LIQUEFACTION-INDUCED SETTLEMENTS OF BUILDINGS WITH SHALLOW FOUNDATIONS

1. Key parameters found in the field
2. Key parameters found from centrifuge experiments
3. key challenges and paths forward

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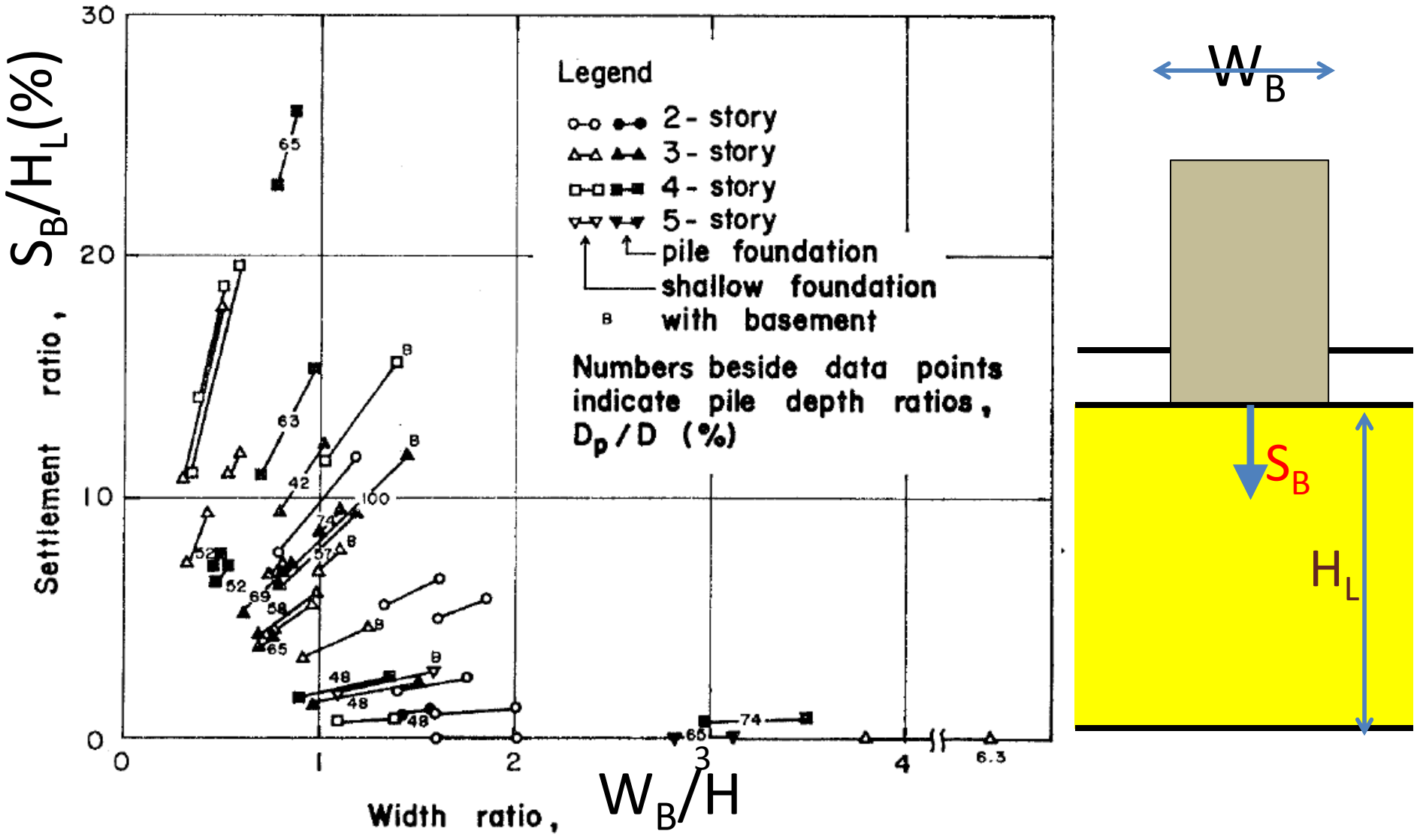
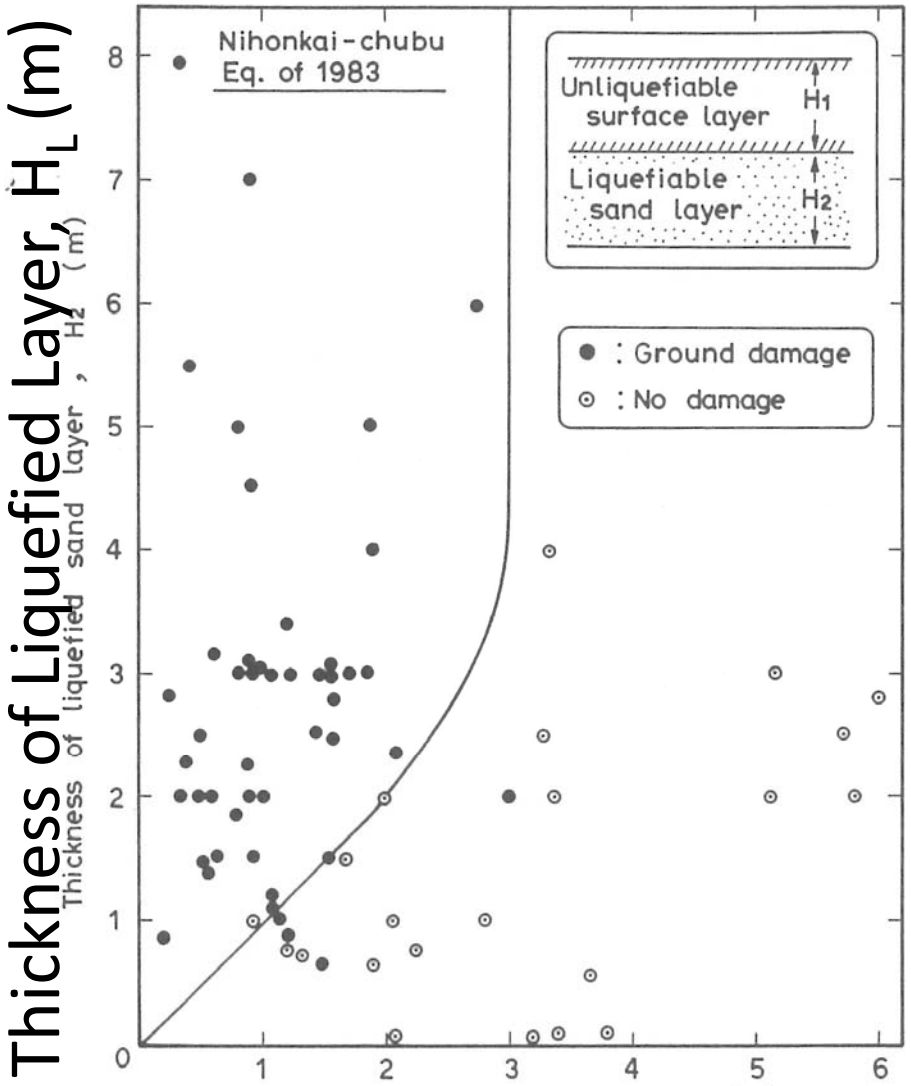
1. Key parameters observed in the field

Effects of W_B/H_L on Normalized building settlement (S_B/H_L)



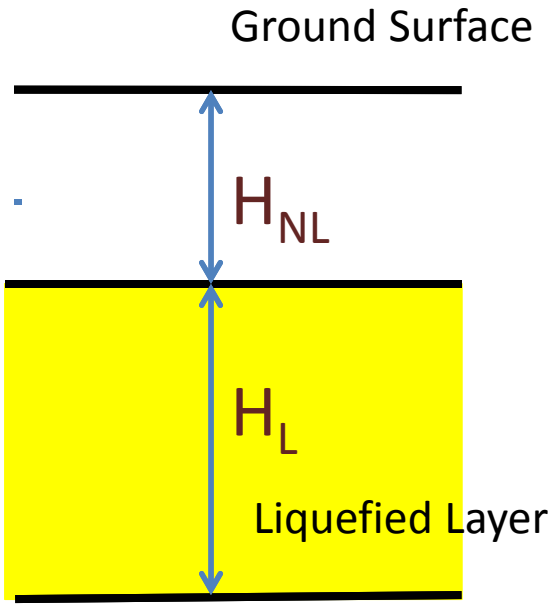
Yoshimi, Y., and Tokimatsu, K. (1977): Settlement of buildings on saturated sand during earthquakes, Soils and Foundations, 17(1), 23–38.

Effects of Thickness of Surface Crust



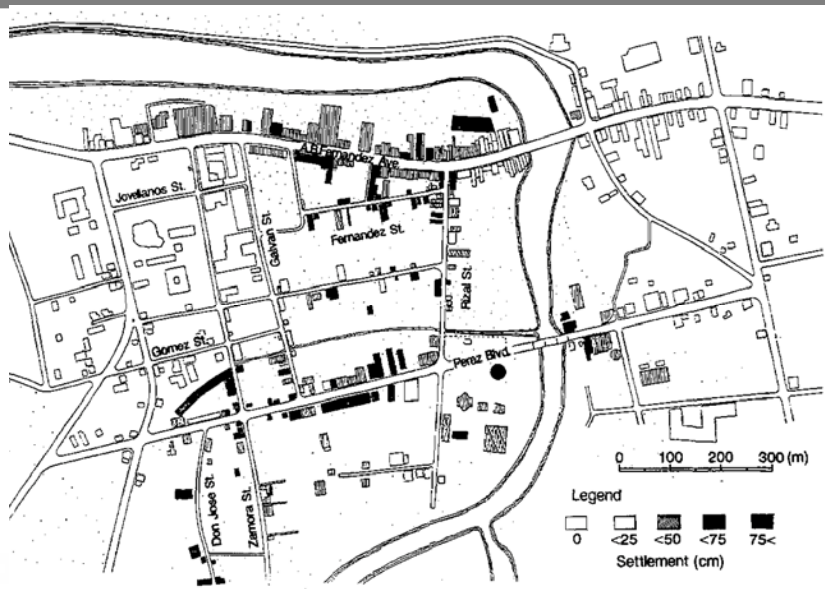
Thickness of Liquefied Layer, H_L (m)

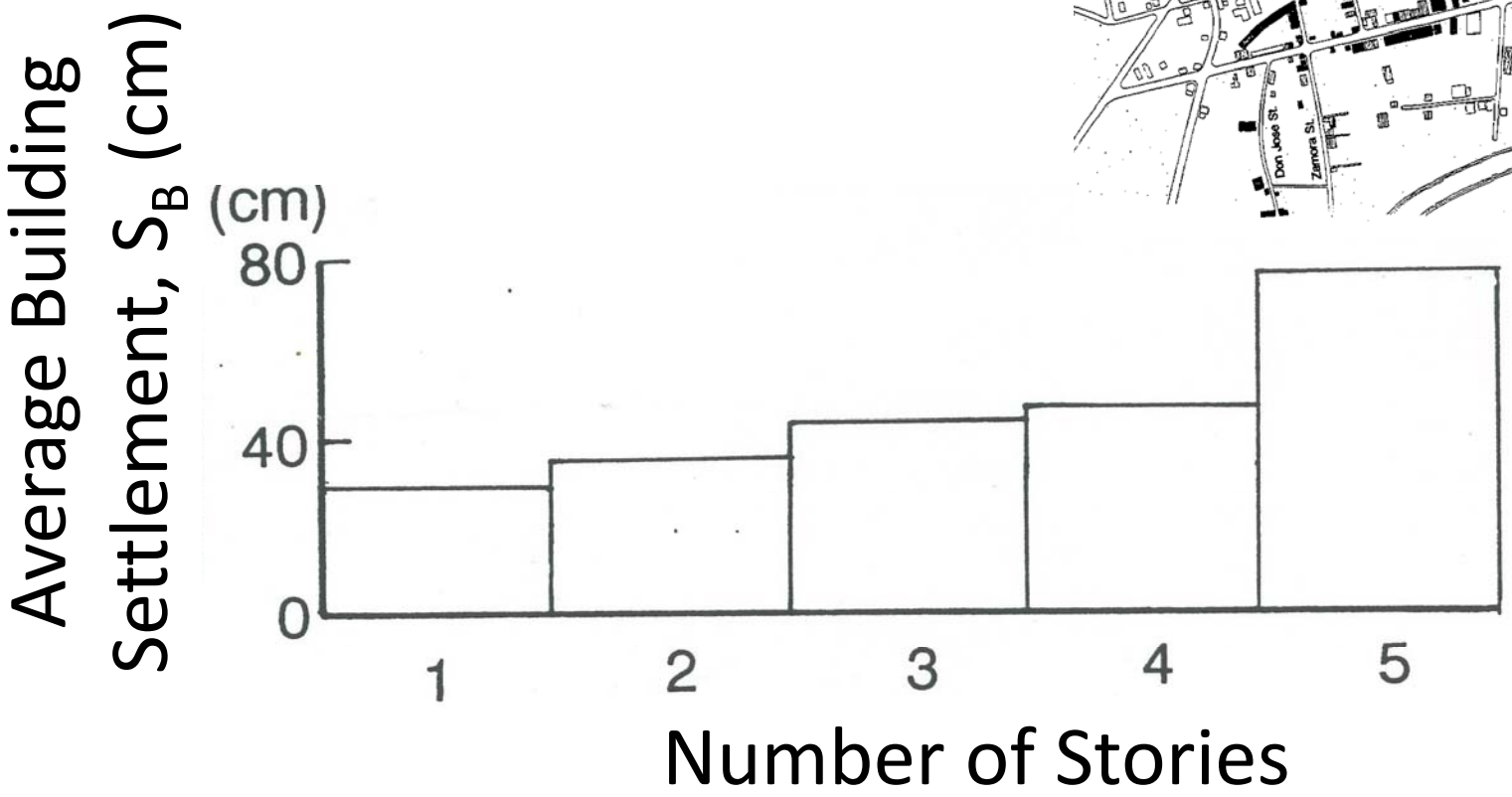
Thickness of Crust, $H_{NL(m)}$



Ishihara, K. (1985): Stability of natural deposits during earthquakes, Proc., 11th ICSMFE, Vol. 1, 321-376.

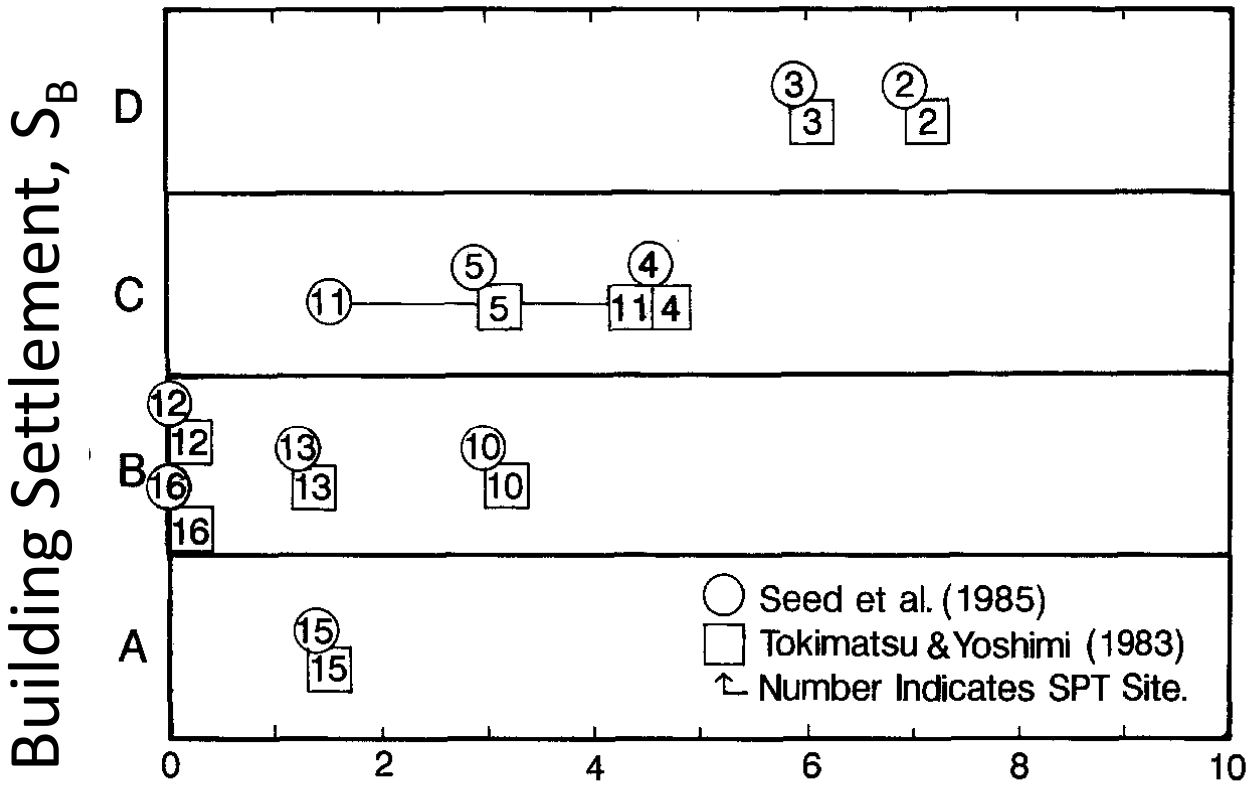
Effects of contact pressure or stories





Tokimatsu, K., Kojima, J., Kuwayama, S., Abe, A., and Midorikawa, S. **(**1994): Liquefaction-induced damage to buildings during 1990 Luzon Earthquake, J. Geotech. Engrg., 120**(**2**)**, 290–307.

Effects of H_L on Building Settlement



Extensive liquefaction with building settlement more than 50 cm

Extensive liquefaction with building settlement less than 50 cm

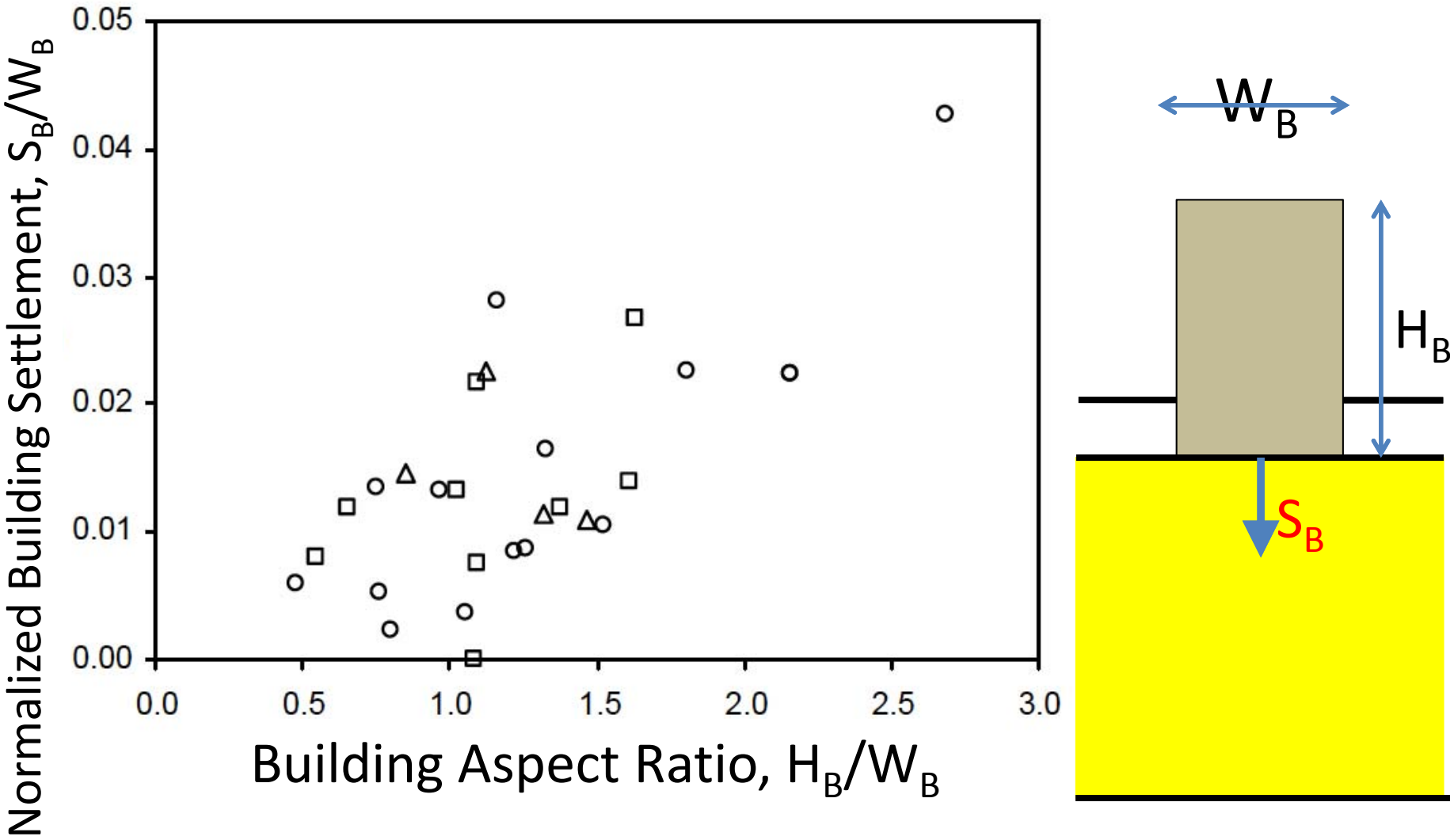
Marginal zone without building settlement

No liquefaction without building settlement

Estimated Thickness of Liquefied Layer, H_L (m)

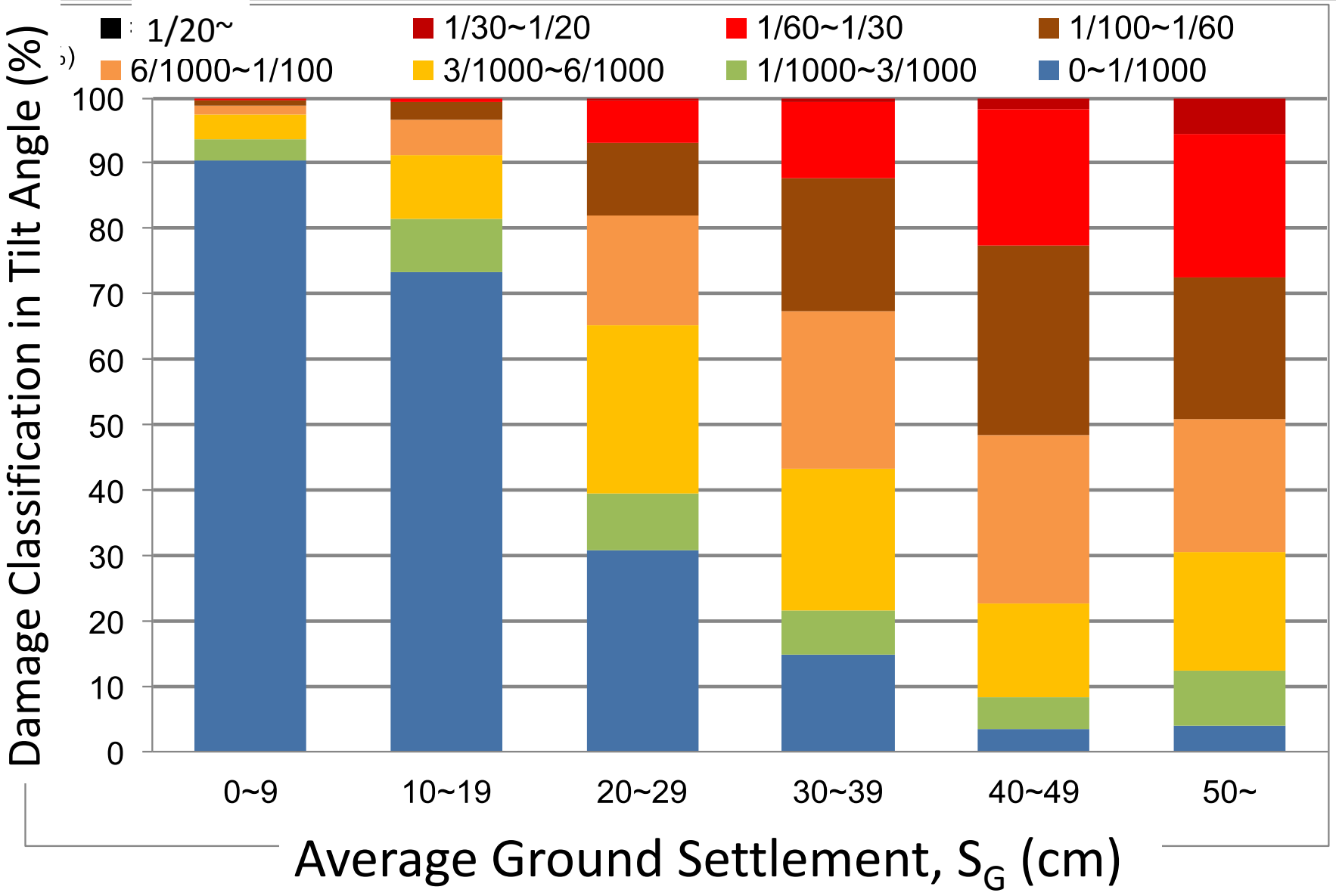
Tokimatsu, K., Kojima, J., Kuwayama, S., Abe, A., and Midorikawa, S. **(**1994): Liquefaction-induced damage to buildings 1990 Luzon Earthquake, J. Geotech. Engrg., 120**(2)**, 290–307.

Effects of aspect ratio on building settlements



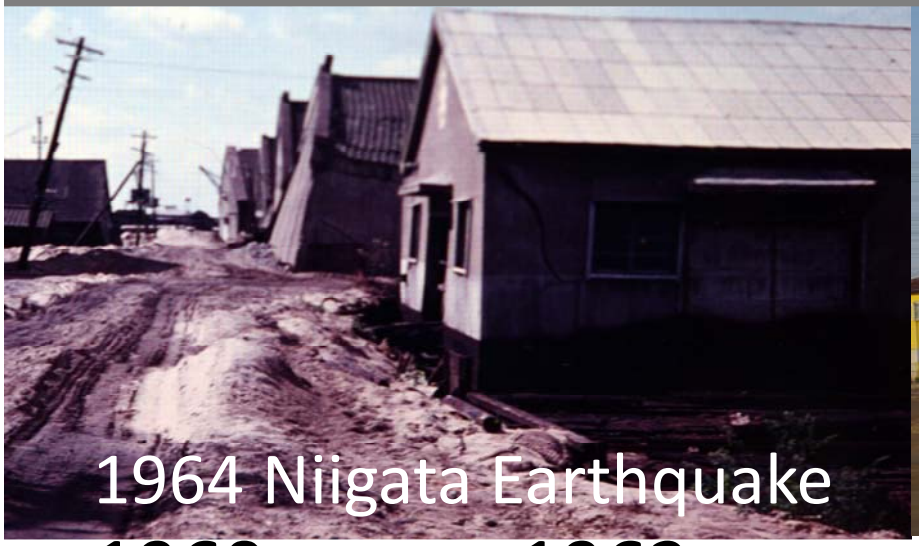
Sancio, R., Bray, J. D., Durgunoglu, T., and Onalp, A. **(**2004**):** Performance of buildings over liquefiable ground in Adapazari, Turkey, Proc., 13th World Conf. on Earthquake Engineering, St. Louis, Mo., Canadian Association for Earthquake Engineering, Vancouver, Canada, Paper No. 935.

Ground Settlement vs Tilt Angle of Houses



Tokimatsu, K., Tamura, S., Suzuki, H., and Katsumata, K. (2012): Building damage associated with geotechnical problems in the 2011 Tohoku Pacific Earthquake, Soils and Foundations, 52(5), 956-974.

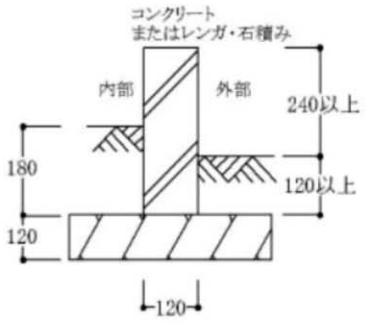
Effects of Foundation Rigidity on Failure Mode

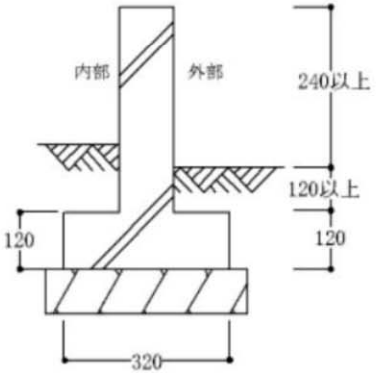


1960 1962 1982 2000

Unreinforced concrete foundations

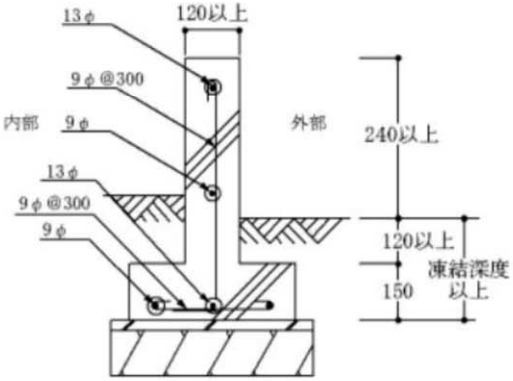
Structural Damage

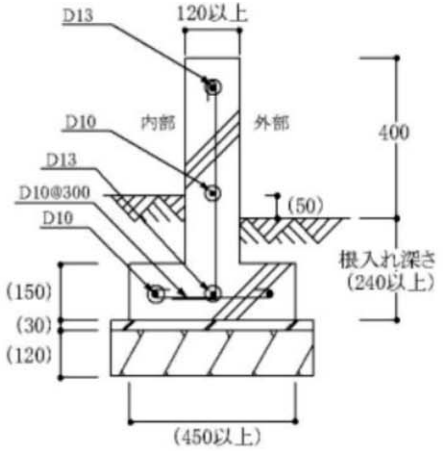




Reinforced concrete foundations

Building settlement & Tilt

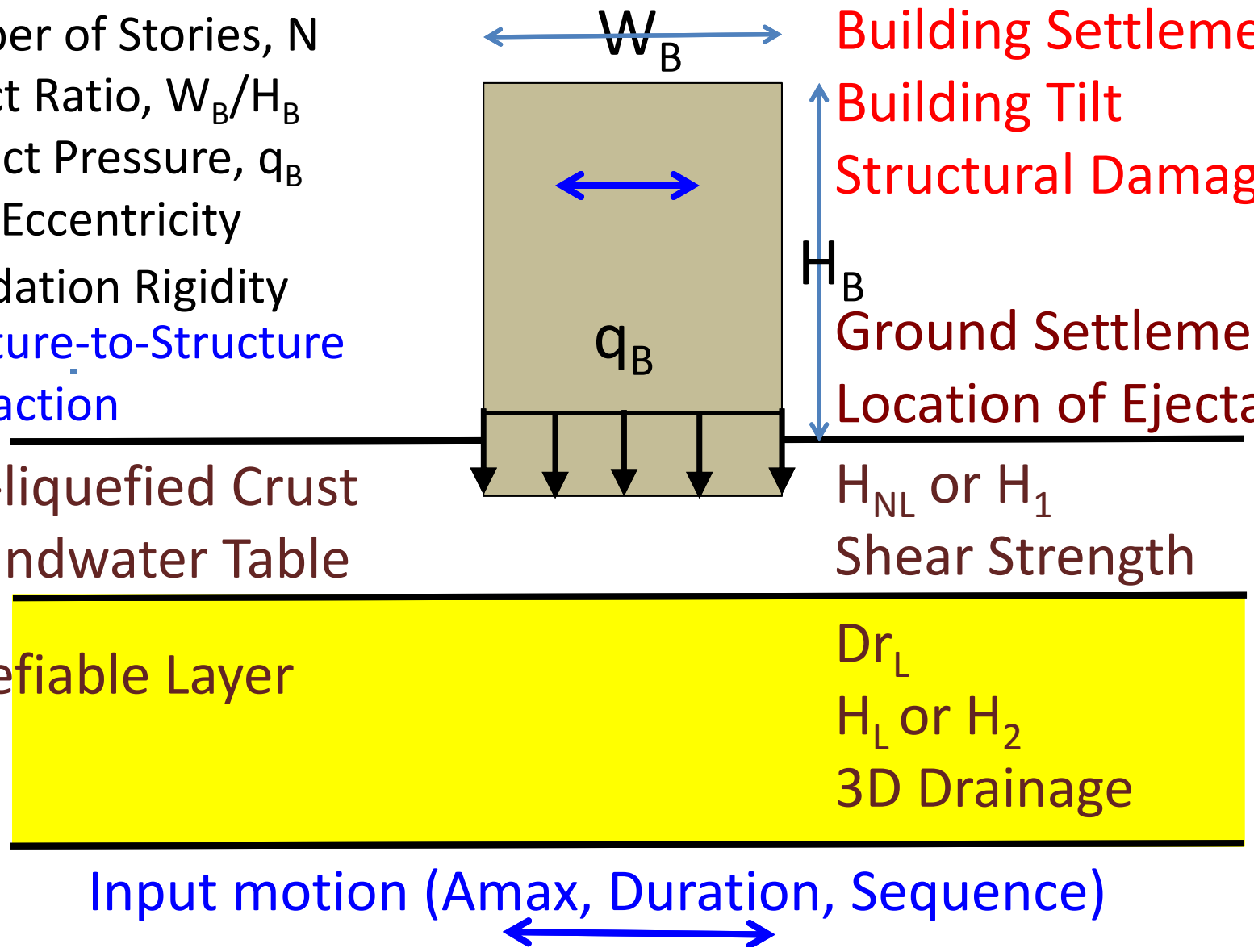




Key Parameters Observed in the Field

Building Response

Number of Stories, N
Aspect Ratio, W_B/H_B
Contact Pressure, q_B
Mass Eccentricity
Foundation Rigidity
Structure-to-Structure Interaction

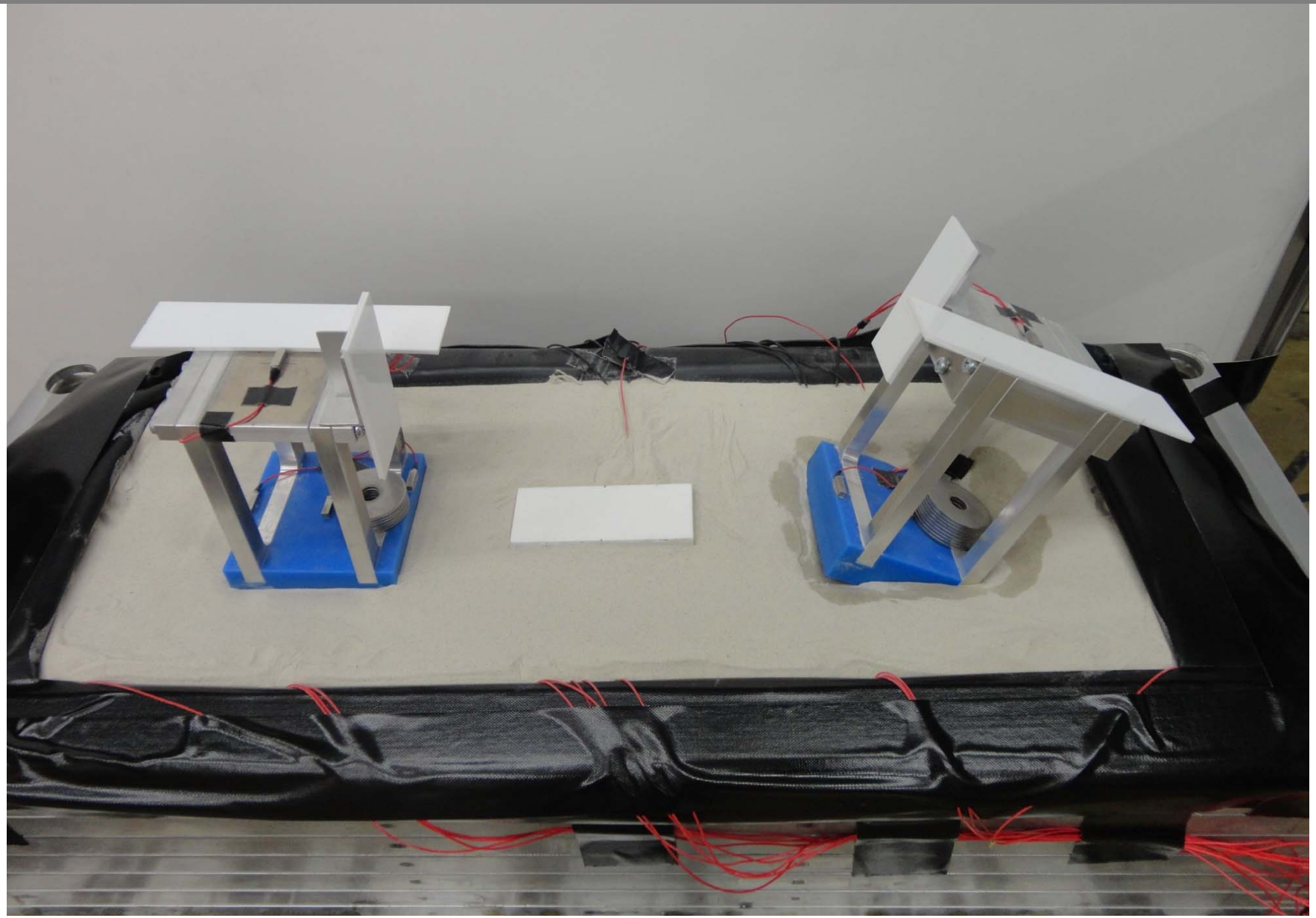


Summary from Field Observation

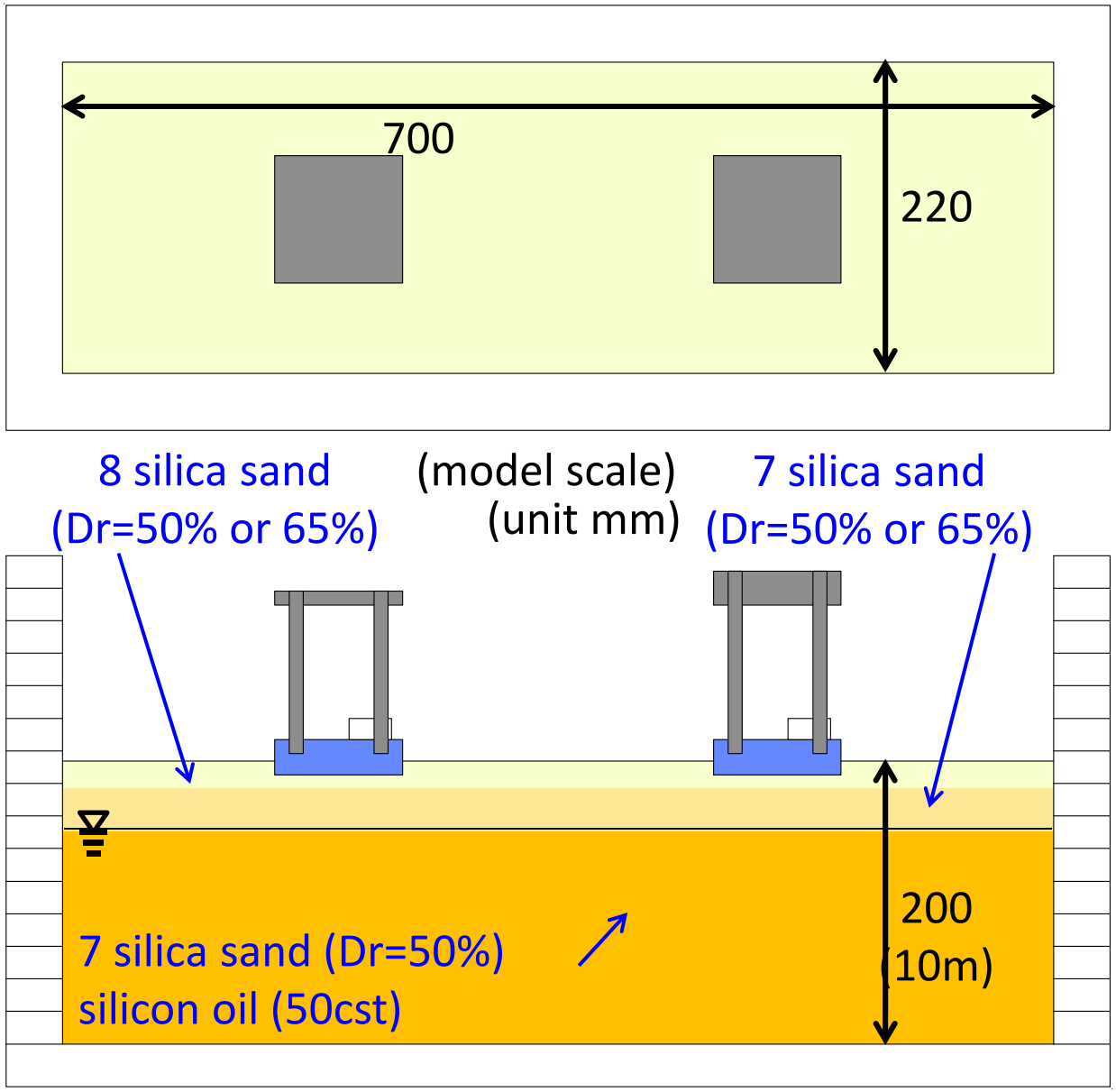
(1) Liquefaction-induced settlements of buildings with shallow foundations were affected by various factors, relative effects of which have not been clearly identified.

(2) A simplified procedure should be pursued for better understanding of the mechanism that could explain building damage in most of the complied case histories.

2. Key parameters found in the lab



Description of Centrifuge Shaking Table Tests

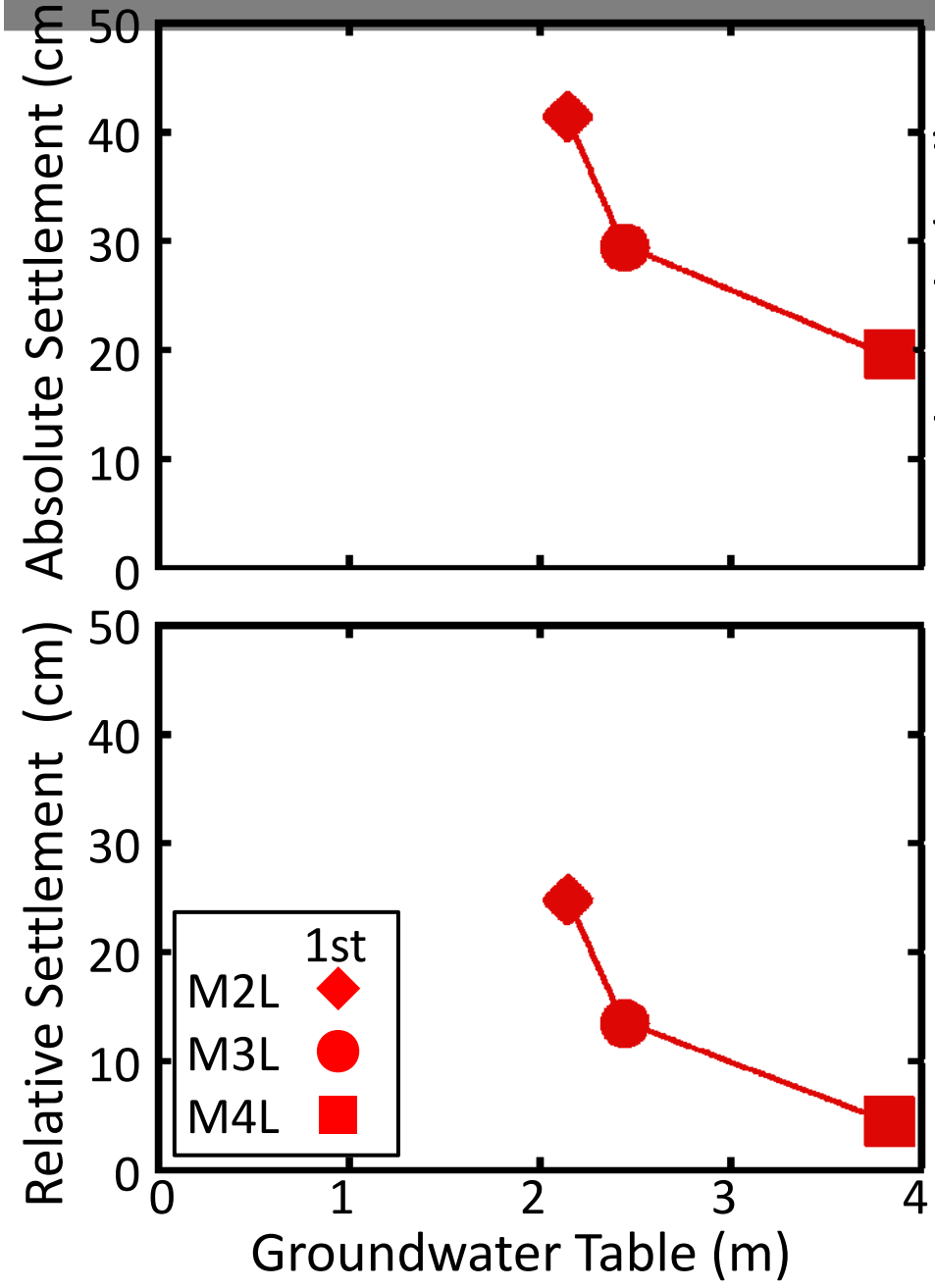


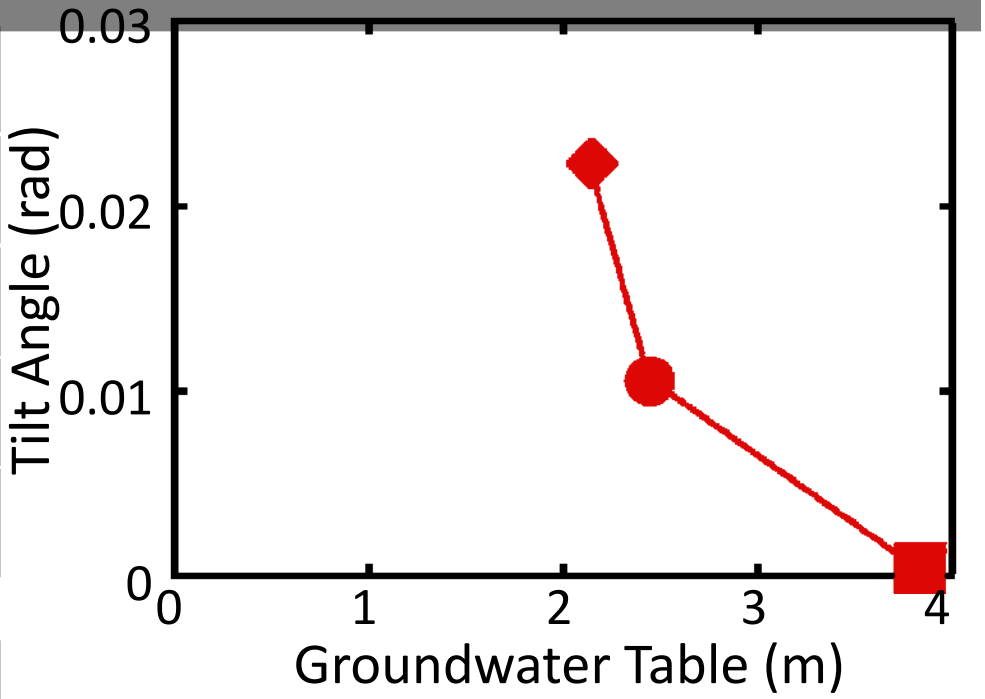
Experimental Variables

Contact pressure
Building height and width
Mass eccentricity ratio
Groundwater depth
Thickness and Density of Liquefied soil

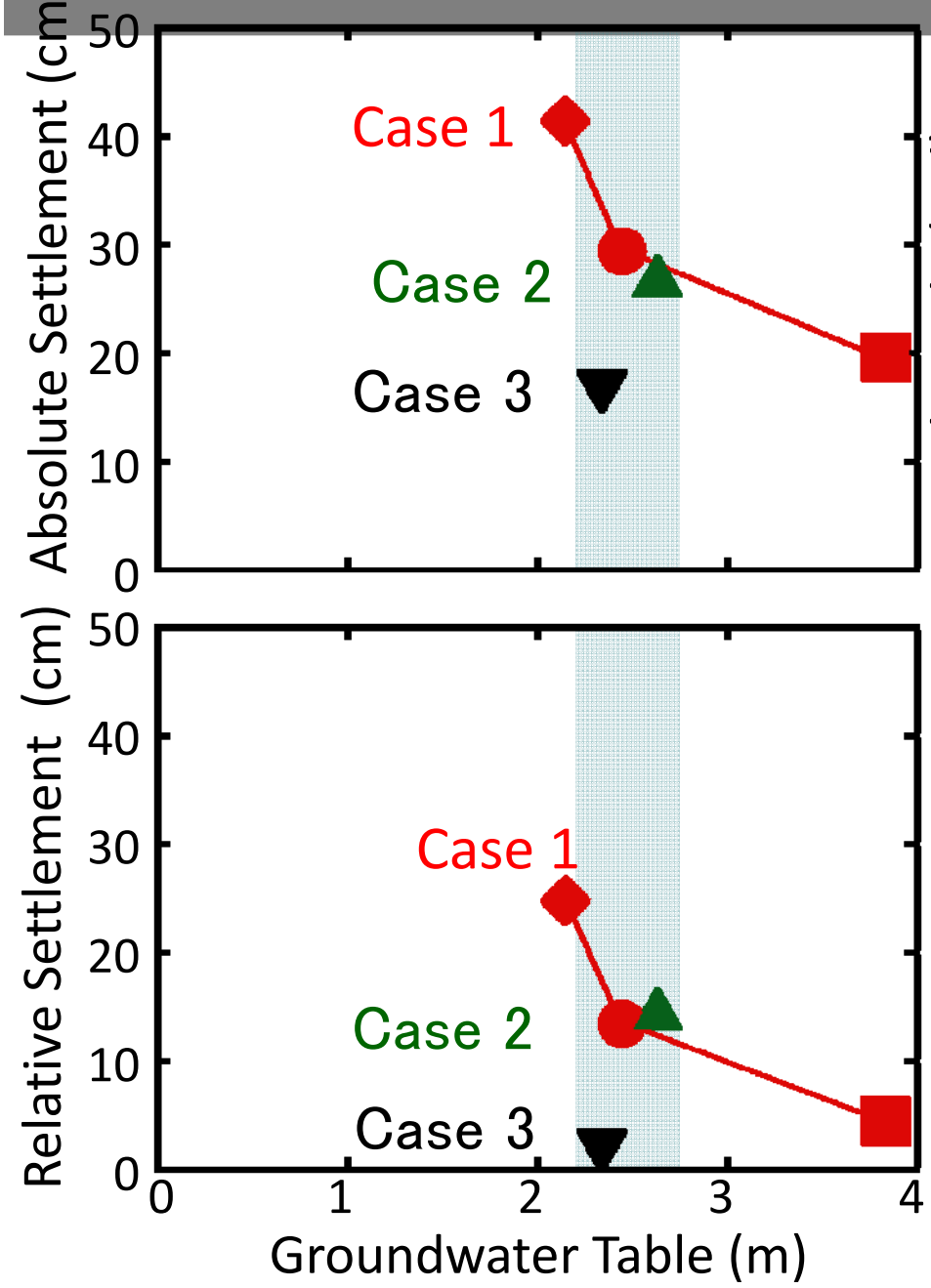
Input PGA
Centrifuge Acceleration
50g with small container
25g with large container

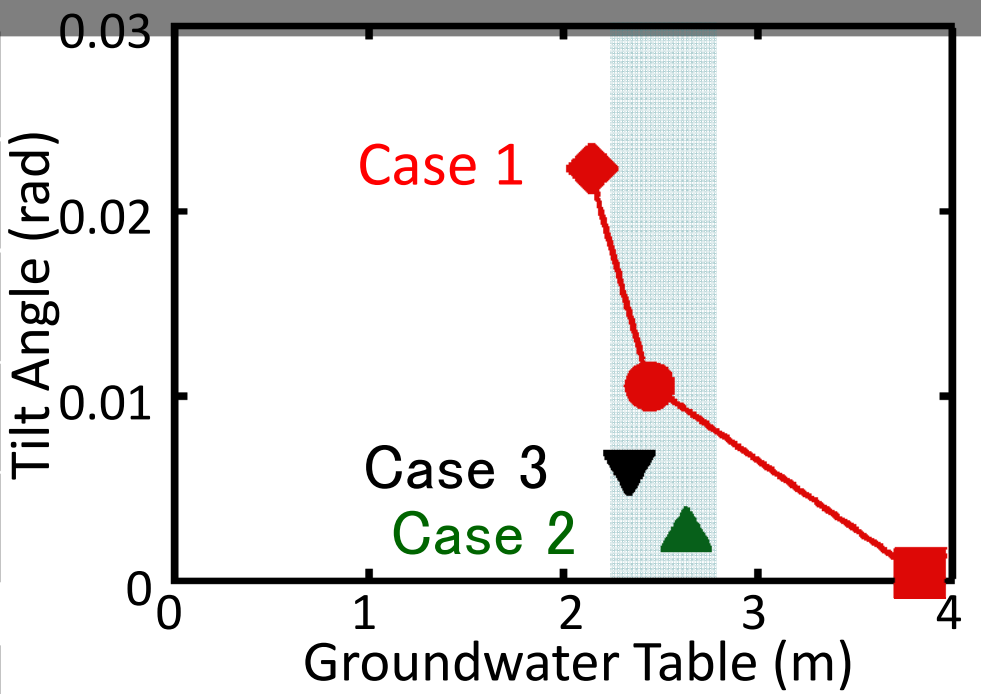
Effects of Groundwater Table

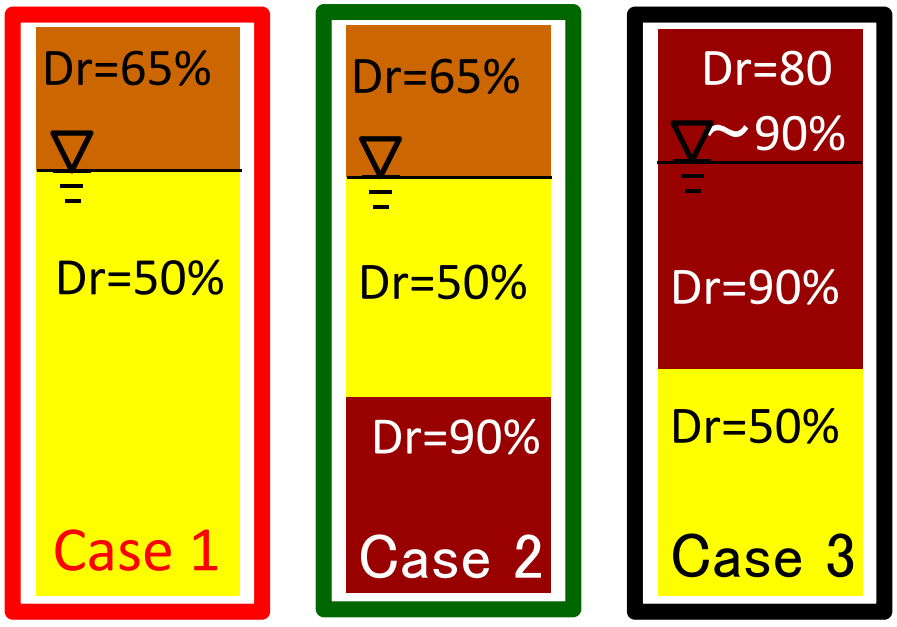




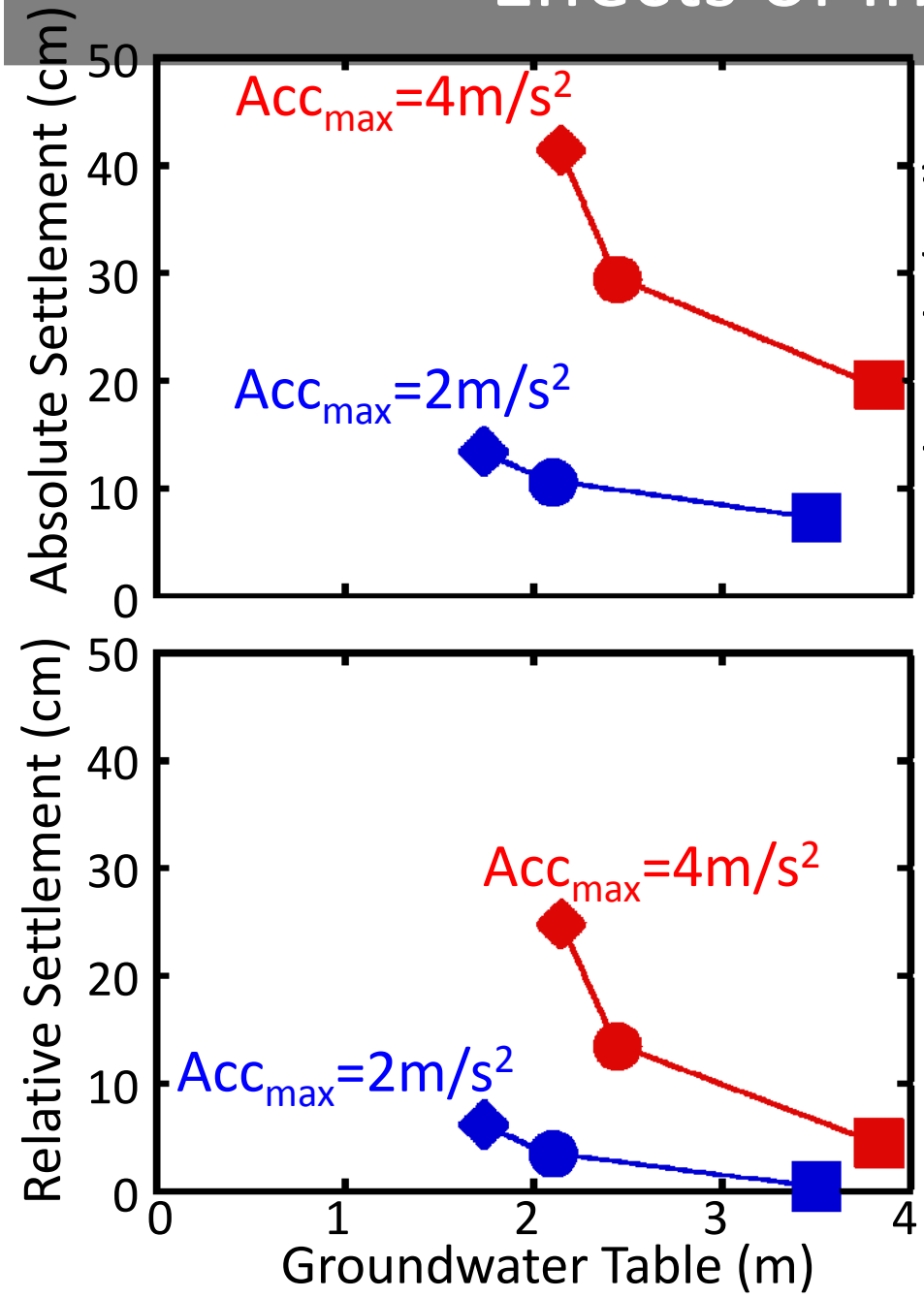
Effects of Soil Density & Location of Liquefied Soil

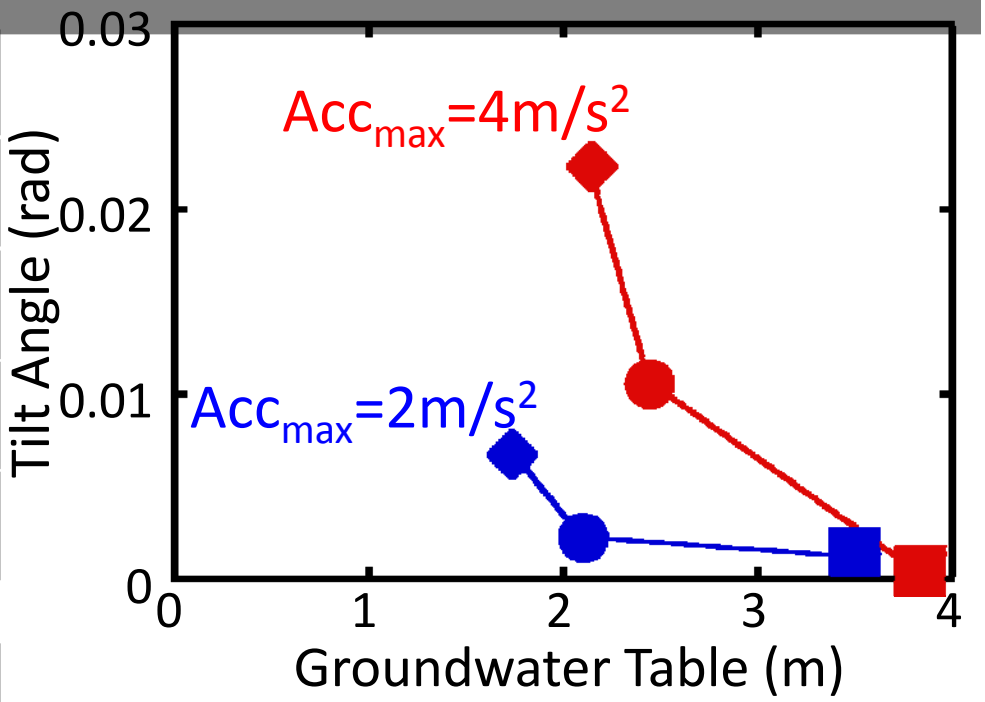






Effects of Input Motions





Factor of Safety against Vertical Load

$$F_{SW} = R_W / L_W$$

Resistance

$$R_W = \int_0^Z (K\sigma_v' \tan\theta)dz \times (2B+2L)$$

Self-Weight of Building

$$L_W = (m_1+m_2+m_e)g$$

K : Earth Pressure Coefficient

σ_v' : Effective Stress

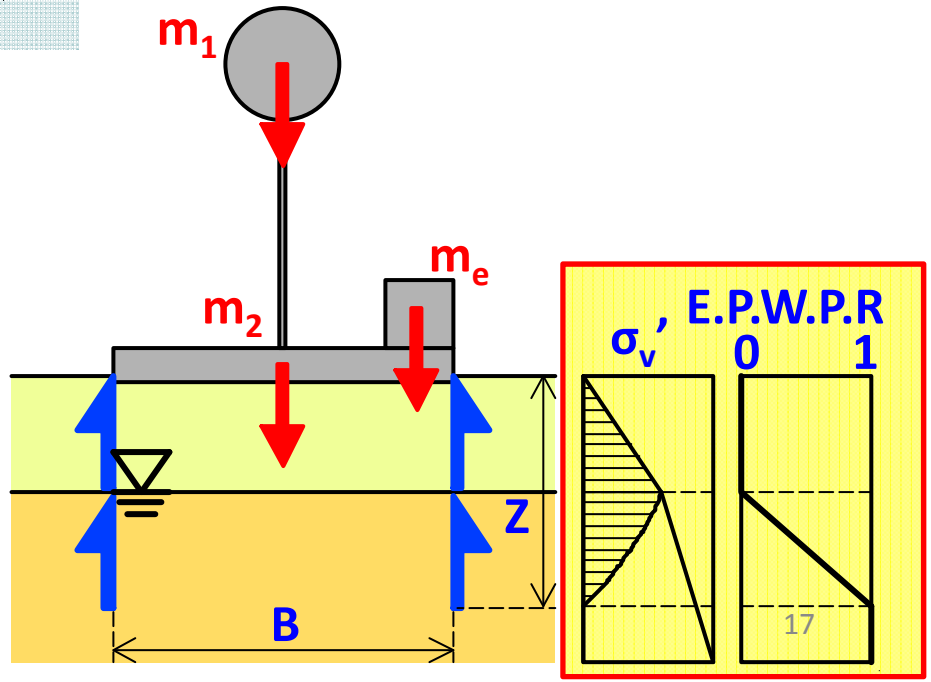
Z : Thickness of Non-liquefied Crust

θ : Internal Friction Angle

B , L : Dimension of Foundation

m_1 , m_2 , m_e : Mass of Building

g : Gravitational Acceleration



Factor of Safety against Overturning Moment

$$F_{SMe} = R_{Me} / L_{me}$$

Resisting Moment

$$R_{Me} = \int_0^Z (K\sigma_v' \tan\theta)dz \times (B+L)B$$

Driving Moment

$$L_{Me} = (m_1 + m_2)gB/2 + m_e g(B/2+e) + m_1 a_1 h_1 + (m_2+m_e)a_2 h_2$$

K : Earth Pressure Coefficient

σ_v' : Effective Stress

Z : Thickness of Non-liquefied Crust

θ : Internal Friction Angle

B , L : Dimension of Foundation

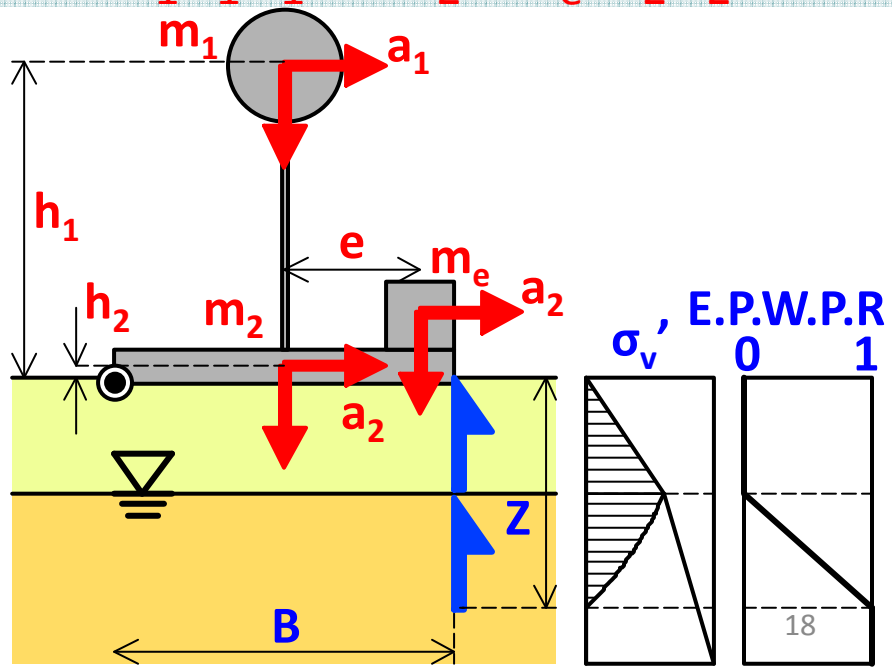
m_1 , m_2 , m_e : Mass of Building

g : Gravitational Acceleration

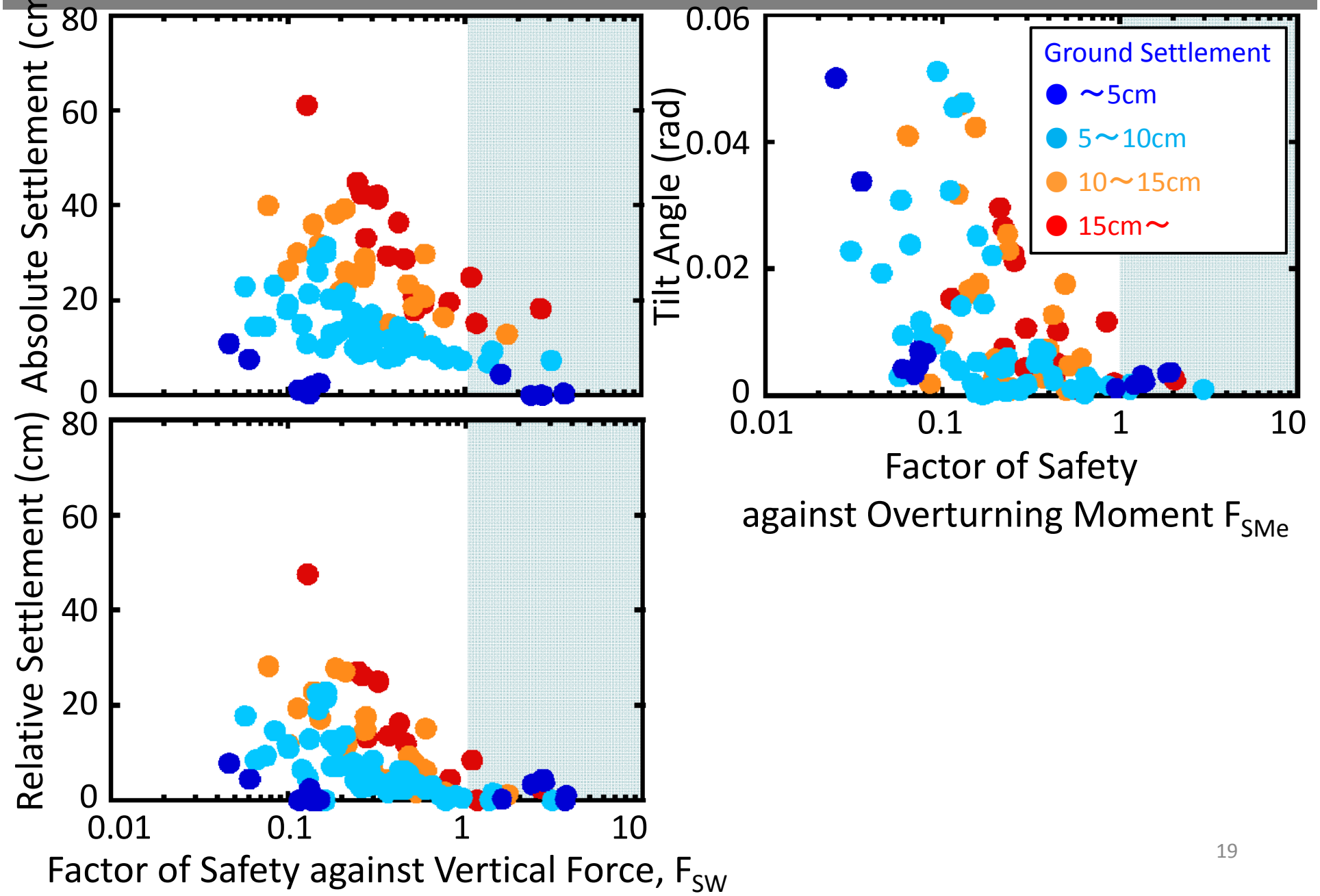
a_1 , a_2 : Building Acceleration

h_1 , h_2 : Height

e :Eccentric Distance



Factors of Safety vs Building Settlement and tilting



Summary from Centrifuge Experiment

(1) The relative settlement and tilt angle of a building decreased as the crust thickness (H_{NL}) and the density of liquefied soil (D_{rL}) increased or the thickness of the liquefied soil (H_L) and building contact pressure (q_B) decreased.
(2) The effects of soil liquefaction on building damage were well accounted for by the safety factors against vertical force and static and dynamic overturning moments of the building together with the liquefaction severity of the underlying liquefiable deposit, represented by the integration of liquefaction-induced volumetric strain with depth.

3. KEY CHALLENGES AND PATHS FORWARD

(1) Compilation/revisit of well documented case histories of liquefaction-induced ground and building settlements during resent earthquakes.

(2) Centrifuge experiments to identify relative effects of key parameters on building settlements.

(3) Development of a simplified procedure that can explain liquefaction-induced building damage in most of the complied case histories and centrifuge experiments.

3. KEY CHALLENGES AND PATHS FORWARD (CONT.)

(4) Refinement of numerical and design procedures to estimate ground and building settlements, which should be substantiated by well-documented case histories and centrifuge experiments.

(5) Development of cost effective mitigation techniques taking into account the key parameters controlling settlement and tilting of buildings.