PEER Annual Meeting
Berkeley, California – January 18-19, 2018

Remediation of liquefaction effects for embankment dams using soil-cement walls

[20-25 min]

UC DAVIS
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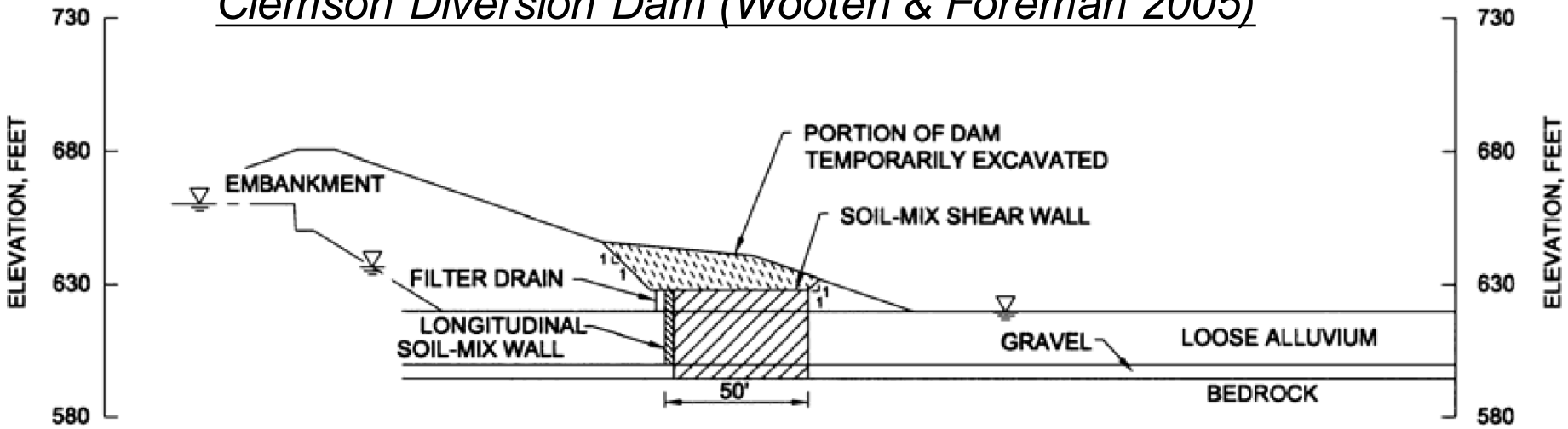
Soil-cement walls/grids in dam foundations

- *Examples of US projects using soil-cement walls/grids*
  - *Clemson Diversion Dams, SC (Wooten & Foreman 2005)*
  - *Sunset North Basin Dam, CA (Barron et al. 2006)*
  - *San Pablo Dam, CA (Kirby et al. 2010)*
  - *Perris Dam, CA (Friesen & Balakrishnan 2012)*
  - *Chabot Dam, CA (EBMUD 2016)*
- *Common analysis approach is a 2D section with composite (area-weighted) properties for the treatment zone*

Clemson Diversion Dam (Wooten & Foreman 2005)



Motivation for present study

- *Questions:*
  - *Will soil-cement walls or grids be effective in reducing deformations if they crack extensively during shaking?*
  - *Do our 2D analysis methods adequately predict the benefits of soil-cement wall or grid reinforcements?*
- *Approach:*
  - *Dynamic centrifuge model test with soil-cement walls designed to*
    - *not shear or crack (extensively) in a smaller shaking event*
    - *shear/crack extensively in a larger shaking event*
  - *2D nonlinear dynamic analyses (NDAs) using composite properties for the treatment zone*

Outline of presentation

- *Dynamic centrifuge model test*
  - *Configuration and a few observations*
- *Nonlinear dynamic analyses*
  - *Model development and parameter calibration/selections*
  - *Results for the two large shaking events*
- *Discussion & concluding remarks*

Acknowledgments

- *Collaborators & coauthors*

Mohammad Khosravi
Post-doc UC Davis

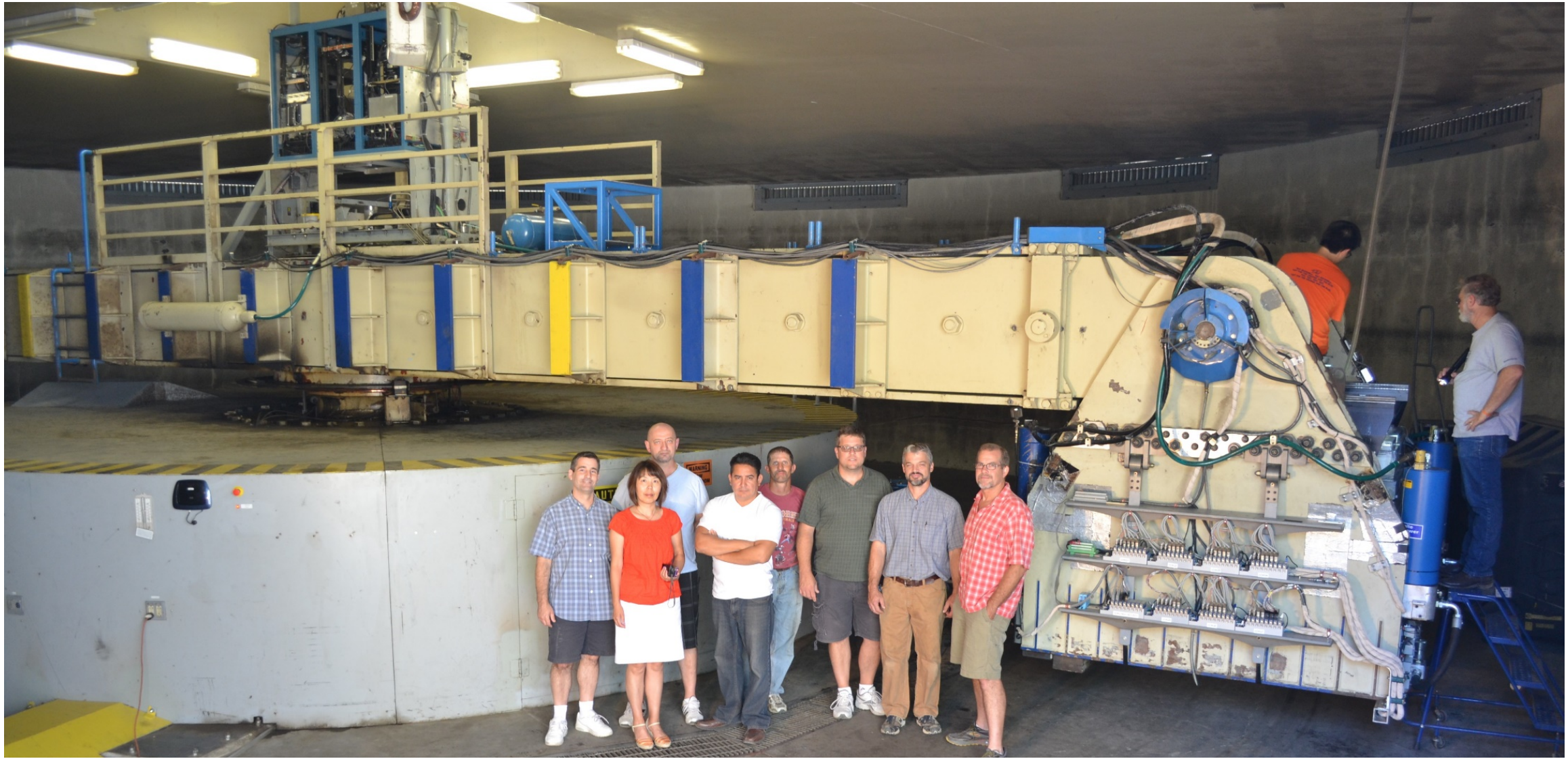
Ali Khosravi
Sharif Tech U

Dan Wilson
Assoc. Director CGM

Centrifuge test

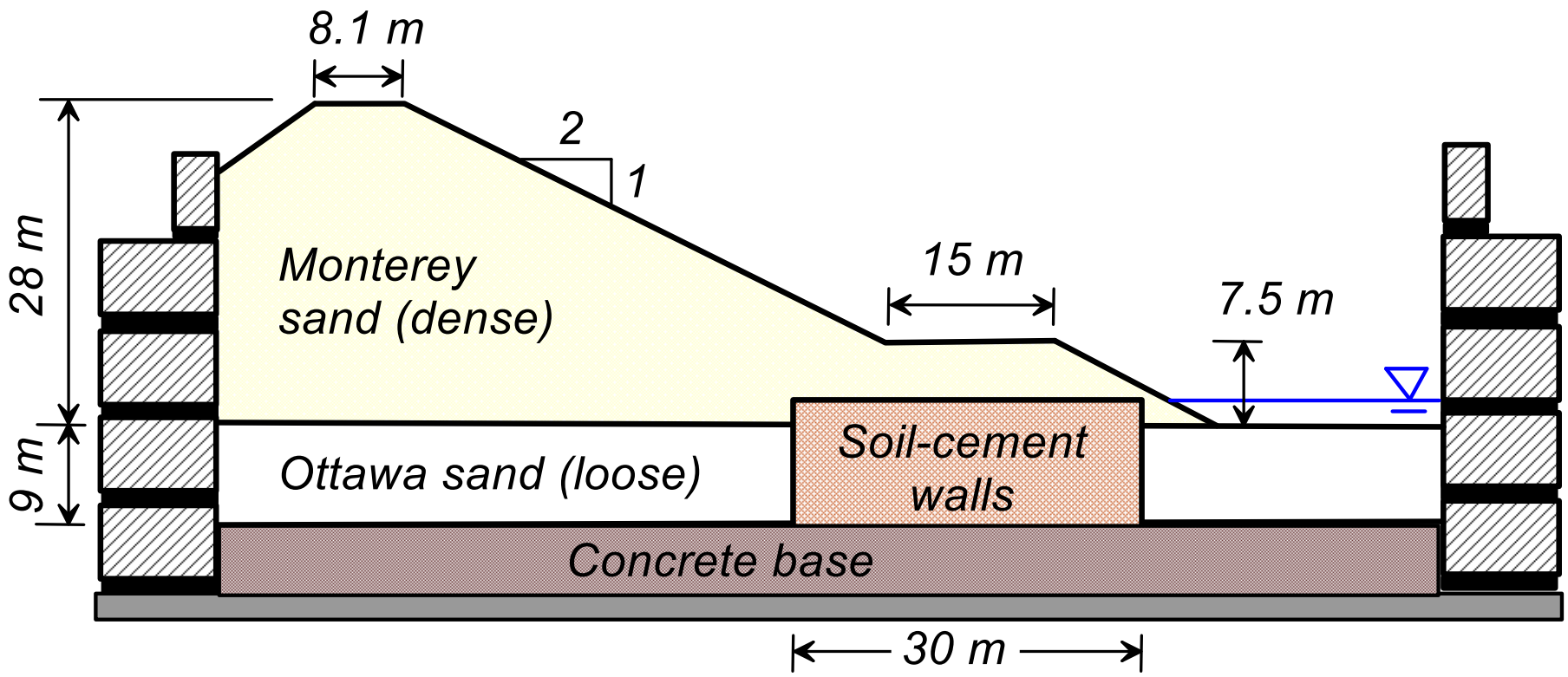
9-m radius centrifuge at UC Davis

- *A national shared-use NHERI Equipment Facility sponsored by NSF*



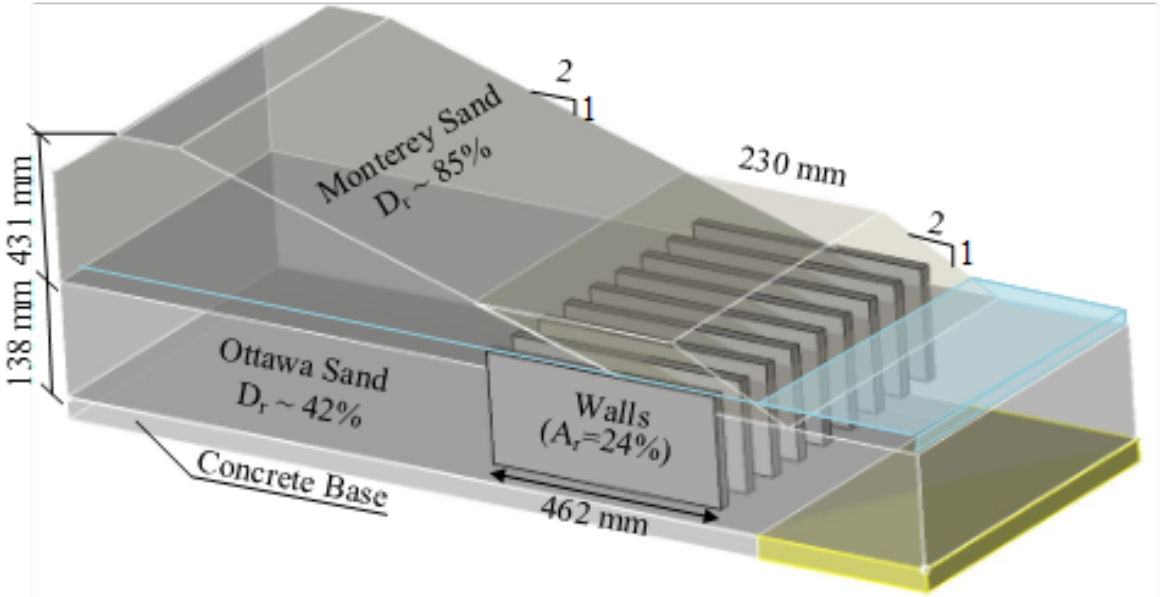
Model configuration

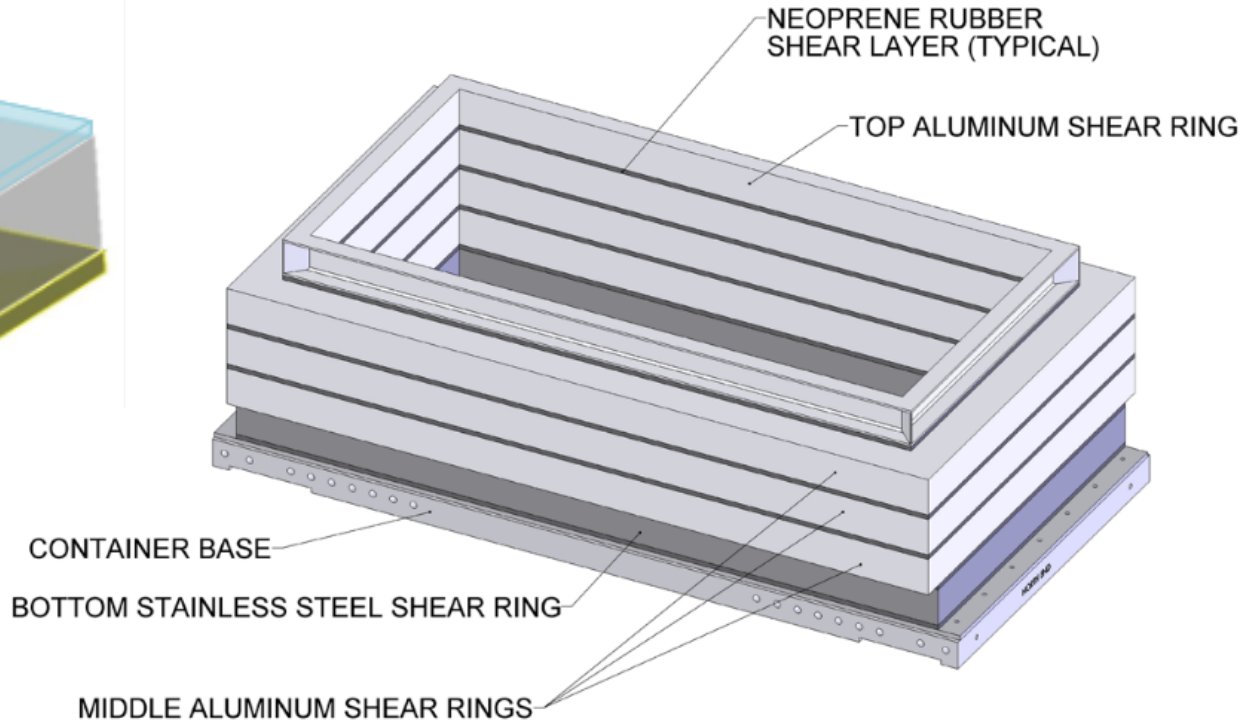
- Test at 65g; Results in prototype units unless specified otherwise
- 28-m tall embankment over 9-m-thick loose sand layer
- Pore fluid was methylcellulose mixture with viscosity of about 15 cP



Model configuration

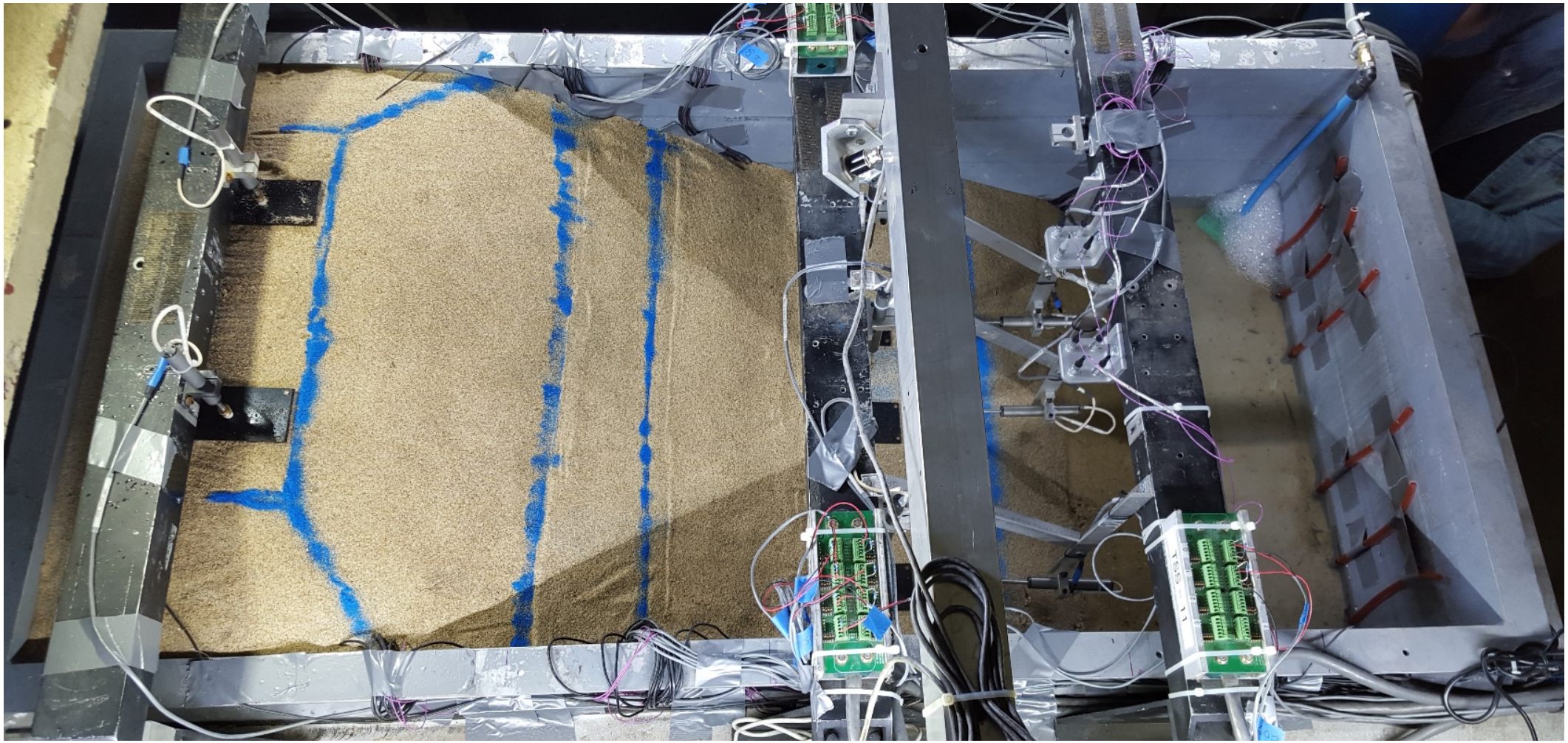
- 9 walls in longitudinal direction (also shaking direction)
- Flexible shear beam container





Model configuration

- *Model was shaken 3 times with a modified recording from Port Island, 1995 Kobe earthquake*
  - *Scaled to peak base accelerations (PBA) of 0.05, 0.26, & 0.54 g*



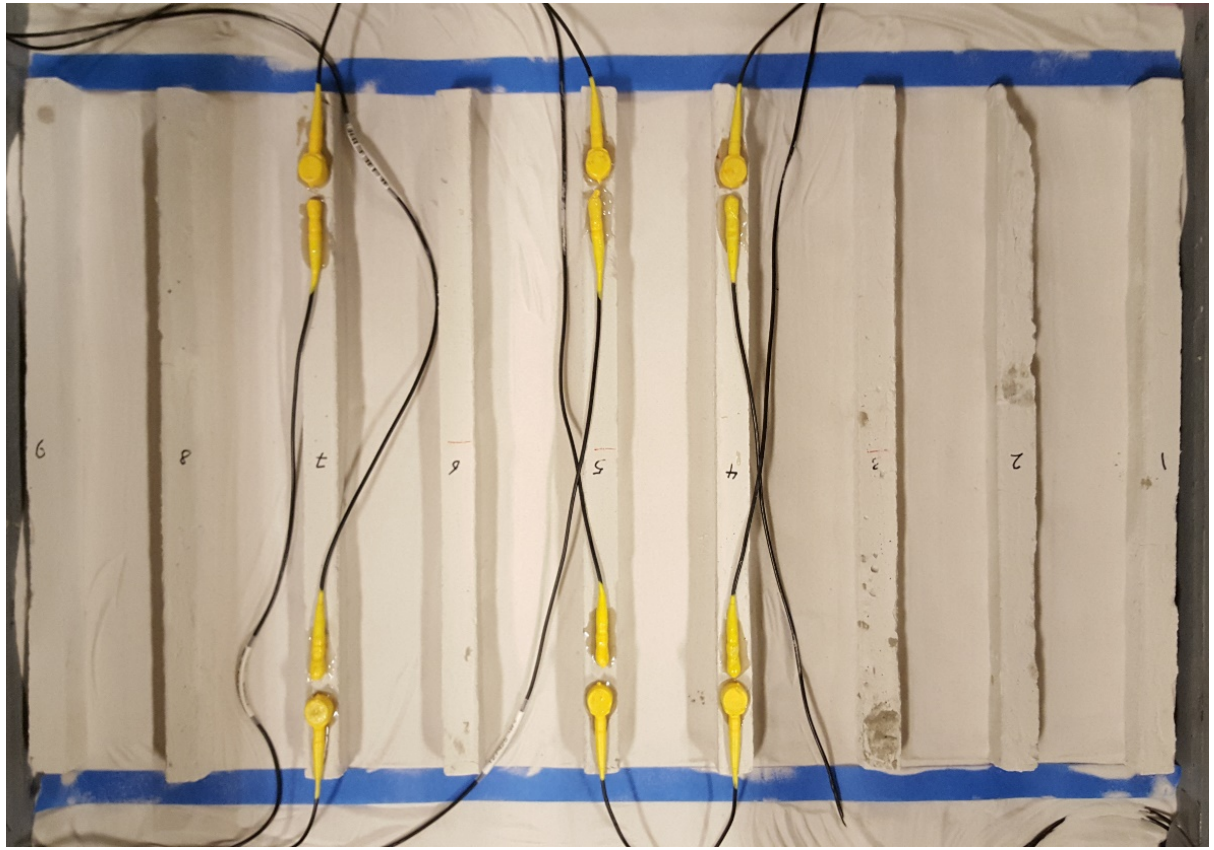
Soil-cement walls

- *Sand-cement mixture formed & cured in molds.*
- *Wall thickness = 1.4 m; Spacing = 5.8 m; Area ratio = 24%*
- q_{ucs} *= 2.0 MPa at time of centrifuge testing*
- *Crack detectors embedded in walls*
- *Post-test excavation photos (toe of berm is to the left side of photos)*

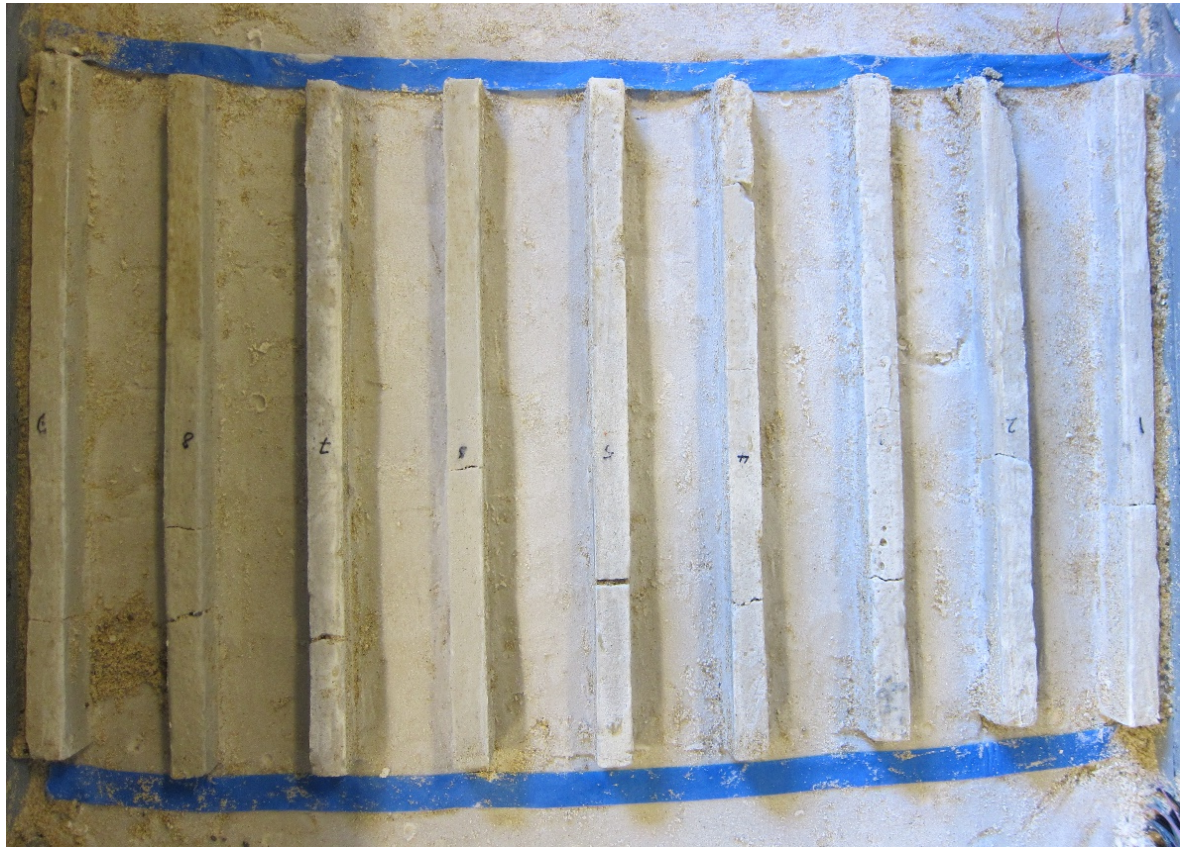
Soil-cement walls

- *Toe of berm is to the bottom of these photos*
- *Liquefied sand extruded up to 0.8 m relative to the walls*

Construction



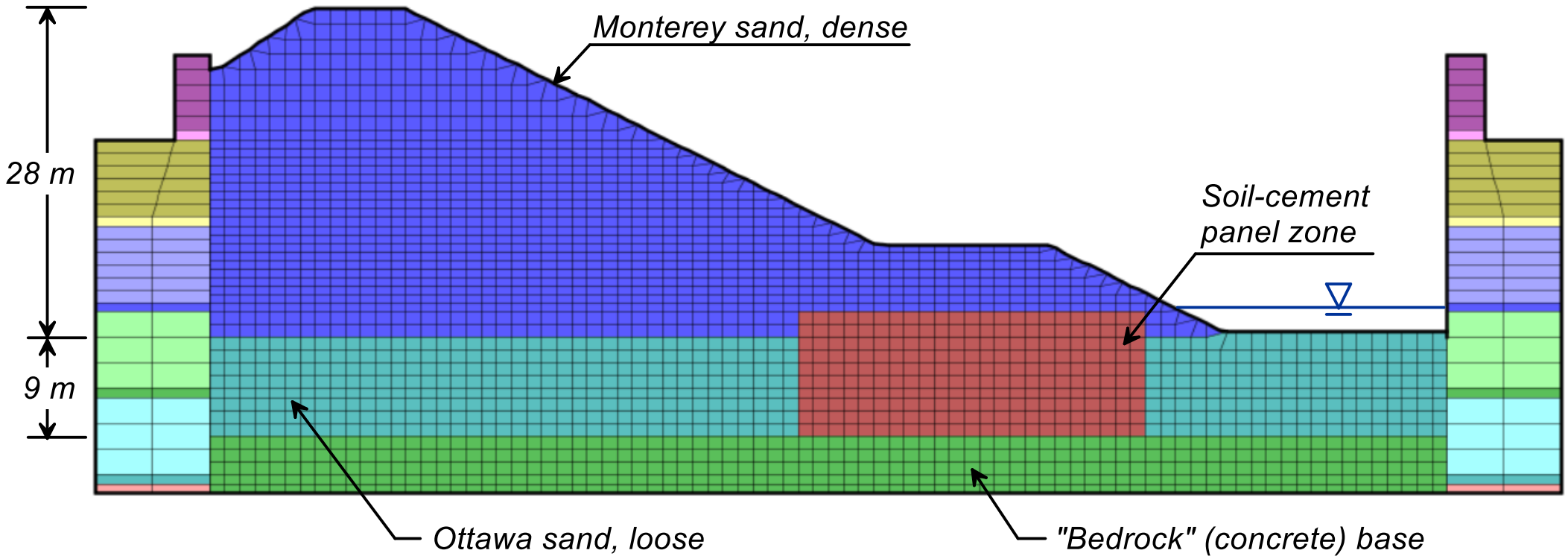
Dissection



NDA model

Mesh and materials

- 2D coupled simulations using FLAC 8.0 (Itasca 2016)
  - Foundation & embankment sands: PM4Sand (version 3)
  - Soil cement: Mohr Coulomb with area-weighted properties
  - Container: Elastic with equivalent density & stiffness per unit width
  - "Bedrock": Elastic



Plasticity model for sand – PM4Sand

- *PM4Sand version 3 by Boulanger & Ziotopoulou (2015) and Ziotopoulou & Boulanger (2016)*
  - *Critical state & stress-ratio based, bounding surface plasticity model developed to approximate stress-strain responses important to earthquake engineering practice*
- *Generalized calibration for liquefaction problems*
  - *Three primary parameters for most applications (D_R, G_o, h_{po})*
  - *Default values for secondary parameters*
- *Implemented as a user-defined dynamic link library (dll) for use with FLAC 7.0 (Itasca 2011) and FLAC 8.0 (Itasca 2016)*
  - *Manual, dll, and example files are at: https://pm4sand.engr.ucdavis.edu/*

Calibration of PM4Sand for Ottawa Sand

- *Secondary parameters: all default values except e_{max}=0.83, e_{min}=0.51*
- *Cyclic strengths from DSS tests by Parra Bastidas et al. (2017)*
- *<u>1st & 2nd events</u>*

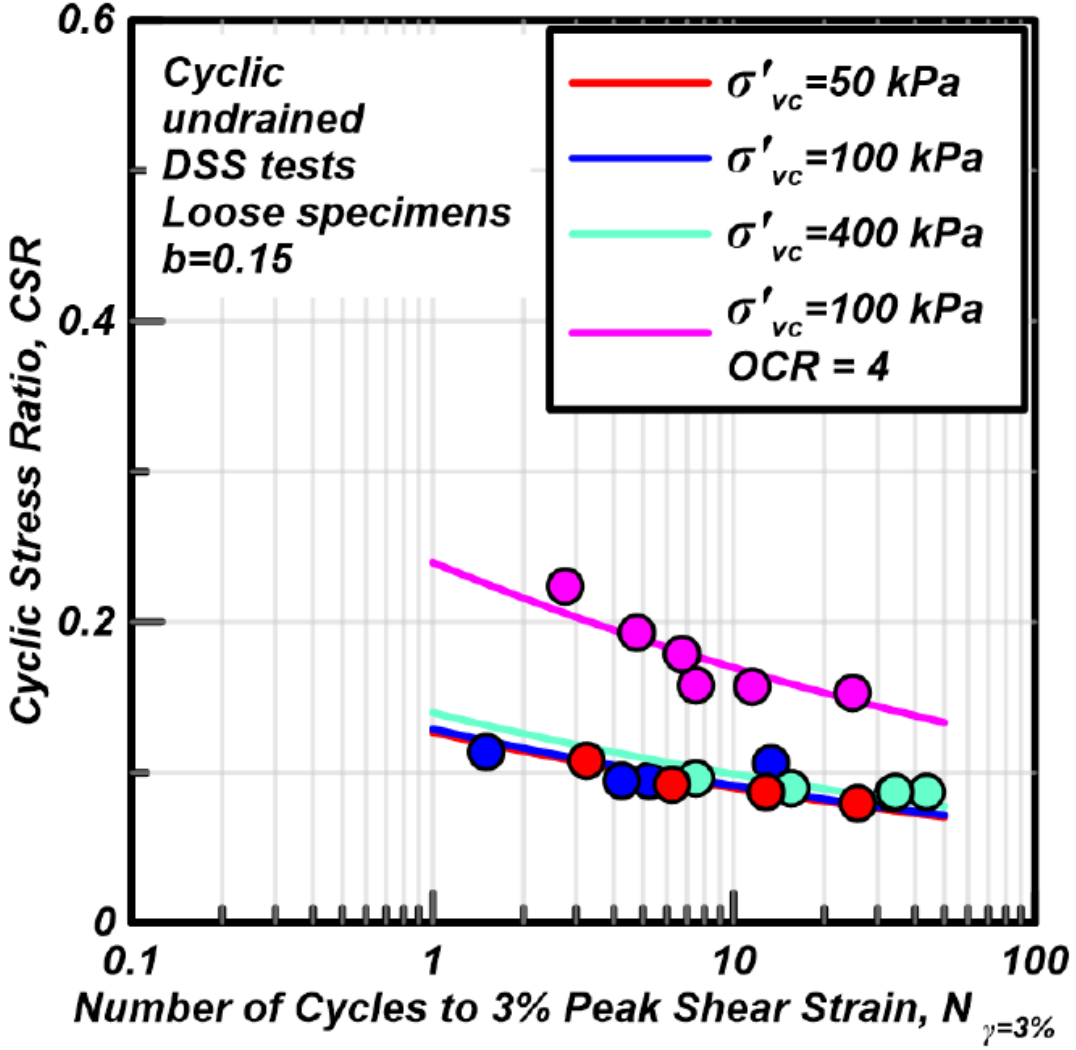
  D_R=42%

  G_o=770 for V_{s1}=185 m/s

  h_{po} = 0.54 for

  $CRR_{15cycles}$= 0.093 at σ'_{vc} = 400 kPa

A.-M. Parra Bastidas (2016)



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- *<u>3nd event</u>*

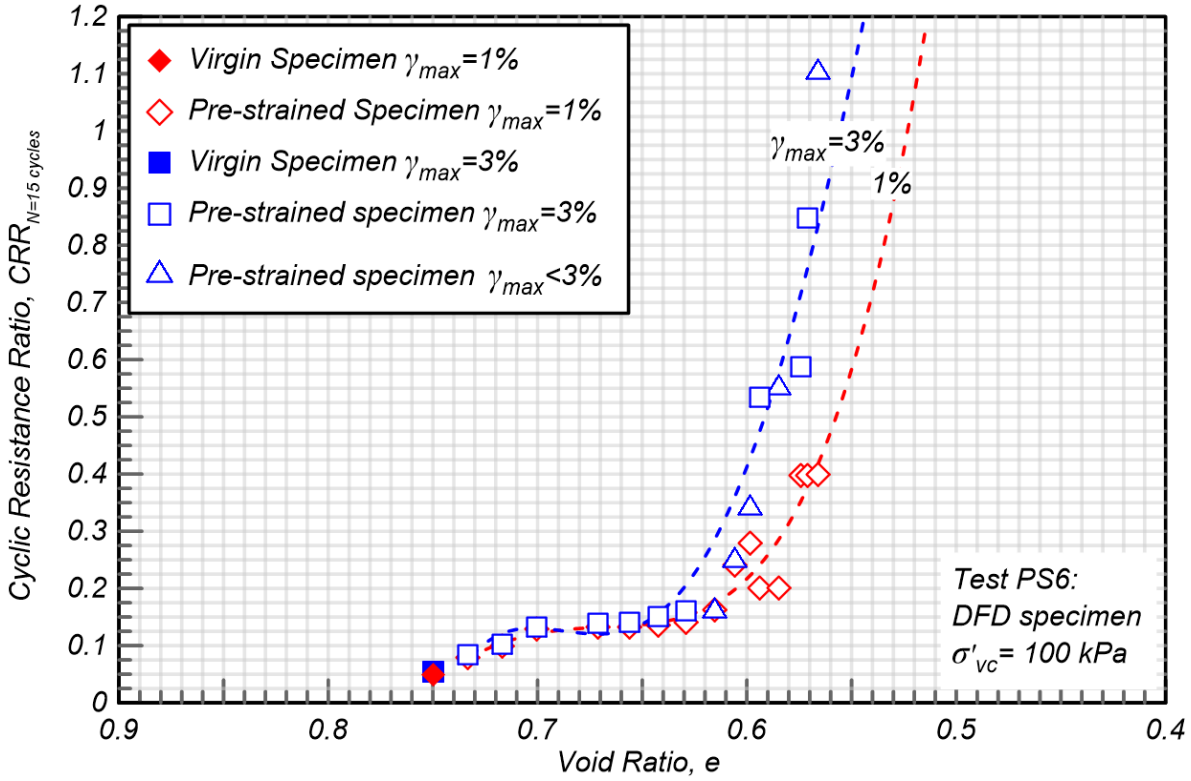
  D_R=45%

  G_o=788 for V_{s1}=187 m/s

  h_{po} = 1.20 for

  $CRR_{15cycles}$= 0.120 at σ'_{vc} = 400 kPa

Parra Bastidas et al. (2017): Evolution of CRR for Ottawa sand with recurrent liquefaction and cyclic pre-straining



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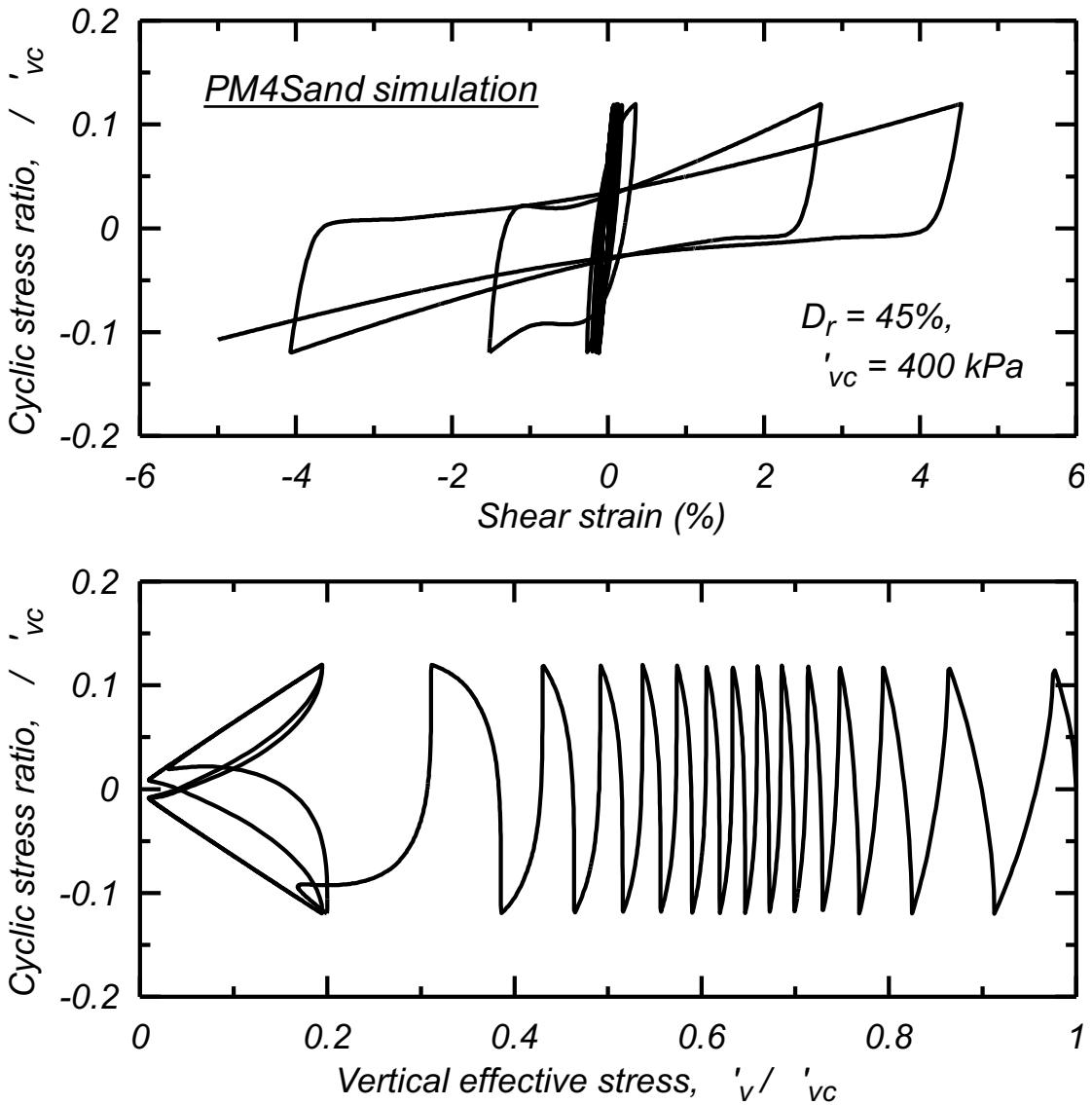
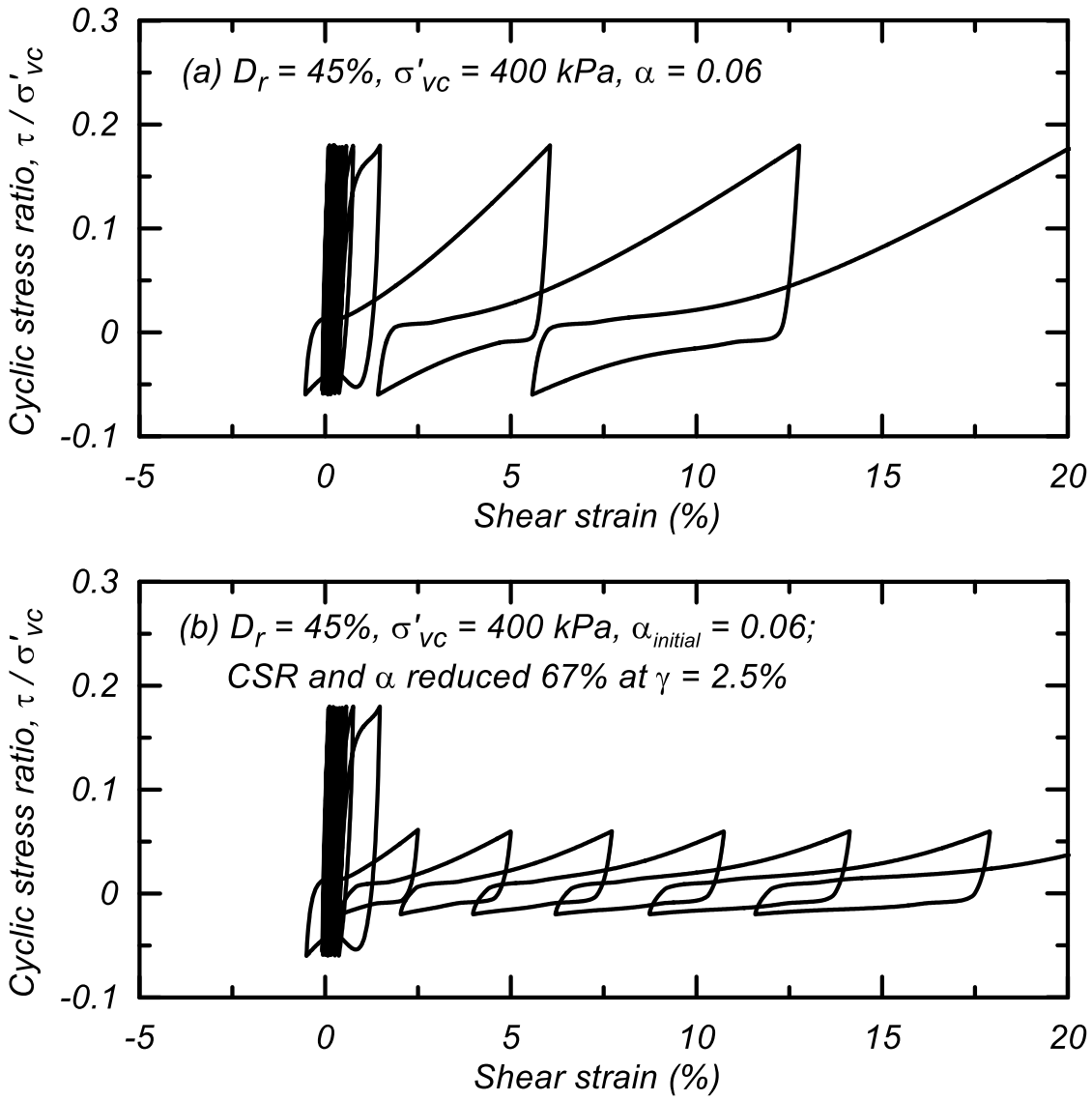


Calibration of PM4Sand for Ottawa Sand

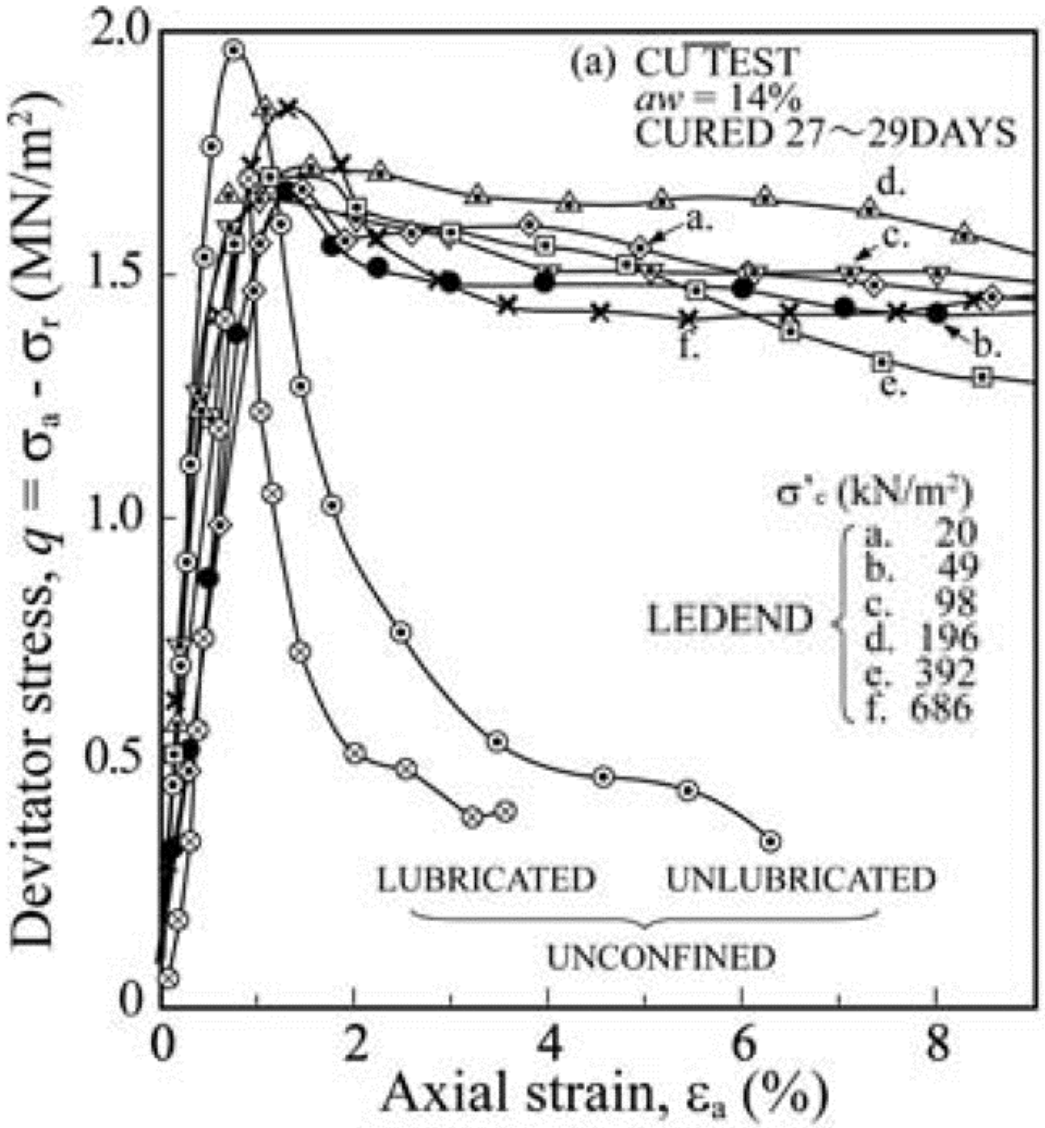
- *Simulated response for an initial static shear bias representative of conditions beneath the embankment:*
  - *a) With uniform CSR loading*
  - *b) With stepped CSR loading*

- *Other key behaviors for the model are illustrated in Boulanger & Ziotopoulou (2015)*



Soil-cement stress-strain responses

- *Tatsuoka & Kobayashi (1983) showed relatively modest strain-softening for cement stabilized Tokyo Bay Clay (LL=100, PI=46) with w=120% and binder factor of 14% in ICU triaxial compression tests*
- *Filz (personal communication) observed a greater rate of strain-softening in ICU triaxial tests for cemented treated loamy soil*
- *The average resistance during shaking will be intermediate to the peak and final strengths and depend on the degree of strain softening*
  - *Used 80% of peak strength for our baseline model*



Composite properties for treatment zone

- *Soil-cement shear strength:*
  - *Mohr Coulomb failure envelope with* $\phi = 0$
  - *Used 80% of peak strength to allow for progressive reduction in shear resistance with increasing strain*
  - *Baseline case is therefore* $(S_u)_{panel} = 0.8\ (q_{ucs}/2)$
- *Composite strength in saturated loose sand layer*
  - *Assumed zero shear resistance in the loose sand between the panels because it liquefies and the panels are much stiffer*
  - *Area-weighted strength for Mohr Coulomb (c-*ϕ*) model is*

    $c = A_r\ (S_u)_{panel}$ *with* $\phi = 0$
- *Composite strength in dense embankment sand*
  - *Assumed drained strength for the dense Monterey sand*
  - *Area-weighted strength for Mohr Coulomb (c-*ϕ*) model is*

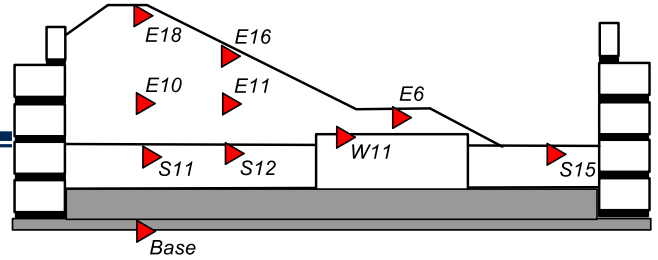
    $c = A_r\ (S_u)_{panel}$

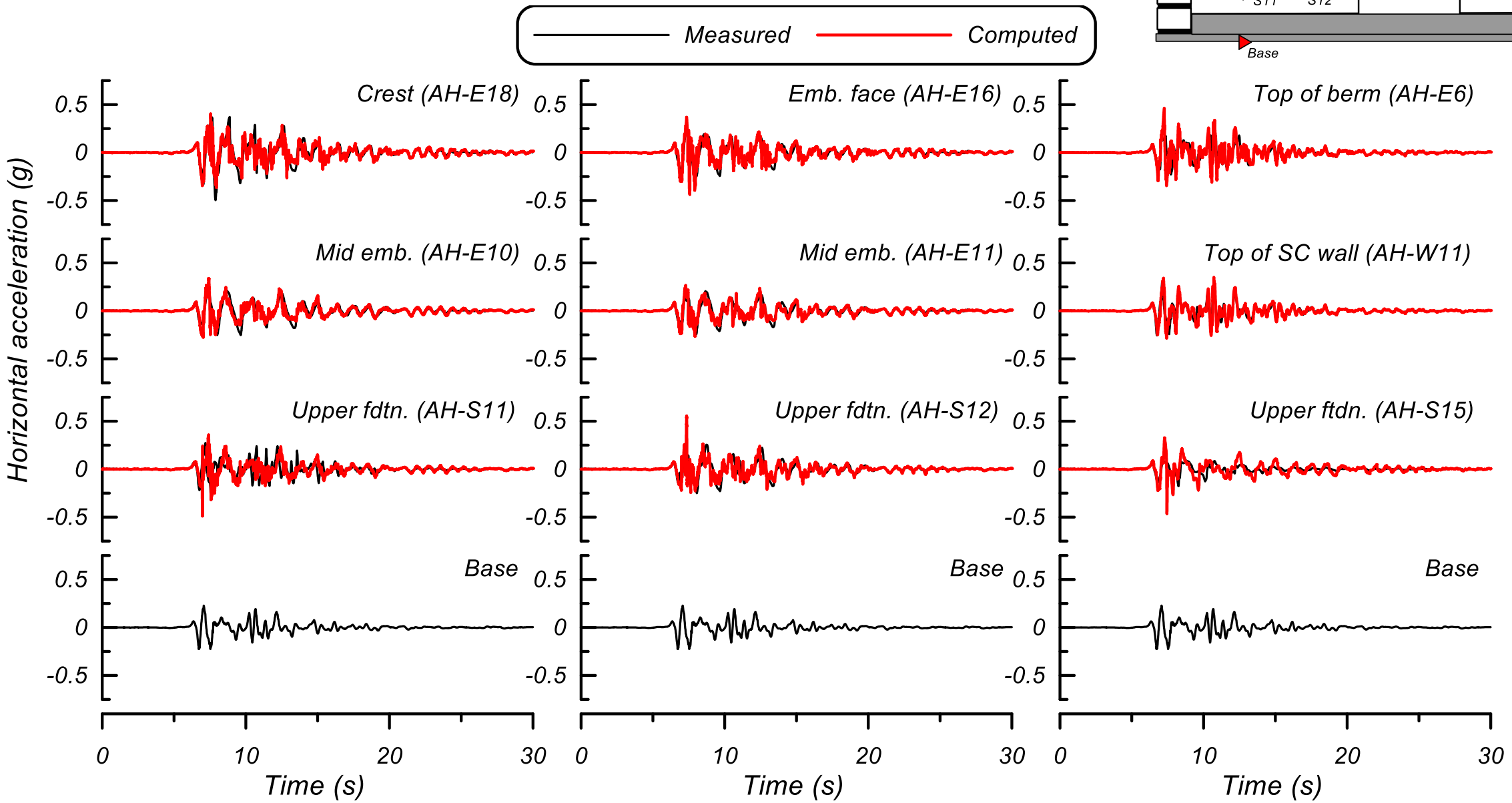
    $\phi = \tan^{-1}[(1-A_r)\tan(\phi)_{sand}]$

NDA results for baseline model:

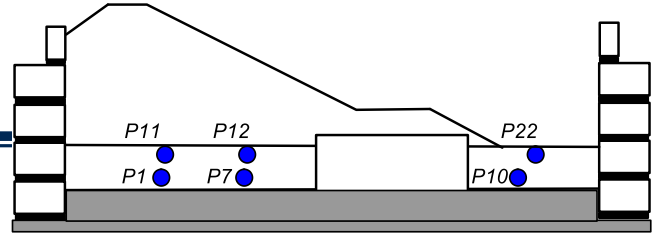
Kobe 0.26 g event

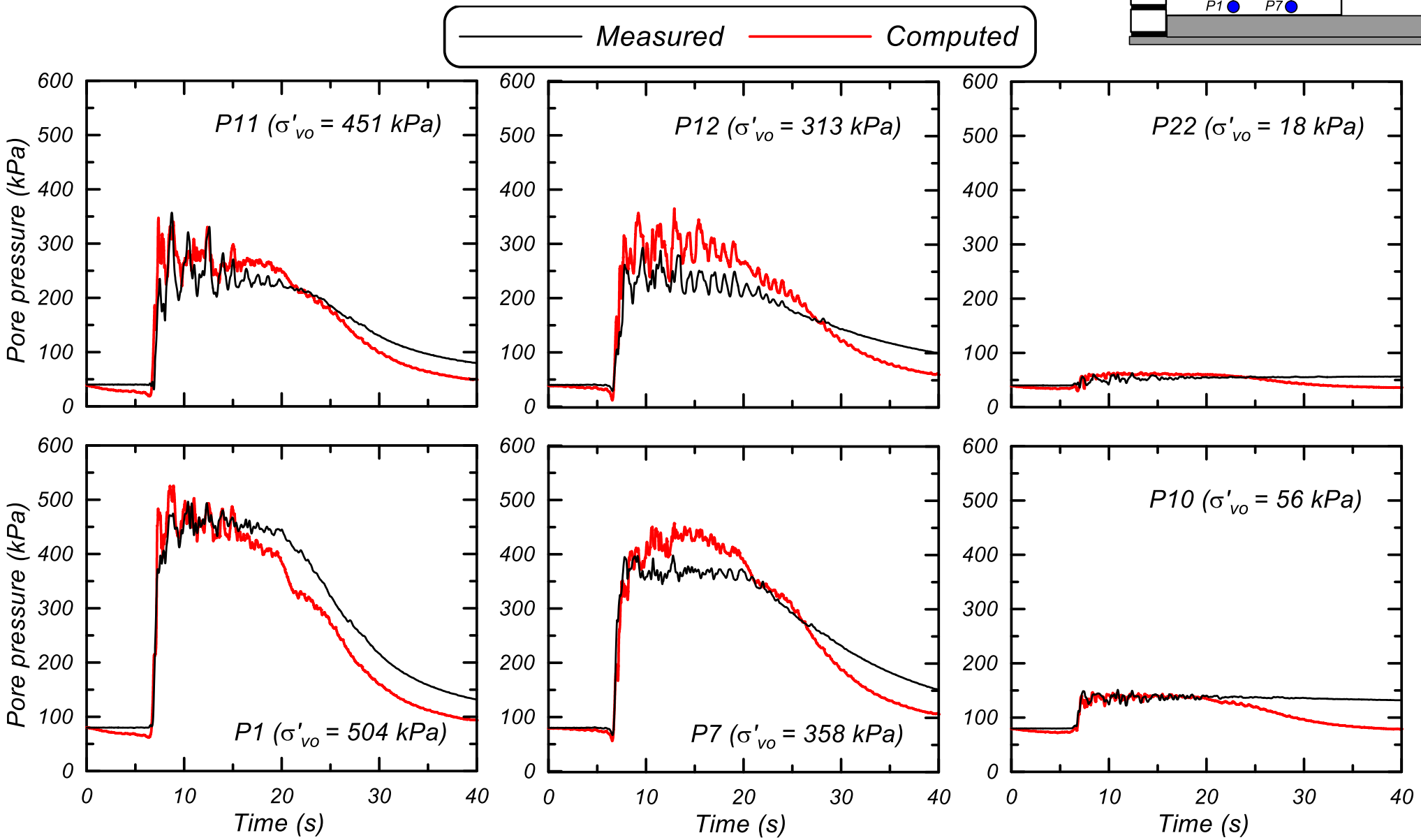
Baseline model – Kobe 0.26 g event





Baseline model – Kobe 0.26 g event





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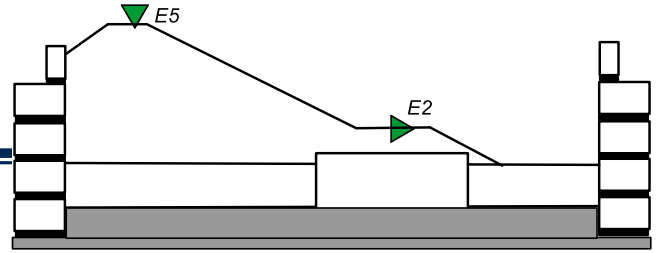

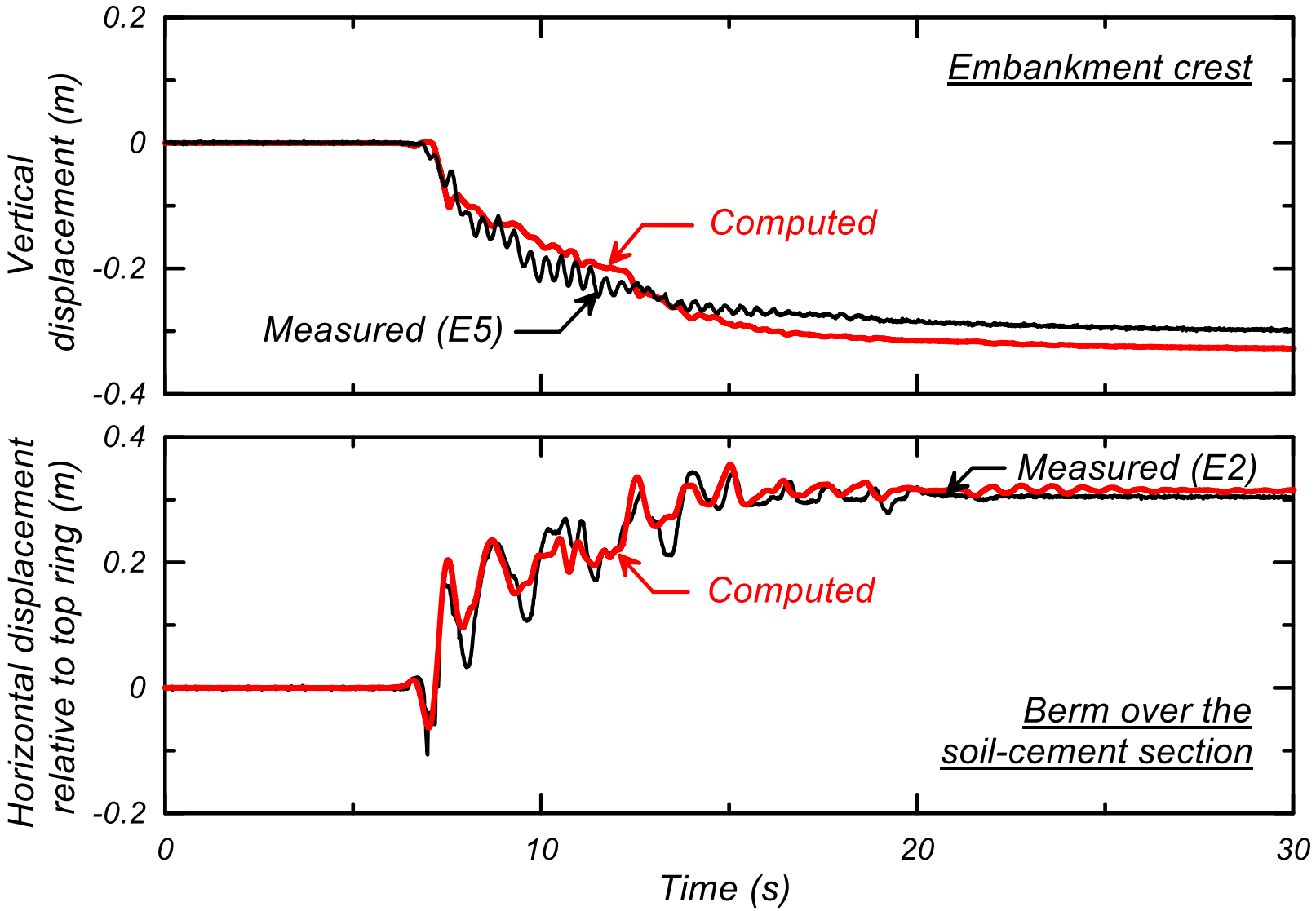

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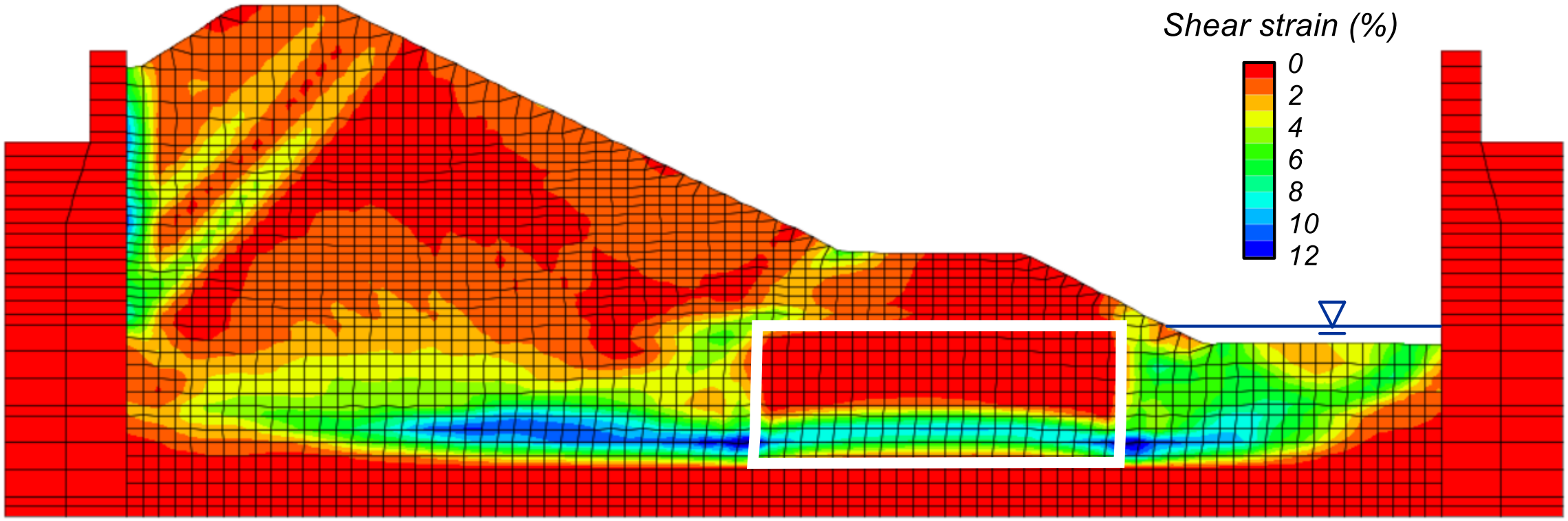
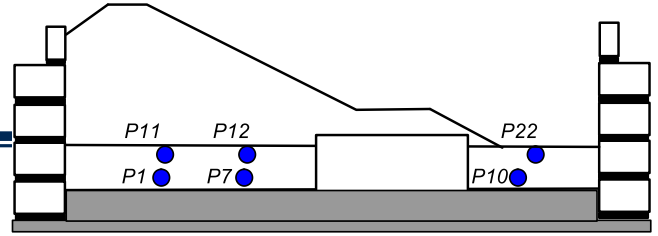
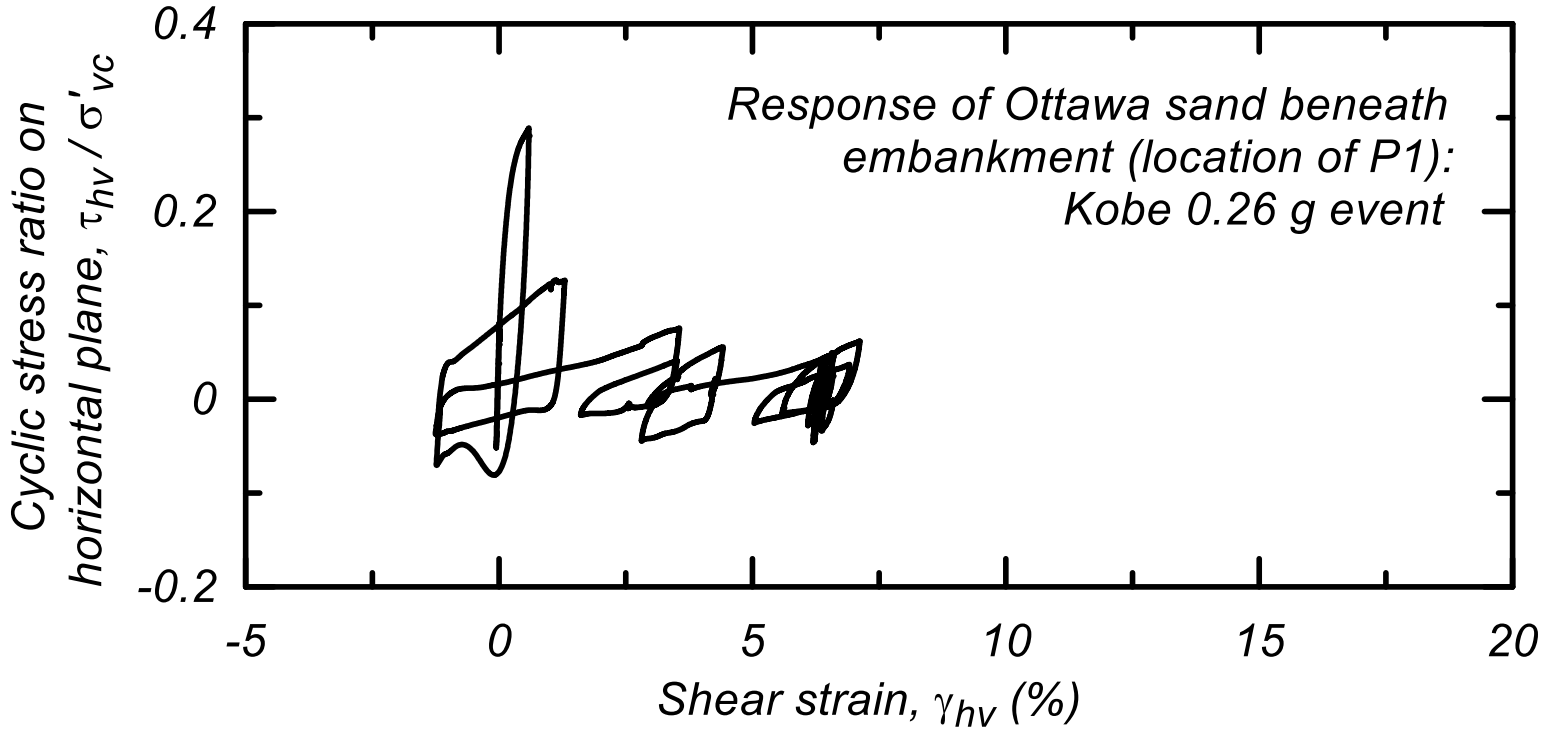


Baseline model – Kobe 0.26 g event

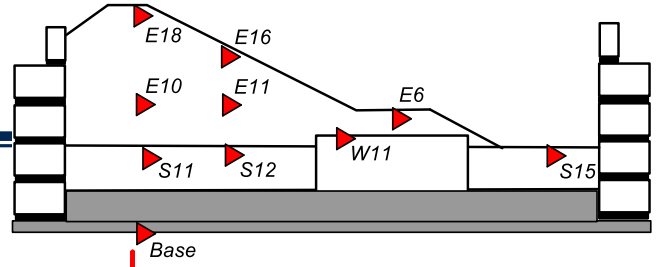


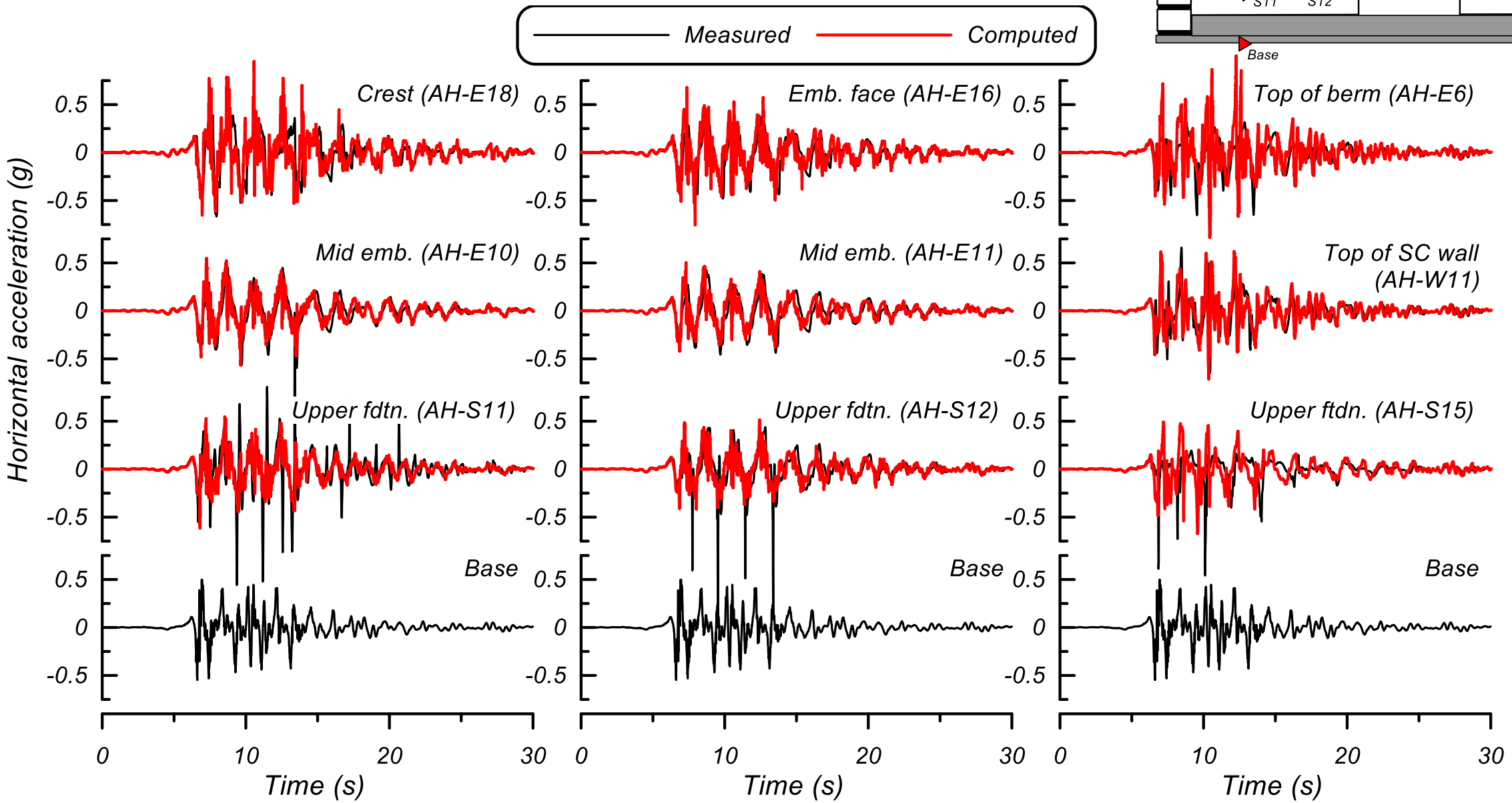


NDA results for baseline model:

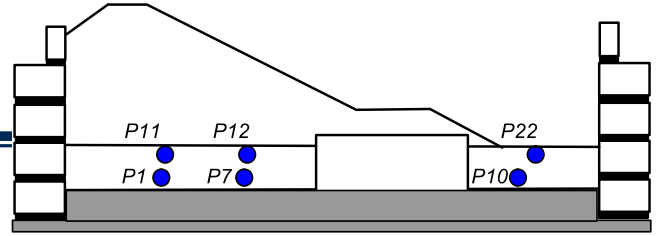
Kobe 0.54 g event

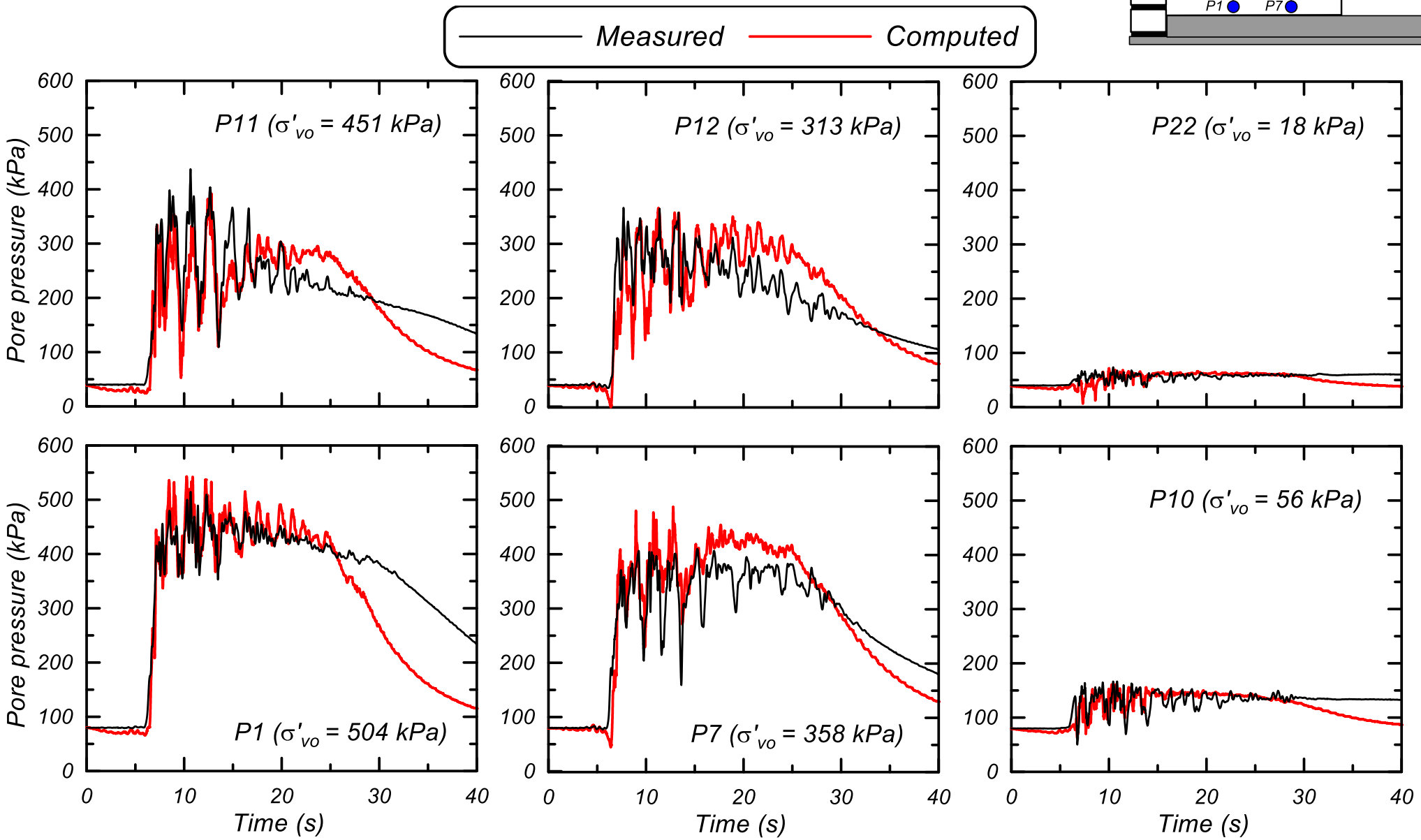
Baseline model – Kobe 0.54 g event



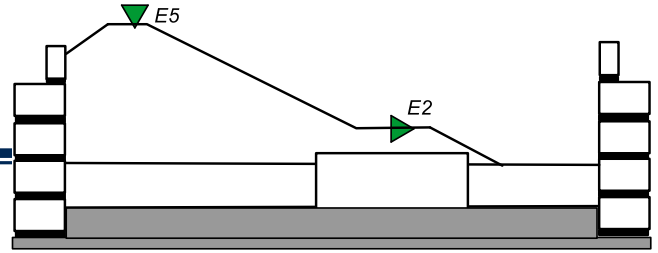


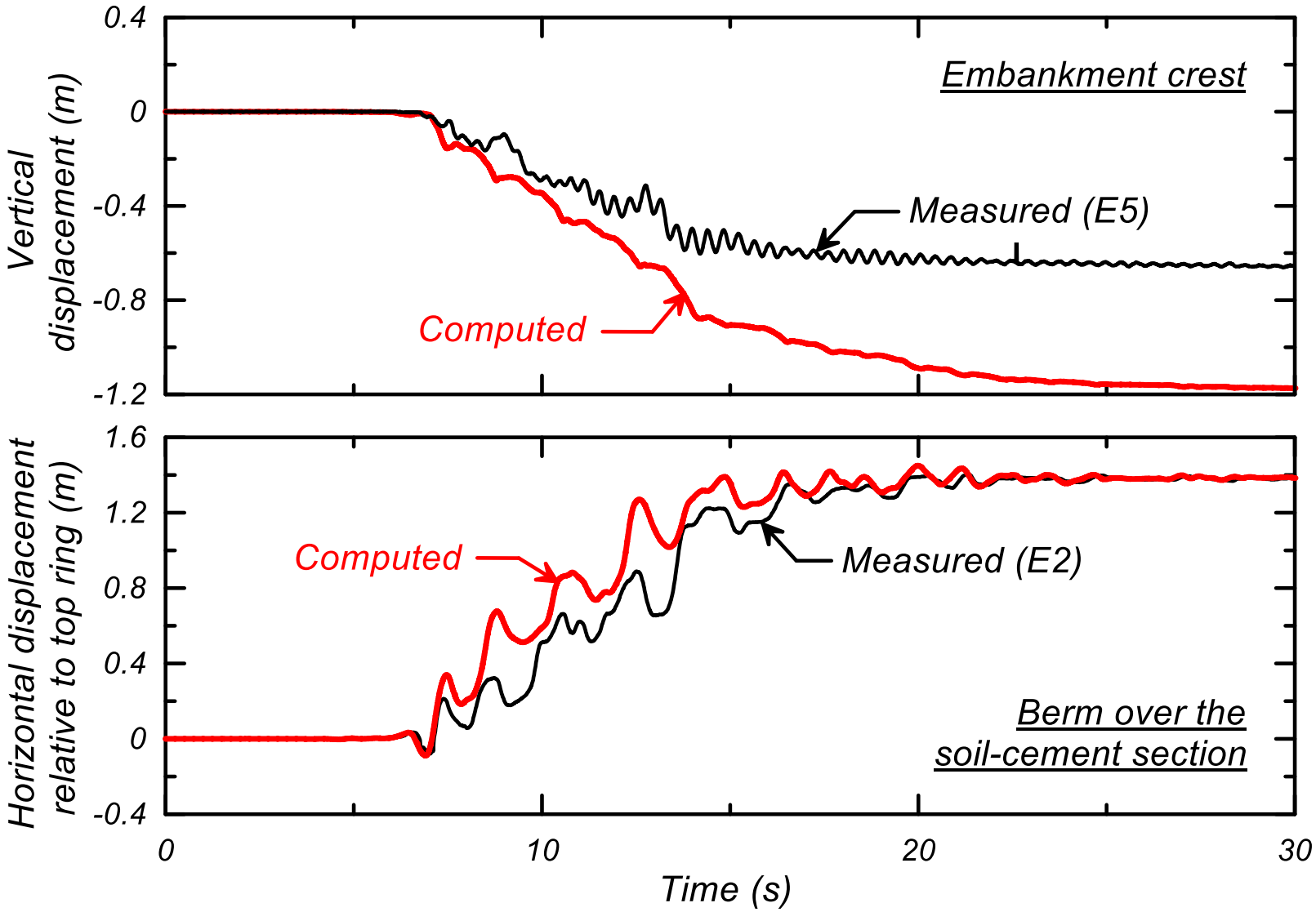
Baseline model – Kobe 0.54 g event





Baseline model – Kobe 0.54 g event





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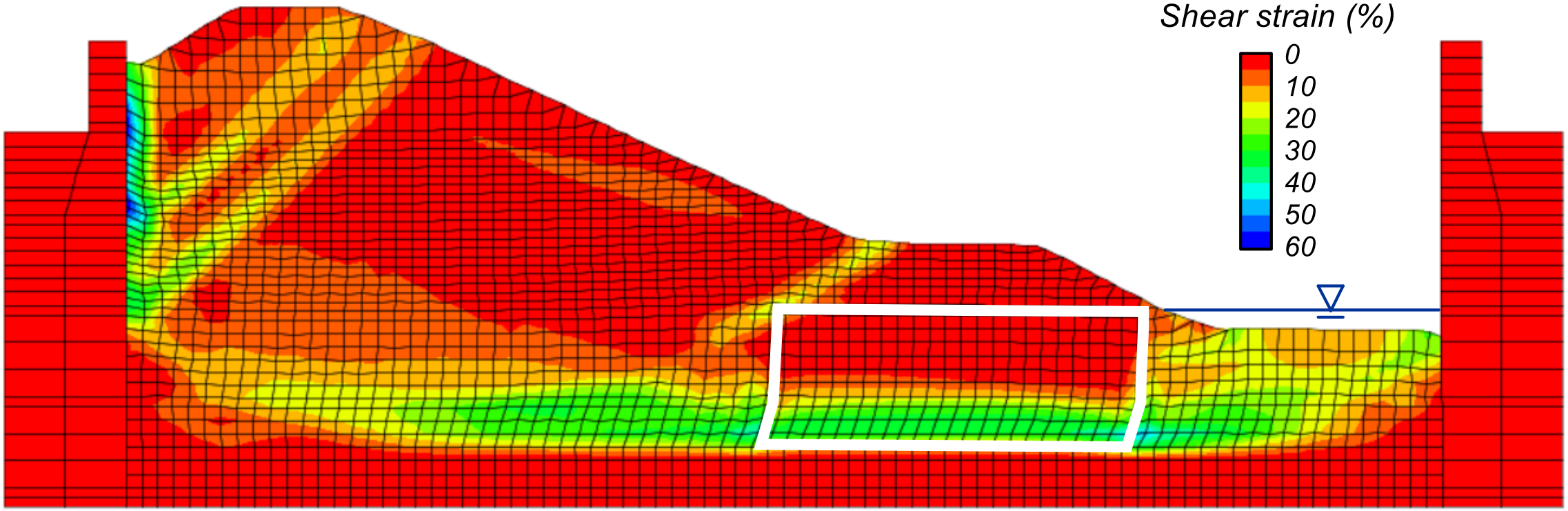

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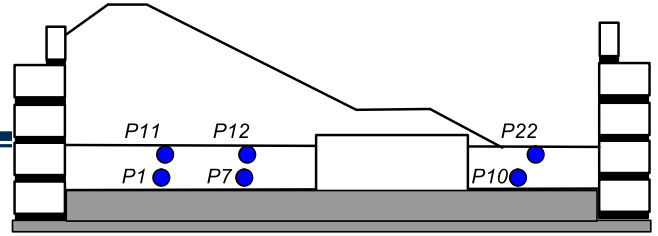
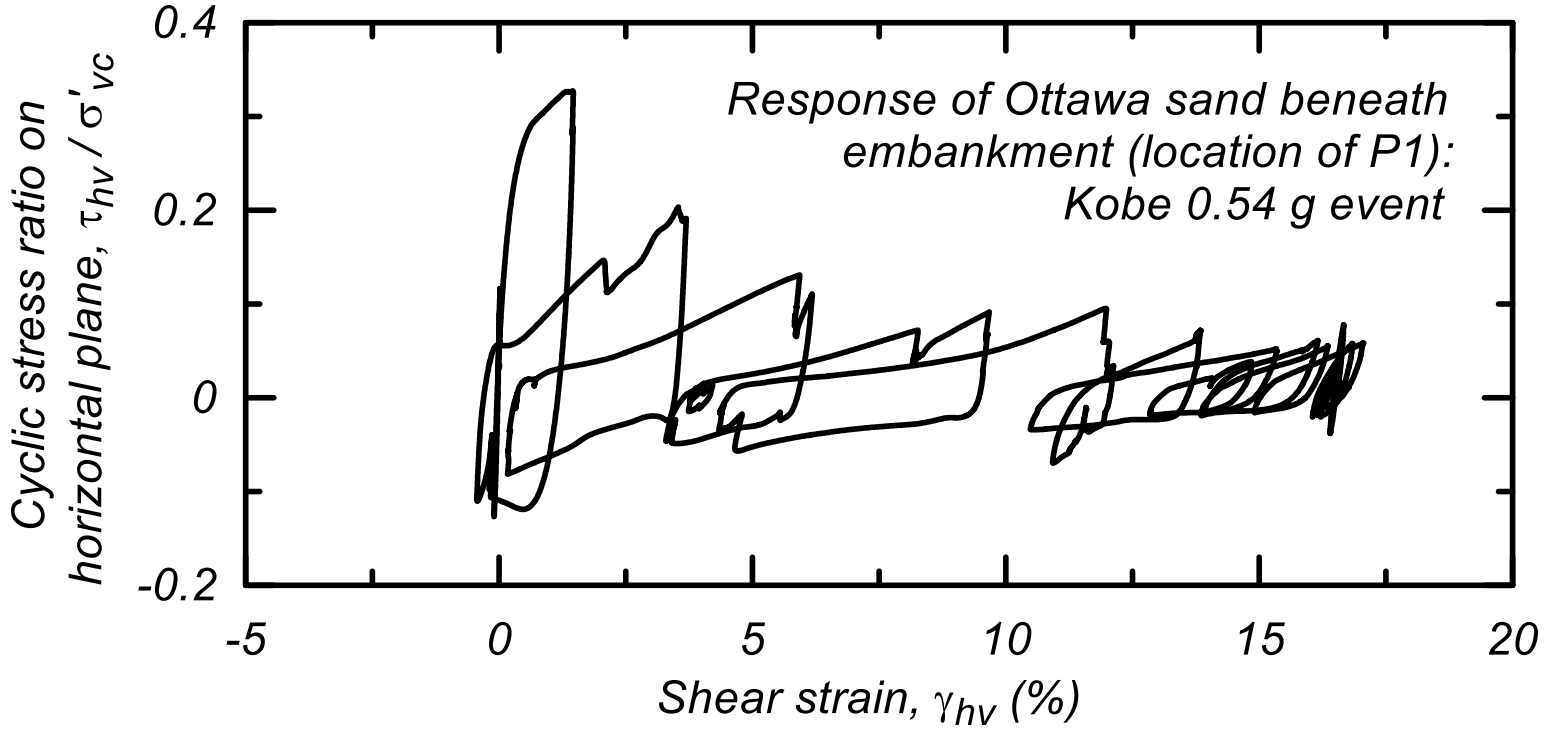
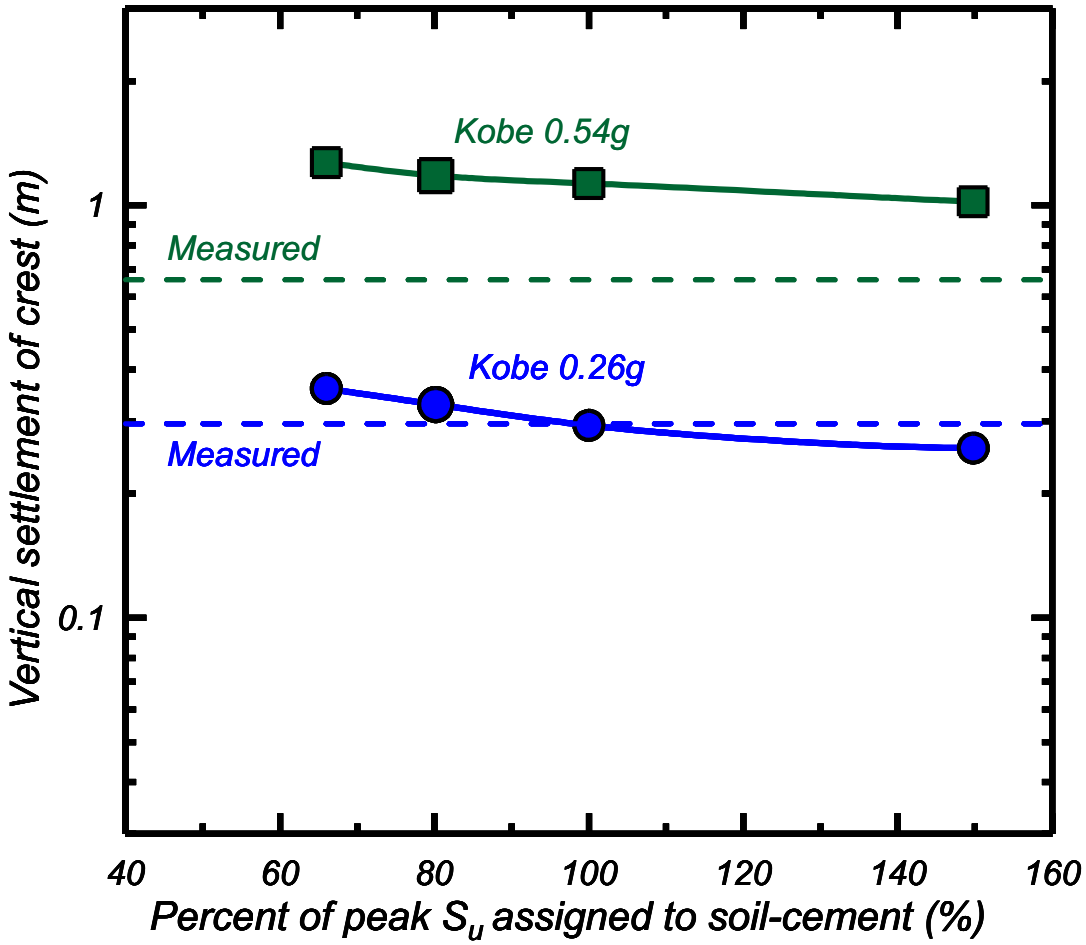


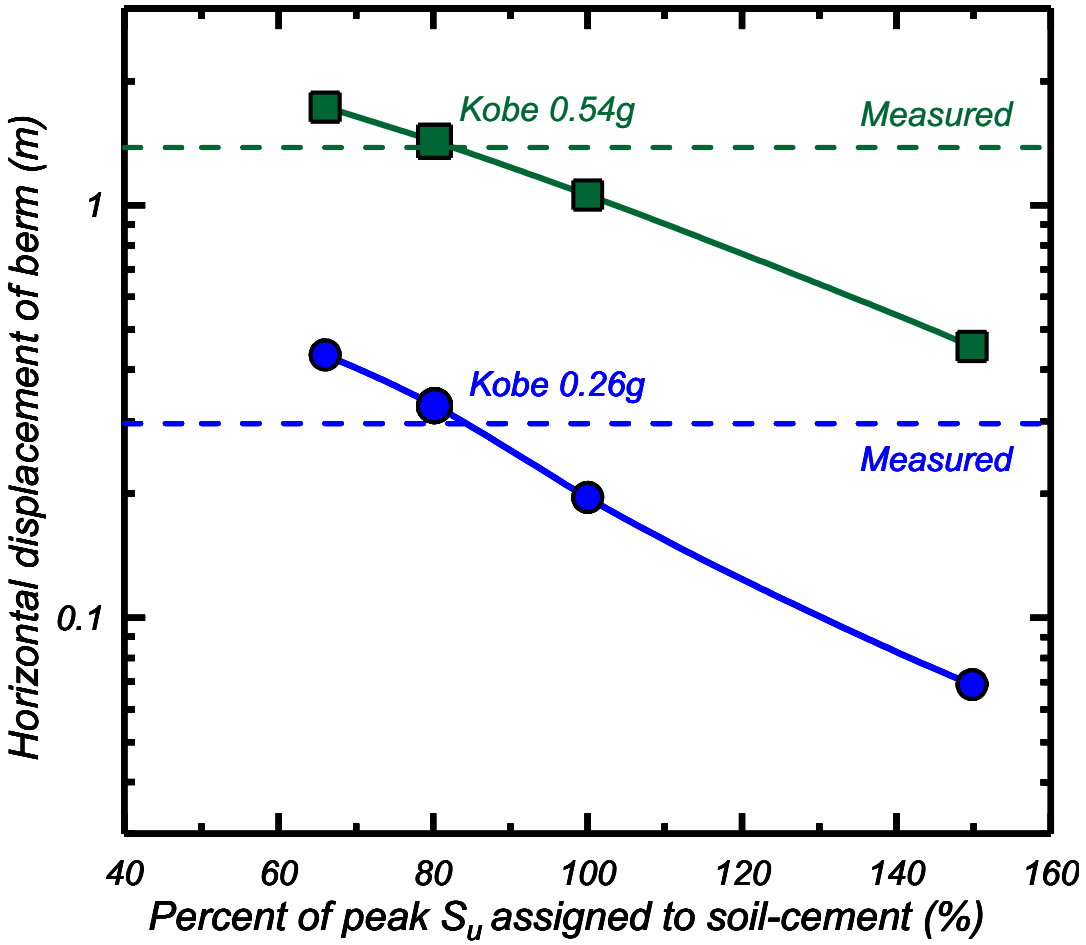


Sensitivity analyses

Percent of peak S_u assigned to soil-cement

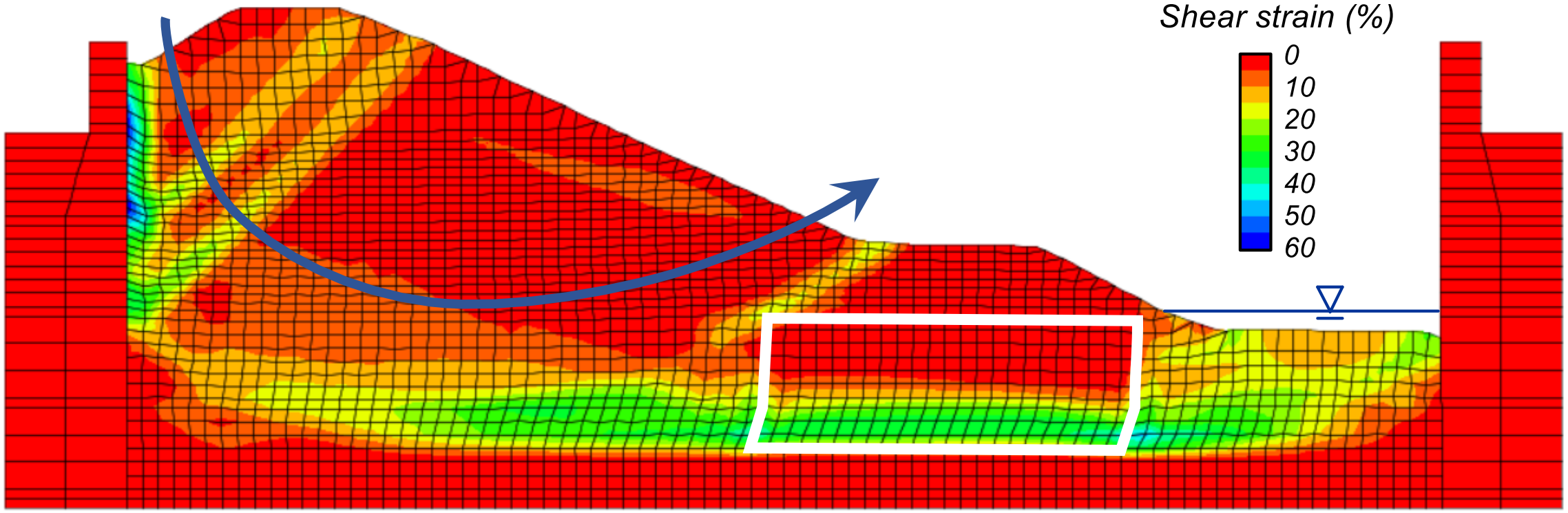
- 80% of peak S_u for soil-cement gave best overall results
- Over-estimating crest settlement in Kobe 0.54g event in all cases





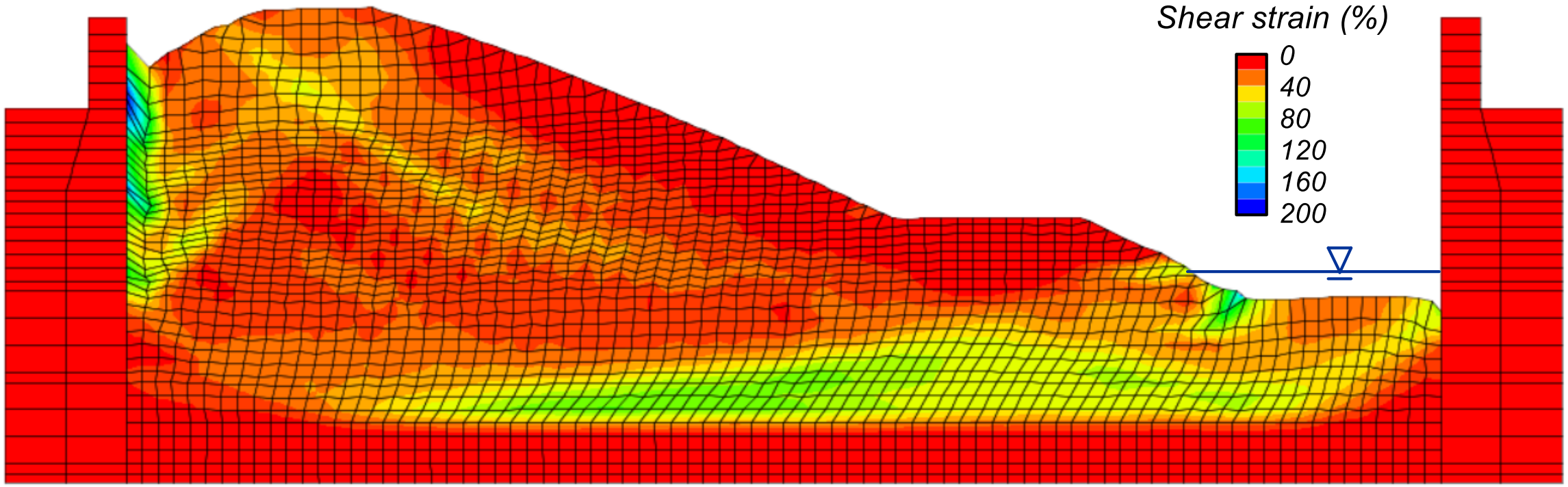
Over-estimating crest settlement in Kobe 0.54g event

- *Rotational deformations in embankment appear to be greater in the simulations than in the test*
- *Strengthening the embankment (D_R, n_b) or loose sand (D_R, h_{po}, n_b) reduces the over-prediction of crest settlement in this event, but results in under-prediction of deformations for other events/locations*



Non-treated case in Kobe 0.54g event

- *Simulations without the treatment zone showed*
  - *crest settlements of 3.1 m (4.7 times the value measured with soil-cement walls)*
  - *berm horiz. displacements of 5.0 m (3.6 times the value measured with soil-cement walls)*



Discussion

Complexity of deformation mechanisms

- *Equivalent 2D model does not account for a number of mechanisms*
  - *Extrusion of sand between soil-cement walls – greatest at downstream end with local slumping of the overlying berm*
  - *Irregular cracking and offsets that varied along the length of the soil-cement walls and between adjacent walls*
  - *Offsets along irregular cracks likely accompanied by local fluctuations in normal stress, which would contribute to changes in excess pore pressure in the shear zones/cracks*
  - *Excess pore pressures in soil-cement shear zones are likely negative based on the strength of the soil-cement*
  - *Expect pore water to flow from the liquefied sand between the walls into the cracks in the soil-cement walls; rate should depend on hydraulic conductivities, crack apertures, wall thickness, and the hydraulic gradients*
  - *Shear resistance along the cracks likely degrades progressively during shaking as the cracks grow and offsets develop*

Conclusions

Conclusions

- *The 2D NDAs were in reasonable agreement with the responses recorded in the centrifuge model, providing support for the use of these numerical modeling procedures in practice*
  - *Soil cement walls had limited cracking in the 0.26g Kobe event, but were sheared through in the 0.54g Kobe event*
  - *Deformation in the treatment zone included complex cracking patterns, offsets along wall cracks, & extrusion of liquefied soil*
  - *Analyses represented the treatment zone with area-weighted properties, a non-degrading Mohr Coulomb model, and an average soil-cement shear strength* $S_u = 0.8\ (q_{ucs}/2)$
  - *Analyses do not recreate the complex local mechanisms of deformation in the treatment zone, but appear to approximate the global behavior reasonably well*
- *2D nonlinear dynamic analyses of the embankment <u>without</u> the treatment zone indicate that the soil-cement walls were effective in reducing embankment deformations even though the walls were extensively damaged in the 0.54g Kobe event*
- *Soil-cement walls/grids can be an effective remediation strategy for embankment dams with liquefiable or weak foundation soils*

Acknowledgments

- *Funding for the centrifuge facility*
  - *National Science Foundation (NSF) through NEES & NHERI*
- *Funding for the centrifuge tests*
  - *Pacific Earthquake Engineering Research (PEER) Center*
- *Funding for the numerical analyses*
  - *California Department of Water Resources (DWR)*
- *Assistance with centrifuge tests:*
  - *W. Yunlong (China Earthquake Administration)*
  - *Amber Pulido (CGM undergraduate assistant)*
  - *CGM staff (Chad Justice, Tom Kohnke, Anatoliy Ganchenko)*

References

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