BENCHMARK LINEAR FINITE ELEMENT ANALYSIS OF LATERALLY LOADED SINGLE PILE USING OPENSEES & COMPARISON WITH ANALYTICAL SOLUTION

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Introduction

In this study:

I) The response of a laterally loaded pile obtained using the OpenSeesPL interface is compared with the analytical elastic solution proposed by Abedzadeh and Pak (2004). Detailed information about the analytical elastic solution is provided in Appendix I.

II) Based on the linear analysis presented below, nonlinear soil response is addressed in Appendix II.

Laterally Loaded Pile

Pile Data

The pile employed in the OpenSees simulation is circular with a diameter of 16" (radius a = 8") while the one for the analytical elastic solution is a cylindrical pipe pile of the same radius and a wall thickness $h = 0.1a$. Both cases have the same pile length l = 33.3 ft ($l/a = 50$). The cross-sectional moment of inertia of the pipe pile $I = \pi a^3 h$ = 1286.8 in^4, which will be used for the circular pile in the OpenSees simulation.

In summary, the geometric and elastic material properties of the pile are listed below:

Radius a = 8"
Pile length l = 33.3 ft
Young's Modulus of Pile E_p = 29000 ksi
Moment of Inertia of Pile I = 1286.8 in^4

Soil Domain

The pile is assumed to be fully embedded in a homogeneous, isotropic, linearly elastic half-space. The elastic properties of the soil are assumed constant along the depth (in order to compare with the analytical elastic solution) and are listed below:

Shear Modulus of Soil G_s = 7.98 ksi
Bulk Modulus of Soil B = 13.288 ksi (i.e., Poisson's ratio ν_s = 0.25)
Submerged Unit Weight γ' = 62.8 pcf

The ratio of Young's Modulus of Pile (E_p) to the Shear Modulus of Soil (G_s):
E_p/G_s = 3634 (which will be used later to obtain the analytical elastic solution by interpolation).

Lateral Load

The pile head (free head condition), which is located at the ground surface, is subjected to a horizontal load (*H*) of 31.5 kips.

Finite Element Simulation

In view of symmetry, a half-mesh is studied as shown in Figure 1. For comparison, both 8-node and 20-node elements are used (2,900 8-node brick elements, 20 beam-column elements and 189 rigid beam-column elements in total) in the OpenSeesPL simulation. Length of the mesh in the longitudinal direction is 520 ft, with 260 ft transversally (in this half-mesh configuration, resulting in a 520 ft x 520 ssoil domain in plan view). Layer thickness is 66 ft (the bottom of the soil domain is 32.7 ft below the pile tip, so as to mimic the analytical half-space solution).

The floating pile is modeled by beam-column elements, and rigid beam-column elements are used to model the pile size (diameter).

The following boundary conditions are enforced:

i) The bottom of the domain is fixed in the longitudinal (*x*), transverse (*y*), and vertical (*z*) directions.
ii) Left, right and back planes of the mesh are fixed in *x* and *y* directions (the lateral directions) and free in *z* direction.
iii) Plane of symmetry is fixed in *y* direction and free in *z* and *x* direction (to model the full-mesh 3D solution).

The lateral load is applied at the pile head (ground level) in *x* (longitudinal) direction.

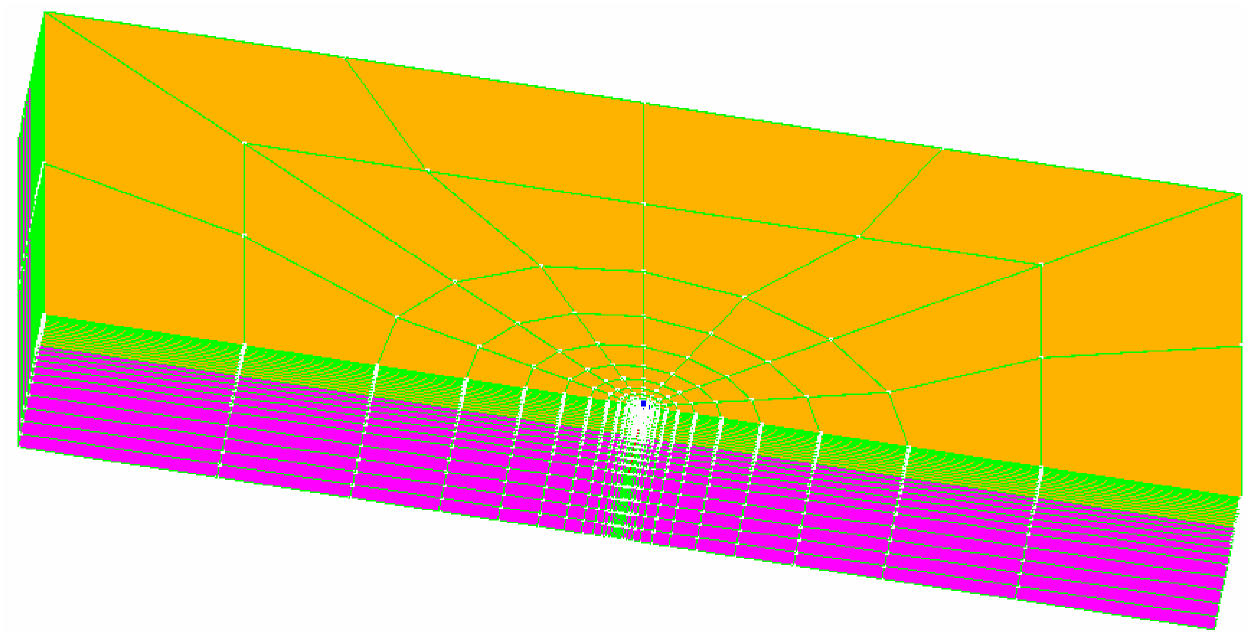
The above simulations were performed using OpenSeesPL (Lu et al., 2006).

Simulation Results and Comparison with Elastic Solution

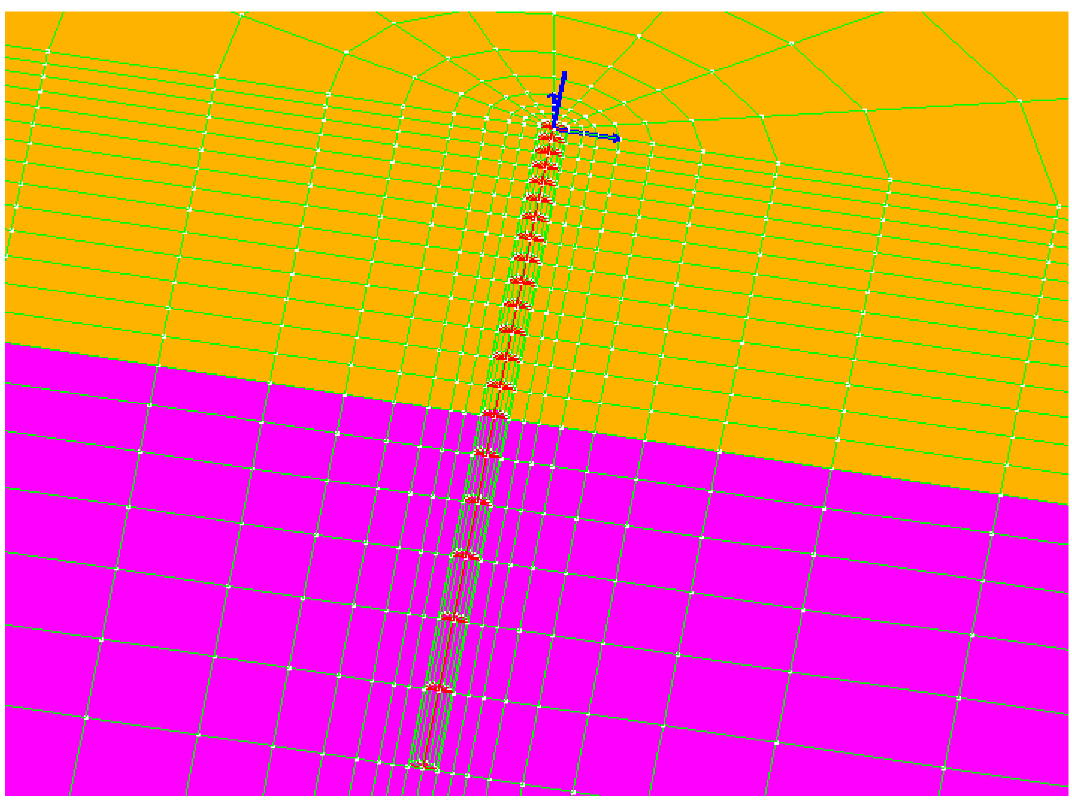
Deflection and bending moment response profiles obtained from OpenSees are shown in Figures 2 & 3, along with the analytical elastic solution by Abedzadeh and Pak (2004) for comparison (note that the elastic solution was obtained by performing a linear interpolation of the normalized deflections and moments shown in Figures 4 & 5 for E_p/G_s = 3634).

The pile head deflection and the maximum bending moment from OpenSees and the elastic solution are also listed in Table 1. In general, the numerical results match well with the analytical elastic solution. The pile head deflection from the 20-node element mesh (0.043") is almost identical to the elastic solution (0.042").

For nonlinear run, please see Appendix II.



a) Isometric view



b) Pile head close-up

Figure 1: Finite element mesh employed in this study.

Table 1: Comparison of OpenSees results and the analytical elastic solution.

	OpenSees Results		Elastic solution by Abedzadeh and Pak (2004)
	8-node element	20-node element	
Pile head deflection (in)	0.039	0.043	0.042
Maximum moment M_{max} (kip-ft)	30	31	27
Depth where M_{max} occurs (ft)	2.87	2.87	2.7

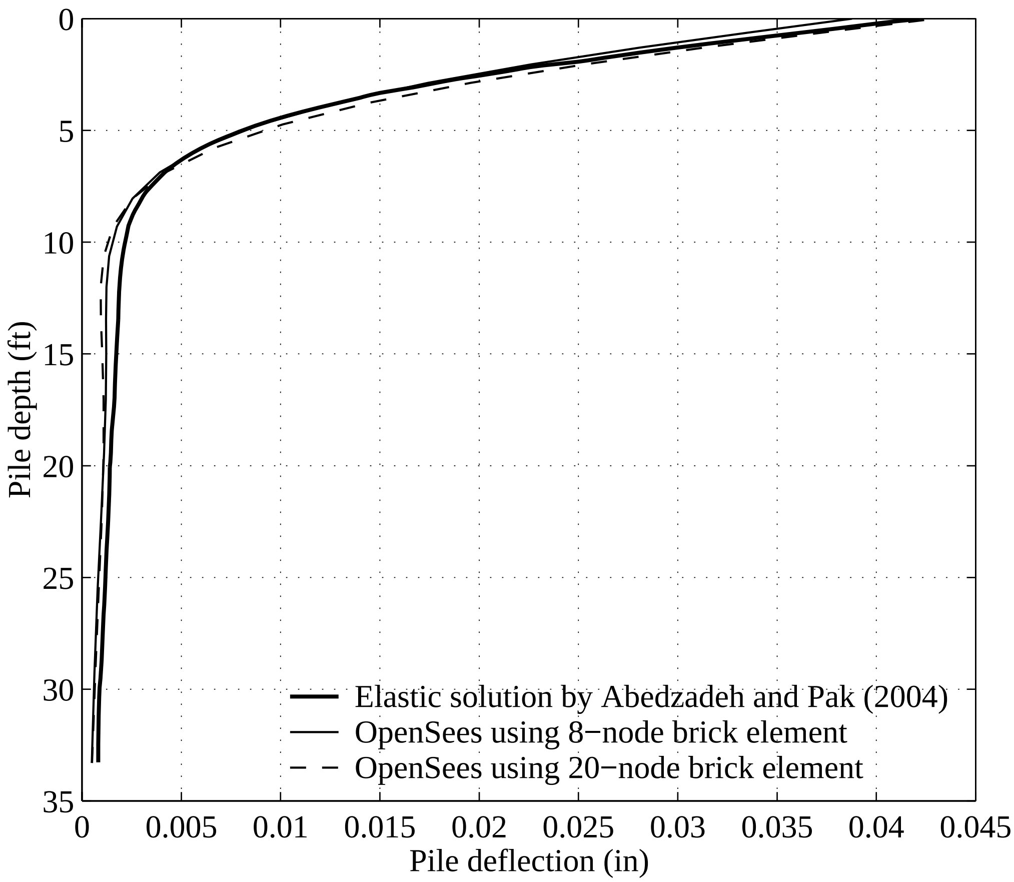


Figure 2: Comparison of pile deflection profiles (ν_s=.25, *l*/*a*=50).

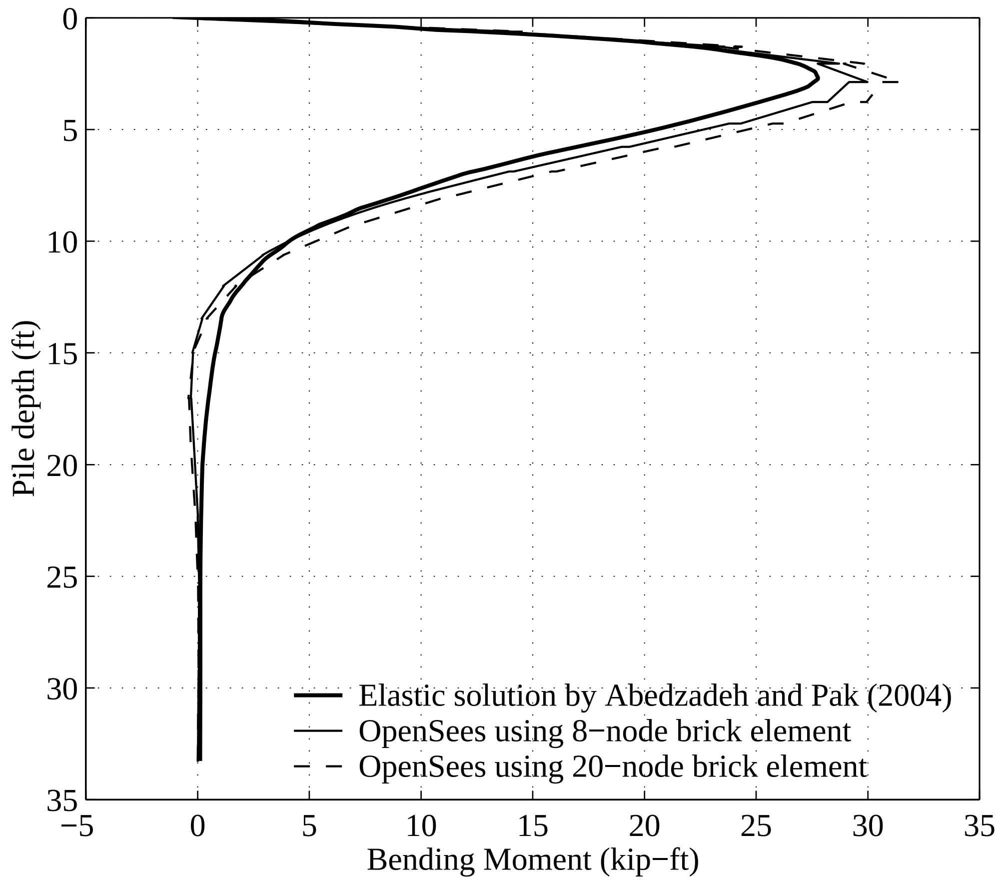


Figure 3: Comparison of pile bending moment profiles (ν_s=.25, *l*/*a*=50).

Appendix I: Elastic Solution of the Response of a Laterally Loaded Pile in a Semi-Infinite Soil Medium with Constant Modulus along Depth

(For details, please see: Farzad Abedzadeh and Y. S. Pak. (2004). “Continuum Mechanics of Lateral Soil–Pile Interaction”, *Journal of Engineering Mechanics*, Vol. 130, No. 11, November, pp. 1309-1318).

Consider a flexible cylindrical pipe pile of radius a, length l, a wall thickness $h \ll a$ (note that the moment of inertia $I = \pi a^3 h$). The pile is assumed to be fully embedded in a homogenous, isotropic, linearly elastic half-space with a shear modulus G_s and a Poisson’s ratio $\nu_s = 0.25$.

Using Eqs. (78)-(83) and Figure 9 of the above reference, the pile response (h/a=0.1, l/a=50) under an applied pure pile-head horizontal load is shown in Figures 4-5, where,
E_p – Young’s Modulus of Pile
G_s – Shear Modulus of Soil
w – Pile deflection (in)
H – Horizontal load (kip)
z – Pile depth (ft)

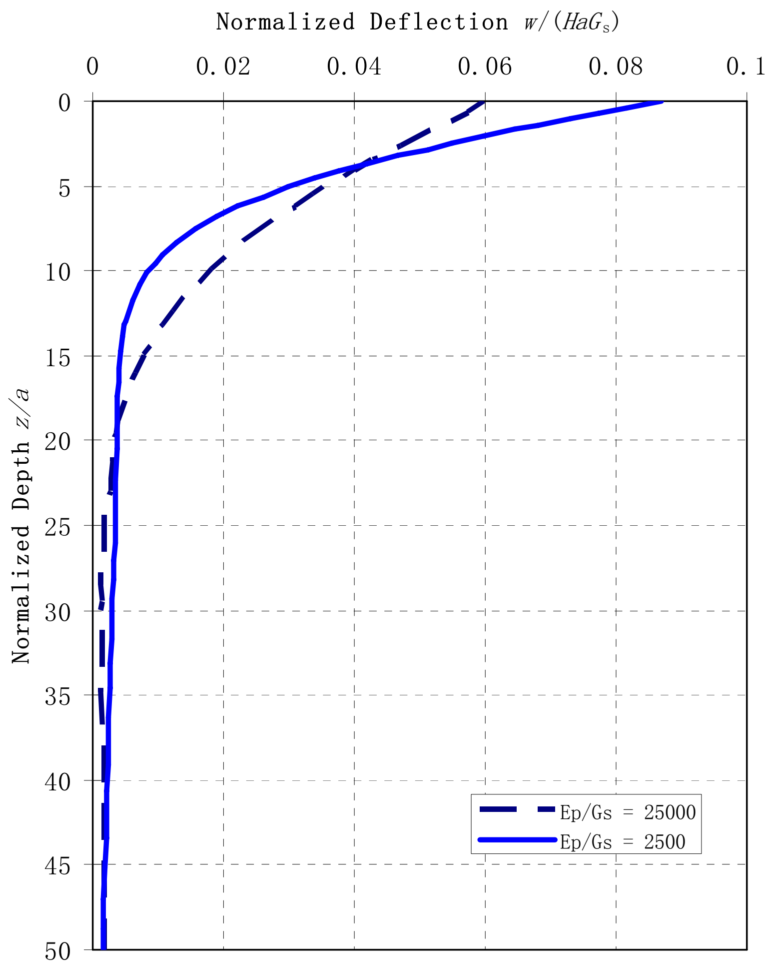


Figure 4: Sample pile deflection (*h*/*a*=.1, *l*/*a*=50) under an applied pure pile-head horizontal load (Abedzadeh and Pak, 2004).

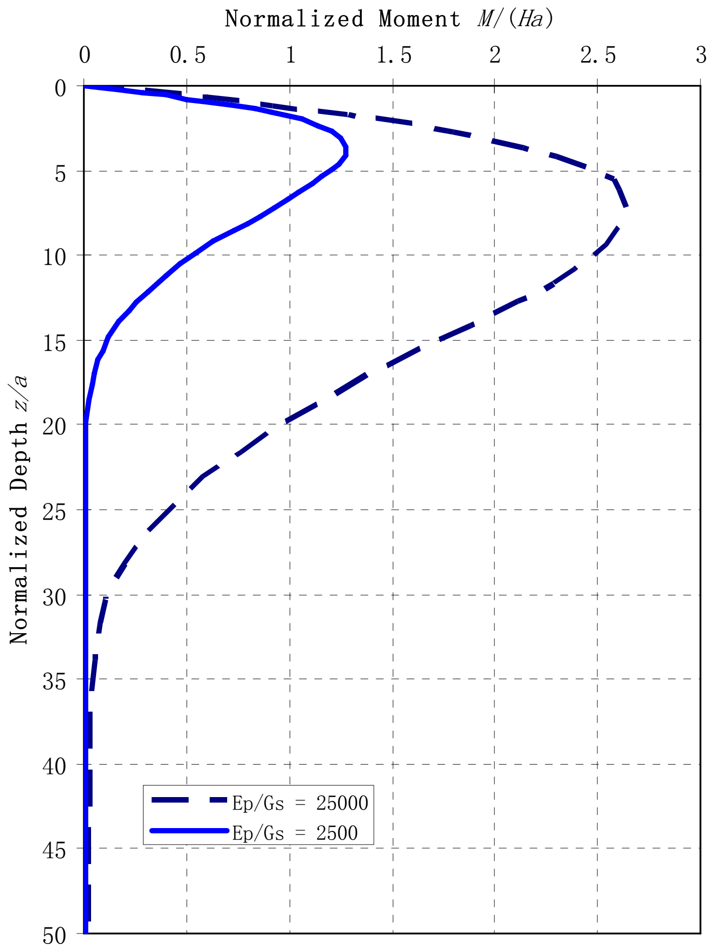


Figure 5: Sample pile bending moment (*h*/*a*=.1, *l*/*a*=50) under an applied pure pile-head horizontal load (Abedzadeh and Pak, 2004).

Appendix II: Nonlinear Response of the Single Pile Model

In the nonlinear run, the same material properties of the linear run are employed except the soil now assumed to be a clay material with a maximum shear strength or cohesion = 5.1 psi, in the range of a Medium Clay. This maximum shear strength is achieved at a specified strain γ_{max} = 10%.

The lateral load (*H*) is applied at an increment of 0.7875 kips and the final load is 94.5 kips (= 3 x 31.5 kips). The 8-node brick element mesh is employed in this nonlinear analysis (Figure 1).

Simulation Results

Figure 6 shows the load-deflection curve for the nonlinear run, along with the linear result (for the 8-node brick element mesh; the final lateral load is also extended to 94.5 kips) as described in the previous sections for comparison. It is seen from Figure 6 that nearly linear behavior is exhibited in the nonlinear run for only low levels of applied lateral load (less than 10 kips).

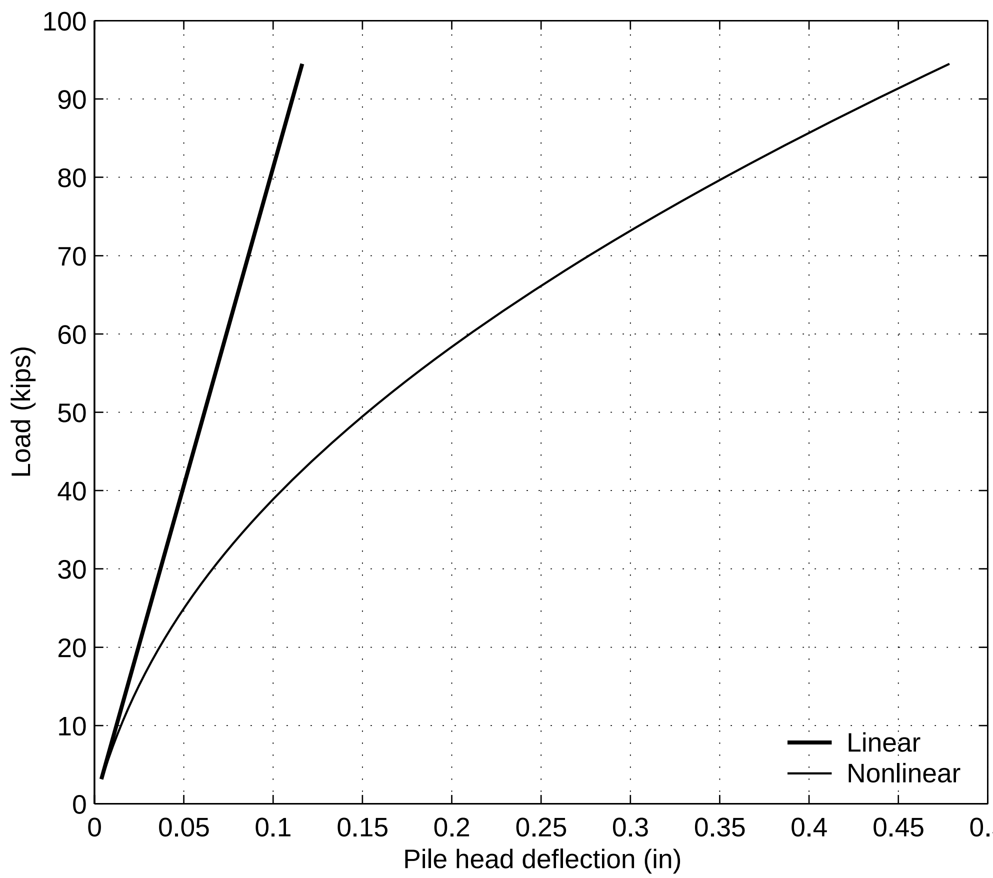
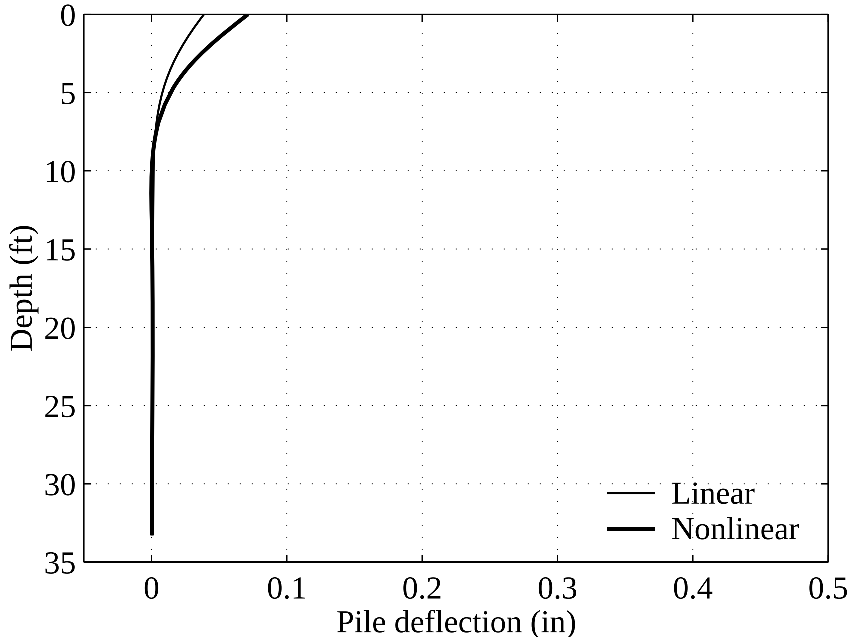
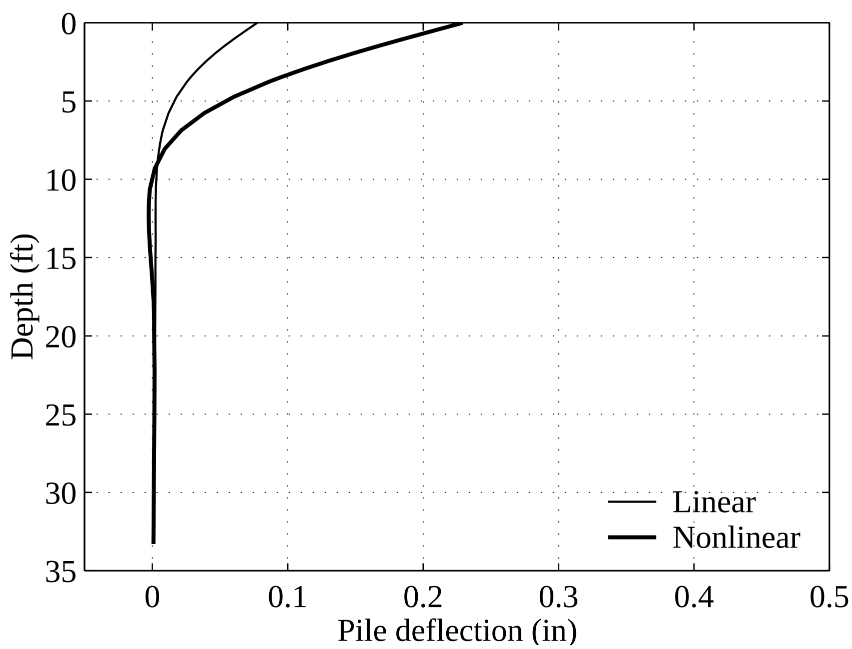


Figure 6: Comparison of the load-deflection curves for the linear and nonlinear runs.

The pile deflection profiles for both linear and nonlinear cases are displayed in Figure 7. For comparison, the linear and nonlinear responses at the lateral load of 31.5 kips, 63 kips (= 2 x 31.5), and 94.5 kips (= 3 x 31.5) are shown (Figure 7). The bending moment profiles for the 3 load levels are shown in Figure 8a-c.

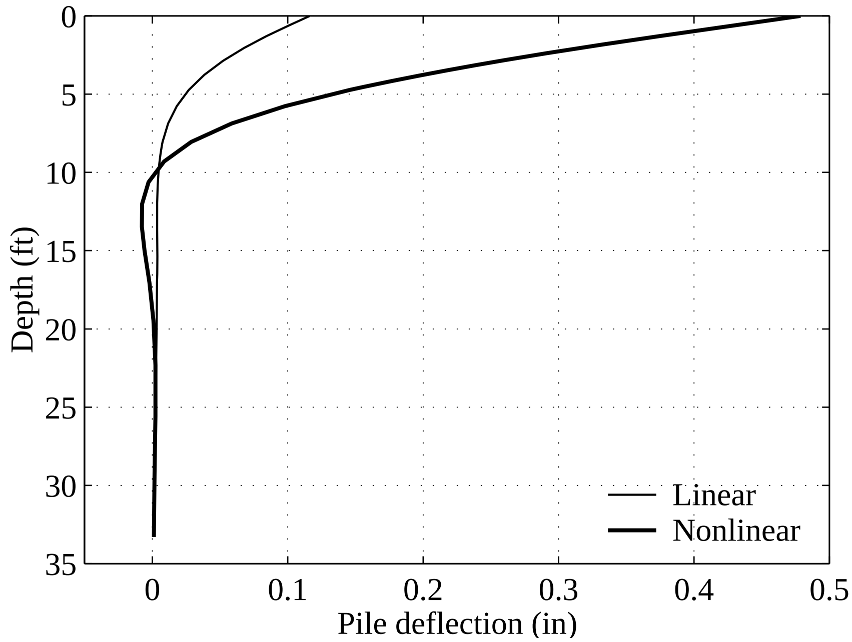


a) $H = 31.5$ kips



b) $H = 63$ kips

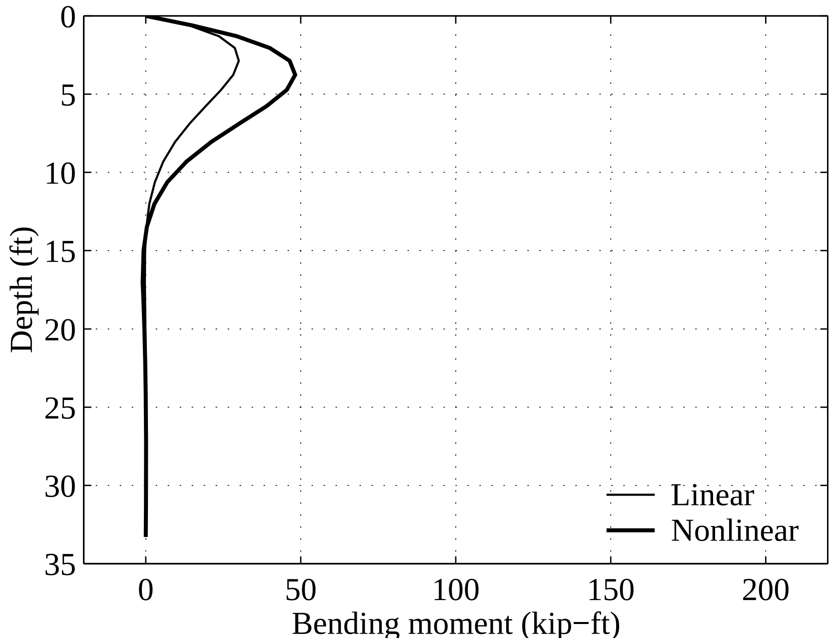
Figure 7: Comparison of the pile deflection profiles for the linear and nonlinear runs.



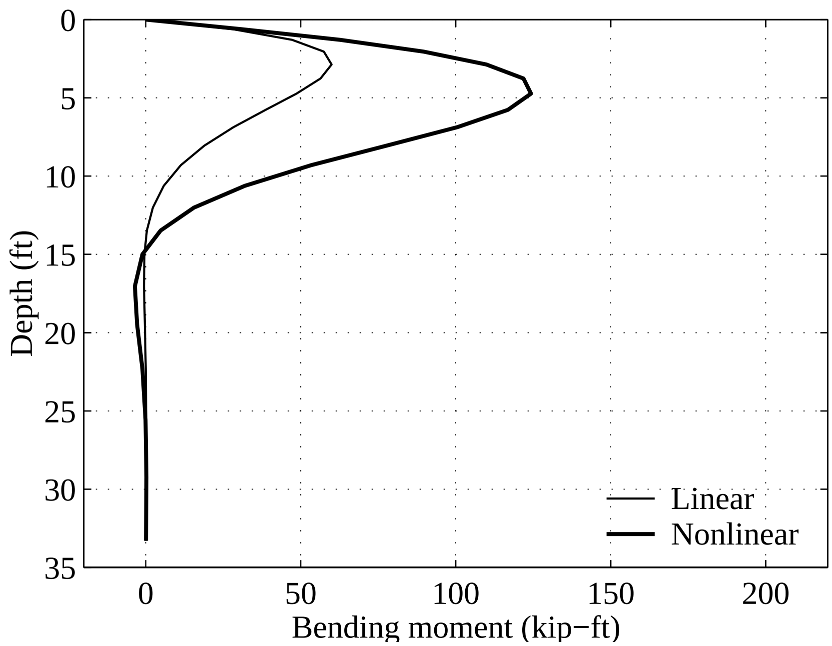
c) H = 94.5 kips

Figure 7: (continued).

The close-up of the final deformed mesh (at H = 94.5 kips) is shown in Figure 9. The pile head deflections and the maximum bending moments for both linear and nonlinear analyses are listed in Table 2. The stress ratio contour fill of the nonlinear run is displayed in Figure 10.

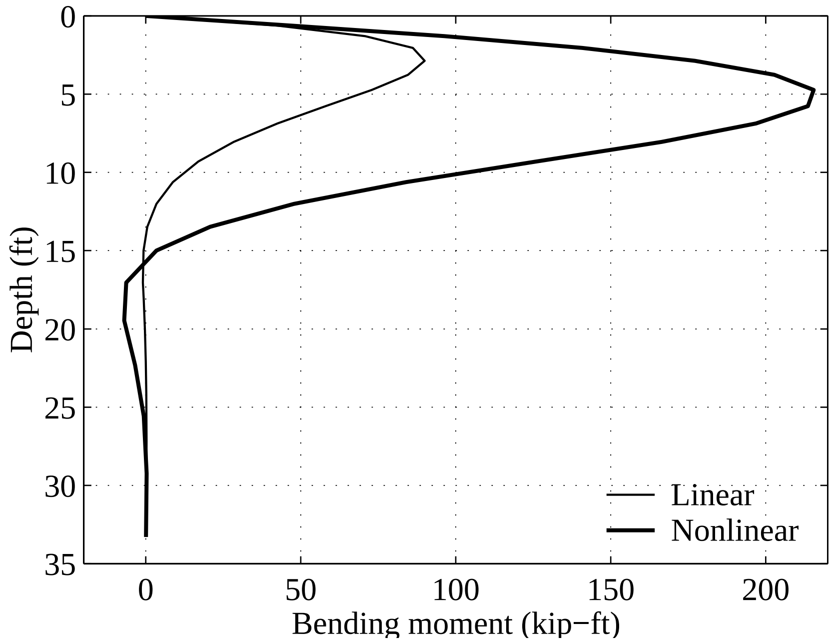


a) H = 31.5 kips



b) H = 63 kips

Figure 8: Comparison of the pile bending moment profiles for the linear and nonlinear runs.

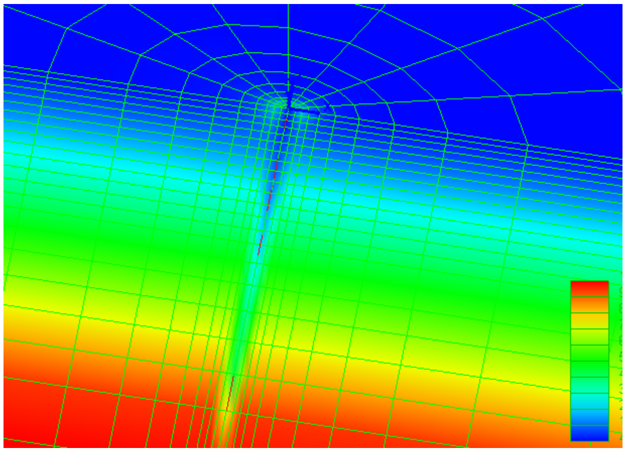


c) H = 94.5 kips

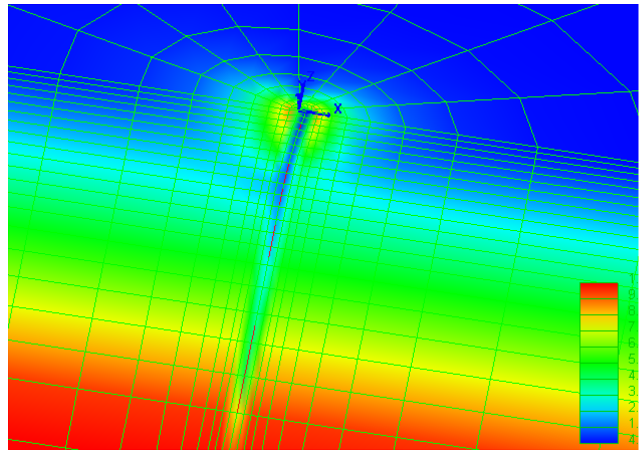
Figure 8: (continued).

Table 2: OpenSees simulation results for the linear and nonlinear runs.

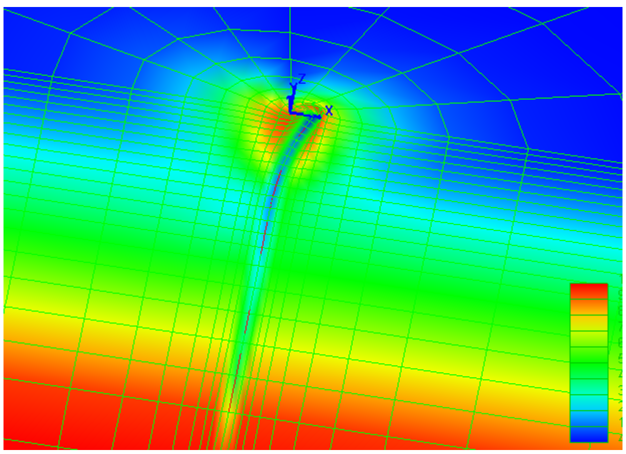
	H = 31.5 kips		H = 63 kips		H = 94.5 kips	
	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
Pile head deflection (in)	0.039	0.07	0.078	0.23	0.12	0.48
Maximum moment M_{max} (kip-ft)	30	48.2	60	124.3	90	215.5
Depth where M_{max} occurs (ft)	2.9	3.8	2.9	4.7	2.9	4.7



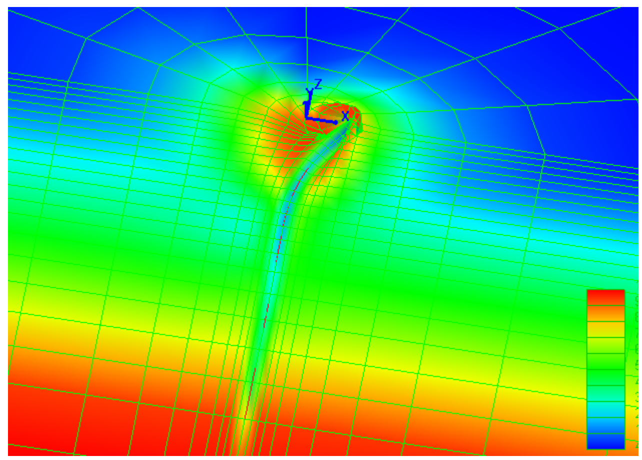
a) First step



b) H = 31.5 kips



c) H = 63 kips



d) H = 94.5 kips

Figure 9: Stress ratio contour fill of the nonlinear run at different load levels (red color shows yielded soil elements).

References

Farzad Abedzadeh and Y. S. Pak (2004). “Continuum Mechanics of Lateral Soil–Pile Interaction”, *Journal of Engineering Mechanics*, Vol. 130, No. 11, November, pp. 1309-1318

Jinchi Lu, Zhaohui Yang, and Ahmed Elgamal (2006). "OpenSeesPL Three-Dimensional Lateral Pile-Ground Interaction, User's Manual, Version 1.00." *Report No. SSRP-06/03*, Department of Structural Engineering, University of California, San Diego.