



Canadian Geotechnical Journal

Tensile monotonic capacity of helical anchors in sand: interaction between helices

Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2018-0202.R1
Manuscript Type:	Note
Date Submitted by the Author:	07-Sep-2018
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Keyword:	helical anchors, sand, capacity, centrifuge tests, plate
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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Manuscript submitted to Canadian Geotechnical Journal on 4th April 2018

Revised manuscript submitted on 7th September 2018.

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No. of words: 3483 (excluding abstract, references and figures)

No. of tables: 4

No. of figures: 12

Abstract

This note examines the interaction between the helices of a multi-helix anchor in terms of the mobilised drained capacity response in tension. Assessments are made on the basis of centrifuge tests in dense silica sand, supplemented with data from existing studies. The centrifuge tests were designed to isolate potential anchor installation effects from those due to the interactions between helices. The data show that additional helices will only contribute to anchor capacity if they are located outside the region of soil mobilised in the failure mechanism of the lower helices. In the dense sand considered in these centrifuge tests, this required that helices needed to be separated by greater than nine diameters, and hence for the lowermost helix to be located at a depth greater than nine diameters. This separation distance is much higher than suggested in previous studies, which tended to attribute the low or nill contribution of additional helices to the soil disturbance generated during anchor installation.

Keywords: helical anchor; sand; capacity; centrifuge tests; plate

Introduction

Helical anchors have seen widespread use in the electrical power industry and are now being increasingly considered as tie-down anchors for structures subject to uplift loading, tiebacks for slope and wall retention and as anchors for offshore structures such as pipelines, wind-turbines and wave energy converters (Merifield et al. 2011; Byrne and Houlsby 2015; Wang et al. 2013). A helical anchor comprises a number of steel helical plates welded to a central steel shaft as shown in Figure 1. The anchor is installed by screwing it into the soil under an applied torque and axial force. Much of the research effort on helical anchors in sand has been through experimental studies where the anchors were in some instances simplified as circular plates. These experiments were conducted at both single gravity (Baker and Kondner 1966; Murray and Geddes 1987; Ghaly et al. 1991, 1998; Ilamparuthi et al. 2002; Liu et al. 2012) and in a centrifuge (Ovesen 1981; Dickin 1988; Tagaya et al. 1988; Tsuha et al. 2012), and the results were expressed as capacity factors or anchor efficiency factors. These studies showed that the capacity of a multiple-helix anchor is much lower than the sum of the bearing resistance on each plate (i.e. anchor efficiency < 1), as assessed by measuring the capacity of single-helix anchors with each helix located at the same depth as the helices in the multiple-helix anchor. Such observations are also reflected in design guidance for helical anchors (Lutenegger 2015), which recommends progressively lower efficiency factors for the deeper helices. However, the interaction between the individual helices in multiple-helix anchor has not been analysed very well, and the low anchor efficiency was attributed to installation effects in Clemence et al. (1994), Lutenegger (2011) and Tsuha et al. (2012).

This paper isolates potential installation effects by considering centrifuge data from monotonic tensile loading tests on pre-embedded helical anchors in dry dense silica sand. The experiments involve single-plate (to provide clarity on the relevance of the helical geometry to the anchor response), single-helix and multiple-helix anchors, buried at up to 12 times the helix or plate diameter, with helix spacing in the range 1 to 6 times the helix diameter.

Testing program

Model anchors

The centrifuge tests were conducted at 20g in the 3.6 m diameter beam centrifuge at the University of Western Australia (UWA). The model anchors were modular, assembled from individual helices or plates with interconnecting shafts, allowing for variations on the overall anchor length and the number of helices and their spacing (see Figure 2). The diameter of the circular plates and helices was $D = 20$ mm (0.4 m in prototype scale) and the pitch of the helices was 5 mm (0.1 m in prototype scale). The circular plates were fabricated from 2 mm thick aluminium and the helices were fabricated from 1 mm thick stainless steel welded to a short shaft section 10 mm in length. The interconnecting shafts were also fabricated from stainless steel with a diameter, $d = 4.7$ mm, such that $d/D = 0.235$, which is sufficiently low for potential shaft resistance to be ignored (as shown experimentally in Tsuha et al. 2012).

Sample preparation

The soil sample was a dry fine to medium sub-angular silica sand with properties as listed in Table 1. The sand samples were prepared at single gravity in centrifuge sample containers measuring $650 \times 390 \times 325$ mm (length \times width \times depth) by air pluviation to give final sample heights of approximately 270 mm. The samples were not saturated to optimise testing productivity, noting that saturated samples were not required as drained behaviour was the focus of the testing program.

The centrifuge tests were designed as ‘wished-in-place’ tests, in order to avoid potential anchor capacity reduction effects associated with anchor installation as discussed earlier. This was achieved by pausing pluviation when the soil reached the targeted height for the lowermost helix or plate. At this point the plate or helix with the first shaft extension segment was located carefully on the surface sample and pluviation recommenced until the sample height reached the targeted location for the next helix. Preparing the samples in this way – rather than locating the fully assembled helical anchor in the sample initially – reduced the potential for local soil density

variations around the anchor due to ‘umbrella’ or ‘shadowing’ effects from the upper helices. After pluviation the soil surface was vacuum levelled and a measurement made of the sample mass. The resulting global sample density was $D_r = 88 \pm 3\%$ for samples 1 to 9 and $D_r = 94 \pm 2\%$ for samples 10 to 13. No more than four anchor tests were conducted in each sample to limit potential interaction effects between adjacent test sites. This was based on a conservatively assumed truncated cone failure surface extending from the lowermost plate or helix at an inclination of 25° (i.e. close to the assumed dilation angle as discussed later in the paper) to the vertical (Cheuk et al. 2008).

Each centrifuge sample was spun to 20g and cone penetration tests (CPTs) were conducted to characterise the sample using a 10 mm diameter model cone penetrometer. Cone resistance profiles are provided in Figure 3, where the variations are slight between samples and consistent with variations in the measured global density.

Testing procedure and program

The monotonic uplift tests were performed using the experimental arrangement shown in Figure 4. An actuator with two degrees of freedom (vertical and horizontal) was controlled in-flight to locate a hook fixed at the base of an axial load cell on the vertical axis of the actuator over an ‘anchor cap’ at the top of the helical anchor. Once in position the actuator’s vertical axis was moved upwards at 0.3 mm/s until either a clearly defined peak resistance was observed or the displacement reached $1D$.

The testing program encompasses 32 tests across 13 centrifuge samples, with variations on the number of helices, n , the spacing between helices, S , and the embedment depth of the lowermost helix or plate, H . The testing program (see Table 2) was designed according to the following objectives:

1. Comparison between single-plate and single-helix anchors. The first group of four single-plate anchors were tested at embedment ratios $H/D = 3, 6, 9$ and 12 , in order to compare with the following tests on single-helix anchors at identical embedment ratios.

2. Investigate the embedment effect for a single-helix anchor. This second group of 16 tests compares results for a single-helix anchor at embedment ratios in the range $H/D = 2 - 12$. The tests in this group also form the base cases for comparison with the multiple-helix anchors.
3. Examine the behaviour of multiple-helix anchors. The third group of 12 tests on multiple-helix anchors (8 double-helix, 3 triple-helix and a single quadruple-helix) were designed to provide insight on the interdependence of helices, examining the effect on capacity due variations on the number of helices, the embedment ratio and the spacing ratio.

Results and discussion

The key results from the experiments are summarised in Table 2. The net ultimate anchor capacity, Q_u , was obtained by deducting the self-weight of the anchor from the peak measured uplift resistance. The anchor mobilisation displacement, u_p , was taken as the anchor vertical displacement at the point where anchor capacity reached or approached a maximum, noting that post-failure load oscillations required judgement on the point of maximum anchor capacity for a number of tests. The anchor capacity factor, N_γ , was calculated as $N_\gamma = Q_u/\gamma AH$, where γ is the unit weight of sand (noting that the effective unit weight, γ' , would be used for saturated conditions), A is the projected area of a single helix or plate ($A = \pi D^2/4$) and H is the embedment depth of the lowermost helix or plate as defined earlier.

Single-helix and single-plate anchors

Load-displacement responses for single-helix anchors at different embedment ratios are compared on Figure 5 and selected load-displacement responses for single-plate and single-helix anchors are compared in Figure 6. The comparisons on Figure 5 and Figure 6 are made on tests from samples with comparable relative densities, $D_r = 88 \pm 3\%$, allowing for the following observations:

1. Anchor capacity increases with helix embedment ratio, reflecting the increasing stress level and hence soil strength with depth, as also evident from the CPT profiles in Figure 3.

2. The load displacement response is typical of that expected for a dense sand, exhibiting a post-peak reduction in capacity as the mobilised friction angle reduces from the peak value to the critical state value. At displacements larger than the anchor mobilisation distance (i.e. $u > u_p$) the capacity response oscillates significantly. This is commonly observed in vertical tensile loading tests of pipes and plates in sand (e.g. Trautmann et al. 1985; Dickin 1994; Cheuk et al. 2008; O'Loughlin and Barron 2012) and is attributed to the progressive infilling of the void that develops underneath the plate. Although the oscillations appear larger as the embedment depth increases, their magnitude is reasonably consistent with the magnitude of the ultimate anchor capacity measured in each test.
3. The stiffness response of the anchor before the ultimate capacity is observed is similar for each test. However, this also means that the mobilisation distances (represented by the solid symbols in Figure 5 and Figure 6) increases as the embedment depth (and hence anchor capacity) increases.
4. Although the pitch of the helix anchor is 25% of the diameter, the difference in the anchor capacity for single-helix and single-plate helical anchors is within 6%, with no clear bias towards a particular geometry. Similarly, there is no clear distinction in the mobilisation distances for either geometry. This is consistent with experimental data reported by Ghaly et al. (1991) that shows no obvious effect on anchor capacity from variations in helix geometry.

Embedment effect for a single-helix anchor

As evident from Figure 5 and Figure 6, anchor capacity for single-helix and single-plate anchors is strongly dependent on embedment depth. This is more clearly shown by Figure 7, which plots the anchor capacity factor as a function of embedment ratio, together with data from previous centrifuge tests reported by Ovesen (1981), Dickin (1988), Tagaya et al. (1988) and Tsuha et al. (2012), and field tests reported by Sakr (2009), Sakr (2011), Lutenegeger (2011) and Giampa et al. (2017). Further details of these centrifuge and field tests are provided in Table 3 and Table 4 respectively. The embedment ratio in Table 3 and Figure 7 was taken as H/D for the circular plates

and H/B for the square plate used in the Dickin (1988) and Ovesen (1981) experiments, where B is the plate breadth. All the centrifuge tests compared in Figure 7 were carried out in dense or very dense dry silica sand, with $D_r > 76\%$. With the exception of the Giampa et al. (2017) study, the field tests were characterised by Standard Penetration Tests, the results of which suggest dense to very dense sand in the Sakr (2009) tests, medium dense to dense sand in the Sakr (2011) tests and medium dense sand in the Lutenegger (2011) tests. Peak friction angles were reported for each of the Giampa et al. (2017) field tests, and only tests with peak friction angles in the range $\phi_p = 45.3 - 49.3^\circ$ (i.e. dense to very dense) are included in Figure 7.

The data on Figure 7 are generally in good agreement, although the capacity factors reported in Tagaya et al. (1988) are obviously lower, which is considered to be due to the lower peak friction angle, ϕ_p , of the Ottawa sand used in the Tagaya et al. (1988) study (see Table 3), noting that a lower mobilised friction angle is also required to predict these tests, as shown later in the paper. The Sakr (2011), Lutenegger (2011) and Giampa et al. (2017) field test results are in good agreement with the centrifuge data, whilst the Sakr (2009) field test result lies above the data, which reflects the high density and strength of this sand, noting that the peak and critical state (triaxial compression) friction angles for this sand have been reported as 50° and 38° (Sharma et al. 1986).

Collectively the data indicate that N_γ increases with embedment depth ratio, H/D , until about $H/D = 9$, beyond which N_γ can be considered constant (albeit with some scatter in the data, which is at least partly due to the variation in relative density). This observation supports the hypothesis that for dense sand at $H/D < 9$ the failure mode is shallow, with a shear failure surface that extends from the helix (or plate) to the soil surface, whereas at $H/D > 9$ the shear failure surfaces are likely to be constrained to a limited area above (and potentially below) the helix or plate. White et al. (2008) considered $H/D = 8$ to be the limiting embedment depth for shallow behaviour of planar pipes, whilst noting that this threshold would change with relative density and hence dilation angle.

White et al. (2008) showed good agreement between predictions and experimental measurements for a large database of uplift tests on pipes and plates, when their limit equilibrium method (LEM)

was applied to a shallow inclined slip failure mechanism (see Figure 8), with peak angles of friction and dilation selected based on Bolton's (1986, 1987) stress-dilatancy correlations. Giampa et al. (2017) extended the White et al. (2008) plane strain limit equilibrium solution for axisymmetric conditions, such that it is applicable to the single-helix and single-plate anchors considered here. A variation of the Giampa et al. (2017) model is adopted here, but with:

- normal stress, σ_n , on the inclined failure surfaces calculated as in the original White et al. (2008) LEM, using an earth pressure coefficient given by $K_n = (1 + K_0)/2 - (1 - K_0)\cos^2\psi/2$ (where $K_0 = 1 - \sin\phi_{cv}$, ϕ_{cv} is the critical state friction angle and ψ is the peak dilation angle).
- shear stresses, τ_f , along the slip surfaces calculated using a mobilised friction angle, ϕ_m , that is lower than the peak friction angle, ϕ_p , to account for the softening induced under certain stress conditions by a non-associated flow rule. The relationship between ϕ_m and ϕ_p is taken as $\tan\phi_m = \sin\phi_p\cos\psi/(1 - \sin\phi_p\sin\psi)$ (see Davis 1968; Drescher and Detournay 1993; Hu et al. 2014).
- the peak friction angle, ϕ_p , calculated as $\phi_p = \phi_{cv} + mI_R$, where $m = 3$ for triaxial conditions and I_R is the relative dilatancy index, calculated as $I_R = 5D_r - 1$ for mean effective stress levels at failure less than 150 kPa (Bolton 1987).
- the difference between the peak and critical state friction angles taken as 0.5 times the peak dilation angle, i.e. $\phi_p - \phi_{cv} = 0.5\psi$. As noted in Chakraborty and Salgado (2010), this is consistent with Bolton (1986) for triaxial conditions, and in the absence of sand-specific calibration of the stress-dilatancy relationships, is broadly appropriate for a database of different sands.

Predictions for the centrifuge data are provided on Figure 9, and show that the LEM is an appropriate and reliable prediction method for shallowly embedded anchors. Acceptable predictions for the Dickin (1988) data required $m = 4.3$, giving $\phi_p = 46^\circ$, which is consistent with measured triaxial peak friction angles reported in Dickin (1988) and Dickin and King (1997), noting rather $m = 3$ gave a much lower $\phi_p = 42.4^\circ$. Figure 9 also shows the importance of selecting an appropriate

dilation angle, ψ , as the alternate LEM predictions assuming normality ($\psi = \phi$, as required by limit theorems, e.g. Ng and Springman (1994) and is typical in finite element analyses, e.g. Merifield and Sloan (2006)) overpredict anchor capacity significantly; the LEM predictions assuming normality are higher than the LEM predictions assuming non-associated flow by 50% at $H/D = 1$, increasing to 183% at $H/D = 9$. The implications for applying the LEM to deeper plate embedment are also made clear in Figure 9a; for instance at $H/D = 12$ and for $D_r = 92\%$ the LEM assumption of a shallow failure mechanism would lead to a calculated $N_\gamma = 64.2$ that is approximately 80% higher than the measurements.

Multiple-helix anchors

The load-displacement responses of multiple-helix anchors are compared with single-helix anchors in Figure 10. The comparisons are made between anchors with the lowermost plate at the same embedment depth and also between samples with approximately the same relative density. Observations from Figure 10 lead to the following comments:

1. Combinations of helices where the lowermost helix is shallower than $9D$ do not provide additional anchor capacity. This is evident from Figure 10a, 10b and 10c that compare single helix anchors with multiple helical anchors where the lowermost helix is at the same embedment depth ($\leq 9D$). In each of these comparisons the peak capacity is approximately the same. This observation indicates that when $H/D \leq 9$ the failure mechanism extends from the lowermost helix to the soil surface, such that any shallower helix is consumed within the mechanism and does not provide any additional capacity.
2. Where the lower most helix is greater than $9D$, additional helices provide moderate extra capacity. This is demonstrated in Figure 10d, which compares a single helix anchor embedded at $10.5D$ with a double helix anchor with the lower most plate embedded at $10.5D$ and the upper most plate embedded at $6D$. The difference in the peak capacity is approximately 18%, which suggests that the single helix embedded at $10.5D$ mobilises soil

above the helix to a height that does not extend to the surface (supported by Figure 7), whereas the combination of helices at $10.5D$ and $6D$ allows soil to be mobilised to the surface. Similar conclusions can be drawn from the comparison of SH12-b and TH12S1.5 on Figure 10e, where the triple helix plate provides an increase in peak capacity of 40% as the uppermost plate is at $H/D = 9$ and is likely to mobilise soil to the surface whereas the extent of mobilisation appears to be limited in the case of the single helix anchor. A further comparison is provided in Figure 10f, which compares a single helical anchor embedded at $12D$ with triple and quadruple helical anchors embedded such that the lowermost plate is also at $12D$. The triple and quadruple helix anchors provide approximately the same capacity as the uppermost and lowermost plates are at the same embedment depth ($6D$ and $12D$ respectively). This capacity is 34% greater than that provided by the single helical anchor embedded at $12D$ as the soil mobilised by the lowermost helix does not extend to the soil surface, whereas the soil mobilised by the shallower helices does.

3. When the helix spacing is less than or equal to $2D$ the post-peak capacity softens significantly and does not exhibit the oscillations associated with progressive infilling of voids that develop beneath the helix. This is evident from Figure 10a, 10b, 10e and 10f and suggests that the sand is 'trapped' between the helices, preventing the development of voids beneath the helices, although a void may still develop beneath the lowermost helix.
4. The pre-peak stiffness response is similar for single and multiple-helix anchors when the lowermost helix is no greater than $9D$ (see Figures 10a, 10b and 10c), but at greater embedment depths the stiffness is higher for multiple-helix anchors (see Figures 10d, 10e and 10f).

In summary, the multiple-helix anchor tests show that an additional helix will only provide extra capacity if they are located higher than the mobilised failure mechanism of the helix underneath. The separation distance for these tests in dense sand appears to be $9D$, consistent with the transition depth between shallow and deep failure modes indicated by Figure 7. This is made clear by Figure

11, which shows that N_γ for a multi-helix anchor exceeds N_γ for a single-helix (or single-plate) anchor at $H/D > 9$, although the improved anchor capacity for $9 \leq H/D < 12$ are masked on Figure 11 by variations in D_r for the various tests.

Mobilisation distance

Figure 12 shows that the mobilisation distance, u_p , for all anchors (represented by the solid symbols in Figure 5, Figure 6 and Figure 10) increases with embedment depth. Also shown on Figure 12 are mobilisation distances from the Tsuha et al. (2012) study, interpreted from the load displacement responses as the distance where the load practically maximises (as adopted for the centrifuge data reported here). This differs from the mobilisation distances tabulated in Tsuha et al. (2012), which were selected to coincide with the maximum anchor capacity and led to unrealistically high values for some tests. Collectively the data on Figure 12 are well captured by the following simple linear expression proposed by Wang et al. (2012) for buried pipelines:

$$\frac{u_p}{D} = M \frac{H}{D} + N \quad (1)$$

using $M = 0.025$ as recommended in Wang et al. (2012) and $N = 0$. At $H/D > 8$ the mobilisation distances are lower than that given by Equation 1 suggesting a mechanism change around $H/D = 8$ which is consistent with the stabilisation of N_γ at about $H/D = 9$ on Figure 7. Interestingly there is no discernible difference in the mobilisation distance for single and multiple helix anchors at $H/D > 8$, indicating that capacity mobilisation may be governed by the lowermost plate.

Concluding remarks

A series of centrifuge tests on helical anchors in dense sand were conducted to assess the drained tensile capacity contribution of a multi-helix anchor relative to a single-helix (or single-plate) anchor at the same embedment depth. The tests were motivated by previous studies that attribute low anchor efficiency in multiple-helix anchors to soil disturbance during anchor installation. Potential installation effects were isolated and removed in the tests reported here by locating the anchors in the soil samples during sample preparation.

The single-helix and single-plate tests, collectively with data from the literature, indicate that in dense sands the failure mechanism is shallow up to a plate embedment of about nine times the plate diameter, although it should be noted that this threshold will reduce as the relative density reduces (e.g. Tom et al. 2017).

The multiple-helix tests reveal that the contribution of additional helices relative to the lowermost helix is complex, and depends on both the helix spacing and embedment depth. The most notable conclusion that can be drawn from these multiple-helix tests – which are free from installation effects – is that additional helices do not provide additional capacity if they are located within the region of soil mobilised in the failure mechanism of a lower helix. This is notable, as it confirms that the conclusion drawn in previous studies that reduced anchor efficiency is due to anchor installation effects is not the case, or at least not the sole reason for reduced anchor efficiency. It is expected that some installation effects will remain, and these may be more prevalent for deeper helices as the changes in soil state brought about during installation will be more relevant if the soil mechanism for the deeper helices is localised to the helix. The centrifuge tests show that an additional helix will only provide additional capacity when it is located at least nine diameters above the adjacent, lower helix. This spacing is entirely consistent with the transition depth between shallow and deep behaviour for a single helix (or plate), although the spacing is expected to reduce with reducing relative density.

Anchor capacity for a shallowly embedded single-plate or single-helix can be reliably predicted using a limit equilibrium approach, when peak angles of friction and dilation are selected based on Bolton's (1986, 1987) stress-dilatancy correlations. Care is required to ensure that this method is not applied beyond the limiting embedment depth for shallow behaviour, as the resulting predictions will be unconservative. Observations from the multiple-helix anchor tests provide direction towards an appropriate prediction model for multiple-helix anchors. Experimental observations of the failure mechanism for a deeply embedded single-helix anchor and of a multiple-helix anchor would provide value in this regard.

Acknowledgements

The study forms part of the activities of the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering and the Lloyd's Register Foundation (LRF) Centre of Excellence. LRF helps to protect life and property by supporting engineering-related education, public engagement and the application of research. The first author acknowledges the financial support of National Natural Science Foundation of China (Grant No. 51308095) and the China Scholarship Council scholarship awarded for her one-year visit to the University of Western Australia.

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Figure captions

Figure 1 Helical anchor showing the uppermost three helices

Figure 2 Anchor models (dimensions in mm)

Figure 3 Profiles of measured cone tip resistance with depth

Figure 4 Loading arrangement

Figure 5 Load-displacement responses for single-helix anchors at different embedment depths in samples with $D_r = 88 \pm 3\%$

Figure 6 Load-displacement responses for single-plate and single-helix anchors, $D_r = 88 \pm 3\%$

Figure 7 Anchor capacity factors for single-plate and single-helix anchors

Figure 8 Inclined slip mechanism assumed in the LEM solution

Figure 9 Calculated and measured anchor capacity factors: (a) this study, (b) existing centrifuge studies

Figure 10 Comparison between multiple- and single-helix anchors

Figure 11 Anchor capacity factors for single- and multiple-helix anchors

Figure 12 Mobilisation distances for single-plate, single-helix and multiple-helix anchors

Table 1 Sand properties

Property	Value
Specific gravity, G_s	2.65
Median grain size, d_{50} (mm)	0.25
Coefficient of uniformity, C_u	1.87
Coefficient of curvature, C_c	0.938
Maximum void ratio, e_{\max}	0.703
Minimum void ratio, e_{\min}	0.516
Critical state friction angle, ϕ_{cv} ($^\circ$)	31

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Table 2 Experimental programme and key results

Test identifier [†]	Plate or Helix	n	S/D	H/D	Sample no.	Relative Density, D_r (%)	u_p/D	Q_u (kN)	N_γ
SP3	Plate	1	-	3	2	85.8	0.050	22.9	9.0
SP6	Plate	1	-	6	2	85.8	0.140	108.7	21.3
SP9	Plate	1	-	9	2	85.8	0.204	236.2	31.0
SP12-a	Plate	1	-	12	2	85.8	0.242	357.5	35.2
SP12-b	Plate		-		6	85.4	0.238	313.4	30.8
SH2	Helix	1	-	2	9	86.7	0.032	9.9	5.8
SH3-a	Helix	1	-	3	1	86.4	0.055	22.1	8.7
SH3-b	Helix	1	-		13	96.2	0.067	22.9	8.9
SH4	Helix	1	-	4	9	86.7	0.091	42.9	12.6
SH6-a	Helix	1	-	6	1	86.4	0.128	108.1	21.3
SH6-b	Helix	1	-		13	96.2	0.146	121.7	23.6
SH7.5	Helix	1	-	7.5	5	90.0	0.180	161.6	25.3
SH8-a	Helix	1	-	8	1	86.4	0.170	176.4	26.1
SH8-b	Helix	1	-		12	96.4	0.188	217.6	31.7
SH9-a	Helix	1	-	9	7	88.8	0.201	249.9	32.7
SH9-b	Helix	1	-		11	96.1	0.192	270.3	35.1
SH9-c	Helix	1	-		13	96.2	0.166	260.0	33.7
SH10	Helix	1	-	10	12	96.4	0.190	309.6	36.1
SH10.5	Helix	1	-	10.5	5	90.0	0.201	271.8	30.5
SH12-a	Helix	1	-	12	6	85.4	0.227	322.1	31.7
SH12-b	Helix	1	-		10	91.7	0.209	364.9	35.7
DH7.5S1.5	Helix	2	1.5	7.5	4	88.7	0.153	158.8	-
DH12S1.5	Helix	2	1.5	12	8	86.6	0.224	383.1	-
DH9S3	Helix	2	3	9	3	89.3	0.198	240.7	-
DH12S3	Helix	2	3	12	9	86.7	0.201	412.0	-
DH10.5S4.5	Helix	2	4.5	10.5	3	89.3	0.198	320.9	-
DH12S4.5	Helix	2	4.5	12	8	86.6	0.220	370.7	-
DH9S6	Helix	2	6	9	13	96.2	0.190	264.7	-
DH12S6	Helix	2	6	12	4	88.7	0.214	384.2	-
TH9S1.5	Helix	3	1.5	9	3	89.3	0.168	222.9	-
TH12S3	Helix	3	3	12	7	88.8	0.211	459.5	-
TH12S1.5	Helix	3	1.5	12	11	96.1	0.209	512.6	-
QH12S2	Helix	4	2	12	5	90.0	0.254	489.4	-

[†] SP, SH, DH, TH and QH indicates single-plate, single-helix, double-helix, triple-helix and quadruple-helix anchors respectively; the subsequent number represents the embedment depth ratio, H/D ; and for multiple-helix anchors, an 'S' is followed by a number that represents the spacing ratio, S/D between helices. Repeat tests are distinguished by appending the test name with '-a', '-b' or '-c' as appropriate.

Table 3 Database of centrifuge tests

Source	Anchor type	D or B (m)	H/D or H/B	d/D or d/B	Sand	Density	ϕ_{cv} (°)	ϕ_p^* (°)
Ovesen (1981)	circular plate	1.455	1 - 3	-*	Dansk normal sand No. 1	$D_r = 108\%^\dagger$	31^\ddagger	43
Ovesen (1981)	square plate	0.75	1.4 - 2.6	-*	Dansk normal sand No. 1	$D_r = 109\%^\dagger$	31^\ddagger	43
Dickin (1988)	square plate	1.000	1 - 8	0.12	Erith sand	$D_r = 76\%$	34^\S	46^\parallel
Tagaya et al. (1988)	circular plate	2.652 - 4.709	0.9 - 5.0	~ 0.10	Ottawa sand	$D_r = 76.7\%$	29.9^\parallel	38.4
Tsuha et al. (2012)	circular helix	0.214 - 0.440	13.5	0.30	Fontainebleau sand (NE34)	$D_r = 85\%$	$29^\#$	41
This study	circular helix, circular plate	0.400	2 - 12	0.24	UWA sand	$D_r = 85 -96\%$	31^\wedge	40.8 - 42.4

* Estimated by Bolton's (1986) correlations

† Reported value

‡ Assumed

§ Required $m = 4.3$ to agree with $\phi_p = 46^\circ$ reported in Dickin (1988) and Dickin and King (1997)

∥ As suggested in Chakraborty and Salgado (2010), triaxial ϕ_{cv} taken as 4° less than the plane strain $\phi_{cv} = 38^\circ$ (Dickin, 1988)

¶ Reported in Negussey et al. (1988) and Guo and Su (2007)

Reported in Gaudin et al. (2005)

^ Reported in White et al. (2008)

Table 4 Database of single helix anchor field tests

Source	<i>D</i> (m)	<i>H/D</i>	<i>d/D</i>	Sand	Density	ϕ_{cv} (°)	ϕ_p (°)
Sakr (2009)	0.406	12.56	0.44	Alberta oil sand	dense to very dense	38*	50*
Sakr (2011)	0.914	6.24	0.44	Northern Alberta sand	medium dense to dense	-†	-†
Lutenegger (2011)	0.203	14.8	0.19	UMass AgFarm sand	medium dense	-†	-†
Giampa et al. (2017)	0.152	2.9 - 7.1	0.23	Golden Flint sand	Dry density, $\gamma_d = 14.7 - 15.8 \text{ kN/m}^3$	33.9	45.3 - 49.3
	0.254	1.8 - 3.1	0.17				

* Reported in Sharma et al. (1986)

† Not reported

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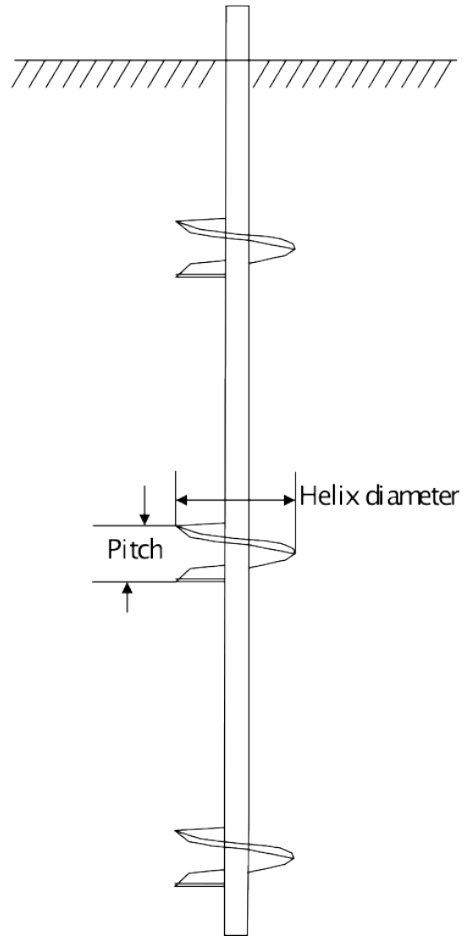


Figure 1 Helical anchor showing the uppermost three helices

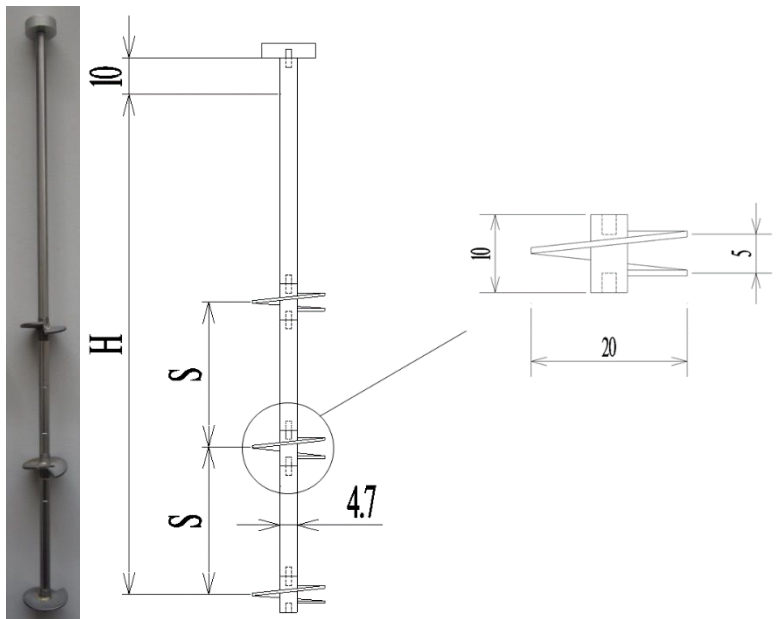


Figure 2 Anchor models (dimensions in mm)

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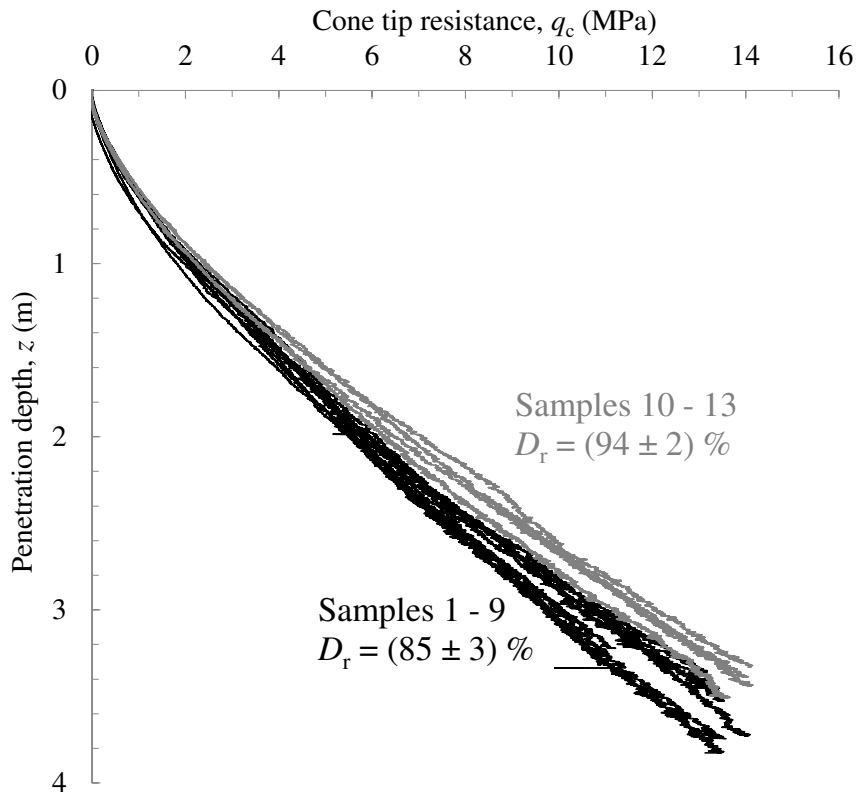


Figure 3 Profiles of measured cone tip resistance with depth

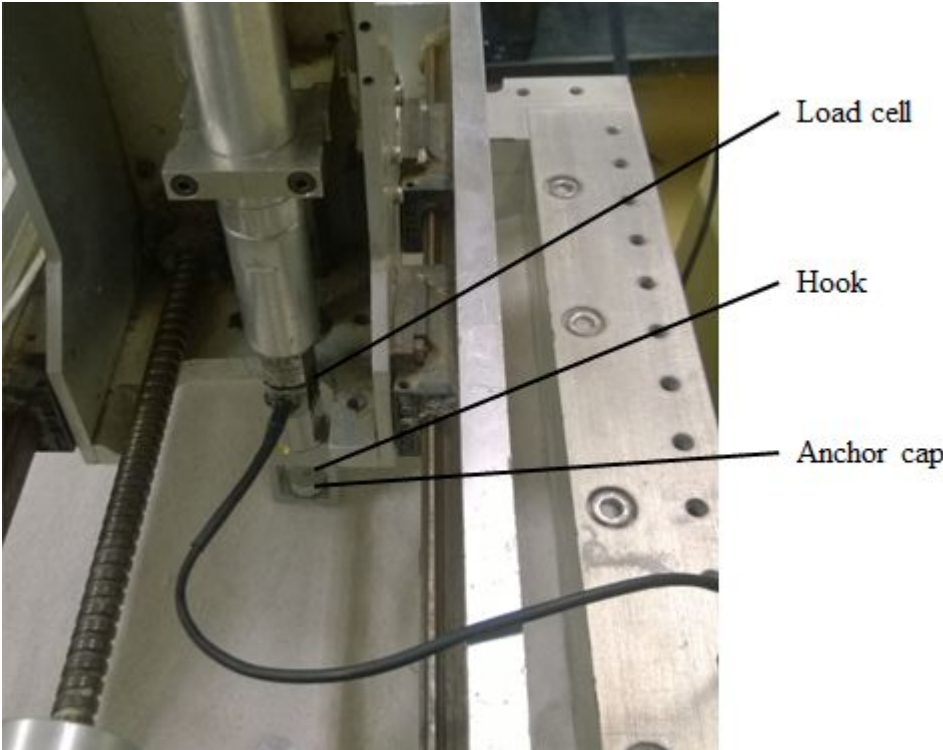


Figure 4 Loading arrangement

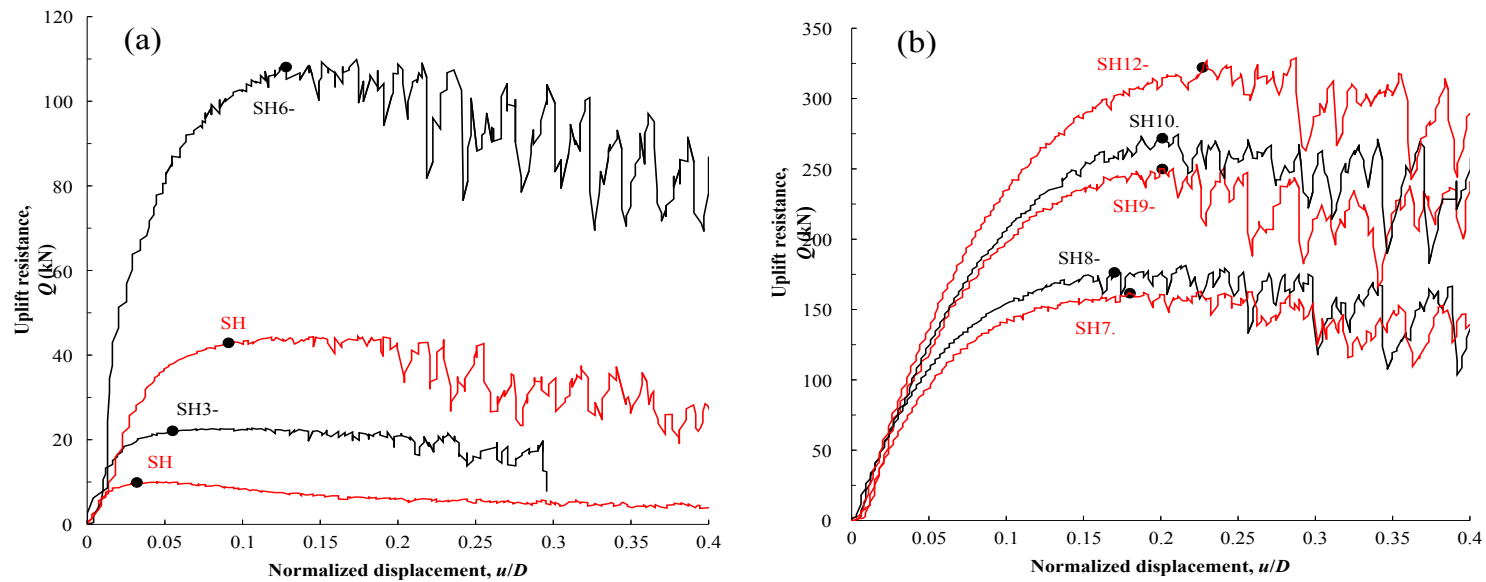


Figure 5 Load-displacement responses for single-helix anchors at different embedment depths in samples with $D_r = 88 \pm 3\%$ (a) $H/D = 2 - 6$ (b) $H/D = 7.5 - 12$

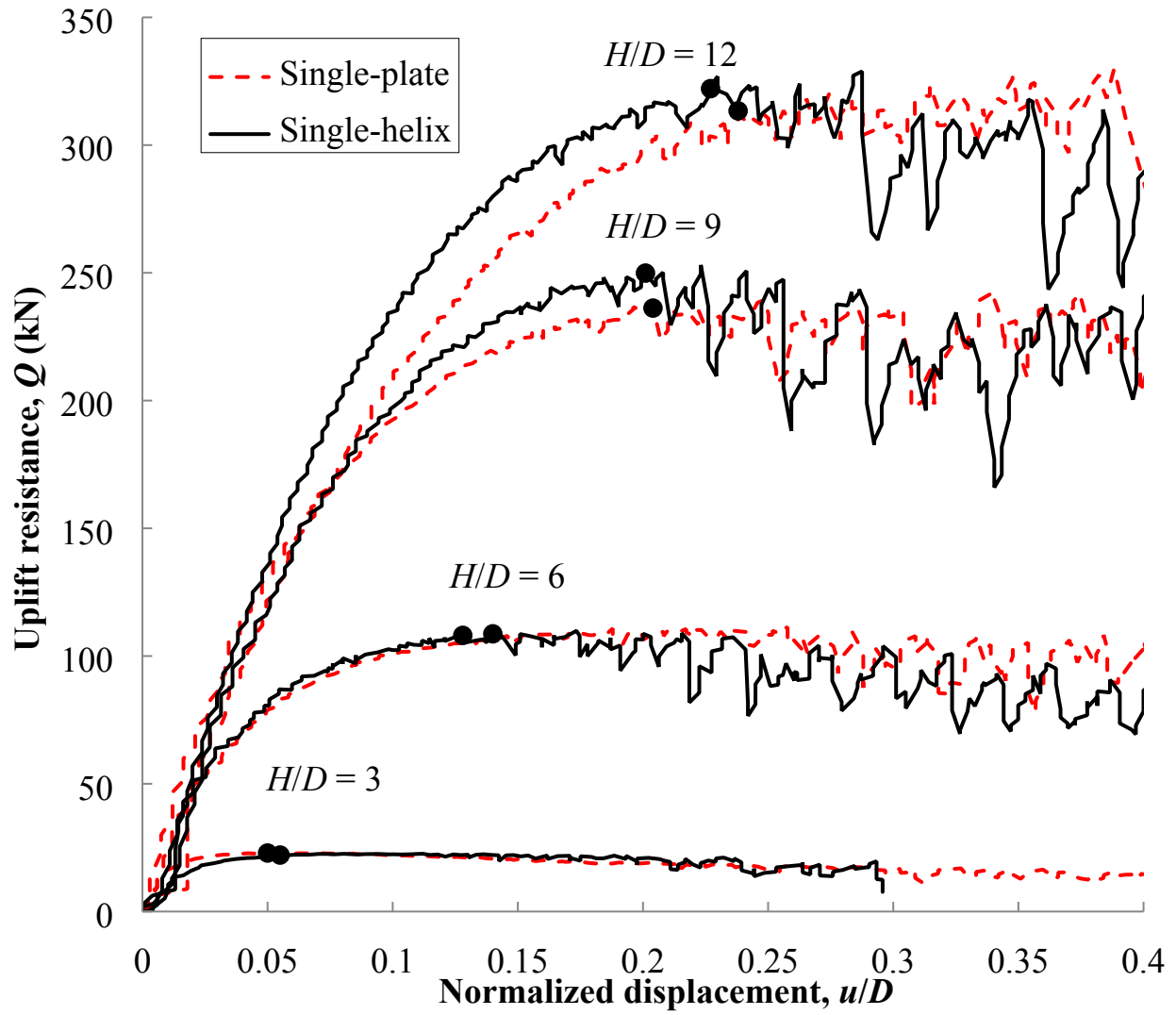


Figure 6 Load-displacement responses for single-plate and single-helix anchors, $D_r = 88 \pm 3\%$

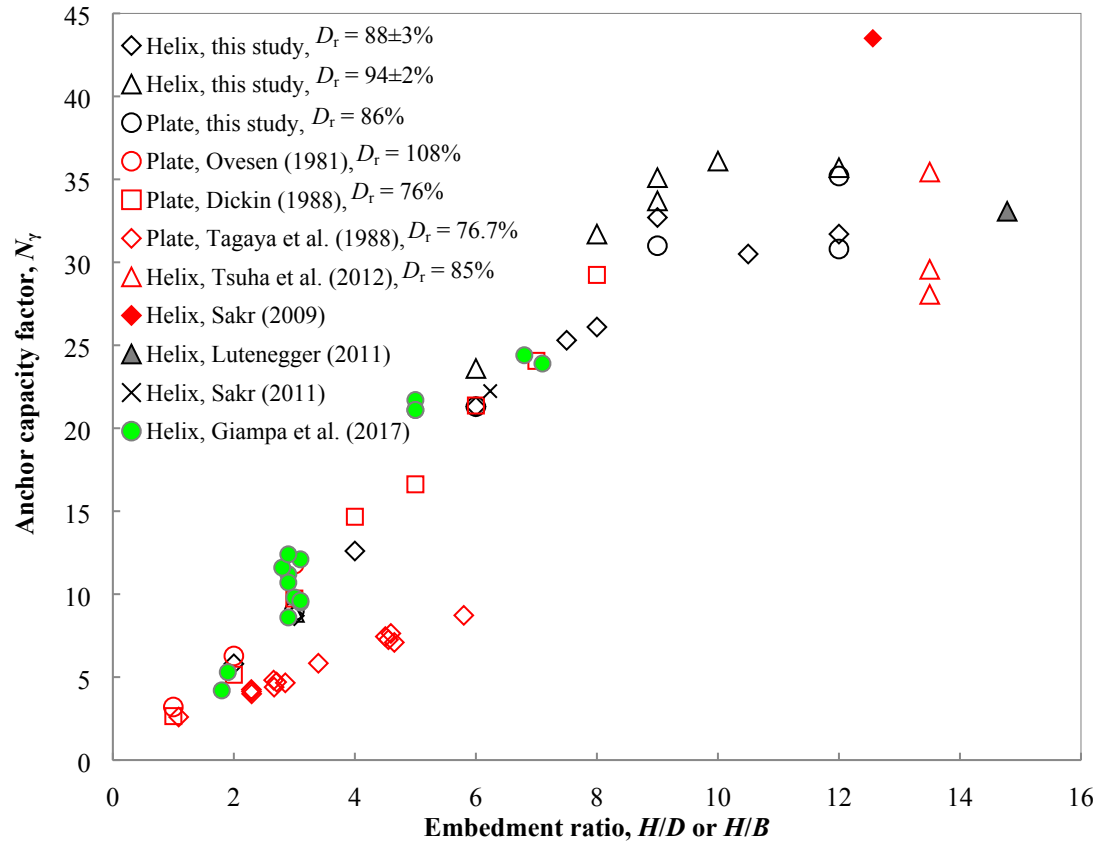


Figure 7 Anchor capacity factors for single-plate and single-helix anchors

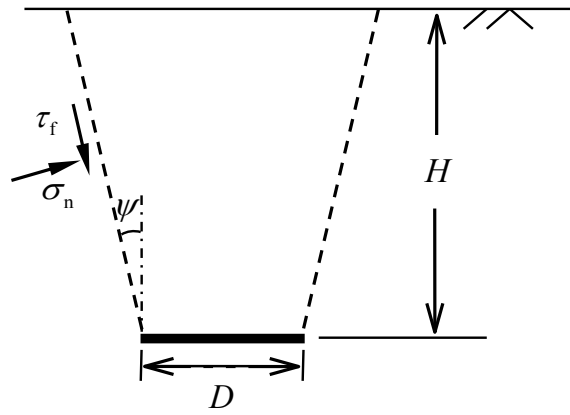


Figure 8 Inclined slip mechanism assumed in the LEM solution

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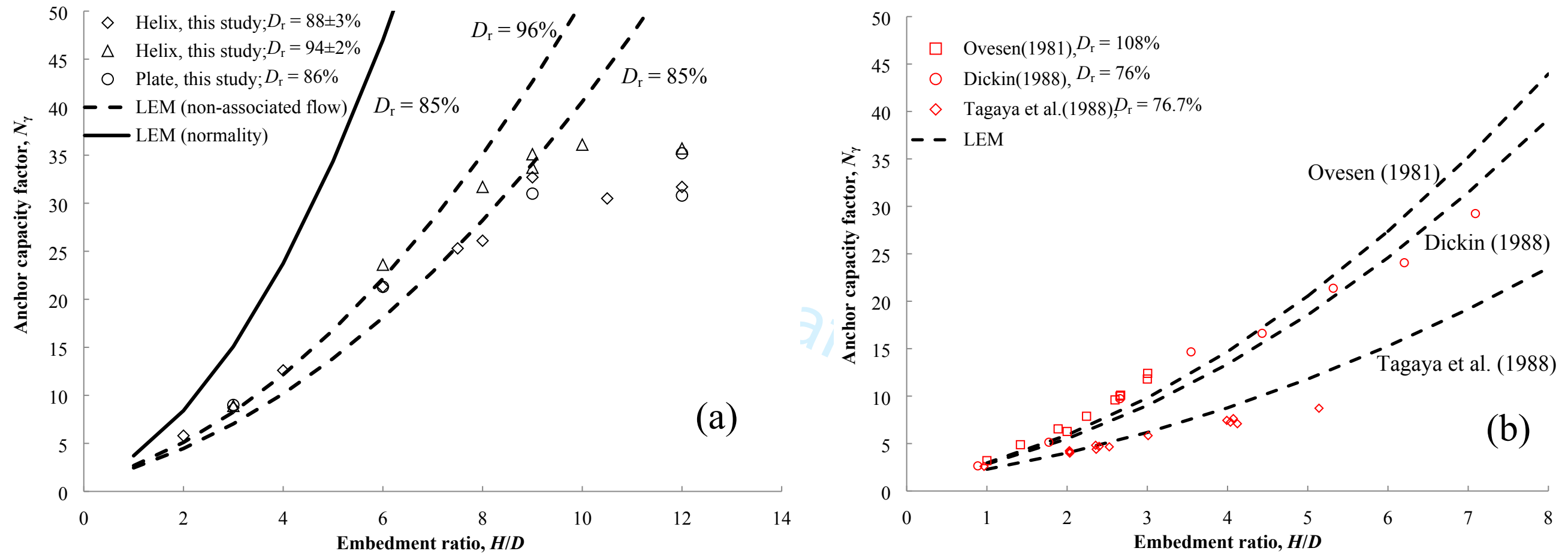


Figure 9 Calculated and measured anchor capacity factors (a) This study (b) Existing centrifuge studies

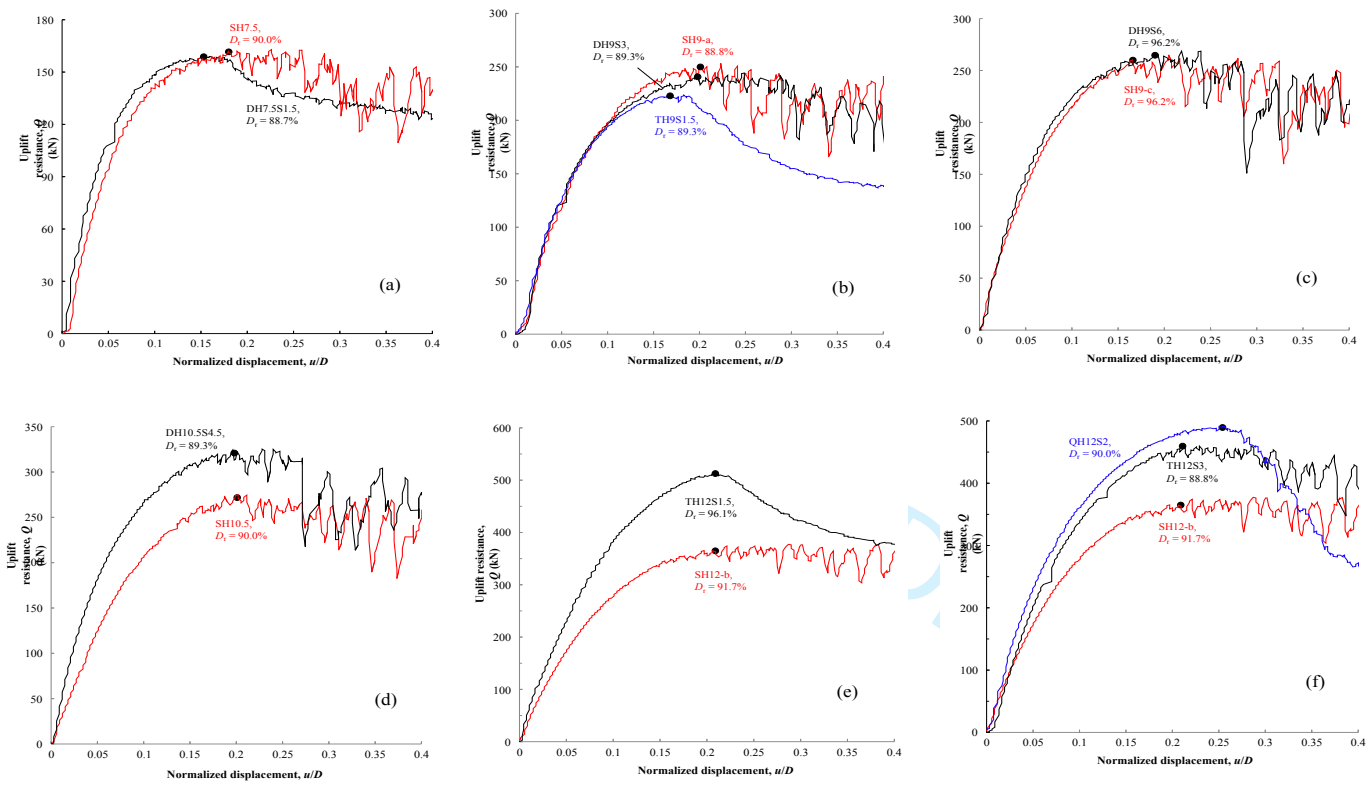


Figure 10 Comparison between multiple- and single-helix anchors (a) $H/D = 7.5$ (b) $H/D = 9$ (c) $H/D = 9$ (d) $H/D = 10.5$ (e) $H/D = 12$ (f) $H/D = 12$

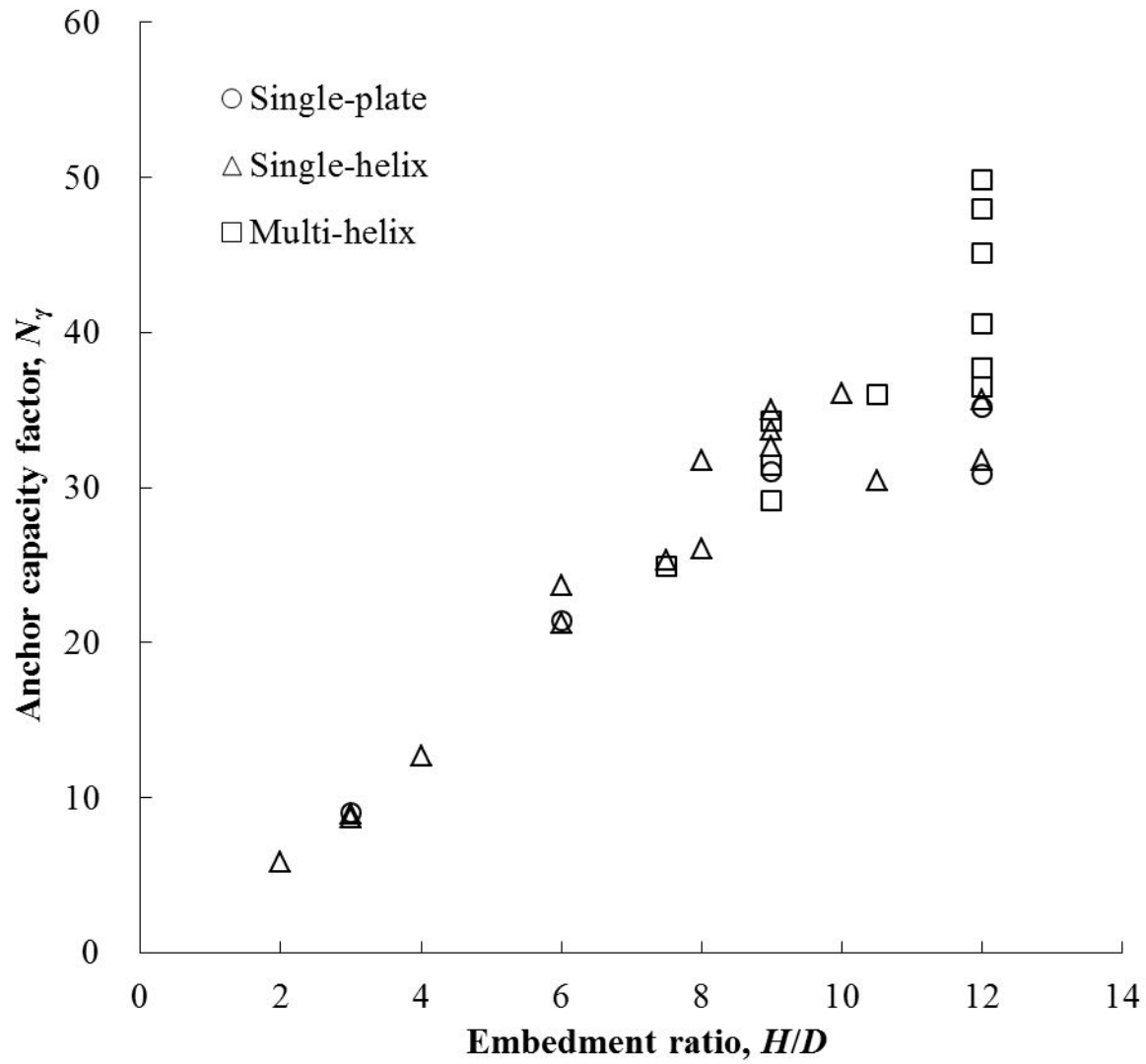


Figure 11 Anchor capacity factors for single- and multiple-helix anchors

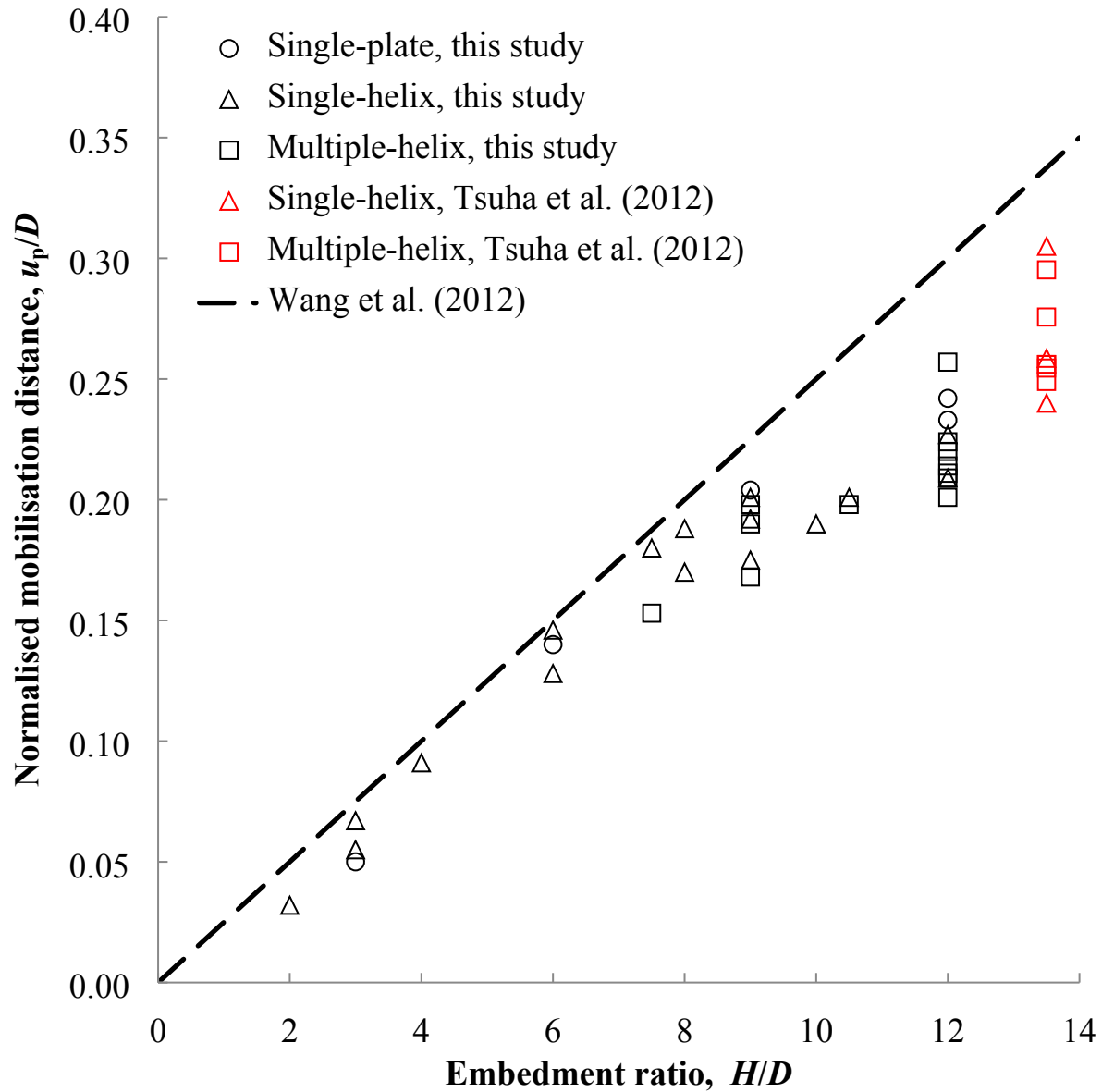


Figure 12 Mobilisation distances for single-plate, single-helix and multiple-helix anchors