Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)

Cite this as: Ling-gang Kong, Zhong-chang Zhang, Yun-min Chen, 2020. Nonlinear analysis of pile groups subjected to combined lateral and torsional loading. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 21(3):179-192.
https://doi.org/10.1631/jzus.A1900590

Nonlinear analysis of pile groups subjected to combined lateral and torsional loading

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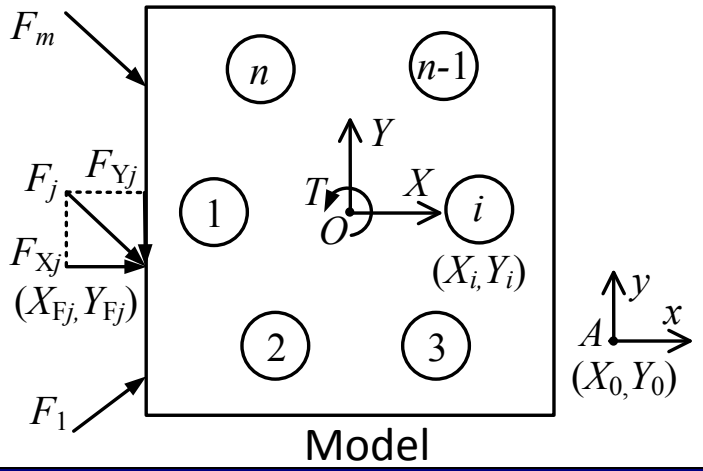
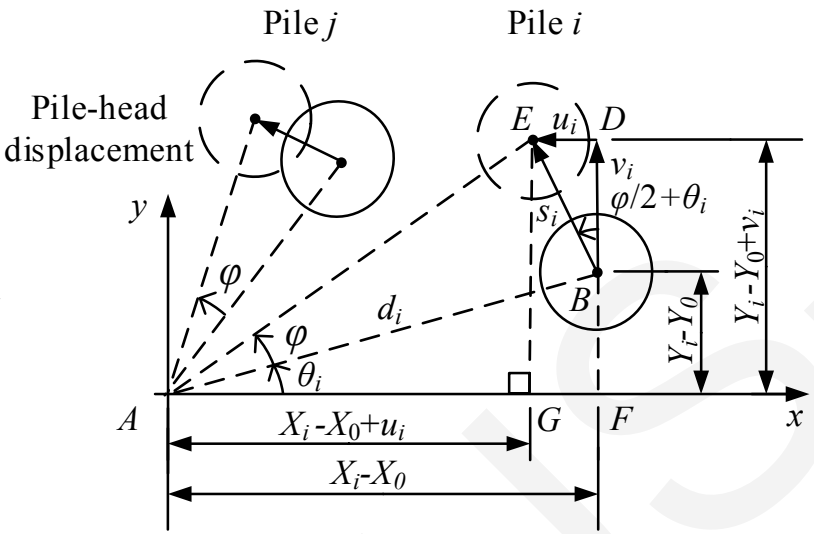
Key words: Combined lateral and torsional loading, Pile groups, Twist center, *p*-multiplier, Group effect



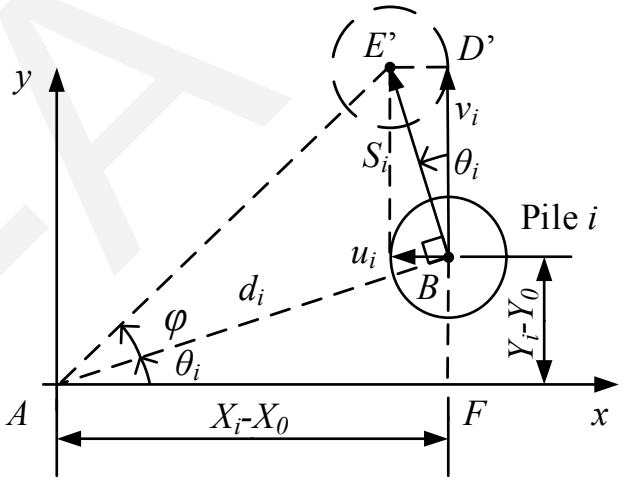
Model

Method of analysis

Pile-head displacements relation is built in these two situations.



Exact Solution



Approximate Solution

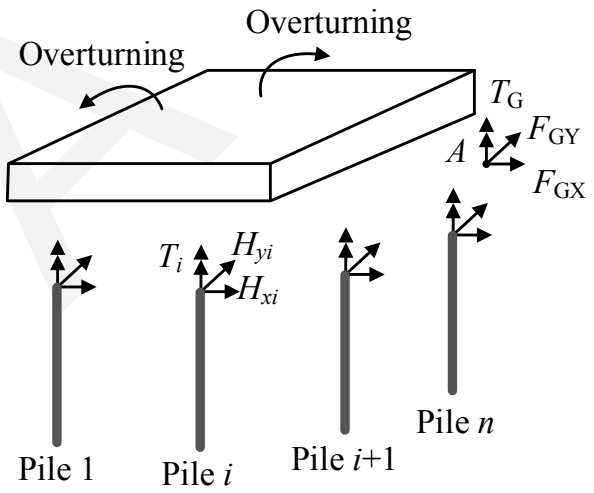
$$\begin{cases} u_i = \dfrac{(Y_i - Y_0)\cos(\dfrac{\varphi}{2}) + (X_i - X_0)\sin(\dfrac{\varphi}{2})}{(Y_{\mathrm{R}} - Y_0)\cos(\dfrac{\varphi}{2}) + (X_{\mathrm{R}} - X_0)\sin(\dfrac{\varphi}{2})} u_{\mathrm{R}}, \\ v_i = \dfrac{(X_i - X_0)\cos(\dfrac{\varphi}{2}) - (Y_i - Y_0)\sin(\dfrac{\varphi}{2})}{(X_{\mathrm{R}} - X_0)\cos(\dfrac{\varphi}{2}) - (Y_{\mathrm{R}} - Y_0)\sin(\dfrac{\varphi}{2})} v_{\mathrm{R}}. \end{cases}$$

$$\begin{cases} u_i \doteq \dfrac{Y_i - Y_0}{X_0 - X_R} v_R, \\ v_i \doteq \dfrac{X_i - X_0}{X_R - X_0} v_R. \end{cases}$$

Method of analysis

Simplified Static Equilibrium Equation of pile cap

$$\begin{cases} \dfrac{v_{\mathrm{R}}}{X_0 - X_{\mathrm{R}}} \displaystyle\sum_{i=1}^{n} K_{\mathrm{H}i}(Y_i - Y_0) = F_{\mathrm{GX}}, \\ \dfrac{v_{\mathrm{R}}}{X_0 - X_{\mathrm{R}}} \displaystyle\sum_{i=1}^{n} K_{\mathrm{H}i}(X_0 - X_i) = F_{\mathrm{GY}}, \\ \dfrac{v_{\mathrm{R}}}{X_0 - X_{\mathrm{R}}} \displaystyle\sum_{i=1}^{n} \{K_{\mathrm{H}i}[(X_0 - X_i)^2 + (Y_i - Y_0)^2] + K_{\mathrm{T}i}\} \\ = \displaystyle\sum_{j=1}^{m} [F_{\mathrm{Y}j}(X_{\mathrm{F}j} - X_0) - F_{\mathrm{X}j}(Y_{\mathrm{F}j} - Y_0)] + T. \end{cases}$$



Solution

$$\begin{cases} X_0 = \dfrac{b}{a} - \dfrac{F_{\mathrm{GY}}(ag + ah + ad - b^2 - c^2)}{acF_{\mathrm{GX}} - abF_{\mathrm{GY}} + a^2q - a^2r + a^2T}, \\ Y_0 = \dfrac{c}{a} + \dfrac{F_{\mathrm{GX}}(ag + ah + ad - b^2 - c^2)}{acF_{\mathrm{GX}} - abF_{\mathrm{GY}} + a^2q - a^2r + a^2T}, \\ v_{\mathrm{R}} = \dfrac{F_{\mathrm{GY}}}{a} \\ \quad - \dfrac{(b - aX_{\mathrm{R}})(cF_{\mathrm{GX}} - bF_{\mathrm{GY}} + aq - ar + aT)}{a^2g + a^2h + a^2d - ab^2 - ac^2}, \end{cases}$$

$$a = \sum_{i=1}^{n} K_{\mathrm{H}i}, \quad g = \sum_{i=1}^{n} K_{\mathrm{H}i} X_i^2,$$

$$b = \sum_{i=1}^{n} K_{\mathrm{H}i} X_i, \quad h = \sum_{i=1}^{n} K_{\mathrm{H}i} Y_i^2,$$

$$c = \sum_{i=1}^{n} K_{\mathrm{H}i} Y_i, \quad q = \sum_{j=1}^{m} F_{\mathrm{Y}j} X_{\mathrm{F}j},$$

$$d = \sum_{i=1}^{n} K_{\mathrm{T}i}, \quad r = \sum_{j=1}^{m} F_{\mathrm{X}j} Y_{\mathrm{F}j}.$$

Method of analysis

Generalized *p*-multiplier of pile *i* (Kong et al., 2019)

$$f_{mi} = \beta_{1i}\beta_{2i}\ldots\beta_{ji}\ldots\beta_{ni}\ (j \neq i),$$

$$\beta_l = \begin{cases} b_l - \dfrac{b_l - a_l}{|\theta_c|}\sqrt{\theta_c^2 - \theta^2} \\ \qquad (0 > \theta \geq \theta_c \ \text{ or } \ \theta_c \geq \theta \geq 0) \\ 1 \quad (0 > \theta_c \geq \theta \geq -90^\circ \ \text{ or } 90^\circ \geq \theta \geq \theta_c > 0) \end{cases},$$

$$\beta_t = \begin{cases} b_t - \dfrac{b_t - a_t}{|\theta_c|}\sqrt{\theta_c^2 - \theta^2} \\ \qquad (0 > \theta \geq \theta_c \ \text{ or } \ \theta_c \geq \theta \geq 0) \\ 1 \quad (0 > \theta_c \geq \theta \geq -90^\circ \ \text{ or } \ 90^\circ \geq \theta \geq \theta_c > 0) \end{cases},$$

Reduction factors of the leading pile and trailing pile, β_l and β_t,

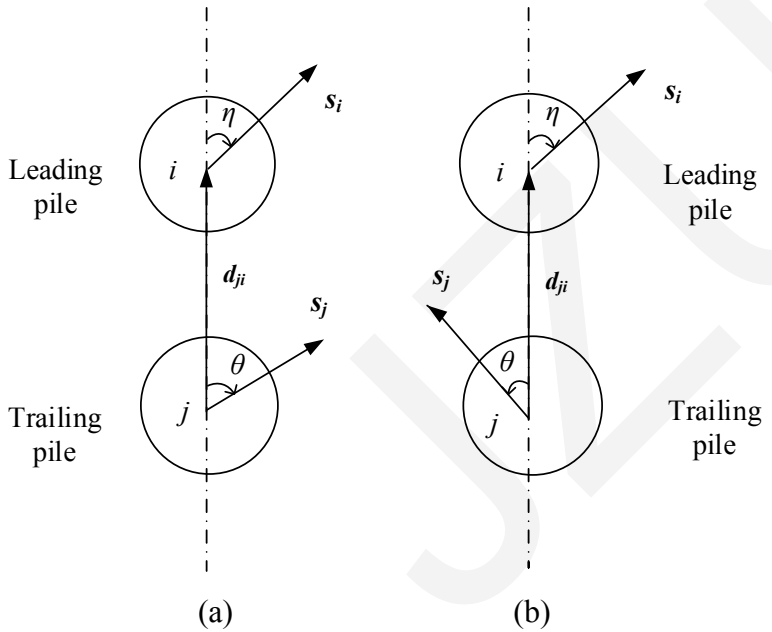
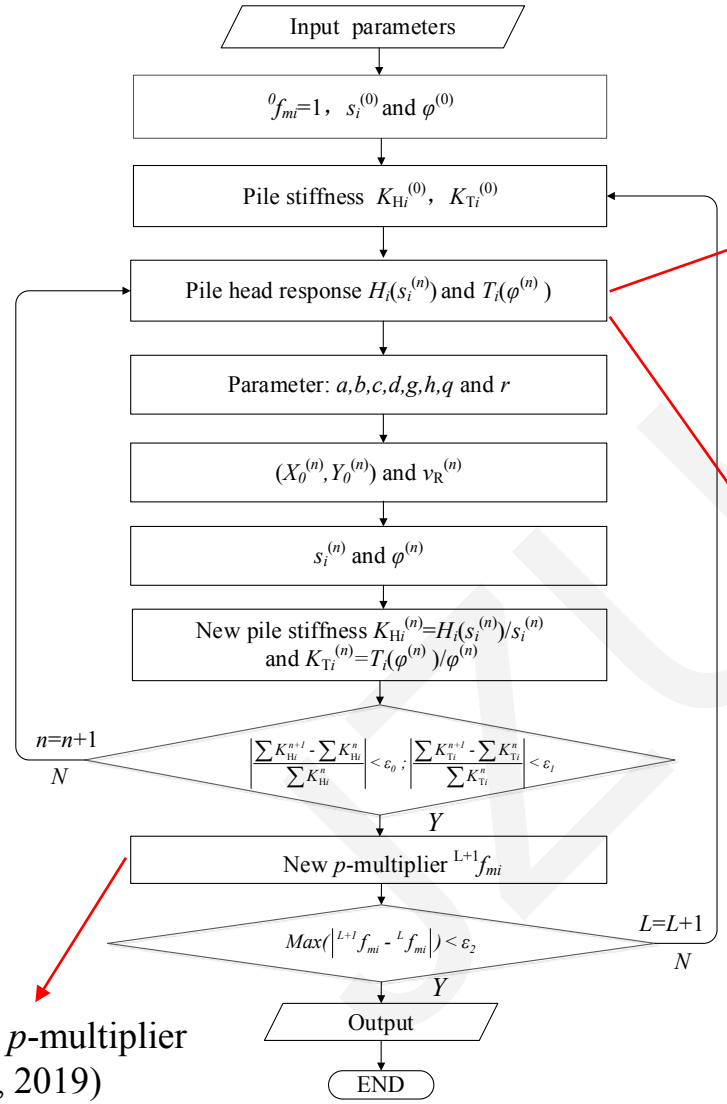


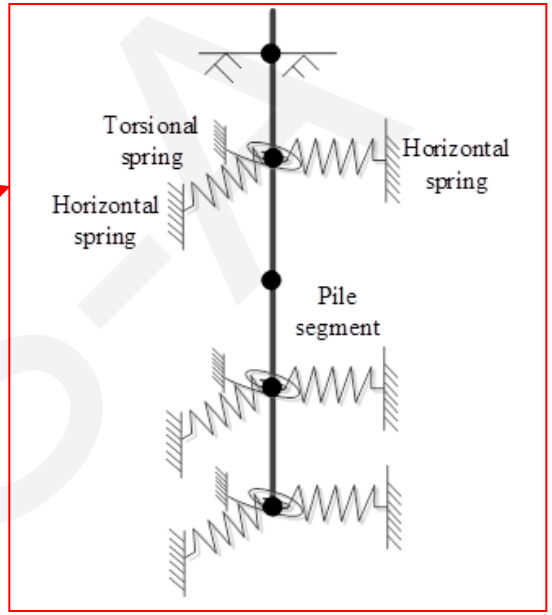
Fig. 4 Two motion states of a double-pile group subjected to combined lateral and torsional loading

More detail refers to:
Kong LG, Fan JY, Liu JW, Chen YM, 2019. Group effect in piles under eccentric lateral loading in sand. *Journal of Zhejiang University-SCIENCE A*, 20(4): 243-257. https://doi.org/10.1631/jzus.a1800617

Flow chart of ELPGROUP



Generalized p-multiplier (Kong et al., 2019)

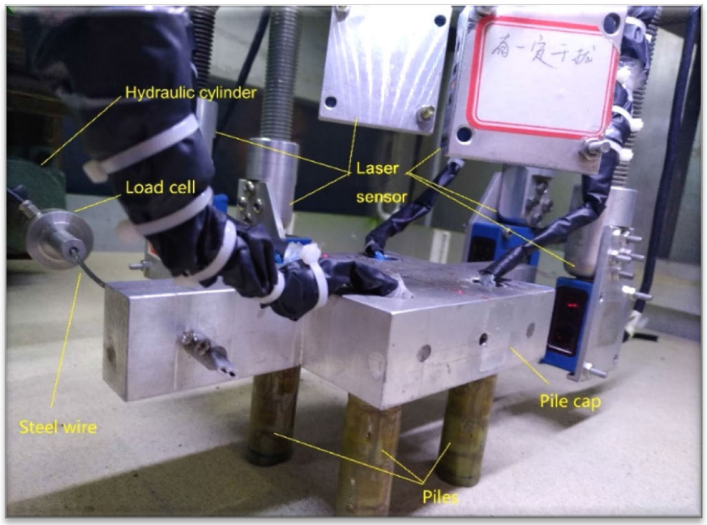


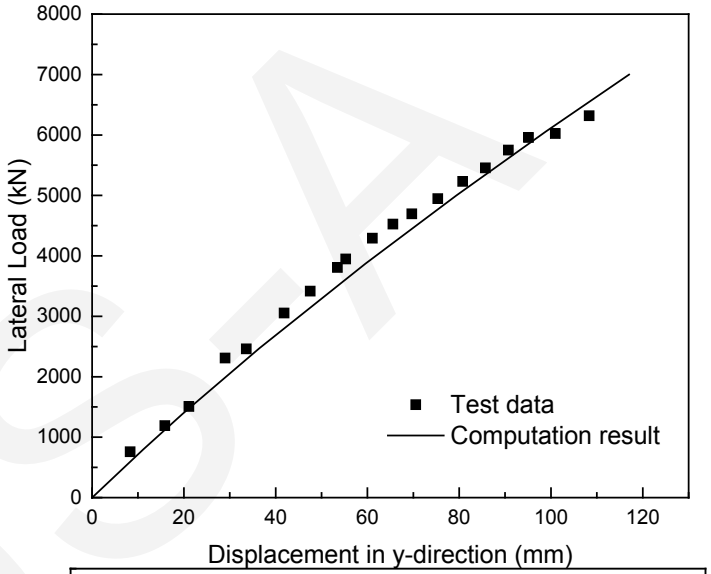
The deflection-torsion coupling effect:

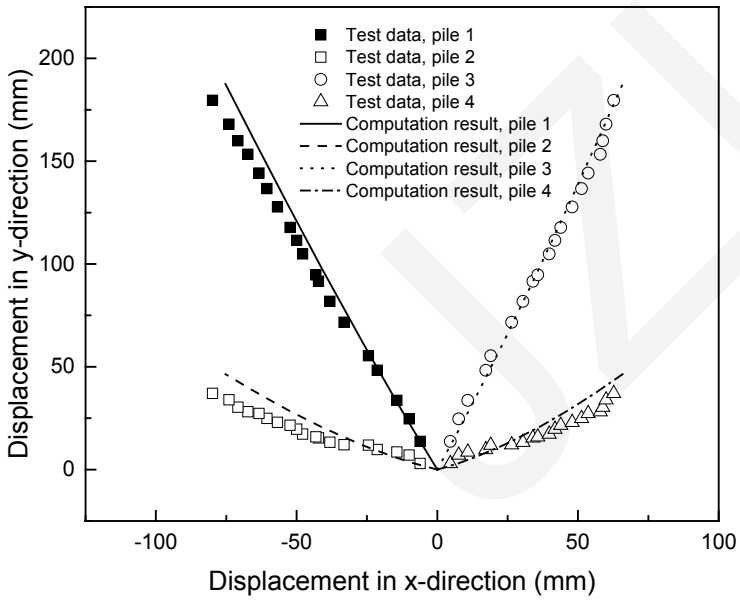
$$\alpha_{TH} = 1 + \left(\frac{\beta_{TH}}{p_a D}\right) p,$$

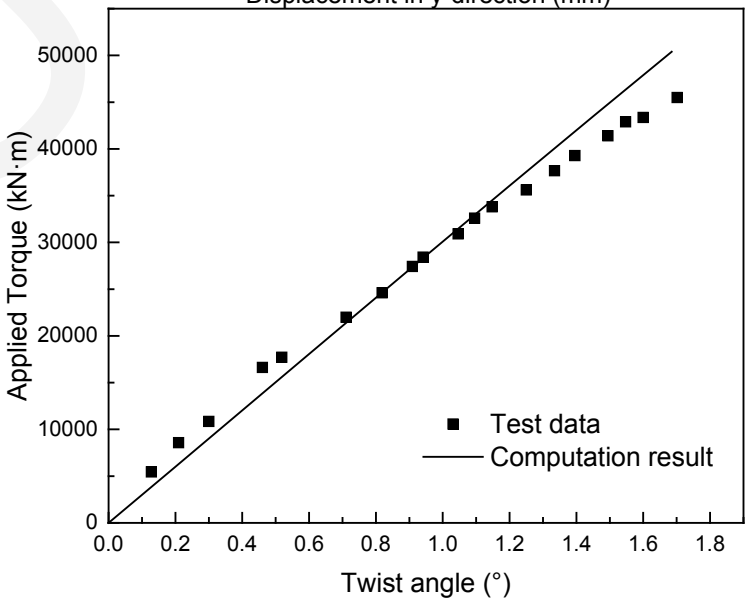
Kong LG, Zhang LM, 2008a. Experimental study of interaction and coupling effects in pile groups subjected to torsion. *Canadian Geotechnical Journal*, 45(7): 1006-1017. https://doi.org/10.1139/t08-038

Test and Prediction Results









Summary

1. A simple and computationally efficient approach has been developed for analyzing the nonlinear response of pile groups under combined lateral and torsional loading.
2. The pile-cap motion of a pile group subjected to combined lateral and torsional loading is a combination of horizontal and torsional movements, and can be seen as a plane rigid-body motion.
3. An explicit pile-head displacement relationship of the grouped piles and static equilibrium equations of the pile cap were derived according to the concept of instantaneous center in a plane rigid-body motion.
4. The generalized *p*-multiplier proposed by Kong et al. (2019) is used in this approach to account for the horizontal interaction among the individual piles, which has a dominant effect on the response of the pile groups.
5. The coupling effect of the lateral resistance and torsional resistance of each pile was quantified using an empirical factor *β.*
6. An approximate equilibrium equation of the pile cap was derived to improve the computational efficiency in iteration.