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Experimental and theoretical studies of laterally loaded single piles in slopes

Ming-hui YANG, Bo DENG, Ming-hua-ZHAO

Key words:
Pile foundation; Slope; Model test; FEM; lateral load; p-y curve

Problem definition



(a)

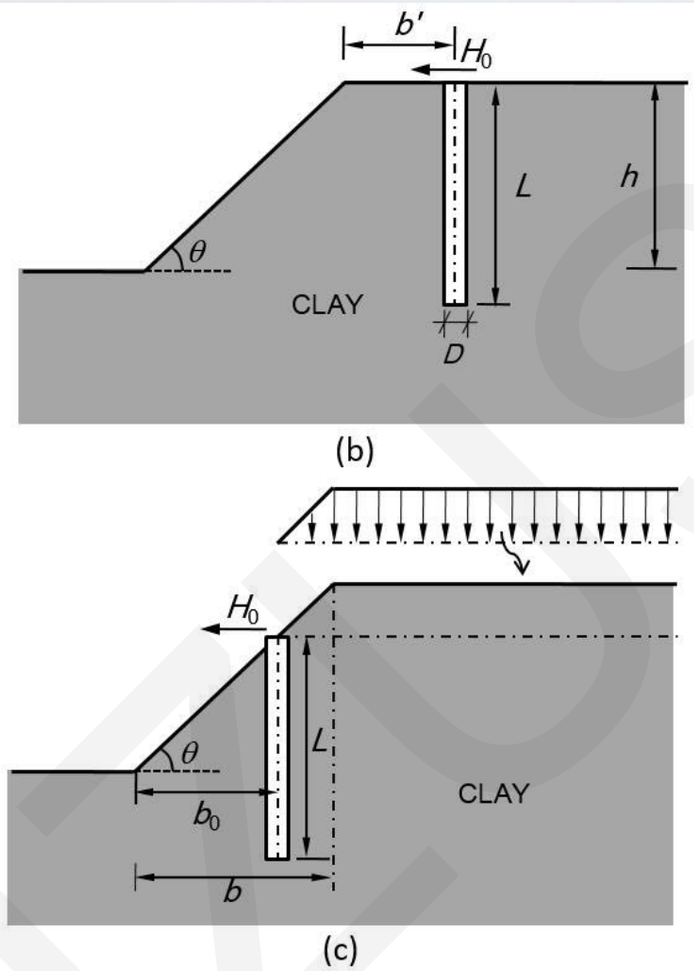


Fig. 1

(1) Many bridge pile foundations are constructed in slopes, as shown in Fig. 1(a), and the idealized problem is presented in Fig. 1(c).

(2) Comparing the case depicted in Fig. 1(b) with that in Fig. 1(c), the lateral behavior of the loaded pile in a slope becomes more complex owing to the extra loading caused by the weight of soil at the opposite side of the slope.

(3) However acceptable solutions that could take account of all the influencing factors including the declination and height of the slope, and the length of pile embedded in slopes, have not so far been reported in the literature.

Analysis methods

Experimental investigation

- Four laboratory model tests with different slope angles (θ), 0°, 30°, 45°, and 60°, were performed, as shown in Fig. 2.
- Applied load: (1) by increments of 0.1 kN; (2) with stabilizing time when increments were continued until the rate of change of pile head displacement versus time was less than 0.01 mm/min or the cumulative rate of change was less than 0.1 mm/h.

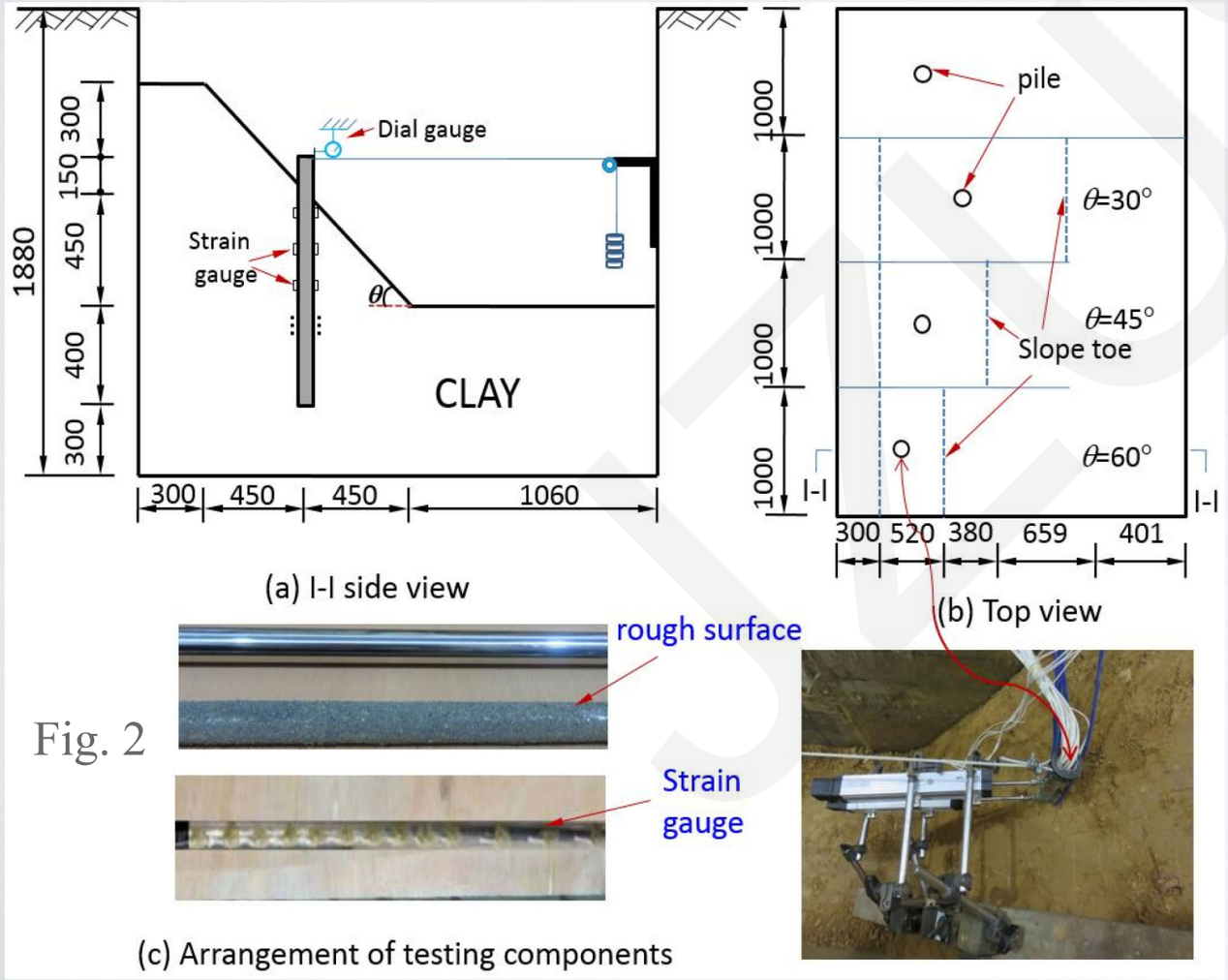


Fig. 2

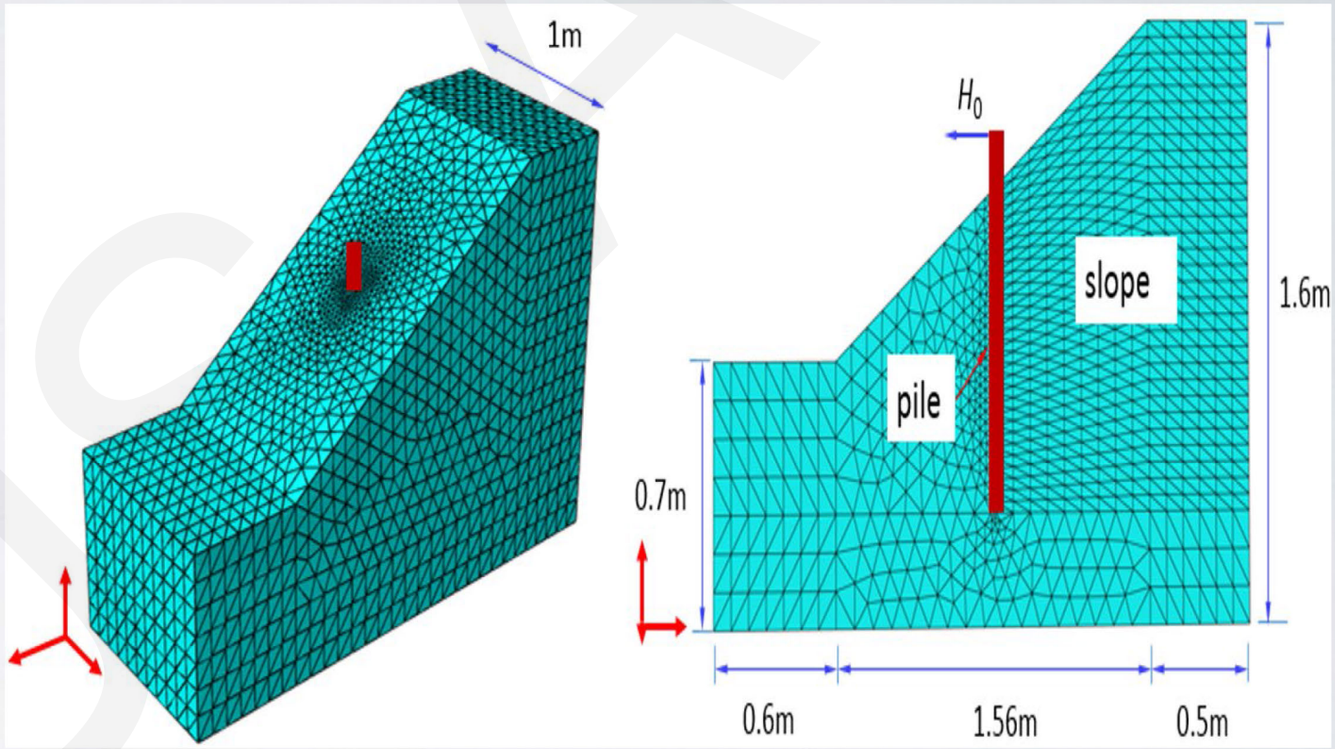
Table 1 Model test program

case	$D_p \times d$ (mm × mm)	L (mm)	L_f (mm)	E_pI_p (N·m²)	θ (°)	β
1	25.04 × 1.02	1000	15	100.85	0	0.5
2	25.06 × 1.04	1000	15	102.47	30	0.5
3	24.98 × 1.00	1000	15	102.35	45	0.5
4	25.01 × 1.03	1000	15	99.80	60	0.5

Analysis methods

3D FE analysis

- FE analysis software: ABAQUS (version 6.14.5)
- Material constitutive model: Mohr-Coulomb model
- Pile-soil interaction model: Coulomb friction model
- Performed with four step: (1) putting initial stresses on the soil by gravity loading without the pile; (2) replacing soil elements located at pile positions with pile elements; (3) simulating the pile-soil interaction using the contact interface element; (4) applying an incremental lateral load at the pile top.



case	L (m)	D (m)	θ (°)	β	γ_s (kN/m³)	C_u (kPa)	E_s (MPa)	v_s	γ_p (kN/m³)	v_p	μ_p
1	1	0.025	0,10,20,30,45,60	1/2	18.3	53.24	30.12	0.35	25	0.2	0.5
2	0.7, 1, 1.5	0.025	30	1/2	18.3	53.24	30.12	0.35	25	0.2	0.5
3	1	0.025	30	x/24 (x=0~24)	18.3	53.24	30.12	0.35	25	0.2	0.5

Analysis methods

New p-y curve

$$p = \frac{y}{1/K_i + y/p_u}$$

$$p_u = N_p \times c_u \times D$$

Georgiadis and Georgiadis (2010)

$$N_p = N_{pu} - (N_{pu} - N_{po}\cos\theta)e^{-\lambda(z/D)/(1+\tan\theta)}$$

Modification of K_i

$$K_{io} = \frac{1.3E_{si}}{1-\nu_s^{\,2}}\left(\frac{E_{si}D^4}{E_pI_p}\right)^{1/12}$$

$$K_{i\theta} = \left[\cos\theta + \frac{z}{6D\tan\theta}(1-\cos\theta)\right]K_{io}$$

Modification of N_P

$$\begin{cases} N_p = N_{pm} + \dfrac{1-2\beta}{N_{pg}-N_{pm}}(0<\beta<0.5), \\ N_p = N_{pm} + \dfrac{2\beta-1}{N_{pc}-N_{pm}}(0.5<\beta<1), \end{cases}$$

$$N_{pc} = N_{pu} - (N_{pu} - N_{po}\cos\theta)e^{-\lambda(z/D)/(1+\tan\theta)}$$

$$N_{pg} = \begin{cases} 3 + \dfrac{\gamma_s z}{c_u} + \dfrac{Jz}{D}, z < z_R \\ 9, z \geq z_R \end{cases}$$

$$N_{pm} = N_{pu} - (N_{pu} - N_{po}\alpha_1^{\,2}\alpha_2^{\,2})e^{-\lambda(z/D)\alpha_1^{\,2}}$$

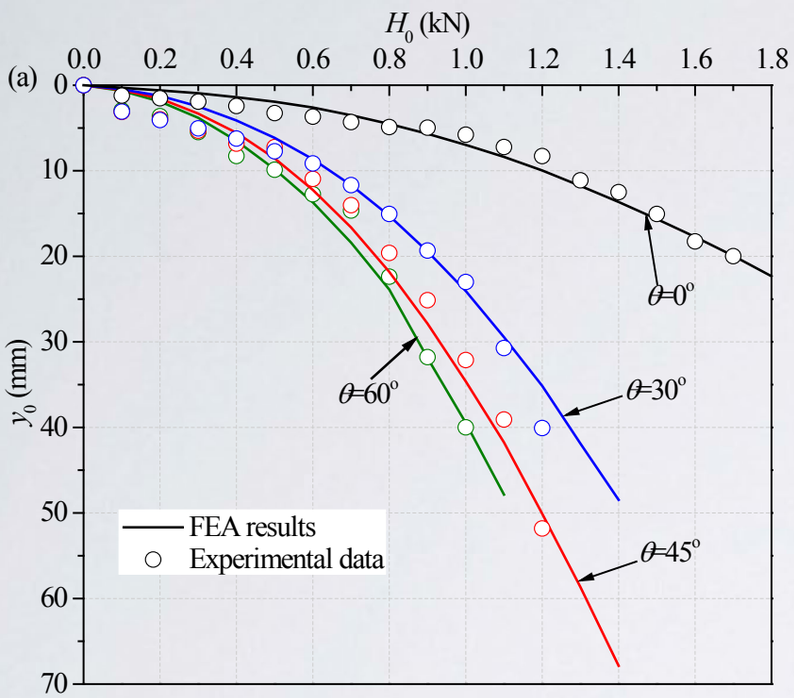
$$\alpha_1 = 1/(1+tan\theta)$$

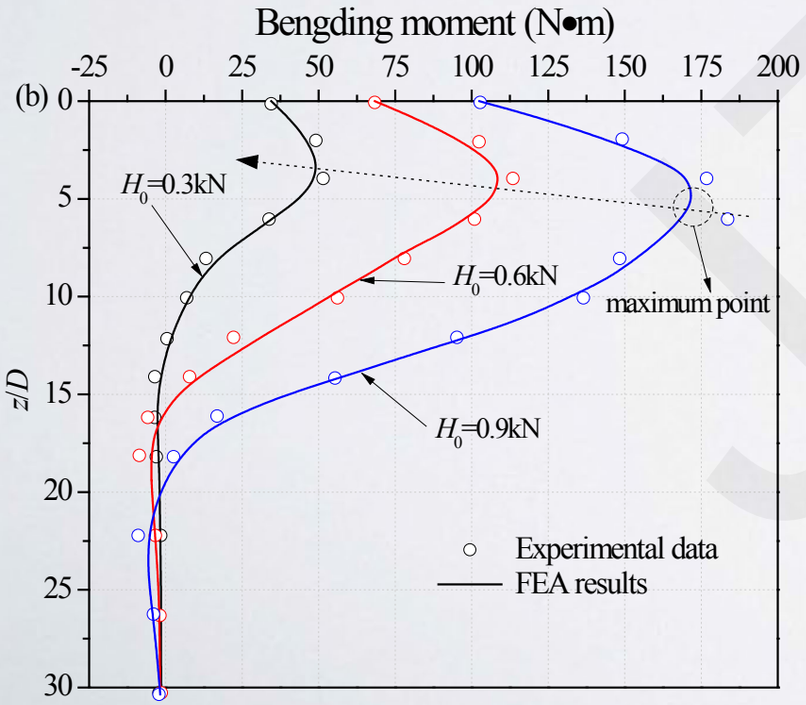
$$\alpha_2 = 1 - sinq/(1+sin\theta)/2$$

$$\begin{cases} \lambda = 0.55 - 0.15\alpha \\ N_{po} = 2 + 1.5\alpha \\ N_{pu} = \pi + 2\Delta + 2\cos\Delta + 4(\cos\dfrac{\Delta}{2} + \sin\dfrac{\Delta}{2}) \\ \Delta = \sin^{-1}\theta \end{cases}$$

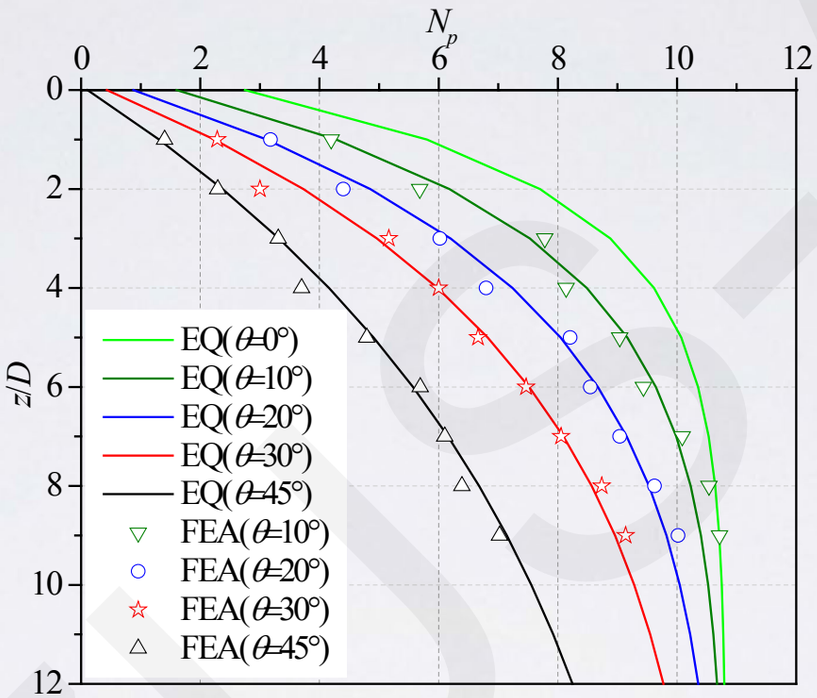
Comparison

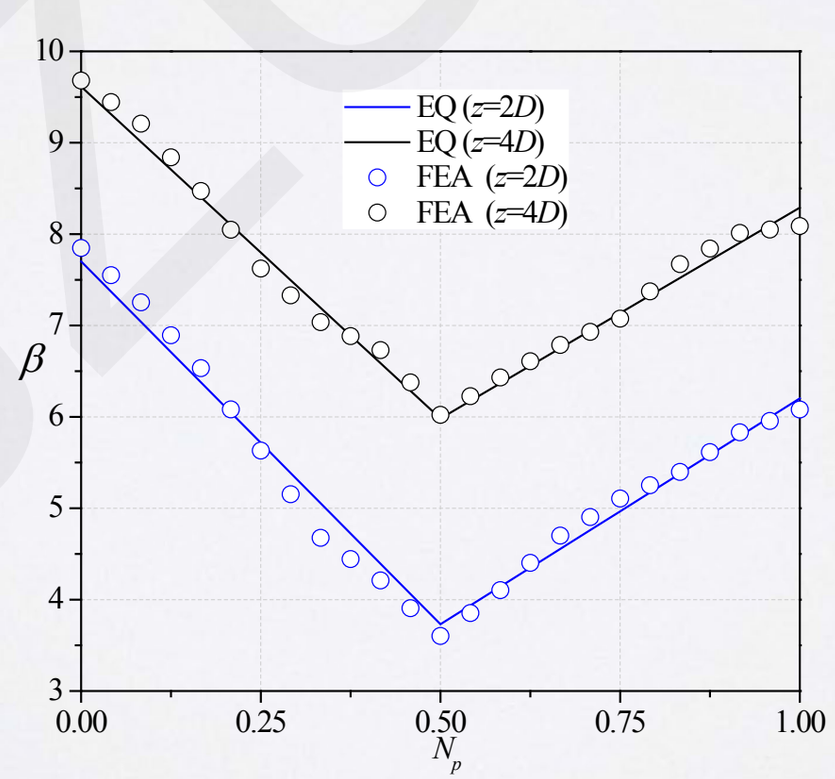
Experimental test and FEA



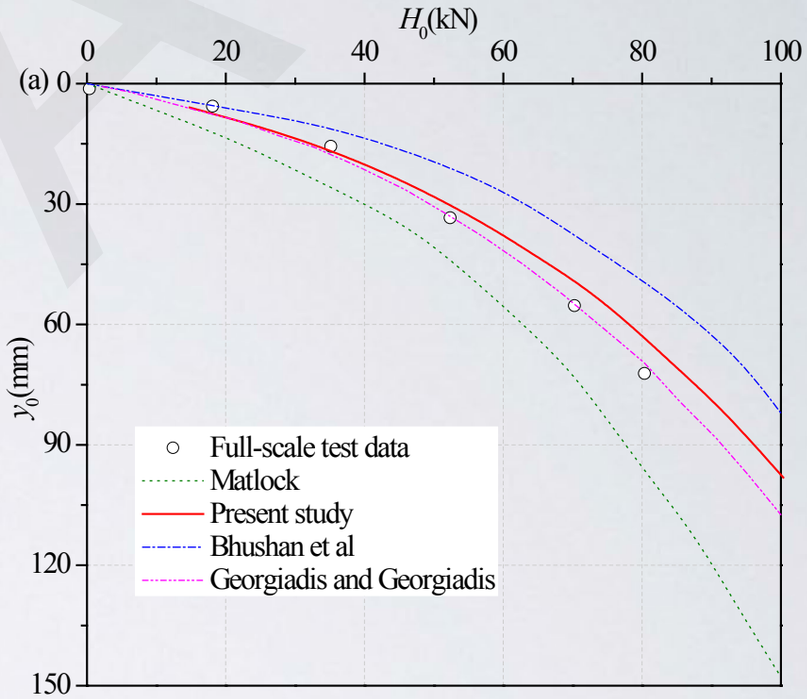


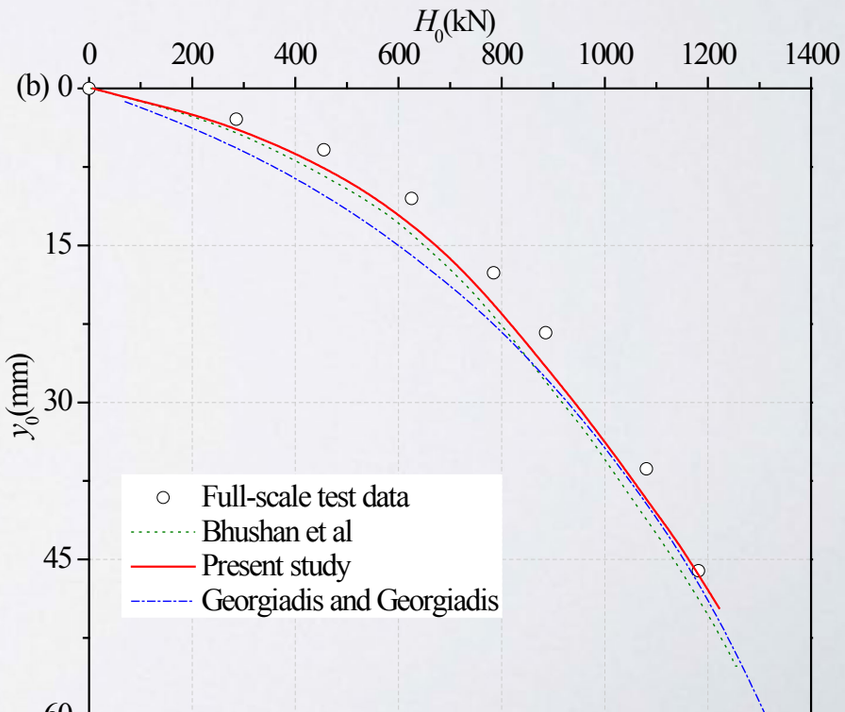
Theoretical analysis and FEA



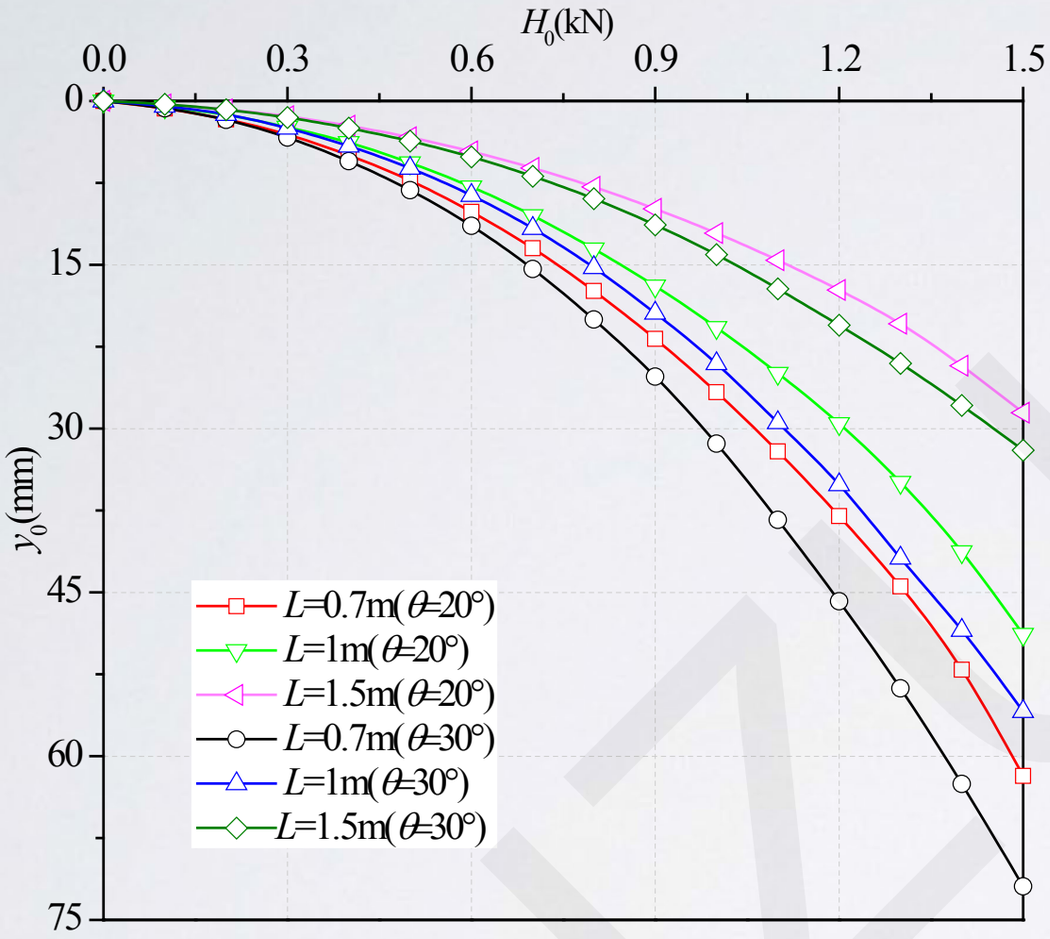


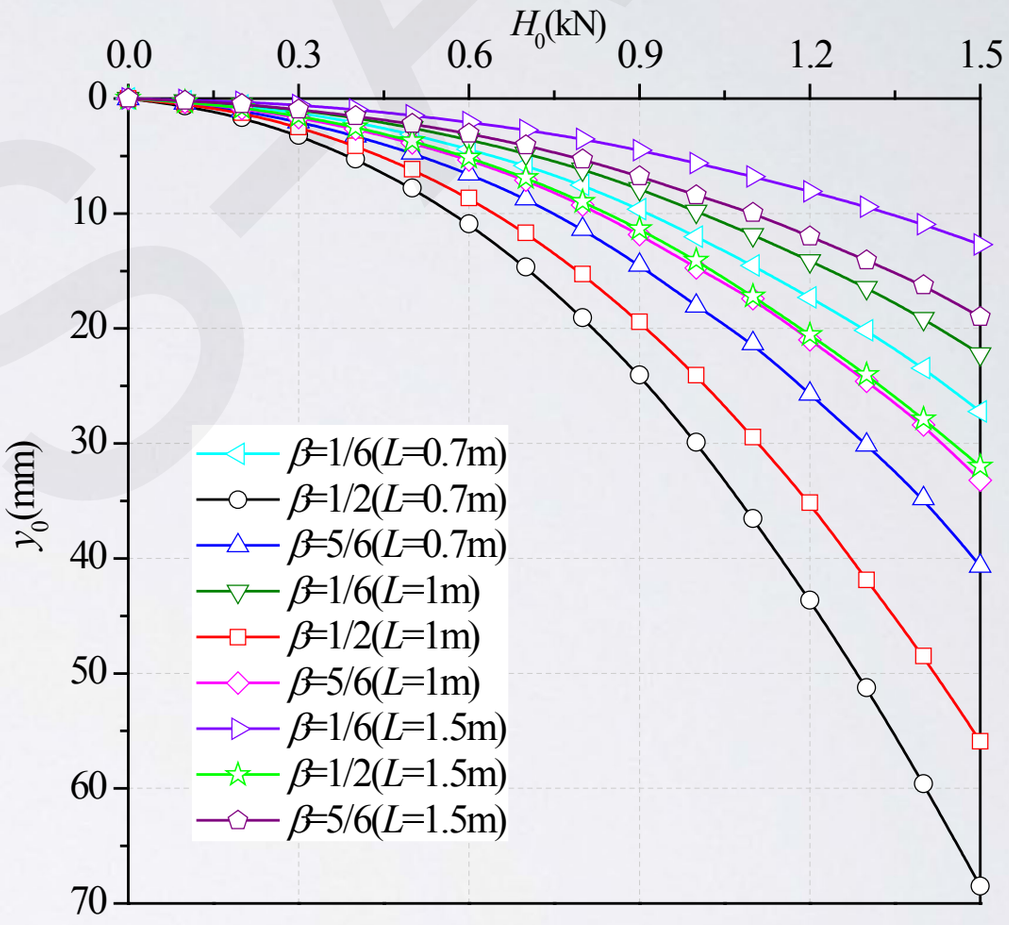
Theoretical analysis and other test





Parameter studies





Main conclusions

- (1) The distribution of the lateral deflection and the bending moment of a lateral-loaded pile in slope along the pile length are similar to those of pile embedded in horizontal ground. However, the slope inclination plays an important role in the lateral-load behavior of a single pile. A higher slope angle can cause a greater pile deformation and moment under the same loading conditions.
- (2) For piles with the same embedded length, the relationship between the ultimate lateral bearing capacity of the pile and the distance from the slope toe to the pile cross section center is approximately bi-linear.
- (3) For the same pile with different embedded lengths, the ultimate lateral capacity of the pile in-creases linearly with increased distance from the slope toe to the pile cross section center.