Computers and Geotechnics 71 (2016) 115–123

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Analysis of pile groups subjected to torsional loading

S.L. Chen [a], L.G. Kong [b,*], L.M. Zhang [c]

[a] Department of Civil & Environmental Engineering, Louisiana State University, Baton Rouge, USA
[b] Institute of Geotechnical Engineering, College of Architectural and Civil Engineering, Zhejiang University, Hangzhou, PR China
[c] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong

ARTICLE INFO

Article history:
Received 20 March 2013
Received in revised form 30 July 2015
Accepted 7 September 2015

Keywords:
Pile groups
Torsion
Group interaction
Laterally loaded piles

ABSTRACT

An analytical method is developed to analyse the torsional response of free-standing pile groups with rigid pile caps. The proposed approach captures the coupling nature of the torsional and lateral resistances in the problem. The general interaction between two identical piles subjected to lateral loads of equal magnitude but in arbitrary directions is first analysed by the use of Mindlin's point load solution. Then, the interaction effects on the horizontal displacement or rotation of one pile caused by the torsional or horizontal loading on an adjacent pile, i.e., torsional–horizontal interactions, are considered. Subsequently, the interactions among the individual piles are combined to obtain the overall torsional stiffness of the pile group as well as the load distribution within the group. The proposed approach is used to predict the behaviour of pile groups considering a range of group sizes, pile spacings, pile stiffnesses and pile slenderness ratios. Finally, the results of centrifuge model tests on 2×2 and 3×3 pile groups embedded in a loose sand bed are used to validate the proposed analysis method. The predicted pile group response and load transfer agree reasonably well with the test results.

1. Introduction

Large structures such as deep-water offshore platforms, offshore wind turbine foundations, tall buildings and high-rise bridge bents are often supported by pile foundations. These structures are usually subjected to lateral loads of considerable magnitude from wind actions, waves or ship impacts. Significant torsional forces can be transferred to the foundation piles due to the eccentricity of these lateral loads.

In contrast to the extensive research work on the analysis of piles under axial and lateral loads (see for instance [1–11]), the analysis of piles under torsional loading has received less attention in the past. O'Neill [12] established a closed-form elastic solution for the pile head torque–twist relationship of single piles and introduced a discrete element model using torsional springs. Similar discrete element formulations were later proposed by Chow [13] and Georgiadis and Saflekou [14]. Georgiadis and Saflekou [14] further considered the response of single piles under coupled axial and torsional loads. In an earlier study, Poulos [15] presented an elastic method for the analysis of the response of a single pile subjected to torsion. Solutions to the response of single piles in a uniform soil and in a soil in which the shear modulus increases linearly with depth were obtained. Randolph [16], Hache and Valsangkar [17], and Guo and Randolph [18] also derived closed-form solutions to the torsional response of piles in homogeneous and non-homogenous media. Particularly, Randolph [16] and Guo and Randolph [18] considered the effect of the relative slip between the pile and the soil.

Different from a single pile, a pile group under a torsional load involves the simultaneous mobilisation of torsional and lateral resistances of the individual piles [19]. Through centrifuge model tests, Kong and Zhang [20] found three group interaction effects among the individual piles in a torsionally loaded pile group: (1) Interaction effects in the pile group in which each of the individual piles is laterally loaded in an arbitrary direction; (2) Interaction effects between the torsional and horizontal displacements of the piles, which are called torsional–horizontal interaction; and (3) Interactions among the piles under torsion. Similar complicated pile-soil-pile interactions have also been reported by Gu et al. [21] in a recent experimental study for the behaviour of 1×2 pile group under eccentric lateral loading.

Randolph [22] developed an approximate solution to take into account the effect of horizontal resistances of the individual piles in a group on the torsional stiffness of the pile group. The solution considers interactions between the horizontal resistances of piles

* Corresponding author at: Institute of Geotechnical Engineering, College of Architectural and Civil Engineering, Zhejiang University, 388 Yuhangtang Road, Hangzhou, PR China. Tel.: +86 (571) 8820 8772; fax: +86 (571) 8820 8793.
E-mail address: klg@zju.edu.cn (L.G. Kong).

http://dx.doi.org/10.1016/j.compgeo.2015.09.004
0266-352X/

Nomenclature

d pile diameter
$\boldsymbol{D}_1$ matrix of finite difference coefficients for fixed-head pile
E_s and E_p deformation modulus of soil and pile
$(GJ)_p$ torsional rigidity of pile
G_s shear modulus of soil
H_{avg} average horizontal load in group
H_j transferred horizontal load to pile j in group
$\boldsymbol{I}$ unit matrix of $(n-1)$ by $(n+1)$
${}_j\boldsymbol{I}$ coefficient matrix of displacement factor due to pressure between soil and pile j
I_p moment of inertia of pile
$I_{\rho F}$ displacement influence factor for fixed-head pile
$I_{G\rho F}$ total displacement influence factor
K_r pile flexibility relative to soil
L pile length
m number of piles in group
n number of elements dividing each pile
$\{p\}$ vector of horizontal stress on pile
$\{p_S\}$ vector of horizontal stress on pile due to its own load
$\{p_P\}$ and $\{p_N\}$ total horizontal stresses on pile 1 due to the loads on piles 1 and 2 at $\gamma = 0°$ and $90°$
$\{p\}_{kj}$ total stress vector on pile k due to presence of pile j
s_k distance between pile k and the group centroid
s_{kj} centre to centre distance between pile j and k
T_G total torsional load on pile group
T_h transferred torsional load at the head of individual pile
α_{kj} angle between the line through piles k and j and that through pile k and the group centroid
$\alpha_{\rho F}$ two-pile interaction factor for an arbitrary γ
$\alpha_{\rho F,P}$ and $\alpha_{\rho F,N}$ two-pile interaction factors at $\gamma = 0°$ and $90°$
$\alpha_{\rho Fkj}$ interaction factor of pile j on pile k
β departure angle between two piles
γ angle between loading on two piles
δ length of pile elements
θ angle between line through two piles and lateral loading direction
λ torsional stiffness ratio of pile
v_p and v_s Poisson's ratios of pile and soil
ρ_F total horizontal displacement of pile due to horizontal loads
ρ_G overall horizontal displacement of pile
ρ_T total horizontal displacement of pile due to torsional loads
ρ_{Tkj} horizontal displacement of pile k due to torsional load on pile j
$\{_s\rho\}$ vector of horizontal soil displacement
ϕ_h pile head rotation

using the well-established interaction factor concept. Xu and Poulos [23] presented a rigorous analysis for pile foundations subjected to general three-dimensional loading by using a boundary element method. Some numerical results for a 3×3 pile group subjected to torsion were reported and compared with Randolph's solution. However, no further discussions on the three involved interactions among the pile group were provided in their work. Kong and Zhang [24] recently developed a "hybrid" approach to analyse the nonlinear behaviour of pile groups subjected to torsion. In that approach, the lateral and torsional resistances of the individual piles in a pile group are modelled by nonlinear $p-y$ and $\tau-\theta$ curves; the interaction among lateral resistances of the individual piles is predicted through Mindlin's [25] solutions while the interactions between the torsional and lateral resistances of the individual piles are considered using Randolph's [22] method.

In this paper, a more systematic study on the interaction effects in torsionally loaded pile groups is proposed. First, the interaction between two identical piles subjected to horizontal loads in arbitrary directions is analysed. Next, the torsional–horizontal interactions between two piles are considered while the interactions among the piles under torsion are ignored. These interaction analyses are then utilised to analyse the response of a general pile group subjected to torsion. The torsional stiffness of the pile group and the torque and lateral load carried by an individual pile can be determined in turn. Solutions to the torsional responses of pile groups of a range of group sizes, pile spacings, pile stiffnesses and pile slenderness ratios are presented. The predicted torsional responses of the 2×2 and 3×3 pile groups are also compared with the available centrifuge model measurements reported by Kong and Zhang [19].

2. Interaction between two piles under lateral loads along arbitrary directions

An individual pile in a pile group under torsion is subjected to both a horizontal load and a torsional load (Fig. 1). In addition to the lateral and torsional stiffness of a single pile, due attention must be given to the interactions between the horizontal displacement or rotation of one pile and the lateral or torsional loads on adjacent piles. This section studies the interaction between two piles laterally loaded in arbitrary directions. The torsional–horizontal interactions will be described in the next section.

The analysis of the interaction effects between two identical piles equally loaded in the same direction based on Mindlin's solution and an integral equation technique has been described by Poulos [3]. For the case of a pile group under torsional loading as shown in Fig. 1, however, the angle between the horizontal loads on two arbitrary piles could be of any value, depending on the geometry of the pile group. Thus, a more general analysis of the interaction between two laterally loaded piles is needed.

Consider two identical piles equally loaded with an arbitrary angle γ between the loading directions, as shown in Fig. 2. Each pile

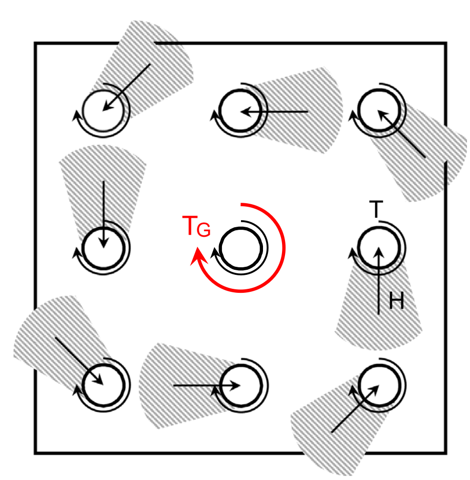

Fig. 1. Load distributions and pile movements in a pile group under torsional loading.