Seismic vulnerability of pile–supported wharves considering recurrent liquefaction–induced damage

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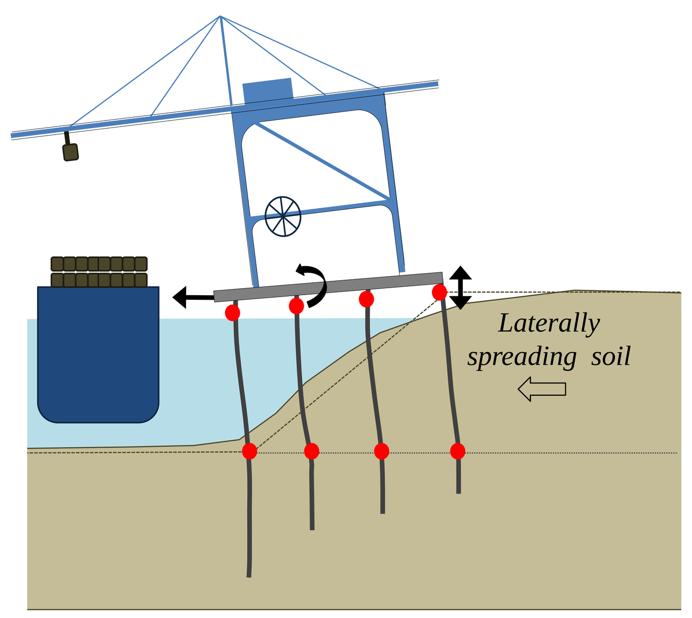
1. Objective

To develop damage state–dependent seismic fragility functions for pile wharves supported on liquefiable soil.

2. Overview

Seaports in seismically active regions may often undergo strong aftershocks following a mainshock event. Due to the short time interval between events in such a seismic sequence, retrofit interventions are often impossible; as a result, the aftershock acts in already damaged structures.

Pile–supported wharves are particularly vulnerable to such seismic sequences with the main cause of damage being the liquefaction of soft underlying soils and/or hydraulic backfills.



Manifestations of liquefaction–induced damage include, among others, horizontal seaward displacement, tilting of the deck, differential settlement between the deck and the backland, and development of pile hinging and cracking.

Question: What is the residual capacity of an already damaged wharf to withstand a future earthquake/liquefaction?

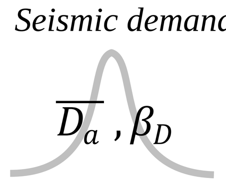
3. State–dependent fragility

The probability (P) of a structure in a given post-mainshock damage state (ds_m) progressing to a worse level of damage (ds_a) during an aftershock, conditioned on a particular level of the aftershock intensity (im_a).

$$P(DS_a \geq ds_a \mid IM_a = im_a, DS_m = ds_m)$$

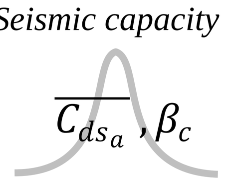
$$=$$

Seismic demand



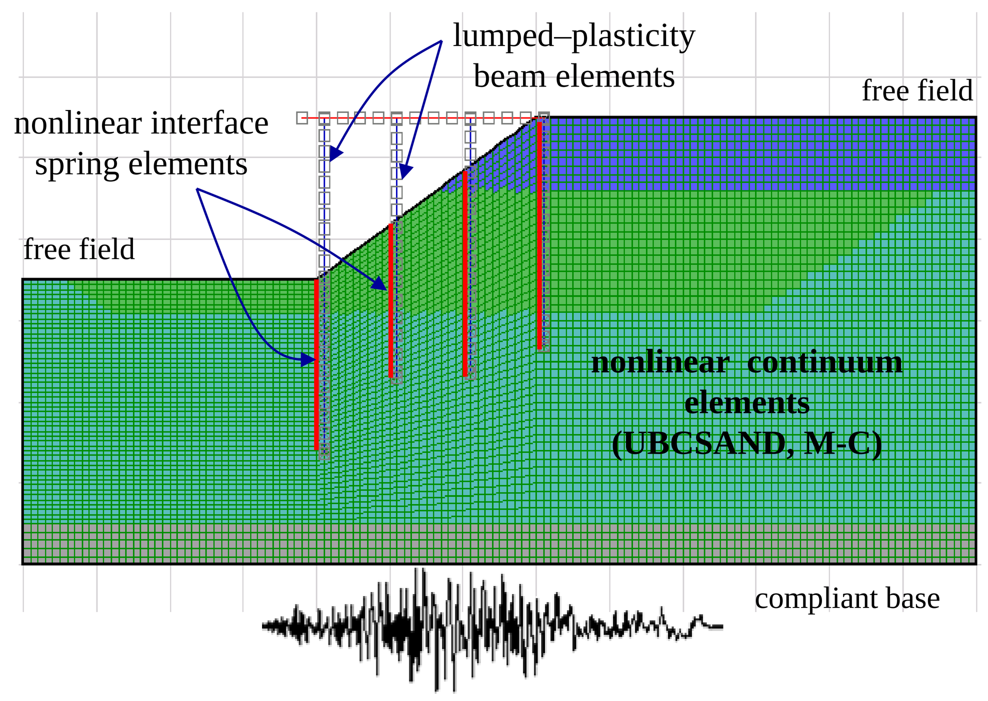
$$\Phi\left(\frac{\ln(\overline{D_a}) - \ln(\overline{C_{ds_a}})}{\sqrt{\beta_D{}^2 + \beta_C{}^2 + \beta_M{}^2}}\right)$$

Seismic capacity



β_M : uncertainty in modelling and analysis procedure

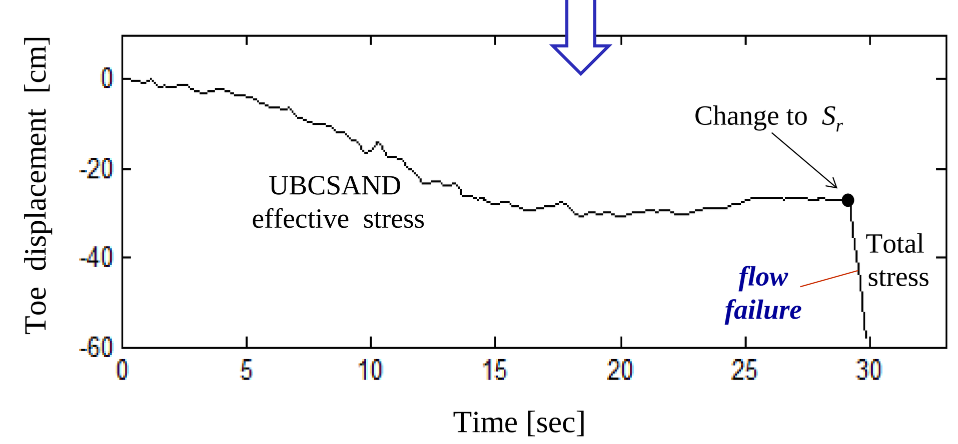
4. Numerical simulation of cumulative damage



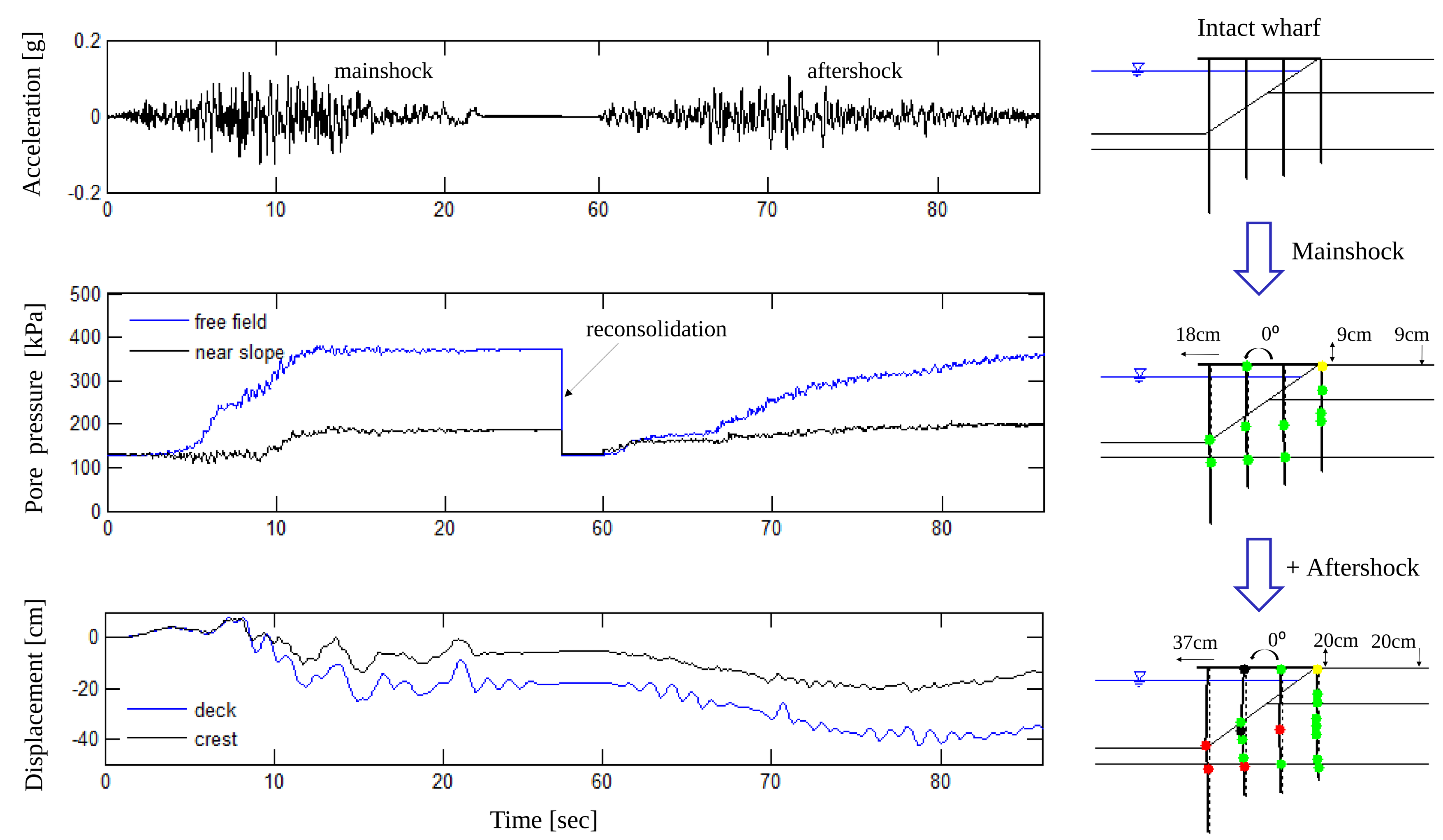
Fully coupled soil–pile–structure interaction model. (FLAC2D) Soil–pile interaction is approximated by connecting the piles to the soil mesh via nonlinear (shear and normal) coupling springs; this formulation allows relative motion between the continuous soil mesh and the pile enabling the liquefied soil to "flow through" the pile . Spring stiffness and strength are continuously updated according to the current effective stresses in adjoining soil elements. Liquefiable soil layers are modelled using the UBCSAND003 effective stress plasticity model throughout the duration of the earthquake shaking.

Analysis sequence:

Initial static → Effective stress (mainshock) → Total stress (residual strength) → Re-consolidation → Effective stress (aftershock) → …



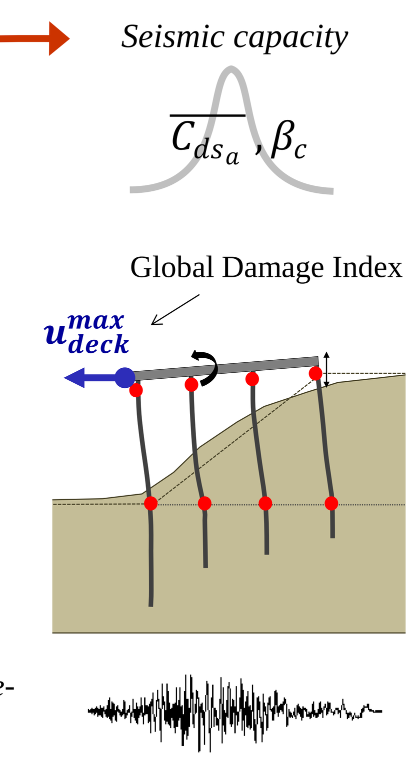
Potential post-liquefaction flow instabilities are evaluated by performing a post-earthquake static analysis where elements that liquefied during the previous effective stress analysis are changed to a total stress model with a specified residual strength S_r that is back-calculated from case histories (see Naesgaard and Byrne, 2007 and/or Ntritsos, 2015)



Characteristic response histories and associated damage for a complete mainshock – aftershock sequence

5. Limit states

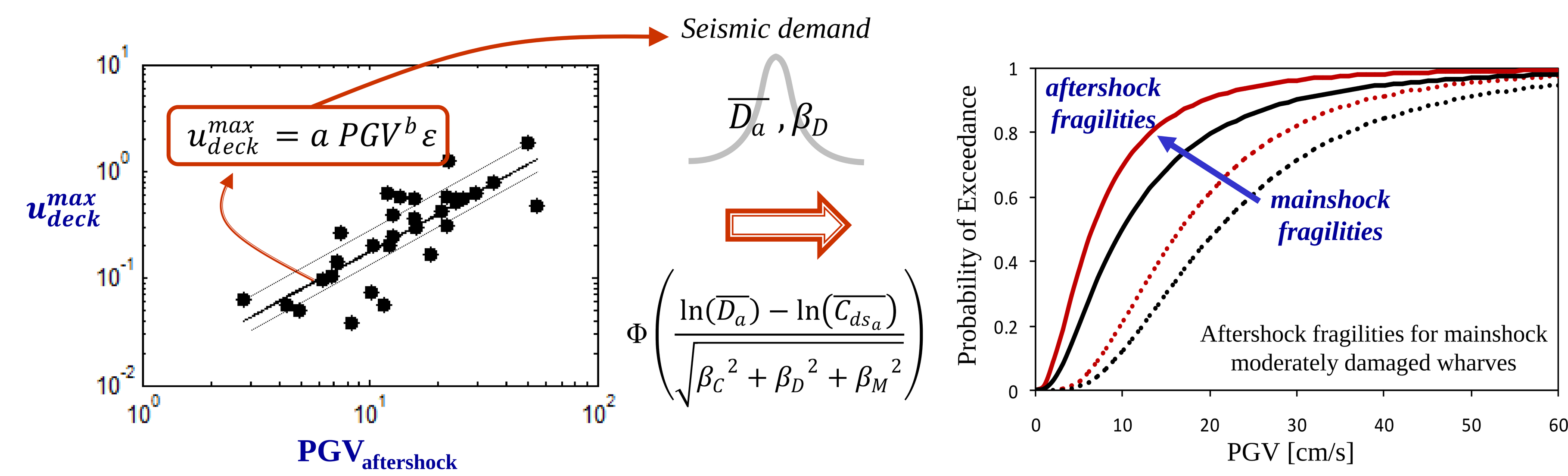
Damage State	Physical Description	Median capacity $\overline{u_{deck}^{max}}$ (cm)	Dispersion β_C
Slight	Essentially elastic response Minor residual displacements	8	0.25
Moderate	Controlled limited inelastic ductile response Residual deformation – structure repairable	21	0.25
Extensive	Ductile response near collapse	32	0.40
Collapse	Beyond the extensive state	42	0.40



Limit state thresholds are determined by correlating the maximum deck displacement recorded during the time-history analyses with the correspondent local damage indices (i.e. differential settlements, tilting, location of plastic hinges and plastic hinge peak rotations)

6. Derivation of fragility curves

1. Assemble a suite of ground motions that can be used to represent both mainshocks and aftershocks in the area of interest.
2. Perform nonlinear time-history analyses on the intact wharf model. This step generates multiple realizations of mainshock–damaged wharves which are distributed along the different damage states.
3. Use the mainshock–damaged wharves (generated in step 2) as input models for the aftershock analyses.



A regression analysis on the data obtained from all the aftershock analyses provides the demand parameters required to build the aftershock fragility functions.

The mainshock damage has significantly increased wharf fragility to aftershock records as indicated by the translation of the fragility curves to the left.

7. References

Naesgaard, E., Byrne, P.M. (2007). Flow liquefaction simulation using a combined effective stress – total stress model. *Proc. Of Geot. Earthquake Eng. Satellite Conf.,* TC4 Committee, ISSMGE, Osaka, Japan.

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