Experimental Pullout Capacity of Screw Piles in Dry Gypseous Soil

Mahdi O. Karkush[1,a *] and Omar J. Mukhlef[1,b]

[1]Civil Engineering Department, University of Baghdad, Baghdad, Iraq

[a]mahdi_karkush@coeng.uobaghdad.edu.iq, [b]omar.fallujii@gmail.com

Abstract. Screw piles are widely used in supporting structures subjected to pullout forces, such as power towers and offshore structures, and this research investigates their performance in gypseous soil of medium relative density. The bearing capacity and displacement of a single screw pile model inserted in gypseous soil with various diameters (D = 20, 30, and 40) mm are examined in this study. The soil used in the testing had a gypsum content of 40% and the bedding soil had a relative density of 40%. To simulate the pullout testing in the lab, a physical model was manufactured with specific dimensions. Three steel screw piles with helix diameters of 20, 30, and 40 mm are used, with a total length of 500 mm. The helix is continuous over the pile's embedded depth of 400 mm. The results of tests revealed that decreasing the length to diameter (H/D) ratio resulted in a higher pullout capacity of screw piles and a lower corresponding displacement.

Keywords: Screw piles; helix; gypseous soil; pullout; displacement.

Introduction

Gypseous soils are found in various parts of the world and cover around 30% of Iraq's land area [1]. Due to gypsum dissolution by groundwater, excessive gypsum content in the soil presents serious problems for structures built on such soils [2-5]. In general, gypseous soil is stiff while dry, but loses strength when wet due to changes in groundwater levels or leakage from pipes or underground tanks, which causes gypsum dissolving and, as a result, increases the volume of cavities in the soil mass. The creation of cavities increases the permeability of gypseous soils, and large cavities can cause structural damage or collapse.

Figure 1 shows a screw pile that differs from ordinary piles in that it is composed of high-quality steel. Screw piles are made up of a shaft and a helix that are attached to the shaft at varied intervals and have a sharp end for easy insertion in the soil [6]. The diameters of the shaft and helix, as well as the spacing between the helices and the space between piles, all influence the behavior of screw piles. Screw piles were originally employed primarily as anchors, but they were later used to sustain tensile loads such as power transmission towers. Their use, however, has expanded to encompass unstable structures and parallel loading [7,8]. In addition to torsion, screw piles can be employed as structural tensile or structural compression members [9-12]. Figure 1 shows the screw pile's fundamental elements.

The ultimate pullout capacity and displacement of screw piles were explored in this work by performing tests on three steel-made screw piles with diameters of 20, 30, and 40 mm. Screw piles are installed in soil with a high gypsum content (40%) and a medium density (Dr = 40%). The screw pile's ultimate pullout capacity is estimated experimentally from the load-displacement curve using a failure criterion of displacement equals 20% from the helix diameter.

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

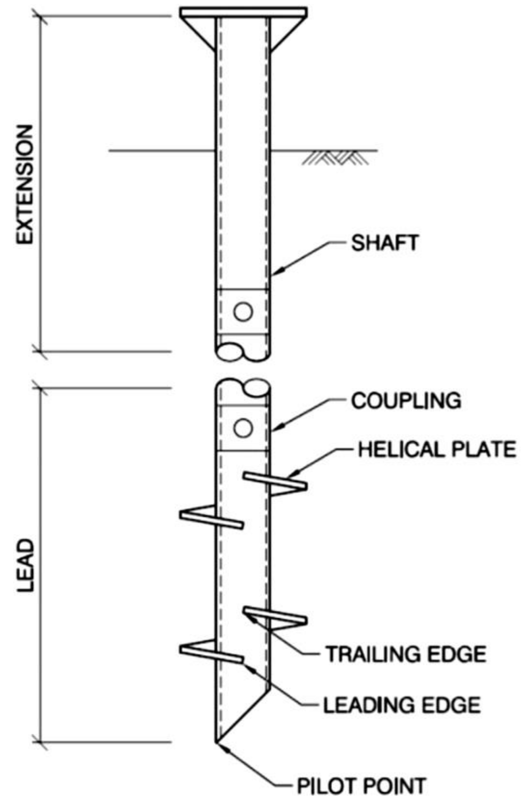

Figure 1. The basic components of the screw pile.

Pullout Capacity of Screw Piles

Screw pile pullout capacity in soils is based on the number of helices, helix diameter, and spacing between helices. Equation 1 shows the pullout capability of screw piles in cohesionless soils; references [13, 14] provide further information. In the design and analysis of the pullout capacity of screw piles in cohesionless soils, the spacing between helix plates and the ratio of embedment are both considered essential variables. Deep foundations, according to Zhang et al. [15], are screw piles under tensile or compression stresses with a ratio of embedment (H/D) greater than 5, where H is the depth from the soil surface to the upper helix of the pile and D is the diameter of the helix. Meyerhof and Adams [13] proposed a critical embedment ratio (H/D)cr to distinguish between shallow and deep foundations. The mechanisms of failure are the main distinctions in the analysis of deep and shallow foundations [13,16].

The bearing zone in the pullout of shallow screw piles will be the area from the upper helix to the ground surface, whereas the bearing zone in deep screw piles will be the entire area below the ground surface [17]. Equation 1 calculates the pullout capacity of a shallow multi-helix screw pile (H/D< (H/D)cr) assuming a cylindrical failure zone. The cylindrical shear failure zone assumes that the soil-pile will fail as a cylindrical block with a diameter equal to the helix's diameter and a length equal to the pile's embedded depth.

$$Q_{total} = 0.5\, P_h\, H\, \gamma'(H_b^2 - H_t^2)K_u\, tan\varphi + \ H\, \gamma'\, A_h\, F_q \quad (1)$$

The pullout capacity of deep multi helix screw pile (H/D>(H/D)$_{cr}$) assuming cylindrical failure zone is given by Eq. 2:

$$Q_{total} = 0.5\, P_h\ \ H\, \gamma'(H_b^2 - H_t^2)K_u\, tan\varphi + H\, \gamma'\, A_h\, F_q + 0.5\, H_{eff}^2\, P_s\, \gamma'\, K_u tan\varphi \quad (2)$$

T Individual bearing capacity can be used to compute the pile's pullout capacity, as shown in Eq. 3. Individual bearing capacity presupposes that the pile's pullout capacity is equal to the sum of individual helix bearing capacity.

$$Q_{total} = \sum Q_{\,bearing\ helix} = \ \sum S\, \gamma'\, A_h\, F_q \quad (3)$$

where

H_{eff} = effective length of screw pile = H-D.
F_q = break out coefficient for cohesionless soils in shallow conditions.
D: the helix diameter.
γ': the effective unit weight of soil.
H: the embedded depth of the pile.
H_b: the distance from soil surface to the bottom helix.
H_t: the distance from soil surface to the top helix.
K_u: the lateral earth pressure coefficient under pullout loading.
A_h: the area of the helix.
P_s: the perimeter of pile shaft [13].
P_h: the perimeter of the helix.
S: the spacing between helixes.

In the literature, there are several approaches for determining the pile's ultimate pullout capacity from the load test. Some of these strategies are described in reference [17], including the Davisson criterion, Brinch Hansen criterion, L1–L2 methodology, Federal Highway Administration (FHWA) (5 percent of the helix diameter), and ISSMFE (10 percent of the helix diameter). In addition, some authors [18] defined the failure load that corresponding to a displacement of 20% of the helix diameter. The majority of prior research focused on the behavior of screw piles in clayey and sandy soils and ignored the impacts of gypsum in the soil. As a result, the current study focused on evaluating the behavior of screw piles in gypseous sandy soil, with a gypsum content of around 40% of the total weight of the soil utilized in the testing. The pullout capacity of numerous screw piles in medium density gypseous soil was measured using a laboratory physical model.

Soil Sampling and Material Properties

The gypseous soil used in the testing was brought in from Fallujah, which is located in western part of Iraq and contains 40% gypsum by weight. he bedding soil utilized in the laboratory physical model was prepared using the raining technique to achieve a relative density of 40%, so the soil can be classed as medium dense soil based on its relative density. Table 1 lists the geotechnical parameters of soil samples utilized in experiments in the laboratory. Screw piles are made up of a steel shaft and helices that are arranged in a spiral pattern across the shaft. The helices run the length of the steel shaft (40 mm), with the remaining 100 mm being a free head of pile that remains above the soil surface. Screw piles are characterized as free head piles as a result. Table 2 lists the dimensions of manufactured screw piles, which are depicted in Figures 2 and 3.

Table 1. Physical and mechanical properties of tested gypseous soil.

Property	Unit	Value	Property	Unit	Value
Saturated unit weight ASTM D1556	kN/m^3	17.8	Specific gravity BS13377: I976, test No. 6	-	2.4
Minimum dry unit weight ASTM D4254	kN/m^3	12.7	Soil classification (USCS)	-	SC
Maximum dry unit weight ASTM D4253	kN/m^3	16.9	Passing sieve #200	%	14.5
Relative density	%	40	Cohesion ASTM D3080	kPa	7.2
Dry unit weight at relative density =40%	kN/m^3	14.1	Angle of friction, φ ASTM D3080	degree	36
Void ratio	-	0.7	Permeability ASTM D 2434	cm/sec	8.04×10^{-4}
Water content	%	25	Gypsum content	%	40
Ku [13]	-	0.95	Fq [15]	-	55

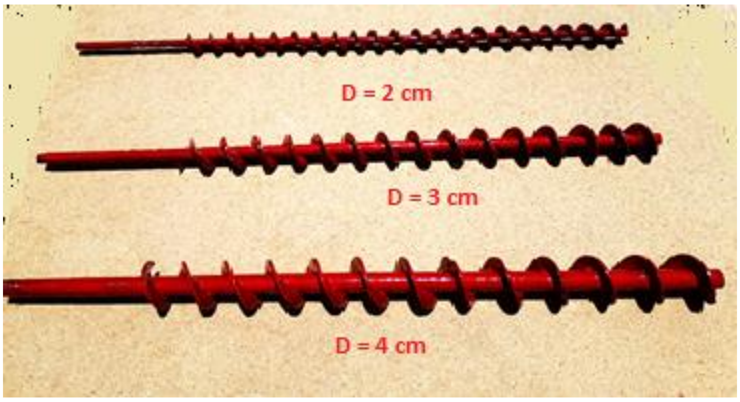

Figure 2. Models of used screw piles.

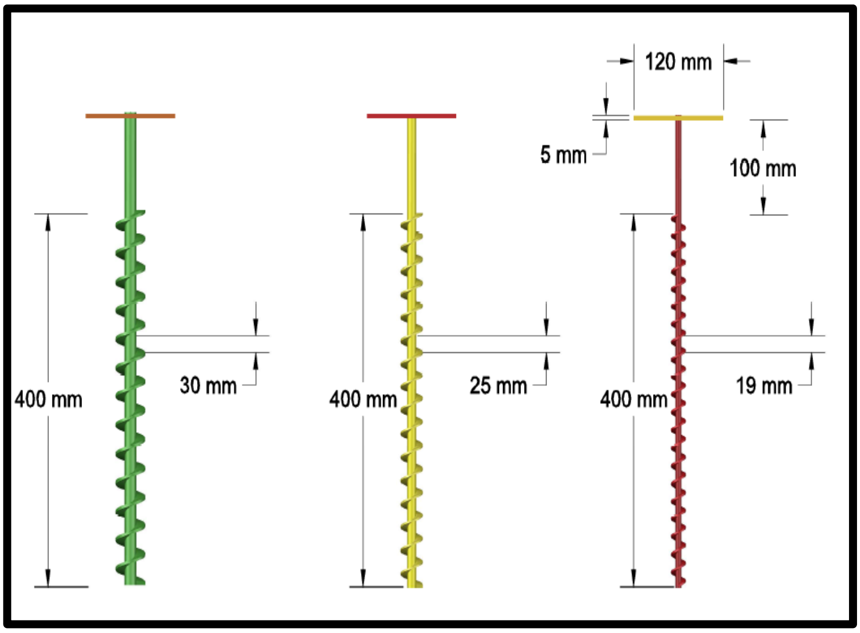

Figure 3. Schematic details of screw piles.

Table 2. Dimensions of tested screw piles.

Screw pile	Shaft diameter	Helix diameter	Total length	Embedded depth in soil	No. of helices	Spacing between helix
D20	8 mm	20 mm	500 mm	400 mm	20	19 mm
D30	12 mm	30 mm	500 mm	400 mm	15	25 mm
D40	16 mm	40 mm	500 mm	400 mm	13	30 mm

The pile cap is composed of steel and is 1201206 mm in diameter. Figure 4 shows how the screw pile is linked to the pile cap with a screw and nut. The experiments were carried out in a steel box with dimensions of (700700600) mm, which was filled with gypseous soil at a relative density of 40%, as shown in Figure 5.

Figure 4. Cap of screw pile (120×120×6 mm).

Figure 5. Insertion and adjustment of screw pile.

Testing Procedure

The dry gypseous soil was poured into the steel box using the raining approach to achieve the correct relative density. A specific raining apparatus was fabricated and measured in order to achieve a uniform layer according to the required relative density. The key elements determining the density of the soil in the raining technique are the pouring height and sand discharge rate. The height of the box was divided into five levels, each with a height of 120 mm. The weight of soil necessary to fill each layer is 83 kg, based on the adopted unit weight of soil of 14.1 kN/m3 and a relative density of 40%. Figure 6 depicts the relationship between the pouring height and the relative density of sand. The free fall height of pouring sand must be equivalent to 720 mm in order to achieve the desired relative density of 40%.

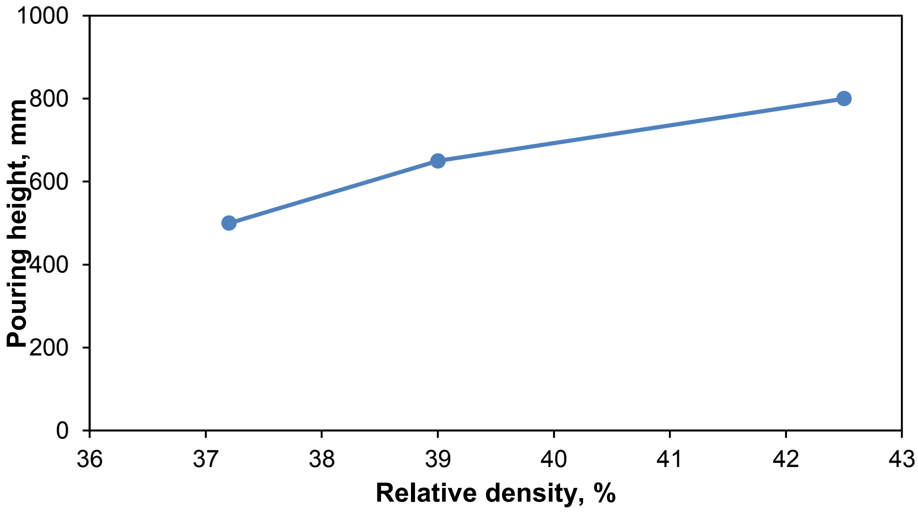

Figure 6. Variation of relative density with pouring height of raining technique.

To measure pullout load-settlement relationship of screw piles inserted in gypseous soil, the following stages are performed:

- Preparing the bedding soil according to the desired unit weight of soil 14.1 kN/m^3, which be satisfied by dropping the soil from a height of 720 mm.
- Install the screw pile manually by applying torque to the pile head to reach the required embedded depth of 400 mm and leaving 100 mm of pile free above the soil surface, as shown in Figure 7.
- • To measure the displacement of the screw pile, a square plate (pile cap) is fixed to the top of the screw pile, and the dial gauge and LVDT are installed vertically, as illustrated in Figure 7.
- A hydraulic jack system (full capacity of the jack is 5 tons) was installed with a compressor to simulate the axial pullout loads on the screw piles.

- The tool used to pull out the screw pile was a steel wire which was connected from the top to the steel plate and from the bottom to the pile cap. When applying jack pressure to the plate, the steel wire will pull the pile upward and then record the displacement value and the load applied by the installed gauges.
- • To measure the axial loads applied to the screw pile, a load cell is mounted to the shaft of the hydraulic jack and connected to the indicator.
- • The test was conducted 24 hours after the screw piles were inserted into the soil to allow enough time for the soil particles in the steel box to reorganize after remolding.
- Apply the pullout load incrementally starting from 20 N to reach the final increment of 240 N. Using a dial gauge and an LVTD, the average upward movement of the screw pile is measured under each increment of loading.
- • Pullout loading on the screw pile continued to reach the point of failure, which was determined as a load equivalent to a displacement value of 20% of the helix's diameter.

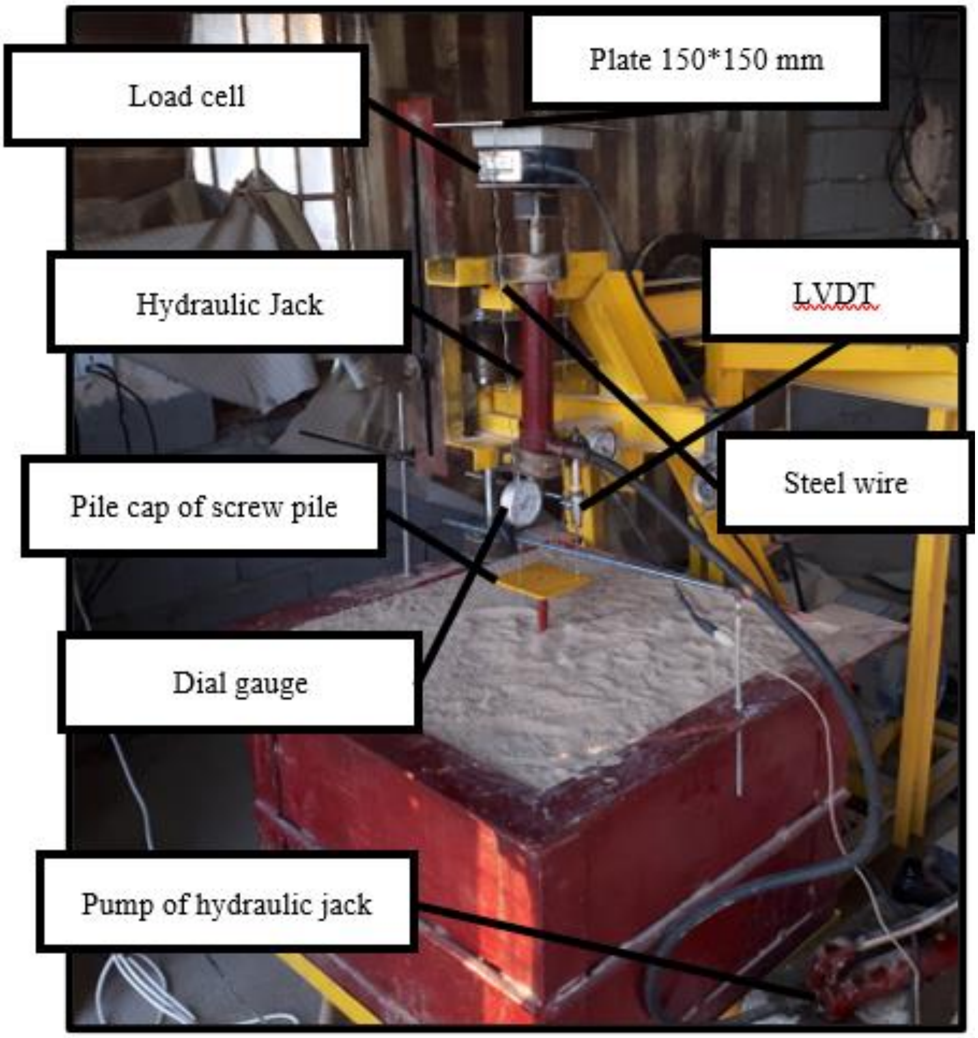

Figure 7. Pullout test of screw pile in dry condition.

Results and Discussion

To evaluate the pullout capacity of piles, laboratory tests were conducted on three screw piles with diameters of 20, 30, and 40 mm inserted in gypseous soils. The piles are classified as free head piles, and the load application continued until the piles failed, which is defined as a load corresponding to a displacement equal to 20% of the helix diameter. Table 3 summarizes the results of the experiments, showing the pile displacement for each load increment applied to the screw piles.

Table 3. Vertical displacement of screw piles for each load increment.

Pullout load (N)	Displacement (mm) D20	D30	D40
0	0	0	0
20	1.15	0.84	0.2
40	1.85	1.71	1.32
60	3.64	2.65	1.75
80	5.52	3.27	2.48
100	8.2	6.45	4.78
120	10.7	8.1	7.2
140	13.2	10.3	8.74
160	15.7	12.47	9.65
180	19.1	16.5	12.3
200	23.5	19.21	15.8
220	26.4	22.5	18.4
240	31.2	27.1	21.1

Figure 9 shows that the screw pile has been resistant to movement since the commencement of the tests. In screw piles, failure is thought to occur when the displacement equals 20% of the helix diameter. The screw pile D20 failed under a force of 65 N, resulting in a displacement of 4 mm, but the screw pile D30 failed under a load of 94 N, resulting in a displacement of more than 6 mm. The screw pile D40 failed with a failure load of 130 N and a displacement of 8 mm. As shown in Figure 8, the failure mechanism in all cases is general shear failure, which is one of the benefits of employing screw piles to resist axial pullout loads in gypseous sandy soils. Based on the findings in Figure 8, a failure criteria of displacement of 20% of helix diameter is quite conservative and can be safely raised to 40% of helix diameter. Calculating the failure load from experimental work and comparing it to existing theoretical approaches can be used to verify the proposed criterion.

The pullout capacity of screw piles calculated from load settlement curves based on the failure criterion of 10% and 20% displacement of helix diameter are compared with those calculated theoretically using Eq. 2 (CSM) and Eq. 3 (IBM) as given in Table 4. Assuming cylindrical shear method CSM of diameter equals to the helix diameter almost gives values more reliable, the values of failure loads are well agreed with those calculated experimentally from load-settlement curves and corresponding to 20% settlement. While the failure loads calculated by the individual bearing method IBM (Eq. 3) can be considered overestimated and oscillate about the values experimentally. Based on these results, it is suggested to increase the ratio of displacement from helix diameter to be 30% instead of 20%. Accordingly, the theoretical equations require more research to define a more reliable failure pullout load of screw piles.

Table 4. Comparison with the experimental results of bearing capacity and theoretical results

Screw pile	Failure load (N) Theoretical CSM	IBM	Experimental At settle. 10% of D	At settle. 20% of D	At settle. 30% of D	At settle. 40% of D
D20	78	220	44	63	70	100
D30	150	370	73	95	140	140
D40	235	550	92	130	180	200

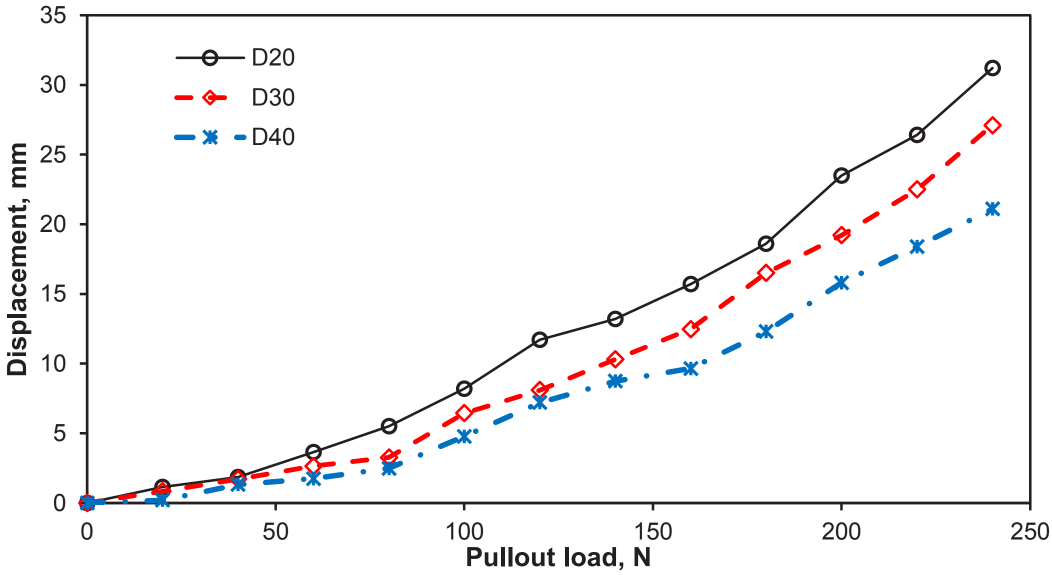

Figure 8. Comparison of pullout load-displacement curves for screw pile D20, D30, and D40.

Conclusions

The pullout capacity of screw piles of various diameters installed in dry gypseous soil of medium relative density was examined in the current study. The following conclusions can be derived from the findings of the current study:

- • For a constant length of pile, decreasing the H/D ratio increases the ultimate pullout capacity of the screw piles.
- • Due to the high strength of dry gypseous sandy soil, increasing the diameter of the screw pile results in a high failure load and little displacement.
- • For piles D20, D30, and D40, the failure pullout load corresponding to displacement equal to 20% of the helix diameter is (63, 95, and 130) N, and the corresponding displacements are 4, 6, and 8 mm, respectively. The failure criterion of 20% is very conservative and gives an underestimation of the failure loads calculated using Eq. 2 of the cylindrical shear method.
- The failure criterion can be increased safely to be 30% displacement of the helix diameter in dry cohesionless gypseous soil.

References

[1] N.S. Al-Dulaimi, Characteristics of gypseous soils treated with calcium chloride solution, M.Sc. Thesis, Civil Engineering Department, University of Baghdad, 2004.
[2] O.J. Mukhlef, M.O. Karkush, and A. Zhussupbekov, Strength and compressibility of screw piles constructed in gypseous soil, In IOP Conference Series: Materials Science and Engineering 901 (1) (2020) 012006.
[3] M.O. Karkush, Y.J. Al-Shakarchi, and A.N. Al-Jorany, Theoretical modeling and experimental investigation of leaching behavior of salty soils, In Conference on Construction and Building Technology (2008) 123-138.
[4] M.O. Karkush, Y.J. Al-Shakarchi, and A.N. Al-Jorany, Leaching Behavior of Gypseous Soils. Journal of Engineering 14(4) (2008) 3077-3089.
[5] M.O. Karkush, M.D. Ahmed, A.A.H. Sheikha, and A. Al-Rumaithi, Thematic maps for the variation of bearing capacity of soil using SPTs and MATLAB. Geosciences 10(9) (2020) 329.
[6] Arup Geotechnics, Design of screw piles: assessment of pile design methodology, Ove Arup & Partners Ltd, London, 2005.
[7] B. Livneh and M.H.M. Naggar, Axial testing and numerical modelling of square shaft helical piles under compressive and tensile loading, Canadian Geotechnical Journal 45(8) (2008) 1142–1155.

https://doi.org/10.1051/e3sconf/202131801002

[8] G. Zhengyang and L. Deng, Field behaviour of screw micropiles subjected to axial loading in cohesive soils, Canadian Geotechnical Journal 55(1) (2018) 34-44.
[9] R. Schmidt and M. Nasr, Screw piles: uses and considerations, Struct. Mag. (2004) 29-31.
[10] D. Xiao, C. Wu, and H. Wu, Experimental study on ultimate capacity of large screw piles in Beijing, In International Congress and Exhibition, Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology (2017) 52-58.
[11] Jr.M. Perlow, Helical pile acceptance criteria, design guidelines, and load test verification, In Geo-Frontiers 2011: Advances in Geotechnical Engineering (2011) 94-102.
[12] M.P. Mitsch and S.P. Clemence, The uplift capacity of helix anchors in sand, In Uplift Behavior of Anchor Foundations in Soil, American Society of Civil Engineers, New York (1985) 26-47.
[13] G.G. Meyerhof and J.I. Adams, The ultimate uplift capacity of foundations, Canadian Geotechnical Journal 5(4) (1968) 225-244.
[14] B.M. Das and S.K. Shukla. Earth anchors. J. Ross Publishing, 2013.
[15] D.J.Y. Zhang, R. Chalaturnyk, P.K. Robertson, D.C. Sego, and G. Cyre, Screw anchor test program (Part I): Instrumentation, site characterization and installation, In Proc. 51st Canadian Geotech. Conf., Edmonton. 1998.
[16] M.F. Bouali, M.O. Karkush, and M. Bouassida, Impact of wall movements on the location of passive Earth thrust. Open Geosciences 13(1) (2021) 570-581.
[17] S.N. Rao, Y.V.S.N. Prasad, and C. Veeresh, C. Behaviour of embedded model screw anchors in soft clays, Geotechnique 43(4) (1993) 605-614.
[18] A.J. Lutenegger, Cylindrical shear or plate bearing? Uplift behavior of multi-helix screw anchors in clay, In Contemporary Topics in Deep Foundations (2009) 456-463.