Technical Note

Laterally Loaded Battered Piles in Sandy Soils

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Abstract: A technique to predict the response of laterally loaded battered piles in sandy soils is developed based on soil–pile interaction. The proposed method employs the concepts of the strain wedge (SW) model, which were originally developed for laterally loaded vertical piles. Unlike current practices that use a multiplier for the *p–y* curve of the vertical pile, the suggested technique accounts for soil and pile properties and the direction and magnitude of the pile batter angle from the vertical position in the calculation of the pile lateral response and the assessment of the *p–y* curves. The developed model shows the effect of pile battering on the predicted *p–y* curve at varying depths compared to the *p–y* curve of the vertical pile (i.e., a varying *p–y* multiplier). The model has been validated through comparisons with full-scale and model-scale pile load tests. **DOI: 10.1061/(ASCE)GT.1943-5606.0002186.**

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Introduction

Battered piles are classified as positive or negative piles according to the angle of pile installation with the vertical axis. A number of researchers have conducted small-scale pile load tests to understand the behavior of battered piles (Juvekar and Pise 2008; Murthy 1964; Meyerhof and Ranjan 1973; Meyerhof and Yalcin 1994; Manoppo 2010). However, such tests were conducted on model piles with diameters less than 30 mm, which may not have reflected actual soil–pile interaction. Based on a number of scale-model centrifuge tests, Zhang et al. (1999) showed that the lateral resistance of negative battered piles increased by 4%, 14%, 24%, and 50% for very loose, loose, medium-dense, and dense sands, respectively, compared to vertical piles. On the other hand, the resistance of positive battered piles decreased by 4%, 5%, 15%, and 35%, for very loose, loose, medium-dense, and dense sands, respectively, according to the same research work. A very limited number of full-scale load tests on battered piles are available in the literature (Alizadeh and Davisson 1970; Nimityongskul et al. 2012, 2018).

The traditional *p–y* curve for a vertical pile (Reese et al. 1974; Meyer and Reese 1979) was modified by some researchers to predict the behavior of the laterally loaded battered piles by applying a modification factor (Ω) to the vertical pile's *p–y* curves. Such a modification factor (Kubo 1962) does not change with soil type (i.e., properties) and is constant with soil depth, as established by Zhang et al. (1999).

Reese et al. (2004) and Reese and Van Impe (2011) adopted the factor Ω presented by Kubo (1962) as a *p*-multiplier to modify the *p–y* curves of vertical piles for the prediction of the lateral response of battered piles. The UFC (2004) design guidelines recommend Kubo's (1962) approach for the design of battered piles under lateral loads only for small projects. Awoshika and Reese (1971) indicated that Kubo's (1962) modification factor only can be applied to positive battered piles.

The strain wedge (SW) method developed by Norris (1986) for a laterally loaded vertical flexible pile in uniform sandy soil and then upgraded for multilayered soils by Ashour et al. (1998) and Ashour and Norris (2000) is modified in the current study to handle the problem of battered piles under lateral loads. Unlike current practice that employs a constant multiplier with the conventional *p–y* curves of an equivalent vertical pile, the presented SW model directly determines the lateral behavior of battered piles and associated *p–y* curves based on the pile's batter angle, soil and pile properties, and soil–pile interaction (i.e., no *p–y* multiplier is required).

Background on the Basic SW Model

The main concept of the SW model is that the traditional one-dimensional beam on elastic foundation (BEF) pile response parameters can be characterized in terms of three-dimensional soil–pile interaction behavior (Fig. 1). The SW model characterizes the stress–strain behavior of the soil as assessed in the triaxial test [as a triaxial specimen at the face of the wedge; Fig. 1(b)] and soil effective stress analysis (Norris 1986; Ashour et al. 1998).

As shown in Fig. 1, the geometry and size of the passive soil wedge (i.e., the wedge depth h, base angle α_m and fanning angle φ_m, which is the mobilized friction angle of the soil) vary according to the lateral stress and strain in the soil ($\Delta\sigma_h$ and ε), as does the shear resistance along the pile sides (τ_s), with the magnitude of the lateral load at the pile head. The major principal stress-strain model ($\Delta\sigma_h$–ε) of the soil [developed by Norris (1986) and adjusted by Ashour et al. (1998)] is employed at any depth x for a soil sublayer i with a thickness H_s and a vertical effective stress $\bar{\sigma}_{vo}$. The horizontal stress change ($\Delta\sigma_h$) that acts at the face of the developing passive wedge is equal to the axial stress change in the conventional triaxial test [Fig. 1(b)], as is the ever-changing Young's modulus $E = \Delta\sigma_h/\varepsilon$ in the soil and triaxial test.

Based on the pile properties, the developing or mobilized geometry of the passive soil wedge, and the variation in soil

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