Micropile Foundations for vertical and horizontal Loads – Design Examples and Load Test Results

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Definition Micropile

Acc. AASHTO LRFD Bridge Design Specification 10.2 Definitions:

A small - diameter drilled and grouted non-displacement pile (normally less than 12 in.) that is typically reinforced“

Acc. actual building code EN 14199 „Execution of Micropiles“ – which is mandatory in 30 member countries of European Union, the term micropile is defined:

„Drilled piles, which have a diameter smaller than 300 mm“
Basic Features of Micropile

- 90% of the axial load is transferred by skin friction
- Higher skin friction and smaller displacement than all larger diameter piles such as drilled shafts or driven piles.
- Efficient load performance in both tension and compression, even in case without pretension
- The Micropiles ductile load bearing element has the same requirements of ductile rebar - class B (Uniform elongation Agt ≥ 5%), to allow elastic/plastic design calculations.
- Load transfer distribution correlates to the crack width distribution within the grout, in relation to the pull-out-capacity within different soil layers.
- Corrosion protection is achieved by the grout cover, as with reinforced concrete.
Aim of Presentation / Agenda

To present design examples of installed Micropile foundations, which have been designed for axial and lateral loads and static or cyclic loads

1. Modelling and analysis of simple raft Micropile foundations to support vertical and horizontal loads.

2. Precast foundations for solar-carports - deep foundations with TITAN 40/20

3. Mono-micropiles with 1.5m shear casing, to achieve additional horizontal loadings of up to 5% of the vertical loads determined from load test results from Prof. Dr. Ing. Herrmann of the University of Siegen.

4. Micropile groups in very soft clay layers (undrained shear strength Cu = 10 kN/m² to support vagabonding horizontal loads as a group in the range of 10 kN. Load test results University of Hannover Prof. Dr.-Ing. Blümel Akz. 10/90.

5. Offshore Micropiles installed to improve the bearing capacity of driven monopiles and to address horizontal loads and scouring.
Lateral loads with Drilled Shafts

Example:

A drilled shaft $D = 600 \text{ mm}$ can take a horizontal load $H = 120 \text{ kN}$

$\frac{H}{D} = \frac{120 \text{ kN}}{60 \text{ cm}} = 2$; a horizontal displacement of $\delta = 3 \text{ mm}$ is estimated.

This also applies to driven piles. Design calculations for the horizontal loads of monopiles (p-y-curves) are available from the American Petroleum Institute (API).

Horizontal load-settlement curves for drilled shafts in different ground conditions

Source: Dr.-Ing. H.G. Schmidt, Pfahl-Symposium 1992, TU Braunschweig

Micropiles, mono-micropiles and raft-micropile foundations possess low flexural stiffness for additional lateral loads, which results in a different design approach.
1. Raft – Micropile Foundation

Traditional Raft-Micropile analysis is based on the static model shown:

Assumptions are:

- Micropiles are hinged columns with bearings at the head and the toe
- The toe bearing is fixed
- The micropiles are adopted as elastic elements
- The flexibility of the load bearing ground is incorporated within the pile
- The flexural stiffness of the raft or the superstructure is large in comparison to the pile stiffness.
- The stiff raft distributes the loads according to the linear elastic stiffness $E \times A$ of the micropiles.
1. Raft – Micropile Foundation

Examples of raft-micropile analysis for a micropile foundation:

Designed to support compressive and horizontal loads from a highway messaging gantry.

Highway Gantry, Motorway M4, UK founded with Micropiles

Subsurface profile at traffic sign gantry
1. Raft – Micropile Foundation

Specific site conditions are:
1. Upper soft layer consists of approximate 8m of cohesive material
2. Installation with minimal disruption to traffic
3. Difficult access to the site
4. Existing utilities

Original design concept with drilled shafts installed into the highway embankment

Messing Gantry with Raft-Micropile Foundation

\[
\begin{align*}
\Sigma V &= 0 \\
\Sigma H &= 0 \\
F &= F_1 + F_2 \\
F &= 177.5 \text{kN} + 146 \text{kN} \\
F &= 324 \text{kN} \leq F_w = 400 \text{kN} \\
F &= \text{Axial load micropile} \\
F_1 &= \frac{1000}{6 \times 0.939} \\
F_1 &= 177.5 \text{kN} \\
F_2 &= \frac{100}{2 \times 0.342} \\
F_2 &= 146 \text{kN}
\end{align*}
\]
2. Precast footings for Solar Carports – Prestressed

“double up” as parking for cars, whilst generating renewable solar energy:

- Without constructing footings for the shelters, by installing two drilled and grouted TITAN 40/20 Micropiles through the precast footing.

- Designed and pre-stressed to take compression and tension loads, for example heave from the effect of freezing/thawing and

- Horizontal impact caused by cars.

- Micropile is used as an electric earth to protect the steel shelters against the effects of lightening.

Solar Carport Deep foundation using drilled and pressure grouted micropiles TITAN 40/20 micropiles
2. Precast footings for Solar Carports – Prestressed

Pre-tension of each micropile with $N_k = 20 \text{kN}$ to mobilise horizontal friction resistance $R_{ZD} = 9.46 \text{kN}$

$$R_{ZD} = \frac{N_k \times \tan \delta_k}{\gamma_{GL}}$$

$\delta_k = 2/3 \times \varphi_k$

$\delta_k = 27.5^\circ$

$$R_{ZD} = \frac{20 \times \tan 27.5^\circ}{1.1}$$

$R_{ZD} = 9.46 \text{kN} \geq H = \frac{12}{2} = 6 \text{kN}$

$$\mu = \frac{H}{R_{ZD}} = \frac{6}{9.46} = 0.64 \leq 1.0$$

Pre-tension of each micropile with $N_k = 20 \text{kN}$ to mobilise horizontal resistance $R_{ZD} = 9.46 \text{kN}$
3. Mono Micropiles with Shear Casing

- Usually mono-micropiles are designed to be loaded by axial loads only, compression or tension.

- Occasionally mono-micropiles can be exposed to additional load cases such as horizontal loads, shearing or eccentric loads.

- TITAN Micropiles can be protected and reinforced at the head of the micropile with a plastic, smooth HD-PE tube or a steel tube, both typically 0.5m in length.
3. Mono Micropiles with Shear Casing

This system has been used on mono-micropiles on several different applications. One example is on the foundations of avalanche protection barriers. A larger diameter steel tube or permanent shear casing was installed to increase the flexural stiffness and horizontal load capacity of the pile.

Now, for the first time Prof. Herrmann of the University of Siegen and Ischebeck have examined load tests results to determine the optimum diameter and length of the permanent steel shear casing.

Six test cases - Micropiles with permanent steel shear casing at the top of the pile
3. Mono Micropiles with Shear Casing

Various sand layers

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>64.00</td>
<td>Mutterboden, dunkelbraun</td>
</tr>
<tr>
<td>63.00</td>
<td>Feinsand, gelb/graum</td>
</tr>
<tr>
<td>62.00</td>
<td>Fein- bis Mittelsand, GW bei 2.30 m, gelb/graum</td>
</tr>
<tr>
<td>60.00</td>
<td>Feinsand, gelb/graum</td>
</tr>
<tr>
<td>59.00</td>
<td>Mittel- bis Feinsand, gelb/graum</td>
</tr>
<tr>
<td>58.00</td>
<td>Fein- bis Mittelsand, gelb/graum</td>
</tr>
<tr>
<td>57.00</td>
<td>Feinsand, gelb/graum</td>
</tr>
<tr>
<td>56.00</td>
<td>Fein- bis Mittelsand, gelb/graum</td>
</tr>
<tr>
<td>55.00</td>
<td>Fein- bis Mittelsand, gelb/graum</td>
</tr>
</tbody>
</table>

Cone resistance CPT-test
3. Mono Micropiles with Shear Casing

Test site showing a Mono-Micropile with a permanent shear casing designed to take additional horizontal loading of up to 5 % of the vertical load.

Testfield University of Siegen, Prof. Dr. Ing. Herrmann
3. Mono Micropiles with Shear Casing

Pile head with D Ø 300 mm
PVC and steel

Cracks behind PVC tube  D = 300 mm reinforcement
3. Mono Micropiles with Shear Casing

Summary of test results:

- The horizontal load capacity of a mono-micropile is increased by a factor 4 when a permanent 1.5m shear steel casing is used on top section of the micropile.

- Additional horizontal loads of up to 5% of vertical load are achieved with the use of a lost shear casing.

- Type 2 and type 5 Mono-micropiles which were installed with a 1.5m x 298mm diameter permanent steel casing, performed the best in terms of horizontal load and minimal settlement.
3. Mono Micropiles with Shear Casing

Pile Type 1 - Horizontal Load v Settlement Curve

Load $F$ [kN] vs Settlement [mm] graph for two types of micropiles: 1a H and 1b H. The graph shows the load-settlement relationship under horizontal load. The load at which the settlement is 5% of the vertical load is marked with a red line, and the corresponding load value is indicated as 22 kN.
3. Mono Micropiles with Shear Casing

Pile Type 2 - Horizontal Load v Settlement Curve

- 2a H
- 2b H

\[ \Delta 9\% \text{ of vertical load} \]

DØ 298 mm Steel

Cross Cut Bit 175 mm

Type 2a; 2b
3. Mono Micropiles with Shear Casing

Pile Type 3 - Horizontal Load v Settlement Curve

- 3a H
- 3b H

Δ 5% of vertical load

Load F [kN]

Settlement [mm]

DØ 300 mm PVC

Cross Cut Bit 175 mm
Type 3a; 3b

TITAN 40/20

The 12th International Workshop on Micropiles, Krakow, Poland – June 11-14, 2014
3. Mono Micropiles with Shear Casing

Pile Type 4 - Horizontal Load v Settlement Curve
3. Mono Micropiles with Shear Casing

Pile Type 5 - Horizontal Load v Settlement Curve
3. Mono Micropiles with Shear Casing

Pile Type 6 - Horizontal Load vs Settlement Curve

- 6a H
- 6b H

Load F [kN]: 0, 10, 20, 30, 40, 50, 60

Settlement [mm]: 0, 2.0, 4.0, 6.0, 8.0, 10.0, 12.0

\[ \Delta = 5.4\% \text{ of vertical load} \]

DØ 300 mm PVC

Cross Cut Bit 175 mm Type 6a; 6b
3. Mono Micropiles with Shear Casing

<table>
<thead>
<tr>
<th>Granular Soil Consolidation</th>
<th>loose</th>
<th>medium dense</th>
<th>dense</th>
<th>very dense</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 4 MN/m³</td>
<td>3 - 10 MN/m³</td>
<td>8 - 15 MN/m³</td>
<td>12 - 20 MN/m³</td>
<td></td>
</tr>
</tbody>
</table>

EAB table 102-1 Bedding modulus below the water table

Bedding Modulus $K_s$ is determined by:

$$K_s = \frac{H}{A \times S}$$

$H$ = horizontal load
$A$ = contact surface $D \times 1.5m$
$S$ = 5 mm settlement

Bedding Modulus for 5 mm horizontal settlement of the micropile head

Back analysis carried out on the results of the horizontal load ($H$) and horizontal settlement confirms the estimated values according to table EAB 102-1.
3. Mono Micropiles with Shear Casing

Horizontal load for maximum 5 mm horizontal Settlement

Ranking List

Horizontal Load [kN] vs. Horizontal Settlement [mm] for different types of micropiles:
- Type 1: ▲
- Type 2: ○
- Type 3: ■
- Type 4: ▽
- Type 5: ●
- Type 6: ★

The chart illustrates the performance of each type under given load conditions.
4. Micropile Group in very soft clay layers

Load test results obtained by University of Hannover Prof. Blümel Akz. 10/90

Research was compiled from micropile foundations for transmission pylons founded on very soft clay layers, close to the delta of large rivers or in rice fields.

Horizontal loads, caused by wind, with changing directions, are called “vagabonding horizontal loads”.

The question is, whether a group of micropiles, as a unit, can support horizontal vagabonding loads, independent of the configuration of the micropiles as a group.

ABB Leitungsbau Mannheim, Vertical and horizontal Tension tests with micropile group 1 and 2 University of Hannover, Prof. Dr. Ing. Blümel
Both groups were initially tested in compression only. 

**Results:** ultimate loads  
Group 1  189 kN  
Group 2  220 kN  

Afterwards the horizontal loads were tested:  
Group 1  15 kN  
Group 2  15 kN  

**4.2. Summary:** 
Micropile groups in very soft clay layers (\( Cu = 10 \text{ kN/m}^2 \)) are able to support vagabonding, small horizontal loads in the range of 10 kN.
5. Offshore Application of Micropiles

Large diameter steel tubes or monopiles are often used for offshore foundations for dolphins, seamarks and harbour construction.

- Typically monopiles are vibrated to their design depth
- A minimum of three inclined micropiles are drilled, if possible down to bedrock.
- The steel tube is filled with concrete to enable the load transfer from the monopile to the micropiles.

Installing three drilled micropiles in conjunction with the monopile improves the horizontal load performance of the system compared with the driven pipe pile (allows for only bending and bedding).
Advantages of this technology include:

- Smaller and lighter equipment
- Pull out resistance of the micropiles can be determined before concreting
- Faster installation
- Stiffer bearing capacity than driven pipe piles

Navigational Aid founded on driven pipe piles, which are reinforced by drilled TITAN 73/45 micropiles (one micropile per one driven pile)
5. Offshore Application of Micropiles

Transmission Pylones for 34.5 kV
5. Offshore Application of Micropiles

Dolphins from driven pipe piles – reinforced with drilled micropiles
TITAN 103/51 micropiles

Jetty with Dolphins - reinforced with drilled TITAN 103/51 micropiles
6. CONCLUSIONS

Standard foundation design with micropiles is based on the well-known concept of raft-pile foundations. A stiff raft, which balances and distributes only axial loads according to the axial stiffness $E \times A$ of the micropiles.

Beside the most usual micropile design four special applications are presented:

- **Precast footing prestressed against the soil i.e. for solar-carports**
  Pre-tension of each micropile with $N_k = 20$ kN to mobilise horizontal resistance $R_{ZD} = 9.46$ kN

- **Micropiles, reinforced by a pile neck protection tube**
  to support horizontal loads in the range of min. 5 % of the axial load.

- **Micropile groups in very soft clay layers**
  to support “vagabonding” horizontal loads as a group in the range of $H = 10$ kN (SWL).

- **Offshore application of micropiles**
  Used for a reinforcement of driven monopiles, well rings etc. to improve the loading capacity, the ductility and performance of the foundation.
Thank you for your Attention