Electronic Supplementary Materials

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Centrifuge model testing to ascertain vertical displacements of a pile under cyclic lateral loads

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Data S1 Simple computational model

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In the simple model, the soil was idealized as springs connected to the pile. The springs connected to the pile base were termed base springs, which only worked in axial direction (see in Fig. S1), and the springs connected to the pile shaft were termed shaft springs, which included springs in the radial direction, springs in the horizontal shearing direction and springs in the vertical shearing direction, as shown in Fig. S1.

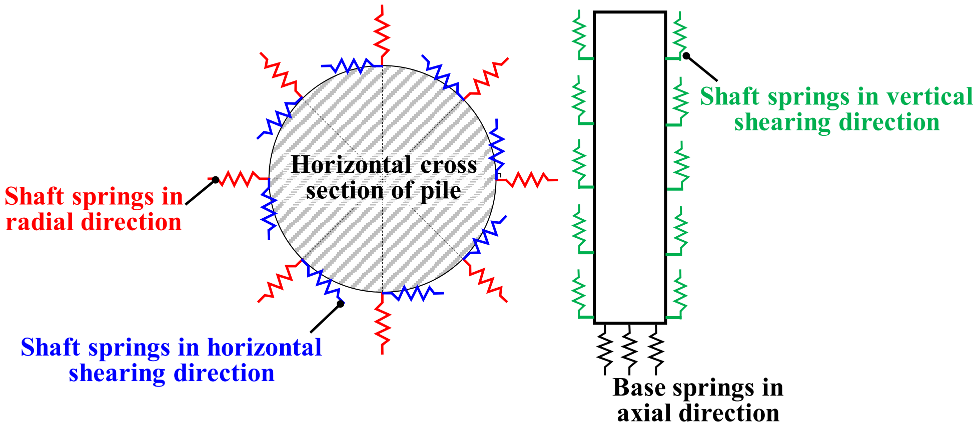


Fig. S1 Schematic of the simple model

In this study, the behaviours of the springs were described using ideal elastoplastic model. The behaviour of the shaft springs in the radial direction, as shown in Figs. S2a and S2b, could be expressed by

$$\sigma_{\mathrm{n},n}=\begin{cases}\sigma_{\mathrm{n},n-1}+\eta k_{\mathrm{n,shaft}}\omega_{\mathrm{n}}, & \text{if } \sigma_{\mathrm{n}}<\sigma_{\mathrm{n,max}}, n\geq 1\\ \sigma_{\mathrm{n,max}}, & \text{otherwise}\end{cases} \tag{S1}$$

where σ_n was the normal pressure acting on the pile shaft, and ω_n was the displacement of the springs, $k_{n,shaft}$ was the stiffness of the shaft springs in radial direction and could be calculated by (Li *et al*, 2012)

$$k_{\mathrm{n}}=\frac{4}{\pi D(1-\upsilon)}G_{\mathrm{s}} \tag{S2}$$

where G_s was the initial shear modulus of the soil and could be obtained by:

$$G_{\mathrm{s}}=\chi G_0 \tag{S3}$$

where G_0 was shear modulus of soil, and χ was a coefficient that reflected the effect of the pile installation procedure on the soil shear modulus. In this study, the model pile was installed by wished-in-place method, and χ adopted 1. G_0 could be calculated, according to the Young's modulus, E, of the soil, by

$$G_0 = \frac{E}{2(1+\upsilon)} \tag{S4}$$

The E of the soil could be calculated by (Janbu, 1998)

$$E = m\sigma_r (\frac{\sigma'}{\sigma_r})^{1-j} \tag{S5}$$

where σ' is the effective stress of the soil; j is the stress exponent and adopted 0.5 in this study, and σ_r' is the reference stress, a constant, which is equal to 100 kPa. In Eq. (S5), m is modulus number, which was related to the relative density of the soil (Fellenius, 2020). The void ratio of the sample measured before the test begun was about 0.75. The maximum and minimum void ratio were 1.04 and 0.597 (Ishihara 1993), respectively. Therefore, the relative density of the sand sample was about 65%, and the value of m adopt 210 in this study. In Eq. (S1), η was sign function which could be expressed by

$$\eta = \begin{cases} 1, & \text{Springs on the front side} \\ -1, & \text{Springs on the back side} \end{cases} \tag{S6}$$

$\sigma_{n,max}$ was the maximum pressure of the shaft springs in radial direction, and could be calculated by (Zhang *et al*, 2005)

$$\sigma_{\text{n,max}} = K_p^2 \gamma z \tag{S7}$$

where γ was the unite weight of the soil, K_p was the passive earth pressure coefficient and could be calculated by

$$K_p = \tan^2(45^\circ + \varphi/2) \tag{S8}$$

Considering that the dry sand could not sustain tensile stress, in this study, it was stipulated that the σ_n could not be smaller than 0.

In this model, the behaviours of the shearing springs (Fig. S2c), were expressed by:

$$\tau_{\text{v(h)}} = \begin{cases} \tau_0 + k_s\, \omega_{\text{v(h)}}/r, & \text{if } \tau < \tau_{\max} \\ \tau_{\max}\quad, & \text{otherwise} \end{cases} \tag{S9}$$

where $\tau_{v(h)}$ was the shear stresses acting on the pile in vertical shearing direction (or horizontal shearing direction), $\omega_{v(h)}$ was the shearing displacement of the springs in vertical shearing direction (or horizontal shearing direction), k_s was the shearing stiffness of the shaft springs and could be calculated by (Li *et al*, 2012)

$$k_s = \frac{G_s}{\varsigma} \tag{S10}$$

where ζ is the dimensionless extent of the zone of the influence and adopted 4 in this article (Li *et al*, 2012). In Eq. (S9), τ_{max} was the maximum stresses in shaft springs and could be calculated by

$$\tau_s = \tan\delta\sigma_n \tag{S11}$$

where δ is the interface friction angle between the pile and soil and adopted 0.8 φ.

The behaviour of the base springs, Fig. S2d, could be expressed by

$$\sigma_b = \begin{cases} \sigma_{b0} + k_b s_b, & \text{if } \sigma_b < \sigma_{b,max} \\ \sigma_{b,max}, & \text{otherwise} \end{cases} \tag{S12}$$

where s_b was the settlement of the pile, $\sigma_{b,max}$ was the maximum pressure in the base springs, and could be calculated by

$$\sigma_{b,max} = k_b s_{max} \tag{S14}$$

where σ_{b0} was the tip resistance of the pile before the lateral load was applied, s_{max} was the settlement that would mobilize the maximum stresses in the base springs. According to the suggestion of Li *et al* (2012), in this article, s_{max} was 0.2 D. In Eq. (S12), k_b was the stiffness of the base springs and could be determined by

$$k_b = (1 - \frac{\sigma_{b0}}{\sigma_{b,max}})k_{b0} \tag{S13}$$

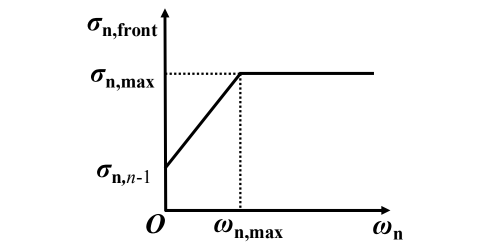
where k_{b0} was the initial stiffness of the soil, and according to the suggestion of Li *et al* (2012), k_{b0} could be calculated by

$$k_{b0} = \frac{8}{\pi D(1-\upsilon)} G_s \tag{S14}$$

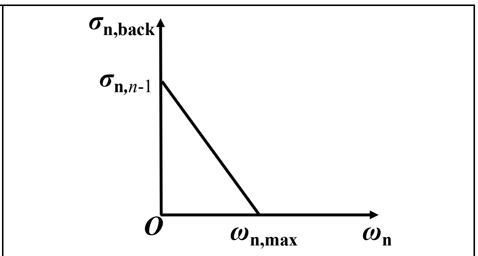
According to the Chari & Meyerhof (1983) and Prasad & Chari (1999), the pile in this study could be considered as rigid pile, and the deformation of the pile could be neglected. Following the suggestion of Prasad & Chari (1999), the depth of rotation centre, D_R, could be calculated by

$$D_R = [-(0.567L + 2.7e_L) + (5.307L^2 + 7.29e_L^2 + 10.541e_L L)^{0.5}] / 2.1996 \quad \text{(S15)}$$

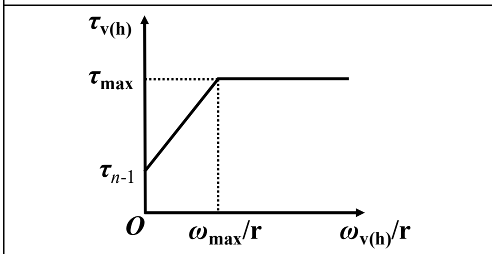
where L was the embedded length of the pile, e_L was the eccentricity of the lateral load.



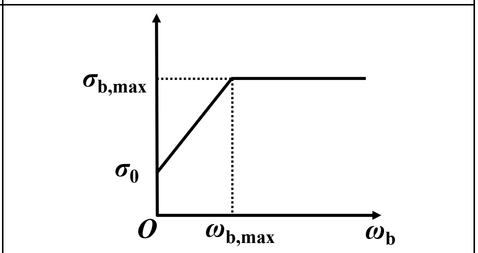
(a) Deformation curve of the shaft springs on front side in radial direction



(b) Deformation curve of the shaft springs on back side in radial direction



(c) Deformation curve of the shaft springs in shearing direction



(d) Deformation curve of the base springs

Fig. S2 Deformation curves of the springs connected to the pile