Ground deflection walls to mitigate lateral spreading forces on foundation systems

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ASCE Oregon Section
Geotechnical Engineering Technical Group
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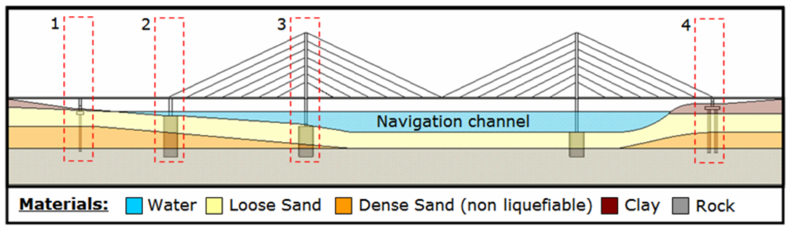

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Acknowledgements

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Presentation outline

- ***Motivation***
- *Centrifuge testing program*
- *Instrument response and ground behavior*
- *Analytical models*
- *Novel lateral pressure mitigation method*

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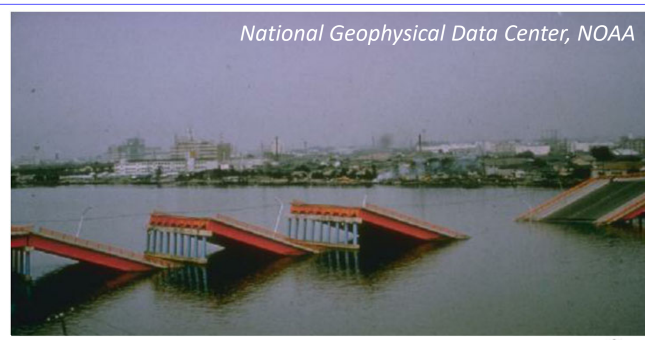
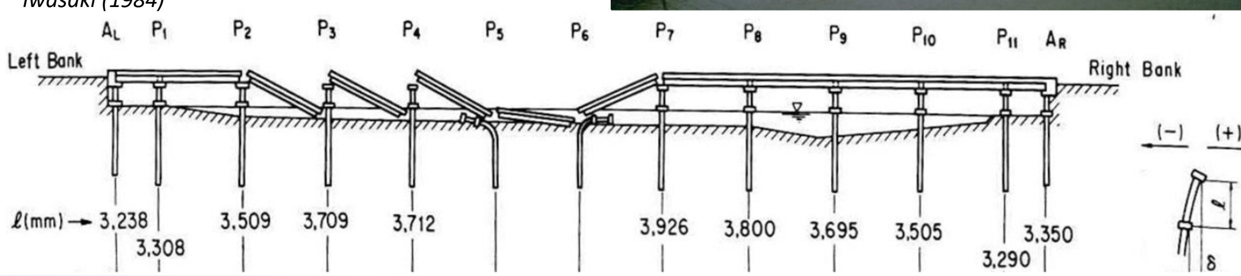
The motivation

- *Showa bridge, 1964 Niigata earthquake, Japan*



National Geophysical Data Center, NOAA

Iwasaki (1984)



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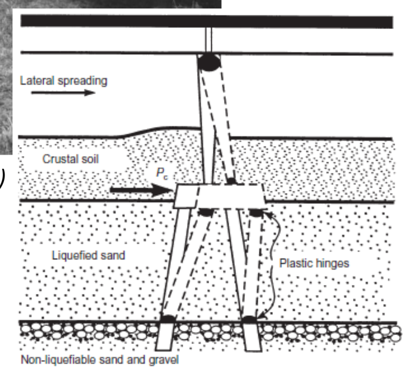
The motivation

- *Showa bridge, 1964 Niigata earthquake, Japan*
- *Landing Road bridge, 1987 Edgecumbe earthquake, NZ*



Berrill et al. (2001)

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The motivation

- *Showa bridge, 1964 Niigata earthquake, Japan*
- *Landing Road bridge, 1987 Edgecumbe earthquake, NZ*
- *Nishinomiya-ko bridge, 1995 Kobe earthquake, Japan*

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The motivation

- *Showa bridge, 1964 Niigata earthquake, Japan*
- *Landing Road bridge, 1987 Edgecumbe earthquake, NZ*
- *Nishinomiya-ko bridge, 1995 Kobe earthquake, Japan*
- *Llacolen and Puento Viejo bridges, 2010 Maule earthquake, Chile*

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The motivation

- *Bill Emerson Memorial bridge (I-55) over the Mississippi River, Cape Girardeau, MO*

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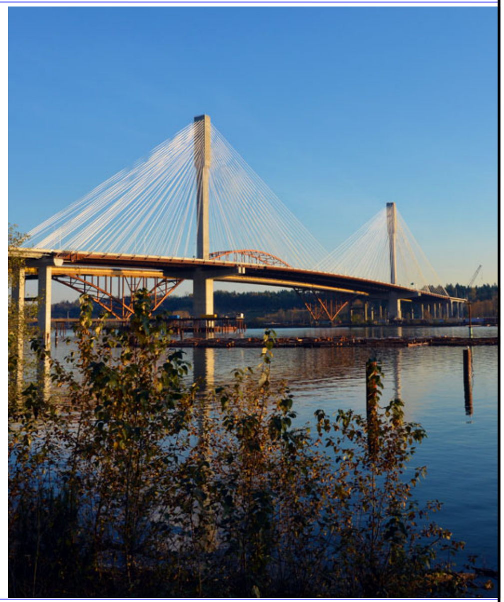
The motivation

- *Bill Emerson Memorial bridge (I-55) over the Mississippi River, Cape Girardeau, MO*
- *Port Mann bridge over the Fraser River, Vancouver, BC*



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The motivation

- *Bill Emerson Memorial bridge (I-55) over the Mississippi River, Cape Girardeau, MO*
- *Port Mann bridge over the Fraser River, Vancouver, BC*
- *Stan Musial Veterans Memorial bridge (I-70) over the Mississippi River, St. Louis, MO*

idot.Illinois.gov

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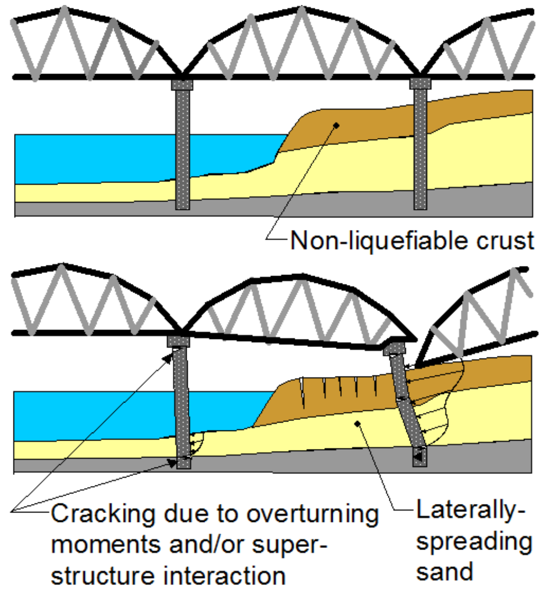
The motivation

- *Increasing infrastructure demand and higher seismic loads (in many areas) require larger foundations*
- *Engineers lack adequate design tools when dealing with lateral spreading forces against large foundation systems*
- *Most solutions involve potentially conservative designs*



Muszynski et al. (2013)

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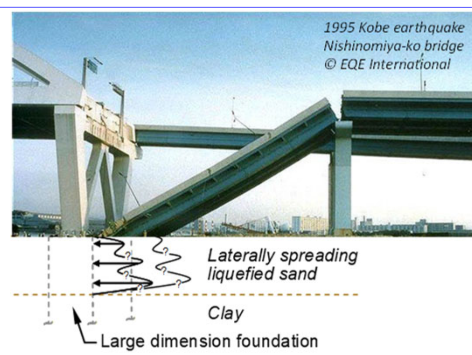
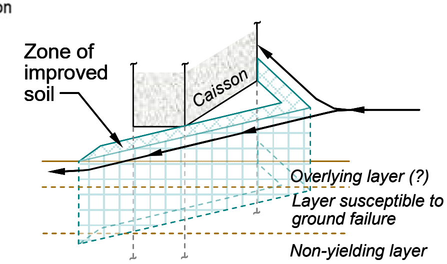
Objectives of this study

- *Measure lateral spreading-induced pressures against a rigid foundation element*
- *Develop practical design guidelines for predicting these pressures against large foundation used in design*
- *Explore novel approaches to mitigate effects of the increase in lateral pressure*





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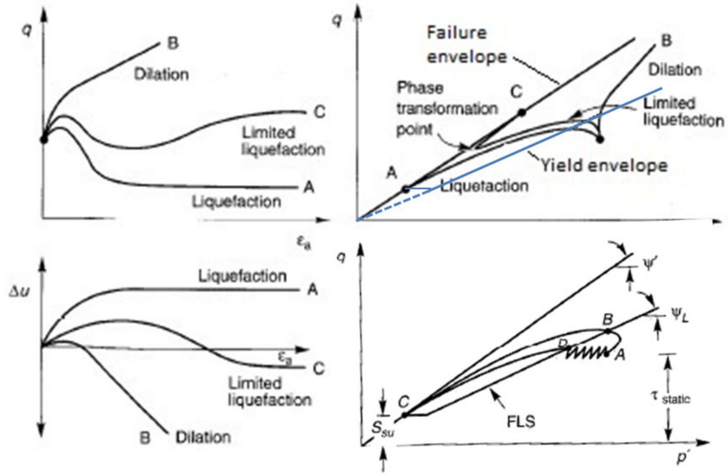
Liquefaction and lateral spreading

- *Fundamentally, liquefaction can be induced by monotonic or cyclic loading*
- *Lateral spreading is a consequence of cyclic mobility of liquefiable soil located below gently sloping ground or near a surface incision*



modified from Kramer (1996)

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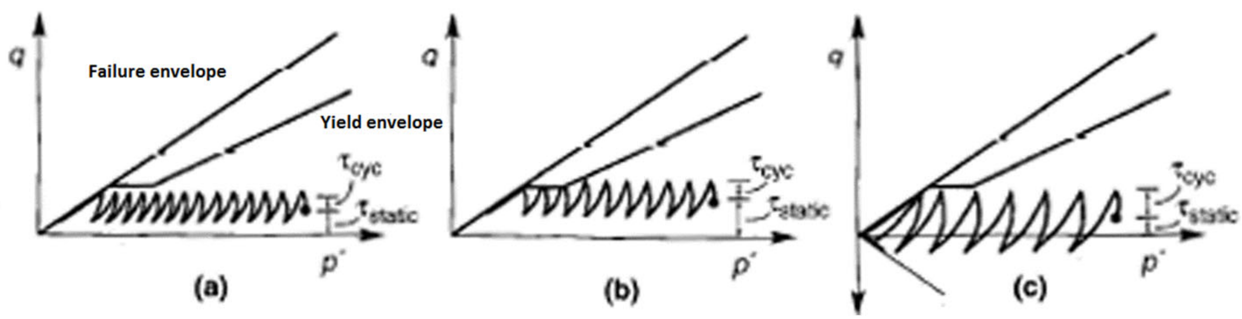
Liquefaction and lateral spreading



modified from Kramer (1996)

- *Lateral spreading is a consequence of cyclic mobility of liquefiable soil located below gently sloping ground or near a surface incision*
- *Lateral spreading is possible when initial shear stress is smaller than the liquefied shear strength*

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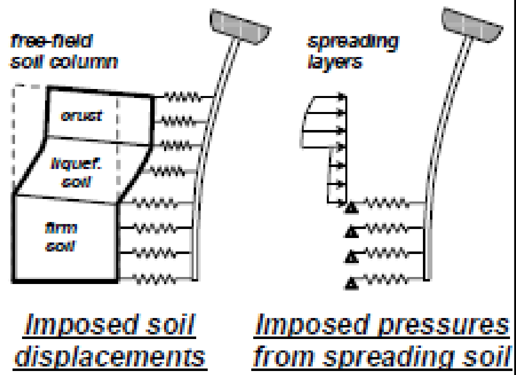
Approaches to estimate lateral pressures on foundations

- *Lateral loads on flexible foundations involves a complex, kinematic soil structure interaction phenomenon driven by the permanent lateral displacement of the ground in the free-field (Dobry et al. 2003)*
- *Approach 1: Use p-y curves for soil considering the relative movement of the foundation and laterally spreading soil (soil-structure interaction method)*



Boulanger et al. (2003)

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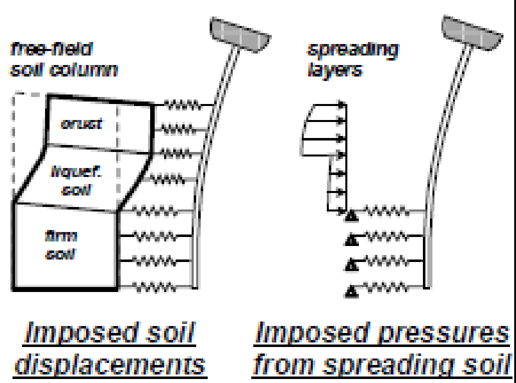
Approaches to estimate lateral pressures on foundations

- *Lateral loads on flexible foundations involves a complex, kinematic soil structure interaction phenomenon driven by the permanent lateral displacement of the ground in the free-field (Dobry et al. 2003)*
- *Approach 2: Assign a peak pressure against the foundation based on the shear strength of the soil (limit equilibrium method)*



Boulanger et al. (2003)

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Presentation outline

- *Motivation*
- ***Centrifuge testing program***
- *Instrument response and ground behavior*
- *Analytical models*
- *Novel lateral pressure mitigation method*

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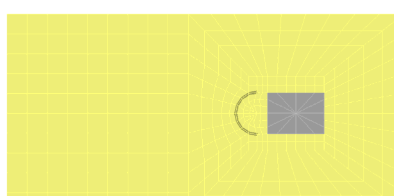
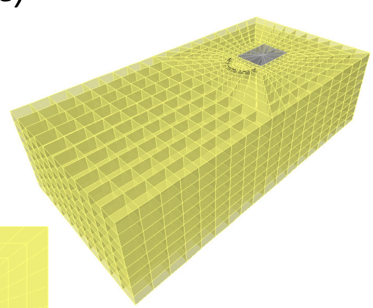
Research program

- *Physical modeling and analytical method development (Muszynski 2013)*
- *Numerical simulations (Phillips 2013 – not detailed here)*





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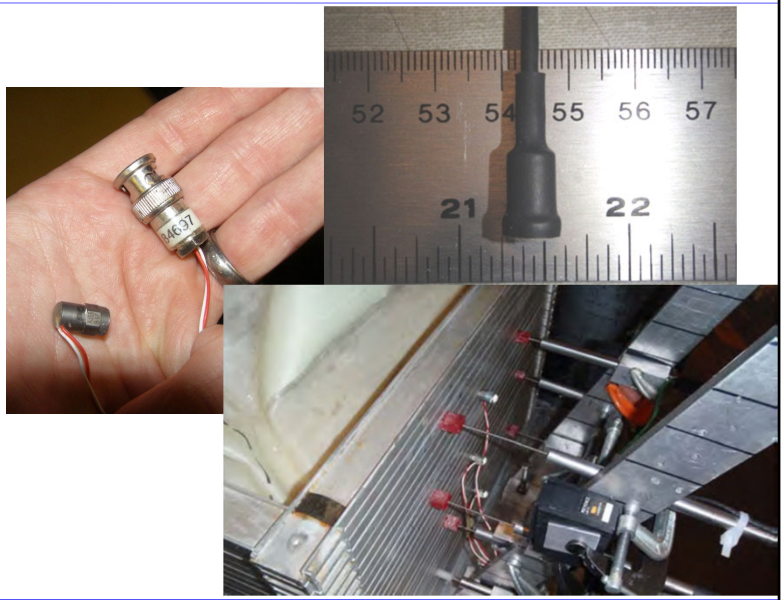
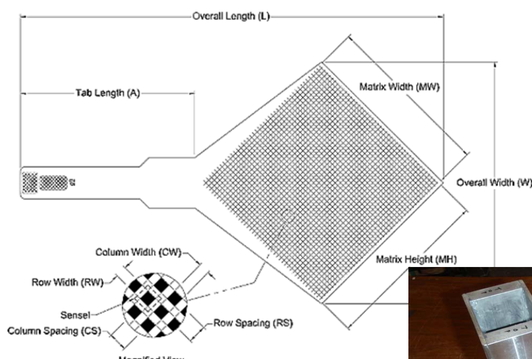
Equipment and instruments

- *Centrifuge facility*
- *Accelerometers*
- *Pressure transducers*
- *Linear voltage differential transformers*
- *Laminar container*
- *High-speed camera*
- *Laser displacement sensors*
- *Tactile pressure sensors*



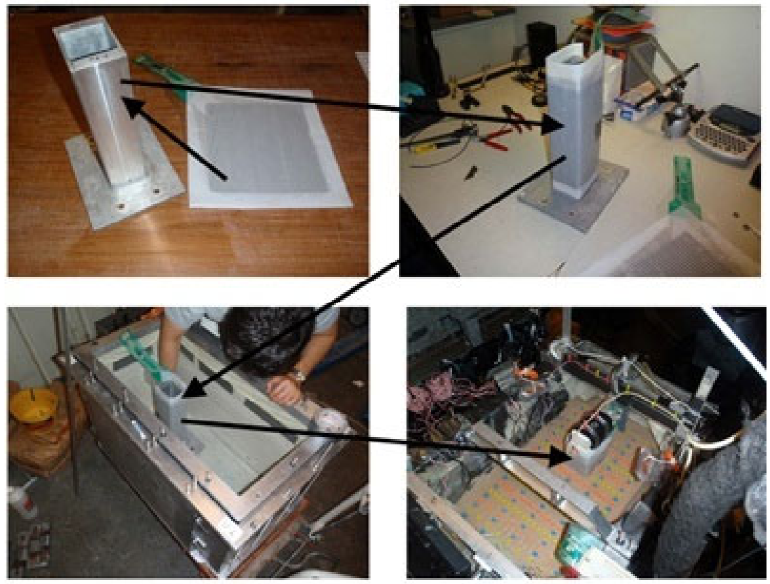
Equipment and instruments

- *Tactile pressure sensors laminated prior to use for protection and waterproofing*
- *Outfitted with Teflon to decrease shear stresses and increase protection*



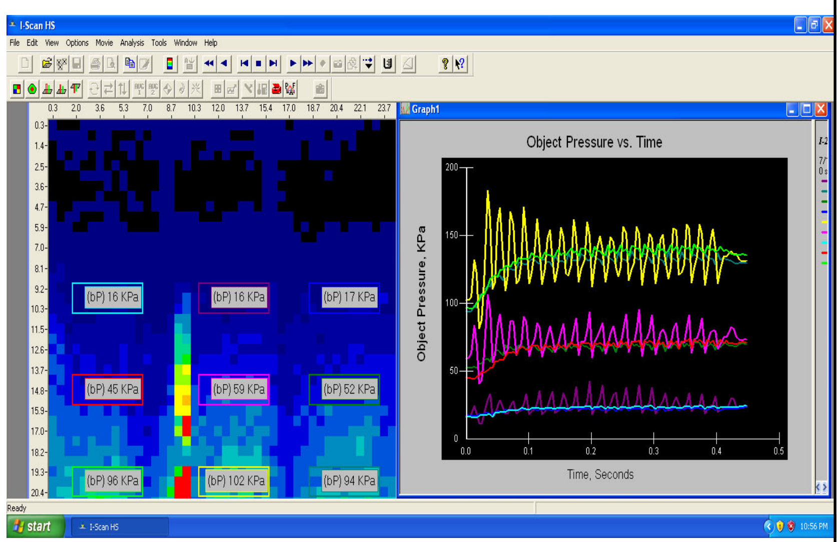
Equipment and instruments

- *Tactile pressure sensors wrapped around rigid caisson bolted to base of laminar container*



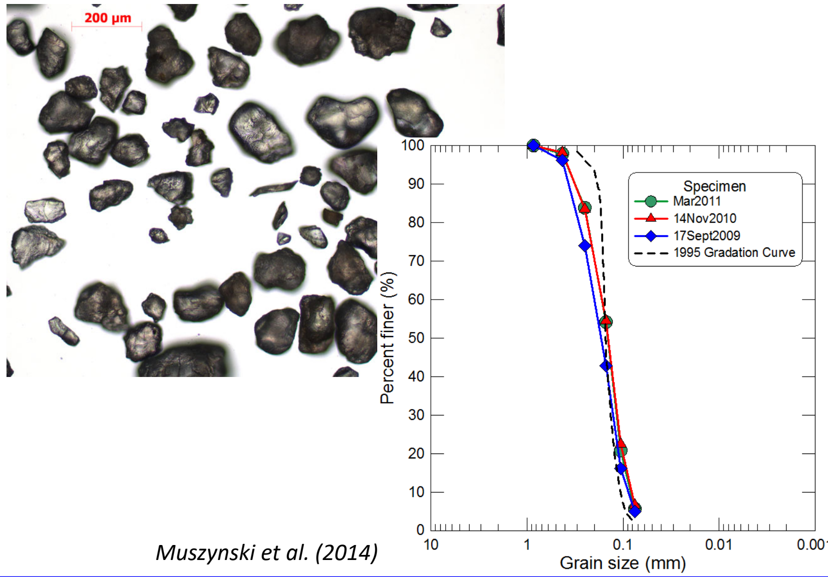
Equipment and instruments

- *Tactile pressure sensors wrapped around rigid caisson bolted to base of laminar container*
- *Typical tactile pressure sensor output*



Nevada sand physical properties

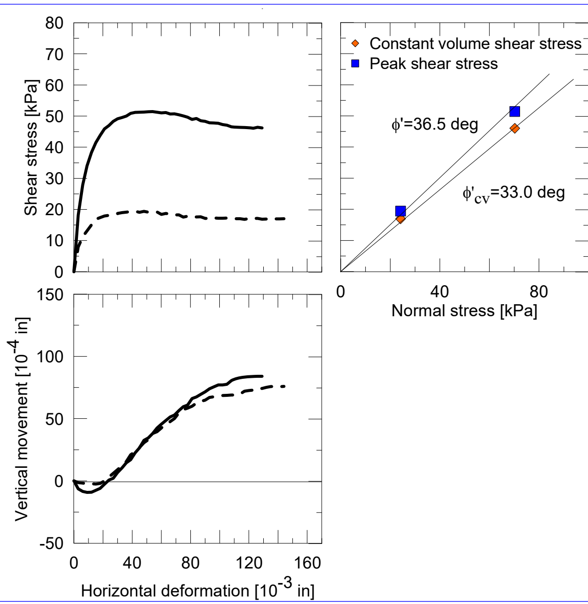
- *Uniform, subangular quartz sand*
- *D_{50} = 0.16mm*
- *D_{10} = 0.075mm*
- *C_u = 2.2*
- *C_C = 0.75*
- *e_{max} = 0.828*
- *e_{min} = 0.521*
- *Gs = 2.68*



Muszynski et al. (2014)

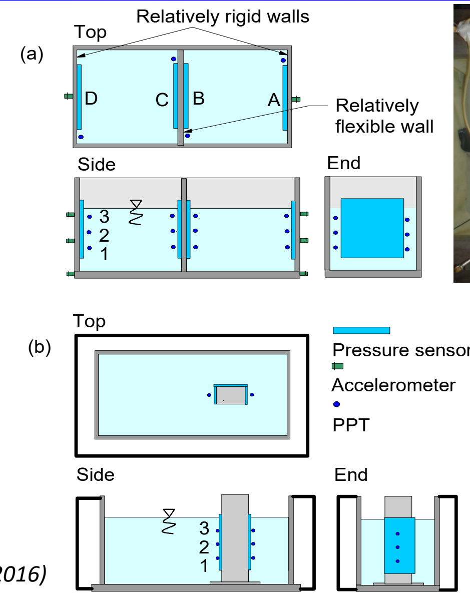
Nevada sand physical properties

- *ϕ'$_{peak}$ ≃ 36° (D_R = 30 to 40%)*
- *ϕ'$_{cs}$ ≃ 33°*
- *ϕ'$_{repose}$ ≃ 34°*
- *At effective normal stresses less than 100 kPa, sand was slightly dilative*



Hydrostatic verification testing

- *Used tactile pressure cells along rigid and flexible walls to measure hydrostatic pressures*
- *Pressure transducers also used as a 'control' measurement of hydrostatic pressures*



Muszynski et al. (2016)

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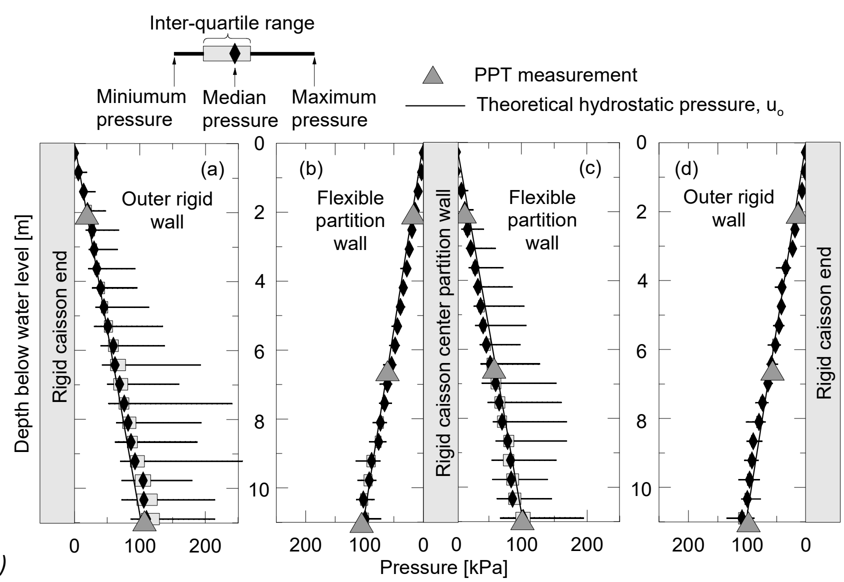
Hydrostatic verification testing

- *Used tactile pressure cells along rigid and flexible walls to measure hydrostatic pressures*
- *Pressure transducers also used as a 'control' measurement of hydrostatic pressures*



Muszynski et al. (2016)

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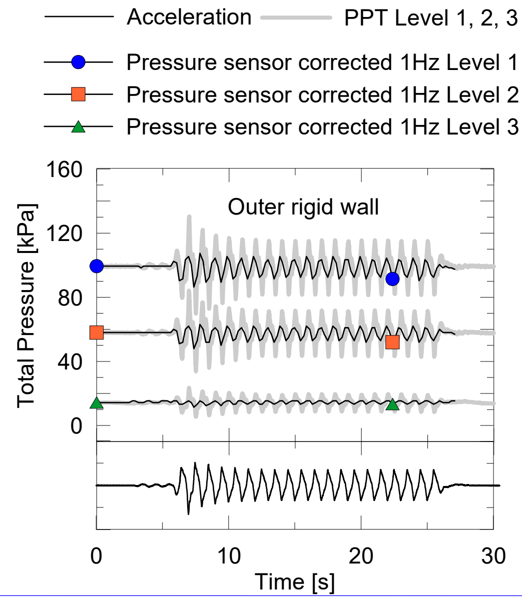
Hydrodynamic testing

- *Used tactile pressure cells along rigid and flexible walls to measure hydrodynamic pressures during shaking event*
- *Pressure transducers also used as a 'control' measurement of hydrodynamic pressures*
- *Maxima and minima pressures measured by tactile pressure cells were smaller than PPT*



Muszynski et al. (2016)

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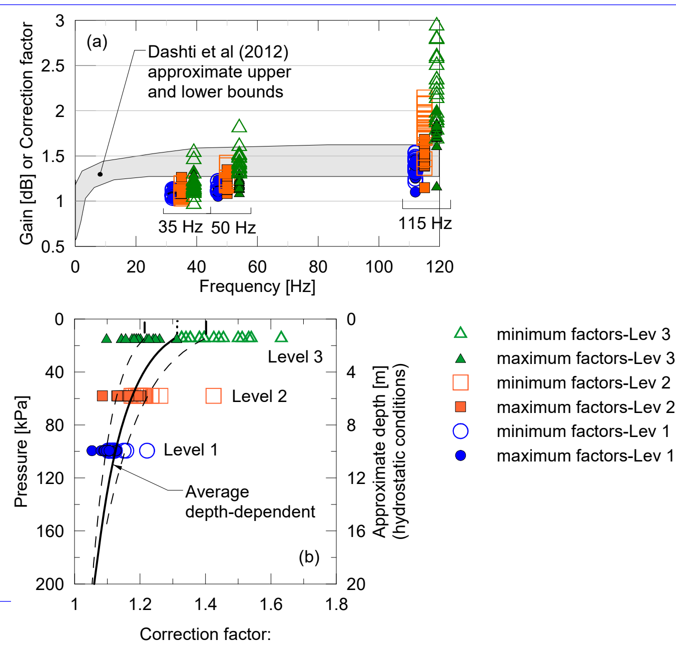
Hydrodynamic testing – Depth-dependent correction

- *Using tactile pressure sensor and PPT measurements, we developed depth-dependent correction functions for dynamic pressures*
- *Correction factors generally were consistent with those reported by Dashti et al. (2012), but were both frequency- and depth-dependent*

Muszynski et al. (2016)



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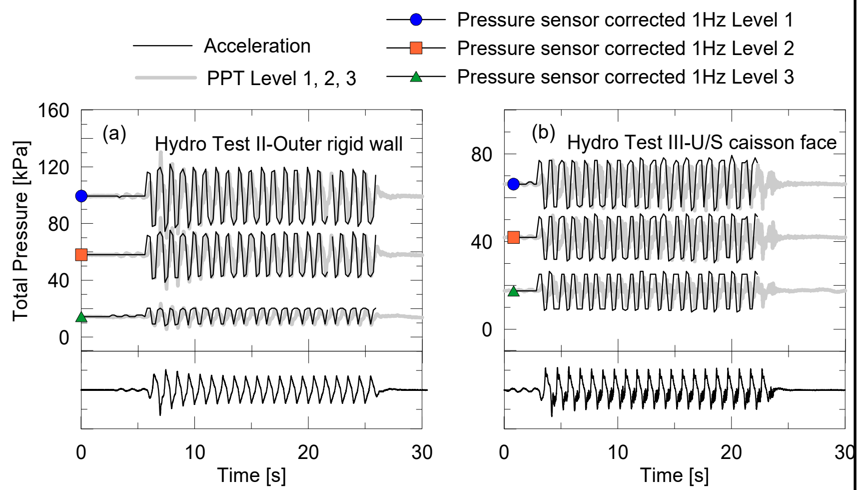
Hydrodynamic testing – Applying correction

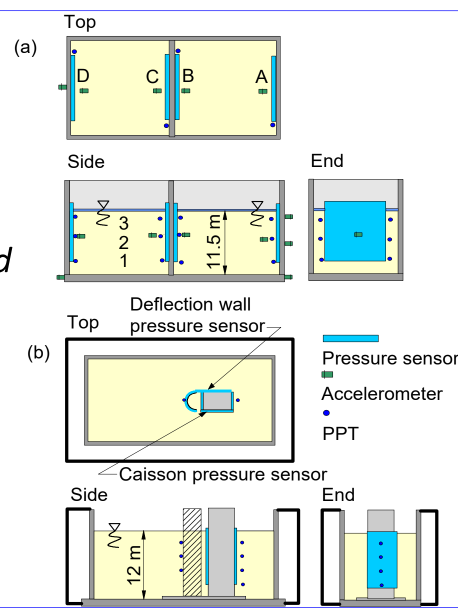
- *Using tactile pressure sensor and PPT measurements, we developed depth-dependent correction functions for dynamic pressures*
- *Correction validated against a 2nd hydrodynamic test*

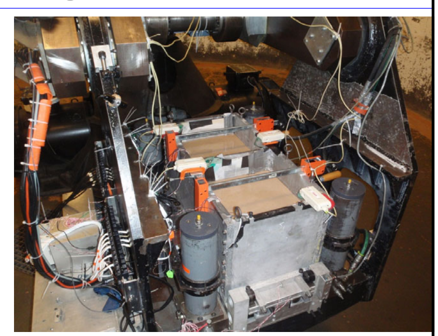


Muszynski et al. (2016)

Geostatic verification testing

- *Used tactile pressure cells along rigid and flexible walls to measure geostatic pressures in saturated sand*

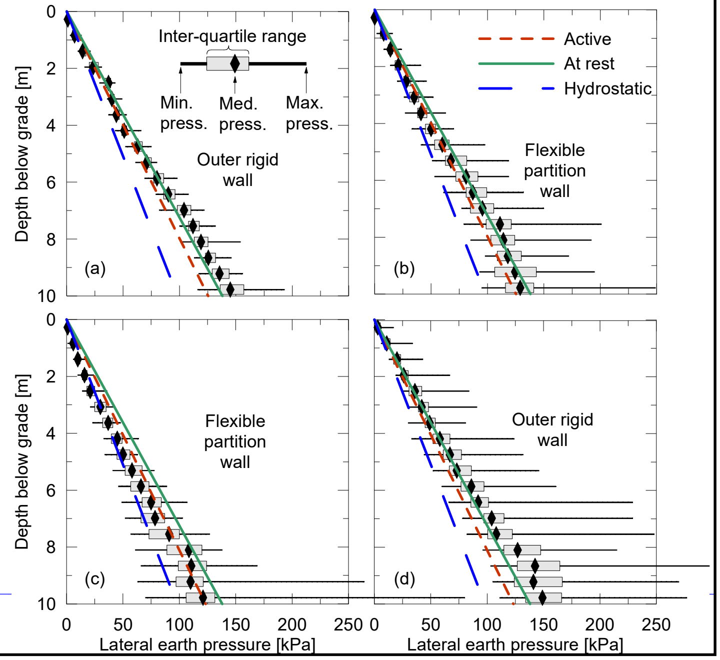




Muszynski et al. (2016)

Geostatic verification testing

- *Geostatic pressures generally agreed with theory*
- *Wall stiffness significantly affected pressure measurements*



Muszynski et al. (2016)

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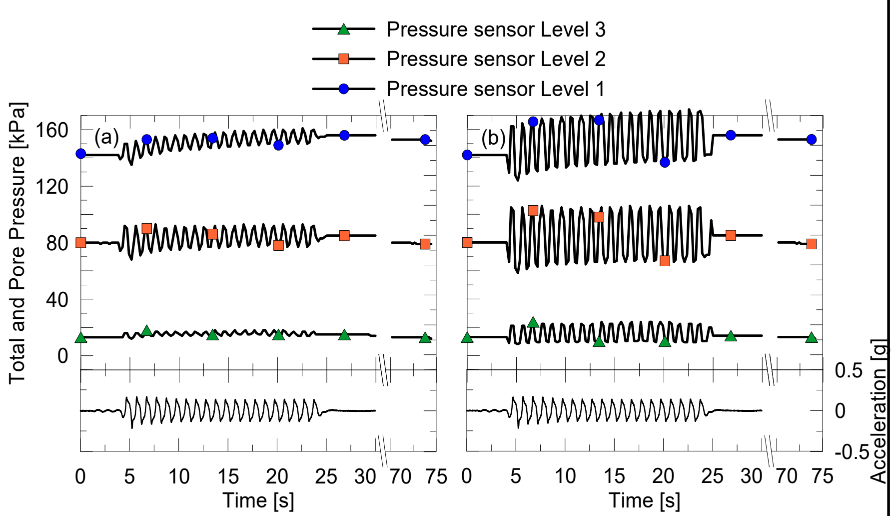
Geodynamic testing

- *Geodynamic pressures pressures generally consistent and in phase with applied base acceleration*
- *Dynamic correction important for estimating realistic dynamic pressures*



Muszynski et al. (2016)

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Presentation outline

- *Motivation*
- *Centrifuge testing program*
- ***Instrument response and ground behavior***
- *Analytical models*
- *Novel lateral pressure mitigation method*

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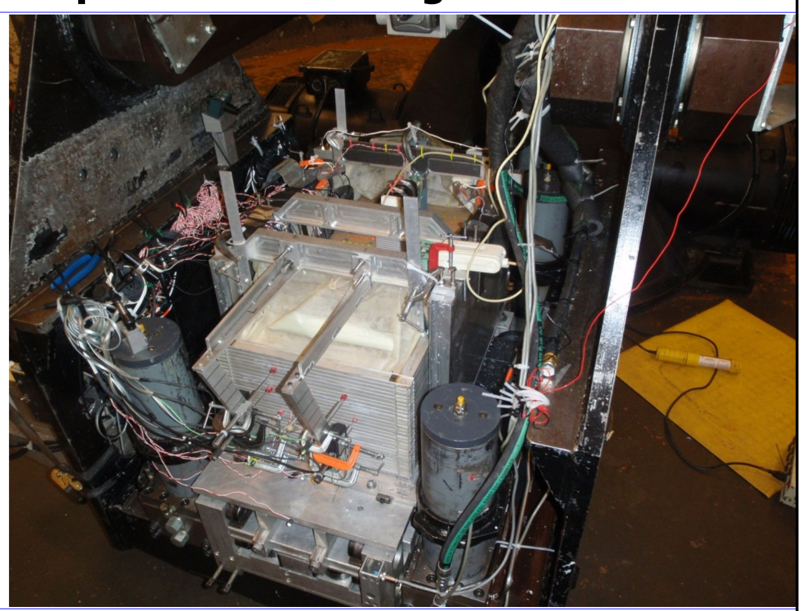
Ready for production testing

- *Free-field models*
- *Caisson models*
- *Ground deflection wall models*



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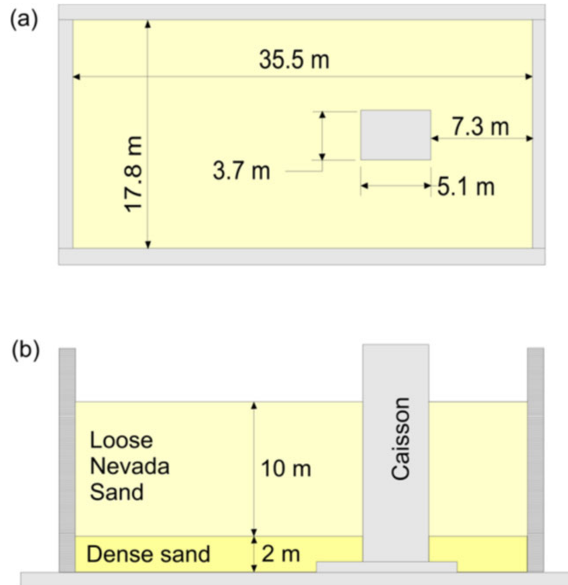
Ready for production testing

- *Free-field models*
- *Caisson models*
- *Ground deflection wall models*
- *Prototype dimensions: 35.5m (length) x 17.8m (width) x 12m (depth)*



Muszynski et al. (2014)

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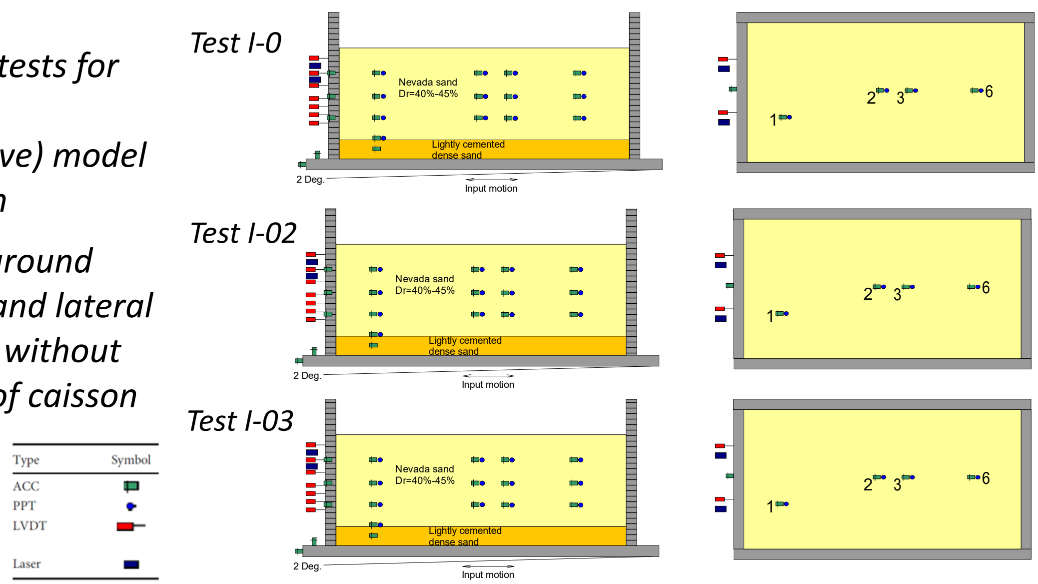
Free-field tests

- *Free-field tests for numerical (constitutive) model calibration*
- *Evaluate ground response and lateral spreading without presence of caisson*



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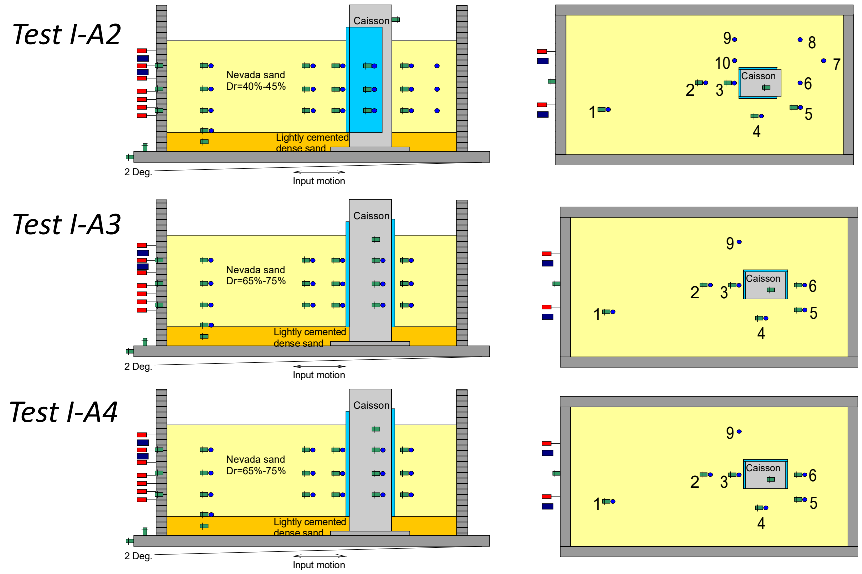
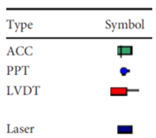
Unprotected caisson tests

- *Unprotected caisson tests with all sand or sand with clay cap*
- *Obtained lateral spreading-induced pressures on caisson*





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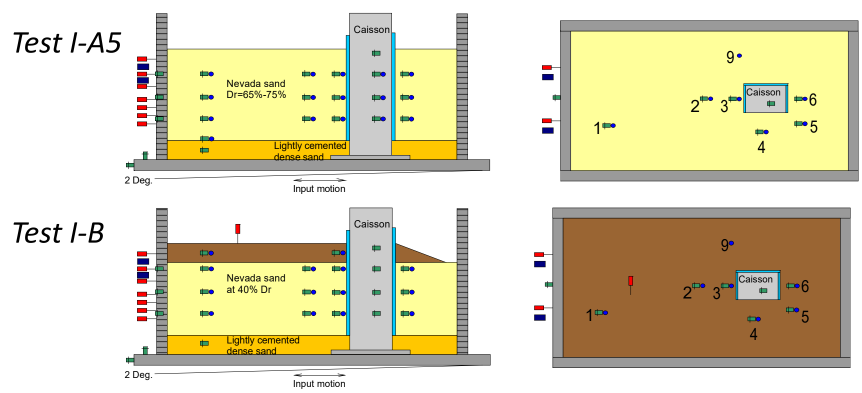
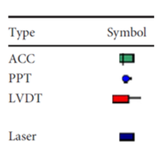
Unprotected caisson tests

- *Unprotected caisson tests with all sand or sand with clay cap*
- *Obtained lateral spreading-induced pressures on caisson*
- *Clay cap imposed excessive shear stress on pressure sensors invalidating the measurements*





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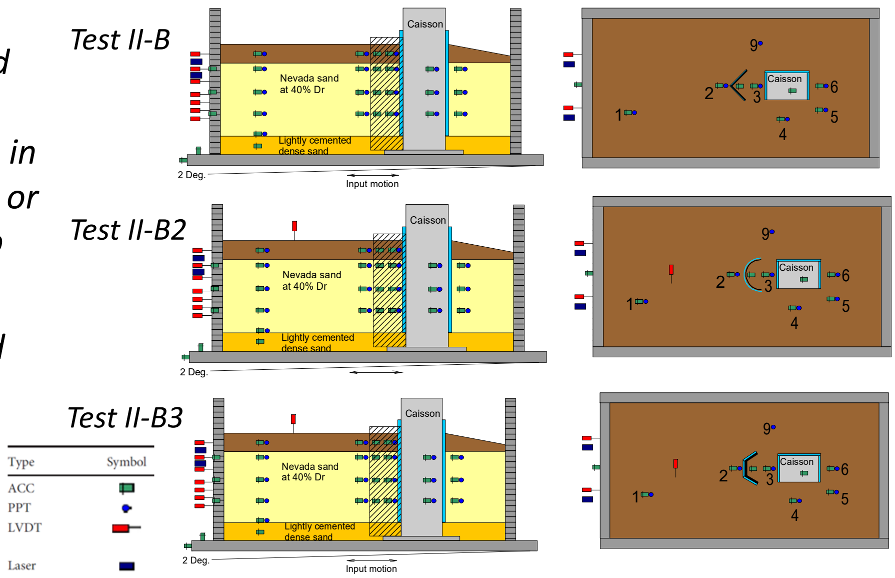
Protected caisson tests

- *Addition of ground deflection wall upslope of caisson in an all-sand profile or sand with clay cap*
- *Obtained lateral spreading-induced pressures on protected caisson*
- *Clay cap shearing affected results*



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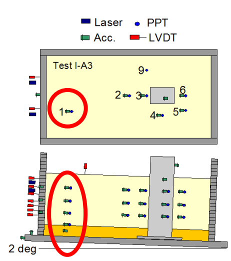
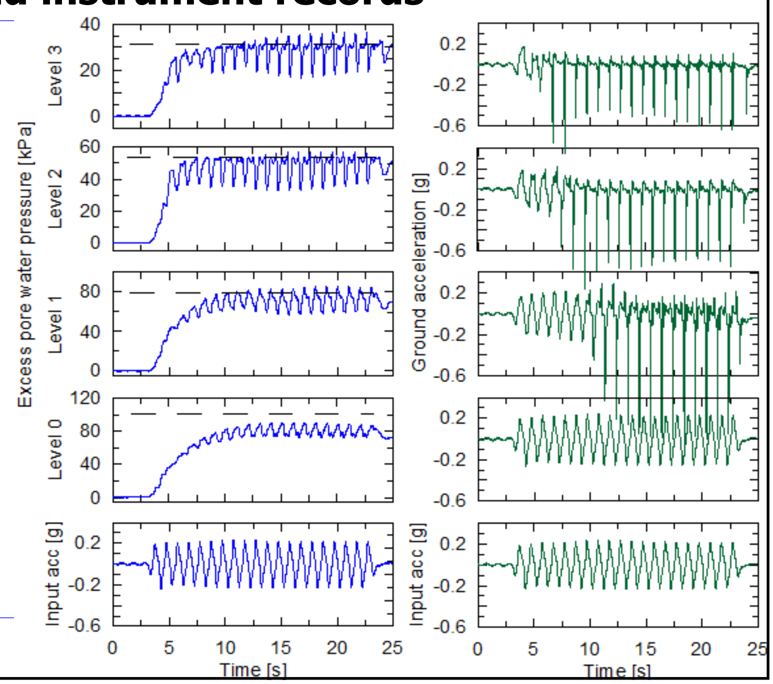
Free-field instrument records

- *Free-field instrument array showed clear evidence of liquefaction and lateral spreading*





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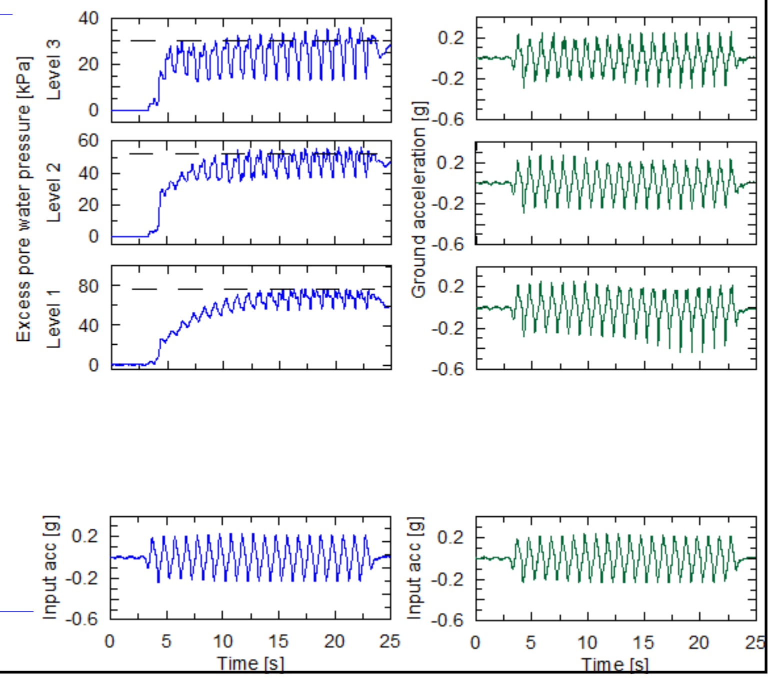
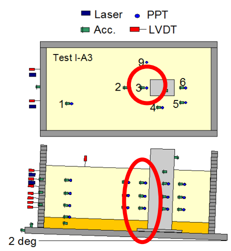
Near-field instrument records

- *Near-field instrument array showed clear evidence of liquefaction but no dilation spikes*





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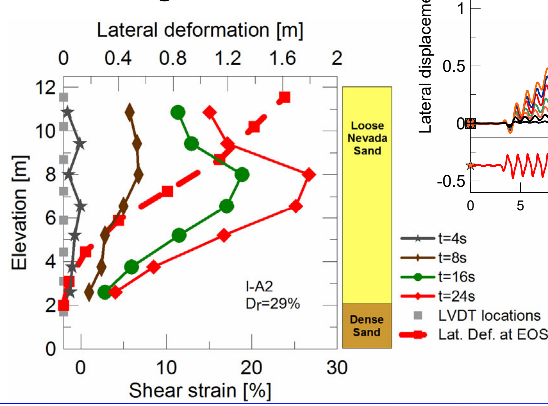
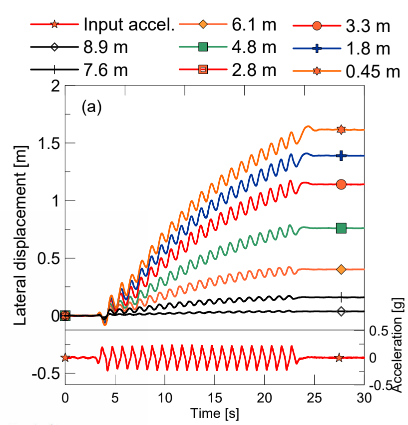
Lateral displacement & shear strain

- *Maximum shear strain typically occurred around 4 to 6 m below surface*
- *Free-field surface displacement ranged from 1.5 to 4.0 m*





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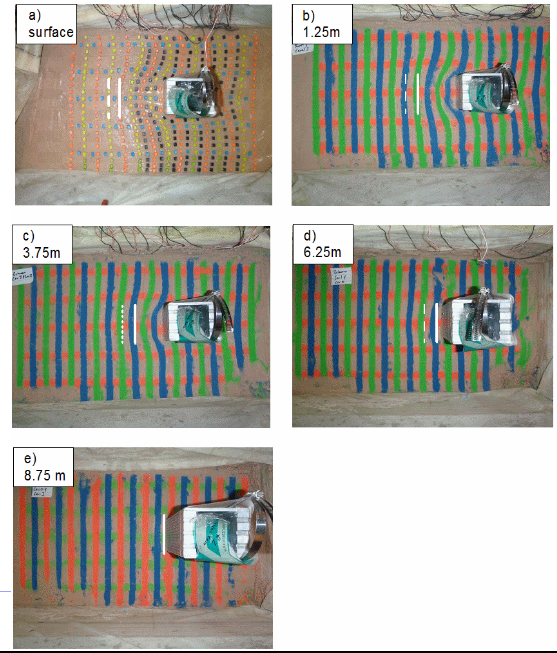
Lateral displacement & tracking data

- *Example ground deformation at surface and subsurface levels*
- *Greatest displacement near surface, decreasing with depth*
- *Indication of the passive wedge shape and size inferred from displacements of colored sand layers*



Olson et al. (2017)

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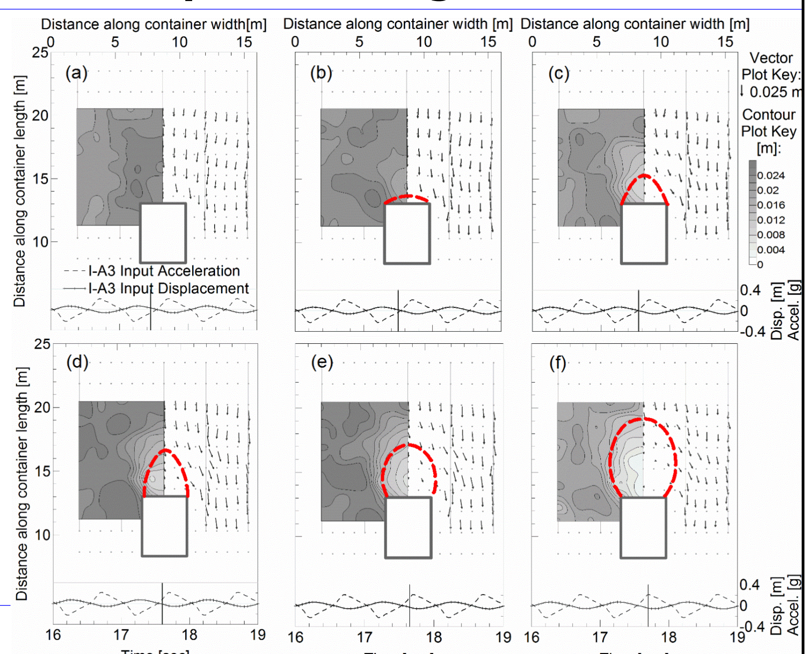
Development of passive wedge

- *Example ground deformation at surface*
- *Used high-speed camera to track surface markers (zip-tie heads)*



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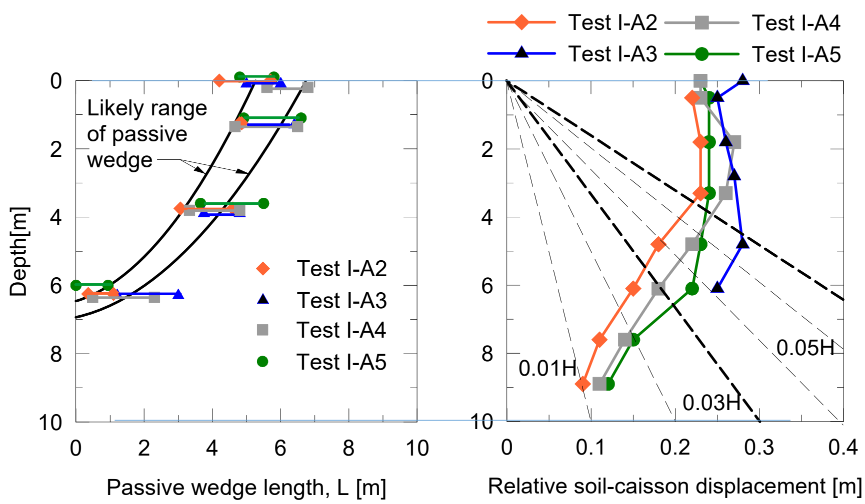
Passive wedge depth

- *Determining the depth of the passive wedge, h*
- *6 to 7m for these tests*
- *Failure surface (passive wedge) is curved*



Olson et al. (2017)

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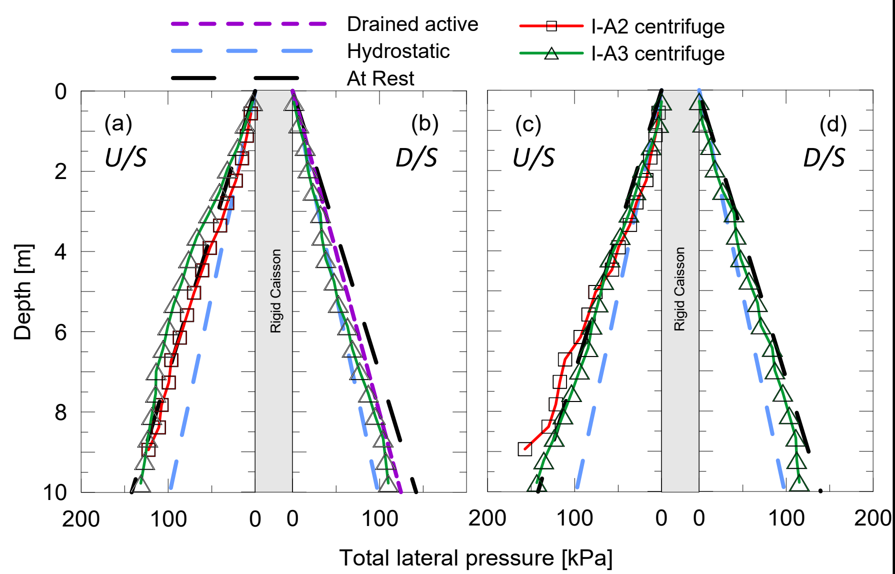
Geostatic lateral pressures

- *Geostatic pressure distribution for Tests I-A2 and I-A3*

  a-b) before shaking

  c-d) after shaking



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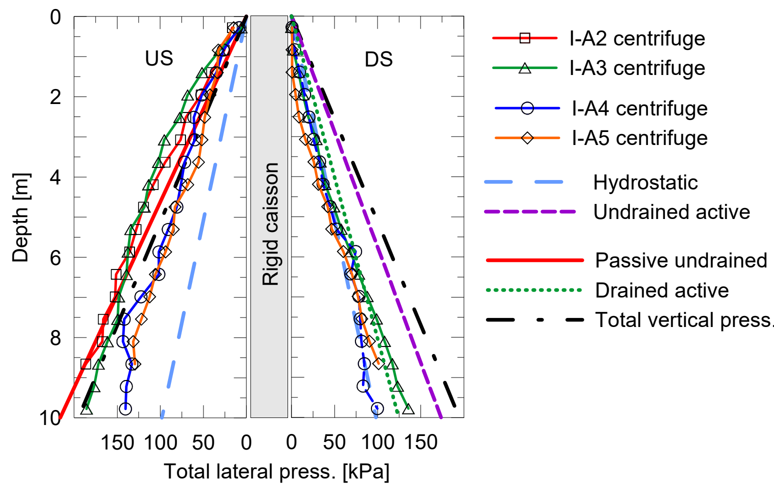
Geodynamic lateral pressures

- *Geodynamic pressure distribution for Tests I-A2 and I-A3*
- *Pressures correspond to time after onset of liquefaction at which maximum moment acts on caisson*



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Presentation outline

- *Motivation*
- *Centrifuge testing program*
- *Instrument response and ground behavior*
- ***Analytical models***
- *Novel lateral pressure mitigation method*

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Formulation of analytical approaches

- *Strain wedge model (SWM; Ashour et al. 1998, Ashour and Norris 2003)*
  - — ϕ_m
  - — *Passive wedge depth, h*
  - — *Porewater pressure ratio, r_u, distribution*
  - — *Used with effective stresses*

- *Modified Broms' method (Olson et al. 2017)*
  - — *Developed using undrained shear strength parameters*
  - — *"Passive wedge factor" (PWF)*

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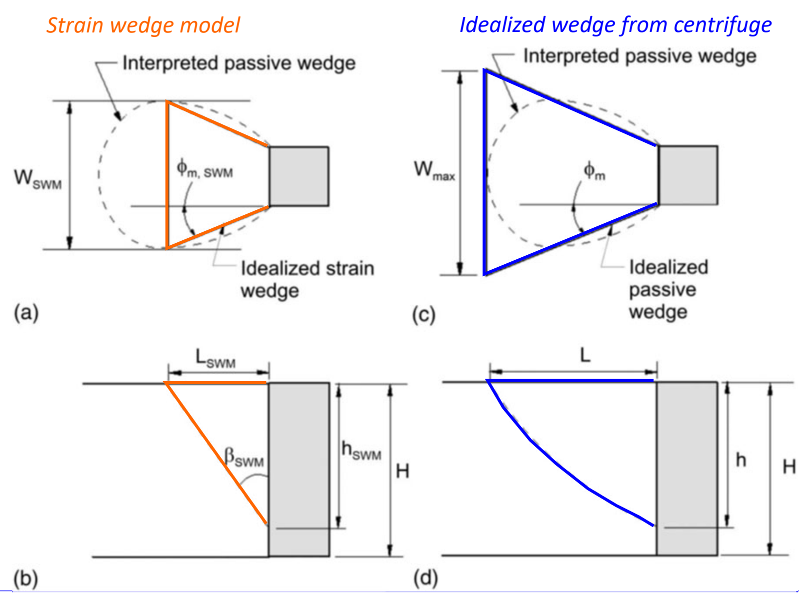
Passive wedge geometry for SWM

- *SWM requires geometry of passive wedge to estimate lateral pressures*
- *Estimated based on ϕ_m*



Olson et al. (2017)

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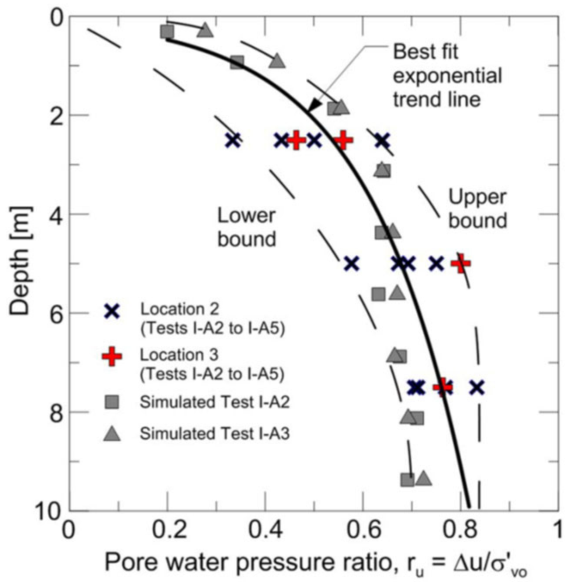
Porewater pressure distribution for SWM

- *SWM requires effective stresses to estimate lateral pressures*
- *Excess porewater pressure, r_u, distributions from centrifuge test measurements and numerical simulations*



Olson et al. (2017)

Development of modified Broms' method

- *Broms' (1964a,b; 1965) method estimates limiting (ultimate) lateral pressures*

$P_{ult} = 3\sigma'_v K_p B$ *(sands)* $P_{ult} = 9s_u B$ *(clays)*

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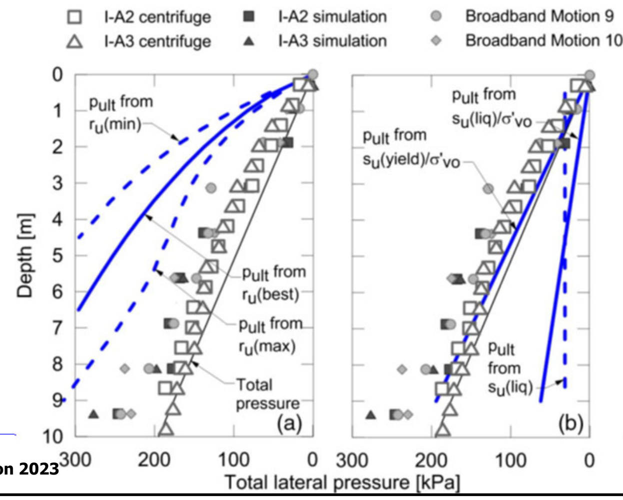

Olson et al. (2017)

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Development of modified Broms' method

- *Broms' (1965) method estimates limiting (ultimate) lateral pressures*

$P_{ult} = 3\sigma'_v K_p B$ *(sands)*

- *Modified Broms' method for undrained conditions in sand developed to remain simple but faithful to measured data in centrifuge tests*

$P_{ult} = PWF[\gamma_{sat} h + 2 s_u(liq)]B$

$\sigma_{h,passive} = PWF[\gamma_{sat} h + 2 s_u(liq)]$ *for* $z \le h$

$\sigma_{h,passive} = \gamma_{sat} h$ *for* $h \le z \le h_{liq}$

- *PWF incorporated to account for 3D effects on lateral stresses*

Olson et al. (2017)

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Olson et al. (2017)

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Olson et al. (2017)

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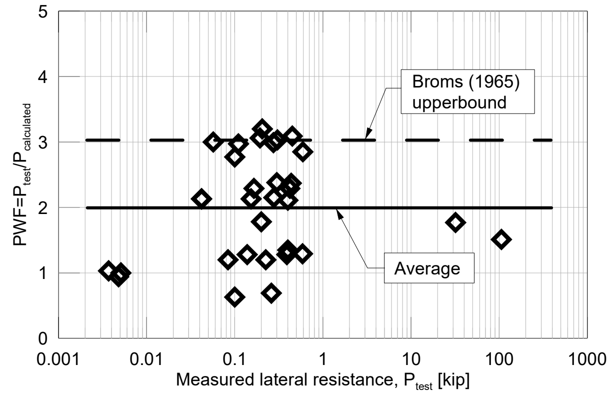
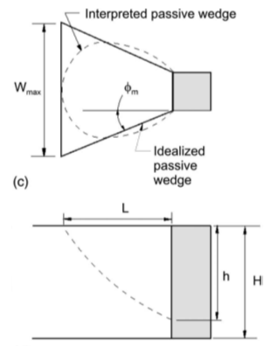
PWF from Broms' data

- *Broms' (1965) used upper limit for 3D effects throughout pile depth*
- *Average PWF = 2*





$$PWF = PWF_{max} - \frac{z}{h}(PWF_{max} - 1) \geq 1$$

$$PWF_{max} = \frac{W_{max}}{B} = \frac{B + 2(h \tan\beta)\tan\phi_m}{B} \leq 3$$

Olson et al. (2017)

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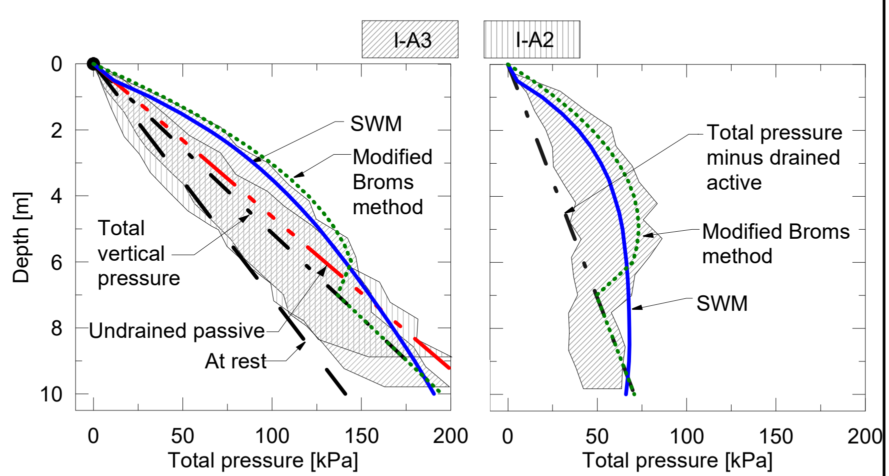
PWF from Broms' data

- *Upslope total pressures reasonably consistent with modified Broms' method and SWM (using max r_u)*
- *Net pressures better represented by modified Broms' method*



Olson et al. (2017)

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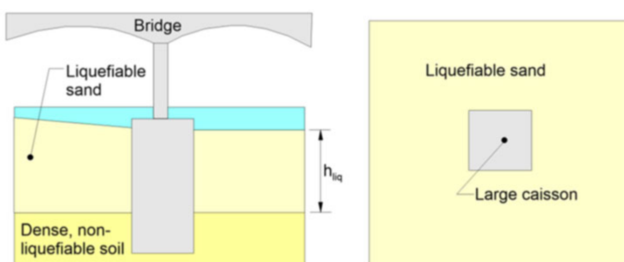
Mitigating lateral pressures

Olson et al. (2021)

- *Increase caisson size*



(a) (b)

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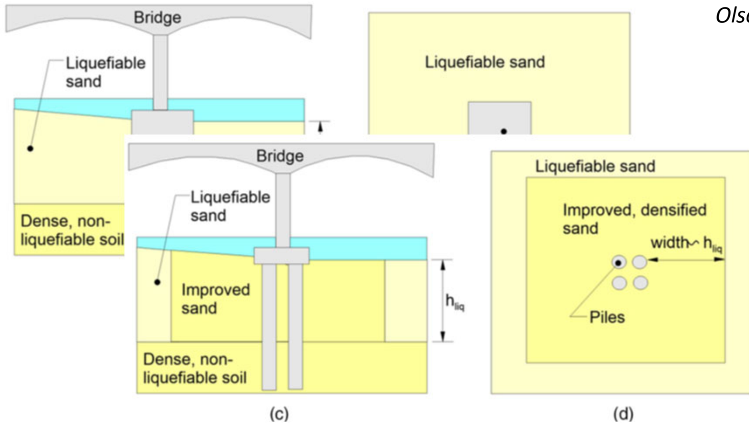
Mitigating lateral pressures

- *Increase caisson size*
- *Substantial ground improvement*

Olson et al. (2021)



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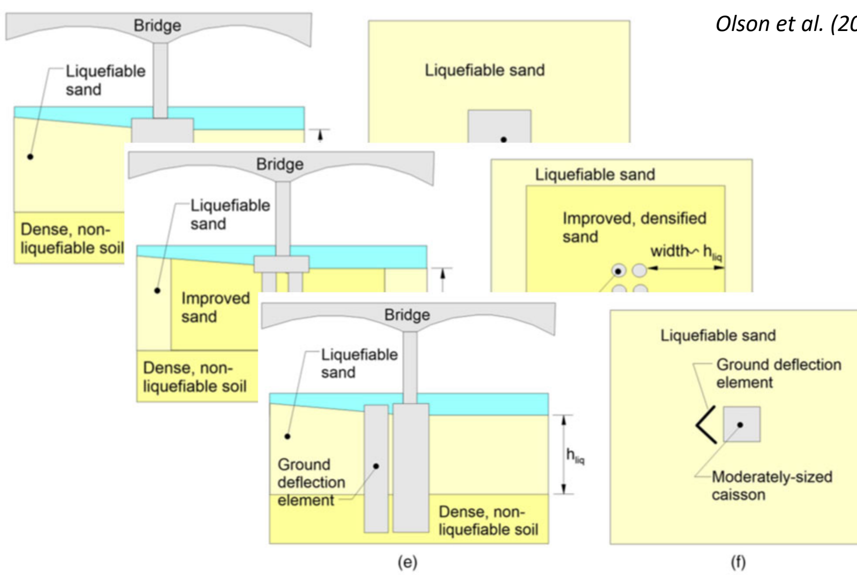
Mitigating lateral pressures

- *Increase caisson size*
- *Substantial ground improvement*
- *Novel ground deflection wall*

Olson et al. (2021)



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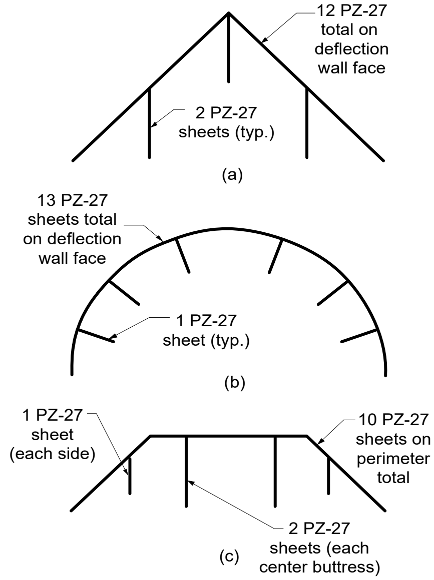
Mitigating lateral pressures with ground deflection walls

- *Three deflection walls considered*
- *Modeled after potential buttressed sheet pile wall installations*

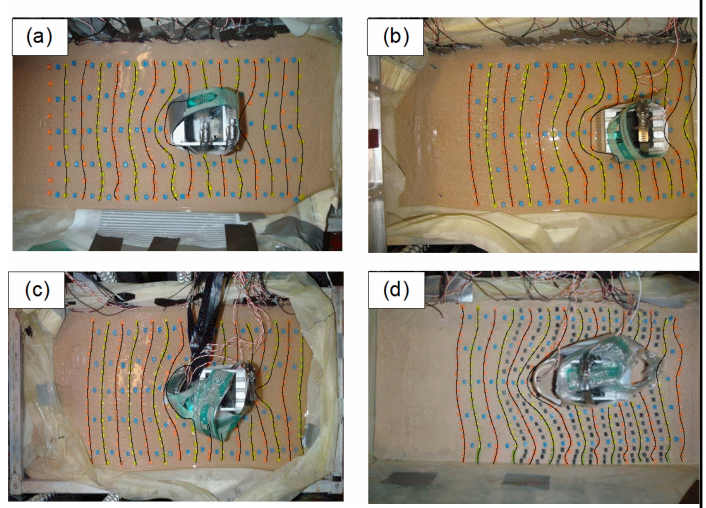


Olson et al. (2021)

Performance of ground deflection walls

Olson et al. (2021)

- *Deflection walls re-directed the laterally spreading ground around the caisson*
- *Surface displacements for models with deflection walls were nearly identical to free-field tests*



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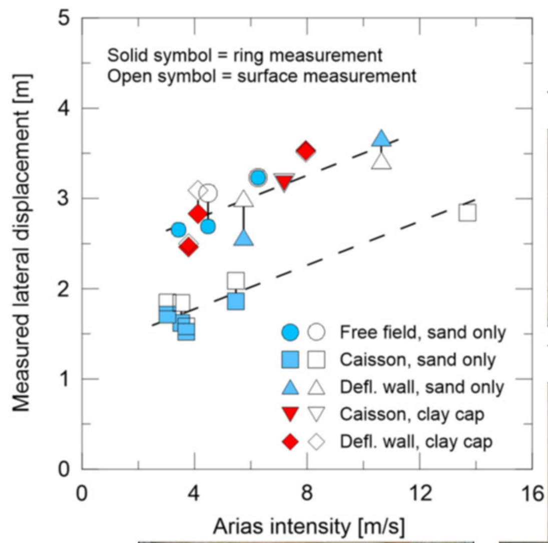

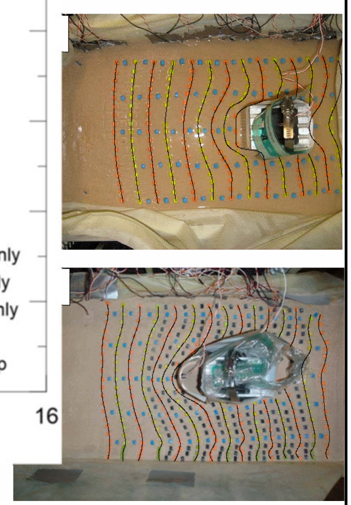

Olson et al. (2021)

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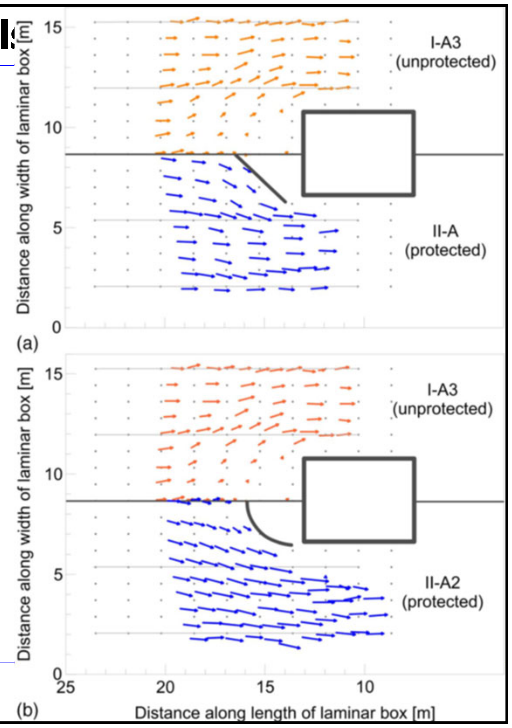
Performance of ground deflection walls

- *Displacement vector plots used to quantify differences*
- *Passive wedge poorly developed upslope of protected caisson*
- *Displacements adjacent to caisson larger and more consistent in protected case*

Olson et al. (2021)



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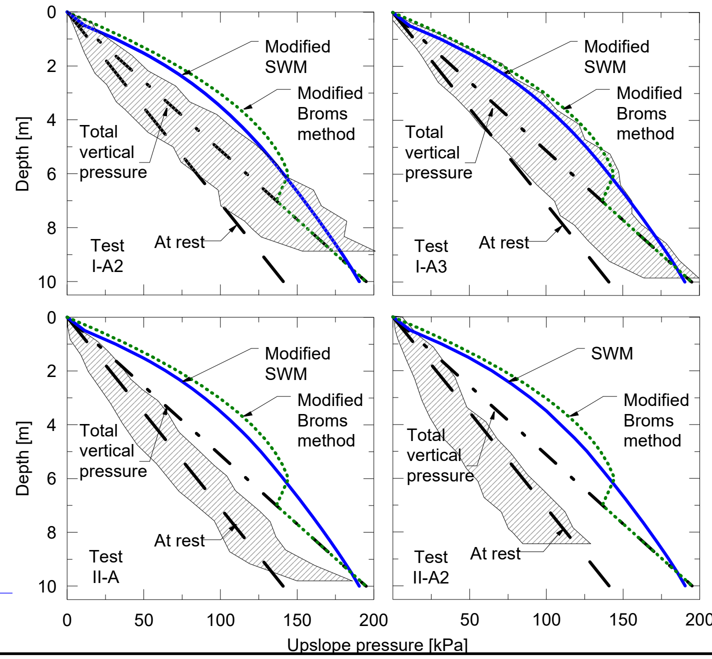
Performance of ground deflection walls

- *Pressures directly against deflection walls were unusable because of shear stresses*
- *However, upslope lateral pressures against unprotected walls significantly larger than against protected walls*



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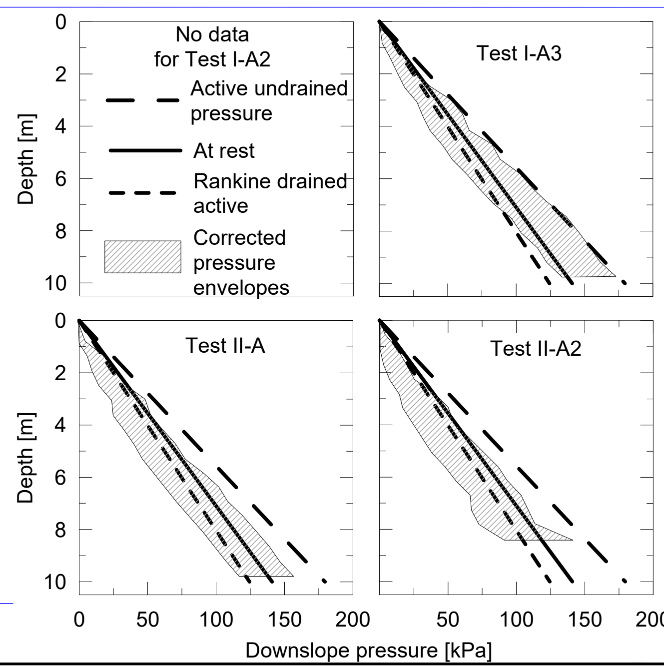
Performance of ground deflection walls

- *Downslope lateral pressures were nearly the same regardless of the presents of a deflection wall*



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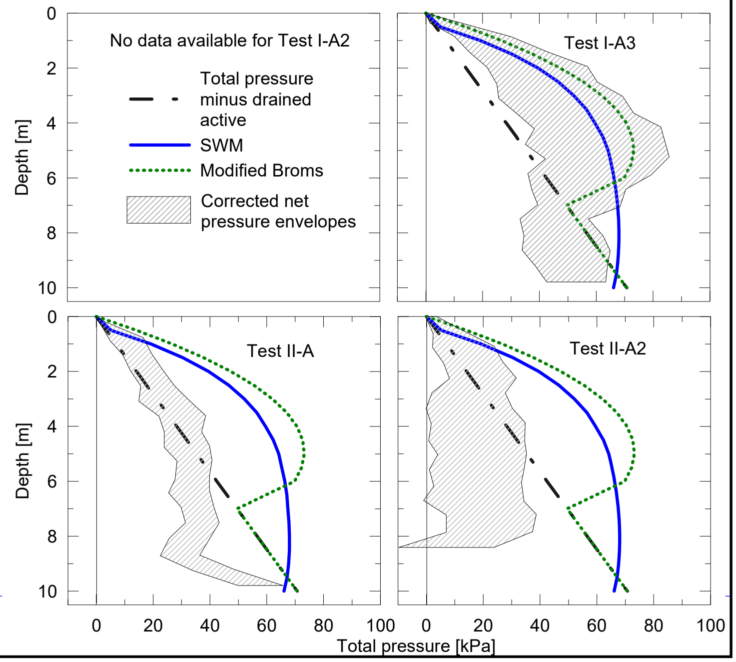
Performance of ground deflection walls

- *Net lateral pressures against unprotected walls significantly larger than against protected walls*



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Summary and conclusions

- *Lateral spreading can cause significant damage to pile foundations*
- *Existing methods to evaluate this problem have focused on individual piles and relatively small pile groups where soil-foundation interaction is key*
- *These existing methods generally do not apply to rigid foundations*
- *Integrated centrifuge testing and numerical simulation program was conducted to develop analytical tools, numerical models, and novel mitigation methods to address this problem*
- *Modified Broms' method in concert with yield or liquefied shear strengths can be used to reasonably predict 3D passive (limiting) pressures*
- *Ground deflection walls, potentially constructed using buttressed sheet piles or specific foundation shapes/layouts, may significantly reduce lateral pressures acting on foundations during lateral spreading*

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Thanks for your attention!

Questions?

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