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VERIFICATION OF SIGNAL POLE SHAFT FOUNDATION LRFD DESIGN USING FINITE ELEMENT METHOD

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This study presents verification methods of current shaft foundation design under linear lateral and torsional loads. Shaft is used as a foundation to support mast arm signal pole structure and transfer loads from superstructures to ground. The capacity of current shaft foundation deployed in the State of Maryland is re-verified due to higher sub-structural strength requirement against super-structural fatigue proposed from the AASHTO LRFD Specification (2015). The shaft foundation verification includes embedment length and torsional capacity. For embedment length check, lateral reactions between soil and shaft are verified by comparing analytical method and finite element method. Wind-induced torque is a design concern for the shaft of a single pole cantilever structure. However, torsional capacity of the shaft foundation of signal pole structures is rarely mentioned in the current design specification. By verifying finite element models with analytical method, torsional effect is further simulated to finite element models to evaluate the adequacy of current shaft foundation design. Results show existing design of shaft foundation could meet requirements to resist lateral force under extreme conditions. For torsional effect, current torsional capacity is less than the torque induced by wind load in the worst soil conditions.

Keywords: Pile foundation, Soil-structure interaction, Lateral capacity, Torsional capacity.

1 INTRODUCTION

In Maryland, drilled shaft is used as the foundation of mast arm traffic signal structures. The drilled shaft can be referred as a bored-cast-in-situ pile and it is one type of deep foundations which facilitate load from superstructures to transfer to deeper firm strata (Murthy 2003). Drilled shafts are generally utilized for bridges and large-scale structures since they may resist high vertical force, lateral force, ground moment and torsional load. The mast arm signal pole structures in the State of Maryland are designed based on 1994 AASHTO. However, fatigue design was not made in the AASHTO Specifications until 2001, and thus fatigue load demand on mast arm signal support structures. To provide more resistance against fatigue, the size of super-structures is required to be modified. Along with size enlargement, reactions from super-structure applying on the shaft also increase. Therefore, the capacity of shaft is supposed to be verified to meet higher requirement. Shaft embedment length is a main factor of checking to provide adequate load capacity and acceptable displacement with various soil properties.

2 LITERATURE REVIEW

2.1 Lateral Soil Reaction

According to the category in Broms (1964), behaviors of shaft can be classified as long pile and short pile for free-head and fixed-head piles by a dimensionless quantity, $\beta = (\frac{kD}{4EI})^{0.25}$, shown in Table 1, where EI is stiffness of pile section, k is coefficient of horizontal subgrade reaction, D is diameter of pile, and L is length of pile.

Table 1. Pile classification under laterally loaded (Broms 1964).

Pile type	Long Pile	Short Pile
Free-head Pile	$\beta L > 2.5$	$\beta L < 2.5$
Fixed-head Pile	$\beta L > 1.5$	$\beta L < 1.5$

Shaft foundation is usually classified as a short pile which behaves rigidly. Failure of laterally loaded pile occurs either when bending moment of pile reaches ultimate or lateral earth pressure reaches ultimate lateral soil resistance. Soil is assumed as a series of linear or non-linear springs connected with pile foundations to represent the interaction between soil and piles. Unlike rigid analyses merely viewing soil reaction as a force, the soil-structure interaction, soil's response to lateral loads and deformation of soil, is considered. Those assumptions are essential to conduct numerical analyses and finite element model establishment. Soil spring is a concept proposed by Winkler which is numerical solutions of soil lateral force termed as soil. Soils surrounded with pile foundation are approximated by a series of independent elastic springs. However, Winkler's hypothesis does not account for soil deformation and limited with surface load applied. The p-y method simulates the soil resistance as nonlinear behavior, where p is the soil pressure per unit length of the pile and y is the pile deflection which is applicable for numerical model by using a two-dimensional finite difference analysis.

2.2 Torsional Capacity

In the AASHTO Standard Specifications for Structural Support for Highway Luminaires, and Traffic Signals (2015), torsional capacity of shaft foundation is not considered in the design procedure. However, torsional load transfer between drilled shaft and soil is relatively critical when wind load is applied. In the analytical method, torsional capacity consists lateral resistance and bottom resistance and could be expressed as in Eq. (1) (Stuedlein *et al.* 2016):

$$T_{total} = T_s + T_b \tag{1}$$

where T_{total} is total torsional resistance, T_s is lateral torsional resistance and T_b bottom torsional resistance. The torsional resistance is caused by either cohesion of soil or friction between soil and shaft. For cohesive soil, the resistance is caused by cohesion of soil related to soil contacting area of foundation. The adhesion factor, α, is the ratio between cohesion and undrained shear strength. For cohesionless soil, the resistance is mainly from the friction between shaft and soil caused by earth lateral force and self-weight of foundation. The β-Method (O'Neill and Hassan 1994) is employed to estimate unit torsional resistance for shaft surrounded with cohesionless soil under axial loading. β factor is the load transfer ratio of effective soil stress and soil resistance. Comparison of different methods is shown and discussed below.

3 ANALYTICAL VERIFICATION

3.1 Embedment Length

For cohesive soil, the shaft embedment length is determined by shaft diameter (D), ultimate shear strength of soil, moment, and shear at groundline. The required embedment length (L) can be defined in Eq. (2) as:

$$\boldsymbol{L = 1.5D + q[\,1 + \sqrt{2 + \frac{(4H+6D)}{q}}\,]} \tag{2}$$

where $\boldsymbol{H = \frac{M_F}{V_F}}$, $\boldsymbol{q = \frac{V_F}{9cD}}$,$\boldsymbol{M_F}$ is factored moment at groundline, $\boldsymbol{V_F}$ is Factored shear at groundline, and c is the ultimate shear strength of cohesive soil. For cohesionless soil, shaft embedment length is determined by shaft diameter, angle of internal friction, effective unit weight, moment, and shear at groundline (Eq. (3) and Eq. (4)),

$$\boldsymbol{L^3 - \frac{2V_F L}{K_p \gamma D} - \frac{2M_F}{K_p \gamma D} = 0} \tag{3}$$

$$\boldsymbol{K_p = \tan^2(45 + \frac{\varphi}{2})} \tag{4}$$

where $\boldsymbol{\gamma}$ is unit weight of cohesionless soil.

3.2 Torsional Capacity

There are four analytical methods including Florida Structure Design office method (FSDM), Florida District 7 (FD7), Colorado DOT (CDOT), and Illinois DOT (IDOT) used for torsional capacity check as Table 2,

Table 2. Torsional capacity methods.

Method	**Soil Type**	**Unit resistance (r_s)**	**Lateral resistance (T_s)**	**Bottom resistance (T_b)**
FSDM	cohesionless	$K_0 \sigma'_{vz} tan\delta$	$0.5\pi D^2 L r_s$	$DWtan\delta/3$
FD7	cohesionless/cohesive	$\alpha S_u K_0 + \sigma'_{vz} tan\delta$	$0.5\pi D^2 L r_s$	$4D(W + Q_a)tan\delta/9$
CDOT	cohesionless	2L(1-sinφ) $\sigma'_{vz} tan\delta/3D$	$0.5\pi D^2 L r_s$	$DWtan\delta/3$
	cohesive	Su	$0.5(\pi D^2)(L\text{-}1.5D)Su$	$(\pi D^3)Su/12$
IDOT	cohesionless	$\beta\sigma'_{vz}$	$0.5\pi D^2 L r_s$	
	cohesive	αSu	$0.5\pi D^2 L r_s$	

where $\boldsymbol{K_0}$ is the at-rest lateral earth pressure coefficient, $\boldsymbol{\sigma'_{vz}}$ is the effective vertical stress at the midpoint of the layer of interest, and $\boldsymbol{\delta}$ is the effective soil-shaft interface friction angle, D is the shaft diameter, and L is the shaft length, W is the shaft weight, the axial load applied on the drilled shaft, and $\boldsymbol{S_u}$ is the average undrained shear strength over the depth of interest. The major differences between those methods are unit resistance estimate and bottom resistance. The β-Method for shafts under axial loading is used by IDOT. β is the load transfer ratio for effective-stress normalized unit shaft resistance and has been correlated to depth and the STP blow count, N. In CDOT Design Method, the unit shaft resistance in cohesive soils is equal to the undrained shear strength over the depth of interest, and the side resistance in cohesive soils for the top 1.5D of the shaft is neglected.

4 ANALYTICAL VERIFICATION FOR GENERAL SOIL IN MARYLAND

In the embedment length check, soil conditions are assumed as general soil properties in Maryland shown in Table 3.

Table 3. Assumed properties of soil for hypothetical cases.

Soil Type	Soil Category	Shear Strength	Unit Weight	Internal Friction Angle
Cohesive	Stiff clay	2.16 (ksf)	N/A	N/A
Cohesionless	Clean gravel-sand	N/A	0.12 (kcf)	30

4.1 Embedment Length Check

The external loads including ground and moment are factored by LRFD Strength I. Both resultant shear force and moment are the root mean square of combined loads in the x and z directions and the load factor is 1.6. The highest required length case is 75 feet arm structure in cohesive soil and its required length is 9.33 feet close to current design length 10 feet.

4.2 Torsional Capacity Check

In cohesive soil, the torsional capacity estimated by all of four methods is enough to resist horizontally rotation factored by LRFD Strength I load combination in worst condition. In cohesionless soil, most of torsional capacity is insufficient when external load reaches the peak value. The torsional check result is listed in Table 4.

Table 4. Torsional capacity check (kip-ft).

Cohesive				
Method	**Lateral**	**Bottom**	**Total Capacity**	**Maximal Torque**
FD7	290.80	19.34	310.14	> 131.81
CDOT	214.14	36.19	253.33	> 131.81
IDOT	298.57	N/A	298.57	> 131.81
Cohesionless				
Method	**Lateral**	**Bottom**	**Total Capacity**	**Maximal Torque**
FSDOM	43.53	14.51	58.04	< 131.81
FD7	37.00	19.34	56.34	< 131.81
CDOT	72.55	17.65	90.20	< 131.81
IDOT	161.81	N/A	161.81	> 131.81

5 FINITE ELEMENT MODELING

The shaft foundation dimension and soil properties are given in Table 3. Two-dimensional (2D) model is designed for Broms' simplified analysis mentioned in AASHTO, as shown in Figure 1. The model is built on XY plane and the external force including shear force and moment at groundline. The soil spring is assumed homogeneous and located at the other side of shear force. Three-dimensional (3D) model is designed for all external forces including three translational forces (i.e., moments about the z and x axes, and torsion) as shown in Figure 2.

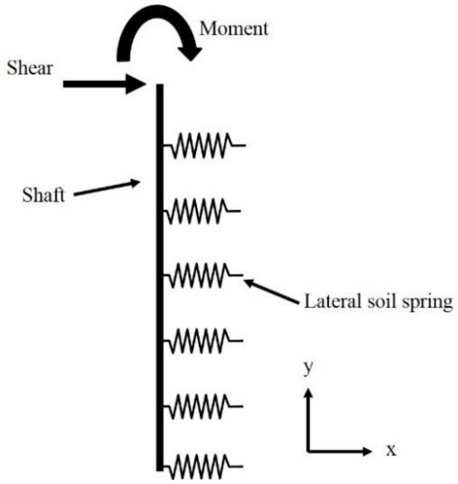

Figure 1. 2D Model demonstration.

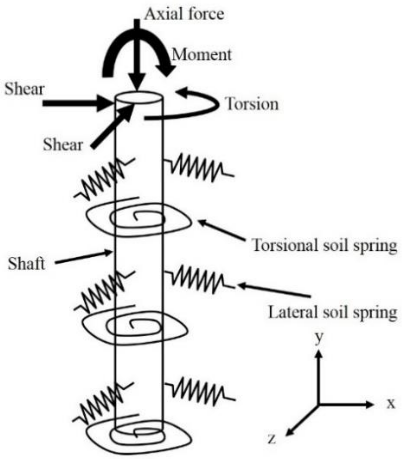

Figure 2. 3D Model demonstration.

The method to estimate soil subgrade modulus is first proposed by Terzaghi in 1955. Modulus of subgrade reaction of soil could be transformed into stiffness of soil spring representing the relationship between soil deformation and reaction from lateral, vertical, and torsional directions. Rigid analyses are used for light weight and short pile loaded laterally such as highway sign (Coduto 2001). Since shaft is defined as short pile and external loading is static and specified, the soil spring is considered under linear range. Based on soil properties mentioned before, lateral and vertical soil springs stiffness could be obtained from the Table 5 (Fu and Wang 2014). For cohesive soil, the stiffness of lateral soil spring is associated with undrained shear. The soil properties are assumed homogeneous; therefore, the stiffness of cohesive lateral soil spring stays constant along depth. For cohesionless soil, the stiffness of lateral soil spring is a function of depth. Thus, the stiffness distribution is triangular. Vertical soil spring is designed for controlling shaft's vertical displacement under acceptable range. The vertical soil spring is defined as a point spring which is either associated with undrained shear strength for cohesive soil or average standard penetration blow count. Torsional spring is currently used in pile foundation analysis program such as FB-MultiPier (2011). The torsion-angle (T-θ) curve is assumed as a hyperbolic curve and torsional stiffness listed in Table 5 is the slope of T-θ curve function at certain angle.

For finite element model, beam element with tension, compression, and bending capabilities is used to represent shaft body and spring-damper element without mass is used as soil spring to restrict shaft's horizontal, vertical and torsional degree of freedom. By assigning external force at shaft top, the maximal reaction moment is used as an indicator to compare the difference between finite element methods and analytical method. The results of 2D model ($\boldsymbol{M_{f2D}}$), 3D model ($\boldsymbol{M_{f3D}}$) and analytical method ($\boldsymbol{M_u}$) are listed in Table 6.

Table 5. Parameters for soil spring.

	Lateral springs		Vertical springs		Torsional springs	
Soil type	P_u	k_h	$q_{max}(ksf)$	k_q	**G**	k_t ***(kip-ft)***
Clay	$9c_uB$	$67c$	$9c_u$	$8N_{corr}$	$kz/2(1+v)$	$4\pi Gr^2\Delta L$
Sand	$3\gamma Bk_px$	n_px	$10q_{max}/z_c$	$10q_{max}/z_c$	$\beta C_u/2(1+v)$	$4\pi Gr^2\Delta L$

Table 6. Maximal moment from Analytical and FEM methods.

Length (ft)	**Soil Type**	**M_u (kip-ft)**	**M_{f2D} (kip-ft)**	**Diff %**	**M_{f3D} (kip-ft)**	**Diff %**
50	Cohesive	147.07	149.56	1.66	149.43	1.57
	Cohesionless	133.62	139.92	4.5	139.89	4.48
60	Cohesive	166.28	166.14	-0.08	165.82	-0.27
	Cohesionless	145.09	151.78	4.4	151.81	4.42
70	Cohesive	199.06	198.87	-0.09	198.37	-0.34
	Cohesionless	175.58	182.38	3.78	182.29	3.68
75	Cohesive	206.98	206.80	-0.08	206.24	-0.35
	Cohesionless	183.11	189387	3.56	189.75	3.49

6 CONCLUSION

The finite element model has been demonstrated to be an effective approach to simulate shaft foundation of mast arm signal pole structure under linear range in the previous chapters. Results from traditional analytical method should be more conservative but easier to obtain. Based on general soil properties in Maryland, the existing design of shaft foundation can resist lateral force sufficiently. However, along with increasing arm length, required embedment lengths are close but adequate to the design lengths. Torsional capacity is less than the torque induced by wind load in the worst case when the shaft foundation is installed in cohesionless soil.

The outcome from two-dimensional and three-dimensional models is consistent in either cohesive or cohesionless soils. Results from various dimensions of shaft are also consistent in 2D and 3D models. Therefore, 3D model could be simplified by vector summing moments and shears along two horizontal axes as 2D model in lateral reaction analysis. The lateral reaction performance of the 3D model assigned with all external loads seems less conservative than Broms' analytical method. Therefore, foundation design based on the current AASHTO design specifications would cover lateral soil reaction capacity even considering the torsional effect (Hou 2017).

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