Displacement-based calculation method on soil-pile interaction of PHC pipe-piles

Dr. Huang Fuyun

Fuzhou University

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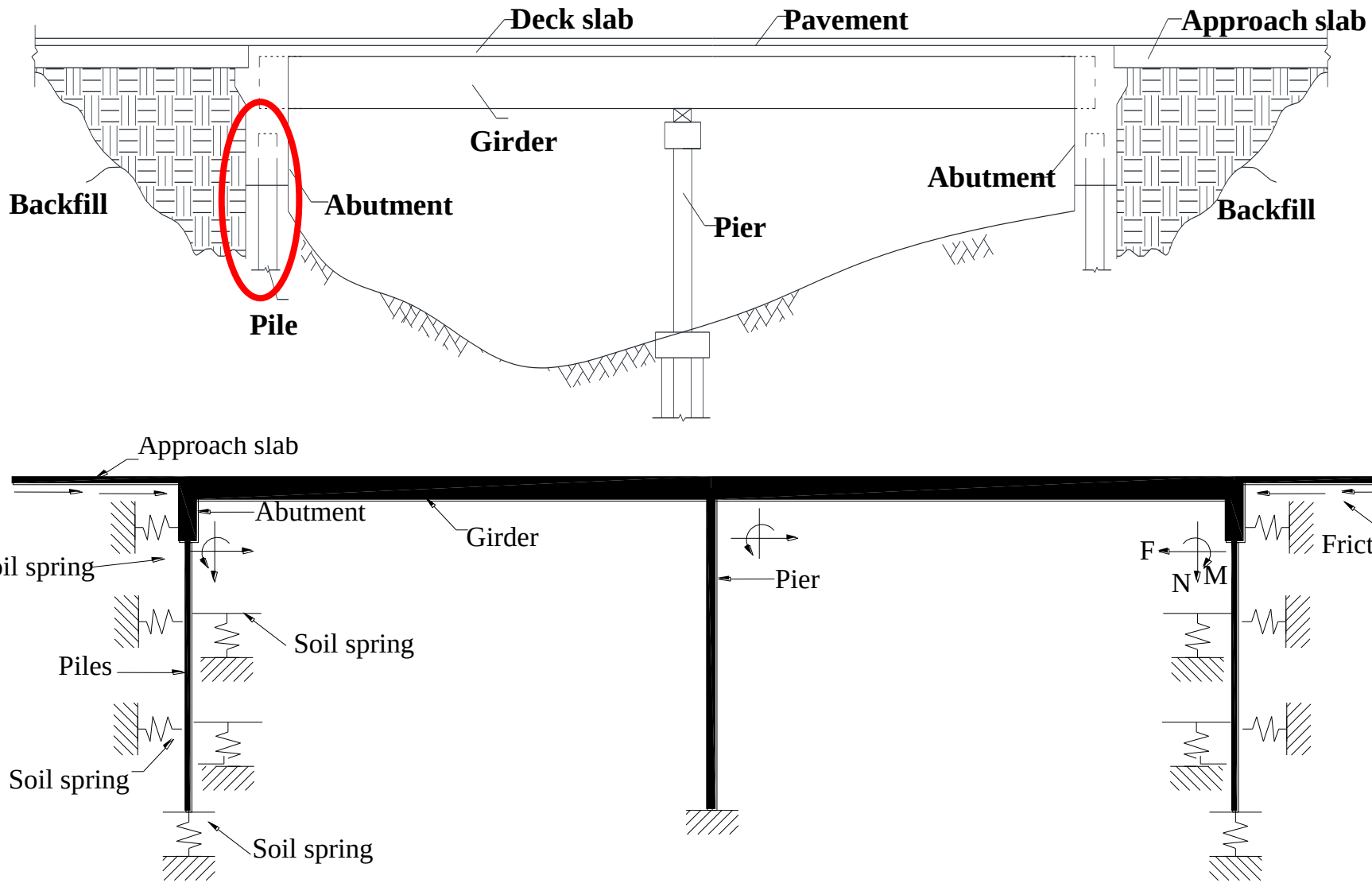
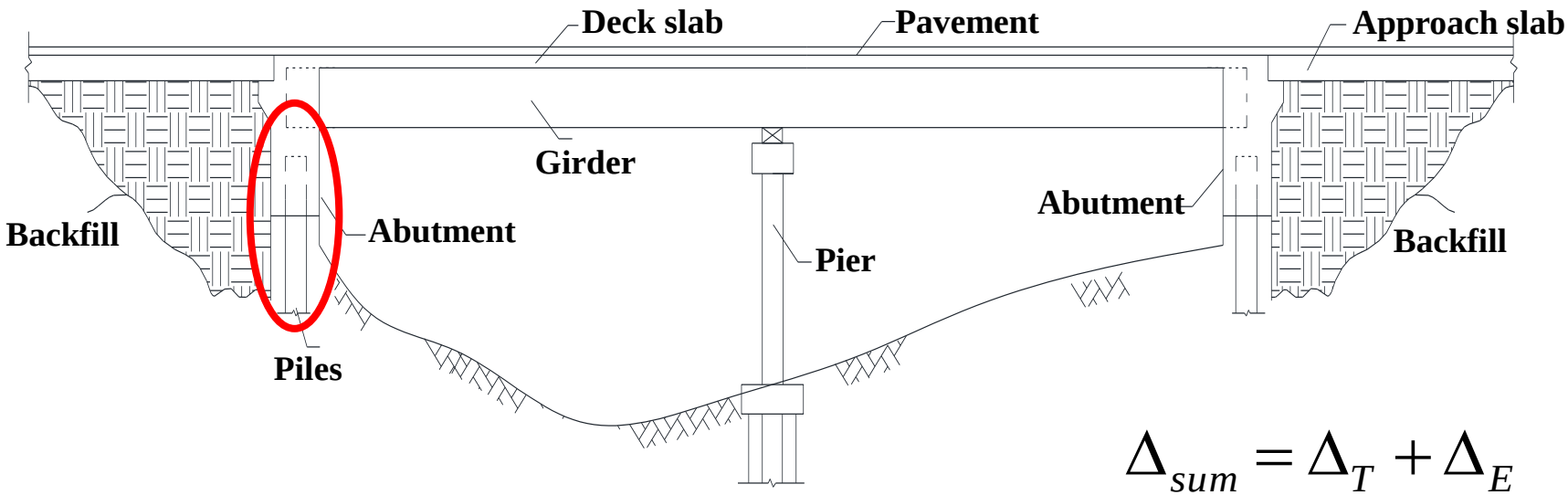
Outline

- **Background**
- **Testing introduction**
- **Testing results**
- **Simple calculation**
- **Conclusions**

1.Background



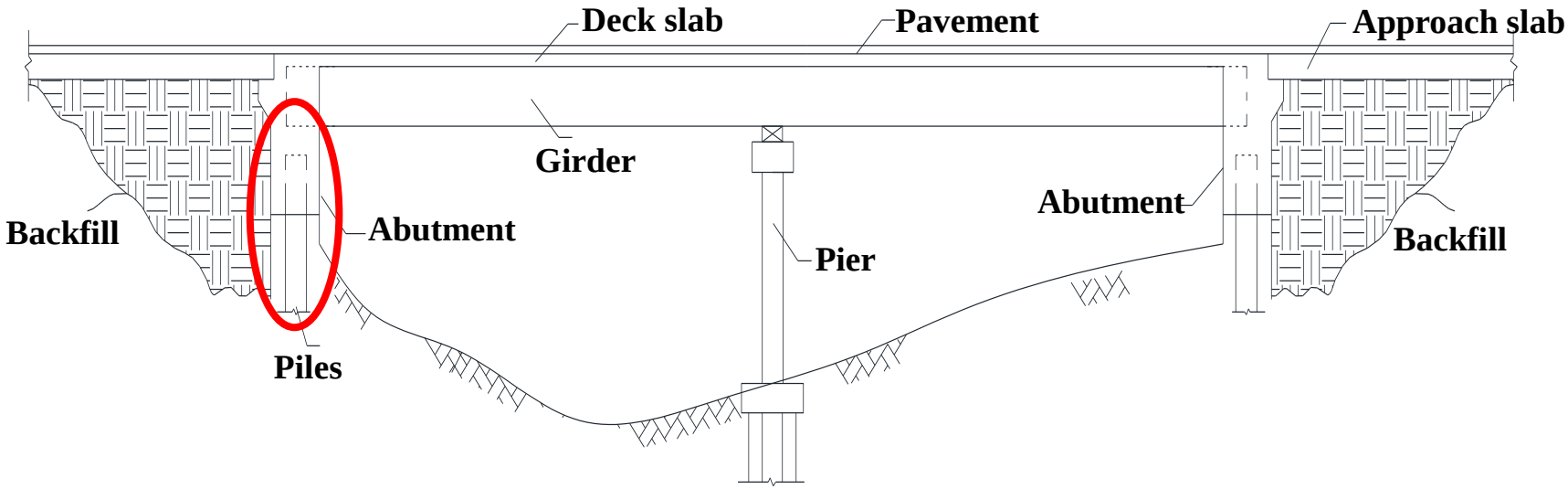
1.Background



$$\Delta_{sum} = \Delta_T + \Delta_E$$

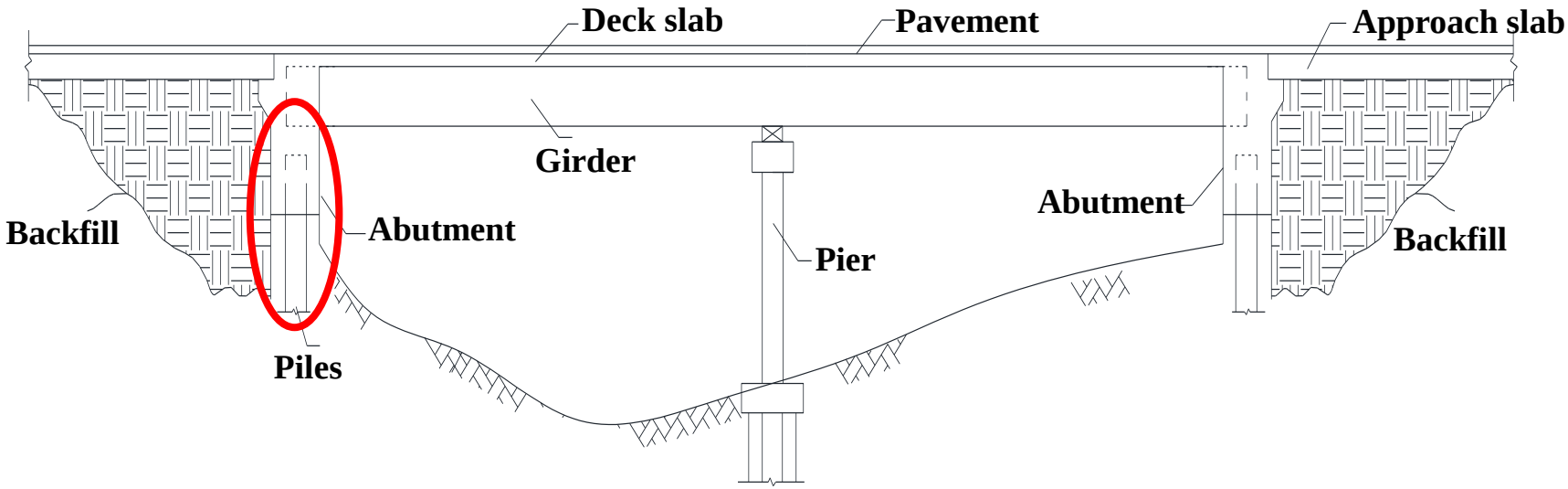
- Under temperature and seismic load, displacement of superstructure is absorbed by piles and piles are under cyclic load. To satisfy demand of superstructure deformation, flexible piles are used most frequently.
- H-steel piles have been widely used under Integral Abutment in North America and Europe, because of good flexural property and ductility.

1.Background



- Researchers of Iowa State University used PC piles in IJB and did researches on behavior of these piles and field monitoring on IJB using PC piles.
- 2004, researches on behavior of prestressed concrete square piles were conducted by Prof. Edwin from Tennessee University, which proved that PC piles can be used in IJB.

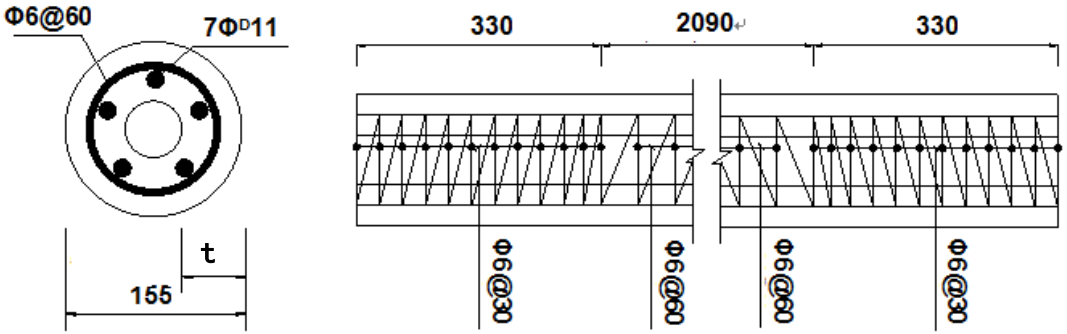
1.Background



- “m” method is linear and elastic with a limit 8-10mm in Chinese Code.
- “p-y” method is complex or accurate enough for RC piles?

2. Testing introduction

- PHC model piles
  - C80 concrete (has a compressive strength of 82.1 MPa)
  - With a diameter of 155mm，length of 2.75m
  - 7-wires prestressed steel strand with a diameter of 11.10mm
  - Labeled as PHC-1 to PHC-4



Number	Diameter（mm）	Pile Length（m）	Wall Thickness（mm）	Prestressed Degree λ	Stirrup Spacing（mm）	Deformation Coefficient a	Calculate Pile Length（m）
PHC-1	155	2.75	52.5	0.0	60	1.697	3.988
PHC-2			52.5	0.25	60	1.697	3.988
PHC-3			52.5	0.50	60	1.697	3.988
PHC-4			40.0	0.57	60	1.715	4.031

2. Testing introduction

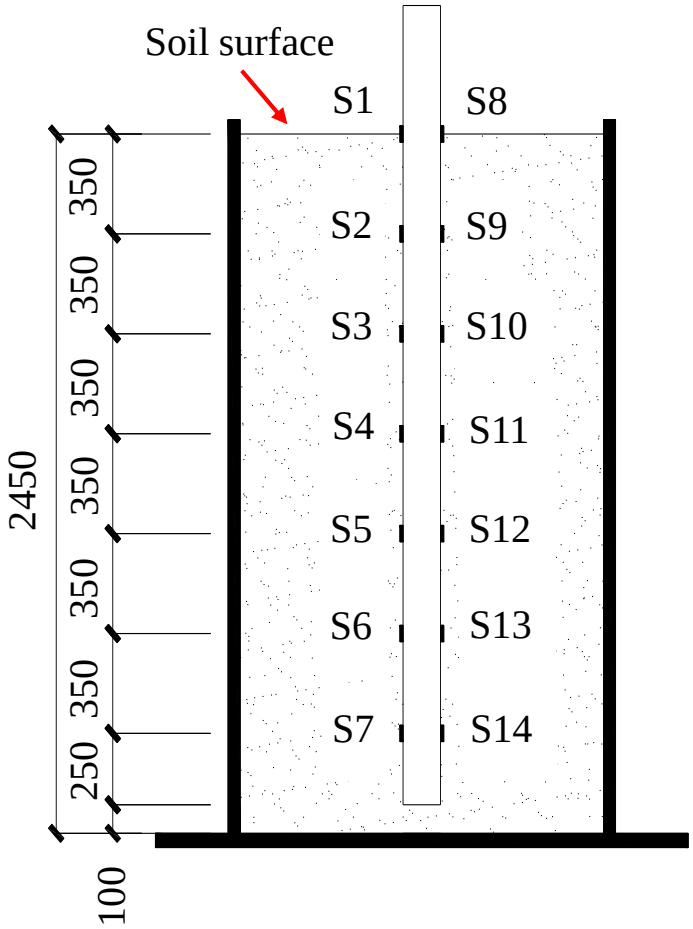
- Soil Container (rigid box)
  - Circular
  - Height of 2.5m
  - Diameter of 1.5m
  - Wall thickness of 10mm
  - 4 diagonal braces

- Soil (medium dense sand)
  - Sand from Min River

Water Content (%)	Density (g/cm^3)	void ratio	Internal friction angle (°)	Average SPT blow count
4.6	1.90	0.59	35	11

2. Testing introduction

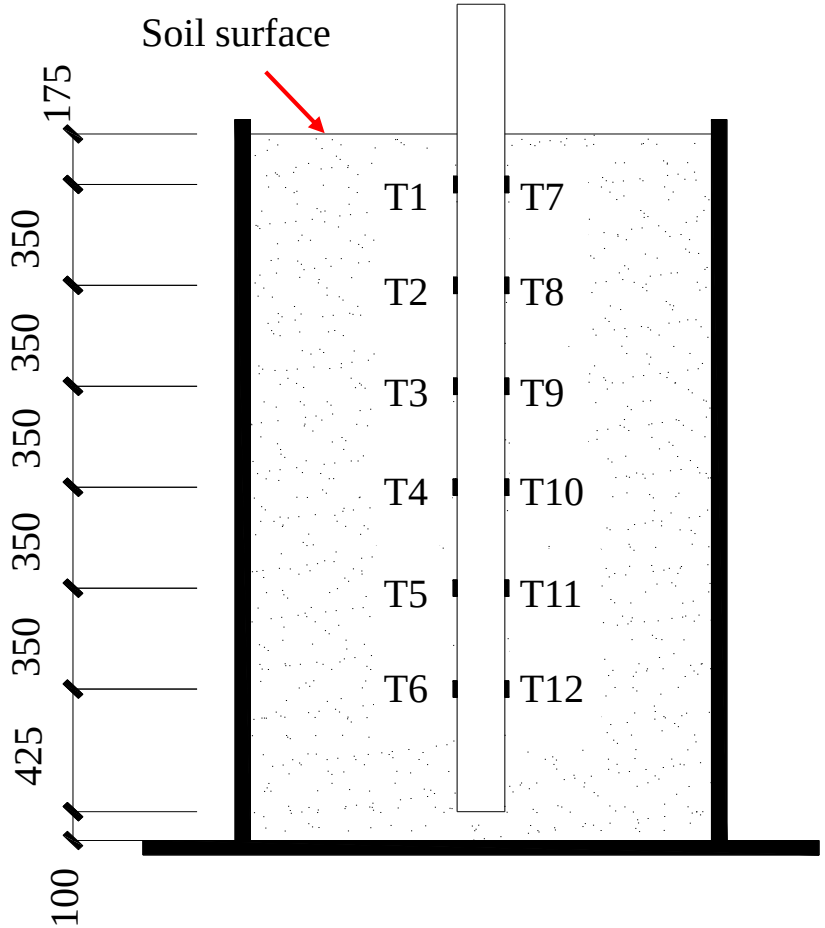
- Sensor arrangement
  - Strain gages



14 strain gages were installed on piles with an equal spacing of 350mm, labeled as S1 to S14.

2. Testing introduction

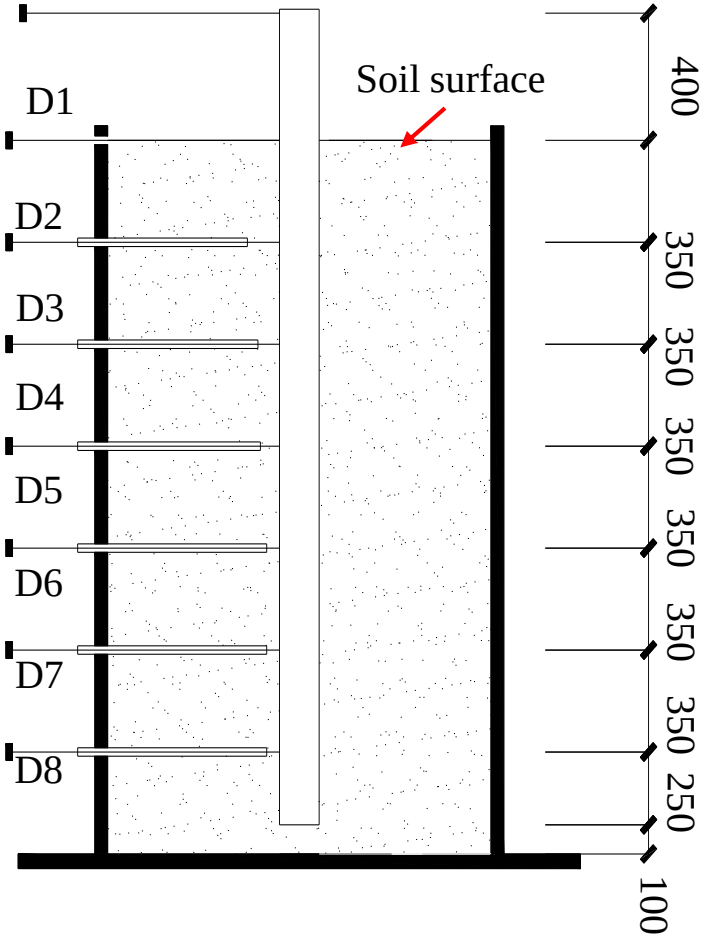
- Sensor arrangement
  - Earth pressure cells



12 earth pressure cells were installed on piles with an equal spacing of 350mm, labeled as T1 to T12.

2. Testing introduction

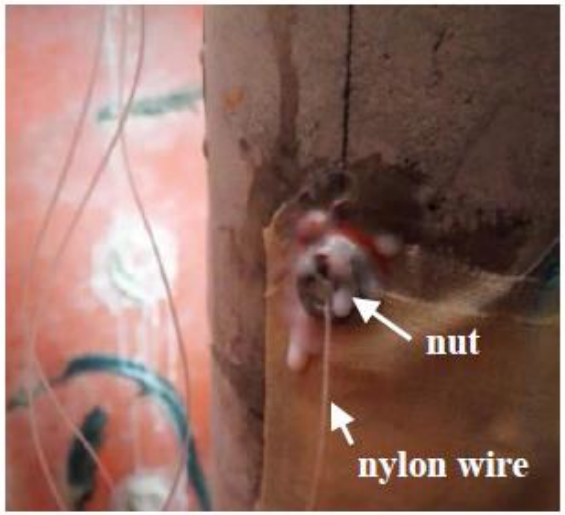
- Sensor arrangement
  - Displacement meters



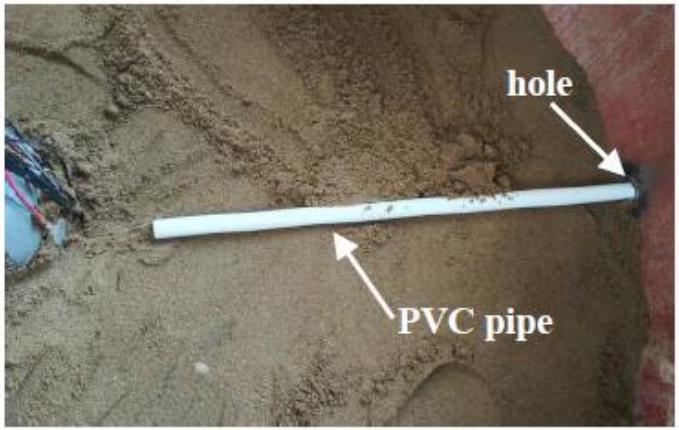
8 displacement meters were installed, labeled as D1 to D8.

2. Testing introduction

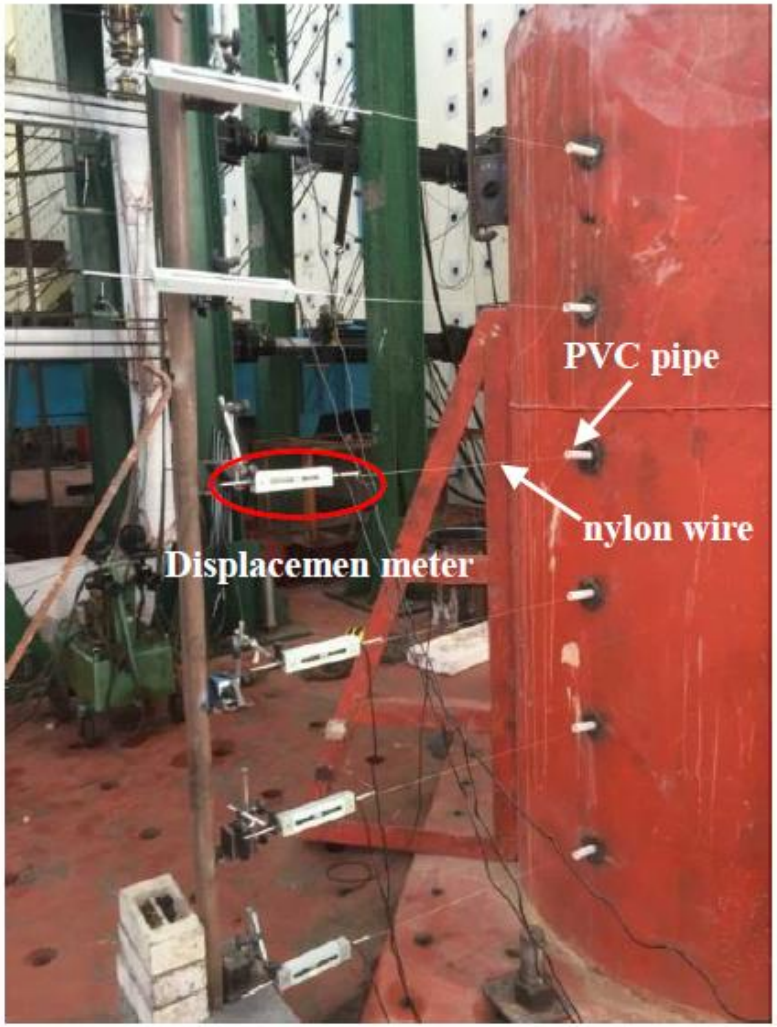
- Method of displacement meters placement



（a）test points



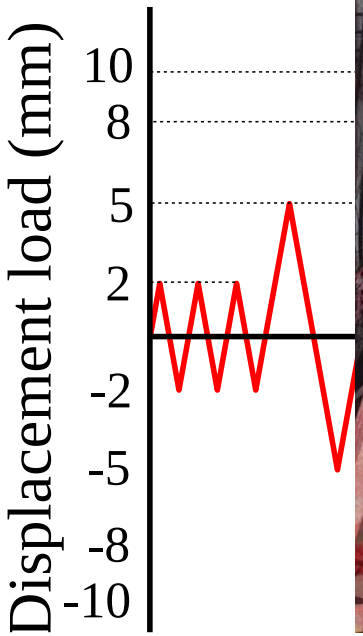
（b）PVC casing pipe

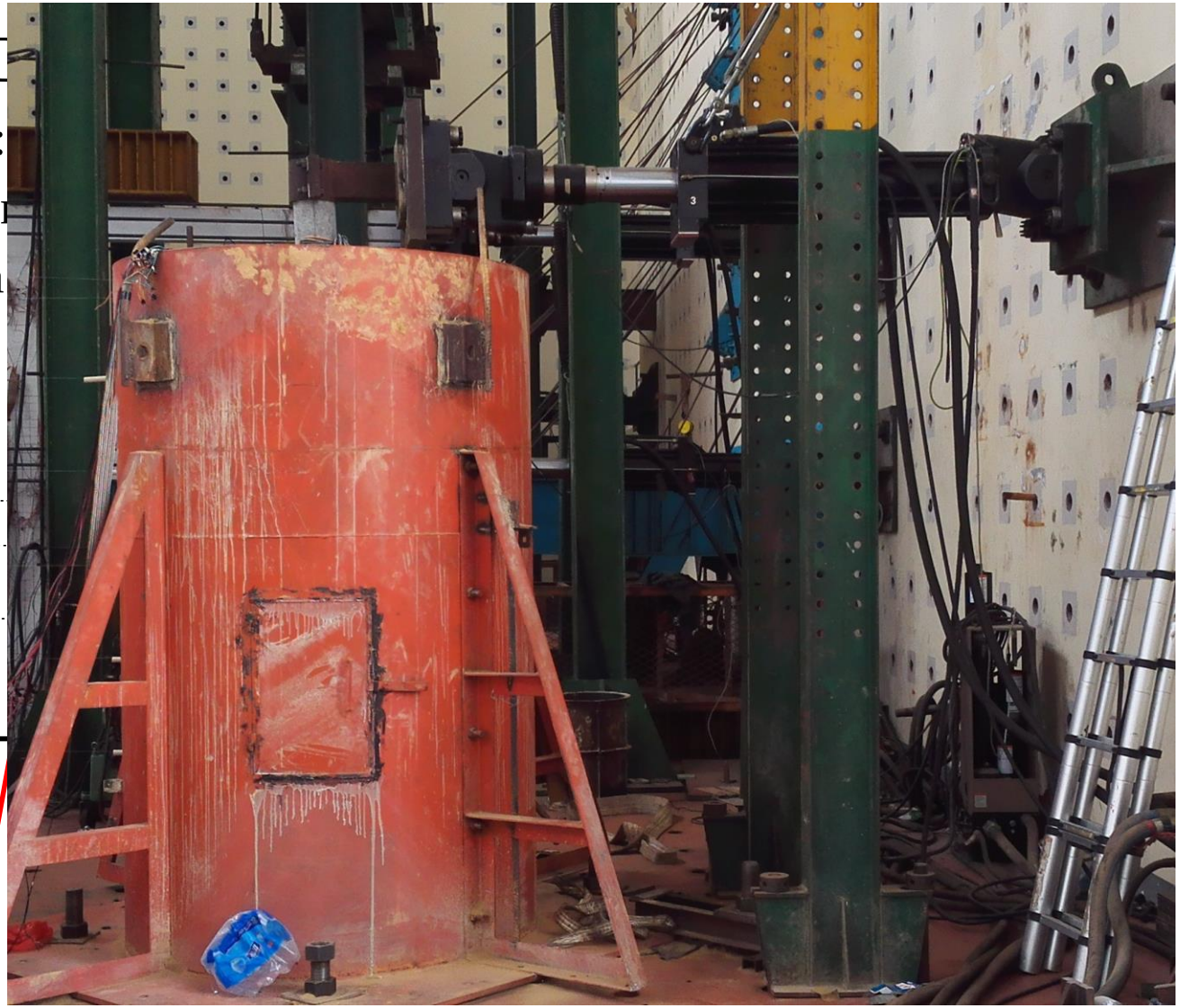


（c）displacement meters

2. Testing introduction

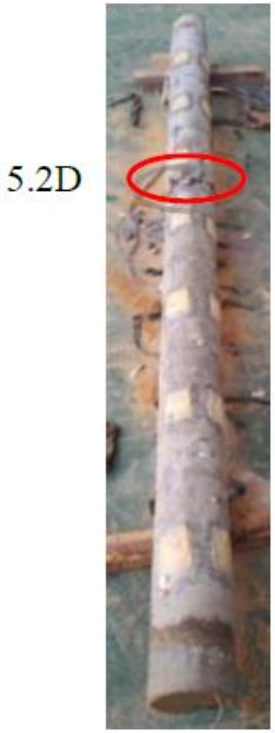
- Loading（I
  - Initial stage:
  - 10mm to 30
  - After 30mm decreases to
  - Load speed:





3. Testing Results

3.1 Failure modes

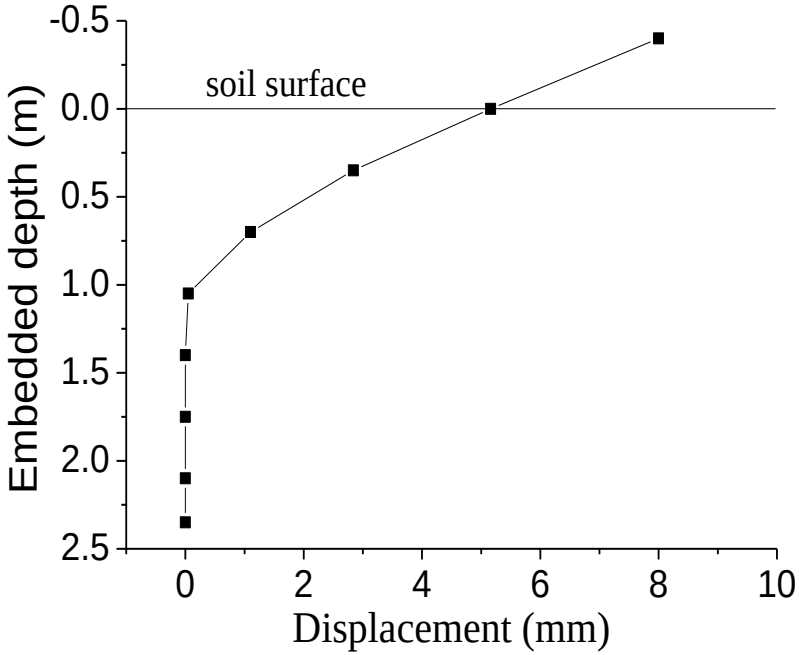


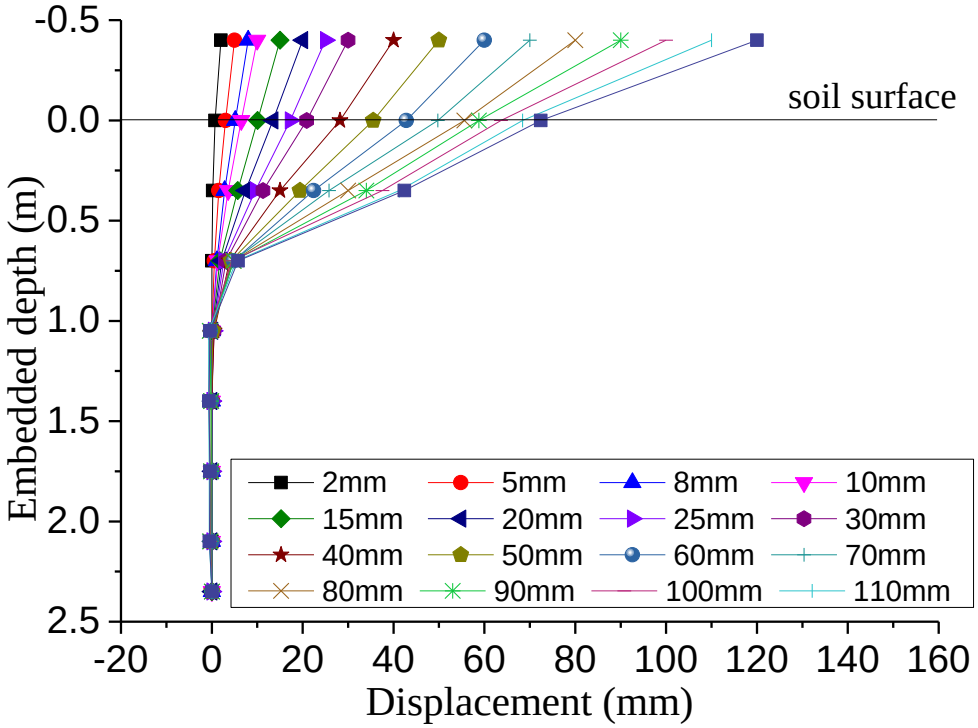
PHC-2

PHC-4

3. Testing Results

3.2 Displacement

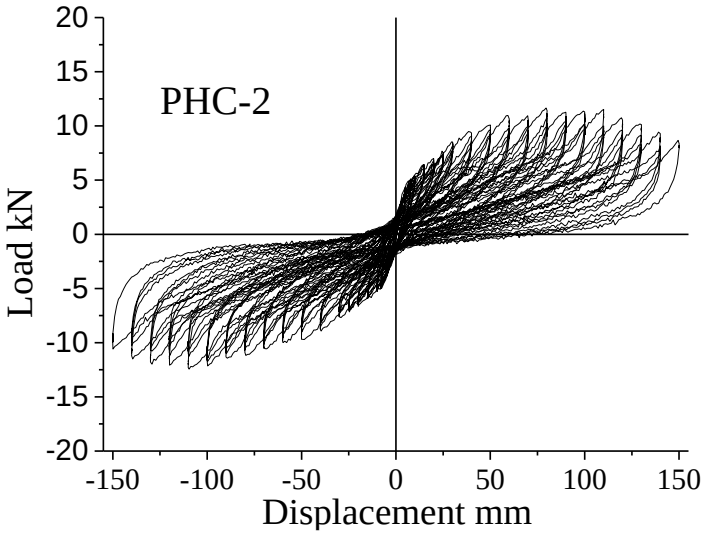


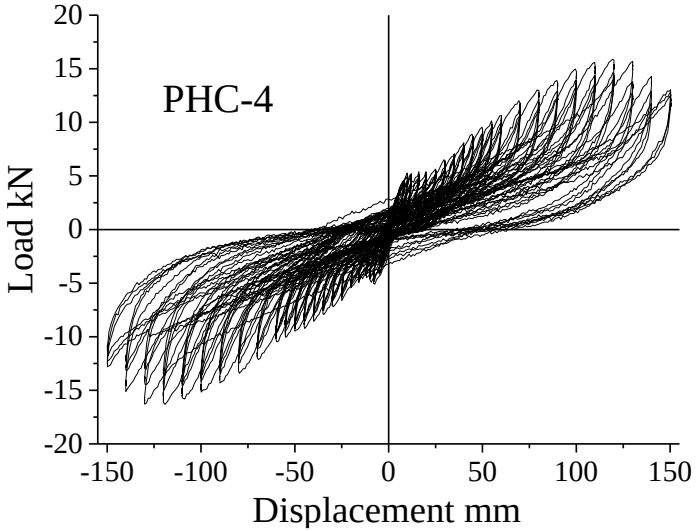


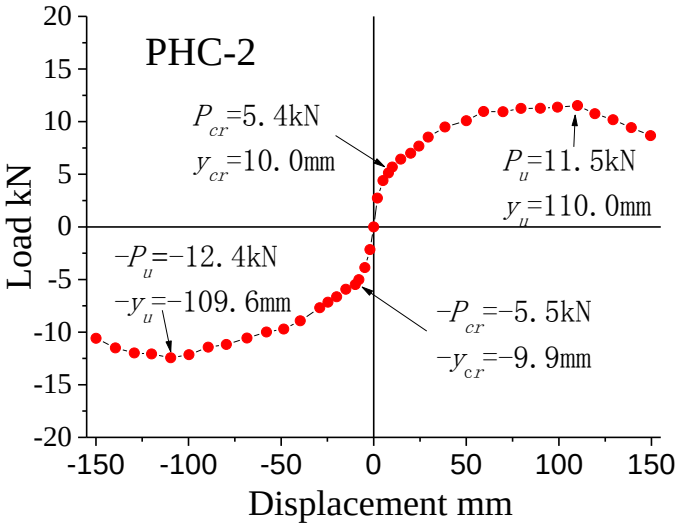
PHC-4

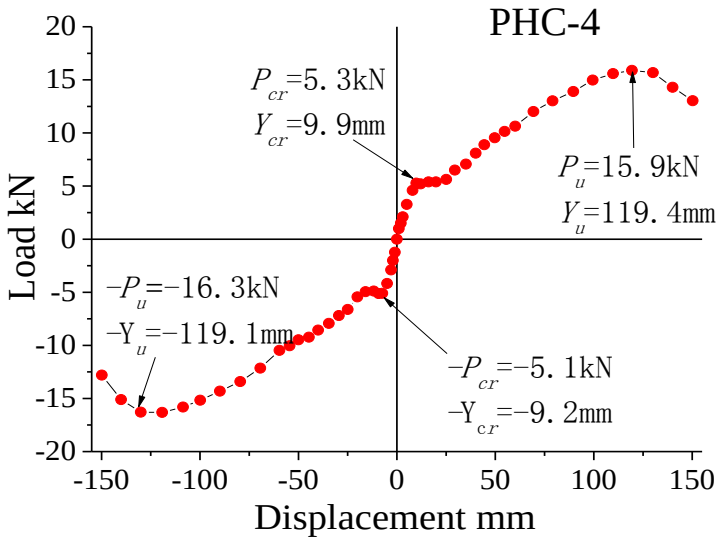
3. Testing Results

3.3 Hysteretic curve and skeleton curve



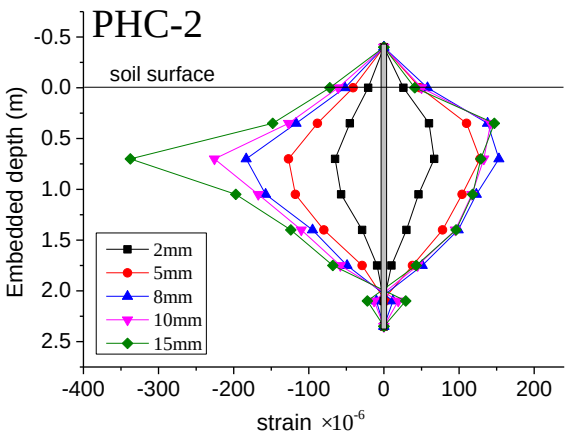


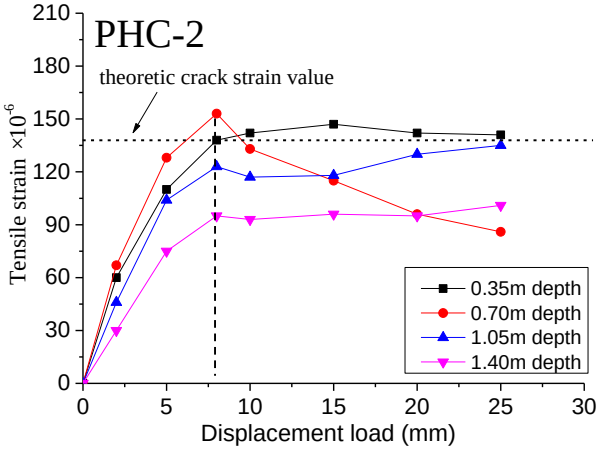


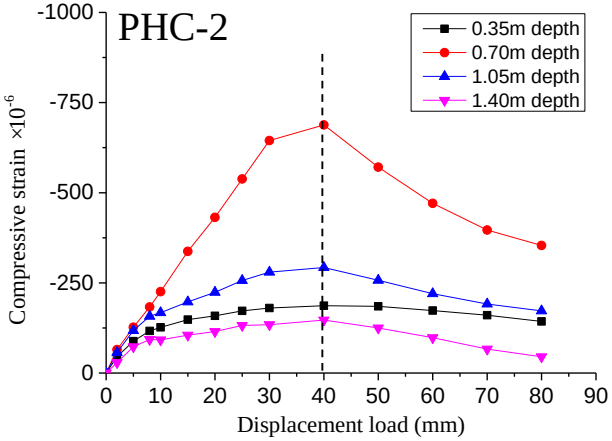


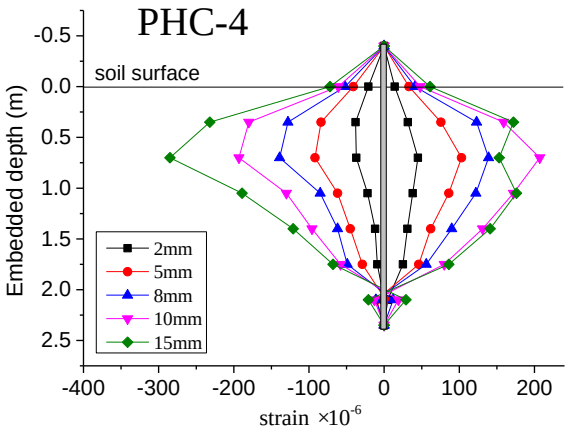
3. Testing Results

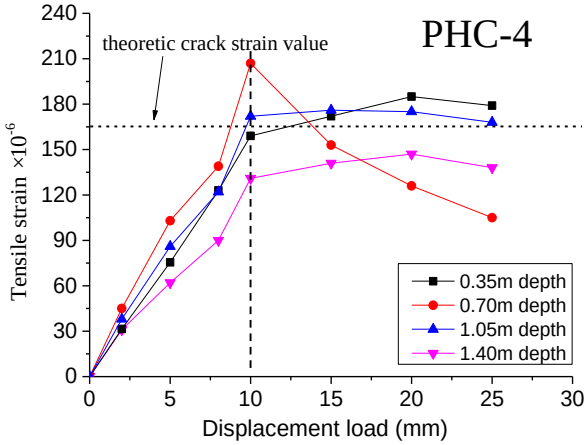
3.4 Strain distribution and strain history

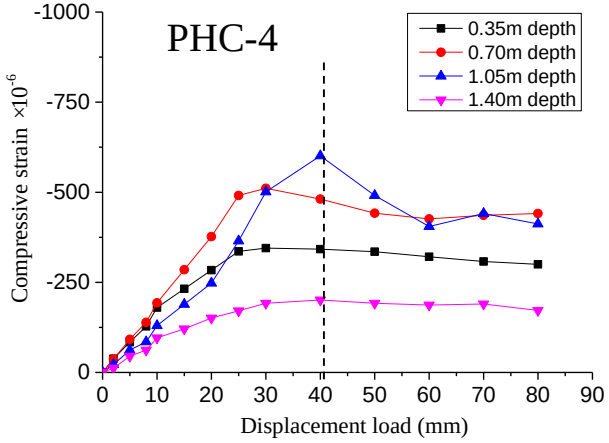






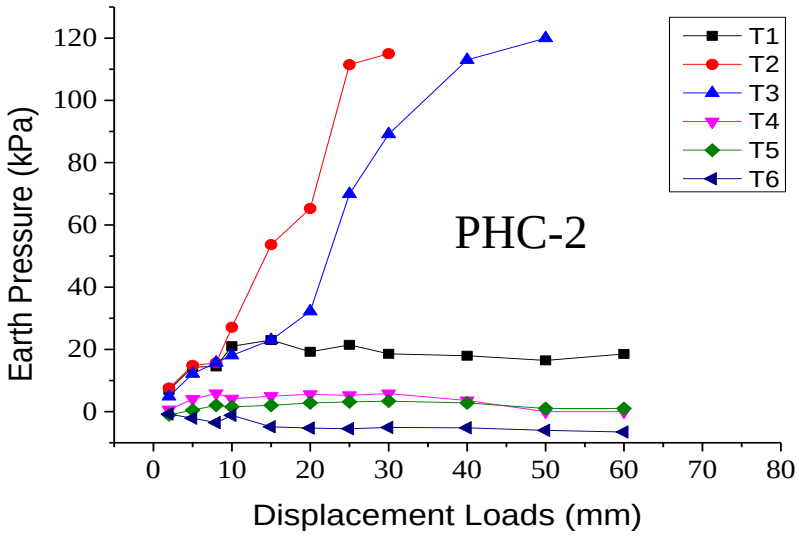


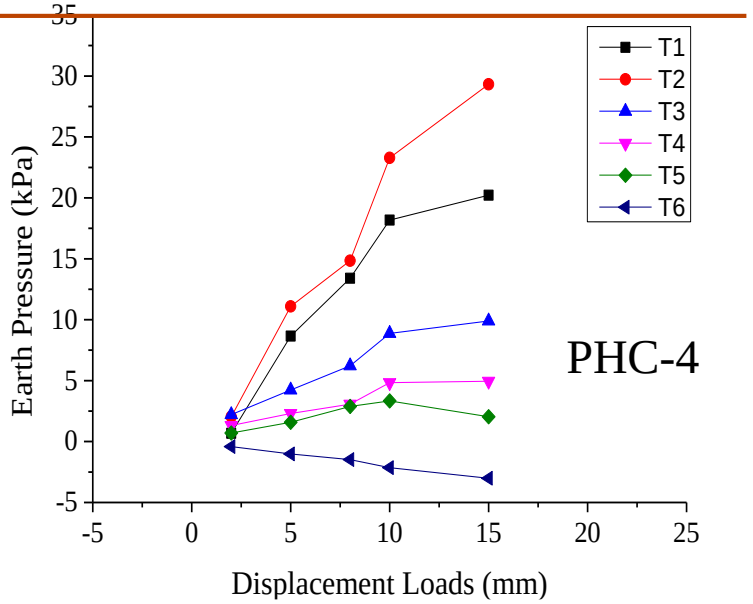


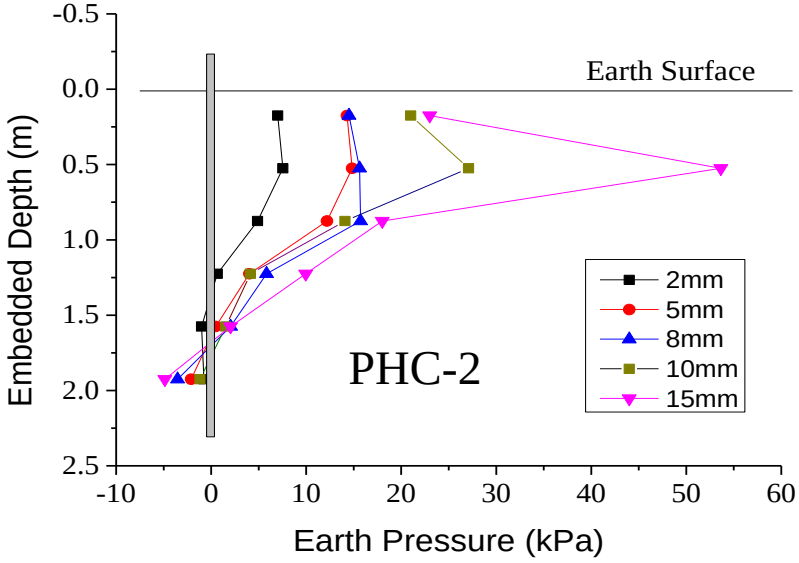


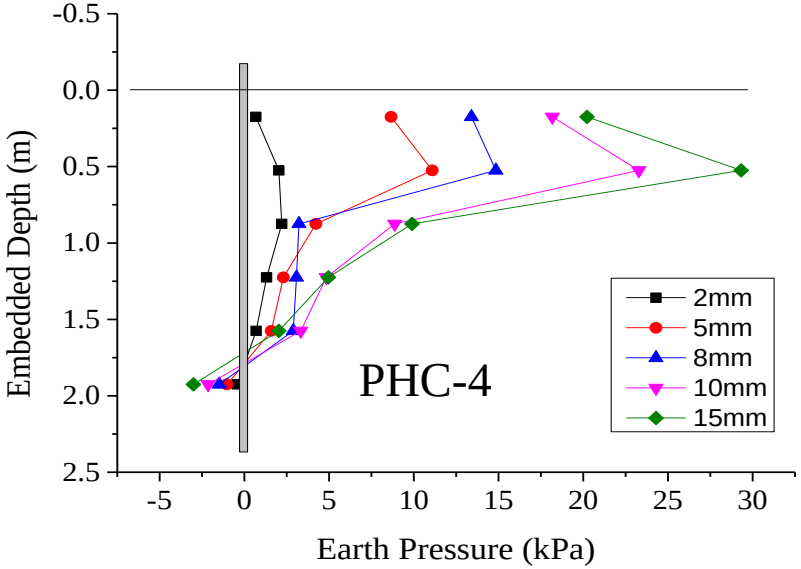
3. Testing Results

3.5 Pile soil pressure









4. Calculation on pile-soil interaction

4.1 Soil pressure calculate

API

$$P_u = \min\left[(C_1 z/d + C_2)\gamma_s z,\quad C_3\gamma_s z\right]$$

Reese LFP

$$P_u = A\gamma_s z[K_s \cdot \frac{z}{D} \cdot \frac{\tan\phi \cdot \sin\beta}{\tan(\beta-\phi)\cdot\cos a} + \frac{\tan\beta}{\tan(\beta-\phi)}(1+\frac{z}{D}\cdot\tan\beta\cdot\tan a)+$$

$$K_s \cdot \frac{z}{D}\cdot\tan\beta(\tan\phi\sin\beta-\tan a)-K_a]$$

Broms

$$P_u = 3\gamma_s K_p D z$$

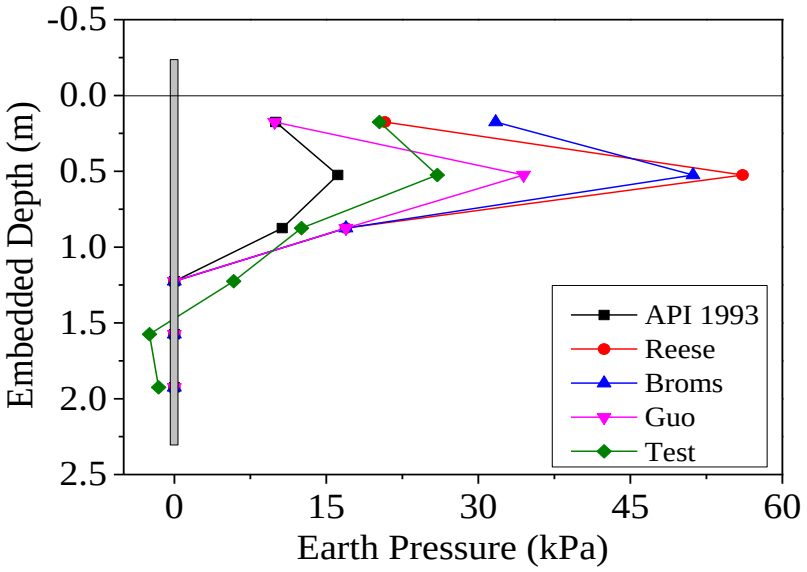
Guo

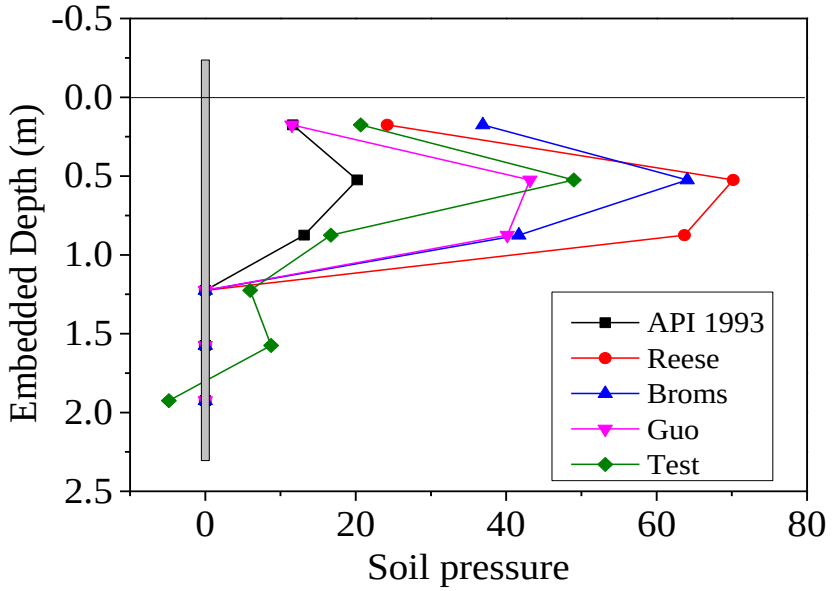
$$P_u = \gamma_s S_r K_p^2 D^{2-n}(z+a_0)^n$$

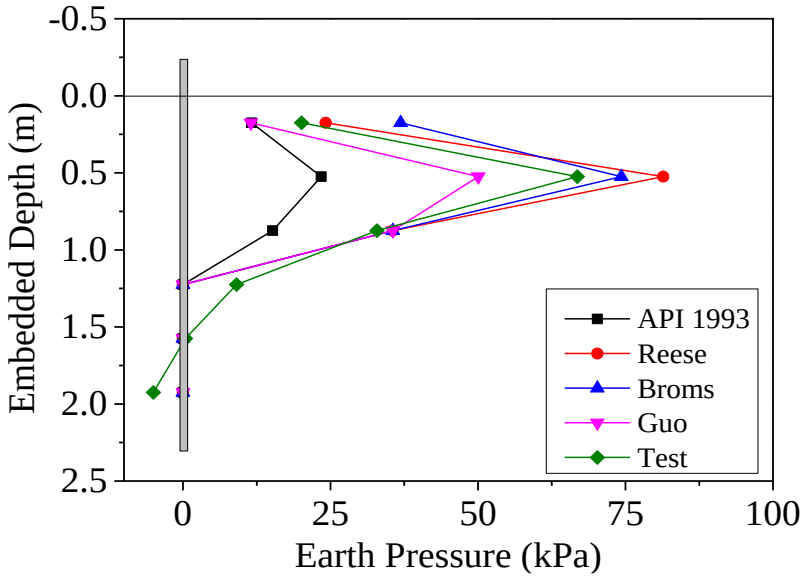
“m”

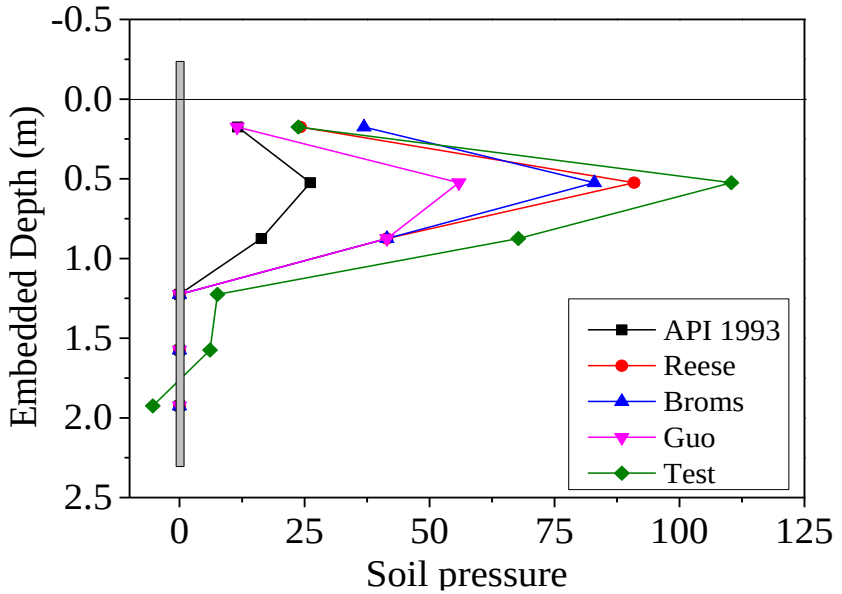
$$P_u = m\cdot z\cdot y_z$$

4. Calculation on pile-soil interaction

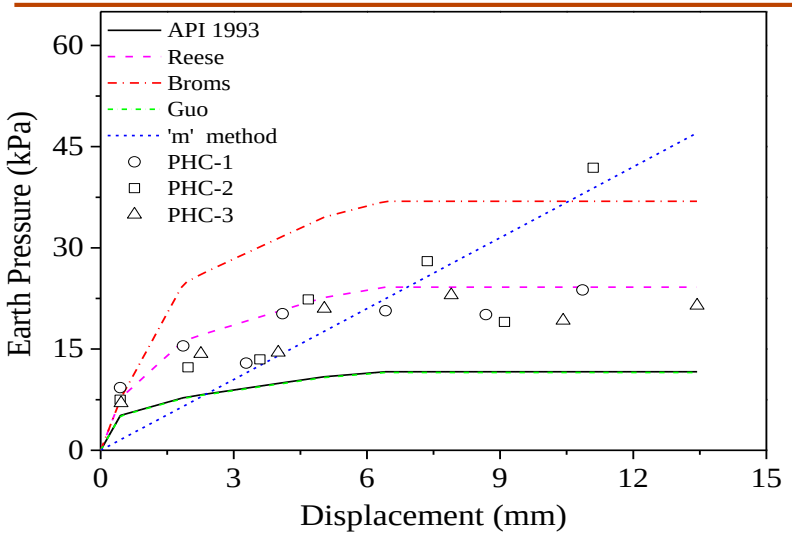




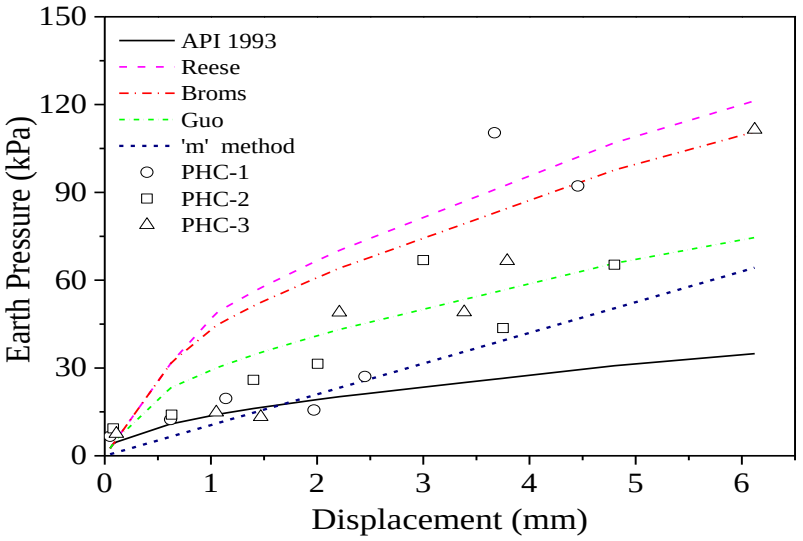




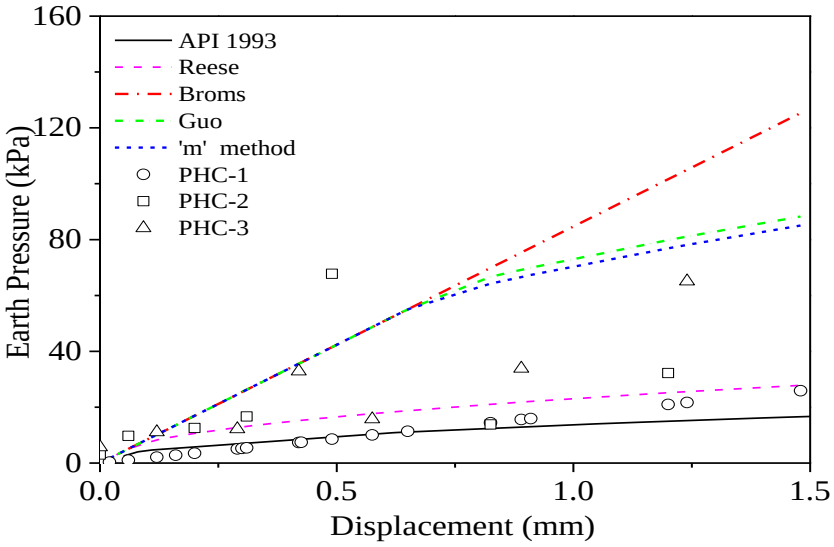
4. Calculation on pile-soil interaction



Deep in 0.175m



Deep in 0.875m



Deep in 1.25m

$$P_u = \begin{cases} A\gamma_s z[K_s \cdot \dfrac{z}{D} \cdot \dfrac{\tan\phi \cdot \sin\beta}{\tan(\beta-\phi)\cdot\cos a} + \dfrac{\tan\beta}{\tan(\beta-\phi)}(1+\dfrac{z}{D}\cdot\tan\beta\cdot\tan a) \\ \qquad + K_s \cdot \dfrac{z}{D}\cdot\tan\beta(\tan\phi\sin\beta - \tan a) - K_a] \\ \gamma_s S_r K_p^2 D^{2-n}(z+a_0)^n \\ \min\left[(C_1 z + C_2 D)\gamma_s z, \quad C_3\gamma_s z\right] \end{cases}$$

4. Calculation on pile-soil interaction

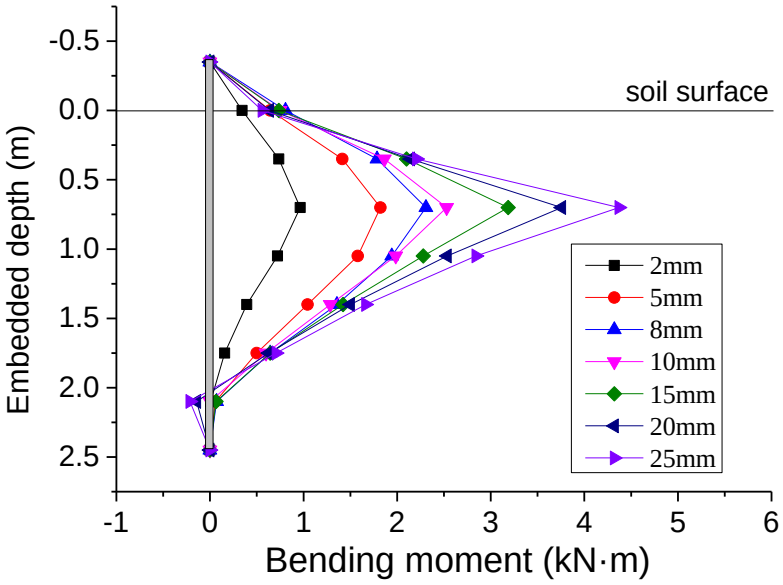
4.2 Bending moment

$$M = \frac{EI \bullet \Delta\varepsilon}{D}$$

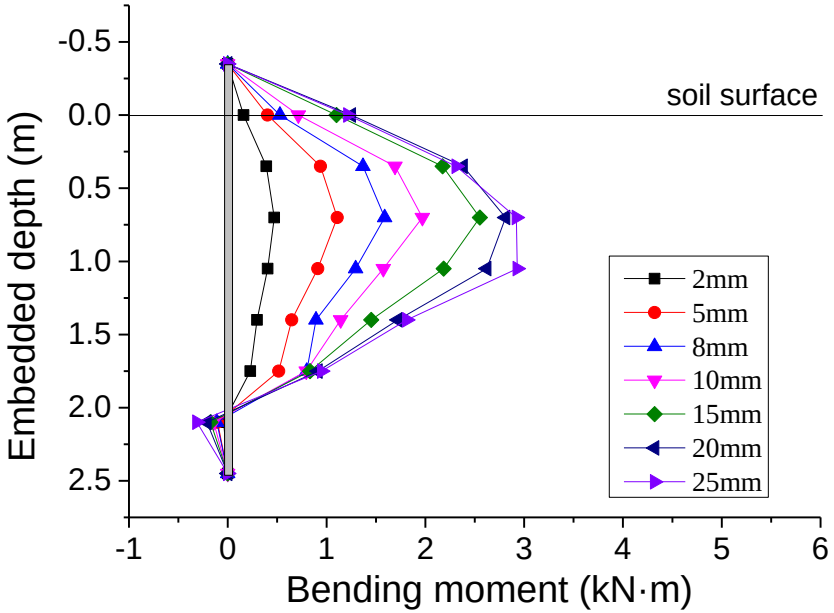
Strain ⟹ Bending moment of pile

When the pile is elastic

$$M = \frac{EI\Delta\varepsilon}{D} = EId^2y/d^2z$$ ⟹ Get displacement by quadratic integral of bending curvature



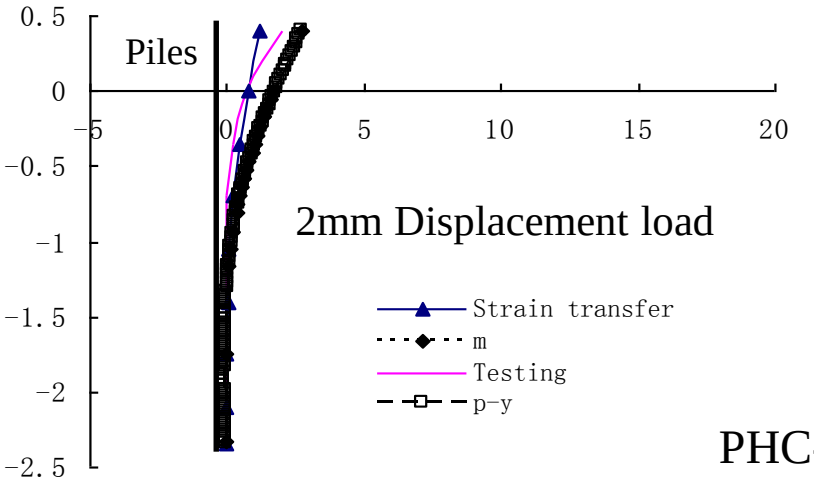
PHC-2



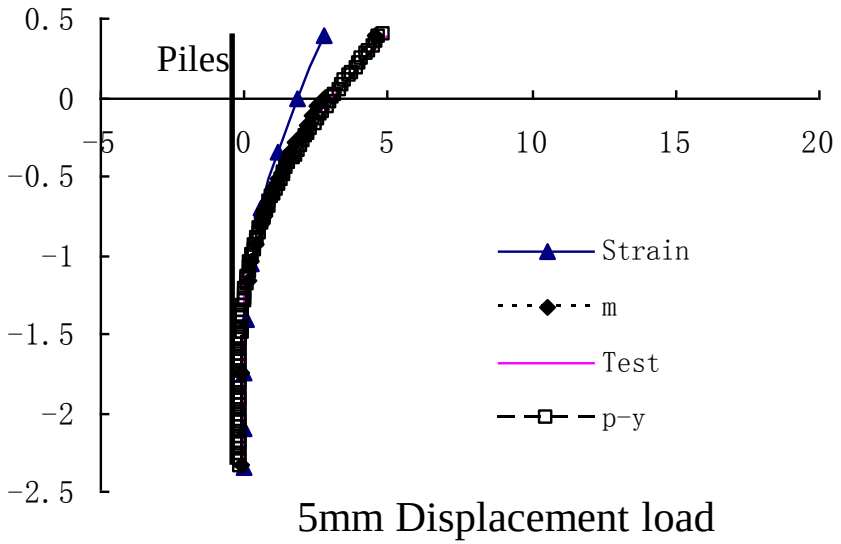
PHC-4

4. Calculation on pile-soil interaction

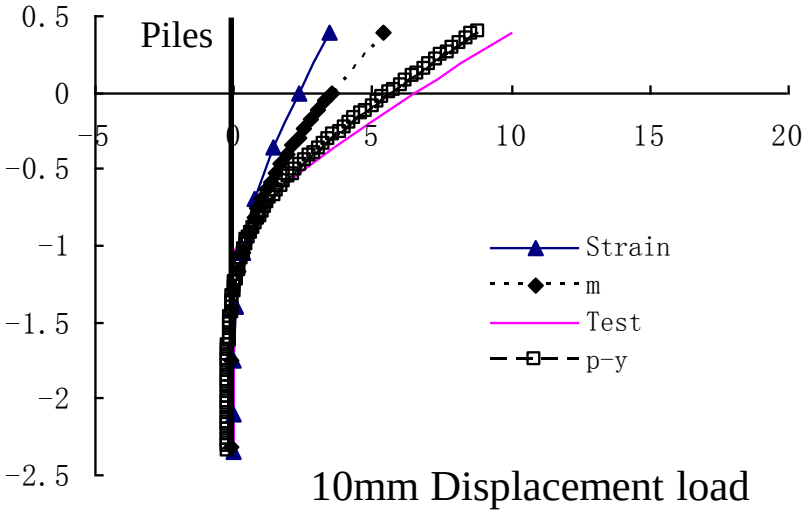
4.3 Displacement comparisons



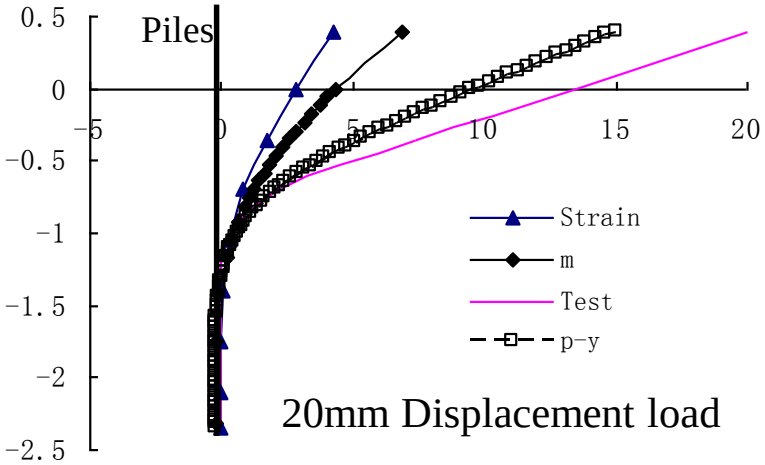
PHC-4



5mm Displacement load



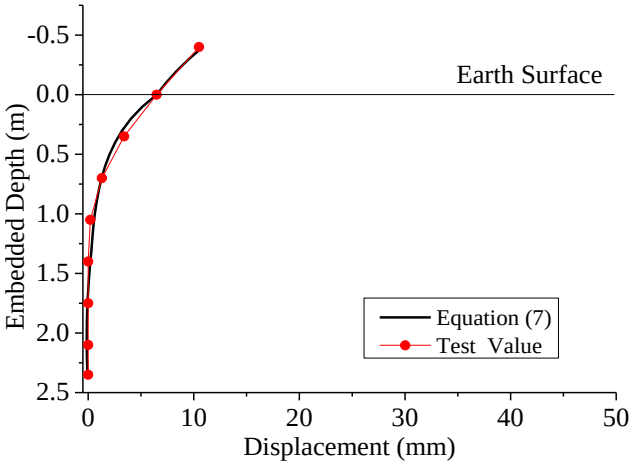
10mm Displacement load



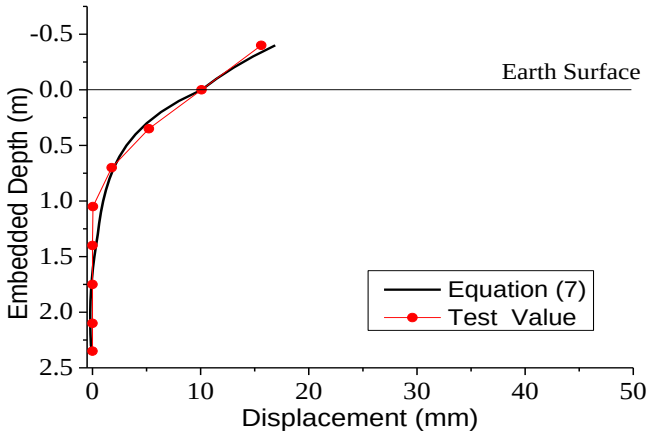
20mm Displacement load

4. Calculation on pile-soil interaction

4.2 New displacement method

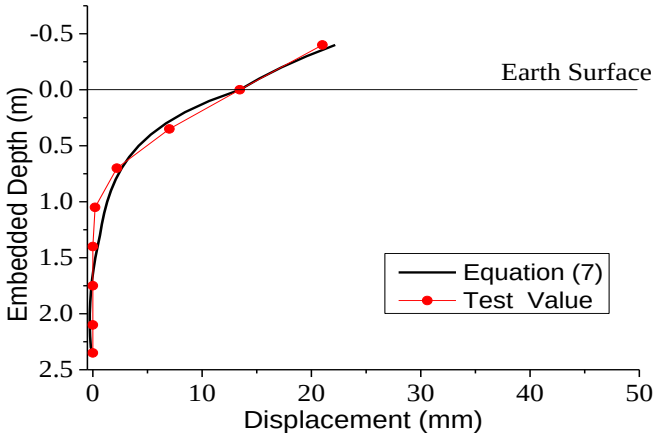


（a）10mm Displacement load

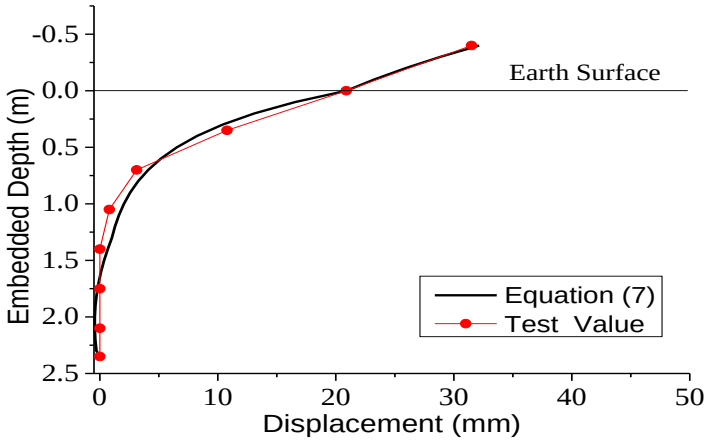


（b）15mm Displacement load

PHC-4



（c）20mm Displacement load



（d）30mm Displacement load

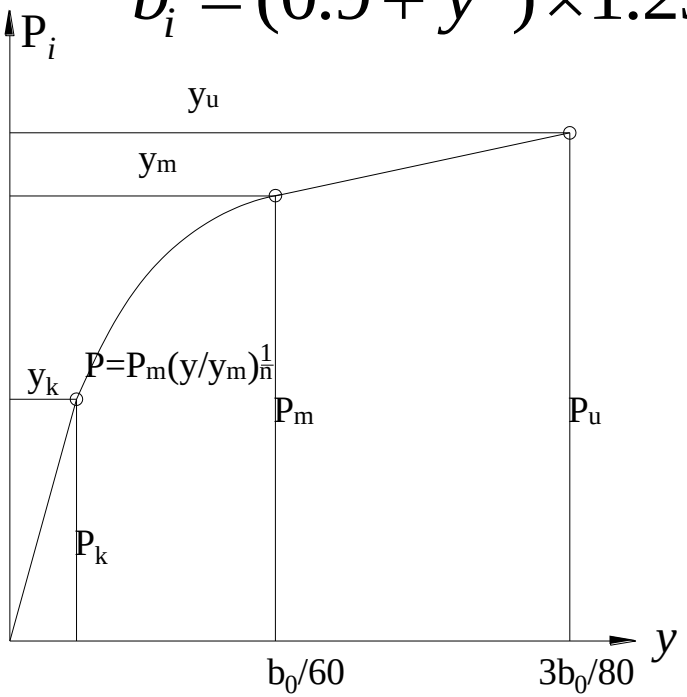
4. Calculation on pile-soil interaction

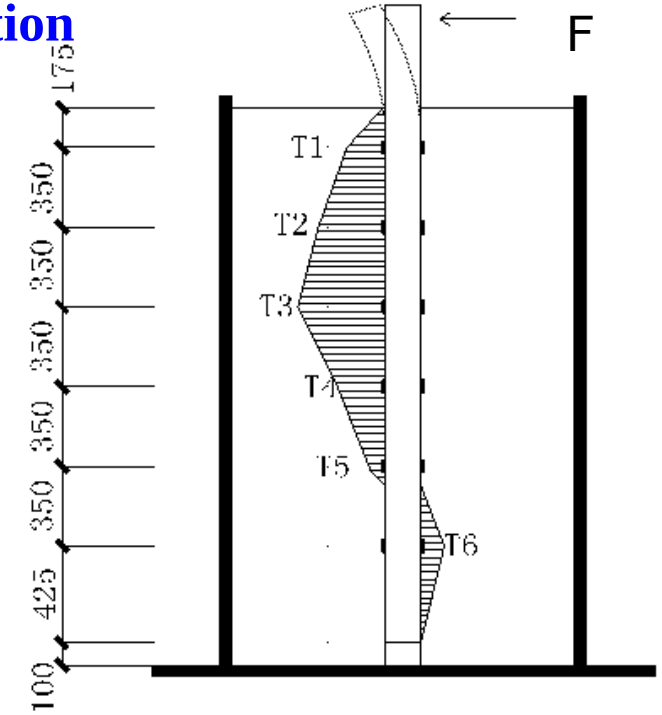
4.3 Simple calculation on pile-soil interaction

$$F = \sum_{i=1}^{6} T_i$$

$$T_i = P_i \times \Delta Z \times b_i$$

$$b_i = (0.9 + y^n) \times 1.25 \times D$$





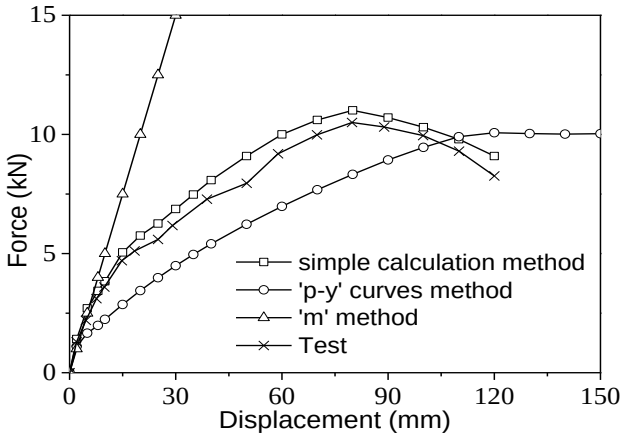
$$p_k = k_h y_k \frac{z}{D}$$

$$p_i = p_m \left(\frac{y}{y_m}\right)^{1/n}$$

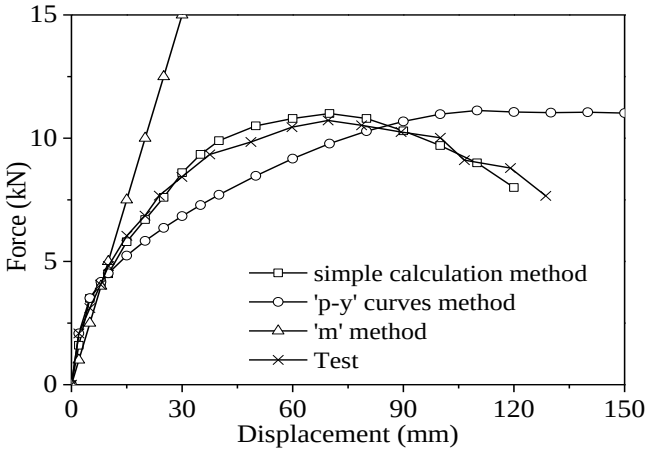
$$p_i = \frac{(p_u - p_m)y + (p_m y_u - p_u y_m)}{y_u - y_m}$$

4. Calculation on pile-soil interaction

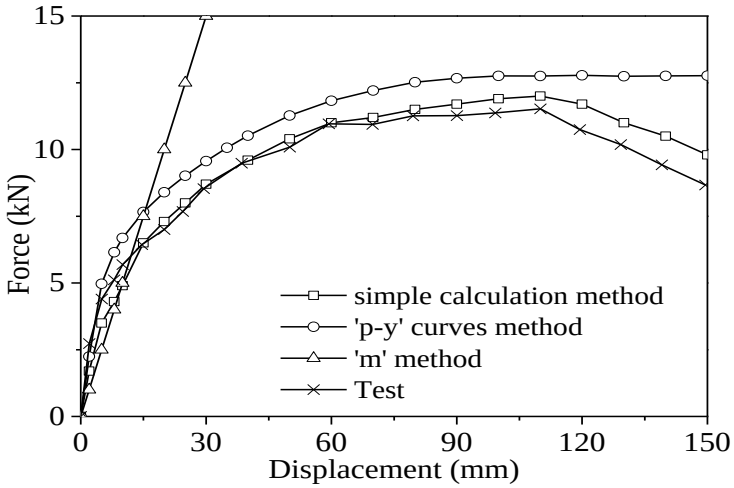
4.4 Results comparisons



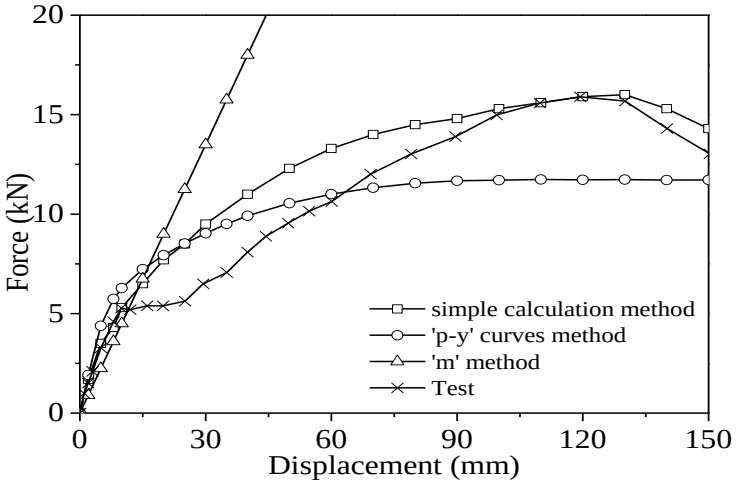
（a）PHC-1



（b）PHC-2

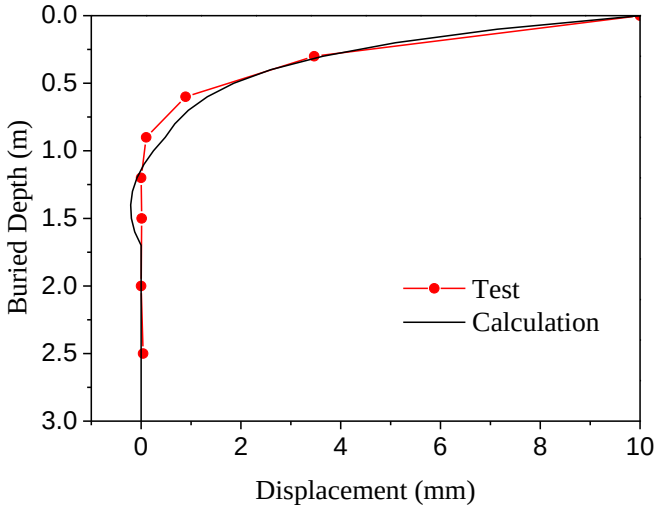


（c）PHC-3

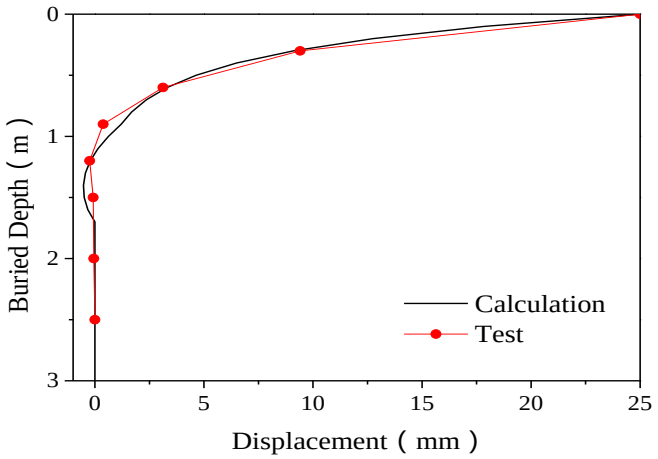


（d）PHC-4

4. Calculation on pile-soil interaction

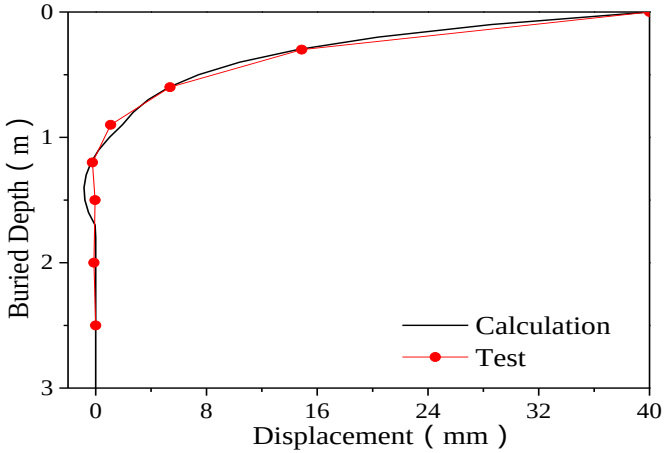


(a) 10mm Displacement Loading

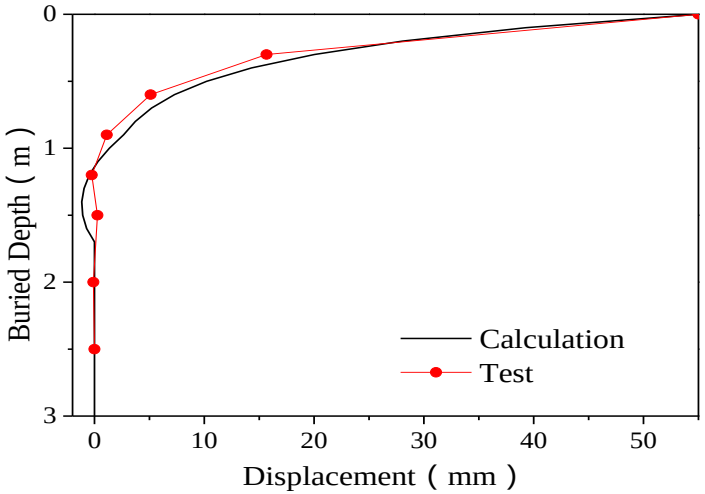


(b) 25mm Displacement Loading

Fan(2014)

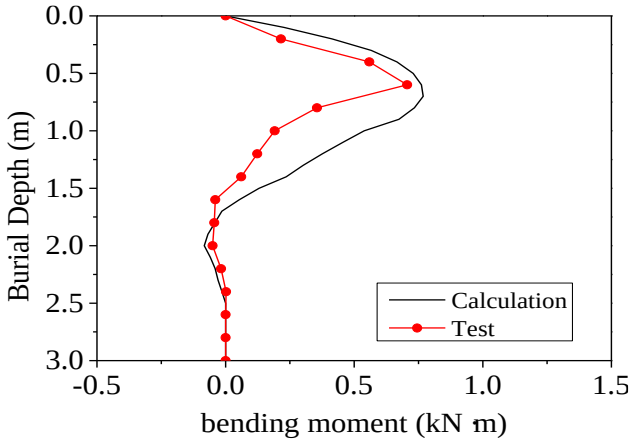


(c) 40mm Displacement Loading

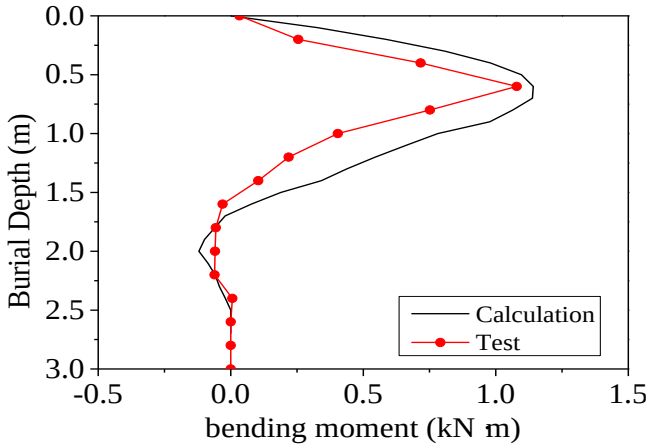


(d) 55mm Displacement Loading

4. Calculation on pile-soil interaction

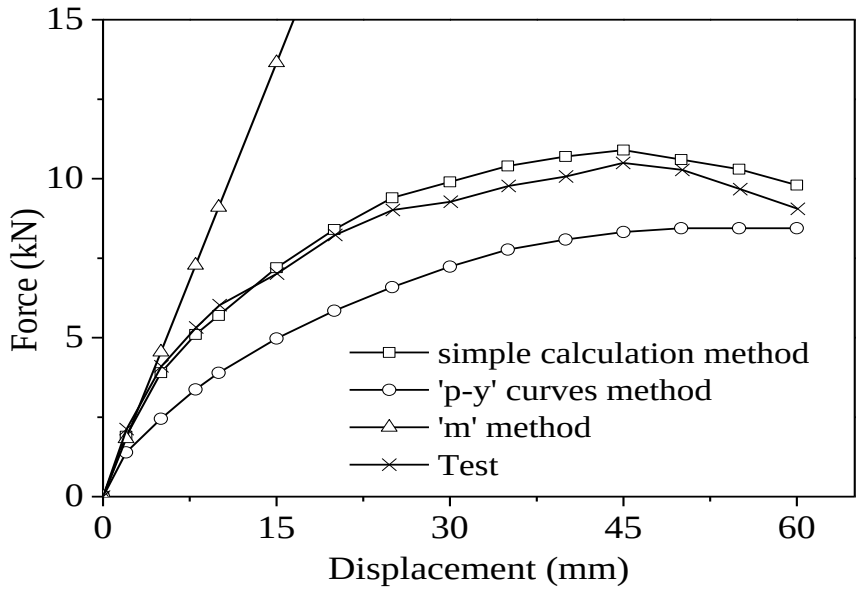


(a) 5mm Displacement load



(b) 10mm Displacement Load

Fan(2014)



5. Conclusion

- Maximal bending moment locates at 5.0D to 6.0D embedded depth, concrete of pile cracks around this area primarily.
- Degree of prestress and reinforcement ratio has a significant influence on failure mode of PHC piles.
- There are four stages for PHC piles: (1) elastic stage when the displacement of pile head below 8mm~10mm. (2) Concrete of tensile zone cracked, which means soil-pile system become elastic-plastic. (3) Reaching 40mm displacement load, concrete of compressive zone are out of work, stiffness of pile decreases gradually. After that, soil-pile separation has a significant influence. (4) failure stage: lateral bearing capacity drops dramatically.
- The test indicate that the distribution law of soil pressure is that with the change of pile depth, the side earth pressure of pile increased first and then decreased, and reversed in a certain depth.

5. Conclusion

- PHC piles performs a good plastic property and deformation ability considering soil-pile interaction, which is a suitable type used in IJB.
- With the increase of displacement loads, the pressure of shallow soil grows faster and its maximum is close to the limit passive earth pressure, while that of the deep soil is relatively slow or even increase reversely.
- It can be seen that the transformation method and the 'm' method to calculate the horizontal deformation of pile are not accurate for nonlinear elastic and larger deformation. Although the 'p-y' curves method takes the non-linear effects of soil into account , there still exists a large error in calculating the large deformation value.
- The horizontal displacement calculation method of pile-soil interaction that obtained by tests can calculate precisely and accurately the pile displacement.

Thanks for your attention!