), pp. 307-322.

Koseki, J., O. Matsuo, K. Kondo and T. Yoshizawa. [1998]. *Effects of Compaction of Liquefiable Sandy Soil Surrounding Pile Foundation*, Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp.277-282.

Kutter, B. L. [1995]. *Recent Advances in Centrifuge Modeling of Seismic Shaking*, Proc. Intl. Conf. on Recent Advances in Geotechnical Engineering and Soil Dynamics (S. Prakash, ed.), St. Louis, MO, April 2-7, Vol. II, pp. 927-941.

Kutter, B. L. and A. Balakrishnan. [1998]. *Dynamic Model Test Data from Electronics to Knowledge*, State-of-the-art paper, Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 2, pp. 931-943.

Lee, C.-J., R. Dobry, T. Abdoun and B.-R. Wu. [1999]. *Centrifuge Modeling of Lateral Spreading Behind a Caisson Type Quay Wall During an Earthquake*, Proc 7th US-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Seattle, WA, August 15-17, 15 pages

Liu, L. and R. Dobry. [1995]. *Effect of Liquefaction on Lateral Response of Piles by Centrifuge Model Tests*, NCEER Bulletin, January, pp. 7-11.

Liu, L. and R. Dobry. [2001]. *Lateral Response of Piles in the Presence of Liquefied Soil by Centrifuge Model Tests*, Technical Report MCEER-FHWA Project, Multidisciplinary Center for Earthquake Engineering Research, SUNY-Buffalo, Buffalo, NY (submitted).

Ohtomo, K. [1996]. *Soil Force on Conduit Pile System Due to Liquefaction-induced Lateral Flow*, Proc. Sixth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Technical Report NCEER-96-0012, NCEER, SUNY-Buffalo, NY, pp. 541-550.

Ramos, R. [1999]. *Centrifuge Study of Bending Response of Pile Foundation to a Lateral Spread Including Restraining Effect of Superstructure*, Ph.D. Thesis, Dept. of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY

Ramos, R., T. H. Abdoun and R. Dobry. [1999]. *Centrifuge Modeling of Effect of Superstructure Stiffness on Pile Bending Moments Due to Lateral Spreading*, Proc. Seventh U. S.-Workshop Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Seattle, WA, August 15-17, 10 pages.

Ramos, R., T. H. Abdoun and R. Dobry. [2000]. *Effect of Lateral Stiffness of Superstructure on Bending Moments of Pile Foundation Due to Liquefaction-induced Lateral Spreading*, Proc. 12th World Conf. on Earthquake Engineering, Auckland, New Zealand, Jan. 30 - Feb. 4, 8 pages.

Sakajo, S., J. C. Chai, K. Nakajima and M. Maeda. [1995]. *Effect of Group Pile on Liquefaction Resistance of Sandy Ground*, Proc. 1st Intl. Conf on Earthquake Geotechnical Engineering (K. Ishihara, ed.), Tokyo, Japan, Nov. 14-16, Vol. 2, pp. 755-760.

Sato, M., Y. Shamoto and J.-M. Zhang. [1995]. *Soil-pile-structure During Liquefaction on Centrifuge*, Proc. Third Intl. Conf on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (S. Prakash, ed.), St. Louis, MO, April 2-7, Vol. I, pp. 135-142.

Sato, M. and J.-M. Zhang. [1998]. *Liquefaction-induced Damage to Caisson-type Quay Wall and its Neighboring Pile Foundation*, Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp.371-376.

Satoh, H., N. Ohbo and K. Yoshizako. [1998]. *Dynamic Test on Behavior of Pile During Lateral Ground Flow*, Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp.327-332.

Schofield, A. N. and R. S. Steedman. [1988]. *Recent Developments of Dynamic Model Testing in Geotechnical Engineering*, Proc. 9th World Conf. Earthquake Engng., Tokyo-Kyoto, 2-9 August, Vol. VIII, pp. 813-824.

Sharp, M. K. [1999]. *Development of Centrifuge Based Prediction Charts for Liquefaction and Lateral Spreading from Cone Penetration Testing,* PhD Thesis, Dept. of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Steedman, R. S. [1991]. *Centrifuge Modeling for Dynamic Geotechnical Studies,* State-of-the-art paper, Proc. Second Intl. Conf on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (S. Prakash, ed.), St. Louis, MO, March 11-15, Vol. III, pp.2401-2417.

Steedman, R. S. and Habibian, A. [1987]. *Modelling the Failure of Coastal Dykes During Earthquakes,* Proc European Conf. on Soil Mechanics and Foundation Engineering, 9, Vol. 2, pp. 633-636.

Steedman, R.S., R. H. Ledbetter and M E. Hynes. [2000]. *The Influence of High Confining Stress on Cyclic-induced Pore Pressure,* Proc. Geotech. Spec. Conf., ASCE, No. 107, Soil Dynamics and Liquefaction, GeoDenver.

Taboada, V. M. and R. Dobry. [1998]. *Centrifuge Modeling of Earthquake-Induced Lateral Spreading in Sand,* J. Geotechnical and Geoenvironmental Engineering, ASCE, 124(12):1195-1206.

Takahashi, A., J. Takemura, Y. Kawagushi, O. Kusakabe and N. Kawabata. [1998]. *Stability of Piled Pier Subjected to Lateral Flow of Soils During Earthquake,* Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp.365-370.

Taji, Y., M. Sato and E. Yanagisawa. [1998]. *Modeling of a Protoype Soil-pile-structure system During Seismic Ground Liquefaction,* Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp.283-288.

Tamura, K. and T. Azuma. [1997]. *Experimental Study of the Effects of Liquefaction-induced Ground Flow on Bridge Foundation,* Proc. Thirteenth U.S.-Japan Bridge Engineering Workshop, U.S.-Japan Panel on Wind and Seismic Effects, UJNR, Tsukuba, Japan, Oct. 2-3, 14 pages.

Tokida, K.-I., H. Matsumoto and H. Iwasaki. [1992]. *Experimental Study on Drag Acting on Piles in ground Flowing by Soil Liquefaction,* Proc. Fourth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures For Soil Liquefaction, Technical Report NCEER-92-0019, NCEER, SUNY-Buffalo, NY, Vol. II, pp. 511-523.

Towhata, I. [1995]. *Liquefaction and Associated Phenomenon,* Theme lecture, Proc. 1st Intl. Conf on Earthquake Geotechnical Engineering (K. Ishihara, ed.), Tokyo, Japan, Nov. 14-16, Vol. 3, pp. 1411-1434.

Van Laak, P., A.-W. Elgamal and R. Dobry. [1994a]. *Design and Performance of an Electrohydraulic Shaker for the RPI Centrifuge,* Proc. Intl. Conference Centrifuge'94,

Singapore, August 31-Sept. 2, (C.F. Leung, F.H. Lee and T.S. Tan, eds.), A.A. Balkema, Rotterdam, pp. 139-144.

Van Laak, P., V. Taboada, R. Dobry and A.-W. Elgamal. [1994b]. *Earthquake Centrifuge Modeling Using a Laminar Box*, Dynamic Geotechnical Testing II (R. J. Ebelhar, V. P. Drnevich and B. L. Kutter, eds.), ASTM STP 1231, pp. 370-384.

Van Laak, P., K. Adalier, R. Dobry and A.-W. Elgamal. [1998]. *Design of RPI's Large Servohydraulic Shaker*, Proc. Intl. Conf. Centrifuge'98 (T. Kimura, O. Kosakabe and J. Takemura, eds.), Tokyo, Japan, Sept. 23-25, Vol. 1, pp. 105-110.

Wilson, D. W. [1998]. *Soil-pile-superstructure Interaction at Soft and Liquefying Soil Sites*, PhD Thesis, U. of California at Davis, Davis, CA.

Wilson, D. W., R. W. Boulanger, B. L. Kutter and A. Abghari. [1998]. *Lateral resistance of Liquefying Sand*, Proc. 5th Caltrans Seismic Research Workshop, Sacramento, CA, June, 10 pages.

Wilson, D. W., R. W. Boulanger and B. L. Kutter. [1999]. *Lateral Resistance of Piles in Liquefying Sand*, Analysis, Design, Construction and Testing of Deep Foundations, Proc. OTRC'99 Conf. Honoring Lymon C. Reese (J. M. Roesset, ed.), Geotechnical Special Publication No. 88, ASCE, Reston, VA, pp. 165-179.

Wilson, D. W., R. W. Boulanger and B. L. Kutter. [2000]. *Observed Seismic Lateral Resistance of Liquefying Sand*, J. Geotechnical and Geoenvironmental Engineering, ASCE, 126(10): 898-906, October.

Yasuda, S., T. Kobayashi, H. Nomura and T. Terauchi. [1996]. *Shaking Table Tests on the Lateral Flow of the Liquefied Ground Behind Quay Walls*, Proc. Sixth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Technical Report NCEER-96-0012, NCEER, SUNY-Buffalo, NY, pp. 275-288.

Yokoyama, K., K. Tamura and O. Matsuo. [1997]. *Design Methods of Bridge Foundations Against Soil Liquefaction and Liquefaction-Induced Ground Flow*, 2nd Italy-Japan Workshop on Seismic Design and Retrofit of Bridges, Rome, Italy, February 27-28, 23 pages.