Quality control of helical piles in sand

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ABSTRACT
The installation torque of helical piles has been employed as a tool for quality control on site of this type of foundation. This procedure is based on the empirical torque correlation factor K_T, which relates the uplift capacity to the torque required to install helical piles to the desired depth. This work presents a simplified theoretical equation that describes the physical meaning of K_T, recommended to helical piles installed in sand. A series of centrifuge and direct shear interface tests were performed in order to validate the component of this proposed expression related to the contribution of helical plates to the uplift capacity. A comparison of uplift helix bearing capacity from theoretical and experimental results showed good agreement. In addition, the measured results of K_T obtained in this study were compared with field and laboratory results reported in the literature. The results of this evaluation showed that the magnitude of K_T decreases with an increase in pile dimensions and in sand friction angle. These observations are confirmed by the expression proposed in this paper.

RÉSUMÉ
Le couple nécessaire à la mise en place de pieux hélicoïdaux a été utilisée comme outil de contrôle de la qualité de ce type de fondation. Cette procédure est basée sur le facteur empirique de couple K_T, qui est la relation entre la capacité portante et le couple requis pour l'installation des pieux hélicoïdaux à la profondeur désirée. Ce travail présente une équation simplifiée théorique qui décrit la signification physique de K_T, recommandé au pieux hélicoïdaux installés dans le sable. Des essais en centrifugeuse et des essais à la boîte de cisaillement ont été réalisées afin de valider la composante de cette expression proposée relative à la contribution des hélices à la résistance à l'arrachement. La comparaison entre les résultats théoriques et expérimentaux de la charge d'arrachement relative aux hélices ont montré un bon accord. En plus, les résultats mesurés de K_T obtenus dans cette étude ont été comparés aux résultats sur site et de laboratoire rapportés dans la littérature. Les résultats de cette évaluation ont montré que le facteur K_T diminue avec une augmentation des dimensions du pieu et de l'angle de frottement du sable. Ces observations sont confirmées par l'expression proposée dans le présent papier.

1 INTRODUCTION

Helical pile foundations are usually used to resist tensile loads. The use of helical pile includes foundations for transmission towers, light poles, residential and commercial buildings, and many other structures. They are made out of helical-shaped circular steel plates welded to a steel shaft at a given spacing. This type of pile is installed into soil by applying a torque to the upper end of the shaft using hydraulic motors mounted on light equipment.

The uplift capacity of helical piles has been controlled by the torsional resistance to the pile penetration recorded during installation. This practice is based on the empirical torque correlation factor K_T, which relates the uplift capacity to the torque required to install helical piles to the desired depth, although a number of theoretical correlations had been reported in the literature (Narasimha Rao et al., 1989; Ghaly et al., 1991; Ghaly and Hanna, 1991; Perko, 2000; and Perko 2009).

This empirical correlation, supported by statistical analysis, is widely used in the industry to predict the uplift capacity of helical piles because it is simple to use and provides a procedure to verify if the predicted design loads have been reached at the site location (Zhang,1999).

Tsuha & Aoki (2010) presented a theoretical model which correlates the uplift capacity with the installation torque of helical piles in sand, recommended to be employed as a tool for quality control, inspection and performance monitoring of helical piles. This relationship expresses the physical meaning of the empirical relationship symbolized by K_T in sandy soils.

Series of centrifuge model tests were carried out on twelve types of model piles, installed in two sand samples with different relative densities, in order to validate the component of expression described in Tsuha & Aoki (2010) related to the contribution of helical plates to the uplift capacity. In addition, as the residual friction angle between helix surface and surrounding sand is a fundamental parameter of the theoretical relationship proposed in this work, direct shear interface tests were conducted to find the residual interface friction angle between helix material and the surrounding sand employed in centrifuge tests.

This manuscript presents a comparison of uplift helix bearing capacity from theoretical and experimental results. Also, the measured results of the torque correlation factor K_T found in the present investigation were compared with the available field and laboratory results reported in the literature.

2 THEORETICAL MODEL

The resisting moments acting on a three-helix helical pile during installation and the resisting forces to the upward pile movement in sand, assumed in the present theoretical model, are shown in Figure 1.

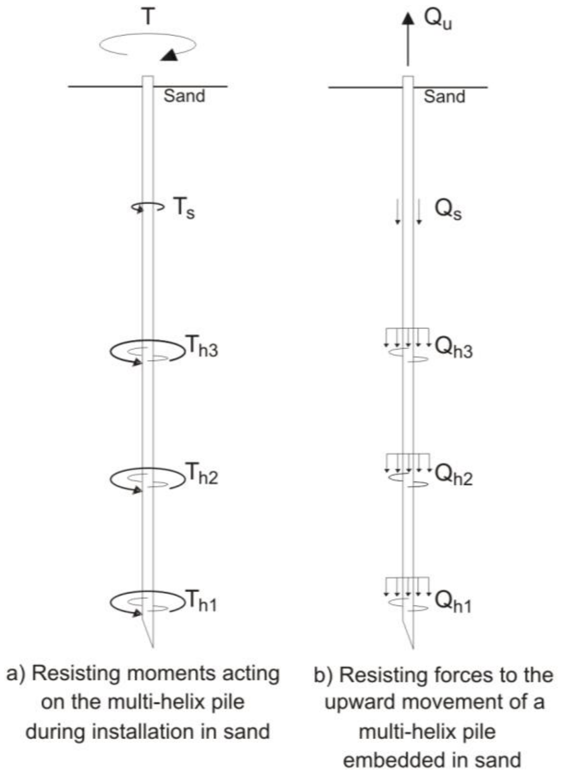

Figure 1. Assumed resisting moments and forces in the present approach (Tsuha et al.,2007).

The torque required to pile installation *T*, can be given by the following expression:

$$T = T_h + T_s \qquad [1]$$

where *T* = installation torque; T_h = resisting moment acting on the helix; and T_s = resisting moment acting on the pile shaft.

The resisting moment acting on the helix T_h is expressed as:

$$T_h = \sum_{i=1}^{N} T_{hi} \qquad [2]$$

where T_{hi} = resisting moment acting on the helix *i*; *i* = index from 1 to *N*; and *N* = number of helices.

The uplift capacity Q_u, showed in Figure 1, can be given by the following equation:

$$Q_u = Q_h + Q_s \qquad [3]$$

where Q_u = uplift capacity; Q_h = uplift helix bearing capacity; and Q_s = shaft resistance.

The uplift helix bearing capacity Q_h is expressed as:

$$Q_h = \sum_{i=1}^{N} Q_{hi} \qquad [4]$$

where Q_{hi} = uplift bearing capacity of the helix *i*; *i* = index from 1 to *N*; and *N* = number of helices.

The present model considers that failure occurs above each individual helix as the A.B. Chance method reported by Clemence et al. (1994). Consequently, this approach is recommended for helical piles which have the space between any two helices larger than three times the helix diameter.

There are two fundamental physical relationships in this proposed model deduced in Tsuha & Aoki (2010). The first is between the shaft resistance Q_s and the resisting moment acting on the pile shaft T_s. The second is between the uplift helix bearing capacity Q_h and the resisting moment acting on the helices T_h.

2.1 Relationship between Q_s and T_s

The shaft resistance of helical piles under axial loading is represented by the shaft resistance derived from the torsional loading during pile installation. The relationship between shaft resistance Q_s and resisting moment acting on the pile shaft T_s, measured at the end of pile installation, can be given by the following equation, presented in Tsuha (2007):

$$Q_s = \frac{2T_s}{d} \qquad [5]$$

where *d* = shaft external diameter.

2.2 Relationship between Q_h and T_h

The proposed relationship between the uplift helix bearing capacity Q_h and the resisting moment acting on the helices T_h at the end of pile installation is given by the following equation, proposed by Tsuha (2007):

$$Q_h = \frac{2T_h}{d_c . tg(\theta + \delta_r)} \qquad [6]$$

where d_c = diameter of a circle corresponding to the helix surface area, where the resisting forces are concentrated during pile installation (Equation 7 and Figure 2); θ = helix angle with the horizontal at d_c (Equation 8 and Figure 2); and δ_r = residual interface friction angle between helix material and surrounding sand.

$$d_c = \frac{2}{3}\left[\frac{D^3 - d^3}{D^2 - d^2}\right] \qquad [7]$$

$$\theta = tan^{-1}\left(\frac{p}{\pi d_c}\right) \qquad [8]$$

where *D* = helix external diameter; *d* = shaft external diameter; and *p* = helix pitch.

This relationship presented in Equation 6 is applicable to helical piles in dry sand with one or more identical helical plates, spaced in a distance larger than three times the helix diameter (spacing currently used for helical piles in the practice).

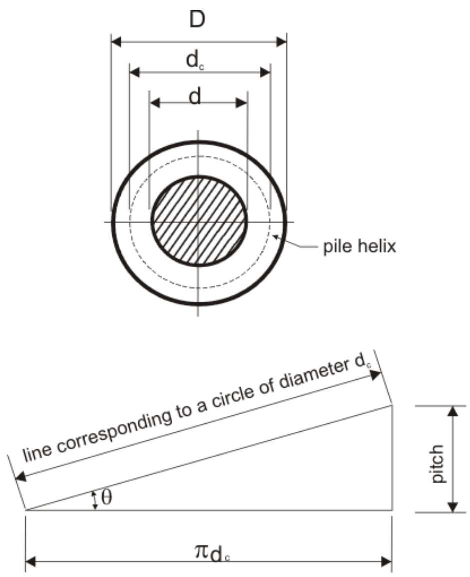

Figure 2. Helical pile helix (Tsuha, 2007)

2.3 Relationship between Q_u and T

Substituting Equations 5 and 6 in the Equation 3, the relationship between the uplift capacity Q_u and the components of the installation torque T_h and T_s can be expressed by the following equation:

$$Q_u = \frac{2T_h}{d_c.tg(\theta + \delta_r)} + \frac{2T_s}{d} \qquad [9]$$

Therefore, Equation 9 is composed of two parts. The first component is the uplift helix bearing capacity Q_h represented by Equation 6, and the second component is the shaft resistance Q_s represented by Equation 5.

3 TORQUE CORRELATION FACTOR

The torque correlation factor K_T indicates the magnitude of the relationship between uplift capacity and installation torque of helical piles. This factor is typically used in the practice of helical piles as a instrument for the pile capacity control during installation. The verification of this factor K_T at the end of helical pile installation is equivalent to the verification of the permanent set of driven piles. The both procedures are useful tools for the capacity control of piles during installation.

Hoyt and Clemence (1989) expressed the uplift capacity calculated from installation torque as:

$$Q_u = K_t.T \qquad [10]$$

where K_T = torque correlation factor (K_T = 33 m^{-1} for all square-shaft anchors and round shaft less than 89 mm diameter, 23 m^{-1} for 89 mm diameter round-shaft anchors, and 9.8 m^{-1} for anchors with 219 mm diameter extension shafts); Q_u = uplift capacity; T = average installation torque (the installation torque should be averaged for the final distance of penetration equal to three times the diameter of the largest helix).

3.1 Physical meaning of K_T in sand

Combining the Equation 6 with the Equation 10 it could be possible to obtain the torque factor K_T for the cases where there is no shaft resistance during pile installation and loading (it was considered that $Q_u = Q_h$ and $T = T_h$). In this situation the torque factor K_T is:

$$K_T = \frac{2}{d_c.\tan(\theta + \delta_r)} \qquad [11]$$

The Equation 11 is suggested to deep helical piles in sand, with identical helix dimensions (d_c and θ) and surrounding sand δ_r, when the fractions of the uplift capacity and of the installation torque associated to the resistance on pile shaft, are not significant. In cases where the shaft resistance is considerable, the torque factor K_T must be obtained by combining the Equations 9 and 10. Therefore, the factor K_T can be calculated by the following equation:

$$K_T = \frac{2\left(\frac{T_s}{d} + \frac{T_h}{d_c.\tan(\theta + \delta_r)}\right)}{T} \qquad [12]$$

The torque factor K_T for helical piles with different helix diameters and surrounding sand could be obtained by combining Equations 2 and Equation 12, as illustrated by the following expression:

$$K_T = \frac{2\left(\frac{T_s}{d} + \sum_{i=1}^{N} \frac{T_{hi}}{d_{ci}.\tan(\theta_i + \delta_{ri})}\right)}{T} \qquad [13]$$

The Equations 11 to 13 show the physical meaning, for deep helical piles embedded in sand, of the empirical relationship K_T, frequently used as an instrument to the quality control on site of the uplift capacity.

4 CENTRIFUGE TESTS

Centrifuge modelling tests were carried out at the Laboratoire Central des Ponts et Chaussées (LCPC) in France to validate the Equation 6. This equation, related to the contribution of helical plates to the uplift capacity, corresponds to the major component of the proposed relationship between uplift capacity and installation torque presented by Equation 9.

The Equation 6 contains five variables: d_c, θ, δ_r, Q_h, and T_h. In this investigation, d_c and θ values were determined by Equations 7 and 8. The results of Q_h, T_h, and δ_r were obtained by centrifuge and direct shear interface tests, respectively.

The present centrifuge physical modeling allowed the carrying out of several experiments on different models of helical piles in the same mass, with known properties.

Twenty-four pile loading tests were performed in this experimental investigation. Twelve model piles were tested in two different sand containers (Table 1).

Table 1. Sand properties.

Fontainebleau silica sand	
Property	Value
Grain-shape	Sub-angular
Unit weight of soil particles (kN/m^3)	25.90
Maximum dry density (kN/m^3)	16.68
Minimum dry density (kN/m^3)	14.13
Maximum void radio	0.834
Minimum void radio	0.550
Maximum porosity	0.455
Minimum porosity	0.355
Container 1	
Unit weight (kN/m^3) [a]	15.46
Density index (%) [a]	56
Friction angle (º) [b]	31
Container 2	
Unit weight (kN/m^3) [a]	16.30
Density index (%) [a]	85
Friction angle (º) [b]	41

[a] Estimated from four calibrated boxes placed on the bottom of each container
[b] Measured from direct shear test

Twelve types of model piles were fabricated with or without helix (Table 2 and Figure 3) to estimate the fraction of installation torque and uplift capacity related to the helical plates.

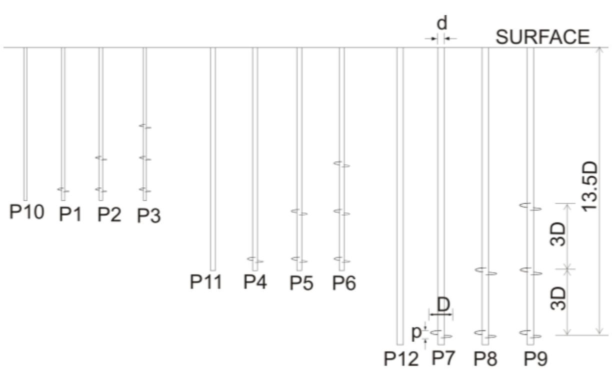

Figure 3. Model piles embedded in the sand sample.

Table 2. Model piles in prototypes dimensions.

Pile	Nº of helix	Shaft diameter (mm)	Helix diameter (mm)	Helix pitch mm)	Prototype embedded depth (m)
P1	1	64.3	214	64.3	3.1
P2	2	64.3	214	64.3	3.1
P3	3	64.3	214	64.3	3.1
P4	1	97.7	326	69.5	4.6
P5	2	97.7	326	69.5	4.6
P6	3	97.7	326	69.5	4.6
P7	1	132.0	440	77.0	6.2
P8	2	132.0	440	77.0	6.2
P9	3	132.0	440	77.0	6.2
P10	-	64.3	214	64.3	3.1
P11	-	97.7	326	69.5	4.6
P12	-	132.0	440	77.0	6.2

The centrifuge test model results converted into prototype scale are presented in Table 3. In this table, the results of resisting moment acting on the helix are the average values recorded at the end of pile installation (which corresponds to the resistance of the soil layer where the helices are finally installed), and the uplift capacity data correspond to the peak value (maximum value) found at the force versus displacement curve. More details about these centrifuge tests are given in Tsuha et al. (2007).

The results of Q_h and T_h were calculated by the difference between the records obtained from the tests performed on piles with helix and piles without helix, both with the same diameter and embedded depth in the sand mass.

Table 3. Centrifuge tests results in prototype values.

Sand mass	Model pile Nº	Resisting moment acting on the helix T_h (kN.m)	Uplift helix bearing capacity Q_h (kN)
Container 1 (I_D = 56%)	P1	0.3	14
	P2	0.4	19
	P3	1.0	43
	P4	1.6	46
	P5	3.2	83
	P6	3.3	112
	P7	4.1	69
	P8	4.9	108
	P9	5.3	150
Container 2 (I_D = 85%)	P1	1.9	60
	P2	2.8	88
	P3	4.1	116
	P4	7.7	177
	P5	12.5	234
	P6	10.7	275
	P7	22.4	413
	P8	35.1	475
	P9	35.1	475

The theoretical results of uplift helix bearing capacity Q_h were determined by substituting the experimental results of T_h (Table 3) and of δ_r in Equation 6. The values of δ_r were obtained by interface direct shear tests between helical plate material (surface roughness R_{max} between 4.7 and 8.7 μm) and sand samples used in the centrifuge tests. In these tests, the measured results of δ_r are 10.6 and 15.1 degrees (from sand samples of container 1 and container 2, respectively).

The comparison between predicted and measured uplift helix bearing capacity Q_h, converted to prototype results are illustrated in Figure 4. This figure shows a good agreement between theoretical and experimental results obtained from centrifuge tests.

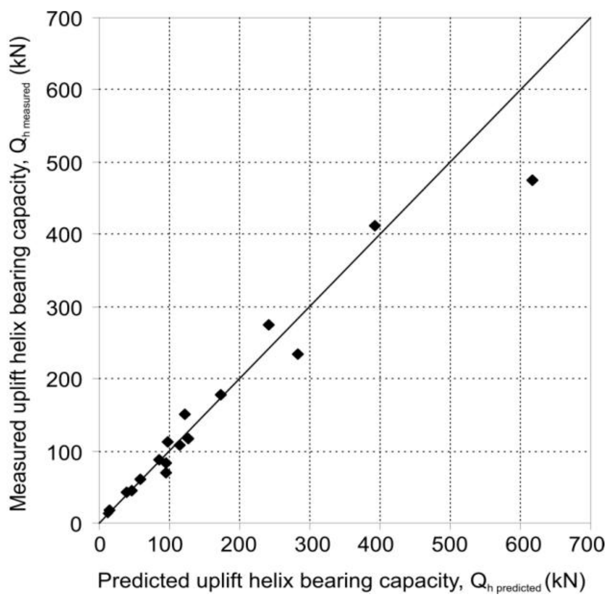

Figure 4. Comparison of measured and predicted uplift helix bearing capacities (Tsuha et al. 2007).

5 DIRECT SHEAR INTERFACE TESTS

Direct shear interface tests were carried out to obtain values of residual interface friction angles between helix material of a typical helical screw pile and different surrounding sands δ_r, to be employed in the determination of the theoretical torque factor K_T for helical piles in sandy soils.

Uesugi and Kishida (1986) demonstrated that coefficient of friction is influenced by the steel roughness, the average grain size (D_{50}), and sand type. Based on this fact, a sample of steel helical plate used in a typical helical screw pile (ASTM A36 surface roughness R_{max} =22.3μm) was tested with three types of sand with different D_{50}, relative density, and mineralogical properties (grain roundness and crushability).

The direct shear interface tests were performed with the Casagrande box. The sand was placed in the upper half of the box at the plate contact. These plates were dragged horizontally at a constant velocity. Table 4 shows the physical properties of the tested sands.

Table 4. Physical properties of tested sands (Tsuha & Aoki, 2010).

Property	Value
Sand 1	
Maximum dry density (kN/m^3)	15.88
Minimum dry density (kN/m^3)	13.68
Effective size, D_{10} (mm)	0.06
D_{50} (mm)	0.13
D_{60} (mm)	0.16
Grain-shape	subangular
Sand 2	
Maximum dry density (kN/m^3)	15.32
Minimum dry density (kN/m^3)	13.62
Effective size, D_{10} (mm)	0.12
D_{50} (mm)	0.29
D_{60} (mm)	0.33
Grain-shape	angular
Sand 3	
Maximum dry density (kN/m^3)	16.54
Minimum dry density (kN/m^3)	14.42
Effective size, D_{10} (mm)	0.20
D_{50} (mm)	0.52
D_{60} (mm)	0.61
Grain-shape	subangular

The results of a typical helical screw pile and different surrounding sands δ_r are presented in Table 5. This table shows that for this tested steel roughness the average grain size D_{50}, relative density, and mineralogical composition do not influence the results of the residual interface friction angles. This fact agrees with the conclusion drawn in Yoshimi and Kishida (1981), which stated that the frictional resistance between sand and metal surface was primarily governed by roughness of the metal surface. Also, Porcino et al. (2003) performed normal stiffness direct shear tests between aluminium plates at different surface roughnesses and sand samples with different mineralogical characteristics (different percentages of quartz), and the results showed that for plates with more significant roughness (30 μm) the δ_r (residual strength parameter) are similar and do not depend of the quartz percentage.

Table 5 shows that the sand relative density should be considered relatively uninfluent. Porcino et al. (2003) mentioned that it could occur because of the collapsible nature of the structure inside the shear band. The collapse of the structure would cause a loose interface to behave like a denser one.

The average value of δ_r found in these tests was 19.8° with a coefficient of variation of 10%. This value of δ_r is suggested to be used in the Equations 11 to 13 to control on site the uplift capacity of deep helical piles, fabricated with ASTM A-36 steel helical plates, or of similar roughness, installed in sandy soils.

Table 5. Interface residual friction angles between helix material of a typical helical screw pile and different surrounding sands (Tsuha & Aoki, 2010).

6 COMPARISON WITH THE LITERATURE RESULTS

Sand type	D_{50} (mm)	Density index I_D (%)	Residual interface friction angles δ_r
Sand 1	0.13	25	18.8º
		55	19.8º
		85	20.7º
Sand 2	0.29	25	19.0º
		55	21.9º
		85	22.9º
Sand 3	0.52	25	15.9º
		55	19.0º
		85	20.6º
Mean value of δ_r			19.8º
Standard deviation			2.0º
Coefficient of variation			10%

The K_T results reported in the literature for single and multi-helix deep helical piles installed in sand are showed in Table 6. This table presents results obtained from small scale laboratory models and full scale field tests. Also, Figure 5 shows a comparison between the K_T results obtained in the present centrifuge tests and found in the literature.

Table 6 and Figure 5 show that measured values of K_T, from smalls scale laboratory tests, ranged from 47 to 304 m^{-1}, and from centrifuge modeling and full scale field tests, ranged from 7 to 81 m^{-1}. This fact indicates that the torque correlation factor K_T is considerably influenced by the pile dimension. This observation agrees with the Equations 11 to 13 proposed in this manuscript. These equations show that K_T increases with a decrease of helical plate diameter (represented in these equations by d_c) and shaft diameter d.

Table 6. Values of torque correlation factor K_T found in the literature (Tsuha & Aoki, 2010).

Test type	Reference	Depth of top helical plate	Nº of helical plates	Pile dimensions (mm)	Soil	Torque correlation factor K_T (m^{-1})
centrifuge model tests	Tsuha (2007)	7.5 to 13.5 *D*	1 to 3	D = 214 to D=440 (*) d = 64.3 to d=132 (*)	Dry sand ϕ = 31° Dry sand ϕ = 41°	17 to 48 14 to 32
full scale field tests	Adams and Klym (1972)	12.6 *D*	2	D = 203 and 254 d = 89	Dry silty sand ϕ = 40°	16
	Mitsch and Clemence (1985)	8 *D*	3	D = 203, 253 and 287 d = 38	Dry sand ϕ = 35-40°	49 to 81
	Zhang (1999)	10.7 *D*	2 and 3	D = 356 d = 219	Dry sand ϕ = 39°	7
	Tsuha (2007)	44 *D*	2	D = 254 and 305 d = 95	Saturated clayed sand ϕ = 32°	24
	Livneh and El Naggar (2008)	17.3 and 26.3 *D*	3	D = 200, 250 and 300 d = 44.5	Saturated sand ϕ = 38 °	24.3 and 32.7
small scale laboratory model tests	Mitsch and Clemence (1985)	8 *D*	1 and 3	D =96 and D = 68, 84 and 96 d = 44.5	Dry sand ϕ = 35° Dry sand ϕ = 46°	83 to 128 47 to 60
	Ghaly et al. (1991)	8 to 16 *D*	1(**)	D =50 d = 18	Dry sand ϕ = 30° Dry sand ϕ = 35° Dry sand ϕ = 40°	60 to 90 80 to 110 79 to 107
	Ghaly and Hanna (1991)	8 to 16 *D*	1(**)	D =50 d = 16	Dry sand ϕ = 31° Dry sand ϕ = 36° Dry sand ϕ = 42°	253 to 304 241 to 281 167 to 226
	Ghaly (1995)	8 to 16 *D*	1	D =50 d = 18	Dry sand ϕ = 40 ° Saturated sand ϕ = 40 °	78 to 107 55 to 107

Note:
* Pile prototype dimensions
* Multi-helix piles fabricated with helices of the same diameter size
** It was considered only the piles with single medium pitch screw

Additionally, considering the cases in Table 9 where K_T decreases with an increase in ϕ, and that for these tested interfaces, the friction angle δ_r augments with an increase in ϕ, it could be confirmed that K_T reduces with an increase in δ_r, as demonstrated in Equations 11 to 13.

The results showed in Table 9 are in agreement with the proposed equations in this text to estimate theoretically the magnitude of torque correlation factor K_T. Considering that, and the validation of Equation 6 by centrifuge modelling tests (Figure 4) and by field tests (Tsuha, 2007), the present authors recommend the use of K_T calculated by Equations 11 to 13 to be employed to the quality control of helical piles in sand.

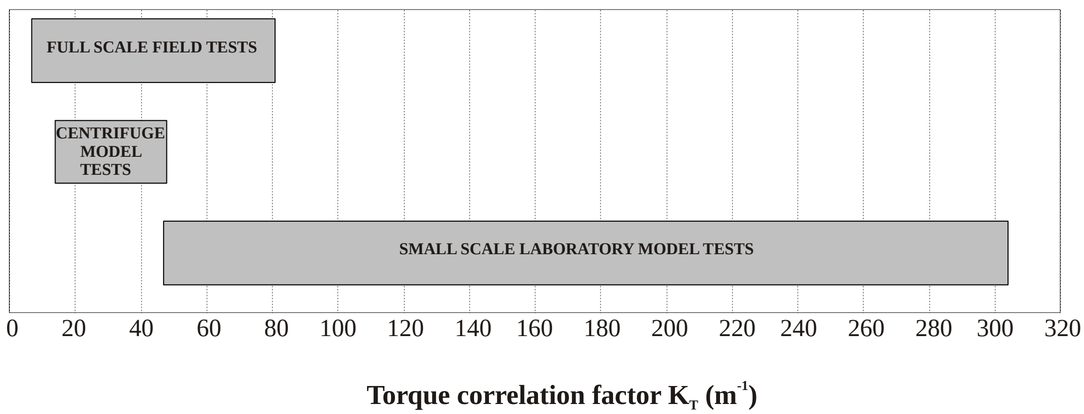

Figure 5. Comparison of measured torque correlation factors K_T (Tsuha & Aoki, 2010).

7 CONCLUSIONS

Based on the results of the present investigation, the following conclusions can be drawn:

1) Tsuha & Aoki (2010) proposed a simplified theoretical expression to correlate the uplift capacity to the torque required to install deep helical piles in sand.
2) The component of the proposed relationship related to the contribution of the helical plates to the uplift capacity was verified by centrifuge tests, and a comparison of uplift helix bearing capacity from theoretical and experimental results showed good agreement.
3) Direct shear tests were performed in this research, and the results of residual interface friction angles between helix material of a typical helical pile and different surrounding sands were suggested to be employed in the calculation of K_T for piles with similar sand-steel interface characteristics.
4) The results of torque correlation factor K_T obtained in this study were compared with field and laboratory results reported in the literature. This comparison shows that the magnitude of K_T decreases with an increase in pile dimensions, and also in sand friction angle.
5) The results of K_T found in this investigation and in the literature review were explained by the equations recommended in this paper to be used as a tool for the quality control of helical piles in sandy soil.

8 ACKNOWLEDGEMENT

The authors thank the following colleagues of the LCPC for valuable assistance on centrifuge tests cited in this present investigation: Jacques Garnier, Luc Thorel, and Gerard Rault.

9 REFERENCES

Clemence, S. P., Crouch, L. K. and Stephenson. R. W. 1994. Prediction of uplift capacity for helical anchors in sand. In Proceedings of *2nd Geotechnical Engineering Conference*, Cairo.

Ghaly, A., Hanna, A. and Hanna, M. 1991. Installation torque of screw anchors in sand. *Soils and Foundations*, 31 (2): 77-92.

Ghaly, A. and Hanna, A. 1991. Experimental and theoretical studies on installation torque of screw anchors. *Canadian Geotechnical Journal*, 28(3): 353-364.

Hoyt R.M. and Clemence, S.P. 1989. Uplift capacity of helical anchors in soil. In Proceedings of *The Twelfth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, pp.1019-1022.

Narasimha Rao, S., Prasad, M.D., Shetty, M.D. and Joshi, V.V. 1989. Uplift capacity of screw pile anchors. *Geotechnical Engineering*, 20 (2): 139-159.

Perko, H. A. 2000. Energy method for predicting the installation torque of helical foundations and anchors. *New Technological and Design Developments in Deep Foundation Technologies*, ASCE: 342-352.

Perko, H. A. 2009. *Helical Piles: Practical Guide to Installation and Design*, John Wiley & Sons, New York, U.S.A.

Porcino, D., Fioravante, V., Ghionna, V.N. and Pedroni, S. 2003. Interface behavior of sands from constant normal stiffness direct shear tests. *Geotechnical Testing Journal*, 26(3): 289-301.

Tsuha, C.H.C. 2007. *Theoretical model to control on site the uplift capacity of helical screw piles embedded in sandy soil*. Ph.D. thesis, Department of Geotechnics, São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil (in Portuguese).

Tsuha, C.H.C., Aoki, N., Rault, G., Thorel, L. and Garnier, J. 2007. *Physical modeling of helical pile anchors. International Journal of Physical Modelling in Geotechnics*, 7 (4): 1-12.

Tsuha, C.H.C. and Aoki 2010. Relationship between installation torque and uplift capacity of deep helical piles. *Canadian Geotechnical Journal*, 47(6): 635–647..

Uesugi, M. and Kishida, H. 1986. Frictional resistance at yield between dry sand and mild steel. *Soils and Foundations*, 26 (4): 139-149.

Yoshimi, Y. and Kishida, T. 1981. Friction between sand and metal surface. In Proceedings of the *10th International Conference on Soil Mechanics and Foundation Engineering,* Stockholm, Vol. 1: 831–834.