Role of Torsional Shear in Combined Loading of Drilled Shaft Foundations
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Abstract: Deep foundations may be subjected to combined torsional and lateral loads. However, there are few full-scale observations to inform a complete understanding of the possible foundation response. This paper describes the generation and transfer of lateral loads that developed within drilled shaft foundations subjected to quasi-static and cyclic torsional loads. Due to differences in stratigraphy, one drilled shaft experienced geotechnical torsional failure, whereas the other did not. Torsional loading to failure produced shear cracks that softened the soil–structure interface and produced a softened response to the lateral load that developed. Cyclic loading resulted in increased lateral displacement at near-constant lateral load amplitude. The maximum bending moment observed in the shaft that experienced torsional failure was significantly greater than that in the shaft in which geotechnical failure did not occur, and greater than that anticipated from lateral loading alone. DOI: 10.1061/(ASCE)GT.1943-5606.0002039, © 2019 American Society of Civil Engineers.

Introduction
Deep foundations commonly experience torsional loads, which may be induced through wind loading on cantilevered traffic signs or seismic loading of skewed bridges and curved, elevated flyovers (e.g., Poulos 1975; Randolph 1981; Li et al. 2017), or may develop from the eccentricity of a lateral load (e.g., Randolph 1981; Duncan and Filz 1995; Hu et al. 2006; Zhang and Kong 2006; Thiyyakkandi et al. 2016). Studies that focused on the effects of pure torsion (e.g., Poulos 1975; Randolph 1981) provide an important baseline for understanding the response of deep foundations to torsion loading; however, there are few cases in which torsion loads are not accompanied with lateral loads. Previous investigations of combined loading focused on the global response at the head of the shaft, such as the centrifuge tests conducted by Herrera (2001), McVay et al. (2003), and Hu et al. (2006) and the full-scale tests performed by Thiyyakkandi et al. (2016) and Li et al. (2017). Herrera (2001), McVay et al. (2003), and Hu et al. (2006) found no influence of lateral loading on the global torsional resistance but significant reduction of lateral resistance caused by torsional loading for drilled shafts in sand. Thiyyakkandi et al. (2016) found that combined torsional and lateral loading reduced the global torsional resistance by approximately 20% in the silty sands investigated. Li et al. (2017) described experiments on two signal mast arm–type drilled shafts tested to observe torsional load transfer at full scale. Li et al. (2017) noted that differential failure between the two shafts arising from differences in the strength and stiffness of the soil–structure interfaces led to the development of an induced lateral load, which was monitored along with the corresponding lateral load transfer.

This paper explores the lateral and flexural response of two relatively stiff drilled shafts subjected to torsional loading. The lateral load develops in response to the differences in the shaft geometry and torsional soil–shaft interface shear stiffness and strength arising from differences in stratigraphy. Torsional shear cracking around one shaft that developed prior to onset of significant lateral load resulted in a softened lateral response. The unintended development of combined loading observed in these experiments can be used to judge the likely global and structural implications that are possible under such conditions and guide recommendations for cases in which such conditions may occur over the life of a supported structure.

Experimental Program

Test Site Description
The loading tests were conducted at the geotechnical engineering field research site at Oregon State University. The test site layout, including the experimental shafts and exploration plan, is shown in Fig. 1(a). The test shafts were designated as the test drilled shaft with production base (TDS) and the test drilled shaft with frictionless base (TDSFB). The subsurface profile was developed using cone and seismic cone penetration tests (CPTu and SCPTu, respectively) pushed at the center of each test shaft and borings for standard penetration testing (SPT) and thin-walled tube sampling (Fig. 2). The general stratigraphy consists of a layer of overconsolidated silty clay to clayey silt from the ground surface to a depth of approximately 5.2 m, underlain by a layer of medium dense sand to silty sand. The consistency of the near-surface soils ranges from very stiff to hard, and the soils form a crust during a period of extended low groundwater levels at the end of summer, as indicated by high qt and SPT N, and soften considerably during extended periods of precipitation and high groundwater levels (as was the case during full-scale testing). The consistency of the medium-stiff plastic silt and clay below the seasonal low groundwater elevation does not vary significantly with season (Martin 2018). A 1.1-m-thick lens of dense silty sand with gravel was encountered in CPT-2, both exploratory borings, and the excavated spoils of TDS.
Fig. 2. Subsurface profile at test site and the location of the test shafts.
This layer produced significant differences in the torsional and lateral response compared with TDSFB. Tables 1 and 2 present the soil properties used to model TDSFB and TDS, respectively, as described in the subsequent analyses. These are slightly modified from previously reported analyses by Li et al. (2017) based on updated information.

**Experimental Details of Test Shafts**

The test shafts were designed to support Oregon Department of Transportation (ODOT) signal pole Type SM3 as specified in Standard Drawing TM651 (ODOT 2014). Based on ODOT design procedures, the shafts were 0.9 m in diameter, \( D \), and embedded approximately 4 m below the ground surface. To avoid shaft-to-shaft interaction, the test shafts were installed 4.6 m apart (∼5\(D \)). According to the Standard Drawing TM651, the maximum design axial, lateral, moment, and torsional loading at the heads of the drilled shafts are 15.5 kN, 34.6 kN, 187.7 kN·m, and 112.4 kN·m, respectively. The embedded lengths of the shafts were calculated prior to exploration using the Broms (1964) method in consideration of lateral loading requirements only, per ODOT (2015) procedures, and assuming that the shafts were embedded in a homogenous deposit of plastic, fine-grained soil. The ODOT (2015) procedures apply an effective factor of safety of 2.15 on lateral capacity. To facilitate the application of torsion, the shafts were extended 1.5 m above the ground surface and an H-pile loading arm was cast through each shaft. The internal steel reinforcement consisted of eight 25-mm-diameter (#8) longitudinal bars at five elevations to measure flexural strains [Fig. 1(b)], in addition to the vibrating wire concrete embedment strain gauges [Fig. 1(b)], used to observe torsional shear strain. Two pairs of RSGs were fixed to the longitudinal bars at five elevations to measure flexural strains [Fig. 1(b)], in addition to the vibrating wire concrete embedment strain gauges (ESG) used to observe torsional shear strain. Two pairs of RSGs were installed at each instrumented elevation for redundancy. The strain limit for the RSGs was 50,000 με, with a gauge factor of 2.13 ± 1%. Two string potentiometers were attached at each end of the loading arms to monitor the individual rotation of each shaft as well as their lateral displacement. Two sets of load cells were used to measure the forces developed on each side of the loading arm, which allowed the magnitude and direction of the torsional and lateral loading to be computed. Additional details were given by Li et al. (2017).

The dry shaft construction method was used to construct the test shafts. The excavation of TDSFB was intentionally overdrilled by 150 mm. Bentonite chips were then placed evenly across the bottom of the cavity and separated from the concrete with plywood to create a near-zero base resistance condition. The cavity of TDS was unintentionally overdrilled by approximately 150 mm. Although the additional length could provide additional lateral and torsional resistance, the contribution of resistance from the additional length in the medium stiff silty clay and clayey silt was significantly smaller than that from the 1-m-thick dense silty sand layer immediately above the base (Fig. 2). The instrumented steel cages were lowered into the excavations using wheel spacers to center the cages. During the casting of the shafts, concrete cylinders were collected, and the compressive strength of the concrete was measured; the average compressive strength of the concrete was 42 and 46 MPa for TDS and TDSFB on the test day, respectively.

**Progressive Development of Lateral Load**

The torsional loading test was conducted using two hydraulic actuators in displacement control. Quasi-static torsional loading was initially conducted with 35 loading increments followed by 20 loading-unloading cycles, as described by Li et al. (2017). Due to the strength of the dense silty sand layer near the base of TDS, and variations in shaft geometry with depth (Li et al. 2017; Li 2017), TDS and TDSFB did not rotate equally throughout the loading test (Fig. 3). Although the self-reacting test setup was designed to produce pure torsion, the differences in shaft geometry and torsional interface shear response resulted in different global twisting stiffness with increasing applied torque. The difference in twisting stiffness between the two shafts and significant softening of the interface for TDSFB, along with the prescribed displacement control of the actuators led to the development of flexure, and nonzero net lateral displacement and corresponding lateral loads as the nonlinear torsion response evolved.

At the end of quasi-static torsional loading, TDS had rotated approximately 0.14° (including 0.04° due to creep), whereas TDSFB rotated approximately 13°. Spiral-type cracks approximately 300 mm in length and 6 mm in width developed adjacent to TDSFB over the course of quasi-static loading as the torsional resistance of the shaft was achieved [Fig. 3(b)]. The manifestation of these shear-induced cracks, developed under largely torsional loads, would provide a soft lateral response in the event of the application of lateral loading due to progressive closure of the gaps followed by passive pressure loading of highly strained soil. Over the course of continued rotation of TDSFB, the difference in mobilized resistance along the various portions of the soil–shaft interfaces indeed resulted in flexure and the progressive development of lateral loads. The development of the lateral loading in this

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manner is possible under displacement-control when differences in shaft geometry (both circumferentially and with depth) and inherent variability of the stiffness and strength of the soil–shaft interfaces exist. When TDSFB was in a state of geotechnical torsional failure, e.g., at a shaft head rotation of 1.75° (corresponding to 0.1° for TDS; Fig. 3), the lateral load that had developed was 5.6 kN. This increased to 73.4 kN by the time TDSFB achieved 13° of head rotation.

**Observed Lateral Response and Discussion**

**Load-Displacement Response at Shaft Head**

The global lateral response at the head of each test shaft was observed throughout the loading tests, as shown in Fig. 4, which indicates significant differences. The global lateral resistance increased near-linearly during the monotonic quasi-static torsional loading for both shafts. However, the initial lateral stiffness of TDSFB was approximately one-fourth that for TDS, which did not achieve an ultimate, quasi-static torsional resistance. The significantly softer response cannot be explained by differences in the soil stratigraphy (Fig. 2), as shown by calculations of the lateral response described subsequently. The maximum lateral displacement at the end of quasi-static loading was 21 mm for TDSFB, whereas TDS exhibited just 5 mm of lateral movement. Upon initiation of the cyclic loading protocol (Li et al. 2017), the incidental lateral load dropped to ~55 kN and was maintained as lateral displacements accumulated in both shafts with increasing number of cycles.

These findings suggest that current design protocols for deep foundations subject to lateral loads may be neglecting a critical mechanism of deformation for scenarios in which combined cyclic loading is possible. Fig. 3 shows that torsional failure is a small rotation phenomenon for relatively rigid shafts [see Li and Stuedlein (2018) regarding effects of torsional rigidity on foundation rotations]. Therefore, where torsional loading produces geotechnical torsional failure prior to the application of a significant lateral load (e.g., sites experiencing forward directivity effects that result in large velocity pulses), the lateral resistance may be significantly smaller than that assumed under the single-load scenario.

The softer response of TDSFB can be attributed to the closure of torsion-induced cracks [Fig. 3(b)] and the shearing of overconsolidated soils that exhibited softening behavior, as reported for axial and lateral loading tests of other drilled shafts by Li et al. (2018) and Li (2017). Although the vertical extent of cracking was not observed, the unit shaft resistance along all instrumented tributary areas of TDSFB was fully mobilized at large rotations (e.g., >0.5°), with some interface depths softening prior to cyclic softening, whereas TDS did not experience rotations sufficient to mobilize the strength along its soil–structure interface (Li et al. 2017). Similar ground cracking was observed by McVay et al. (2003), Hu et al. (2006), and Thiyyakkandi et al. (2016), and the evidence for reduced lateral resistance under combined loading appears to point to torsion-induced softening.

**Lateral Load Transfer**

The curvature, $\phi$, at the instrumented depths, $z$, was calculated using the measured flexural strains and

$$\phi(z) = \frac{\varepsilon_T(z) - \varepsilon_C(z)}{h}$$  

where $\varepsilon_T(z)$ and $\varepsilon_C(z)$ = measured tensile and compressive strain, respectively, at depth $z$; and $h$ = horizontal distance between strain gauges. Bending moment profiles were then computed by relating

![Fig. 3. Relationship between torque and applied rotation for the test shafts under quasi-static loading: (a) full results for very large rotations of TDSFB, with inset showing the rotation response of TDS; and (b) observed and extrapolated torque and applied rotations, with inset photo showing ground cracking.](image)

![Fig. 4. Measured and calculated global load-displacement response for the test shaft using LPILE and DFSAP.](image)
the curvature from Eq. (1) to the simulated moment-curvature response of each shaft (described in Fig. S1 of the Supplemental Data). Fig. 5 shows the measured bending moment profiles for the test shafts and indicate that the shafts responded in a short or rigid manner due to the observed lack of contraflexure (Broms 1964). It appears that the base of shaft TDSFB was relatively free to rotate in bending due to the bentonite layer beneath the shaft, whereas it may be inferred that the soils at the base of shaft TDS provided partial restraint in bending. The maximum induced bending moment for TDS and TDSFB was 192 and 280 kN·m, respectively (~28% and 40% of $M_{ult}$). Although differences in the observed moment profiles between TDS and TDSFB can be attributed to differences between the soil stiffness and strength, the reduction of lateral resistance and the increase in lateral displacement due to the rotational shear-induced softening of the soil surrounding TDSFB can explain the majority of the differences. Torsionally induced shear failure prior to significant lateral foundation movements can thus lead to bending moments that will be greater than those anticipated for lateral loading alone. Both shafts remained essentially elastic in flexure, whereas shaft TDS performed inelastically in torsional shear as indicated by the structural shear cracking described by Li et al. (2017).

**Numerical Analysis for Test Shafts under Lateral Loads**

In an effort to demonstrate deviations in the observed lateral response from that expected in the absence of torsion, the lateral load transfer of the tests shafts was computed using commonly available

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**Fig. 5.** Comparison of the measured bending moment profiles at different pile head displacement and the calculated profiles: (a) using LPILE for TDS; (b) using LPILE for TDSFB; (c) using DFSAP for TDS; and (d) using DFSAP TDSFB.
software LPILE version Lpile2016 (Ishenower and Wang 2015) and DFSAP version 1.0 (Singh et al. 2006). LPILE is generally used to analyze deep, flexible foundations under lateral loading using the p-y method (e.g., Matlock 1970; Cox et al. 1974; Reese et al. 1975; Reese and Welch 1975; API 1993), whereas DFSAP is based on the strain wedge model developed by Norris (1986) and Ashour et al. (1998). The p-y curve models used in LPILE and other soil properties used in LPILE and DFSAP are summarized in Tables 1 and 2 for TDS and TDSFB, respectively. DFSAP requires the specification of zero base shear resistance. However, the expected unit shear resistance-displacement curve at the toe of TDS was modeled in LPILE in an effort to capture this anticipated effect. Fig. 4 compares the calculated and measured global load-displacement response for each test shaft. The calculated initial global response of TDS was best modeled using the strain wedge formulation by DFSAP, because LPILE produces a somewhat stiffer initial response. Both LPILE and DFSAP produced significantly stiffer initial responses than those observed for TDSFB, indicating that the lack of incorporation of torsional-induced shear softening resulted in an overestimation of the response. The calculated bending moment profiles for each test shaft at selected lateral displacements were compared with the measured profiles in Fig. 5. It appears that both models can capture the general depth-dependent trend of the bending moment; DFSAP was more accurate for the magnitudes of global lateral displacements imposed. In addition, the maximum bending moment computed using DFSAP was more accurate for the range of head displacements observed during the tests. However, neither model captured the location of the observed maximum bending moment accurately, nor the effect of combined torsional and lateral loading. Clearly, numerical approaches that can consider combined loading need to be developed.

Summary and Conclusions

The effect of combined torsional and lateral loading was evaluated using full-scale loading tests of instrumented drilled shafts. During the larger magnitudes of applied torsion, lateral loads developed in response to the differences in the soil–structure interaction of the two shafts and due to nonuniform shaft geometries and closure of torsion-induced shear cracking and soil softening. During the loading test, both shafts performed essentially elastically in flexure, whereas shaft TDS exhibited inelastic torsional shear and produced structural shear cracking. The global lateral load-deflection response of the shaft that experienced geotechnical torsional failure was significantly less stiff than the shaft that did not experience geotechnical torsional failure. The torsional response of deep foundations is significantly affected by weak and/or strain-softening soils, the latter of which may result in torsional-induced shear cracking and corresponding flexure. Critically, torsionally induced shear failure prior to significant lateral movements can lead to displacements and bending moments that may be significantly greater than those foundations subject to lateral loading alone.

Acknowledgments

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Supplemental Data

Fig. S1 is available online in the ASCE Library (www.ascelibrary.org).

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