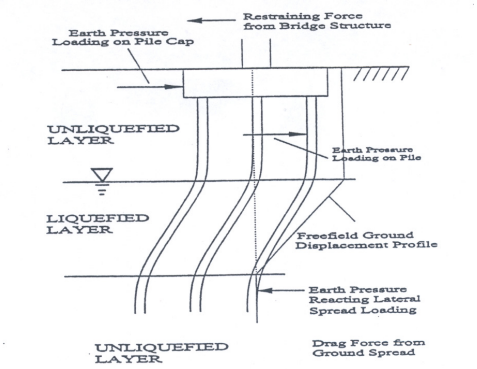
Overview

- **Introduction**
  - Background & Common Practice
- **3D Analysis of Soil-Pile Interaction**
  - Beam-Solid Approach
  - Contact Formulation & Implementation
  - Practical Applications
- **Summary and Conclusions**

Problem Description



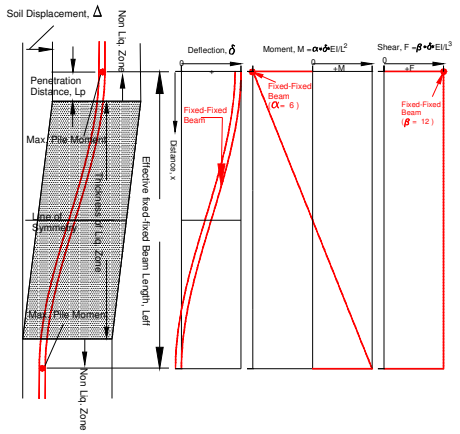
Kinematic loading on the pile from the upper unliquefied soil mass displacing relative to the underlying stable lower soil mass

Slippage displacement concentrated on a usually thin liquefied soil layer between the two stiffer soil masses

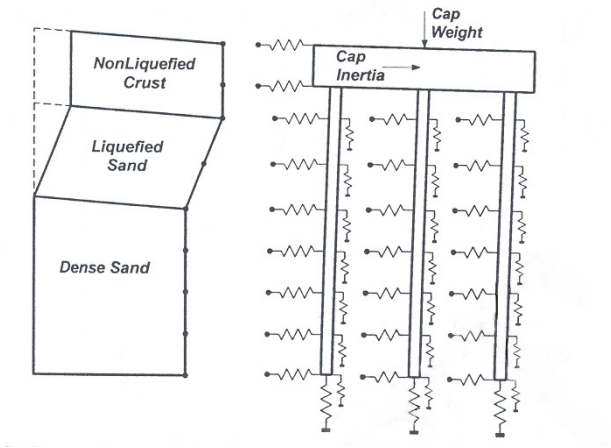
Common Solution strategies

- Fixed-fixed beam
- Uncoupled free-field displacement
- Uncoupled displacement considering pile pinning
- 2-D FEM analysis
- 3-D FEM analysis

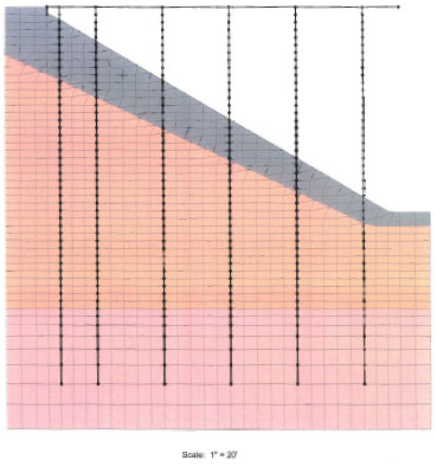
Fixed-fixed approach



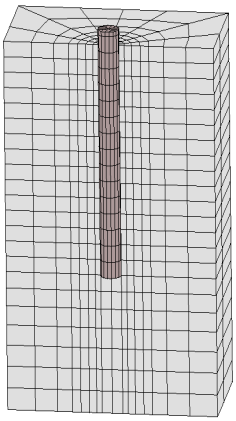
Uncoupled free-field displacement
(with and without pinning effect)



2-D FEM analysis

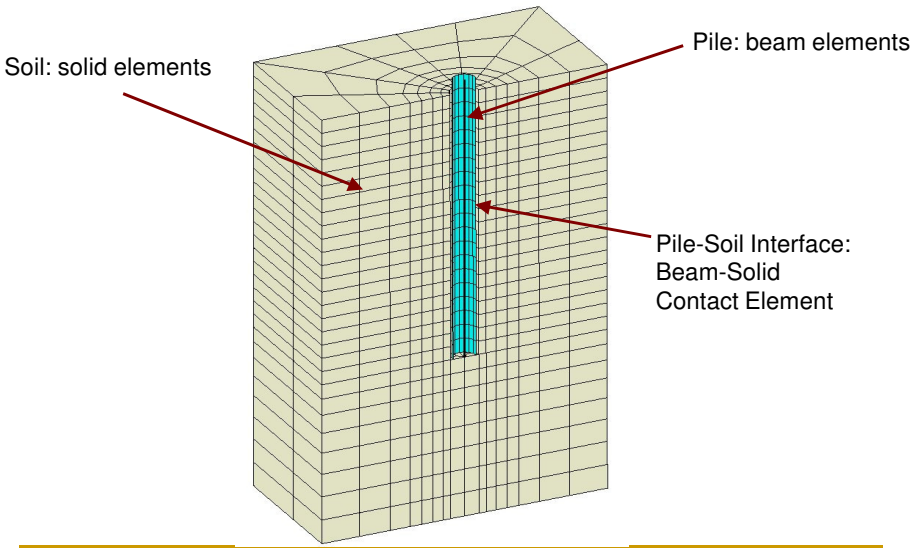


3D FEM Analysis



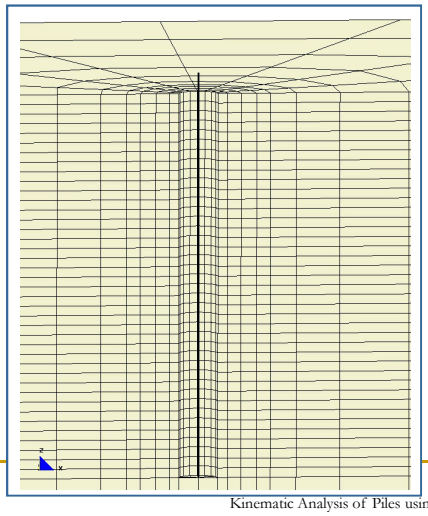
Solid-Solid Model

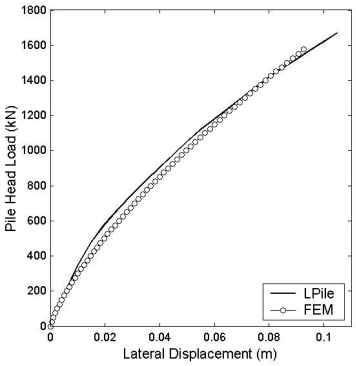
New approach: Beam-Solid Contact Element



Laterally Loaded Piles (comparison with LPILE)

- Perform numerical load test
- Compare results





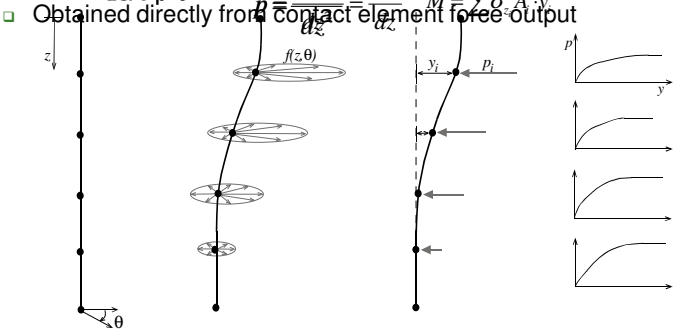
3x Magnification

Laterally Loaded Piles

- Numerical p-y curves:
  - Obtained by differentiation of pile bending moments
  - Obtained directly from contact element force output

Beam pile: $p = \frac{d^2M}{dz^2} = \frac{dV}{dz}$ $M = \sum \sigma_z A_i y_i$

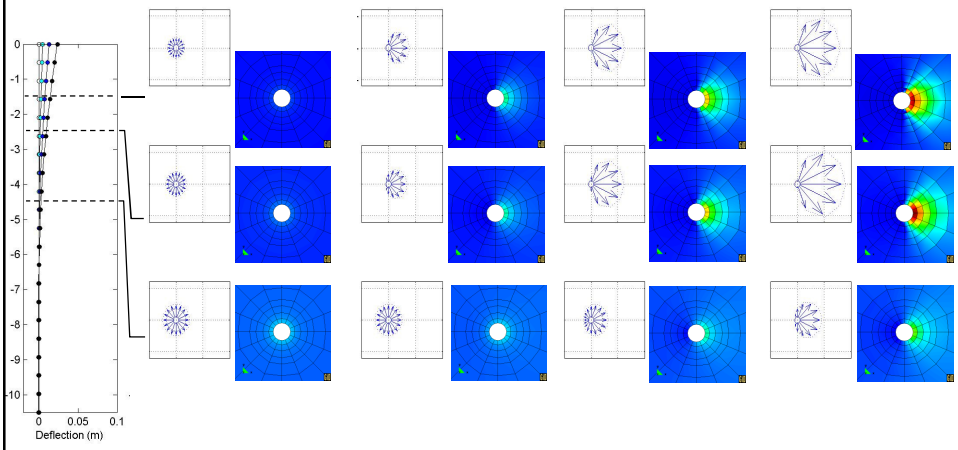
Solid pile:



Discretized beam | Deformed beam with interface forces, $f(z,\theta)$ | Deformed beam with interface forces, $p_i = \Sigma f(z,\theta) r\, d\theta$ and displacement, y_i | p-y curves

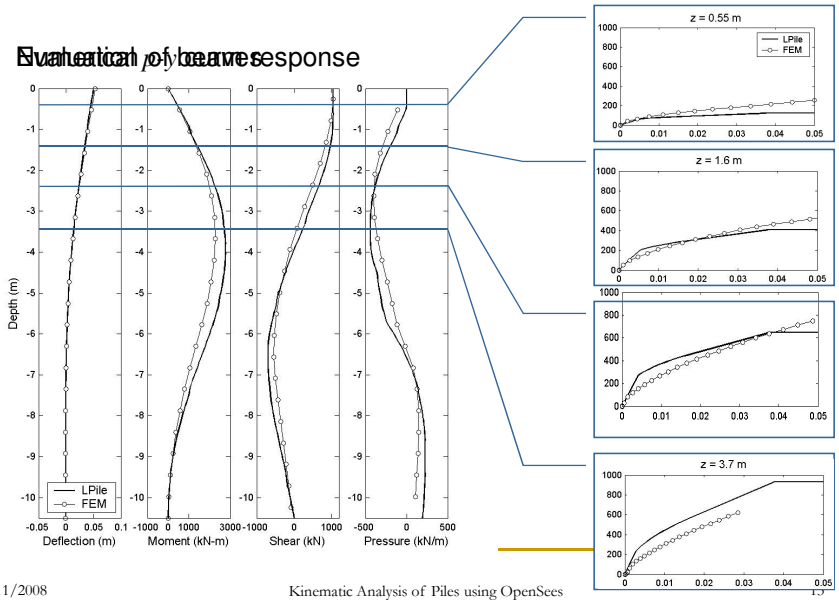
Laterally Loaded Piles

- Normal interface stresses and radial soil stresses



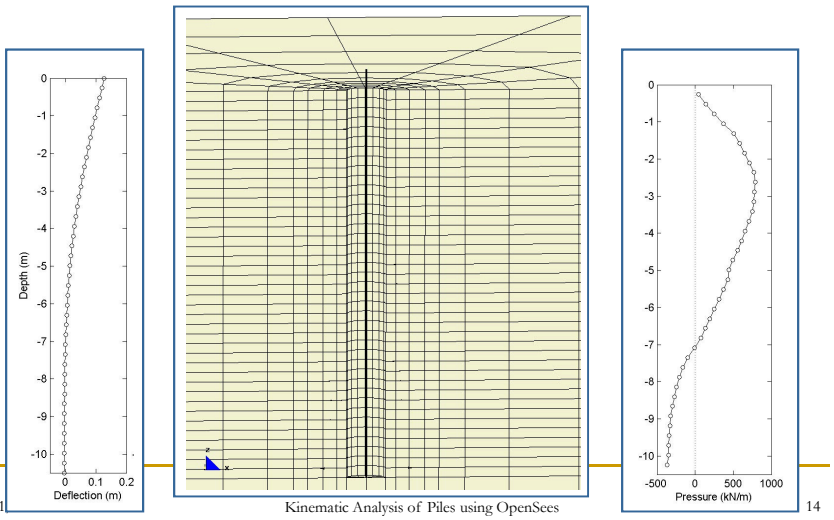
Laterally Loaded Piles

- Evaluation of beam response

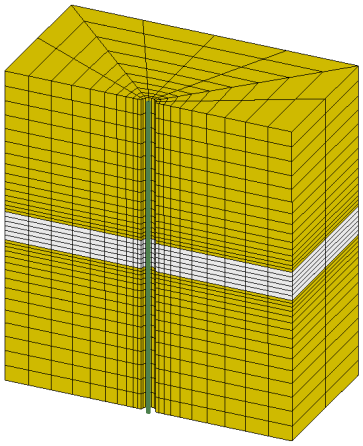


Laterally Loaded Piles

- GiD Visualization of pile and soil deformation with interface forces



Back to our problem…



Undeformed mesh

Base Soil & Pile Properties

Elastic isotropic soil properties

Soil profile	E [kPa]	Poisson's ratio	Unit weight [kN/m^3]
Top strong layer (brown)	25,000	0.35	17.0
Middle soft layer (white)	2,500	0.47	17.0
Bottom strong layer (brown)	25,000	0.35	17.0

Elasto-plastic (Drucker Prager) soil properties

Soil profile	K [kPa]	G [kPa]	Friction angle ϕ [degrees]	Cohesion c [kPa]	Unit weight [kN/m^3]
Top strong layer (brown)	27778.0	9259.3	32	5	17.0
Middle soft layer (white)	13888.0	862.0	0	10	17.0
Bottom strong layer (brown)	27778.0	9259.3	325	5	17.0

Base Soil & Pile properties

Pile elastic properties

Beam material	Diam	Area [m2]	I [m4]	E [kPa]	G [kPa]
RC Concrete beam	2.5m	2.4544	1.7854	25,000,000	12,5000,000
RC Concrete beam	54"	0.73878	0.04780	25,000,000	12,5000,000
RC Concrete beam	24"	0.146	004680	25,000,000	12,5000,000

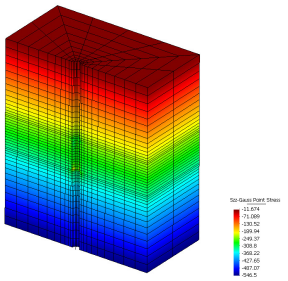
Contact element material properties

Interface	Friction coefficient (μ=tan(ϕ))	Stiffness (for sticking) [kPa]
Beam-solid contact	0.1	1000

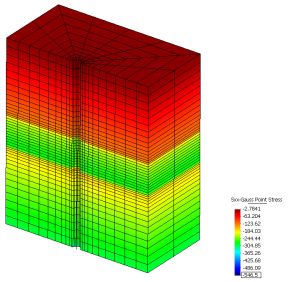
GiD post processing

Self Weight - Vertical and Horizontal stresses due to self weight (notice near isotropic condition in liquefied layer)

Notice horizontal and vertical stresses are similar (fluid) in the liquefiable layer

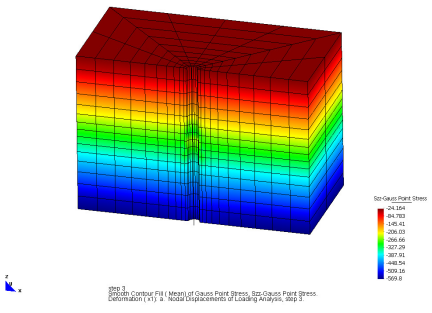


Vertical Stress



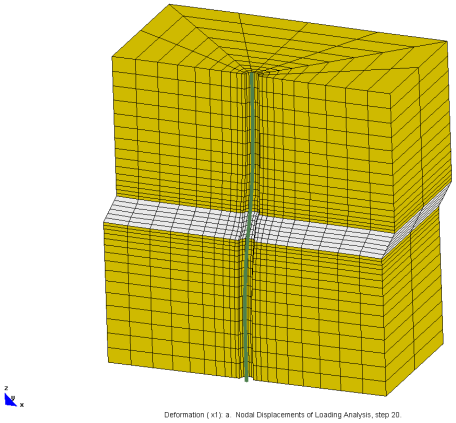
Horizontal Stress

GiD post processing
Initial Conditions OpenSees



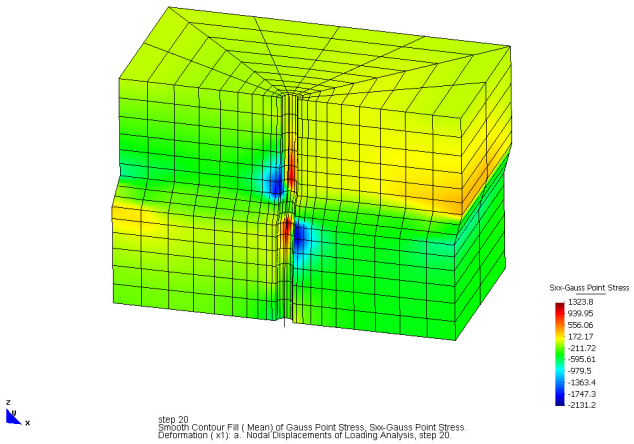
Vertical stresses **Contact Forces**

Push-over deformation pattern



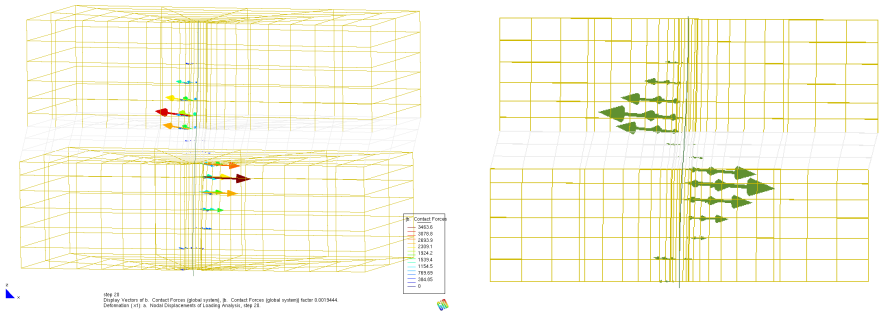
GiD post processing

σ_{xx} stresses after displacement



GiD post processing

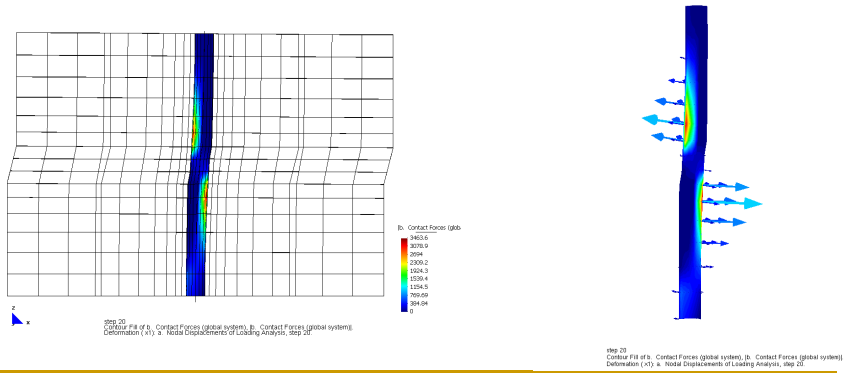
Contact Forces at the end of displacement



Perspective View **XZ Plane View**

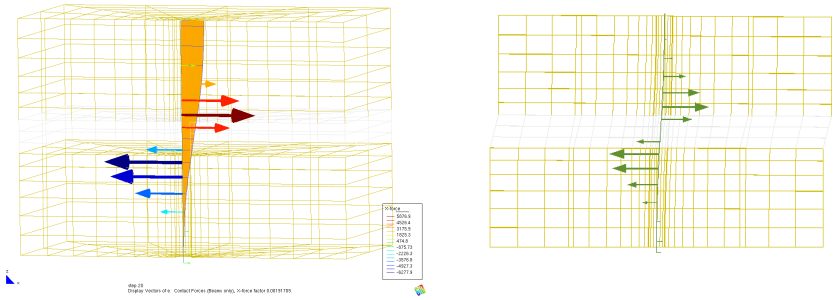
GiD post processing

Contours of Contact Forces at the end of Displacement



GiD post processing

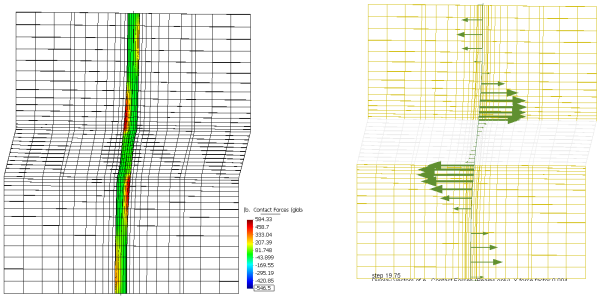
Forces in the Beam at the End of Displacement



Perspective View **XZ Plane View**

GiD post processing

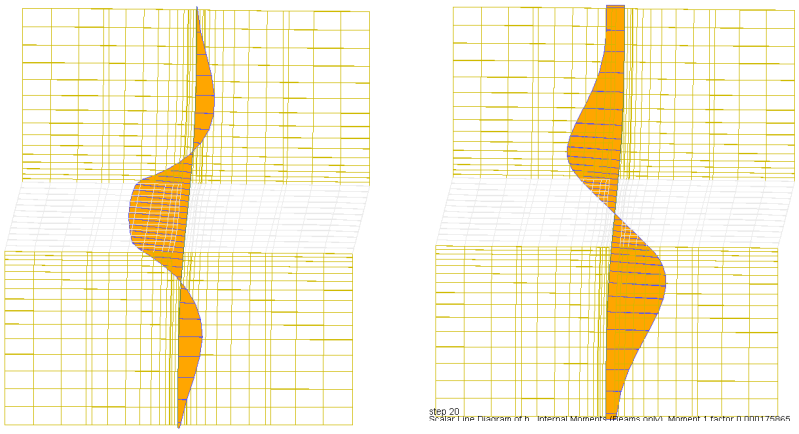
(a) Contact forces at soil-pile interface and
(b) Horizontal pile forces at the end of loading



GiD Diagrams

Shear diagram

Bending moment diagram



Parametric Study

- ***Pile diameters***
- D1=2.50 m, D2=54in., and D3=24in.

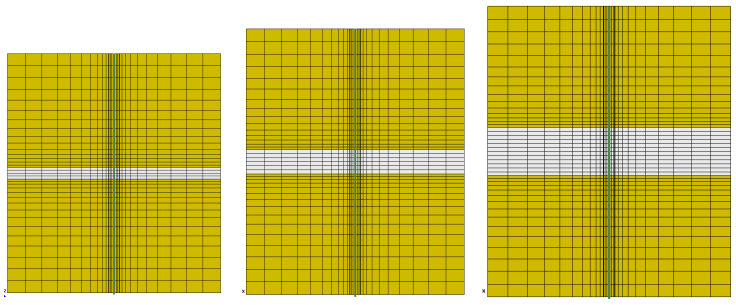
- ***Soft Layer Thicknesses***
- T1=1D, T2 = 2D, and T4=4D.

- ***Piles stiffness, EI***
- (scale factors for base EI values
- "E-3"=0.125, "E-2"=0.25, "E-1"=0.50, "E0"=1.0, "E1"=2.0, "E2"=4.0, and "E3"=8.0.

- **Total cases = 84 cases**

Final OpenSees Meshes

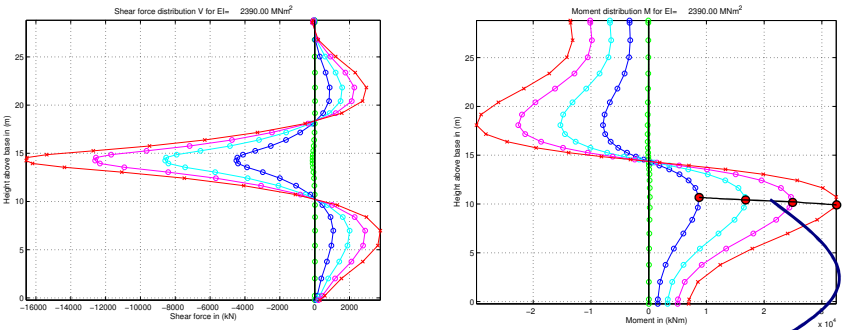
Finite element meshes for different soft layer thickness. (a)T=1D, (b)T=2D, and (c)T=4D



Characteristic Results of Parametric study
Effect of soil displacement

Shear diagrams

Bending Moment diagrams

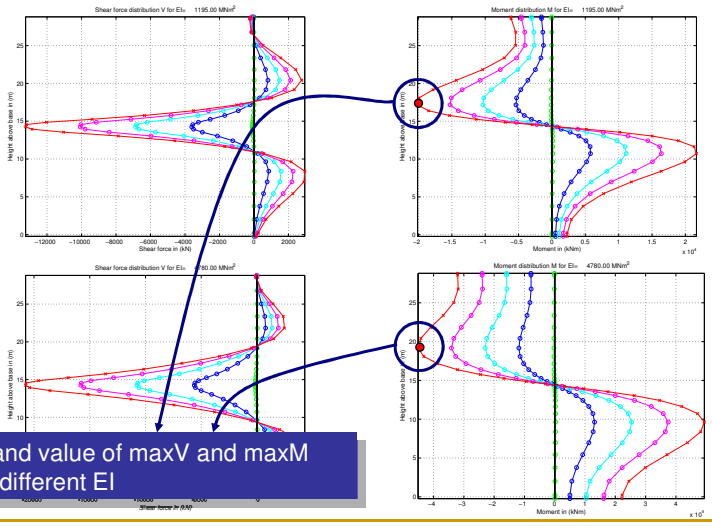


Location and value of maxV and maxM changes with soil displacement

Characteristic Results of Parametric study
Effect of pile stiffness EI

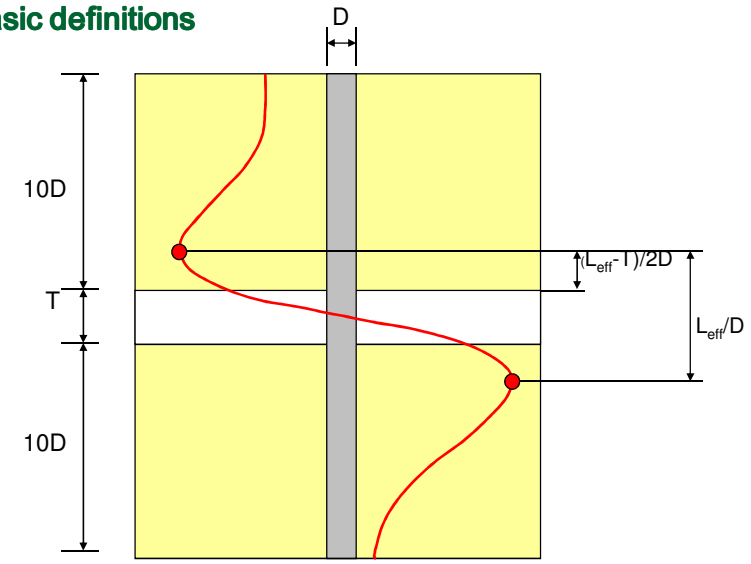
EI_1 **less stiff**

EI_2 **stiffer**

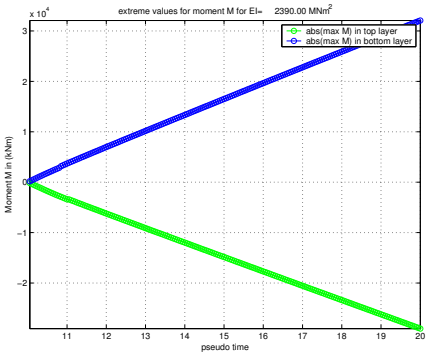


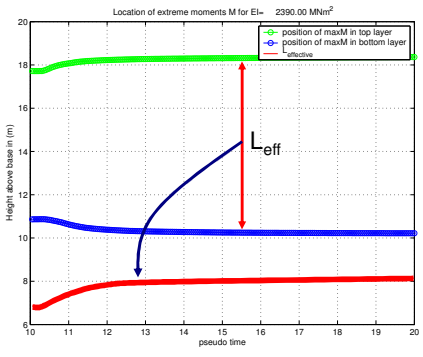
Location and value of maxV and maxM varies for different EI

Characteristic Results of Parametric study
Basic definitions

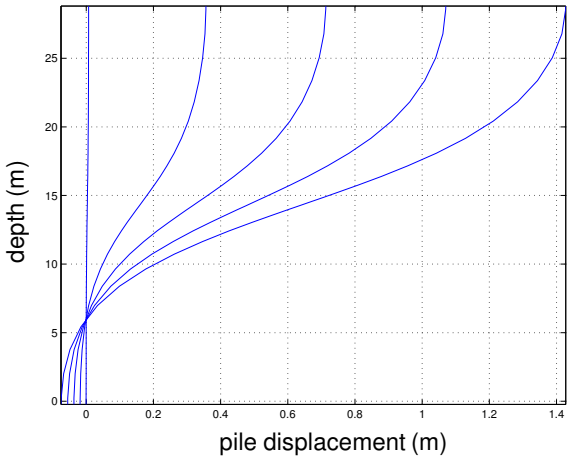


Characteristic Results of Parametric study
maxM and location





Characteristic Results of Parametric study
Pile deformation

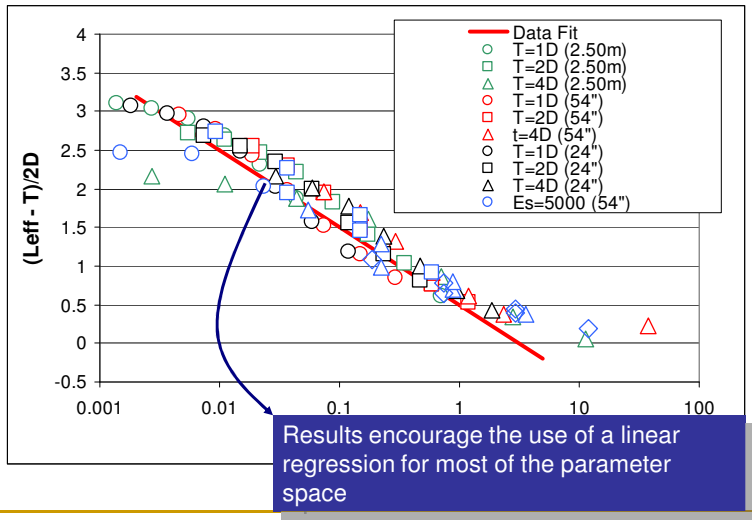


Non-dimensional characteristic parameter

$$\beta = \frac{E_s T^2 D^2}{EI}$$

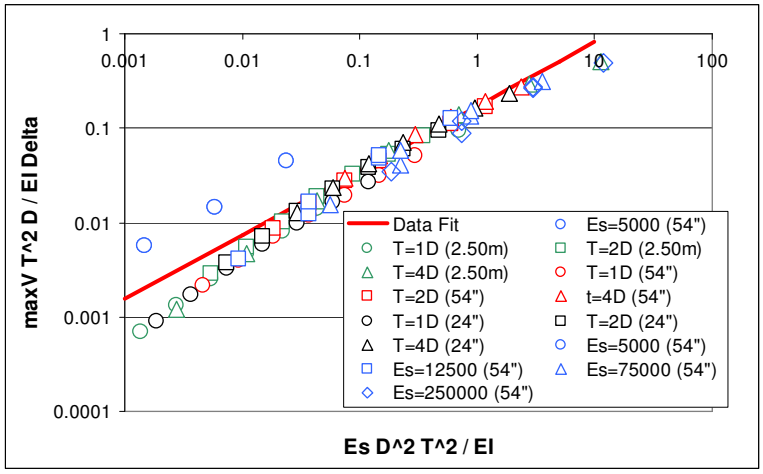
- E_s modulus o elasticity of stiff soil layer
- EI stiffness of pile
- T thickness of liquefiable layer
- D outer diameter of pile

Embedment length in stiff soil layer (approximated as average of top and bottom layer)

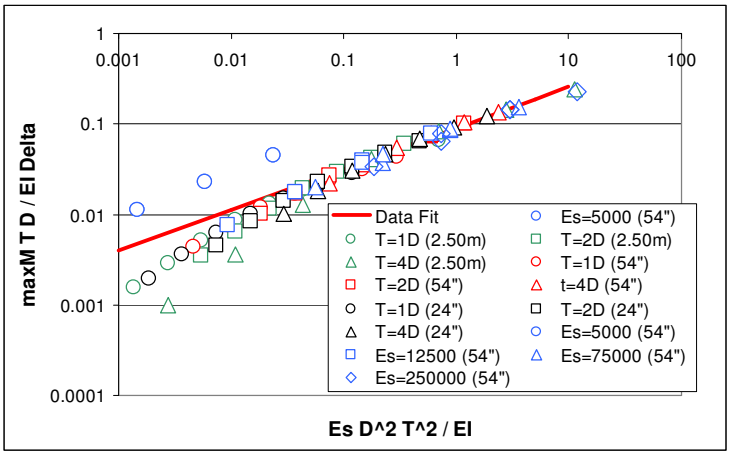


Results encourage the use of a linear regression for most of the parameter space

Dimensionless **shear force demand**. Maximum shear occurs within the liquefied layer



Dimensionless **bending moment** (or curvature demand). Max M occurs at from the layer interface within the stiff layer



Design Procedure

$$\max V = \gamma_V \frac{EI}{T^2}\frac{\Delta}{D}$$ → Maximum shear force in the pile

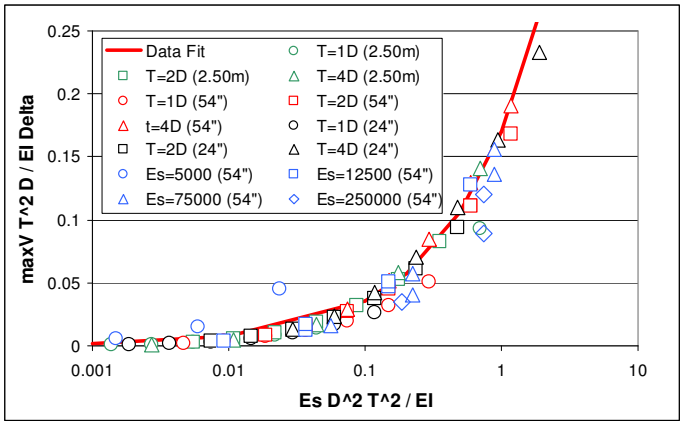
$$\max M = \gamma_M \frac{EI}{T}\frac{\Delta}{D}$$ → Maximum moment in the pile

$$L_{embed} = \gamma_L D$$ → Location of maximum moment

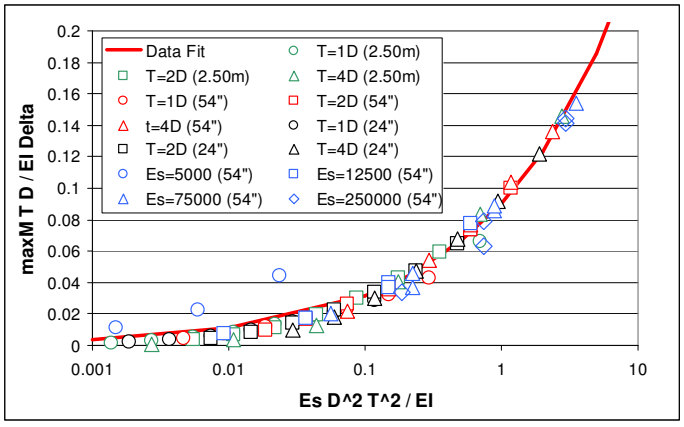
$$\gamma_L = 0.5 - \log_{10}\beta$$
$$\gamma_V = 0.17\beta^{0.68}$$
$$\gamma_M = 0.09\beta^{0.45}$$
→ Non-dimensional coefficients

$$\beta = \frac{E_s T^2 D^2}{EI}$$ → Dimensionless characteristic parameter

Dimensionless shear force demand. Maximum shear occurs within the liquefied layer.



Dimensionless bending moment (or curvature demand). Max M occurs at L_{embed} from the layer interface within the stiff layer.



Comparison of fixed-fixed vs. OpenSees