TECHNISCHE UNIVERSITÄT MÜNCHEN

Zentrum Geotechnik

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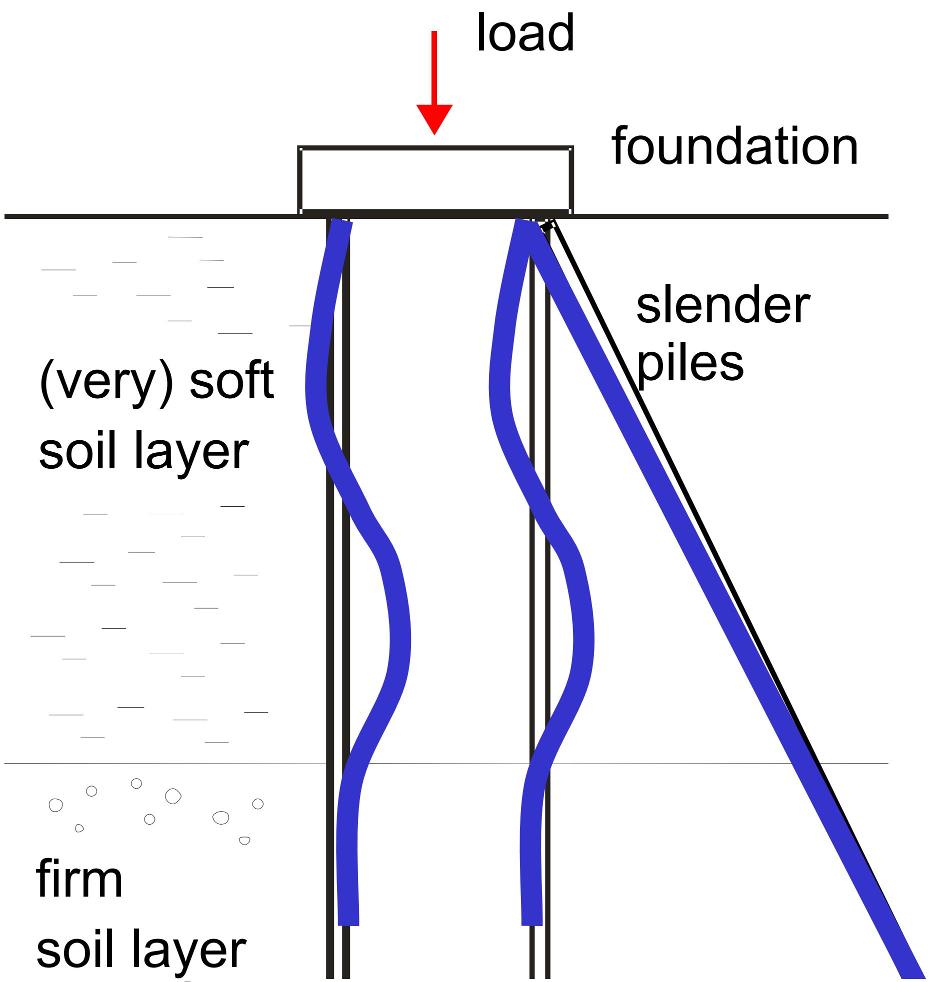
Buckling of slender piles in soft soils –

Large scale loading tests and introduction of a simple calculation scheme

Research work at the Zentrum Geotechnik

Motivation



Has buckling to be expected ?

Research work at the Zentrum Geotechnik

Motivation

EC 7:
„.. check for buckling is not required if c_u exceeds 10 kPa..“

Other codes set this limit of undrained shear strength at 15 kPa or 10 kPa
(eg. DIN 1054, 2005 or the national technical approvals for micropiles)

We asked:

→ Are the standards requirements save enough?

Research work at the Zentrum Geotechnik

Motivation

Reviewed papers:

Vik (1962),
Wenz (1972),
Prakash (1987),
Wennerstrand&Fredriksson (1988),
Meek (1996),
Wimmer (2004),
Heelis&Pavlovic&West (2004)

We asked:

→ Are the published design methods capable to simulate the interaction between the supporting soil and the pile?

Research work at the Zentrum Geotechnik

Introduction

Literature research

Development of a numerical FE-Model

Model scaled tests

In situ field load test

Large scaled loading tests

Development of a simple design method

→ Summary of the results obtained in the first step

→ Reported by Prof. N. Vogt at the IWM 2004 in Tokyo

1.) The standards rules underestimate the possibility of pile buckling

2.) An elastic approach to describe the lateral soil support is not appropriate

3.) Most published calculation methods cannot simulate the pile‘s behavior properly

Research work at the Zentrum Geotechnik

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→ Aim:

Proofing the obtained expertise with large scaled loading tests on single piles

Development of a simple design method that can simulate the main effects recognized in the loading tests

Large scaled loading tests

Loading of 4 m long single piles

Container made up with concrete segments

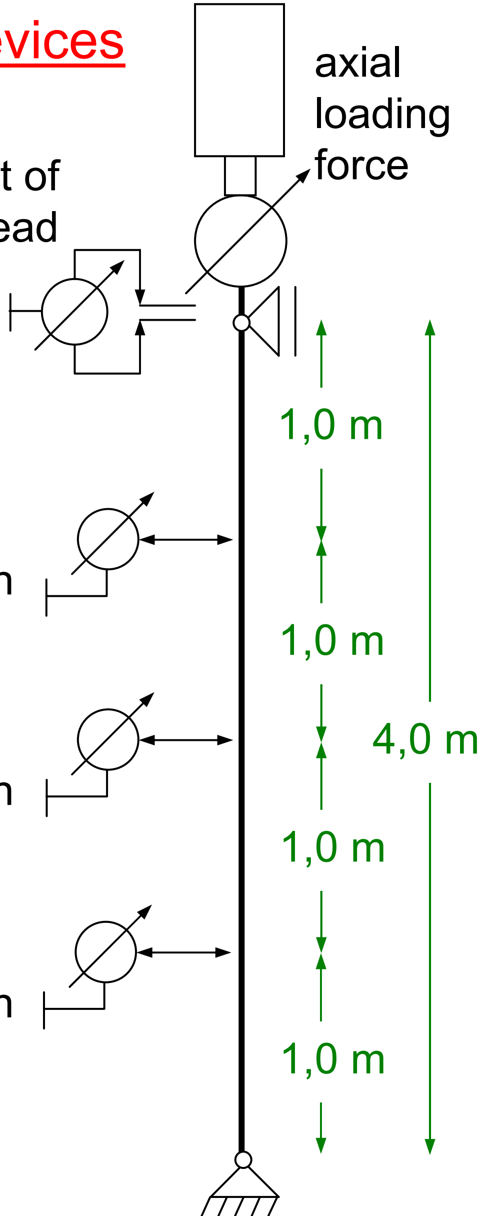
Pile is pinned top and bottom

Large scaled loading tests

Loading of 4 m long single piles

Container made up with concrete segments

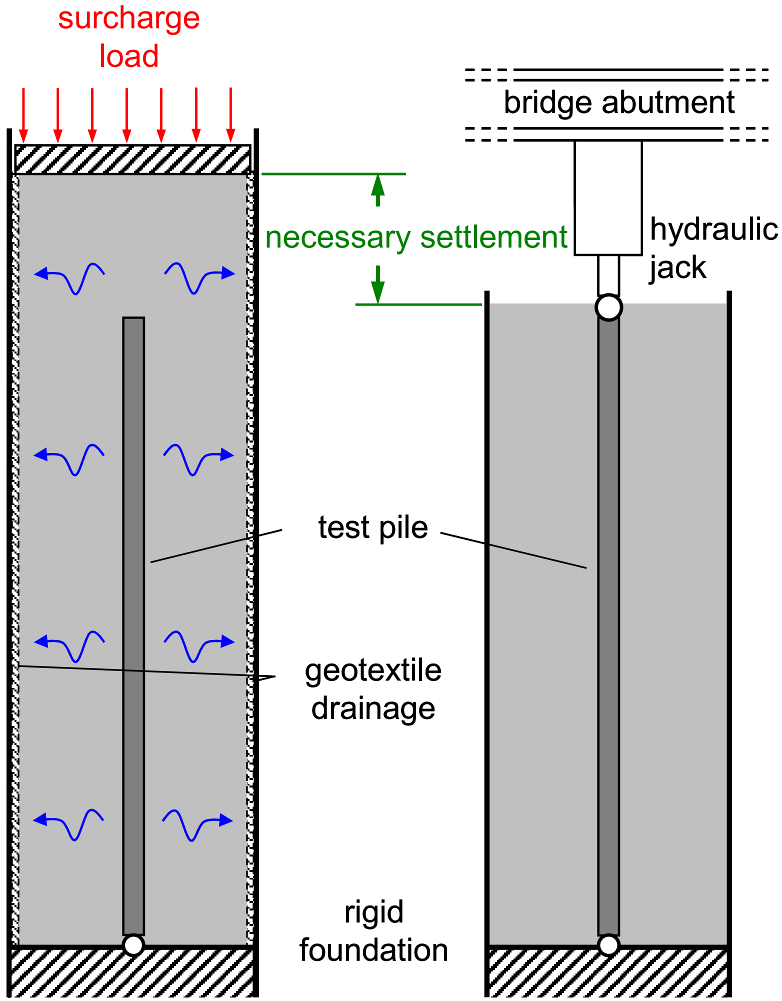
Measuring devices



Large scaled loading tests

Mixing up the soil in a liquid consistency

Filling the containers by pumping the liquid soil – following consolidation with the help of the electro osmotic effects



Draining system

Pumping the liquid soil

Large scaled loading tests

Pile type I:
Composite cross section GEWI28
Steel rod d = 28 mm
Hardened cement slurry   D = 100 mm

Pile type II:
Aluminum profile
Thickness = 40 mm
Width = 100 mm

Large scaled loading tests

Exemplary illustration of a loading test:

Alu-pile surrounded by a supporting soil of c_u = 18 kPa

Large scaled loading tests

Shear vane tests: Soil support of c_u = 18 kPa

Statistical analysis:

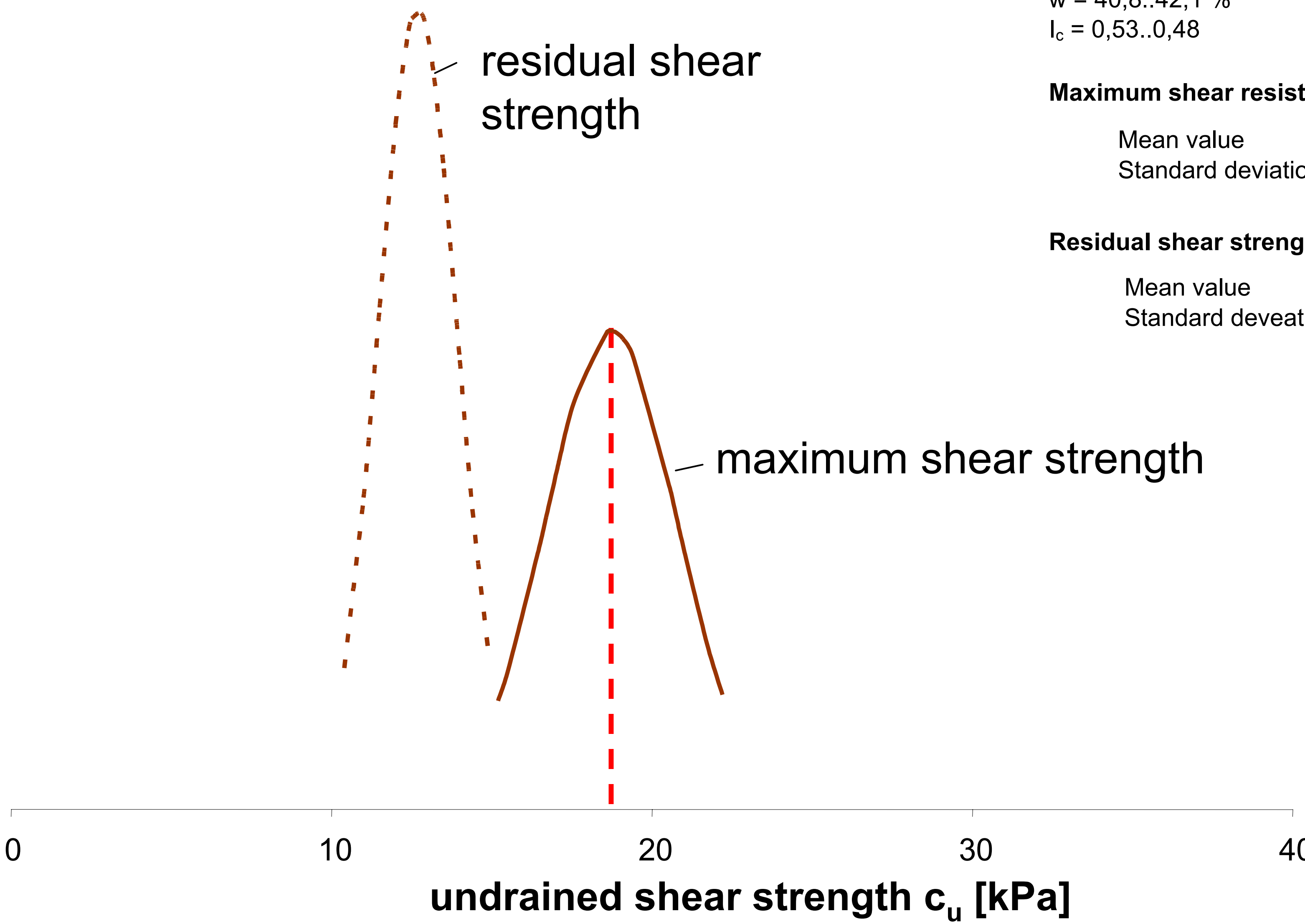
Normal plastic clay TM
w = 40,8..42,1 %
I_c = 0,53..0,48

Maximum shear resistance c_{fv}

Mean value = 18,7 kN/m²
Standard deviation = 2,1 KN/m²

Residual shear strength c_{Rv}

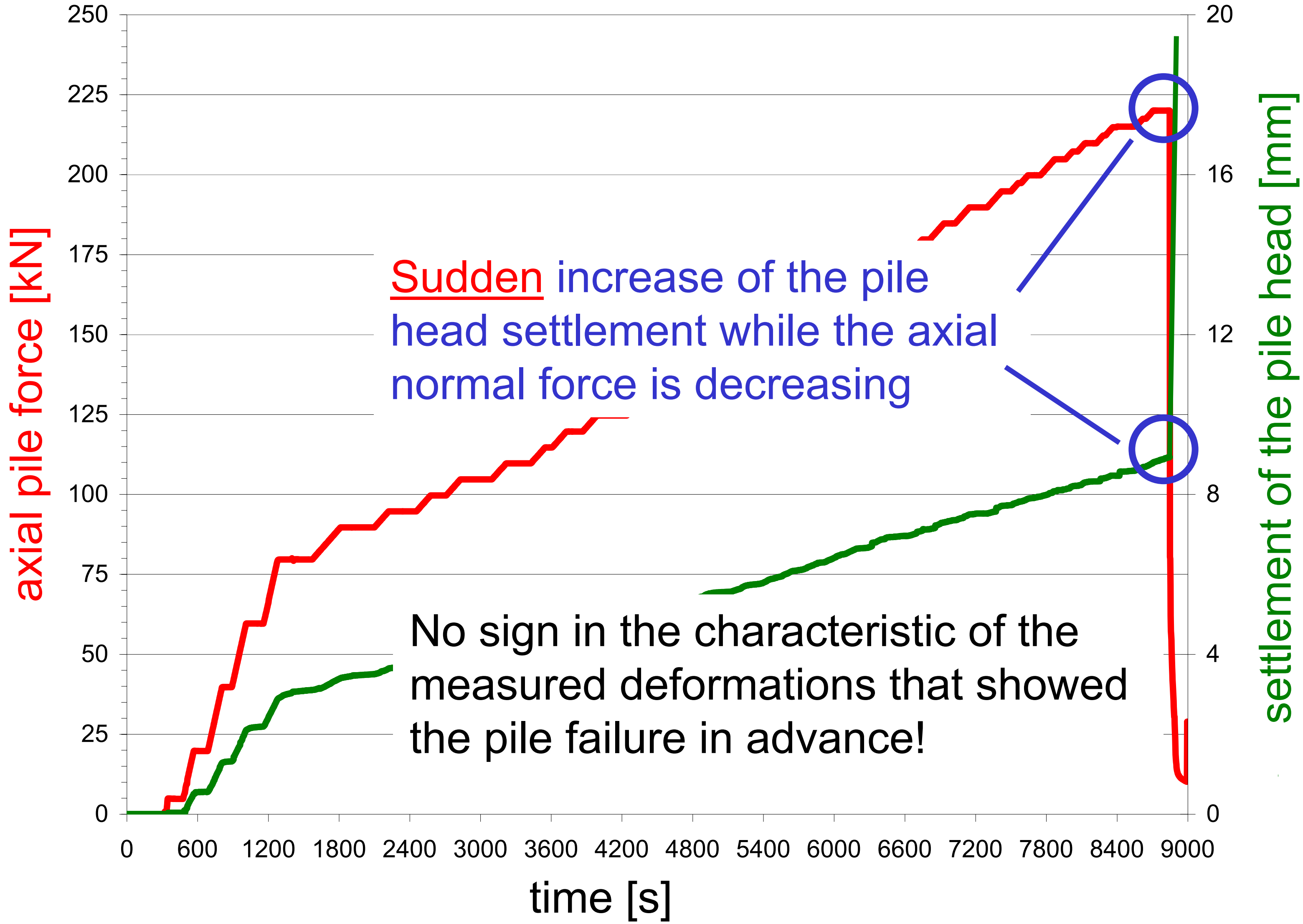
Mean value = 12,7 kN/m²
Standard deveation = 1,2 KN/m²



Large scaled loading tests

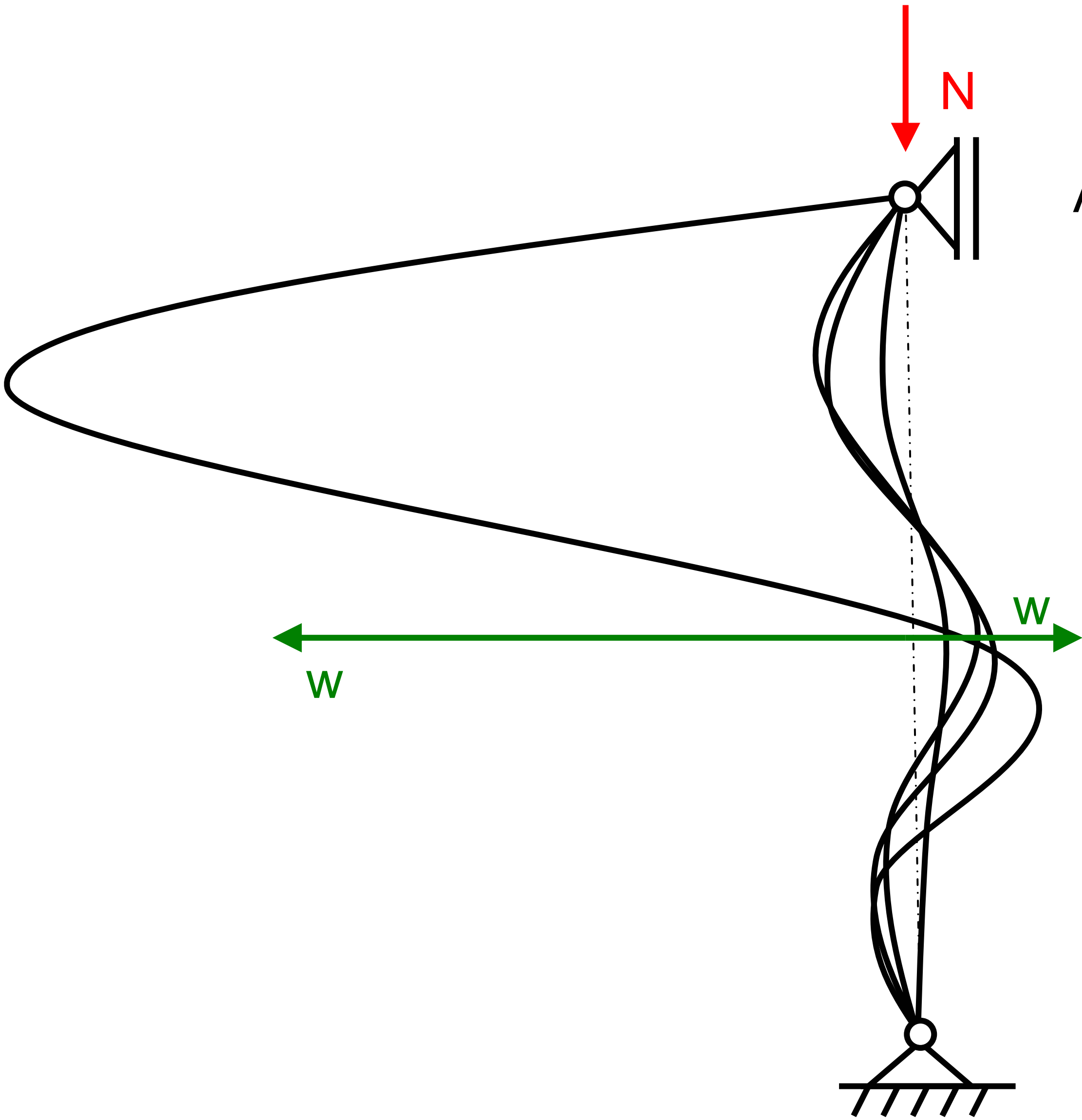
Loading characteristic: Soil support of c_u = 18 kPa

Settlement of the pile head



Large scaled loading tests

Lateral deflection: Soil support of c_u = 18 kPa



Axial force N	deflection w
50 kN	0,4 mm
100 kN	0,9 mm
212 kN	1,2 mm
220 kN (ultimate)	9 mm

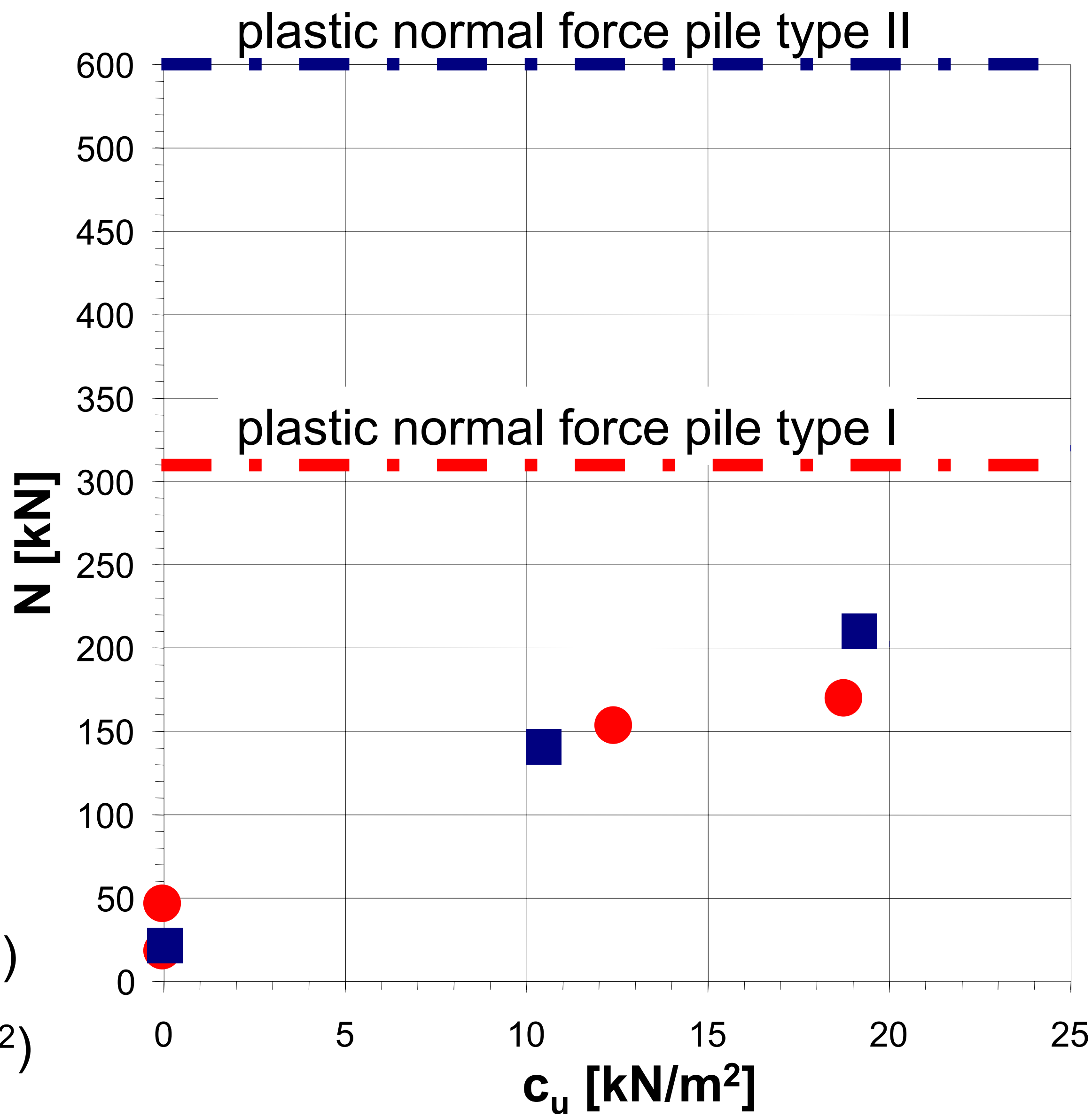
Large scaled loading tests

Analysis

Results:

- With an increasing soil's undrained shear strength c_u the ultimate bearing capacity rises

- Buckling regularly determined the ultimate state of the system, even in soils with an undrained shear strength of c_u > 15 kN/m²



● pile type I ($E_p \cdot I_p$ = 55 kNm²)

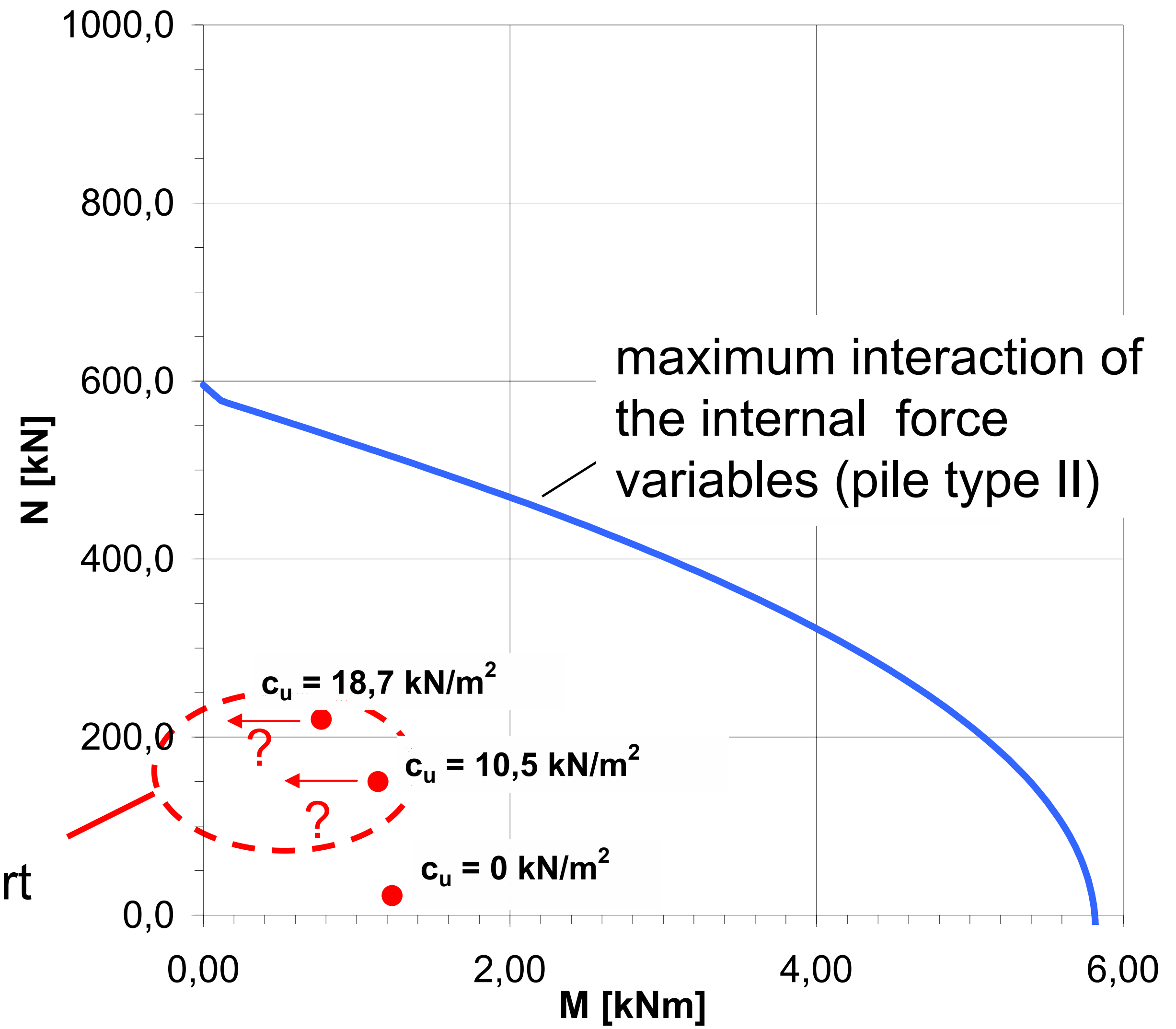
■ pile type II ($E_p \cdot I_p$ = 38 kNm²)

Large scaled loading tests

Analysis

Results:

No failure due to a limited pile‘s material strength!



Even the backing moment out of the lateral soil support is not considered

Large scaled loading tests

Analysis

Results:

For lower axial forces the lateral deflections of the pile remain very little (stiff behavior)

The failure of the micro piles occurred suddenly (no sign of failure from the measured deformations)

The halve waves of the buckling pile‘s bending curve were always smaller than the full pile‘s length (from joint to joint)

Introduction of a simple design method

Introduction of a simple design method

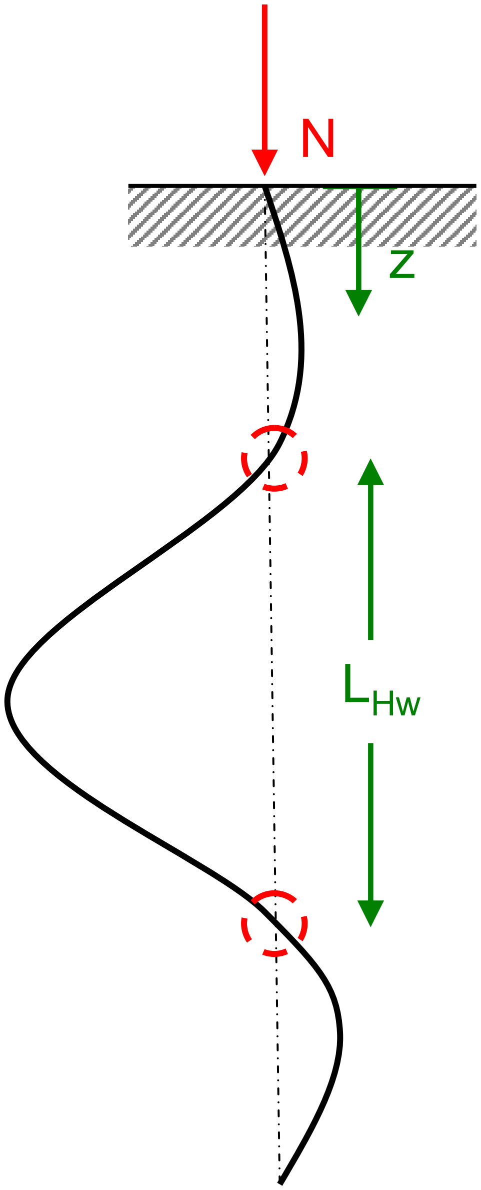
Finding a static system

Substituted mechanical system with a buckling length of L_{Hw}

→ the length of the effective buckling figure's half wave L_{Hw} can develop freely for the most conditions in situ at the upper and lower boundaries of the soft soil layer

→ the large scaled loading tests showed that the length of the buckling figure's half waves were smaller than the maximum possible length of 4 m;

→ an infinite long pile can be assumed for the calculations;



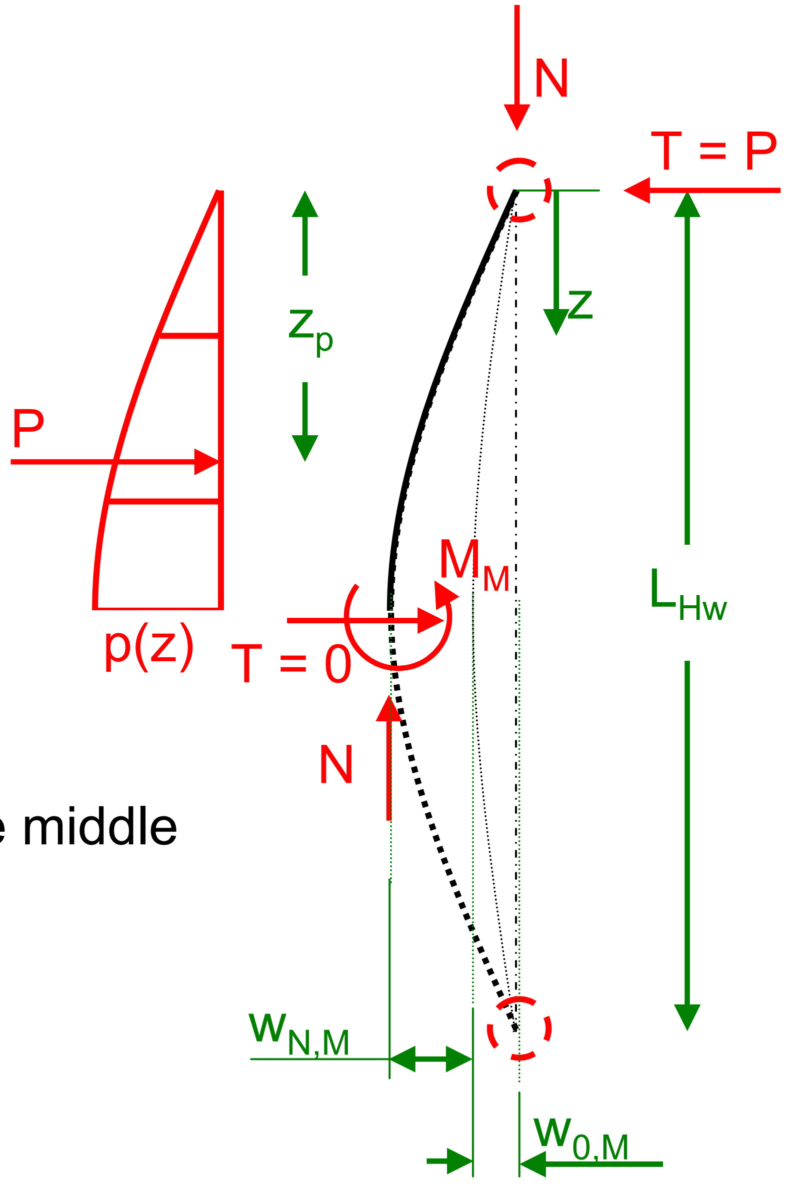
Introduction of a simple design method

Finding a static system

All forces acting on the static system with a length of L_{Hw}

Lateral soil support

Bending moment in the middle



Introduction of a simple design method

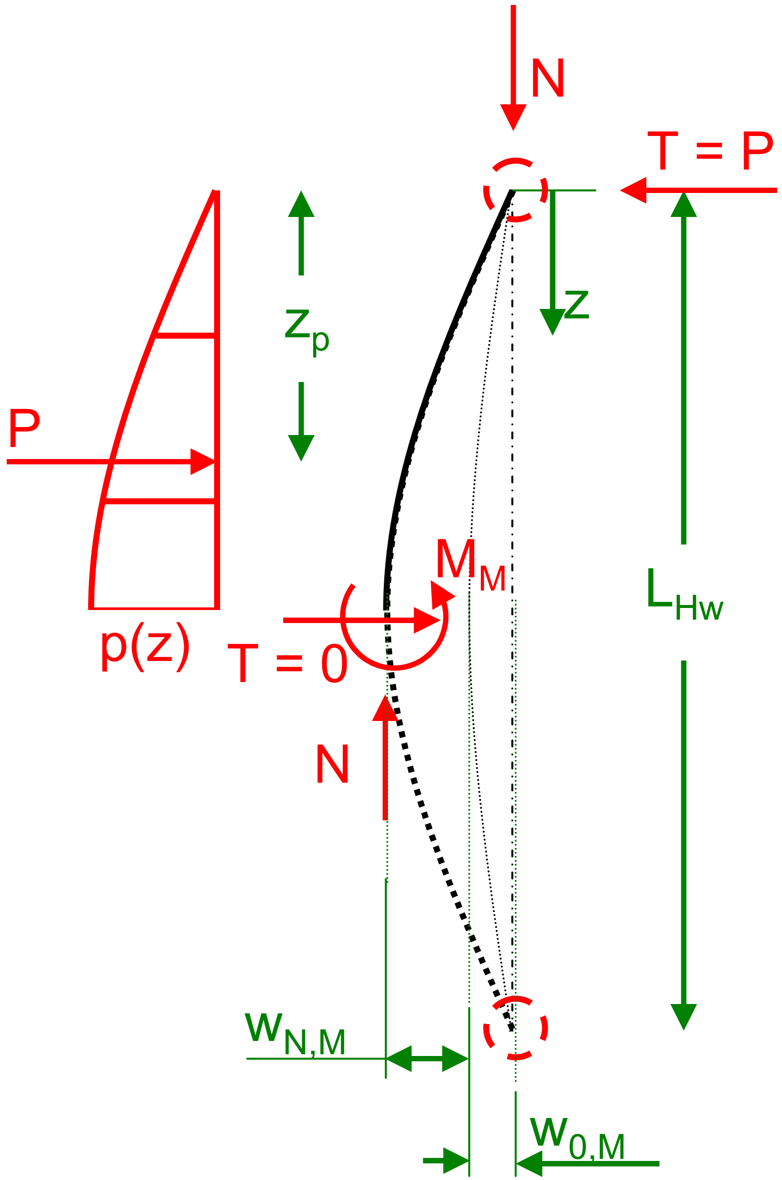
Derivation

Setting up equilibrium:

Condition ∑M = 0 at the pinned top

$$M_M = N \cdot \left(w_{N,M} + \frac{L_{Hw}}{imp} \right) - P \cdot z_p$$

Force from the lateral soil support is defined piecewise in order to a elastic-plastic soil resistance



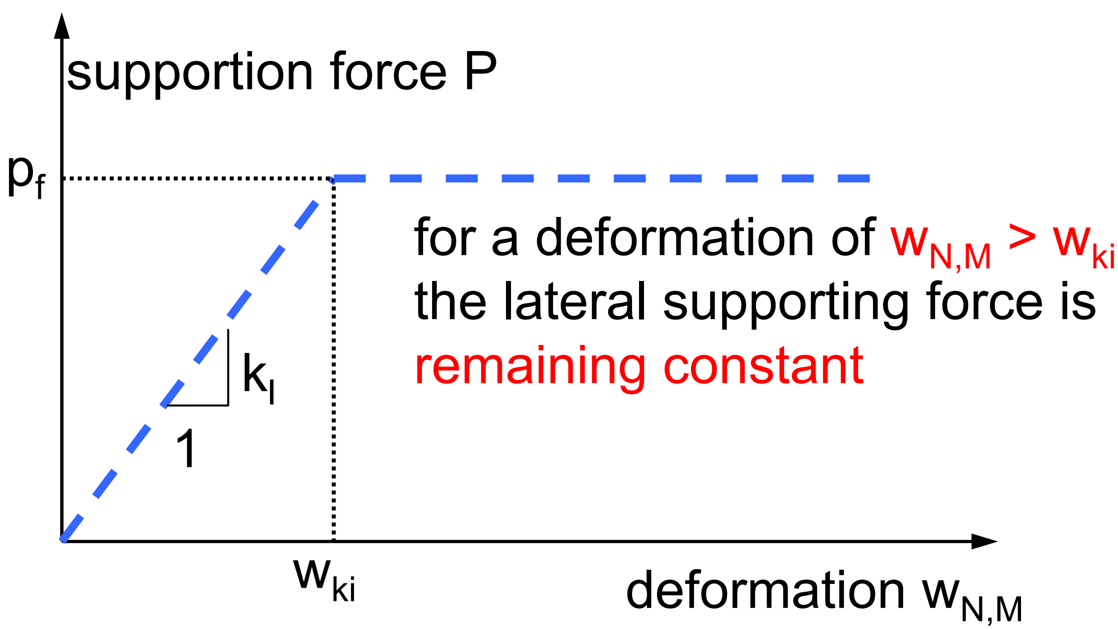
Introduction of a simple design method

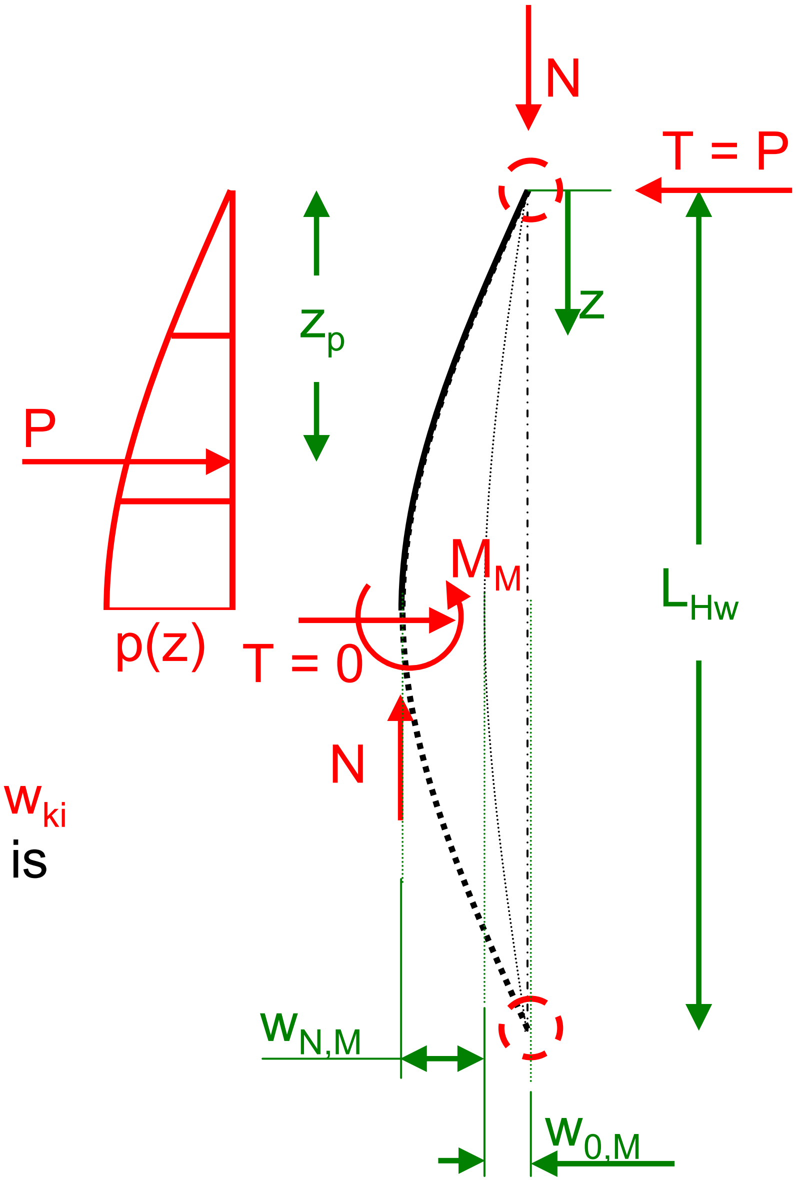
Derivation

Force P from a bi-linear approach of the supporting soil:

$$P = k_l \cdot w_{N,M} \cdot \frac{L_{Hw}}{\pi} \qquad \text{for: } w_{N,M} < w_{ki}$$

$$P = k_l \cdot w_{ki} \cdot \frac{L_{Hw}}{\pi} \qquad \text{for: } w_{N,M} \geq w_{ki}$$





Introduction of a simple design method

Derivation

Condition ∑M = 0 at the pinned top

$$M_M = N \cdot \left(w_{N,M} + \frac{L_{Hw}}{imp} \right) - P \cdot z_p$$

Assumption: The pile's material remains elastic

$$M_M = -E_p \cdot I_p \cdot w_{N,M}''$$

defined picewise

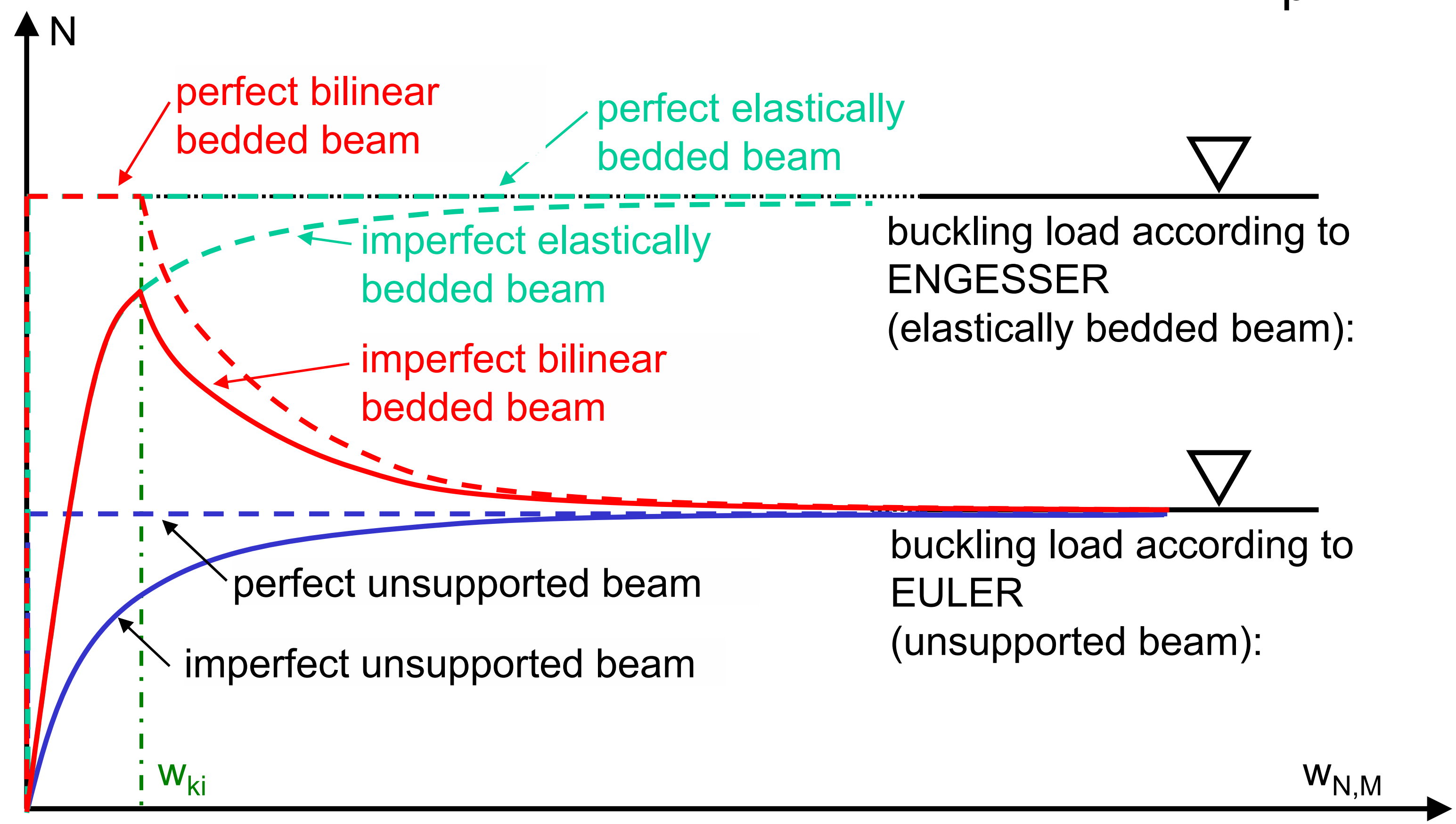
$$N = \frac{w_{N,M} \cdot \frac{\pi^2}{L_{Hw}^2} \cdot E_p \cdot I_p + \frac{1}{\pi^2} \cdot p_M \cdot L_{Hw}^{\;\;2}}{w_{N,M} + \frac{L_{Hw}}{imp}}$$

Introduction of a simple design method

Presentation

$N = F\ (w_{N,M},\ E_p \cdot I_p,\ imp,\ L_{Hw}$ and the soil support: p_f and $w_{ki})$

$$N = \frac{w_{N,M} \cdot \frac{\pi^2}{L_{Hw}^2} \cdot E_p \cdot I_p + \frac{1}{\pi^2} \cdot p_M \cdot L_{Hw}{}^2}{w_{N,M} + \frac{L_{Hw}}{imp}}$$



Introduction of a simple design method

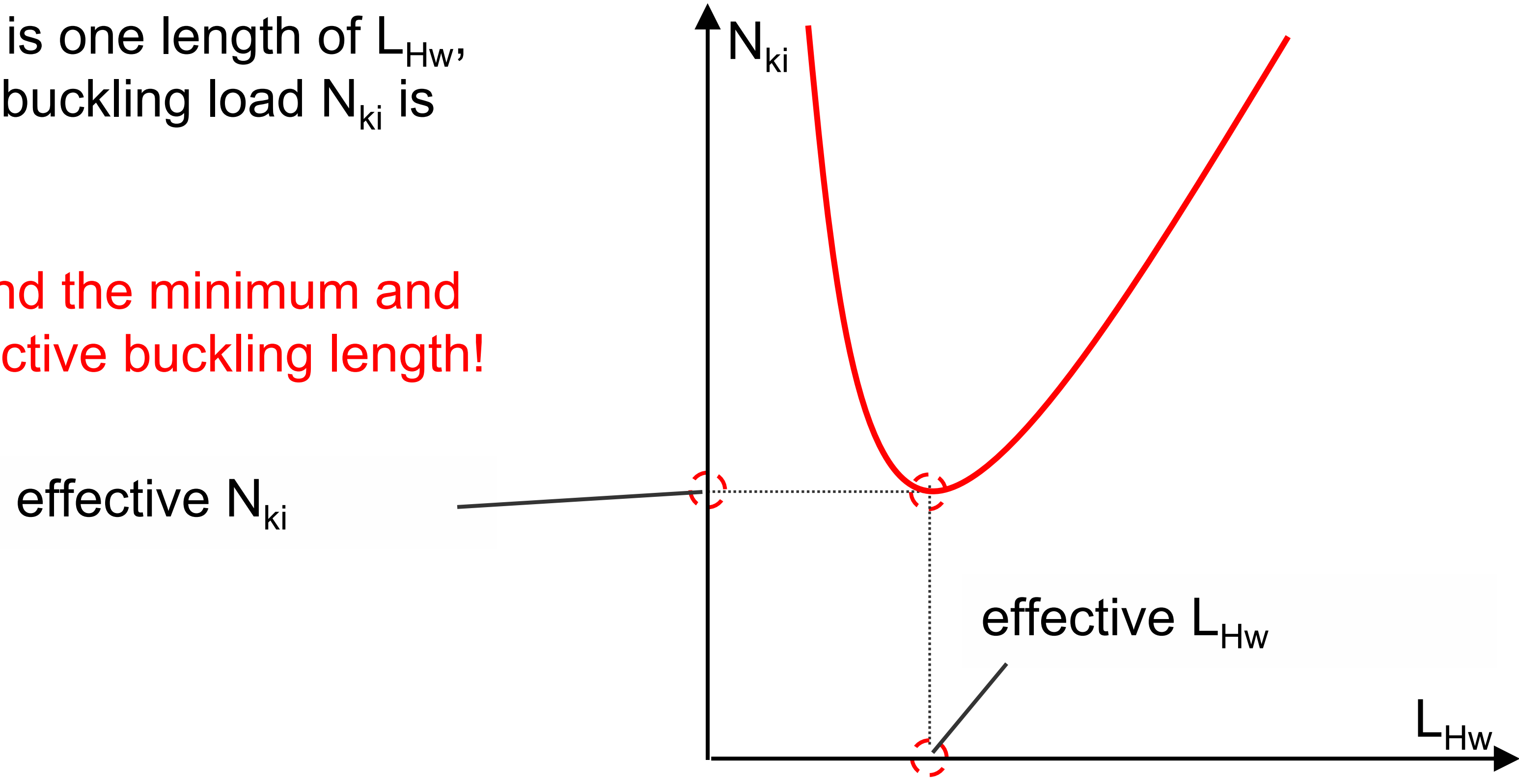
Presentation

L_{Hw} is unknown!

For defined parameters (soil support, imperfection and flexural rigidity) there is one length of L_{Hw}, for which the buckling load N_{ki} is minimal

$$N_{ki} = \frac{w_{ki} \cdot \frac{\pi^2}{L_{Hw}^2} \cdot E_p \cdot I_p + \frac{1}{\pi^2} \cdot w_{ki} \cdot k_l \cdot L_{Hw}^2}{w_{ki} + \frac{L_{Hw}}{imp}}$$

Vary L_{Hw} to find the minimum and therefore effective buckling length!



Introduction of a simple design method

Summary of the calculation sequence:

1.) Define the parameters of the lateral soil support p_f und w_{ki}

2.) Define an imperfection and the flexural rigidity of the pile's cross section

3.) Evaluate the effective buckling half wave's length L_{Hw}

4.) Calculate the buckling load N_{ki}

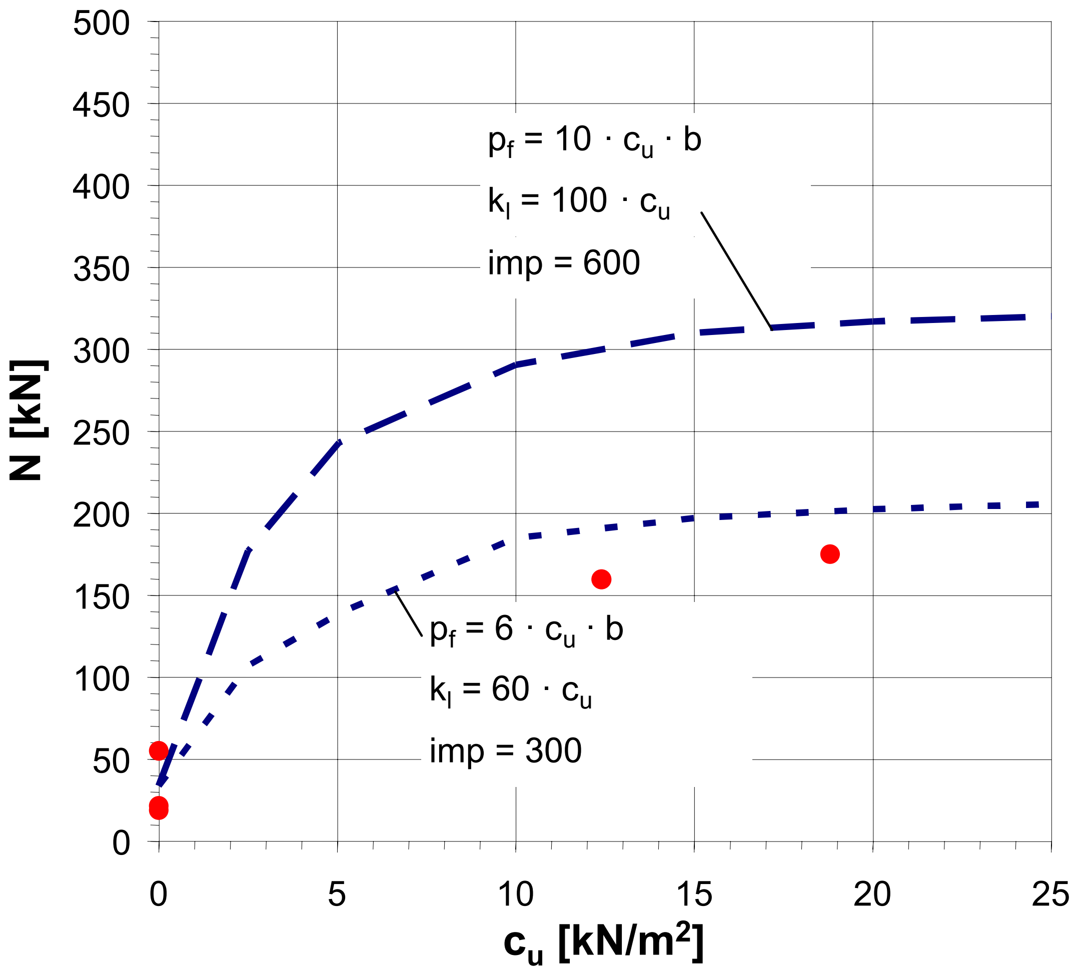
5.) Check if the pile's material strength governs the maximum bearing capacity (this means: "does the pile's material yield before the buckling load is reached")

→ You may download an Excel-Sheet at www.gb.bv.tum.de

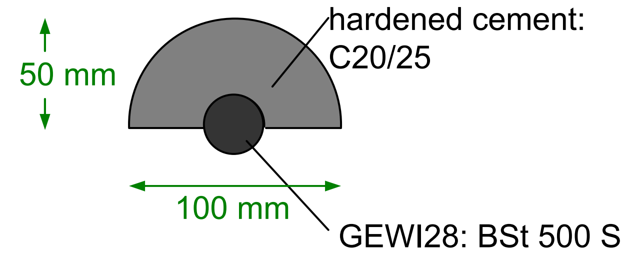
Introduction of a simple design method

Back-calculation of the large scaled tests

Pile type I



<u>Used: half side cracked cross section (no tension stresses in the hardened cement)</u>

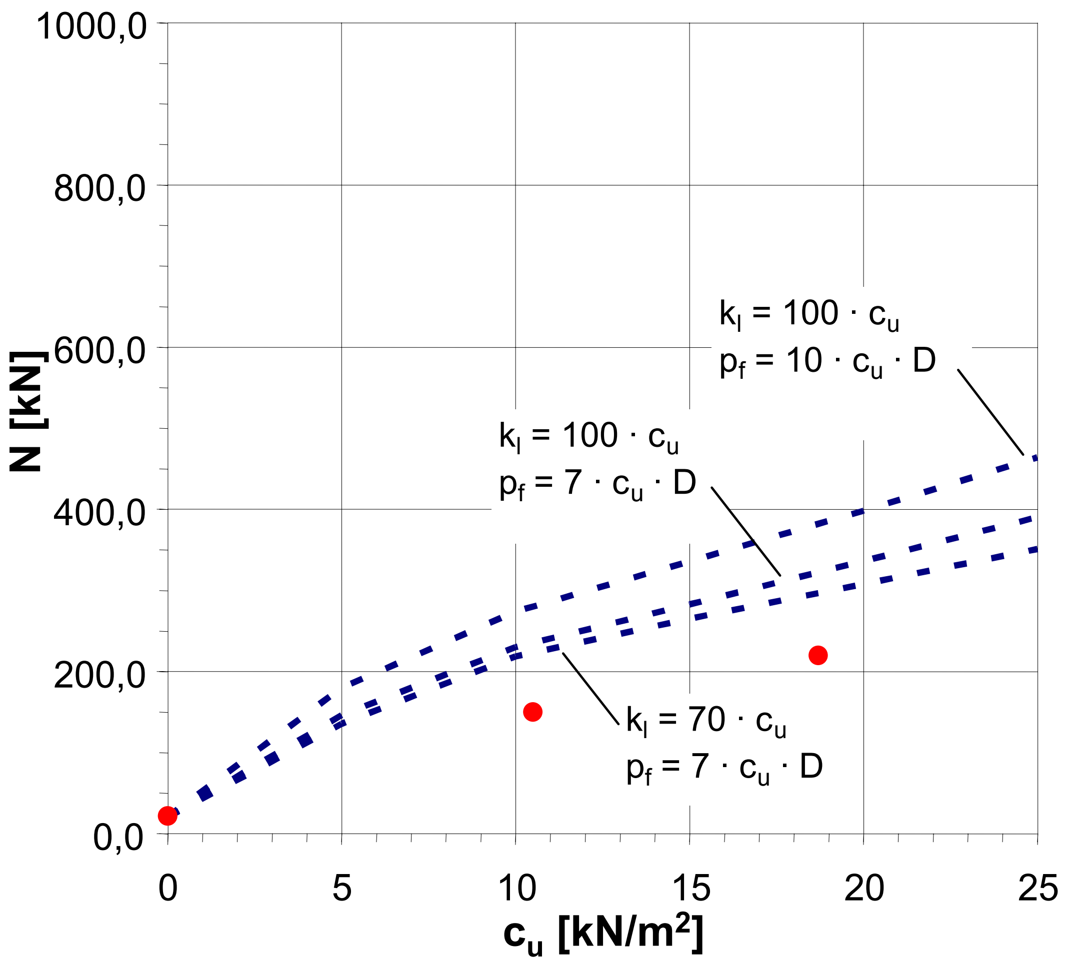


$E_p \cdot I_p = 55\ kNm^2$

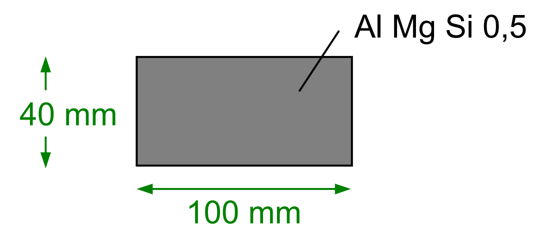
Introduction of a simple design method

Back-calculation of the large scaled tests

Pile type II



Alu-pile:



$E_p \cdot I_p = 38\ kNm^2$

Summary

In (very) soft soils pile buckling should always be verified!

With the help of the presented design method the main effects of the loading tests can be considered in basic.

The insecurities upon the design method is based and which are recognizable comparing the theoretical results with the data form the pile load tests must be covered by partial safety factors on the structural part and the soil resistance.

- Compound effects steel-concrete
- Soil resistance (w_{ki}, p_f)
- Viscous influence
  → creep and relaxation

Thank you for your Attention!

Research work at the Zentrum Geotechnik

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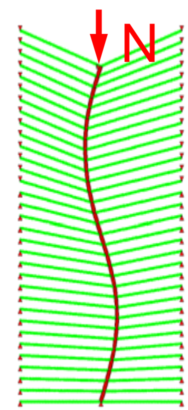
In situ field load test

Large scaled loading tests

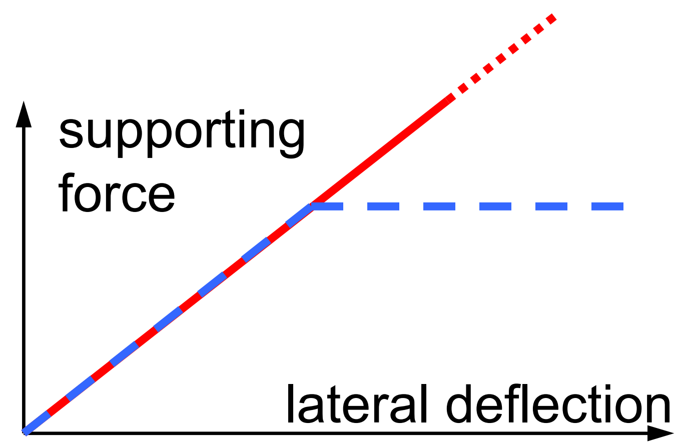
Development of a simple calculation scheme

→ beam supported by springs



→characteristic of the lateral reaction forces

elastisch or **elastisch-plastisch**



Research work at the Zentrum Geotechnik

Introduction

Literature research

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Model scaled tests

In situ field load test

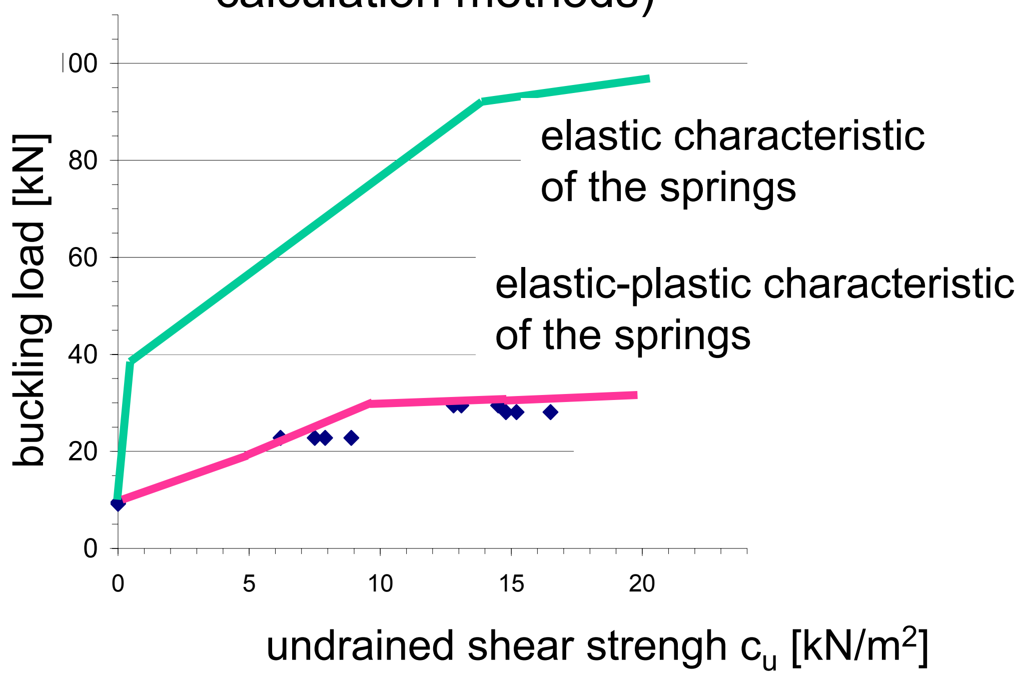
Large scaled loading tests

Development of a simple calculation scheme

→ Loading tests on 80 cm long model piles

→ Varying soil strengths and cross sections

→ Comparison of the test results with the predicted buckling loads (both numerical FEM and published calculation methods)



Research work at the Zentrum Geotechnik

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Large scaled loading tests

Development of a simple calculation scheme

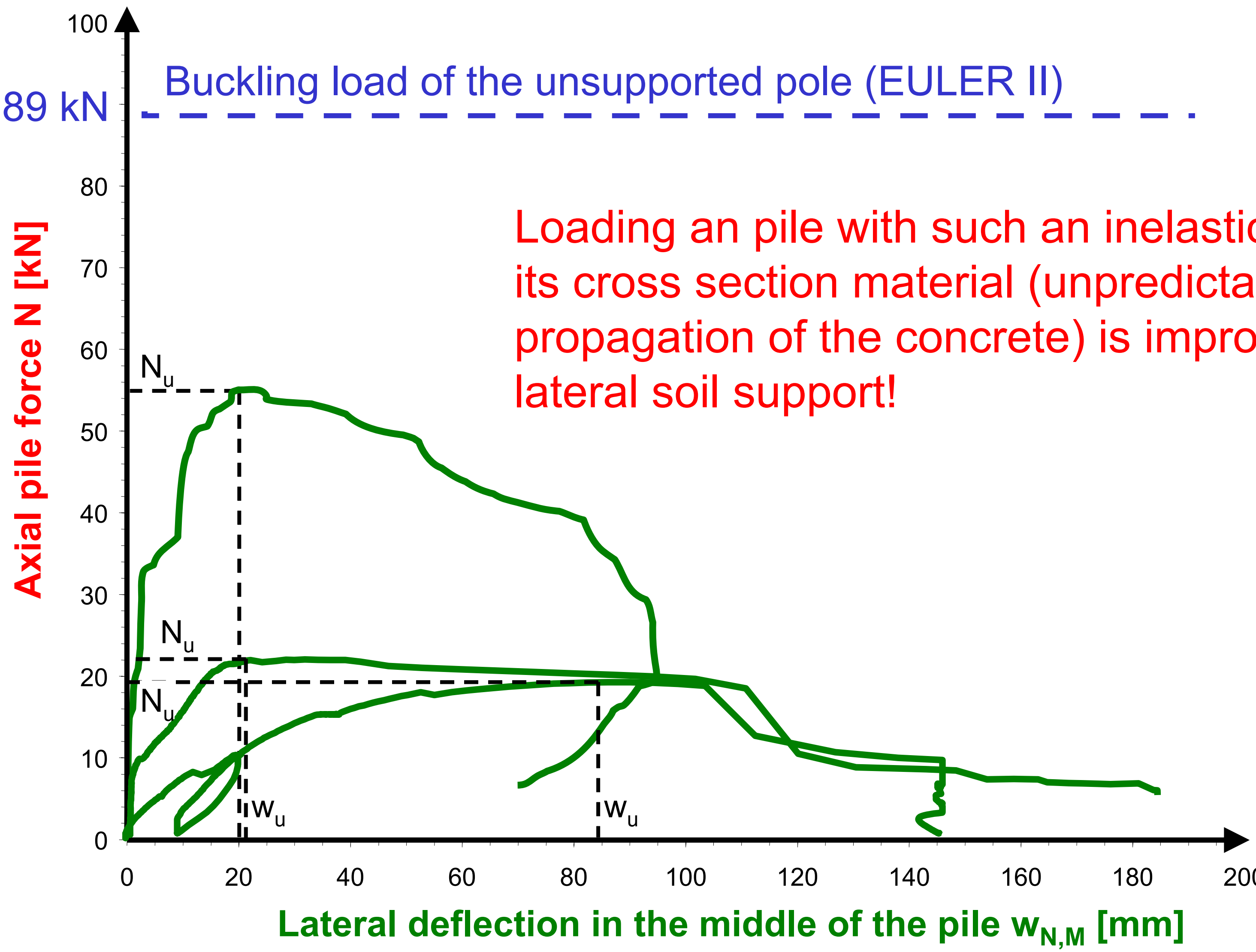
→ Loading test of a GEWI-pile in soft, organic soil

→ Sudden pile failure at a load very little above the design load

Large scaled loading tests

Results of the loading tests of three unsupported composite piles

Why to use an aluminum pile?



Loading an pile with such an inelastic behavior due to its cross section material (unpredictable crack propagation of the concrete) is improper to qualify the lateral soil support!

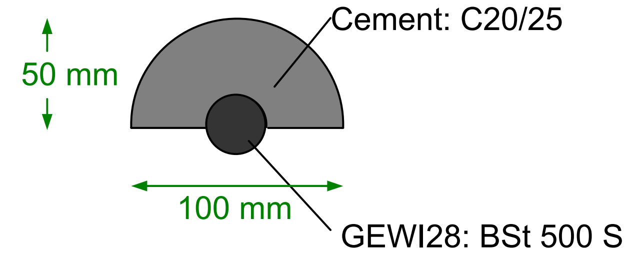
Large scaled loading tests

Pile type II: Aluminum profile

Some pile is needed which behaves elastically over a wide range of lateral displacements and which reproduces the buckling load according to EULER in the unsupported case.

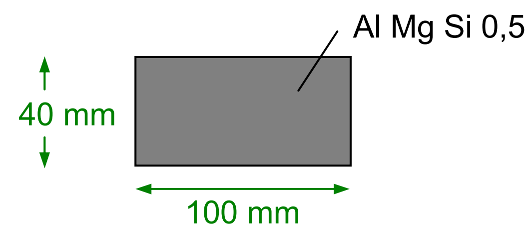
Solution: A aluminum pile that has a similar flexural rigidity compared to the cracked composite cross section.

Composite cross section, cracked half side



$E_p \cdot I_p = 55 \text{ kNm}^2$

Aluminum profile



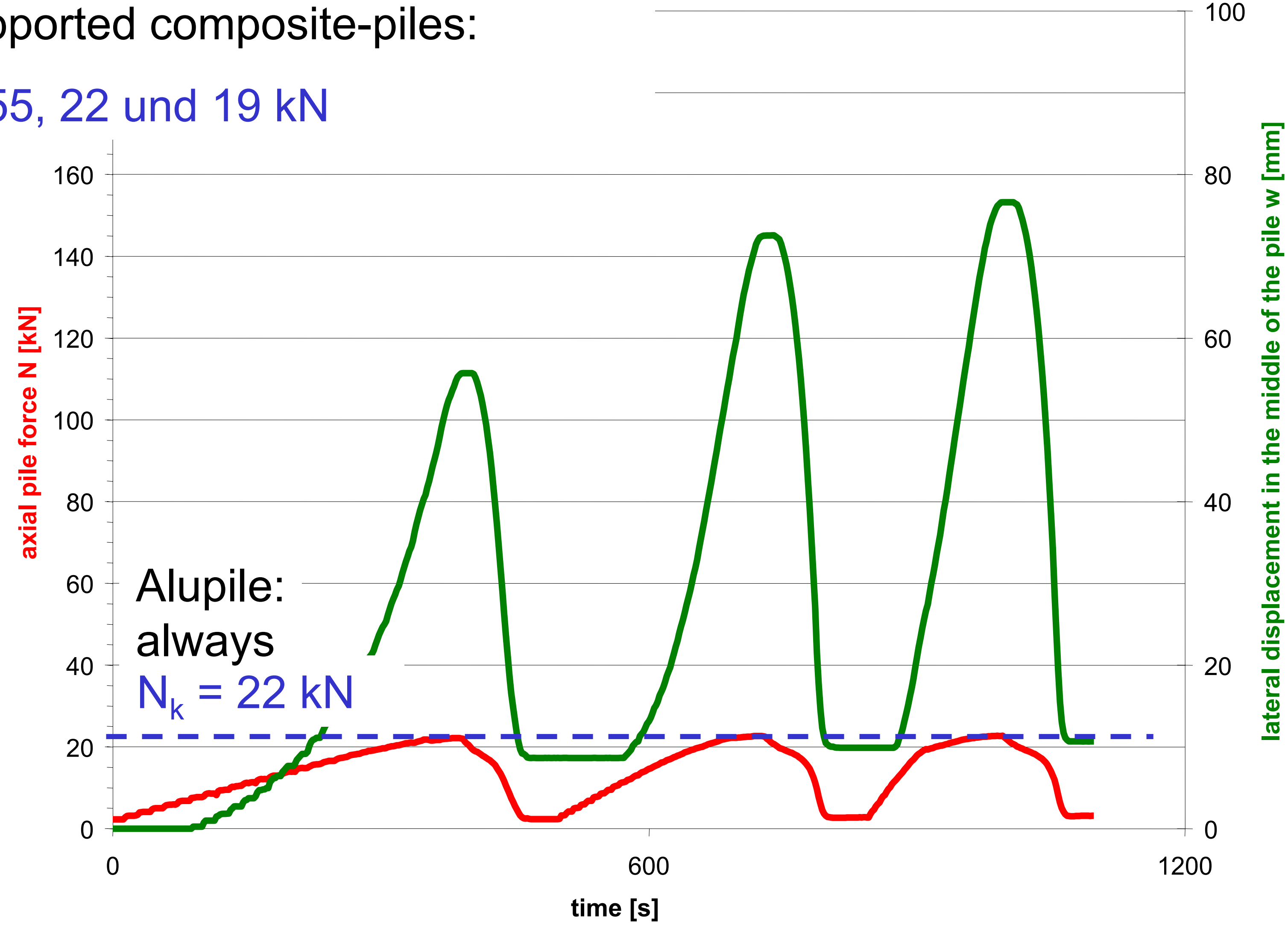
$E_p \cdot I_p = 38 \text{ kNm}^2$

Large scaled loading tests

Test results obtained by loading of an unsupported alu-pile

Ultimate bearing capacity of the unsupported composite-piles:

N_k = 55, 22 und 19 kN



Introduction of a simple design method

Derivation

Assumption of a sinus shaped deformation due to imperfection

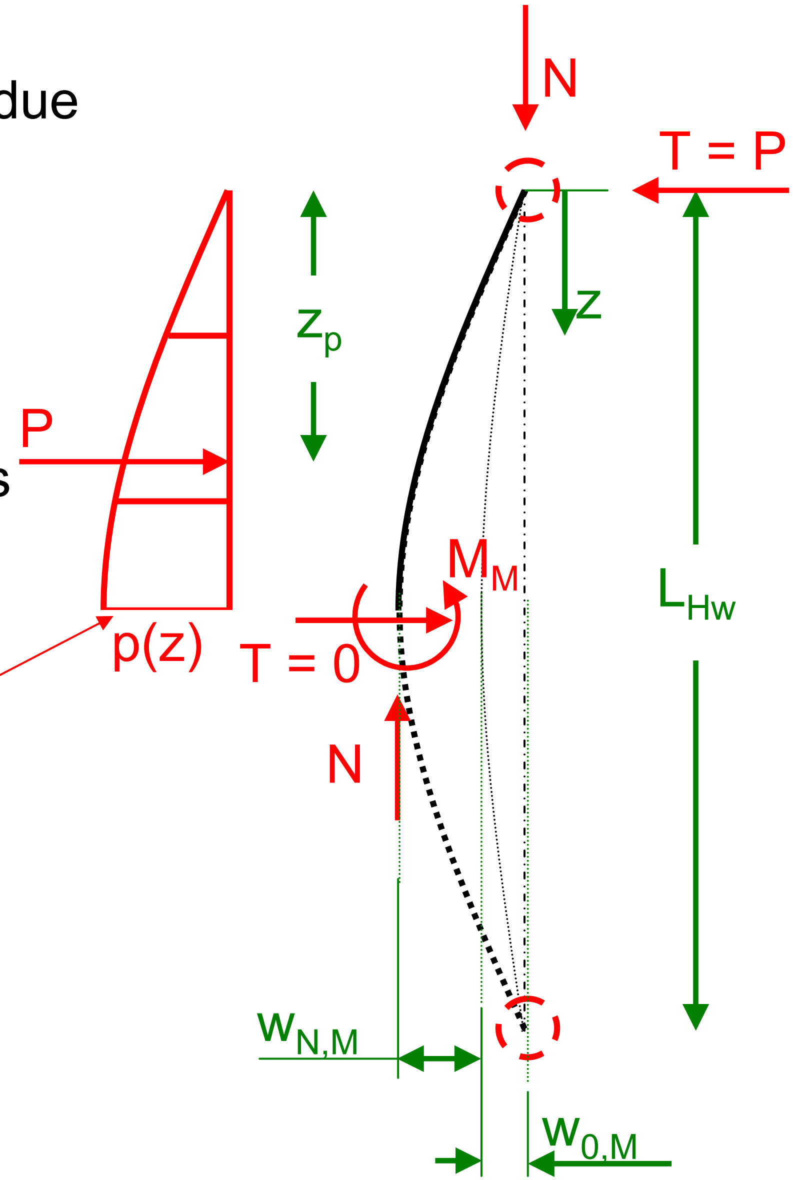
$$w_0(z) = w_{0,M} \cdot \sin\left(\frac{\pi}{L_{Hw}} \cdot z\right)$$

Assumption of sinus shaped bending curves

$$w_N(z) = w_{N,M} \cdot \sin\left(\frac{\pi}{L_{Hw}} \cdot z\right)$$

This yields to a sinus shaped form of the load per unit length due to the lateral soil support

$$p(z) = p_M \cdot \sin\left(\frac{\pi}{L_{Hw}} \cdot z\right)$$



Introduction of a simple design method

Is the decisive buckling load N_{ki} the ultimate axial load N_u of the micropile?

The pile's material may yield before the buckling load is reached. In this case the pile's material strength governs the ultimate load.

$$M = M_{pl} \cdot \left(1 - \left(\frac{N}{N_{pl}}\right)^{\alpha}\right)$$