Loading Effects on Battered Micropiles Supporting
Lateral and Compression Forces

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Abstract

The use of battered pile foundations has gone from being 'in-vogue' to 'verboten,' in particular for seismic design, during the 20th century. This flip-flop in design and construction practice is examined in this paper. There are several reasons for these changes. In particular, popular pile types have changed significantly over the years. This paper examines the reasons for changes in practice affecting the use of battered piles and in particular looks at the effects of compression and lateral loads on micropiles. Micropiles have small cross-sectional areas. They also have limited resistance to lateral loads and bending moments when installed in vertical configurations due to their small diameters. Therefore, using micropiles at a batter can be particularly advantageous to carry lateral loads. However, using battered micropiles indiscriminately, without understanding the effects of soil loading on the piles and the impacts of increased foundation stiffness, can lead to unsatisfactory performance of the foundation system. Analysis methods for evaluating battered pile foundations vary and some common design methods may be incorrect. These errors could lead to yielded piles in service – particularly for uncased bar or hollow-bar micropiles. This serious concern is discussed and methods of correcting this common problem are presented. Moreover, this paper discusses the compression and lateral loading induced forces on battered micropiles used for foundation support.

A Bit of History

Battered piles have had a tough time lately. In 1998, ASCE's Technical Council on Lifeline Earthquake Engineering recommended that "The use of Batter piles at ports is typically not encouraged because of their poor seismic performance during past earthquakes" (Kavazanjian, 2006). This warning concerning battered pile use was generated primarily through the observed performance of pre-stressed concrete battered piles at port facilities in California during the 1989 Loma Prieta and 1994 Northridge earthquakes as well as the 1996 Manzanillo, Mexico earthquake. During these events, battered pile heads typically sheared off and tremendous damage was done to the port facilities (Kavazanjian, 2006).

The history of deep foundations carrying lateral loads is worth noting. The lateral foundation loads requiring deep foundation support discussed in this paper are typically generated from earth, wind, seismic, water currents, vehicle braking forces, impact, etc. The types of structures that are required to support these lateral loads include bridge piers and abutments, anchored bulkheads, retaining walls, docks and building foundations (Kavazanjian, 2006). It should also be noted that many of these loads are transient – of short duration. More severe lateral loads from seismic events are also discussed.

In the first half of the 20th century, battered piles were not often utilized in the United States to carry lateral loads due to the types of commonly available and economically viable deep

foundation types in use. Timber piles, Franki™ piles and Raymond Step-Taper™ piles (Kavazanjian, 2006) were very difficult to analyze under lateral loadings. Each of these deep foundation types contained varying cross-sections that, at a glance, would not perform well when loaded laterally while also carrying the required vertical loads. Features like knots in wood, cold joints in concrete and highly variable cross-sections do not lend themselves well to analysis or satisfactory lateral performance. However, towards the end of the 20th century, battered piles were the 'go-to' solution to carry lateral foundation loadings. Steel H Piles and Pipe piles as well as pre-cast concrete piles offered uniform geometric shapes and plenty of steel area to carry lateral loads. Throughout the 1960's, 12 and 14 inch H piles were commonly used to support lateral loads for bridge piers and abutments. Augercast/CFA piles appeared in the late 60's and early 70's, but were not accepted for use on most public works projects until recently. Then, in the 1970's and 1980's, vertical drilled shafts often replaced both vertical and battered piles as foundation support for many bridges, mainly due to a push from the Federal Highway Administration (Kavazanjian, 2006). This push was supported by the availability of new, accurate software for analysis of vertical deep foundations subjected to lateral loading and new construction procedures and equipment available to reliably install the drilled shafts. However, battered piles were still often used on many projects to carry lateral loads until the earthquakes in California and Mexico mentioned above.

Micropiles, conceived in Italy in the 1950's, have been in use in North America since 1973. Micropile use and technology grew rapidly in North America starting in the mid-1980s (Sabatini, 2005). Micropiles are used extensively for industrial, commercial and transportation structures to both underpin existing structures and to support new structures. Often, micropiles are required to carry both axial and lateral loads. Micropiles exhibit excellent axial load carrying capacity, however due to the relatively small diameters typically installed, they have little lateral load carrying capacity when compared with steel H or pipe piles or drilled piers. This small lateral load carrying capacity many times necessitates battering of micropiles to resist lateral loads. Of note is that the installation of micropiles on a batter does not add cost to most projects. The rigs that install micropiles can easily drill at a batter. The cost per linear foot for battered piles is the same as for vertical piles. Only the small additional footage to extend the pile to depth on the angle must be paid for. The design and analysis of vertical micropiles is well understood by the engineering community, however the design and analysis of battered micropiles is much less well understood.

Deep Foundation Comparisons
Battered piles are defined as deep foundations that are installed at an inclination from vertical. Typical batter angles are 5 to 10 degree or up to 30 degrees from vertical. However, greater batter angles have been used. The use of battered micropiles can be an important element in the design of an efficient arrangement for a deep foundation system. Due to their relatively small diameter compared to their relatively large axial capacity, micropiles are at a distinct disadvantage to resist lateral loads compared to many other larger foundation systems. As an example, the table below presents a standard sized micropile as compared to a standard sized H-pile and corresponding capacities as per the International Building Code (IBC). We have

presented the HP 14 (360 mm) since it has a similar allowable load capacity in compression compared to a 7 inch (178 mm) diameter micropile pipe.

Pile Size	HP14 x 73 (Grade 50 ksi) HP360 x 109 (Gr. 345 MPa)	7" x 0.498" (N80) 178 x 12.5 (Gr. 550 MPa)
Allowable Axial (K) (kN)	380 (1,700)	365 (1,625)
Allowable Moment (K*ft) (kN*m)	294 (400)	68 (92)
Moment of Inertia (in^4) (mm^4)	729 (303x10^6)	54 (22.5x10^6)
Area of Steel (in^2) (mm^2)	21.4 (13,806)	10.2 (6,581)
Axial Stiffness-EA (K) (kN)	620,600 (2,760,430)	295,800 (1,315,718)
Bending Stiffness EI (K*ft^2) (kN*m^2) Weak Axis	525,625 (217,083)	108,895 (44,974)
Bending Stiffness EI (K*ft^2) (kN*m^2) Strong Axis	1,468,125 (606,366)	108,895 (44,974)
Weight per Foot (lb) (kg/m)	73 (109)	35 (52)

Table 1. H Pile to Steel Pipe Comparison

Table 1 shows that there is a large lateral capacity versus axial capacity discrepancy for micropiles as compared similar axial capacity driven piles. The ability of the micropile to carry significant axial load is due to the higher working load stress level enabled by higher strength pipe (Fy = 80 ksi (550MPa)). While the driven H pile and the micropile exhibit similar axial capacities, the allowable bending stiffness and moment resistance of the H pile are much greater than the micropile, even in the weak axis of the H pile. Note that the micropile pipe has less than on-half of the weight per foot of the H pile. Further, the driven pile has a significantly larger effective diameter with which to transmit lateral load to the soil. The same holds true for drilled piers. Note that the micropile pipe has a substantial area of steel when compared to bars: the equivalent to 2.5 #18 (#57) bars, 4.5 #14 (#43) bars, 6.5 #11 (#36) bars, 13 #8 bars (#25), 23 #6 bars (#19) and 51 #4 bars (#13).

IBC 10.3.3.2 states that the lateral capacity of a pile is half of the load that produces 1 inch (25 mm) of lateral deflection. In practice this typically results in specifications that limit lateral deflection to ½ inch (13 mm). The use of battered micropiles is required many times to meet these specifications and to produce an efficient design.

Batter Angles
Batter angle nomenclature was developed early in pile driving technology. Pile Foreman were given ratios such as 1:12 etc. that could be easily translated to angles by making templates in the field. Tradition has retained these notations, rather than supplying driving angles on plans (J. Nicholson, 2017). For reference, typical batter angles are shown on Table 2.

Batter (H:V)	Angle from Vertical (Degrees)
1:12	4.8
1:10	5.7
1:8	7
1:6	9.5
1:4 3:12	14
1:3 4:12	18.4
1:2	26.5

Table 2: Batter Notation and Resultant Angles from Vertical

What Happened to Battered Piles in the Earthquakes?
Before the California and Mexican earthquakes, the heads of battered piles were typically designed considering the connection as 'pinned.' However, post-mortem on the failed port facility installations showed that design details employed for the heads of the pre-stressed piles hindered rotation and created large shear and moment forces acting on the pile heads. Since the design and the performance conditions did not match, big problems ensued. These unexpected shear and moment loadings resulted in failure of the pile heads and connections (Kavazanjian, 2006). See Figure 8 for an illustration of the difference in the deflected shapes between pinned and fixed piles under load. Table 3 shown below from the FHWA Micropile Manual (Sabatini, 2005) gives some guidance for understanding the level of fixity for micropile-pile cap connections.

The recognition of this problem and ensuing design changes have brought battered piles, when properly designed, back into the fold as an available tool to economically resist large lateral loads from seismic events. Pile heads of pre-stressed concrete piles have been strengthened and new ductile designs have been implemented to allow the pile heads to rotate without loss of capacity e.g. 'the structural fuse.' The use of battered piles to resist seismic loads is therefore no longer 'verboten!' Structural engineers are once again using battered pile to resist seismic forces. The new piers of the San Francisco Bay Bridge East Span incorporate 8 foot diameter driven steel battered piles, which are driven through the soft bay mud into firm to dense sands (Kavazanjian, 2006).

0 % Fixity (Pinned Head Condition)	50 % Fixity[1]	100 % Fixity (Fixed Head Condition)[1]
Casing embedment of 300 mm (12 in.) or less or Reinforcing bar embedment with or without bearing plate or Any detail where top of micropile embedment is at or below the level of the bottom reinforcement of the footing	Casing embedment of 450 mm (18 in.) or Shear connection between casing and existing footing with minimum casing embedment of 450 mm (18 in.)	Casing embedment of 600 mm (24 in.) or more

(1) Guidance provided assumes that footing itself is restrained. For example, if only one row of piles in direction of loading then 0% fixity should be assumed

Table 3: Guidance for Level of Fixity for Micropile-Pile Cap Connections (Sabatini, 2005)

Analysis Methods
The authors have seen many methods employed in the analysis of battered piles. Many of the available static equilibrium-based methods do not actually satisfy static equilibrium. A simple static equilibrium analysis can give good results when the line of action passes through a work point as shown on Figure 1. Some methods simply divide the total lateral load by the number of battered piles required to carry the load, then determine the axial force in the battered piles simply by dividing the lateral load by the sine of the batter angle. A simple free-body diagram will show that this analysis method does not satisfy equilibrium. Designs using these methods may have performed adequately, however, many of these cases have incorporated large pile elements such as big steel H or pipe piles or have been for lightly loaded structures, where small lateral loads and small bending moments are resisted. Potential performance issues have gone unnoticed since they did not result in noticeable deflections that would yield the piles in bending.

Another common misconception about battered piles is zero induced moment. Battered piles in compression will experience bending moments caused by the soil reaction resisting the foundation system deflection under load (Prakash, 1990, Richards, 2004)

The most efficient batter angle is measured as the inverse tangent of the lateral load divided by the axial load. Ideally, all load combinations would produce axial loads and lateral loads where the resultant angle is the same. However, very few structures exist where this happens. As discussed above, even when the forces are resolved into a resultant load applied at the resultant angle, moments still exist in the piles due to soil-structure interaction.

In most structures, there are numerous load combinations, prescribed by Code, that are considered in a design analysis. These load combinations represent the state of the practice to produce a safe and serviceable structure. For battered piles, the most efficient batter balances all of the load combinations to produce the desired serviceability requirements with the least number of piles. The ratio of lateral load and axial load varies for the different load combinations. For example, the axial loads may be very similar in a both wind and seismic conditions, but the lateral demand may vary significantly. If the designer balances the heavy seismic combination, the batter angle will be too great for the lighter wind combination. The art of selecting the batter angle is balancing the batter angle with all of the load combinations.

The authors approach this problem by first applying the various load combinations to determine the induced pile axial loads due to the applied axial loads and moments. After inspection of the axial loads, a determination is made as to what batter angle will roughly balance all the load combinations. The batter angle is then varied until the serviceability requirements are achieved. This analysis is carried out using a program such as Group by Ensoft, Inc.. The Group program allows three-dimensional, nonlinear soil P-Y response and pile interaction analysis.

In addition, the effects of combined loading must also be checked. Stress is induced into the piles both axially and from bending. These stresses must be calculated and checked, particularly at any threaded pipe joint locations (Sabatini, 2005).

Static Equilibrium vs. P-Y Soil Structure Interaction Analysis
In this paper, we compare the results of static equilibrium analyzes and p-y soil structure interaction analysis. In the example shown on Figure 1, the piles are battered at the location of the applied load, and are in-line with a work point at the base of the column. Using this method, the loads are resolved into axial loads in the piles with no net lateral load. The modeled end condition of the piles is pinned. Note that in this example there is no consideration of the effect of embedment in soil on the piles. Thus, no moment is induced into the pile by any vertical or lateral elastic deflection of the pile cap from load.
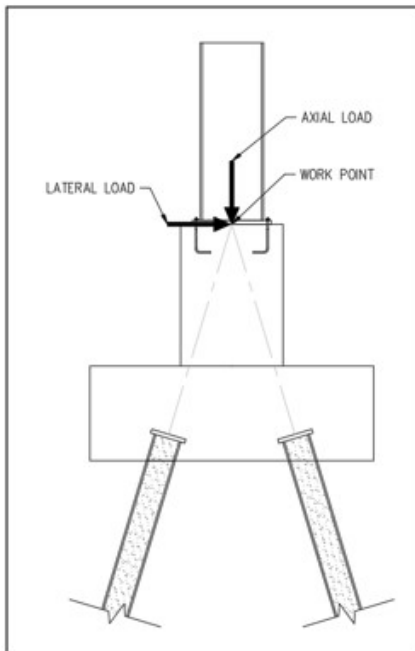

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Figure 1

Figure 2 demonstrates the calculations to determine pile loads in battered piles in compression and lateral load using static analysis. In this case, the piles are aligned through the work point that is the center of the base of the column. As the basic static equilibrium calculations show, the forces resolve readily into axial loads only. The load magnitude is not important, so long as the geometry is maintained, static equilibrium is maintained. A similar analysis with a simple "A-Frame" in any structural software will yield the same results.

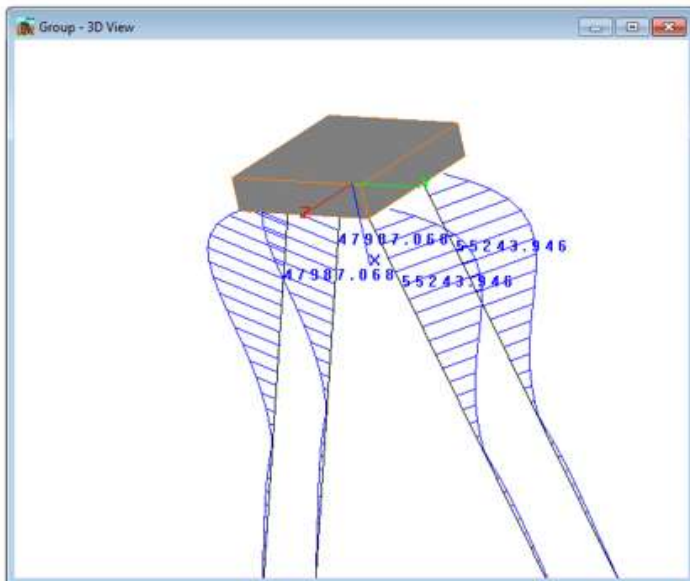|		
Pile Space	3	ft
No. of Piles	4	Ea
Axial Load	600	kips
Lateral Load	100	kips
Load Offset	4.5	ft
Moment due to Offset	450	k*ft
Batter Angle	18.4	deg
Heavy Side Vertical	225	kips
Light Side Vertical	75	kips
Heavy Pile Load	237	kips
Light Pile Load	79	kips
Heavy Lateral Resistance	75	kips
Light Lateral Resistance	-25	kips
Total Lateral Resistance	100	kips

Figure 2

Figure 3

This same (pinned end condition) analysis was then performed in the program Group (2014), produced by Ensoft, Inc. As shown in Figure 3, a moment is induced on the piles. This moment is due to the soil structure interaction – the elasto-plastic 'springs' modeled by the program exert lateral loads on the pile as it deflects outward in response to the load. The pile spacing at the bottom of the cap is rigidly maintained, therefore when the piles elastically shorten the soil resists outward movement of the battered piles, and a shear load and corresponding moment are created. To better illustrate this concept, another analysis was performed where the

lateral load was removed, leaving only the 600 kips (2,669 kN) of vertical axial compression load on the pile cap. Figure 4 shows that there is again a moment induced on the piles, solely from the vertical compression load. Figure 5 shows the vertical displacement of the piles for this case.
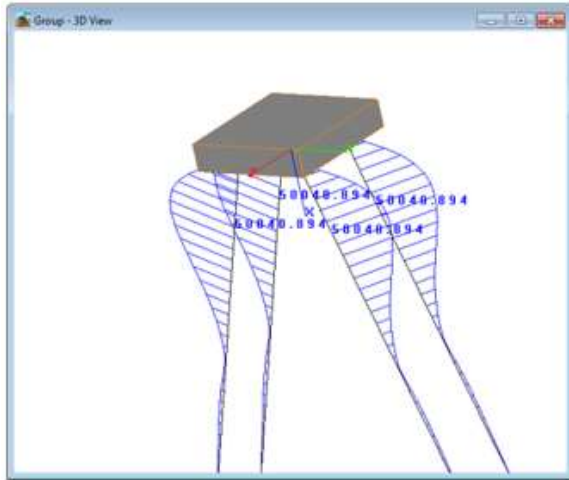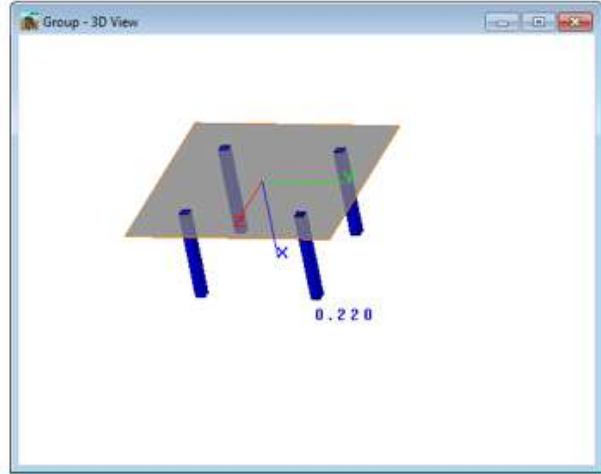

Figure 4

Figure 5

The vertical component of the piles elastic shortening in Figures 4 and 5 is 0.22 inch (5.6 mm). With the batter angle of 18.4 degrees (1H:3V) modeled, the horizontal component of the axial shortening is 0.073 inch (1.8 mm). To further analyze this problem, the axial load (600 kips (2,669 kN)) and the lateral deflection of 0.073 inch (1.8 mm) was input into L-Pile 2015 by Ensoft, Inc. As shown in Figures 6 and 7, the calculated net shear (2.35 K (10.5 kN)) per pile is the same in both the Group analysis (Figure 6) and the L-Pile analysis (Figure 7).
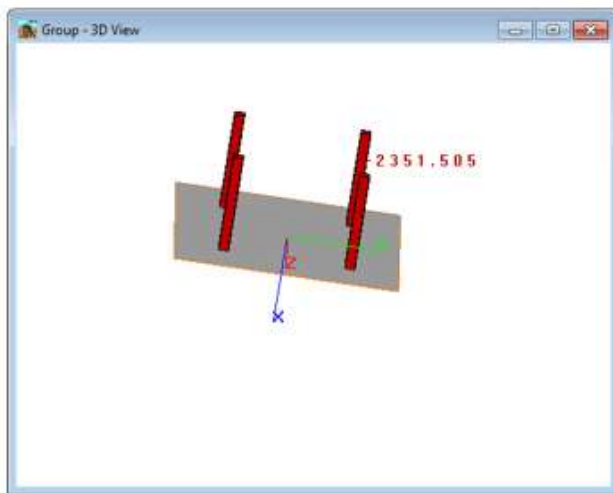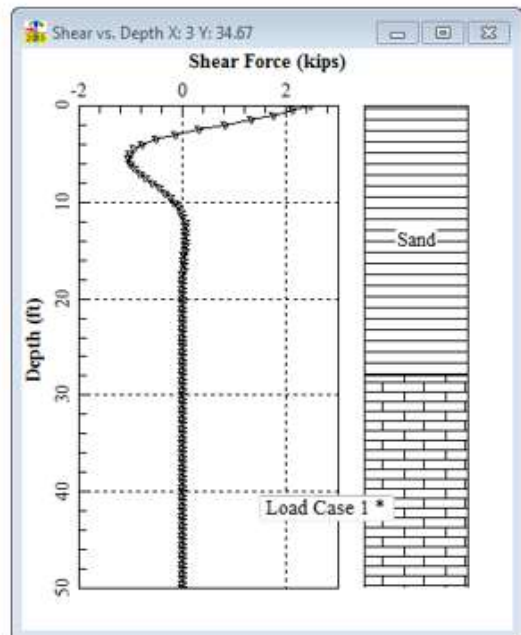

Figure 6

Figure 7

The other aspect that the proceeding analysis doesn't address is construction tolerances and constructability. In practice, piles typically have an installation tolerance of 3 inches (76 mm) in plan-view and an angular tolerance of 1-2 percent. These installation tolerances can also induce more pile bending moment than shown above. To illustrate the point, Figure 8 shows an exaggerated deflection of two conditions, free head and fixed head piles, under vertical load. The first diagram represents a free-head condition. As the piles elastically shorten, the soil around the piles, modeled as elasto-plastic springs, acts on the piles and produces the deformed shape shown, even though the pile heads are modeled as hinges (pinned). The second diagram represents a fixed-head condition. Again, as the piles shorten, the elasto-plastic springs act upon the piles and produce the deformed shape shown. The shapes differ since the fixed-head condition has a pile head that is fixed from rotation. The results are the deflected shapes shown on Figure 8.
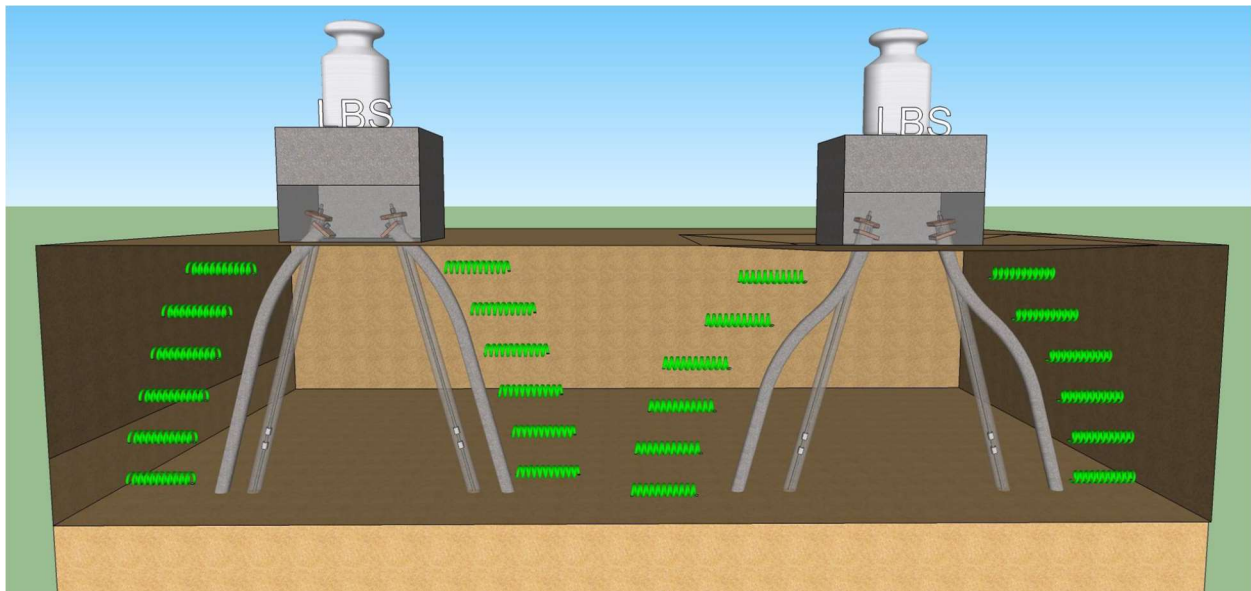

Figure 8: Model of the Exaggerated Deflected Shapes of Free-Head and Fixed Head Piles

Battering of All-Thread Bar and Hollow Bar Micropiles
The discussions in this paper so far have addressed mainly micropiles that include steel pipes. However, grouted all-thread bar micropiles have been used for decades. These types of micropiles consist simply of all-thread bars that are placed and grouted in drilled holes. This type of micropile has a successful track record. However, some designers will incorporate a steel pipe in the upper regions of these micropiles due to concerns over bending moments as shown on Figures 3 and 4. For battered bar piles, many designers consider the addition of these pipes as essential. This practice is highly recommended by the authors. For vertical bar piles, these bending moments can also exist due to location or angular installation tolerances as mentioned above.   A very rough rule-of-thumb is to extend the pipe approximately 20-25 drill-hole diameters from the top of the micropile (Figure 9). The goal is to reinforce the pile to the point of contraflexure, where the bending moment goes to zero.
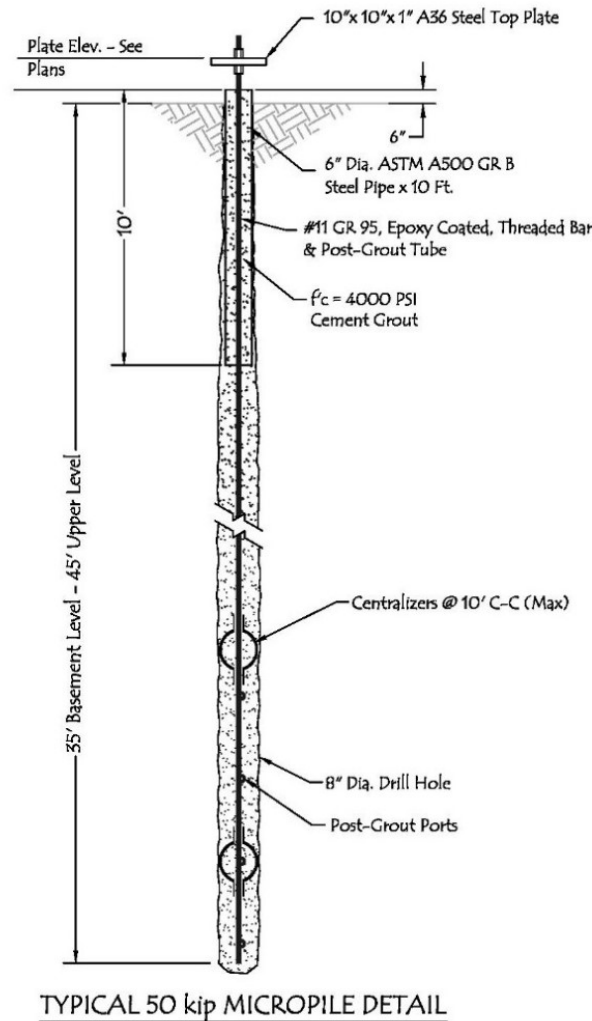
Figure 9: Bar Micropile with Steel Pipe at the Pile Head

As an example, Figure 10 shows a pile cap excavation for a 5 (vertical) pile foundation for a bar micropile project in Puerto Rico. The upper zone of the micropiles was reinforced with a 6 inch (150 mm) diameter steel pipe, 10 feet long. When excavating for the cap, the workers chipped off the grout that was bonded on the outside of the pipes. A plate was placed on the top of the pipe to transfer tension load into the pile. These micropiles were installed vertically and consisted of full-length, epoxy-coated #11 (#35) Grade 95 (655 MPa) bar piles set in grouted 8 inch (203 mm) diameter drill-holes. A 6 inch (152 mm) diameter thin-wall pipe was set at the top of each pile for the upper 10 feet (3 m) to resist any bending loads created by out of tolerance location of the micropiles. The design load was only 25 kips, as the piles were installed in a very soft silt, but the test load was specified to be 2.5 times the design load (Wolosick, 2009).

**Figure 10: Micropile Pile Cap Excavation Showing Bar Piles
with Top Pipe Reinforcement**

Hollow-bar micropiles are often installed when caving and collapsing conditions are expected or encountered during drilling. These types of micropiles may vary significantly in diameter. The smaller diameter bars are of the most concern when using battered piles. These piles are flushed into the ground using disposable drill bits, using rotation from a drilling head and pumping grout through the hollow bar, which exits at the drill bit and flushes the soil up and out of the drill hole. When small diameter hollow bars are used for battered micropiles, bending stresses can be generated as discussed in this paper. Figure 11 shows a bending failure of a hollow-bar after unsatisfactory performance during a compression load test. The micropiles in this application were all battered, and did not include a section of steel pipe at the top of the micropile to help resist the bending stresses.

Figure 11: Hollow Bar Micropile Failure in Bending

Conclusions

As discussed, due to their small size, micropiles have disadvantages over some other foundation systems such as steel H or large pipe piles and drilled shafts when it comes to lateral capacity of vertical elements. In addition, micropiles consisting of grouted bars and hollow-bars have much reduced bending stiffness when compared to large steel pipes or H piles. Battered micropiles can be easily installed to provide an economical and effective design to carry lateral loads. The designer must understand that static equilibrium approaches can be used to determine pile axial loads when the geometry of the system is lined up with a work point, however the static equilibrium approach is simplified and will not determine the induced shears and corresponding bending moments when battered piles are employed.

On lightly loaded projects, the bending stresses may be small. However, they can be significant on heavily loaded structures, and severe in seismic events. The use of design programs such as Group by Ensoft, Inc. will accurately predict the bending moments generated from compression and lateral loads on pile foundations. This analysis is critical when considering heavily loaded uncased bar piles. Foundations using uncased bar piles have become very common, especially with the advent of self-drilling hollow all-thread bars. The use of battered or vertical small diameter all-thread bar or hollow-bar micropiles without steel pipe sections in the upper 20-25

drill-hole diameters (approximately) and under significant compression or lateral loads should be avoided. Some guidance for the design of micropiles is: "If there are lateral loads on your micropile foundation, you should always include a pipe at the pile head!"

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