Simplified Design Procedure for Piles Affected by Lateral Spreading based on 3D Nonlinear FEA Using OpenSees

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Research Objectives

- Increase the capabilities for 3D foundation modeling in the OpenSees finite element analysis platform.

- Use numerical simulations to identify key factors which influence the behavior of pile embedded in laterally spreading soil during or after a seismic event.

- Establish a simple analytic procedure which can be used by designers for the case of a pile subject to the lateral spreading load case.

3D Modeling Approach

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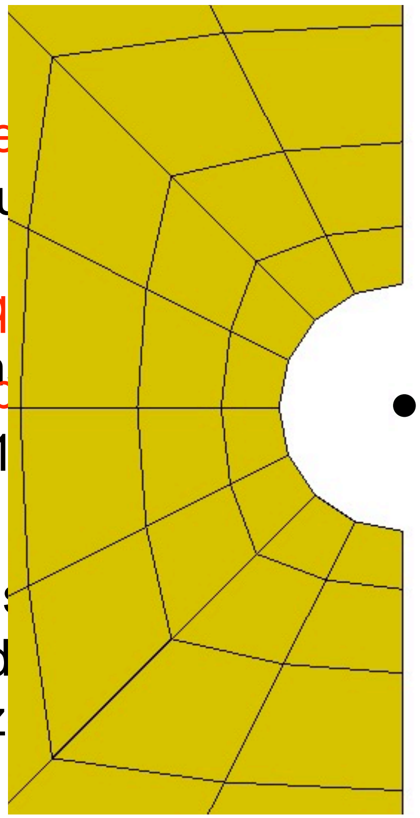
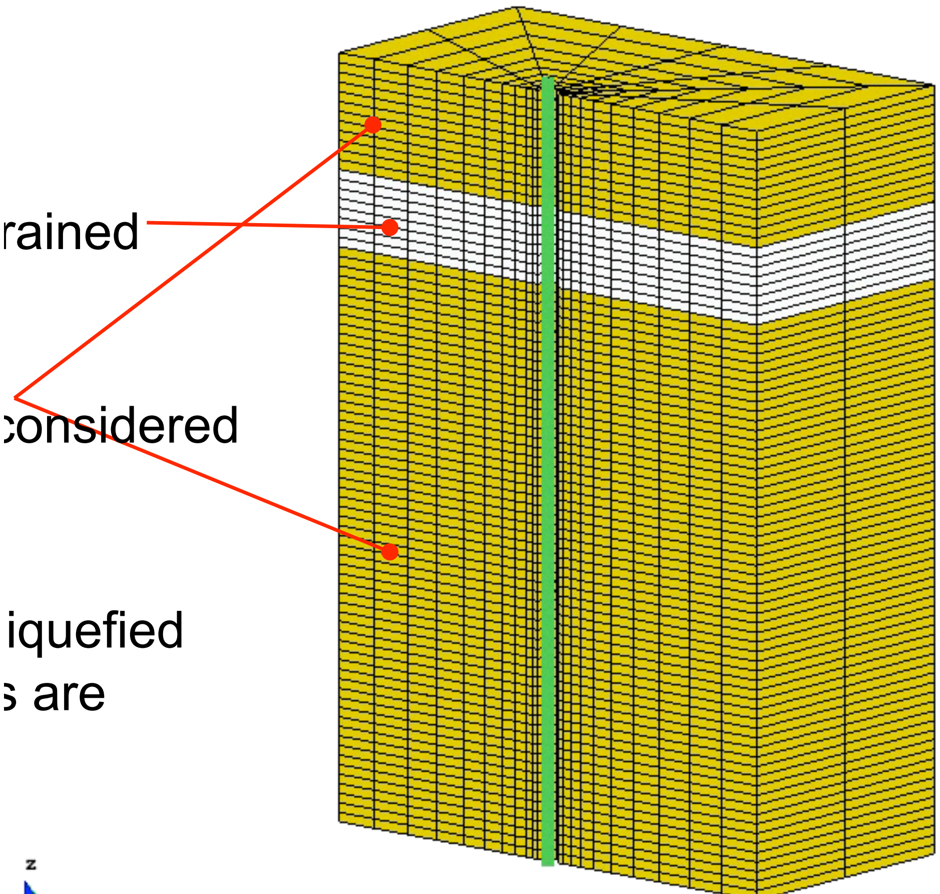


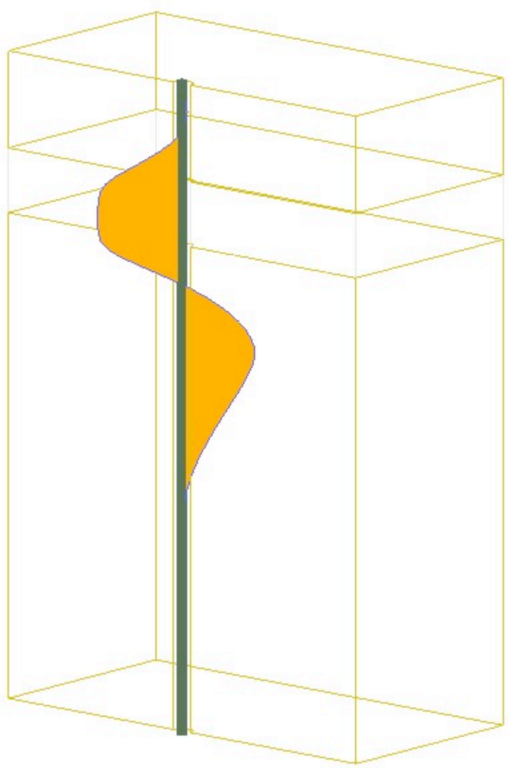


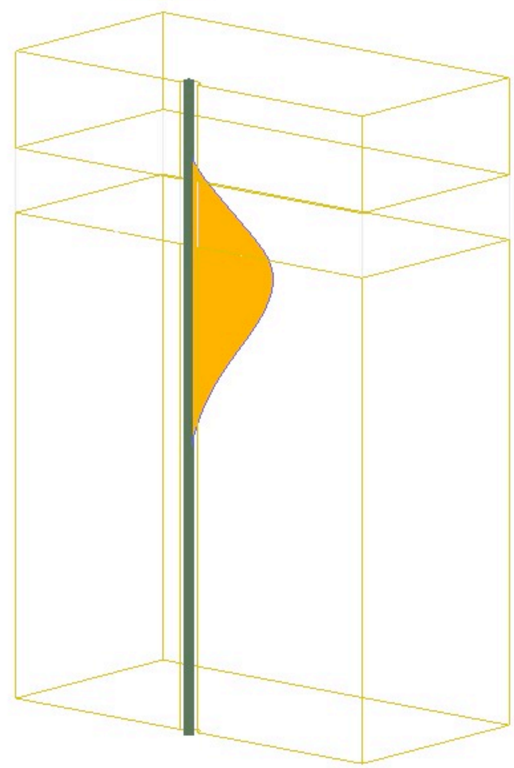
Beam-Solid Contact Elements

The beam-solid contact elements enable the use of standard beam-column elements for the pile

This allows for simple recovery of the shear force and bending moment demands placed upon the pile

Additionally, the surface traction acting on the pile-soil interface can be recovered and resolved into the forces applied by the soil to the pile



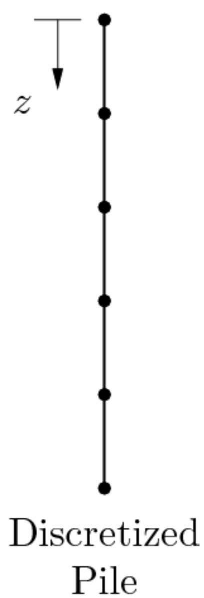


Computing *p-y* Curves: Rigid Kinematic

Work with 3D FE models has shown that use of a general pile deformation creates *p-y* curves which are influenced by the selected pile kinematics

A rigid pile kinematic is used to evenly activate the soil response with depth and to obtain *p-y* curves which are free from the influence of pile kinematics, reflecting only the response of the soil.

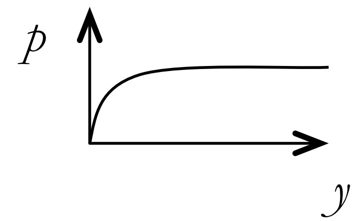
Computational process



Computing *p-y* Curves: Parameters

The computed *p-y* curves are described by the function

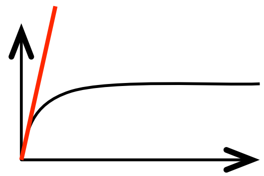
$$p(y) = p_u \tanh\left(\frac{kz}{p_u} y\right)$$



which is fit to the force-displacement data using least squares

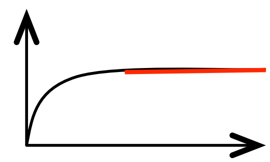
Comparison and evaluation of the computed *p-y* curves is conducted using the two characteristic curve parameters

1. Initial stiffness, k_T



$$k_T = \left.\frac{dp(y)}{dy}\right|_{y=0} = kz$$

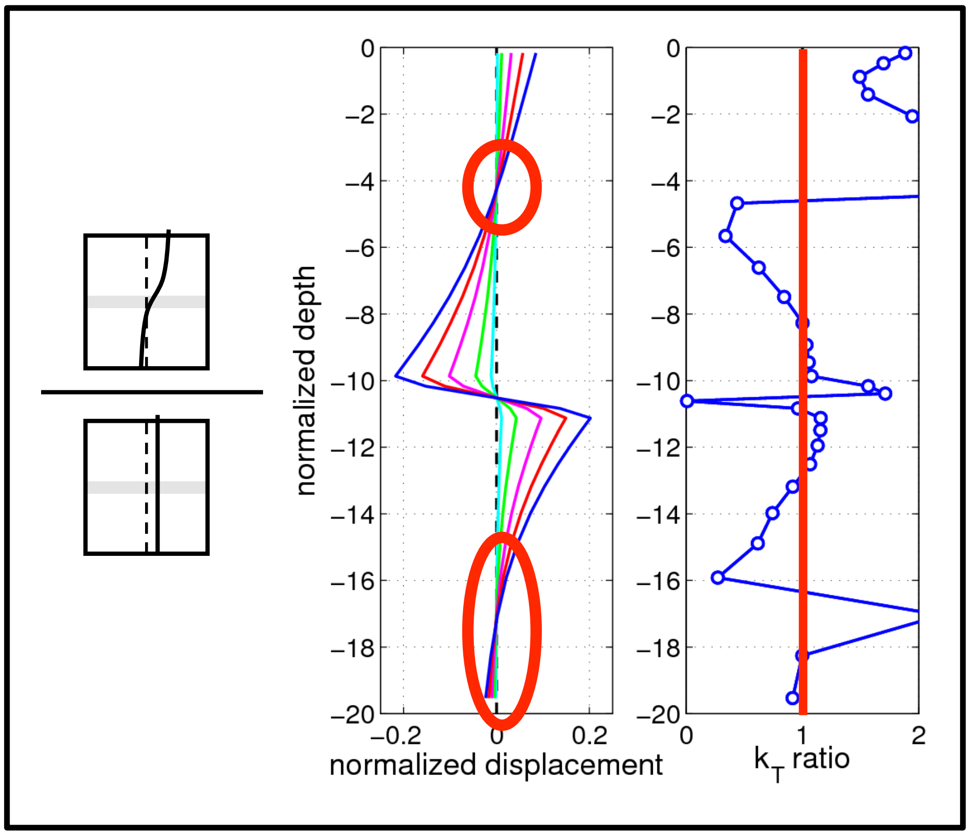
2. Ultimate resistance, p_u

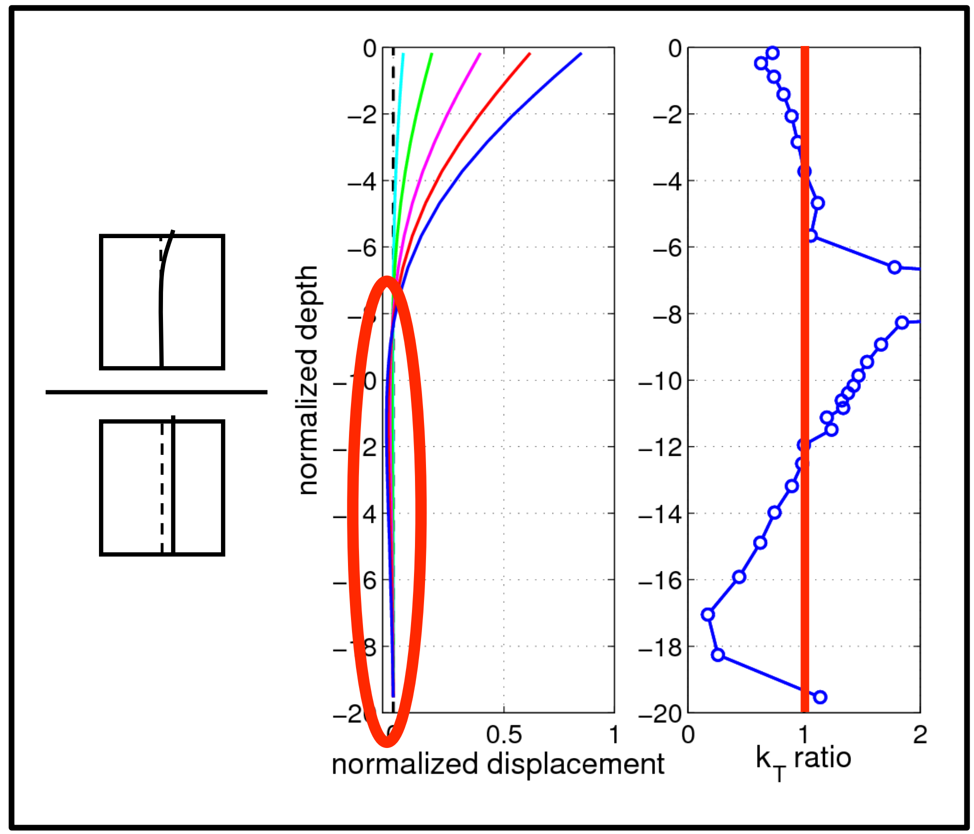


Computing *p-y* Curves: Pile Kinematics

The rigid pile kinematic is used because there are several issues which arise when using general pile kinematics for this purpose:

1. Information which is incomplete or not relevant returned at certain locations
2. The *p-y* curves are influenced by the pile kinematics



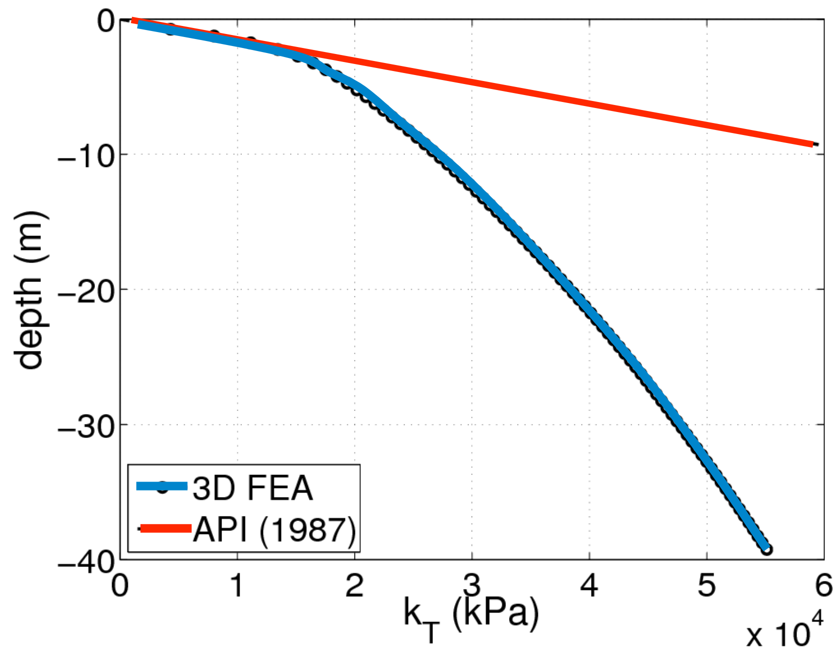


Initial Stiffness

A bilinear variation of initial stiffness is observed with increasing depth in the p-y curves computed using 3D FEA.

A linear variation of initial stiffness is proposed by the API. Here, the slope is matched to the FEA data to accentuate their difference.

The initial stiffness of the 3D FEA curves is similar to the API recommendations near the surface, but is significantly smaller at increased depths



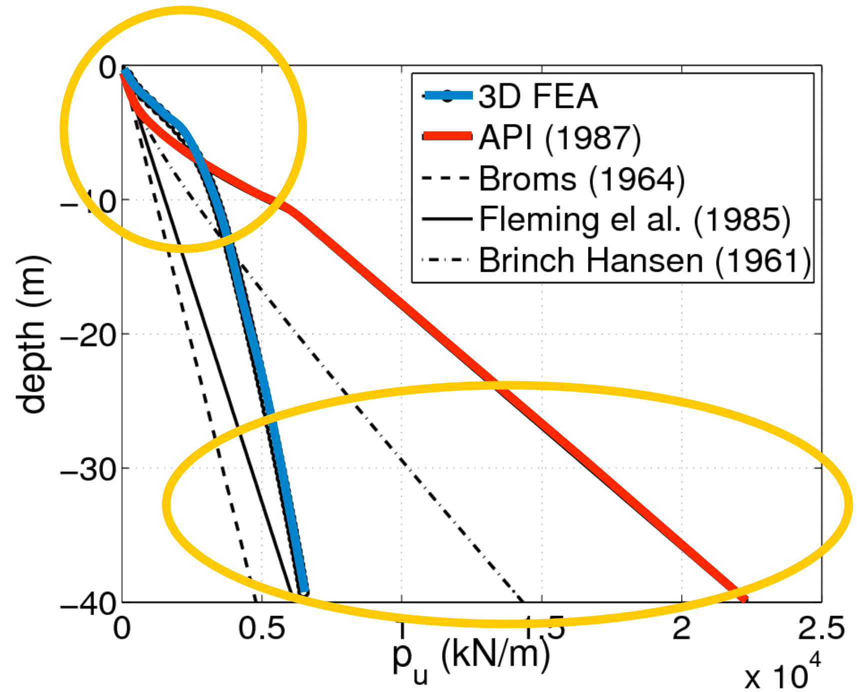
A parabolic distribution of initial stiffness, as used by Brandenberg et al. (2007) and Lam and Cheang (1995), or a similar bilinear distribution to that above is recommended for a static BNWF analysis of lateral spreading.

Ultimate Lateral Resistance

The distribution of ultimate lateral resistance with depth computed by the 3D FEA varies from distributions recommended by other researchers.

At shallow depths, all of the methods produce relatively similar results.

At increased depths, the 3D FEA values are much smaller than those recommended by the API.



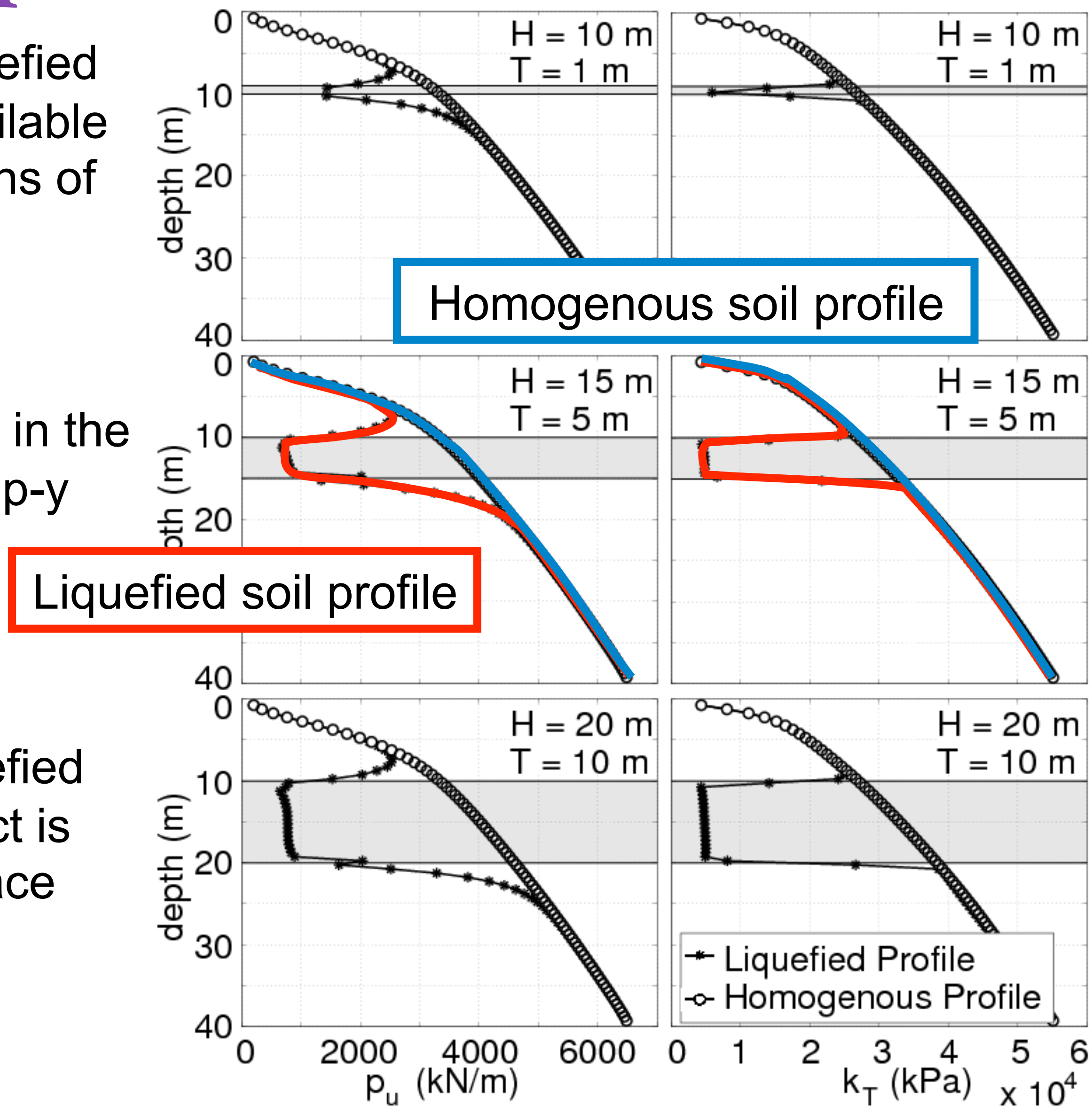
Use of one of the smaller distributions is recommended for *p-y* analyses of lateral spreading or other load cases in which deep soil-pile interaction is anticipated.

Influence of Liquefaction

The presence of the weaker liquefied layer effectively reduces the available resistance of the adjacent portions of the unliquefied soil

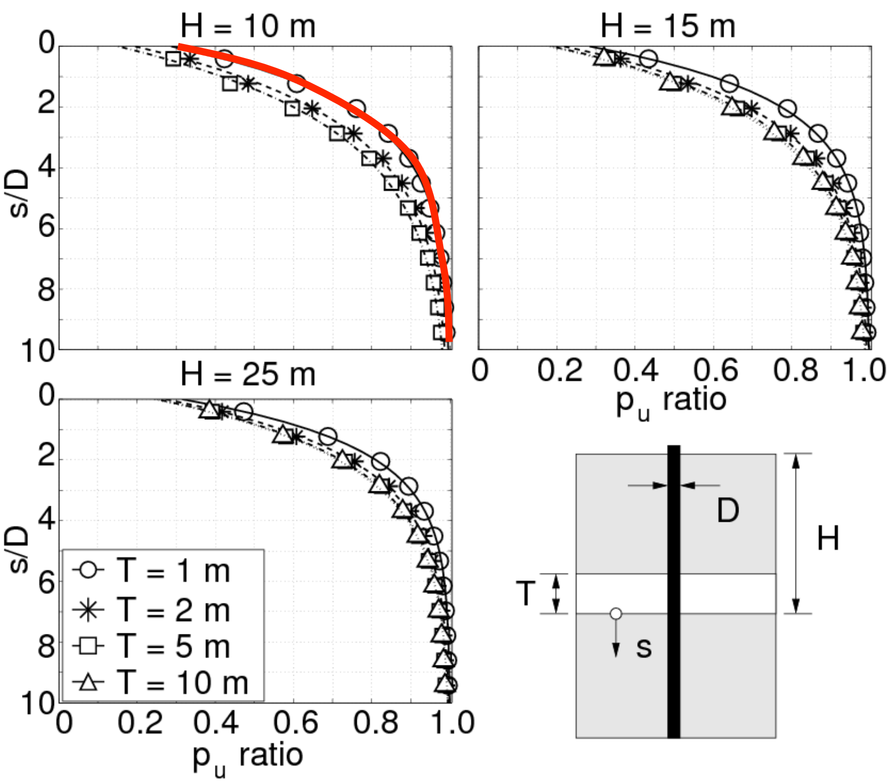
This is manifested in a reduction in the ultimate lateral resistance of the p-y curves near the liquefied layer

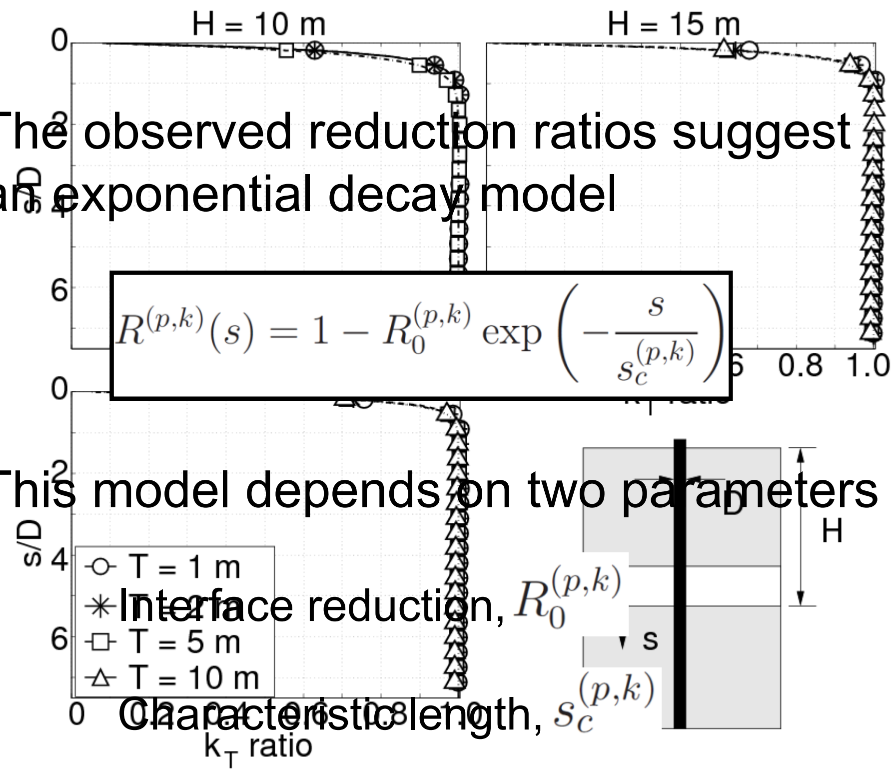
The initial stiffness of the unliquefied soil is also reduced, but the effect is more local to the liquefied interface



Reduction Ratios

The reduction in lateral resistance can be seen more clearly by taking the ratio of the parameters in the liquefied case to those in the homogenous case





The observed reduction ratios suggest an exponential decay model

$$R^{(p,k)}(s) = 1 - R_0^{(p,k)} \exp\left(-\frac{s}{s_c^{(p,k)}}\right)$$

This model depends on two parameters

Interface reduction, $R_0^{(p,k)}$

Characteristic length, $s_c^{(p,k)}$

Parameter Identification

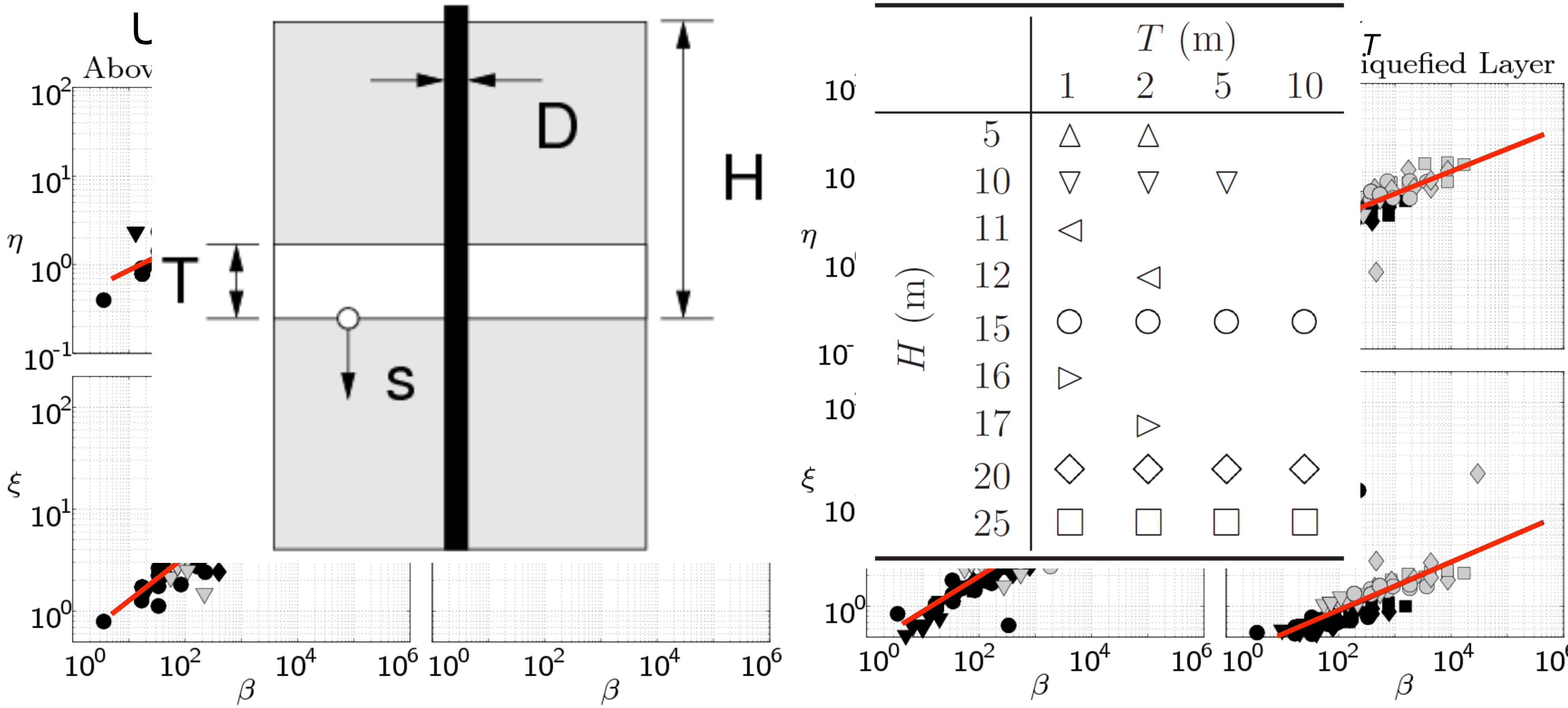
The best fit parameters used to compute the interface reduction and characteristic length for a particular soil profile

Dimensionless parameters [illegible]

For each of three pile diameters, 21 soil profiles are used to compute the reductions [illegible] parameters due to the presence of the liquefied layer

$$R_0^{(p,k)} = \frac{\gamma D}{\sigma'_v \tan\phi} a\beta^b$$

$$s_c^{(p,k)} = \frac{\gamma D^2}{\sigma'_v \tan\phi} c\beta^d$$



H (m)	T (m) = 1	2	5	10
5	△	△		
10	▽	▽	▽	
11	◁			
12		◁		
15	○	○	○	○
16	▷			
17		▷		
20	◇	◇	◇	◇
25	□	□	□	□

Computational Process

Reduction coefficients were computed which describe the best fit lines for the data set

These coefficients are used to compute the interface reduction and characteristic length

$$R_0^{(p,k)} = \ldots$$

Ultimate lateral resistance

	$R_0^{(p)}$		$s_c^{(p)}$	
	a	b	c	d
Above liquefied layer	0.421	0.315	0.474	0.432
Below liquefied layer	0.428	0.343	3.577	0.224

These parameters are used to compute reduction ratios using the exponential decay model

$$R^{(p,k)}(s) = R_0^{(p,k)} \exp\left(-\frac{s}{s_c^{(p,k)}}\right)$$

Initial stiffness

	$R_0^{(k)}$		$s_c^{(k)}$	
	a	b	c	d
Above liquefied layer	0.346	0.220	0.400	0.341
Below liquefied layer	1.000	0.252	0.299	0.239

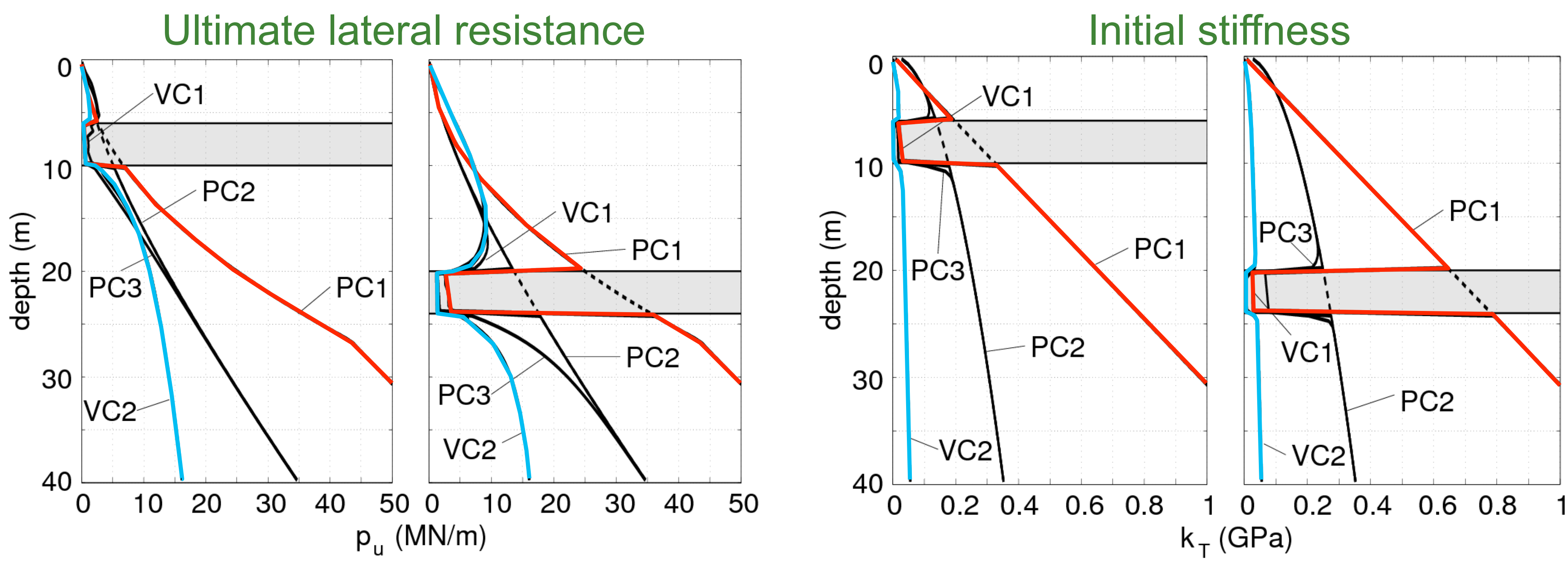
The reduced distributions of initial stiffness and ultimate lateral resistance are determined as functions of distance from liquefied layer through multiplication of the computed reduction ratios with any unreduced distribution

$$k_T^{(\text{reduced})}(s) = R^{(k)}(s) \cdot k_T^{(\text{unreduced})}(s)$$

$$p_u^{(\text{reduced})}(s) = R^{(p)}(s) \cdot p_u^{(\text{unreduced})}(s)$$

Validation of Approach

Static beam on nonlinear Winkler foundation analyses are conducted using different sets of *p-y* curves



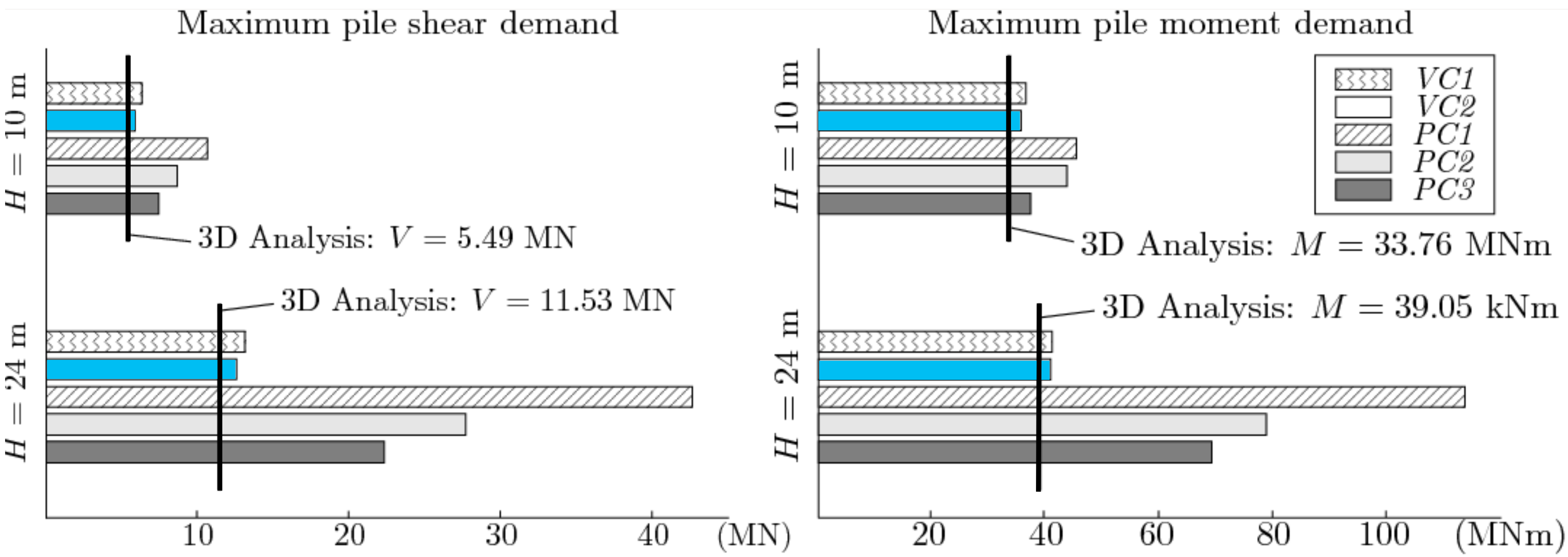
Various methods for defining the distributions of ultimate lateral resistance and initial stiffness with depth were investigated without a liquefied layer, then reduced using the proposed procedure

In red, is the API recommended distribution, only reduced in the liquefied layer

In blue are distributions obtained from 3D FEA. Some are left unreduced, while others are reduced to account for the presence of the liquefied layer using the proposed procedure

Validation of Approach

The maximum pile shear force and bending moment demands obtained from each analysis are compared to each other and to the results of 3D lateral spreading simulations



The 3D results compare well with the results obtained using p-y curves reduced using the proposed procedure for these arbitrary soil profiles

Summary and Conclusions

- 3D FEA are used to analyze the effects of lateral spreading on a single embedded pile foundation.
- Representative *p-y* curves are computed from the 3D model using a rigid pile kinematic and it is found that the computed curves do not compare well with many conventionally-defined *p-y* curves.
- A reduction in the ultimate lateral resistance and initial stiffness of the *p-y* curves is observed in the unliquefied soil near the liquefied zone. The form of this reduction is well expressed by an exponential decay model.
- A parameter study was conducted to establish a means to predict reductions in the *p-y* curve parameters to account for the presence of a liquefied zone of soil.

- McGann, C. R., Arduino, P., and Mackenzie-Helnwein, P. (2010a). "Applicability of conventional p – y relations to the analysis of piles in laterally spreading soil." *JGGE, ASCE, Under review.*
- McGann, C. R., Arduino, P., and Mackenzie-Helnwein, P. (2010b). "Simplified analysis procedure for piles in laterally spreading layered soil." *JGGE, ASCE, Under review.*

Recommendations for Future Work

- Implement a contact search algorithm for the beam-solid contact elements to improve performance and extend applicability.
- Extend the contact element formulation to model the interaction between the pile tip and the surrounding solid soil elements to enable the effects of vertical bearing to be incorporated into the simulations.
- Extend layer interaction/reduction procedure for use in other layered soil applications.
- Experimental work to verify numerical results.

Questions?