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Experiment of single screw piles under inclined cyclic pulling loading

Tian Wen Dong *[1,2] and Ying Ren Zheng [2]

[1] *Department of Road and Bridge Engineering, Liaoning Provincial College of Communications, Shenbei Road, Shenyang, China*
[2] *Department of Architecture & Engineering, Logistical Engineering college, Yuzhou Road, Chongqing, China*

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Abstract. The ultimate pullout capacity under inclined dynamic loading is an important measure of the destruction degree of vertical screw piles (anchors) under dynamic actions. Based on the static and dynamic tests on two kinds of model screw piles, the ultimate bearing capacity was researched considering different distance-width ratio of blade (D/W) and preloading ratio. The results compared well with other experimental data available in the literature. This research reveals that D/W might determine the failure model of the piles (anchors), for example D/W = 3.14 or 5; a critical dynamic-static loading ratio (DSLR) existed in the experiments. The critical DSLR was reached under the conditions of 40%~60% preloading (D/W = 3.14) or 20%~40% preloading (D/W = 5), respectively.

Keywords: ultimate pullout capacity; single screw piles; cyclic loading; inclined static loading test; inclined dynamic loading

1. Introduction

Recently, extreme environmental conditions occur frequently such as ice disasters, storms, earthquakes, etc. Upon such complex loading conditions, the foundations that are designed for single-direction loads may fail.

The dynamic characteristics of straight pile foundations have been studied extensively. However, research on screw anchors or screw piles is still limited. The screw anchor or screw pile consists of a straight central shaft and helical steel blades welded to the straight shaft. The blade is helical or plate like. This type of foundation has been used in power transmission towers, marine structures, slopes or dams. The steel screw pile, whose diameter of helical blade is 650-708 mm, has been used for load transfer in foundations of power transmission towers in coastal and soft soil zones of Liaoning Province. Its bearing capacity is affected by different distance-width ratio of blade (D/W), physical and mechanical property of geomaterial under vertical loading or inclined loading in static loading tests. But, in the dynamic condition, the bearing capacity of screw pile is not clearly, and it will lead to the failure of pile foundation. In 2010, the cover-ice transmission line was affected by strong wind, and some screw pile groups for transmission towers presented

*Corresponding author, Professor, E-mail: dongtianwen111@yeah.net

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the unilateral pullout at the normal direction of line in Liaoning. The disaster also happen in other countries; for example a number of accidents including steel tower structures, foundations and transmission lines in Wisconsin in the U.S. and Quebec in Canada (Peabody and McClure 2002). The dynamic characteristics of large-diameter screw anchors (piles) or other kinds of anchors need to be researched.

In this paper, authors make the inclined dynamic-static tester in using for the pulling test, and analyze the ultimate loads at different conditions of dynamic and static loading.

2. Literature review

A number of model and field pulling tests on vertical anchors or screw piles have been reported in the literature. The ultimately uplift bearing capacity of an anchor is correlated to the embedded depth, geometrical properties and the characteristics of the surrounding soils of an anchor or anchors (Matsuo 1967, Mitsch and Clemence 1985, Hoyt and Clemence 1989, Raham *et al*. 1992, Ghaly and Hanna 1994, Ilamparuthi *et al*. 2002, Rattley *et al*. 2008, Dong *et al*. 2008a, b, Dong *et al*. 2009). Other experimental studies on inclined anchors (screw piles) under axial pullout force or vertical anchors (piles) under inclined loading have also been presented. The characteristic mechanism of inclined anchors embedded in sand is investigated and analysed to define the failure mechanism and the associated rupture surface (Kananyan 1966, Hanna *et al*. 1988, Ghaly and Clemence 1998, Goel *et al*. 2006). The large number of the model or field tests on vertical anchors under inclined loading have also been performed, and the characteristic mechanism of the type of screw piles (anchors) was studied (Dong *et al*. 2008a, b).

Third, the dynamic properties of the vertical screw anchors embedded in sand are only researched in two conditions of horizontal and pullout dynamic loading through experiments. The sinusoidal loading is applied to the plate anchors to study their long-term dynamic characteristics or (Ponniah and Finlay 1983). The lateral cyclic loading effect of helical piles in clay is studied on its L/d (ratio of pile length to diameter). The dynamic lateral capacity was almost the same as the static lateral capacity, when the ratio of lateral cyclic load/static lateral capacity was less than some values (Rao and Prasad 1993). By the long-term dynamic testing at 10Hz and 50Hz frequencies, the static uplift capacity of a 2-helix anchor will be affected (Cerato and Victor 2008). At the conditions of pre-loading, cyclic loading and re-cycling loading, and the static uplift capacity of anchor in clay decreased by 12% (Singh and Ramaswamy 2010).

Based on the literature review, the present study mainly focuses on the ultimate bearing capacity of vertical or inclined anchors under the static or dynamic loading condition, and attempts to find the break out rule and resistance of foundation. In this paper, inclined static and dynamic pullout loading tests on vertical anchors are reported, and observations and comparisons are made between the present results and those predictions by other studies on the pullout bearing capacity.

3. Experimental work

The model tests were carried out in a rectangular steel tank 1,200 mm in length, 1,000 mm in width and 1,300 mm in height. The inclined static loading was applied by a jack and the inclined dynamic loading was applied by an vibration exciter (Figs. 1-2). In Fig. 3, the inclined plate and L type plate were 10 mm steel plate. Angle steels and bars composed the steel frame. 1# and 3#

Fig. 1 Testing photos

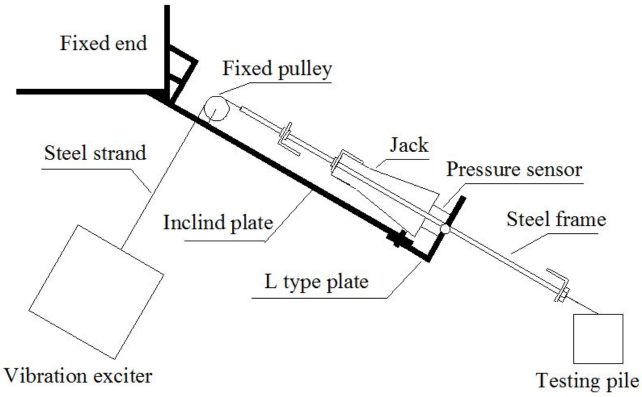

Fig. 2 Inclined loading device

angle steel were fixed by two bars, and 2# angle steel could move along bars. A cylindrical shell and spring were welded on the center of 2# angle steel, and it was the stabilization mechanism of preloading (SMP). The cylindrical shell inner diameter was 50 mm, and the stiffness of spring was 2~3 times large than the calculation by Hook’s law in static loading. The preloading of dynamic testing was applied by screw jack through pushing down the L type plate and pushing upward 2# angle steel. This design of SMP could effectively connect the steel frame with jack in dynamic test.

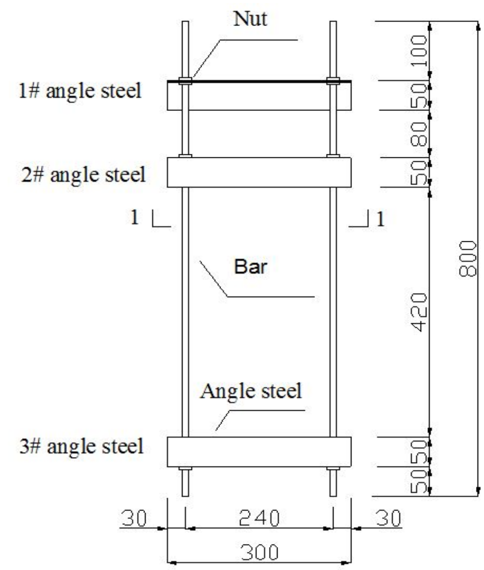

Fig. 3 Steel frame

Table 1 Geometric parameters of model screw piles

Screw pile	h_1 (mm)	h_2 (mm)	h_3 (mm)	l_1 (mm)	l_2 (mm)	W (mm)	L (mm)	d (mm)	D (mm)
1#	360	420	60	150	80	220	800	42	182
2#	260	320	40	150	200	350	800	42	182

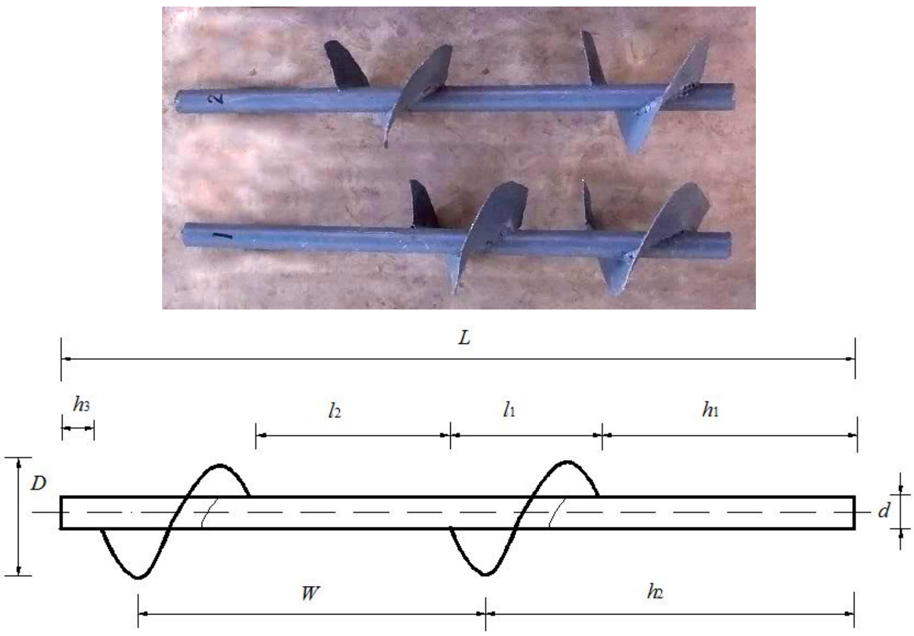

Fig. 4 Geometrical parameters of screw pile model

The model screw piles (anchors) were made of steel pipe (42 mm Dia) and two helical blades of 182 mm projected diameter and 150 mm screw pitch. The helical blades were welded to the surface of pipe. The distances between the helical blades (D) are 220 mm (1# model pile) and 350 mm (2# model pile) separately. The D/W, W indicated the width that the projected radius of blade was reduced from the outer radius of pipe, were determined by the distance-width ratio of the blade, and the D/W for 1# pile was 3.14 and the D/W for 2# pile was 5. The model parameters and models are shown in Table 1 and Fig. 4.

The testing ground was made of sand vibrated by a plate vibrator at a controlled rate and a fixed falling height at a water content of w = 3%. The cumulative percent of weight was 67.46% at d_s (particle size of sand) > 0.5 mm which indicates that the soil was coarse sand; relative density of sand (D_r) was $D_r = 0.248$, so the soil was loose sand. The strength parameters of model soil of laboratory tests are cohesion $c = 2$ kPa and internal friction angle $\varphi = 15.6^o$. The boundary condition of test was enough for the minimum size of pullout tests.

The model tests include the inclined static loading tests and the inclined dynamic loading tests. The angle between the loading and the plane of top pile was 30°. In the dynamic test, firstly, the pile was subject to different static preloading according to the ultimate bearing capacity from static tests. Secondly, the pile is subject to the sinusoidal inclined load with 0.2 mm amplitude, 5 Hz frequency and 10000 cycles, on the basis of Lode Code for the Design of Building Structures, Technical Regulation of Design for Tower and Pole Structures of Overhead Transmission and design requirement. Thirdly, stop the vibration and conduct the inclined static loading test to research the change of ultimate bearing capacity of pile after vibration.

The experimental values of loading and displacement of top pile are investigated by a resistance-strain gage load cell and a displacement transducer. All static loading tests followed the following test procedure:

(1) The loading steps. The alternate of inclined pullout loading was increased in steps, with each step load being 1/10 of the estimated ultimately loading.
(2) The criterion of end loading followed any conditions, which the horizontal displacement of the certain loading grade was more than the sum of displacement of former two grade-loading, or displacement catastrophe presented at loading-displacement curve, or the value of horizontal placement was more than 20~30 mm, or other case unexpected incidents happened.

Table 2 Comparison of ultimate bearing capacity of screw piles embedded in different sand grounds

Screw pile	Static test φ = 15.6°, c = 2 kPa				Static test values from reference (Zhang *et al*. 2010) φ = 25.1°, c = 6.34 kPa			
	Q (N)	V (mm)	$\overline{Q}$ (N)	$\overline{V}$ (mm)	Q (N)	V (mm)	$\overline{Q}$ (N)	$\overline{V}$ (mm)
	225.2	18.45			373.53	9.19		
1# pile	218.8	15.31	222	16.88	354.12	10.47	352.51	9.97
					329.87	10.25		
	217.4	8.9			281.36	6.74		
2# pile	209.2	6.0	213.3	7.45	315.31	11.12	313.70	8.95
					344.42	9.00		

4. Experimental results and analysis

4.1 Results of static pullout loading tests

The loading and displacement values of the static inclined tests are shown in Fig. 5. To estimate the ultimate loading accurately, the Log *Q*-*V* method was used and shown in Fig. 6. When *D*/*W* increases from 3.14 (1# pile) to 5 (2# pile), the limit pullout loading decreases by 4% from 222 N (1# pile) to 213.3 N (2# pile). This variation was similar to the reported results in the literature in Table 2 (Zhang *et al*. 2010). It indicates that the integrity of the soil column between the blades was strengthened, so the displacement of the top pile decreased and the ultimate loading increased.

4.2 Results of pullout capacity after cyclic loading

At the icing or stormy condition, the screw pile foundation for power transmission towers is subject to additional loads caused by wind vibration, which may cause felling tower sometime. Thus, the ultimate bearing capacity under dynamic loading conditions needs to be researched. In the experiments, the applied preloading levels were 0%, 20%, 40%, 60% and 80% the static

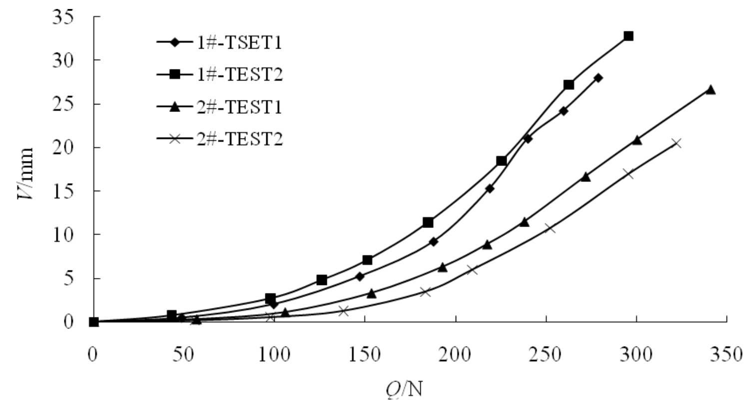

Fig. 5 *Q*-*V* curves for screw piles

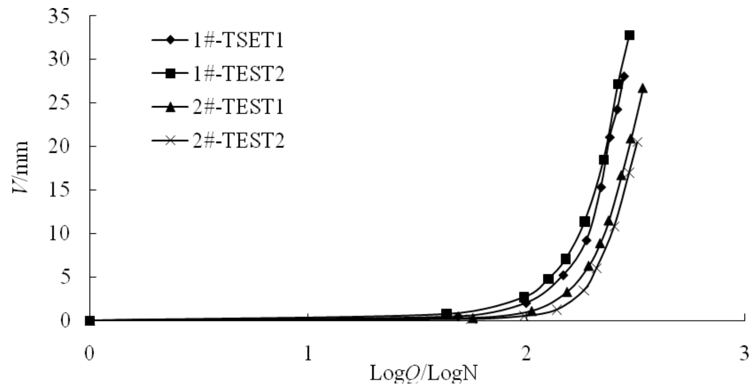

Fig. 6 Log *Q*-*V* curves for screw piles

Table 3 Comparison of ultimately loads

Pile	Preloading ratio	Preloading		Static loading test		DSLR
		Ultimately loading (N)	Displacement (mm)	$\overline{Q}$ (N)	$\overline{V}$ (mm)	
1#	0%	185.9	8.34	222	16.88	0.837
	20%	189.1	7.73			0.852
	40%	178.1	8.91			0.802
	60%	250.9	7.85			1.130
	80%	216.1	17.05			0.973
2#	0%	187.2	7.08	213.3	7.45	0.878
	20%	226.6	6.31			1.062
	40%	202.3	5.37			0.948
	60%	239.9	9.33			1.125
	80%	245.8	11.4			1.152

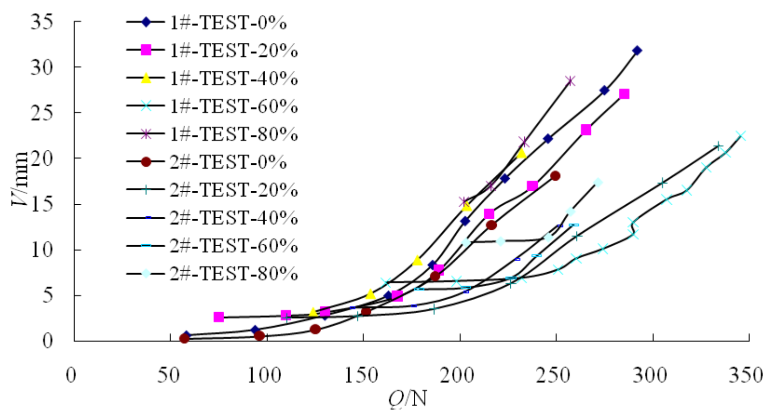

Fig. 7 *Q*-*V* curves after dynamic actions under different preloading levels

ultimate loading, respectively, and the loading-displacement curves (*Q*-*V* curves) are presented in Fig. 7. The ultimate pullout loadings are also listed in Table 3.

In Fig. 8, the ultimate pullout bearing capacity after dynamic tests were marked according to the different preloading of 1# and 2# screw piles. The curve of ultimate loading of 1# screw pile is similar to the curve of 2# pile, but the ultimate loading of 1# screw pile decreases quickly than the values of 2# pile at 80% preloading. It indicates that the ultimate bearing capacity of the screw piles would be affected by preloading and *D*/*W*. When *D*/*W* is less than a certain value, the diameter of the screw pile between blades might be considered as the diameter of the soil column.

In loose sand, when *D*/*W* was less than 3.14, the soil column between the blades was confined by the blades, and the pile-soil interaction and the blade-soil interaction decreased, so the inclined dynamic load was mainly undertook by the pile body of equivalent diameter of soil column. After the applied dynamic force, the ground outer the soil column was loose, and the ultimate pullout loading and the pile displacement would decrease, expect for the 60% preloading condition. But when *D*/*W* was equal to or larger than 5, the pile-soil interaction and the blade-soil interaction

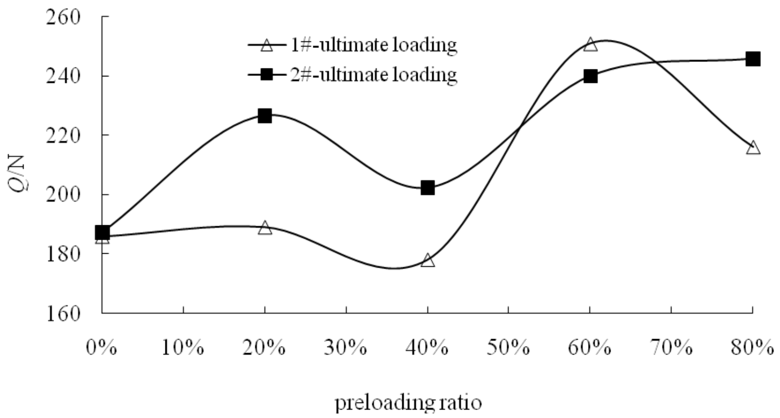

Fig. 8 Ultimate bearing capacity of screw piles at different preloading levels

increased; therefore, the soils around the blades was locally compressed or loosen by dynamic loads. As the angle of inclined pullout force was variable during the tests, the ultimate loads under different preloading levels would obviously be different.

4.3 Comparison of inclined ultimate bearing capacity between the static tests and dynamic tests

After dynamic actions such as the ice storms and wave actions, the bearing capacity of the screw piles might be changed. In this research, the ratio of the ultimate pullout load to the ultimate loading of inclined static loading test was determined by the dynamic-static loading ratio (DSLR), and is calculated in Table 3.

At D/W = 3.14, DSLR are usually less than 1.0. It indicates that the ultimate bearing capacity would be decreased by dynamic actions, but these values increased with increasing preloading. This is because the soils around the pile was obliquely compressed by the soil column between the blades, the pile body and blades, as if the ground around the equal section pile was compressed by the inclined loading. When CSLR of 60% preloading was larger than a critical condition (DSLR = 1.0), the ultimate pullout capacity of screw pile might increase by the dynamic action, where after the ultimate pullout capacity of screw pile decreased and closed to the static value. The DSLR's change range was less than 20%.

At D/W = 5, the value of DSLR is in the range of 0.878~1.152. The dynamic force improved the density of soils around the pile and the blades better than at D/W = 3.14, and the DSLR of 2# pile were total larger than DSLR of 1# pile. When the preloading ratio is from 20% to 40%, the pullout capacity after dynamic action is almost close to the static bearing capacity, and the DSLR's changing range was confined at 15%. That was similar to the predicted results of literature (Singh and Ramaswamy 2010). This phenomenon indicates that the lateral bearing capacity might be an important factor in this experiment.

5. Conclusions

Several cases of single screw piles in loose sand have been investigated through inclined static and dynamic pullout loading tests. The conclusions can be summarized as followings:

- The experimental values of Zhang (2010) were used to compare with the ultimate pullout capacity of screw piles in loose sand. The inclined ultimate loading reduces along with increasing D/W in different density sand.
- When D/W was less than 3.14, the pile-soil and blade-soil interactions decreased in inclined static pullout tests. After the inclined dynamic pullout actions, its failure of ground was laterally pushed by soil column between blades. At $D/W \geq 5$, the pile-soil and blade-soil interactions increased obviously, the soil around the blade was the main failure zone.
- Critical DSLR exist in the experimental study, and it might be related to D/W, physical parameters of ground, embedment depth, preloading, dynamic parameter, angle of applied force, etc. In this research, the critical DSLR values are reached separately at D/W = 3.14 and 40%~60% of preloading or D/W = 5 and 20%~40% of preloading.

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