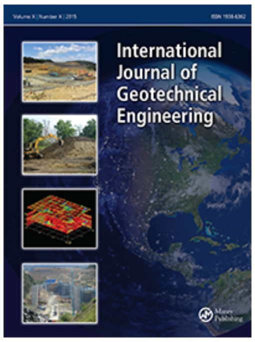

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RESEARCH ARTICLE

Field tests and interpretation of screw micropiles subjected to axial loading in cohesive soil

Alex Sanzeni and Emanuele Giuseppe Danesi

Department of Civil, Environmental, Architectural Engineering and Mathematics, Università Degli Studi Di Brescia, DICATAM, Brescia, Italy

ABSTRACT

Screw micropiles consist of a steel shaft with continuous threads and a threaded tapered tip; the shaft diameter is generally 66–140 mm and the length is 1.0–3.0 m. Screw micropiles are installed by rotary driving, without drilling and grouting, and can be employed in the construction of light structures, houses, photovoltaic power plants, road and railway barriers etc. The literature on this type of foundation is limited and the present paper reports additional findings derived from an ongoing research on screw micropiles subjected to axial loading. In a test field in Italy, 22 new tests were conducted on three models of micropiles with different diameters, lengths and taper angles; tests were conducted with two different procedures. The results confirmed the possibility of computing the ultimate capacity of screw micropiles with appropriate analytical methods, highlighting the influence of the taper angle and the effect of the testing procedure on the observed response.

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KEYWORDS
Screw micropiles; ground screws; tapered pile; load test; ultimate capacity; testing procedure

1 Introduction

Screw micropiles consist of a tubular steel pipe (diameter 66–140 mm), equipped with spiral continuous threads, and a conical threaded tip (generally the thread is extended continuously from the shaft to the tip); the overall length of screw micropiles is generally between 1.0 and 3.0 m (Figure 1). The thread and the conical tip serve two important purposes, namely to allow the installation, which is executed by rotary driving (i.e. screwing), and to enhance the interaction with the surrounding soil in the operating condition. Because of these unique geometrical features screw micropiles are different from helical piles, which are a type of foundation that consists of a steel cylindrical smooth shaft with one or multiple distinct helixes and a truncated base (Elkasagby and El Naggar 2015; Mohajerani, Bosnjak, and Bromwich 2016).

Screw micropiles are a relatively new and increasingly popular type of precast pile foundation (Lutenegger 2013). They can be employed in the construction of temporary as well as permanent structures (housing facilities, road signs and lighting, noise – isolation barriers, railway systems and photovoltaic plants), especially where cast in place foundations cannot be adopted for environmental or supply reasons. Thus, screw micropiles have the potential for a sustainable and attractive alternative to concrete foundations, especially cast in place footings. On the other hand, it is worth noting that, due to the manufacturing process and cost of raw material, screw micropiles generally have a limited range of sizes (most notably, a limited range of length) which, in turn, may limit their applicability and the value of achievable ultimate capacity.

The geotechnical design of screw micropiles subjected to axial loading is currently conducted by performing on–site load tests according to unspecified testing procedures or via empirical correlations with the installation torque (if this measurement is available). Furthermore, this approach generally does not take into account the project requirements or the type of relevant loading (permanent or accidental) and it is based on limited information regarding the geotechnical properties of the soil around and below the screws.

The literature on the behaviour and on the ultimate capacity of screw micropiles is limited. On the subject, the most notable specific studies were recently published by Guo and Deng (2018), Sanzeni and Danesi (2019), Guo, Khidri, and Deng (2019) and by Khidri and Deng (2021). In what can be regarded as the first original contribution on the behaviour of screw micropiles, Guo and Deng (2018) performed a large number of tests on full-scale screw micropiles of different sizes, driven in a uniform clayey soil, and developed an analytical method to compute their ultimate capacity under axial loads. The micropiles were tested according to the 'Quick Load Test Method' included in ASTM Standards D1143 (2007a) and D3689 (2007b), which requires to maintain each load increment for a period of time in the order of a few minutes, regardless of the response of the pile. Also, the 'setup time' (i.e. time between the installation and testing) of each ground screw was at least 48 h. Sanzeni and Danesi (2019) presented the first results of a similar independent study that has been carried out since the end of 2018 in Northern Italy. In this case, tests were conducted according to the 'Standard Loading Procedure' described in the ASTM standards D1143 and D3689, which requires to maintain each load increment until the rate of settlement is not greater than 0.25 mm/h. Moreover, the period of time between installation and testing was between 1 and 2 months. The analysis of the experimental results presented by Sanzeni and Danesi (2019) indicated that it is possible to estimate the ultimate capacity of screw

CONTACT Alex Sanzeni alex.sanzeni@unibs.it Università Degli Studi Di Brescia, DICATAM, Via Branze, 43, Brescia 25123, Italy

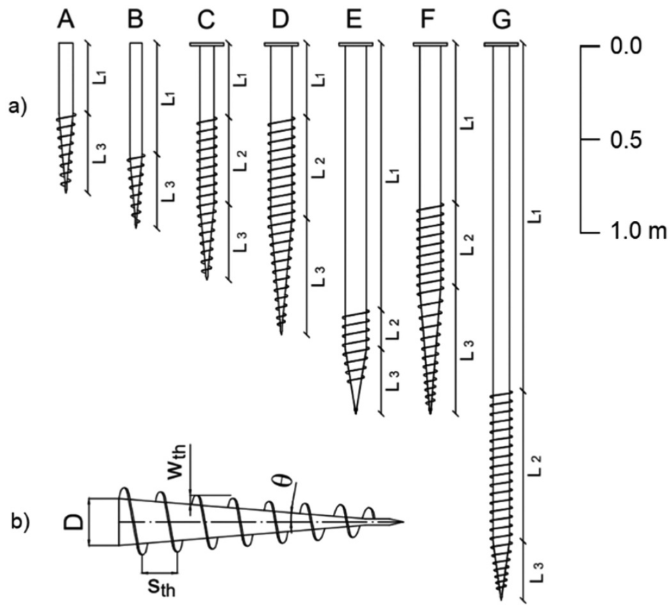

Figure 1. Geometrical features of screw micropiles (a) and detail of the tapered conical tip (b).

micropiles subjected to axial tensile, as well as compressive, loads, with appropriate parameters and contributions to account for different soil, loading and loading conditions. More recent studies by Guo, Khidri, and Deng (2019) and by Khidri and Deng (2021) concentrated primarily on the response of screw micropiles to cyclic loading in cohesive and cohesionless soils, but a comparison between the results obtained by monotonic load tests executed with different procedures (i.e., the 'Quick Load Test Method' and the 'Standard Loading Procedure') in the same clayey soil is not available.

This paper presents additional findings derived from an ongoing experimental study, whose main goal is to improve the knowledge on the behaviour of screw micropiles and to provide practical information on the appropriate design and testing approaches. At a previously selected test site in Cornovecchio (Italy), characterized by the presence of clayey soils, 22 new tests were executed on screw micropiles with diameter varying from 89 to 140 mm, length of 2 and 3 m, and taper angle of 5–9° of the conical tip, therefore larger and longer than the previous screw micropiles tested by the authors in Italy. Tests were conducted by using two different testing procedures, namely the 'Standard Loading Procedure' and the 'Quick Load Test Method', both included in the ASTM Standards D1143 (2007a) and D3689 (2007b). Test results were analysed and compared to the results of the previous experimental campaign from the same Authors (Sanzeni and Danesi 2019), the data were interpreted with the analytical method presented by Guo and Deng (2018) to further identify the most relevant features and parameters for the design procedure, and finally a comparison was made between results obtained with different testing procedures to highlight the effect of the loading rate on the observed response.

2 Features of the tested screw micropiles

Figure 1 shows all the micropile models that have been tested by the Authors in the course of their research project. The

Table 1. Relevant dimensions and geometrical characteristics of the tested screw micropiles.

Screw	D	L	L_1	L_2	L_3	w_{th}	s_{th}	θ
model				(mm)				(°)
A	76	800	380	–	420	10	40	5
B	66	1000	600	–	400	10	40	5
C	76	1300	400	470	430	15	50	5
D	114	1600	400	550	650	15	50	5
E	114	2000	1440	210	350	15	50	9
F	114	2000	900	500	600	15	50	5
G	89	3000	1870	810	320	12	50	8

results presented in this paper refer to the models identified with letters E, F and G in Figure 1; the results of tests performed on models A, B, C and D were presented in a previous publication (Sanzeni and Danesi 2019). All models were manufactured by Krinner Schraubfundamente GmbH (Straßkirchen, Germany) according to the German standards DIN EN 10,219 (2006a, 2006b) and consist of a tubular element and a conical tip, with continuous spiral threads, coated with galvanization to prevent corrosion and improve durability. The pile shaft, the conical tip and the threads are made of S235 structural steel (Young's modulus of 210 GPa, yield strength of 235 MPa) and welded together. The most relevant geometrical features of each micropile model are summarized in Table 1: for models E, F and G the shaft diameter (D) is either 89 or 114 mm, the total length (L) is either 2 or 3 m; the thread pitch (s_{th}) is 50 mm, the thread width (w_{th}) is either 12 or 15 mm, the thickness of the smooth shaft (th) is between 3.2 and 5.0 mm and the taper angle is in the range 5–9°.

3 Test site, experimental programme and testing procedures

3.1 Test field

A test site was selected in 2018 near the town of Cornovecchio (Province of Lodi, Italy) and a comprehensive geotechnical investigation campaign was supervised and conducted by the Authors (Sanzeni and Danesi 2019). Figure 2 shows the test site layout and the location of CPTu tests. Below a 1 m thick layer of fill, the soil at the test field consists of stiff clay, with thin layers of silty sand (Figure 3). The groundwater table is approximately 10 m below the ground surface. From laboratory tests, the upper clay had the following properties: 90–95% of the fine particles (percentage passing no. 200 ASTM sieve), water content w = 20–21%, degree of saturation S_r = 85–90%, liquid limit w_L = 40–44, Plasticity Index I_P = 18–22, liquidity Index I_L = 0.0–0.2, Consistency Index $I_C = (w_L - w)/(I_P)$ = 0.9–1.1. Values of the undrained shear strength (s_u) were estimated from the results of CPTu tests (Lunne, Robertson, and Powell 1997) and compared with values of s_u obtained from unconsolidated – undrained triaxial tests (Figure 3). The sand below the upper clay had the following properties: sand content 55–65%, fines content 35–45%, uniformity coefficient D_{60}/D_{10} = 6–8 and average grain size D_{50} = 0.06–0.10 mm. The estimated in–situ relative density D_r was 50–60%; the friction angle ϕ' was determined in the interval 36–40° from the interpretation of in–situ and laboratory tests.

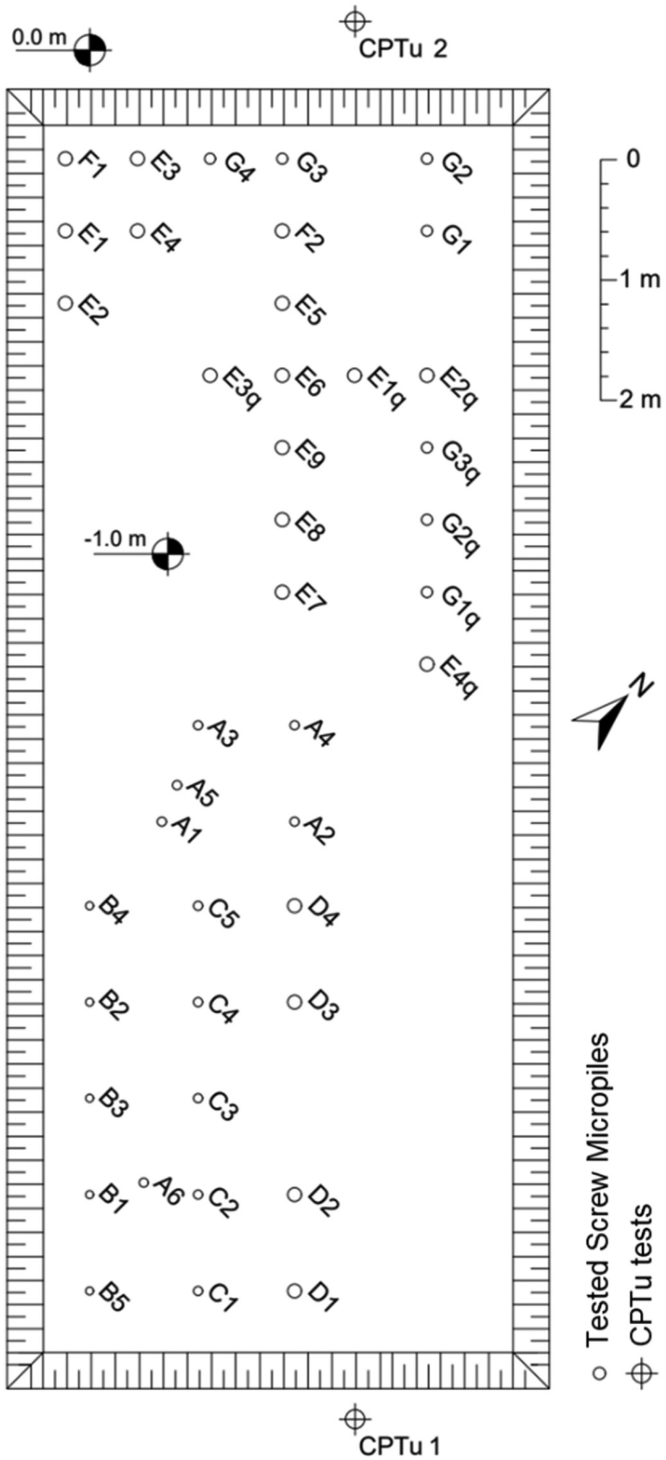

Figure 2. Layout the Cornovecchio test field, with location of CPTu tests and screw micropiles.

3.2 Experimental programme and testing procedures

Twenty-two experiments were executed between May 2019 and September 2020, consisting of a number (generally from one to three) of compressive load tests as well as pull–out tests (layout of test screws in Figure 2). Screw micropiles were installed by rotary driving at the designated test site in undisturbed soil (not previously involved in other pile testing); each element was driven into the soil almost to its full length. The installation of each micropile required 3–10 min depending on the geometrical features of each model type, during which no significant soil churning was observed. Torque measurements were not available; visual inspection carried out from the ground surface before testing did not allow to detect the presence of gaps between the soil and the micropiles along the shaft. The test procedures and equipment conformed to the ASTM Standards D1143 and D3689 (ASTM 2007a; 2007b). In particular, as in Sanzeni and Danesi (2019), all models were tested according to the 'Standard Loading Procedure', usually adopted to test pile foundations under predominantly permanent loads, which requires the application of load increments equal to 25% of the anticipated design load (i.e. approximately 10% of the ultimate capacity) and to maintain each load increment until the rate of settlement is not greater than 0.25 mm/h (up to 0.1 mm/h in this study), but not longer than 2 h. Alternatively, as in Guo and Deng (2018), a number of tests (labelled with the letter 'q' in Figure 2) were also executed according to the 'Quick Load Test Method', also described in the same ASTM Standards, which requires the application of the load with a short and constant time interval between increments (with a minimum of 2 ½ min, 5 min in this study), regardless of the pile response. Moreover, in the case of the former procedure, a setup time of 1 month was allowed between the installation of the piles and testing, whereas for the latter procedure, a shorter 48–72–h setup time was adopted. The spacing between any two micropiles at the test site was kept at least 5–6 times the average diameter. Each screw micropile in this research was subjected to only one loading test. A list of all the experiments is reported in the following section.

4 Results and interpretation

4.1 Results of the experimental campaign

The result of the experimental campaign is summarized in Table 2, which reports the model type (E, F or G), the setup time (long, L, or short, S), the testing procedure adopted (S for Standard, Q for Quick), and the values of ultimate capacity derived from the test results of all micropiles. All tests in this study were interpreted to estimate the value of the ultimate capacity, Q_L, according to the most popular criteria and methods in the literature, such as that by Terzaghi (1942) which identifies the ultimate capacity as the load corresponding to a displacement of 10% of the pile diameter or the hyperbolic method proposed by Chin (1970), which is useful when the geotechnical failure of the soil–pile system is not fully achieved.

A selection of results is presented in Figure 4 in terms of load–displacement curves (Q–w/D), in which the micropile displacement (w) was normalized to the smooth shaft diameter (D). In particular, Figures 4a and Figure 4b refer to tests conducted according to the 'Standard Loading Procedure', while Figures 4c and Figure 4d refer to tests conducted according to the 'Quick load Test Method' procedure. The screw models E, F and G that were tested according to the standard loading procedure, achieved values of ultimate tensile (pull–out) and compressive capacities in the ranges 65–110 kN and 75–125 kN, respectively (Figures 4a and 4b), which are 2–3

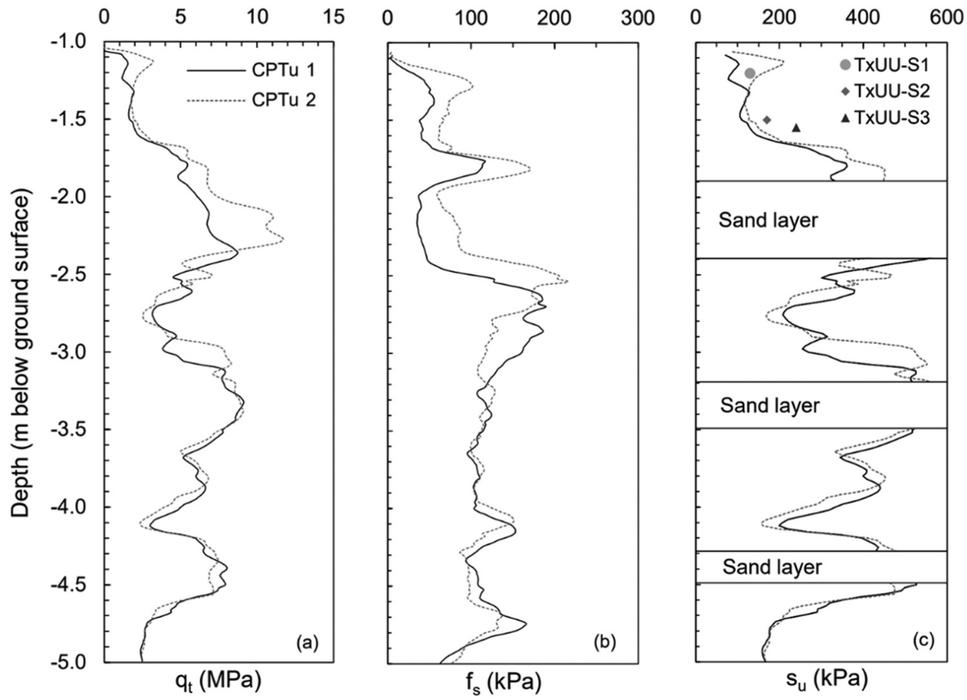

Figure 3. CPTu tests at the Cornovecchio test site: a) tip resistance; b) sleeve resistance; c) estimated undrained shear strength and comparison with results of laboratory tests.

Table 2. Summary of testing programme and estimated ultimate capacities.

Test ID	Screw model	D (mm)	L (mm)	Load type(1)	Setup time(2)	ASTM test procedure(3)	Q_L (kN)
E1	E	114	2000	C	L	S	90.0
E2	E	114	2000	T	L	S	77.1
E3	E	114	2000	T	L	S	68.4
E4	E	114	2000	T	L	S	66.0
E5	E	114	2000	C	L	S	70.0
E6	E	114	2000	C	L	S	75.0
E7	E	114	2000	C	L	S	77.0
E8	E	114	2000	C	L	S	89.9
E9	E	114	2000	T	L	S	66.9
E1q	E	114	2000	C	S	Q	95.0
E2q	E	114	2000	C	S	Q	97.0
E3q	E	114	2000	T	S	Q	66.0
E4q	E	114	2000	T	S	Q	66.0
F1	F	114	2000	C	L	S	110.0
F2	F	114	2000	C	L	S	100.0
G1	G	89	3000	C	L	S	115.0
G2	G	89	3000	C	L	S	125.4
G3	G	89	3000	T	L	S	105.0
G4	G	89	3000	T	L	S	110.0
G1q	G	89	3000	C	S	Q	125.4
G2q	G	89	3000	C	S	Q	99.0
G3q	G	89	3000	T	S	Q	112.2

(1): C,T = compressive, tensile; (2): S,L = short, long
(3): S,Q = standard, quick

times higher than those obtained from tests reported by Sanzeni and Danesi (2019) on shorter and smaller micropiles (models B and C, with length 1.0–1.3 m and diameter 66–76 mm). The same micropile models, E, F and G achieved tensile and compressive capacities in the ranges 65–112 kN and 90–125 kN, respectively, when tested according to the quick-test method (Figures 4c and 4d). The screw micropiles tested in Cornovecchio and reported in this publication achieved values of limit capacity under compressive loads that were 10–30% higher than those under tensile loads, depending on the geometrical features of each model, on the soil–stratigraphy conditions (relative to the pile embedment length) and the type of testing. The difference between values of pull–out and compressive capacity is related to the contribution of the conical threaded tip of the screw micropiles under compressive loads (Guo and Deng 2018; Sanzeni and Danesi 2019). The average normalized displacement required to mobilize the ultimate capacity was 0.05–0.08 (in tension) and 0.06–0.12 (in compression), generally in the same order of magnitude or slightly larger than that reported by Guo and Deng (2018) and by Sanzeni and Danesi (2019).

Figure 5 presents a more comprehensively supported comparison between results obtained from compression tests performed (according to the ASTM Standard Loading Procedure) on the screw models E and F, which have the same dimensions (diameter 114 mm, length 2000 mm) but different thread extension on the tubular shaft and on the conical tip (Figure 1, Table 1). The length of the smooth shaft of model E is 1440 mm, the threaded segment is 210 mm and the conical tip is 350 mm (and only partly covered by threads). By comparison, the screw micropile model F has 900, 500 and 600 mm, respectively, for each segment. Thus, while the overall thread extension of model E is less than 500 mm, in model F it is approximately 1000 mm. Although the taper angle of the tip of the two models is different (9° for model E, as opposed to 5° for model F) and the contribution of the threaded segment on the ultimate capacity of micropile F is more significantly affected by the presence of a 0.5 m–thick-sand layer (Figure 3), the average ultimate capacity of model F (approximately 105 kN) was 30% higher than that of model E (approximately 75–80 kN) and not far off from the capacity of model G (115–125 kN), with greater length (3000 mm) but smaller diameter (89 mm).

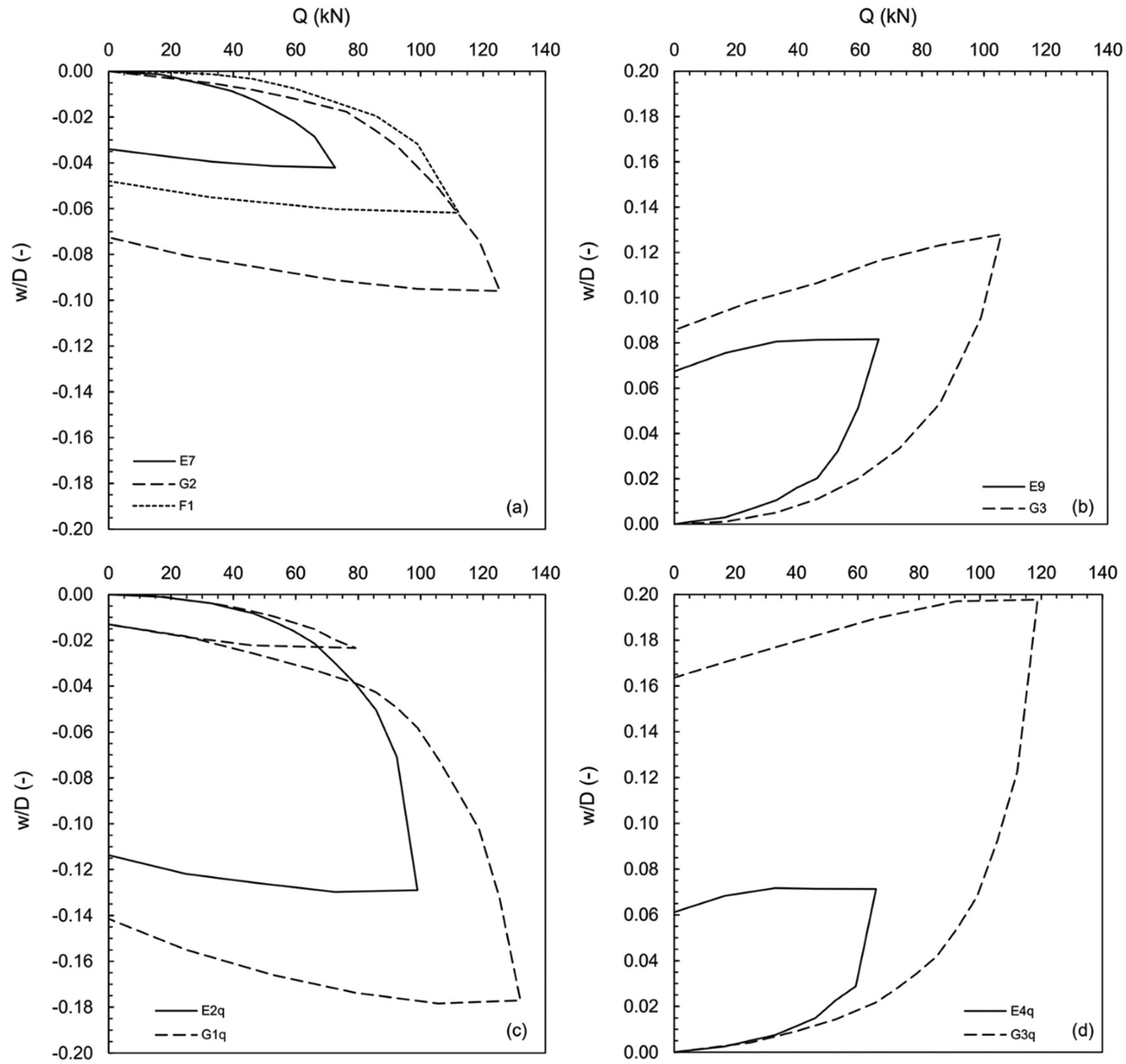

Figure 4. Selection of test results: a) axial compressive test, standard procedure; b) pull–out test, standard procedure; c) axial compressive test, quick test method; d) pull–out test, quick test method.

4.2 Effect of testing procedure and rate of loading

Regarding the possibility to test screw micropiles according to the Standard Loading Procedure or to the Quick Test Method (both described in the ASTM Standards), Figure 6 shows an example of test results which represents the time–displacement as well as the load–displacement curves of two compression tests performed at the Cornovecchio test site. The results refer to load tests performed on two micropiles of the same model E (diameter 114 mm, length 2000 mm, Figure 1 and Table 1). Test #E6 was conducted according to the Standard Loading procedure on a screw micropile that was driven in the soil approximately 1 month before testing. The test lasted approximately 600 min (or approximately 10 h, Figure 6a), the maximum applied load was 72 kN and the corresponding maximum displacement was 6 mm, which equals to 5% of the micropile diameter (Figure 6b). On the other hand, Test #E2q was executed according to the Quick Test Method on a screw micropile that was installed approximately 2–3 days before testing. The test lasted less than 90–100 min (approximately 1.5 h), the maximum applied load was 100 kN and the maximum measured vertical displacement was 15 mm, which corresponds to 13% of the screw diameter. While both tests allowed enough data to be collected to determine the ultimate capacity of the screw micropiles, the most apparent advantage of the quick load test over the standard procedure from the practical point of view was the considerable reduction of time and the ability to explore significantly greater values of pile displacement. However, the observed load–displacement curves are significantly different from each other and time–displacement curves have to be analysed. As presented in Figure 6a for Test #E2q, executed according to the Quick Test Method, load increments were applied in rapid succession and, while displacements associated with early steps rapidly reached a stable value (in the range of loads associated with the working conditions, and up to 40–50 kN in the example of Figure 6), the application of further load increments (towards the geotechnical failure of the pile–soil system) produced a response in which the equilibrium of forces acting on the pile (i.e., the applied load and soil resistance around the screw micropile) was consistently not achieved, most probably due to the generation of excess pore water pressures in the soil

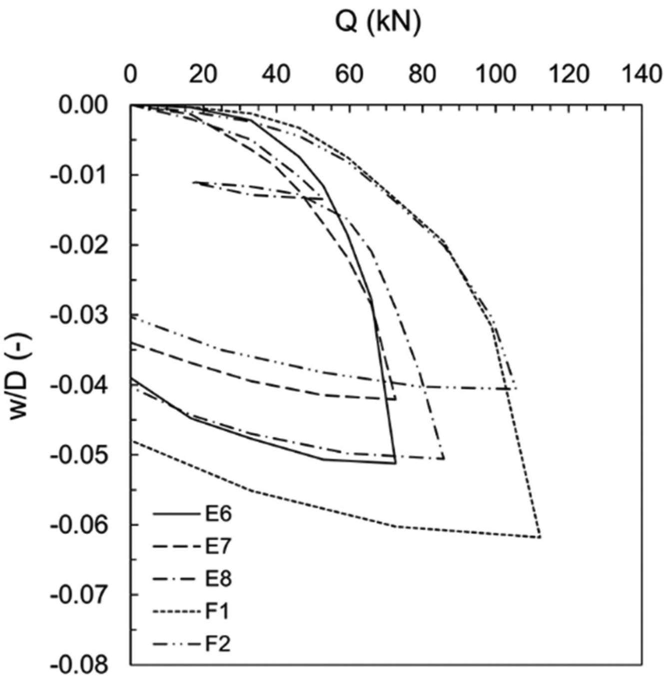

Figure 5. Comparison between results of axial compressive load tests (ASTM D1143, Standard Loading Procedure) on micropile models E and F, with same size but different thread extension.

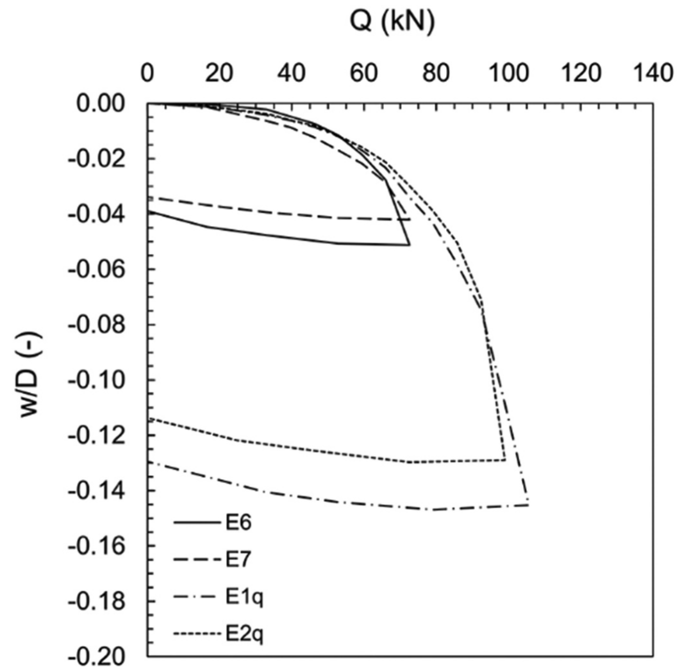

Figure 7. Comparison between results of axial compressive tests, on screw micropile model E, loaded according to the standard and to the quick (q) test procedures by the ASTM.

surrounding the screw micropile and the conical tip. On the other hand, the application of the Standard Loading Procedure in Test #E6 ensured a consistent response of the micropile throughout the duration of the test, regardless of the intensity of the applied load (with the notable exception of the condition associated with the application of loads that are very close, equal to, or greater than the ultimate capacity). The estimated ultimate capacities of the screw micropiles whose tests are reported in Figure 6 were 75 kN and 97 kN, achieved with displacements of about 8–9 mm (estimated value) and 10–12 mm, respectively, which correspond to normalized displacement *w/D* in the range 7–10%.

Figures 7 and Figure 8 present a more comprehensively supported comparison between results obtained from compression and pull–out tests performed according to the Standard and to the Quick Loading procedures of the ASTM on a number of the screw models E in Cornovecchio. From the comparison reported in Figure 7 it appears again that a significantly different response was achieved in compression depending on the type of testing (i.e. on the rate of loading, which, for the purpose of this discussion, can be qualitatively intended as the applied load divided by the duration of the test). Therefore, the estimated values of ultimate capacity, with a difference of over 25% between them in this case, were affected by the adopted testing procedure. On the other hand, the comparison between the results of pull–out tests, carried out on screw micropiles of the same model E (Figure 8) in accordance with the two ASTM procedures, shows that the piles subjected to the quick load test exhibited less upward movements than the piles tested according to the standard

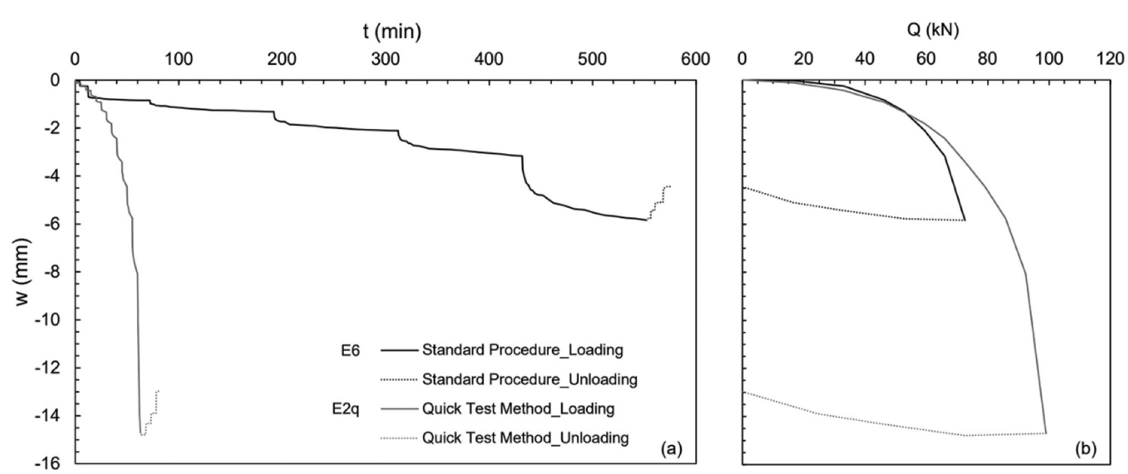

Figure 6. Typical results of tests performed on screw micropiles at the Cornovecchio test field: a) pile displacement vs time; b) pile displacement vs applied load. Comparison between standard loading procedure and quick load test.

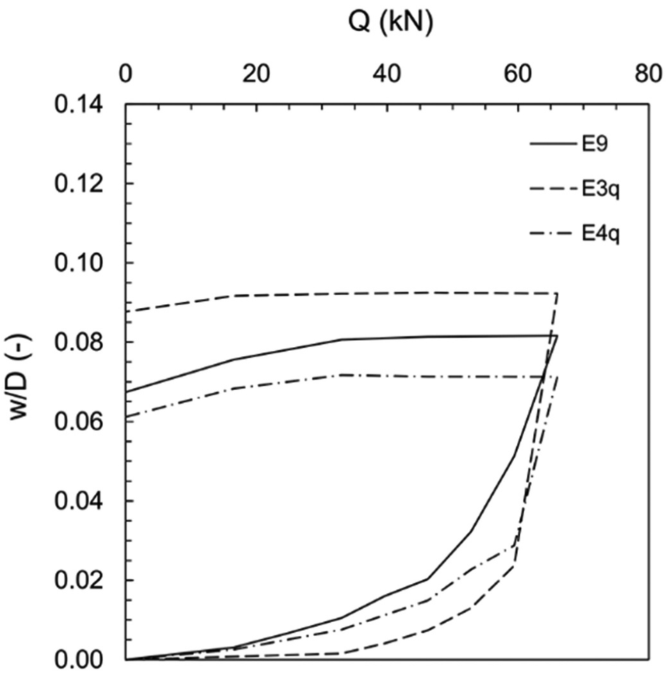

Figure 8. Comparison between results of axial pull–out (tensile) tests, on screw micropile model E, loaded according to the standard and to the quick (q) test procedures by the ASTM.

loading procedure at almost any given load between 20 kN and 60 kN. Ultimately, the screw micropiles achieved practically the same value of pull–out capacity, regardless of the testing procedure. It is worth mentioning that pull–out tests performed according to the standard loading procedure generally required less time (approximately 300 min) than compressive tests (from 600 to 800 min). Therefore, the loading rate of pull–out tests performed according to the standard procedure was only 2–3 times lower than the loading rate of the quick test method. Given the stratigraphy and soil condition at the Cornovecchio field test, the different response obtained from compression and pull–out tests performed according to the quick method could be affected by, or related to, the contribution of the conical tip and to the loading direction. The same response was also observed in the result of tests performed on 3 m-long micropiles (model G, Figure 1), although less significantly, due to the need to execute the tests in 2 days and with an intermediate load cycle before applying loads great enough to reach the ultimate capacity of the pile–soil system. All in all, the result of these comparative tests demonstrate that the testing procedure, i.e. the rate of loading, could significantly affect the response of the screw micropiles in cohesive soils and therefore affect the estimation of the ultimate capacity. In the absence of detailed experimental data, the observed behaviour could be related to the fact that the shear strength of clays depends on the rate of loading and to consolidation processes taking place around the micropile, especially around the conical tip and when compressive loads are involved. Even though initially the soil was not fully saturated (initial S_r was 85–90%), a higher degree of saturation could be achieved due to the installation process and in the course of the compression test, especially around the conical tip. In general terms, the observed behaviour appears to be consistent with the findings reported by the relevant scientific literature on pile foundations driven in cohesive soils (Kraft, Cox, and Verner 1981; Briaud and Garland 1985; Horvath 1995; Al–Mhaidib 2001).

4.3 Remarks on the ultimate capacity

Values of ultimate capacity obtained from the Cornovecchio compression tests that were performed according to the Standard Loading procedure (ASTM 2007a) were back–calculated with the analytical method originally developed by Guo and Deng (2018). According to the aforementioned method, the compressive ultimate capacity Q_L of a screw micropile in a clayey soil with undrained shear resistance (s_u,) is given by three contributions (Q_1, Q_2, Q_3, Equations 1–4), respectively, provided by the soil around the smooth shaft (L_1), the threaded shaft (L_2) and the tapered–threaded tip (L_3).

$$Q_L = Q_1 + Q_2 + Q_3 \tag{1}$$

with

$$Q_1 = \alpha s_u \pi D L_1 \tag{2}$$

$$Q_2 = s_u \pi (D + 2w_{th}) L_2 \tag{3}$$

$$Q_3 = C\left[s_u \pi \left(D_{eq} + 2w_{th}\right) L_3\right] \tag{4}$$

In Equations 2–4, the geometrical features of the screw micropile (D, L_1, L_2, L_3, w_{th}) can be identified in Figure 1 and Table 1. The term α in Equation 2 is the adhesion coefficient between the cohesive soil and the smooth shaft. Equation 3 computes the soil resistance along the threaded shaft by assuming the well–known 'Cylindrical Shear Mode' (CSM) (Narasimha Rao, Prasad, and Veeresh 1993; Merifield 2011; Guo and Deng 2018), with a reference diameter ($D + 2w_{th}$) that includes the width of the threads. In Equation 4, D_{eq} is the equivalent diameter of a cylinder with the same volume and length L_3 of the conical threaded tip, and C is a constant that accounts for the taper angle; thus the contribution of the conical tip is computed as the lateral resistance of the soil around an equivalent cylinder. Sanzeni and Danesi (2019) analysed a number of load tests performed at the Cornovecchio test field (carried out according to the Standard Loading Procedure described in the ASTM D1143 and D3689), and determined the adhesion coefficient along the smooth shaft $\alpha = 0.28–0.30$, a value that is in agreement with the literature on driven piles (Poulos and Davis 1980; NAV FAC 1982), but greater than the 0.1 value proposed by Guo and Deng (2018). Similarly Sanzeni and Danesi (2019) determined that for screw micropiles driven in clayey soils the constant C in Equation 4 can be set to 1.3, similar to the value 1.43 proposed by Guo and Deng (2018), and also suggested that C could be influenced by the soil conditions and stratigraphy immediately below the tip of the micropile.

To analyse the experimental results, the shaft resistance ($Q_1 + Q_2$) of the screw micropiles E, F and G was calculated with Equations 2 and 3, assuming the same hypotheses presented in Sanzeni and Danesi (2019). Most notably, the adhesion factor $\alpha = 0.30$ was adopted to compute the contribution of the smooth shaft, and values of undrained strength (s_u) were assumed in the range 150–350 kPa, depending on the depth of each micropile segment relative to the soil stratigraphy and on the strength profile derived from the CPTs (Figure 2). The contribution of sandy layers to the shaft resistance was also taken into account with Equation 5:

$$Q_s = (\sigma_v K \tan\delta)\pi(D + 2w_{th})L_s \tag{5}$$

where σ'_v is the vertical effective stress at mid-height of the sand layer L_s, K is the earth pressure coefficient (0.7 for the smooth shaft, 1.5 for the threaded shaft, Poulos and Davis 1980; NAVFAC DM–7.2 1982), δ is the angle of friction between soil and micropile (20° for the smooth shaft, ϕ for the threaded shaft, NAVFAC DM–7.2 1982; AGI 1984). Consequently, the balance between the average values of ultimate capacity (Q_{L-ave}) derived from load tests and the terms Q_1 and Q_2 (values reported in Table 2), made it possible to estimate the entity of the term Q_3 of Equation 4, which represents the contribution of the threaded conical tip (L_3). The result of this back – calculation allowed to estimate Q_3 in the range of 38–76 kN which, according to Equation 4, confirmed the capacity of the tapered threaded tip of screw micropiles to sustain compressive loads that are generally 1.4–1.6 times greater than those of the equivalent cylindrical segment. Interestingly, a lower value of the constant C = 1.4 was estimated for model F, which has the same taper angle of 5° of models A, B, C and D tested by Sanzeni and Danesi (2019), while a greater value C = 1.6 was found for models E and G, manufactured with a conical tip with 8–9° taper angle. These findings, although based on a limited database, seem to suggest that the taper angle has a significant effect on the bearing capacity of the conical tip and, in turn, on the ultimate capacity of screw micropiles. Table 3 summarizes the results of the interpretation.

5 Conclusions

The additional findings derived from an ongoing experimental study on the behaviour of screw micropiles subjected to axial loading were presented in this paper and the following conclusions can be drawn from their interpretation:

(1) The tested screw micropiles (length 2–3 m, diameter 89–114 mm) achieved ultimate tensile (pull–out) and compressive capacities in the ranges 65–110 kN and 75–125 kN, respectively, and were 2–3 times higher than those previously reported by the Authors on shorter and smaller micropiles (length 1.0–1.3 m and diameter 66–76 mm). The values of limit capacity under compressive loads were 10–30% higher than those achieved under tensile loads, depending on the geometrical features of the screw micropile, on the soil–stratigraphy conditions at the test field and on the testing procedure. The ultimate capacity of the pile–soil system was fully mobilized with displacement values generally between 5% and 10% of the pile diameter.

(2) The analytical method by Guo and Deng (2018) appeared to be capable of estimating the ultimate axial capacity of screw micropiles, given the appropriate soil stratigraphy and geotechnical parameters. Therefore, from a practical point of view, the geotechnical designer should be encouraged to establish the design capacity of screw micropiles based on the information in the geotechnical report, rather than on empirical methods, indirect measurements or incomplete geotechnical information.

(3) The interpretation of test results allowed to estimate the contribution of the conical threaded tip in the range of 38–76 kN which in turn confirmed the capability of this segment to sustain compressive loads that are generally 1.4–.60 times greater than those of the equivalent cylindrical segment. These findings, although based on a limited database, also suggest that the taper angle may have a significant effect on the bearing capacity of the tapered–threaded conical tip and, in turn, on the ultimate capacity of screw micropiles.

(4) The comparison between results obtained from tests executed on micropiles with the same dimensions (diameter and length) but different extension of the threads highlighted the importance of the threaded cylindrical segment to enhance the ultimate capacity of screw micropiles. This and the considerations developed on the effect of the taper angle of the conical tip, should be taken in consideration by manufactures in the production of screw micropiles that achieve a good compromise between performance and costs of manufacturing.

(5) Regarding the employment of different testing procedures to verify the response of the screw micropiles under working conditions and to determine the ultimate capacity, the results obtained from this investigation confirm that the testing procedure, i.e. the rate of loading, can significantly affect the response of screw micropiles driven in cohesive soil and subjected to axial compressive loads. This evidence is supported by the relevant scientific literature on piles driven in cohesive soils and suggests that the selection of the appropriate testing procedure should be made by the geotechnical designer according to the requirements of the project and to the loading conditions.

Table 3. Relevant dimensions of screw micropiles, minimum, maximum and average values of ultimate capacities ($Q_{L,ave}$) estimated from the experimental campaign, computed values of shaft resistance (Q_1, Q_2) and tip resistance (Q_3), and estimated value of the constant C in Equation 4.

#	L_3, θ (mm, °)	$Q_{L,min/max}$	$Q_{L,ave}$	Q_1 (kN)	Q_2	Q_3 ($Q_L - (Q_1 + Q_2)$)	$C^{(1)}$ (-)
E	350, 9	70.0/90.0	80.0	18.8	20.4	40.9	1.55
F	600, 5	100.0/110.0	105.0	16.9	12.2	75.9	1.38
G	320, 8	115.0/125.0	120.0	22.2	59.4	38.3	1.55

(1): constant in Eq. 4

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Alex Sanzeni holds a degree in Civil Engineering from the University of Brescia (2002) and a Ph.D. degree in Geotechnical Engineering (2006) from the University of Parma, in Italy. He is author of a number of publications in different areas of Geoengineering and Environmental Engineering. His research areas include the characterization of soil mechanical properties and the development of testing techniques and procedures, the reuse of steel slags for bituminous paving mixtures, the hydraulic conductivity of soils, the modelling and monitoring of geotechnical engineering works, the interpretation of shallow landslides triggering mechanisms. He has been involved in a number of engineering projects and has experience in soil investigation, foundation and retaining structures design.

Emanuele Giuseppe Danesi graduated in Civil Engineering in 2018 from the University of Brescia. His research interests include modeling of deep excavations and foundations, soil investigation and soil laboratory testing, pile load-testing and bearing capacity of micropiles under axial and lateral loading.

ORCID

Alex Sanzeni http://orcid.org/0000-0001-9753-310X

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