Contribution of Vertical Skin Friction to the Lateral Resistance of Large-Diameter Shafts

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Abstract: Large-diameter drilled shafts embedded in stiff materials (e.g., clay and weak rock) experience larger lateral resistance compared to the resistance values obtained from available soil-pile models, which usually produce a conservative design. The axial skin friction (i.e., vertical side shear) developed on the side of the large-diameter drilled shafts in stiff clay and weak rock (i.e., cohesive intermediate geomaterials) improves shaft resistance to the lateral loads (i.e., the shaft-head lateral stiffness). This paper presents a model that calculates the vertical skin friction induced by the vertical-displacement component of the shaft deflection and section rotation through the use of the *t-z* relationship. The model determines the shaft-deflection resisting moment caused by the axial skin friction on the passive side of the drilled shaft. Up to a 40% increase in the shaft-head lateral stiffness (K_d) (i.e., stiffer foundations) could develop as a result of the consideration of the vertical side shear resistance. In addition, the lateral response of the superstructure would be influenced by the variation of K_d. This study also shows the degrading effect of vertical side shear on the shaft-head lateral stiffness with the increase in shaft deflection. A number of full-scale drilled-shaft load tests have been used in this comparison, and the results obtained from the presented model highlight the contribution of vertical skin friction caused by the shaft deflection/rotation to the lateral resistance of large-diameter shafts. **DOI:** 10.1061/(ASCE)BE.1943-5592.0000505.

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Introduction

Interest in using large-diameter drilled shafts in bridge foundations has increased over the last two decades because the diameters of some recently constructed drilled shafts have exceeded 6.0 m. Large-diameter drilled shafts are often used when the designer wishes to take advantage of their large lateral load capacity. Analysis often shows that soils in the upper part of the ground profile have the most significant influence on lateral deformations and lateral load transfer. However, the data obtained from several full-scale load tests on laterally loaded large-diameter shafts installed in soil and weak rock exhibit a stiffer shaft-head response compared to the results obtained from the traditional *p-y* curve by Reese and Welch (1975) (Bhushan et al. 1979; Reese 1983; Brown et al. 2001; Qiu et al. 2004; Liang et al. 2007; McVay and Niraula 2009; Sorensen et al. 2009; Lesny and Hinz 2009; Kim et al. 2011). A softer lateral response for large-diameter shafts in stiff clay and weak rock is expected because the pioneering Matlock–Reese *p-y* model was developed for piles of smaller diameters (<0.9 m). Therefore, the vertical side shear resistance (τ_v) on the passive side of the deflected pile does not produce a considerable resisting moment (M_R) against the deflection of such slender piles. McVay and Niraula (2009) addressed the significance of the vertical side shear's contribution to the lateral resistance of piles embedded in rock, including weak rock, using a number of centrifuge model load tests. They proposed a stiffer *p-y* curve compared to the one presented by Reese and Nyman (1978) in order to account for the vertical side shear.

Despite little interest being given to the effect of vertical side shear resistance on the lateral behavior of large-diameter shafts, recent broad use of large-diameter shafts in stiff soils (especially short shafts) encourages the consideration of vertical side shear resistance in any analysis of large-diameter drilled shafts (McVay and Niraula 2009). Liang et al. (2007) addressed the need for a stiffer *p-y* curve for large-diameter shafts in stiff clay (i.e., cohesive intermediate geomaterials) and proposed a modified *p-y* curve based on the results of the finite-element (FE) analysis and validation through field tests. As described by Gonzalez and Digioia (1990), Fig. 1 shows the different forces and moments acting on the large-diameter shafts, including vertical side shear resistance.

The weak rock (i.e., the cohesive intermediate geomaterial) used in this analysis is based on the definitions presented by Santi and Doyle (1997) and Santi (2006), which specify materials with high clay content, low friction angles, and at least a 50% composition of clay-sized particles (i.e., materials dominated by the clay behavior). The compressive strength of the weak rock would be in the range of 1–20 MPa.

Soil-pile/drilled-shaft modeling is characterized by a nonlinear set of the *p-y* and *t-z* curves that reflect the transfer (i.e., the soil-pile interaction) of lateral and vertical loads, respectively. It should be noted that the current *p-y* and *t-z* curves are independent from each other and are a function of lateral (y) and vertical (z) shaft displacement, respectively (see Fig. 2). However, the lateral loading and resulting deflection of large-diameter shafts are associated with both horizontal (y) and vertical displacement (v). Although the horizontal-displacement component (y) dominates the pattern of the large-diameter shaft deflection, the accompanying small vertical-displacement component (v) also develops. This increases the vertical skin friction (τ_v) (i.e., the vertical side shear force, V_v) on the shaft surface in stiff soil by increasing the diameter and the deflection of the drilled shaft. The developing vertical side shear resistance generates a resisting moment, M_R (see Fig. 2), to the lateral shaft deflection. Nevertheless, it is not recommended that the M_R that is

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