Ph.D Thesis Presentation

Numerical Modelling of Structure-Soil-Structure Interaction (SSSI) Affected by Soil Liquefaction

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Soil liquefaction

Settlement of structures during 2011 Tohoku earthquake, Japan (Ashford et al., 2017)

Rotation of a structure during 2010 Maule earthquake, Chile (Bertalot et al., 2013)

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Structure-soil-structure interaction (SSSI) affected by liquefaction

Outward tilt of adjacent buildings during 1999 Kocaeli earthquake, Turkey (Bray et al., 2000)

Inward tilt of adjacent buildings during 2000 Tottoriken-seibu earthquake , Japan (Yasuda and Ishikawa, 2018)

Geotechnical centrifuge test for studying SSSI on softened ground (Hayden et al., 2014)

Geotechnical centrifuge test for studying SSSI on softened ground (Kirkwood and Dashti, 2018)

Limited number of centrifuge tests have been performed recently focusing on SSSI affected by soil liquefaction (Hayden et al., 2014; Kirkwood and Dashti, 2018)

They help the researchers understand the governing mechanisms of the problem and provide data for validation of the numerical models

It is not practically feasible to do parametric studies in centrifuge tests

Numerical modelling is one of the most efficient means of understanding the problem of SSSI on softened ground

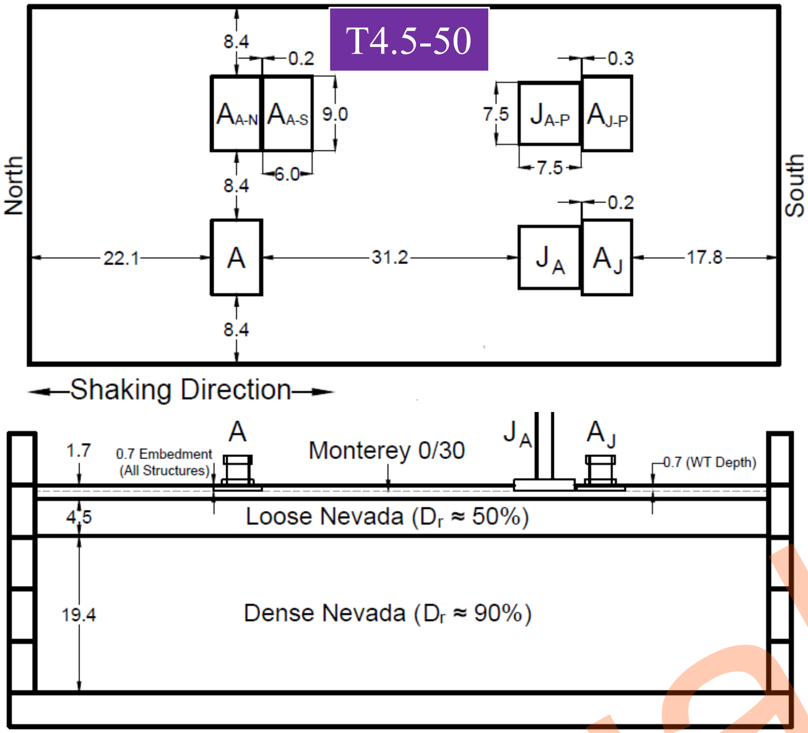
Numerical models need robust validation against experimental data

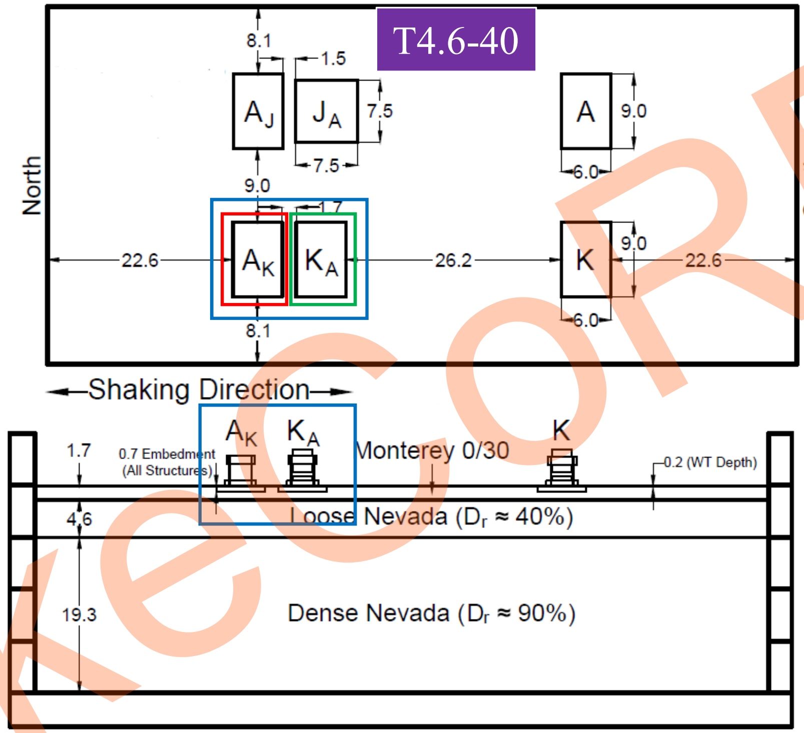
Developing numerical models to study the interaction of adjacent structures on liquefiable ground

1) Validation of the developed models (using different modelling approaches) against high-quality experimental data

- Testing assumptions and develop recommendations to improve the overall performance of the models
- Assessing the ability of the models developed with different approaches to predict the performance of adjacent structures on liquefiable ground
- Finding the strengths and weaknesses of the developed models
- Choosing the most effective modelling approach (results + run-time)

2) Performing sensitivity analyses using the most effective numerical modelling approach to find out the effective parameters of the problem and their relative importance





Event number	Event name	PGA (g)	I_a (m/s)	$D_{5\text{-}95}$* (s)
1	Small Port Island (PRI)	0.05	0.02	7.1
2	Moderate Port Island (PRI)	0.20	0.38	8.1
3	Moderate TCU	0.17	1.20	25.5
4	Large Port Island (PRI)	0.55	4.05	9.1

* Time required for Arias intensity to increase from 5 to 95% of its final value

Structure	Bearing pressure (kPa)	Fixed-base period (s)	Deck center of mass (m)*
A	65	0.33	3.9
K	180	0.38	3.9
J	180	0.85	15

* Measured from bottom of the foundation

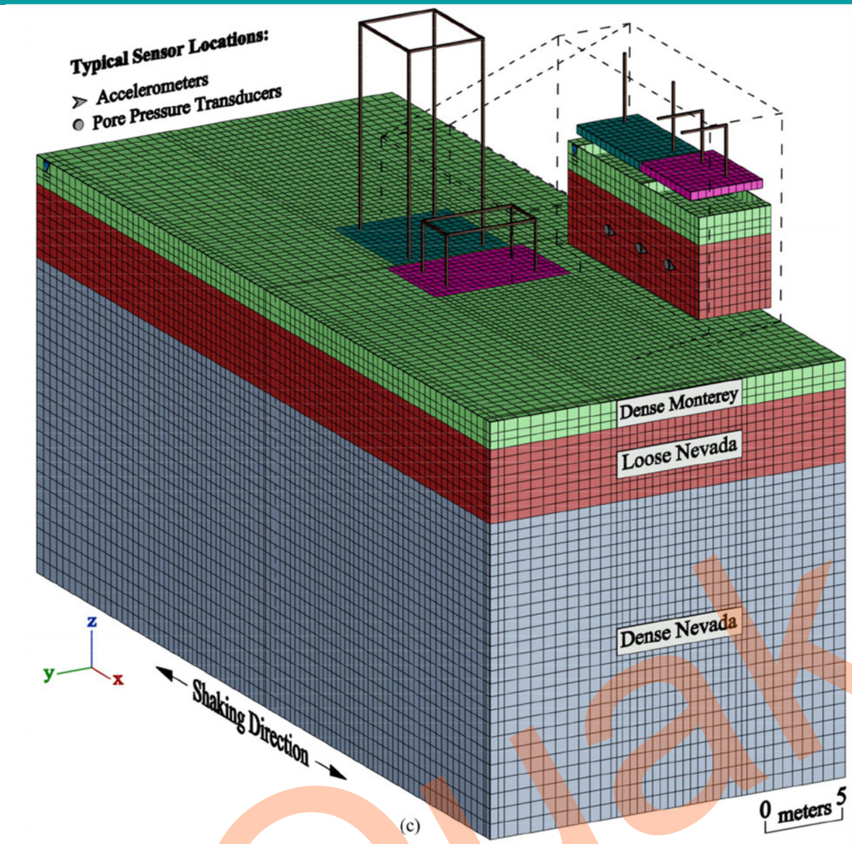
3 isolated and 4 adjacent structures

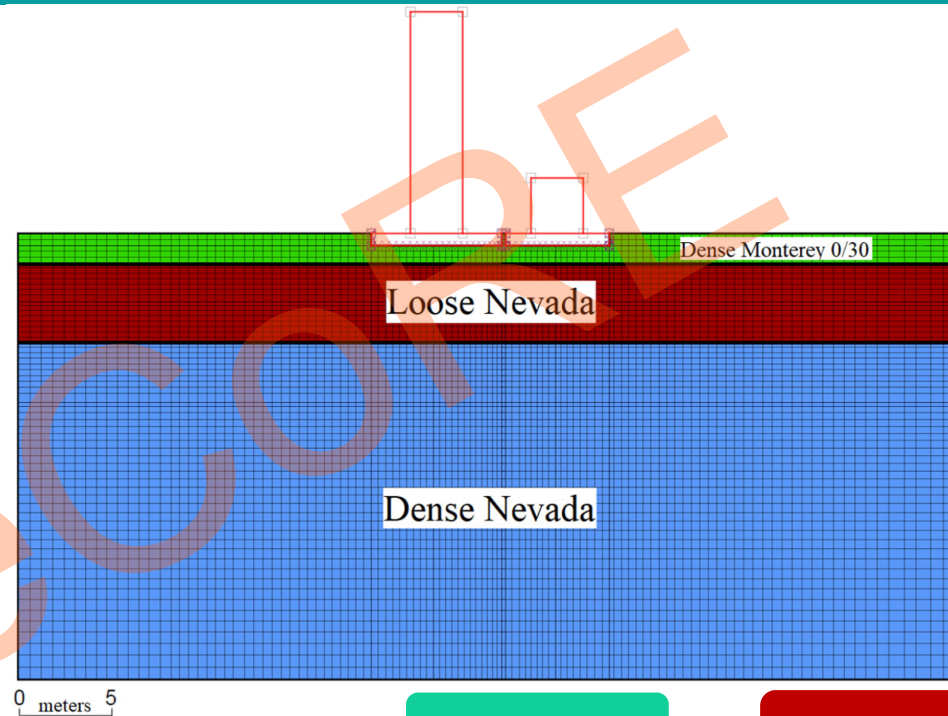
4 different ground motions

2 different ground models

24 total combinations of isolated structures

32 total combinations of adjacent structures





- Modelling approaches
  - 2-D plane strain
    - PM4Sand
    - P2PSand
  - 3-D
    - P2PSand

FLAC 2-D

FLAC 3-D

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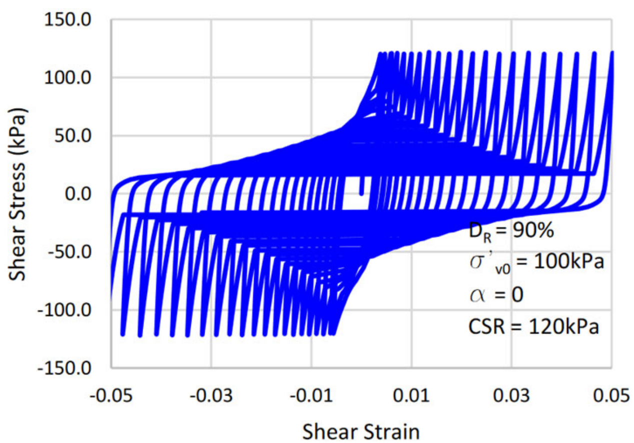
- PM4Sand parameters:
  - Single element FLAC simulation of the available laboratory data.
  - Primary parameters: calibrated for different relative densities of Nevada and Monterey Sands.
  - Secondary Parameters: default values recommended by Boulanger and Ziotopoulou (2017) for the same sand types.
  - More consistent approach with the industry.
  - Changing all the parameters altogether to make the results similar to the centrifuge tests? Cheating!
- P2PSand parameters:
  - Calibration by comparing the formulations to the PM4Sand parameters.



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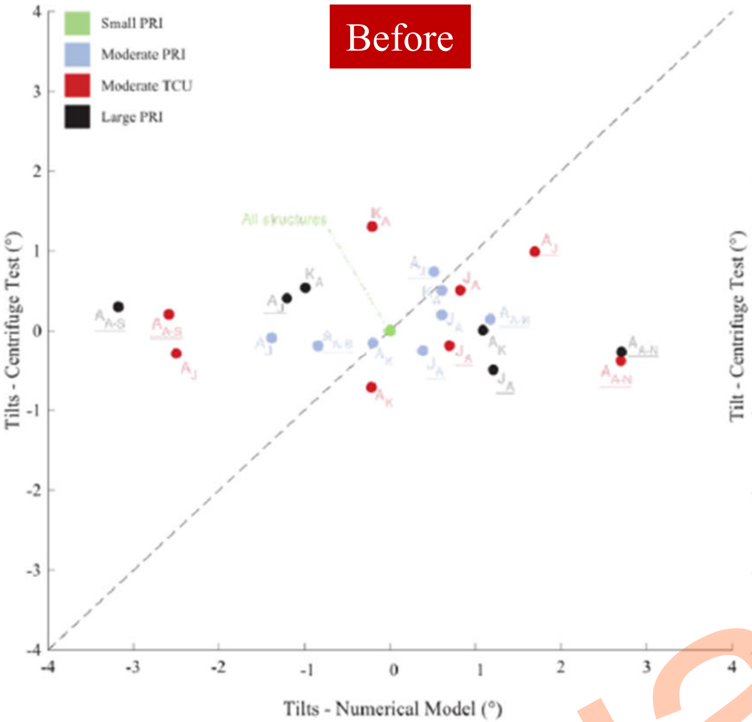
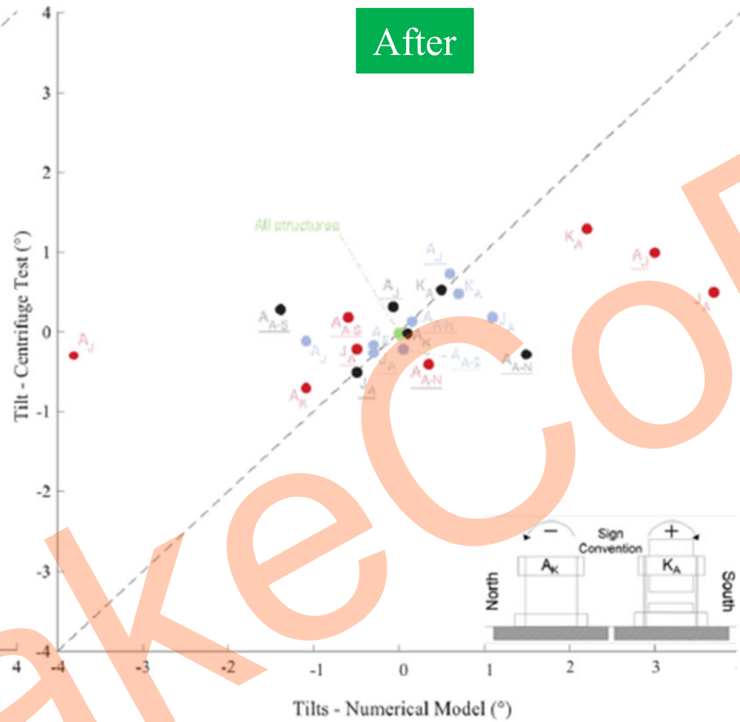
Recommended assumptions

- Applying the initial tilt of the structures
  - Centrifuge tests: consecutive input motions
  - Earthquakes: consecutive shaking events
- Increasing soil horizontal permeability
  - Centrifuge tests: non-uniformity of the sand layer due to air pluviation
  - Plane-strain modelling: effect of 2-D modelling of a 3-D problem

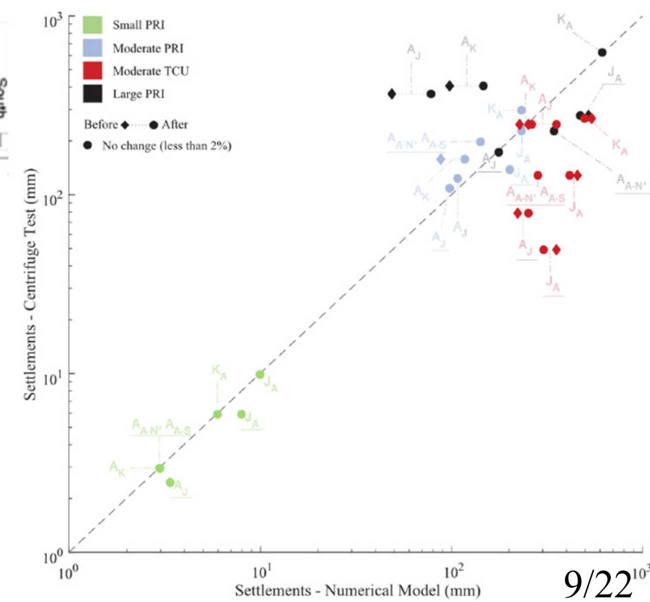
Assumptions and Recommendations to Improve the Numerical Modelling of Centrifuge Experiments





More effect on the rotations

Less effect on the settlements



Case	Isolated structures				Adjacent structures			
Assumption applied	None	Initial tilt	Hydraulic conductivity	Combined	None	Initial tilt	Hydraulic conductivity	Combined
Settlement	145.8	145.5	145.6	145.0	130.0	123.7	120.6	115.0
Rotation	0.50	0.47	0.48	0.45	1.50	1.10	1.30	1.00

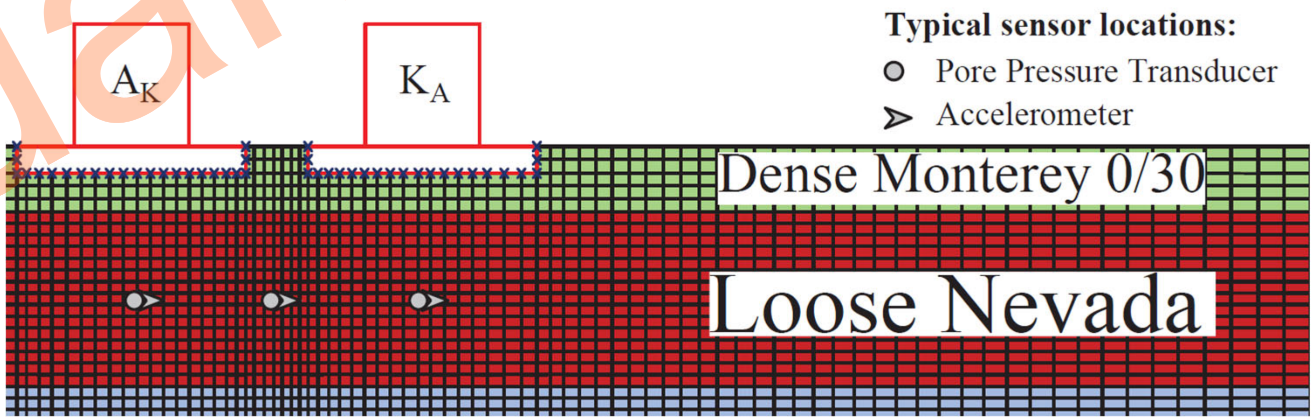
Parameters to compare:

Soil response (middle of the liquefiable layer)

- Pore water pressures under and between the structures
- Soil accelerations under and between the structures

Building response

- Foundation acceleration spectra
- Foundation settlements
- Foundation rotations



Data comparison

- Limited existing criteria for goodness-of-fit of different types of time histories
- No existing numerical modelling for SSSI affected by soil liquefaction

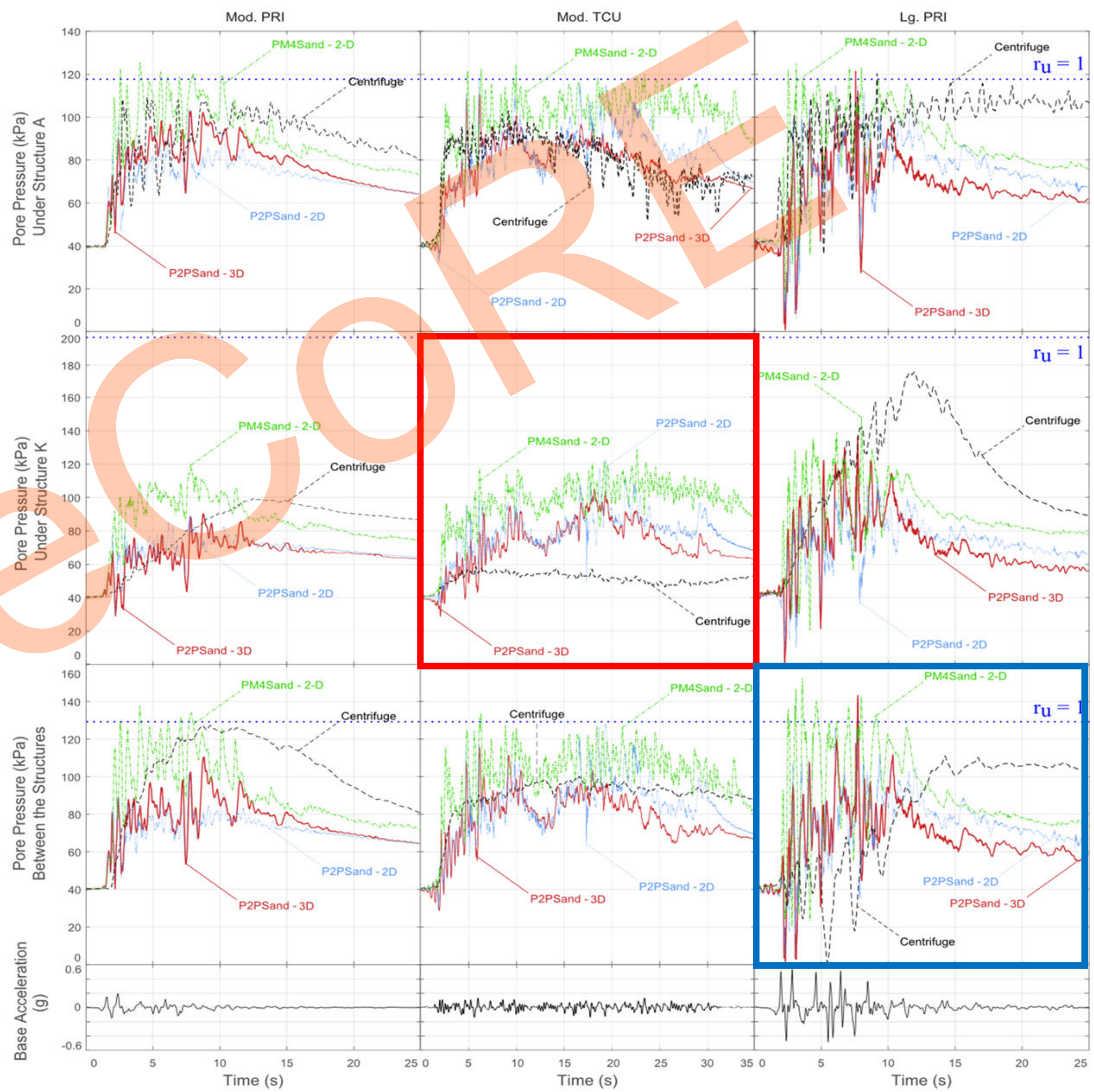
How to compare?

- Qualitative comparison for the time histories
- Quantitative comparison of the final settlement and rotations

Quality of the modelling approach?

- Comparison against the centrifuge tests
- Previous numerical modelling of isolated structures
- Run-time of the analyses

- Pore water pressures:
  - Good overall agreement.
  - All models especially the ones using PM4Sand overestimate the PWPs under the heavier structures during the TCU motion.
  - PM4Sand overestimates the PWPs between the structures during the large PRI motion.
  - 2-D P2PSand and 3-D P2PSand models have similar results due to implementing the recommendations.



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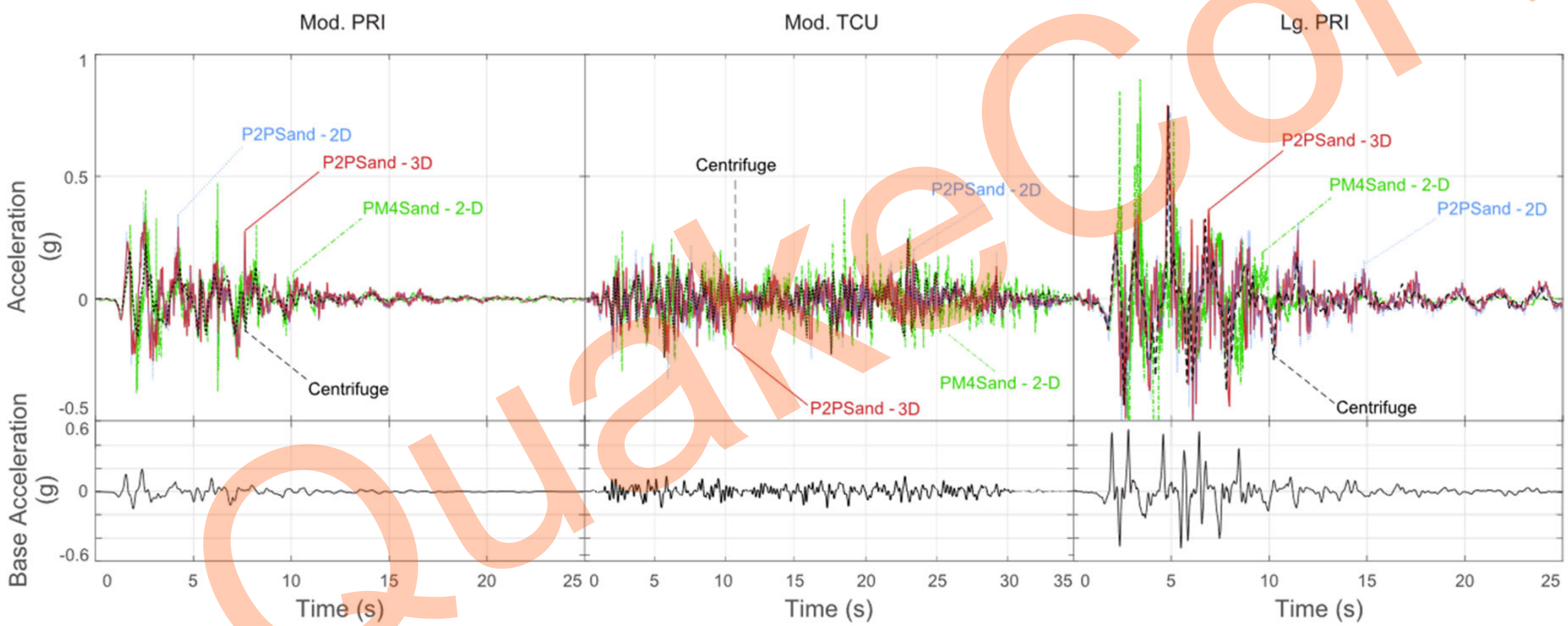
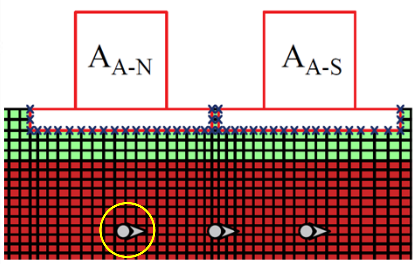
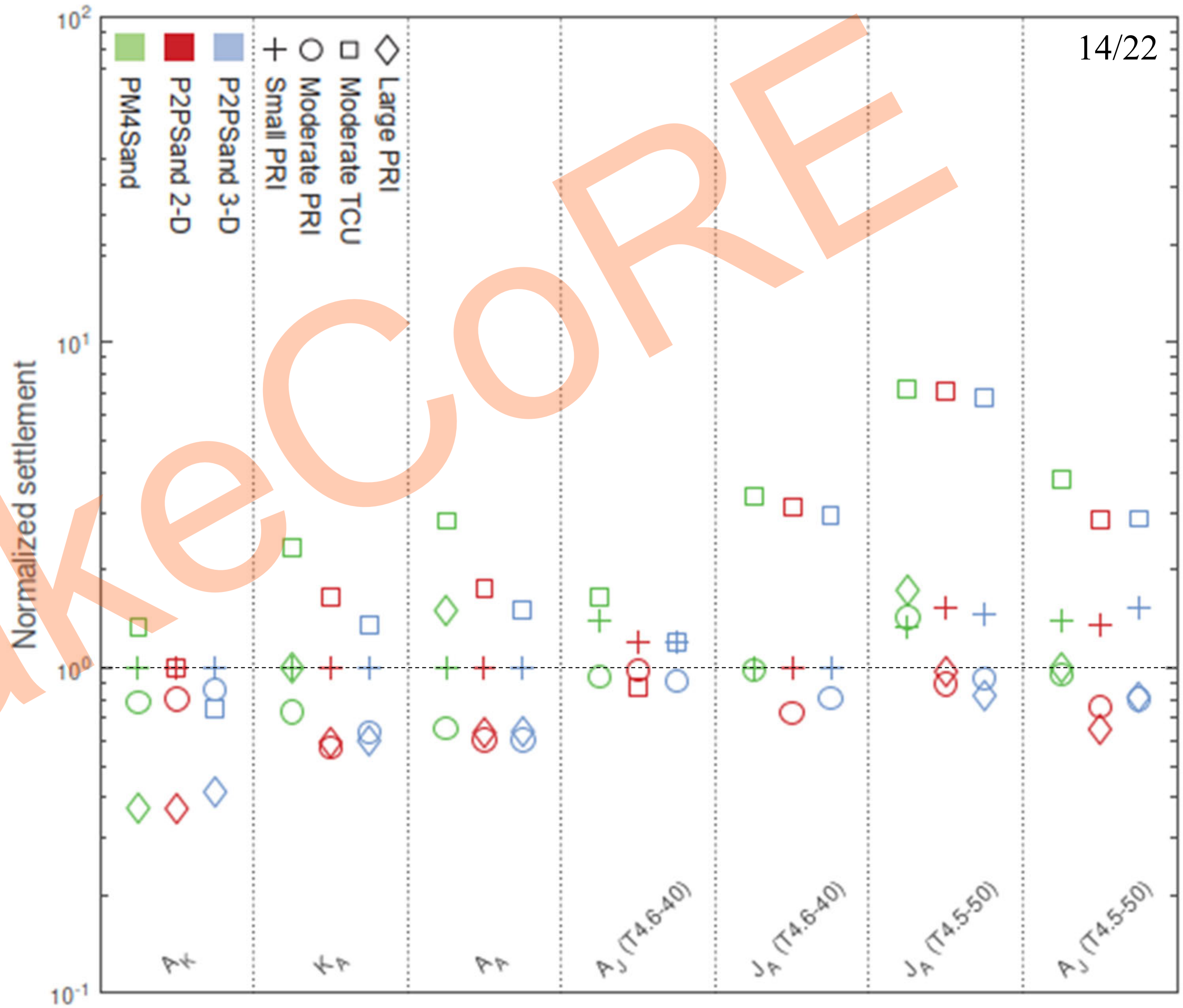
- Soil acceleration (middle of the liquefiable layer):
  - Overall agreement.
  - PM4Sand slightly overestimates the high-frequency spikes attributed to cyclic dilation and re-stiffening.
  - P2PSand 2-D and P2PSand 3-D predictions are generally closer to the experiments.





- Building settlements:
  - All models especially the ones using PM4Sand, overestimate the settlements during the TCU event (□) mainly due to the overestimation of the PWPs.
  - Better performance of the P2PSand 2-D and P2PSand 3-D models.



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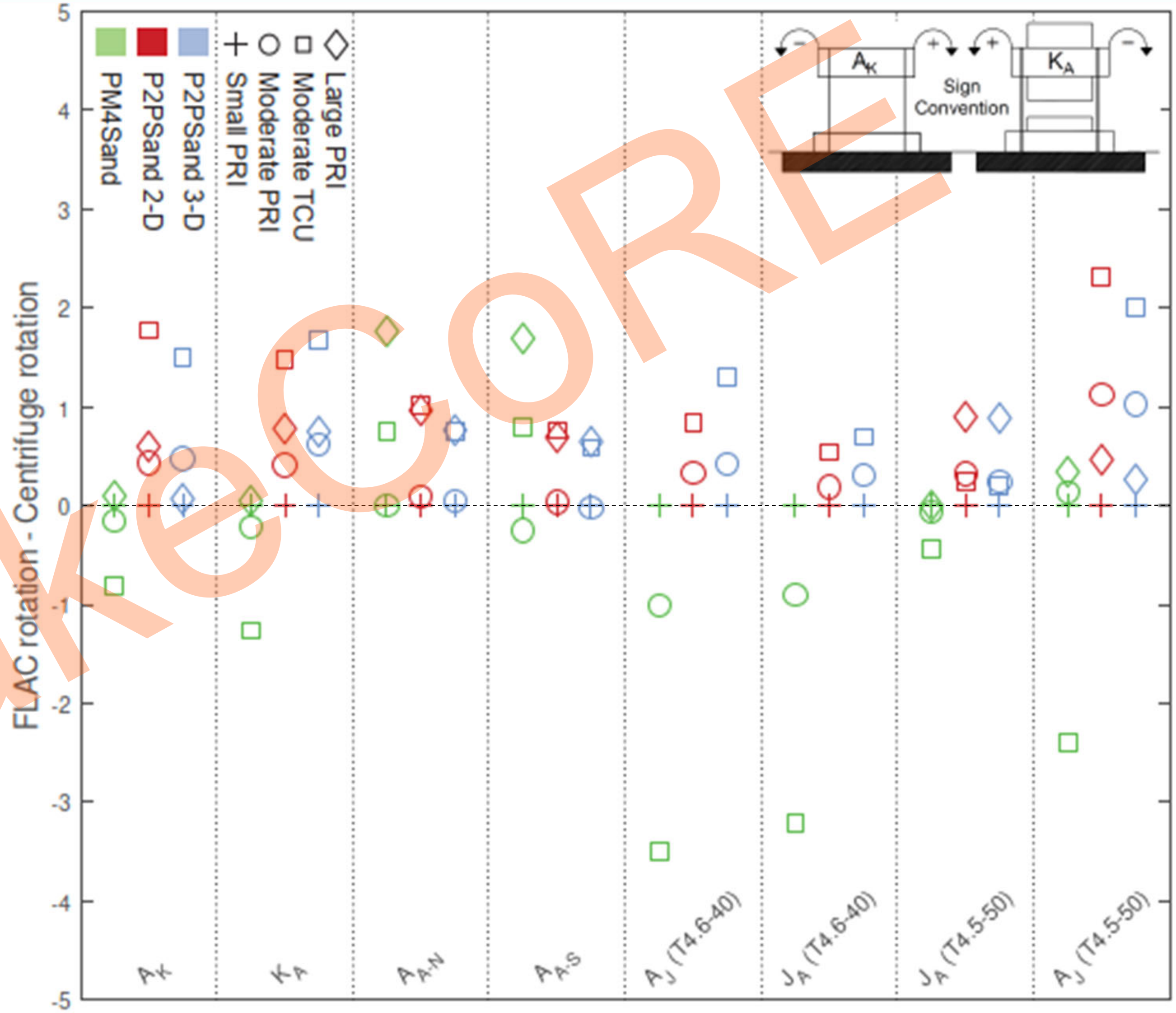
- Building rotations:
  - Unrealistic tilt towards each other.
  - Better performance of P2PSand 2-D and P2PSand 3-D models.

Case	2-D - PM4Sand	2-D - P2PSand	3-D - P2PSand
Adjacent structures - settlements (mm)	115	112	108
Isolated structures - settlements (mm)	153	155	155
Adjacent structures - rotations (°)	1.00	0.75	0.70
Isolated structures - rotations (°)	0.5	0.6	0.5



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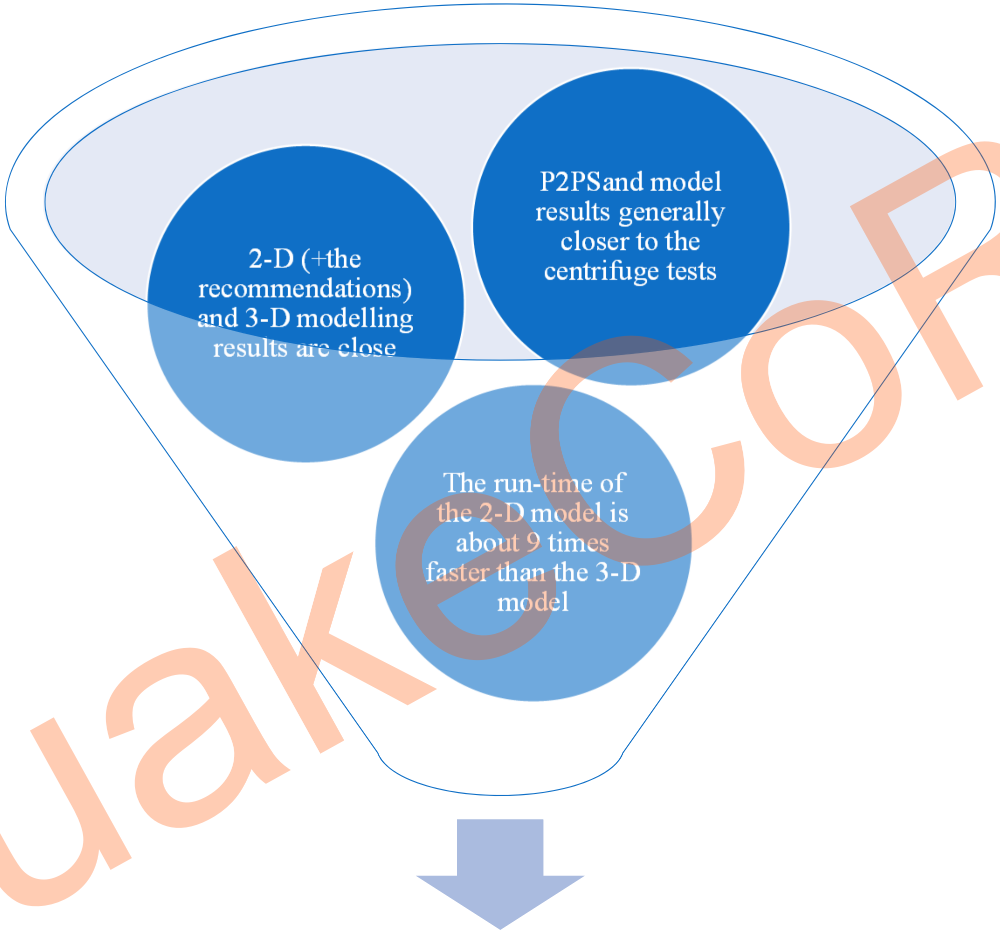
Validation of the Developed Numerical Models Against the Centrifuge Tests



Plane-strain modelling using P2PSand model for the sensitivity analyses

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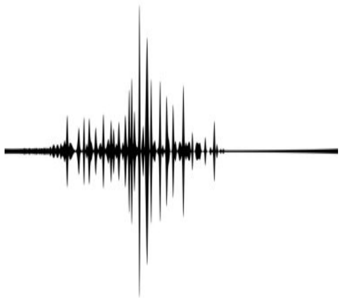
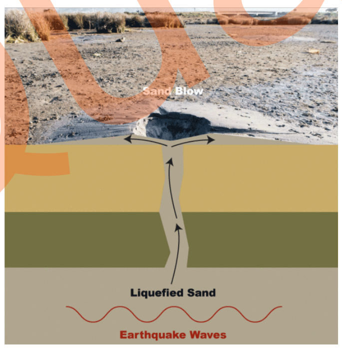


Ground motion

- 150 different motions with different characteristics

Building Properties

- Foundation spacing
- Foundation width
- Foundation bearing pressure



Soil properties

- Thickness of the liquefiable layer
- Depth to the liquefiable layer

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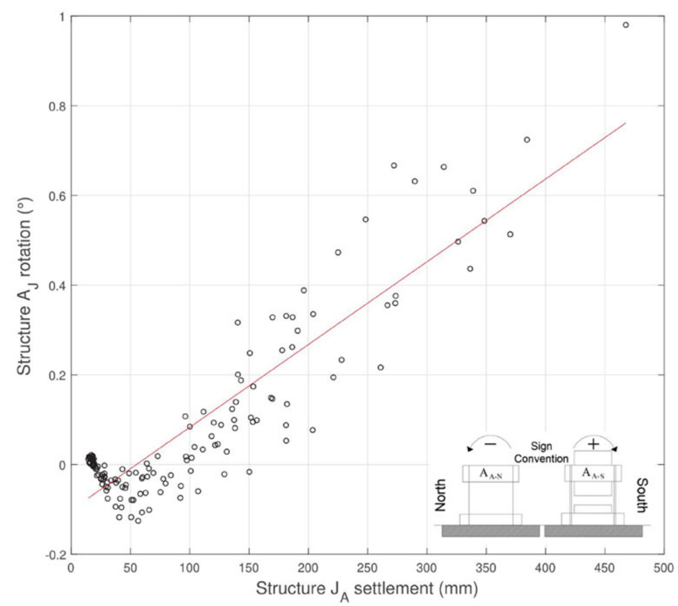
- Ground motion characteristics (150 different motions):
  - CAV ($\int_0^{t_{tot}} |a_{(t)}| dt$) and CAV5 are the best IMs for predicting the settlements and rotations of adjacent structures.
  - When there is a heavy structure next to a lighter building:
    - The displacements of the heavier structure seems to be independent of the lighter structure
    - Especially in stronger earthquakes, the settlement of the heavier structure dominates the settlement and rotation of the lighter building.



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- Building characteristics:

Foundation spacing

The maximum effect of SSSI occurs when the foundation spacing is about half the width of foundations

The buildings start to behave like isolated structures when their foundation spacing is greater than twice their foundation size.

Foundation width of one structure (constant bearing pressure and natural period)

A wider foundation reduces the settlement of rotation of both structures. However, the effect is less significant on the adjacent building with the constant width.

Bearing pressure of one structure (constant foundation width and natural period)

SSSI has a negligible effect on the heavier building when the ratio between the bearing pressures reaches about 3.

Increasing the ratio between the bearing pressures increases the settlement and rotation of the nearby structure.

- Soil properties:

Liquefiable layer thickness

The thicker liquefiable generally layer increases the settlement and the inward tilts of the structures.

The results of the numerical model are not reliable in very thick liquefiable layers (≳ 13 m)

Depth to the top of the liquefiable soil

A deeper liquefiable layer reduces the settlement and rotation of the heavier structures but does not change the displacements of the lighter buildings significantly.

The proposed assumptions and recommendations can improved the 2-D modelling of the 3-D problem and make the sensitivity analyses more feasible.

Despite their good overall performance, current available constitutive models still have some shortcomings in capturing the building response on liquefiable soil.

Using the P2PSand constitutive model will usually result in more accurate estimations.

The response of the adjacent structures on liquefiable ground is governed by the complex interaction of several parameters affecting the soil and building response.

Future work:

New validation studies in the future with the new constitutive models.

More combination of the soil and structures for validation (requires more experiments) to make the results of the validation study more general.

More combination of soil and structures for the parametric studies and the interconnection of different parameters with each other.

Study the effects of more than two structures in the city.

Thank you for your attention

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