ISM 15th International Workshop on Micropiles

Micropiles in the Second Generation of Eurocode 7: Geotechnical Design

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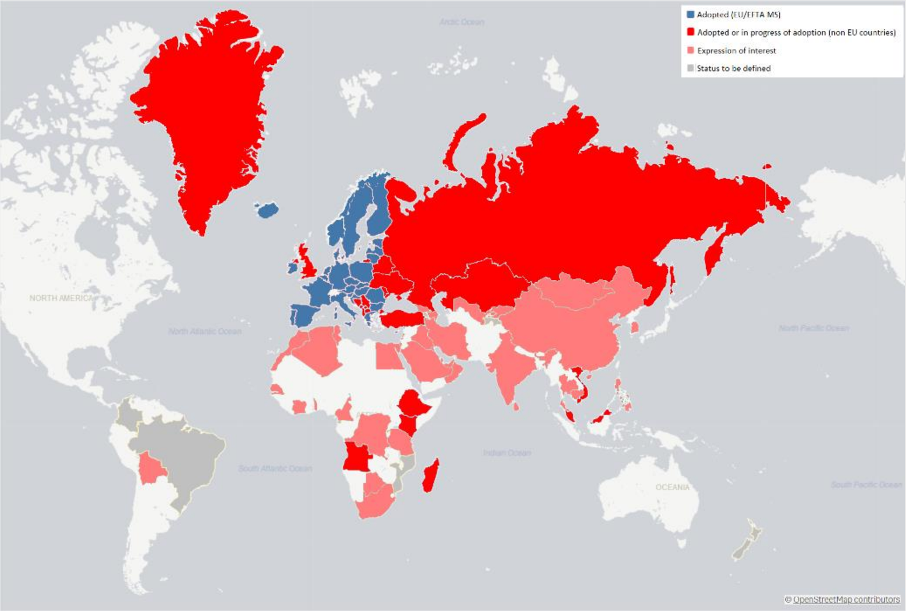
Eurocodes journey and importance



- 1975 – Start by EC
- 2002-2007 – Introduction of the current Eurocodes
- 2011-2016 – Evolution Groups: topics for revision EC7
- **2015-2025 – CEN/TC250 SC7: Drafting of the 2nd generation of EC7: updating, improvements, harmonisation and developments for future**
- 2035-2040 – Next Generation?

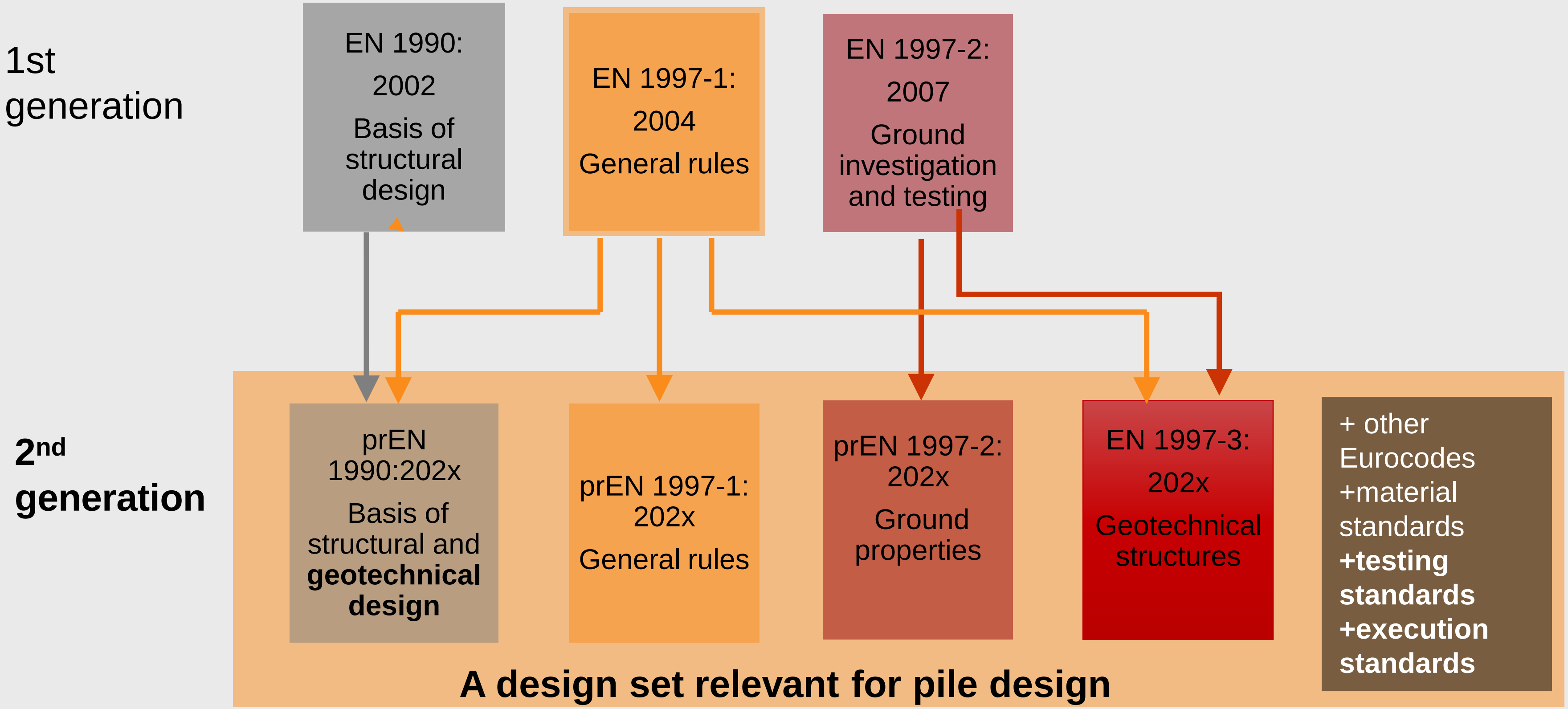
+ ISO/TC 182 Testing of geotechnical structures

+ CEN/TC 288 Execution of special geot. works

- EC establishes principles and requirements for the safety, serviceability, robustness and durability of structures (…) appropriate to the consequences of failure.
- EC describes the basis for structural and geotechnical design and verification according to the limit state principle:

- calculation using the partial factor method or other reliability-based methods (primary method of verification)
- prescriptive rules (conservative and justified by comparable experience)
- testing (direct assessment on an actual scale)
- Observational Method

SECOND GENERATION OF EUROCODES OVERVIEW



- In the current EC7 micropiles were not mentioned (only EN 14199)
- Assumptions: micropiles are one of the pile types, but some rules were troublesome
- In 2nd generation of EC7 pile design significantly evolved
- Micropiles are addressed explicitly
- Some of the new content:
  - Single piles, pile groups and piled rafts under axial and transversal loading and displacements
  - Importance of the settlements and the ground non-linearity
  - New approach for the effect of ground displacement (taking into account SSI)
  - Recommandations for cyclic effects
  - Material, execution and testing requirements

Current EN 1997-1:
Clause 7 Piled Foundations

prEN 1997-3:202x
Clause 6 Piled Foundations

Annex C

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Clause 6 main text

- Essential design rules
- Basic requirements for analysis and verification of ultimate and serviceability limit state
- **Design approach and partial factors (NDP)**

Annex C – calculaiton models

- axial pile resistance based on ground parameters or CPT/ PMT profiles or empirical tables
- downdrag due to vertical ground movements
- **pile groups subject to axial tension**
- single pile settlement using load transfer functions
- single pile lateral displacement using load transfer functions
- **buckling** and second order effects
- determination of axial pile resistance under **cyclic loading**

- Clause 6 applies to single piles, pile groups and piled rafts (N).
- Piles should be **classified** according to their method of execution

→ used to determine different **values of partial and model factors γ_R**

Pile type	Class	Example pile types
Displacement piles	**Full displacement**	Driven cast-in-place concrete piles; Driven closed-ended tubular steel piles; Cast-in-place concrete screw piles Driven micropiles;
	Partial displacement	Driven open-ended tubular steel piles; Driven and grouted steel H-section piles; Cast-in-place concrete screw piles; Drilled or bored pressure-grouted micropiles
Replacement piles	**Replacement**	Bored cast-in-place concrete piles (..) Bored or drilled steel tubular piles; Barrettes, Grouted piles or battetts Drilled or bored micropiles;
Piles not listed above		Steel helical piles; Compressed-air driven piles

- The current Eurocode 7 does not explicitly regulate the material or durability requirements
- Some regulations in EN 14199
- The 2nd generation of Eurocode 7 gives strict rules for materials: references to other structural EC or other standards
- Special provisions regarding ductility (EN 1993-1-1, 5.2.2 or of Class B of EN 1992-1-1)

Permitted steel grades for mircopiles/soil nails/anchors acc. to:

- EN 10025 (all parts), Hot-rolled products of structural steel;
- EN 10080, Steel for the reinforcement of concrete (not all);
- prEN 10138-3 or 4, Prestressing steels - Part 3: Strands or Part 4: Bars (not all);
- EN 10210-1, Hot finished structural hollow sections of non-alloy and fine grain steels;
- EN 10219-1, Cold formed welded structural hollow sections of non-alloy and fine grain steels.

- The 2nd generation of Eurocode 7 gives strict rules for durability: especially for tension elements
- The susceptibility of a steel to hydrogen embrittlement, stress corrosion cracking is highlighted;
- The negative effect of the high strength surface treatment is noted.
- For steel with fy > 600 MPa the corrosion protection shall comply with EN 1537.

The design service life shall be achieved by using one or more of the following **corrosion protection measures**:

- use of additional steel thickness as corrosion allowance (acc. To EN 1993-5 – with a note that valid for black steel, does not consider potential localised corrosion nor potential pitting corrosion);
- grout, mortar or concrete protection;
- grouted duct;
- protective surface coating;
- appropriate steel material;
- use of stainless steel (see EN 1993-1-4).

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Design effect of actions

$$E_d \leq R_d$$

Design resistance

Partial factors may be applied

to actions (Verification Cases 1 to 3)

$$E_d = E\{\underbrace{\Sigma(\boxed{\gamma_F}\psi F_k); a_d; X_{Rd}}_{\gamma_F=\gamma_{Sd}\times\gamma_f}\}$$

or to effects of action (Verification Case 4):

$$E_d = \underbrace{\boxed{\gamma_E}E\{\Sigma(\psi F_k); a_d; X_{Rd}\}}_{\gamma_E=\gamma_{Sd}\times\gamma_f}$$

to material properties (the material factor approach, MFA)

$$R_d = R\underbrace{\left\{\frac{\eta X_k}{\left(\boxed{\gamma_M}\right)}; a_d; \Sigma F_{Ed}\right\}}_{\gamma_M=\gamma_{Rd}\times\gamma_m}$$

for laterally loaded single piles and transverse/combined resistance of group and piled rafts

to resistance (the resistance factor approach, RFA)

$$R_d = \underbrace{\frac{R\{\eta X_k; a_d; \Sigma F_{Ed}\}}{\boxed{\gamma_R}}}_{\gamma_R=\gamma_M=\gamma_{Rd}\times\gamma_m}$$

for axially loaded single piles and vertical resistance of group and piled rafts

- Effect of ground displacement (downdrag, heave, transv.)
- **Axially loaded single piles** (next slides)
- Transeversally loaded single piles
- Pile groups

$$R_{\text{group}} = min\left\{\sum_{i}^{n} R_{\text{i}}\, ; R_{\text{block}}\right\} \qquad R_{\text{d,group}} = \frac{R_{\text{rep,group}}}{\gamma_{\text{R,group}}\gamma_{\text{Rd,group}}}$$

- Piled rafts

$$R_{\text{piled-raft}} = \left(\sum_{i}^{n} R_{\text{c,i}} + R_{\text{raft}}\right) \qquad R_{d,piled-raft} = R_{d,group} + \frac{R_{\text{rep,raft}}}{\gamma_{\text{R,raft}}}$$

- Buckling
- Structural failure
- Serviceability Limit states

AXIALLY LOADED SINGLE PILES ULS DESIGN

$$R_c = R_s + R_b$$
$$R_b = A_b q_b$$
$$R_s = R_{st} = \sum A_{s,i} q_{s,i}$$

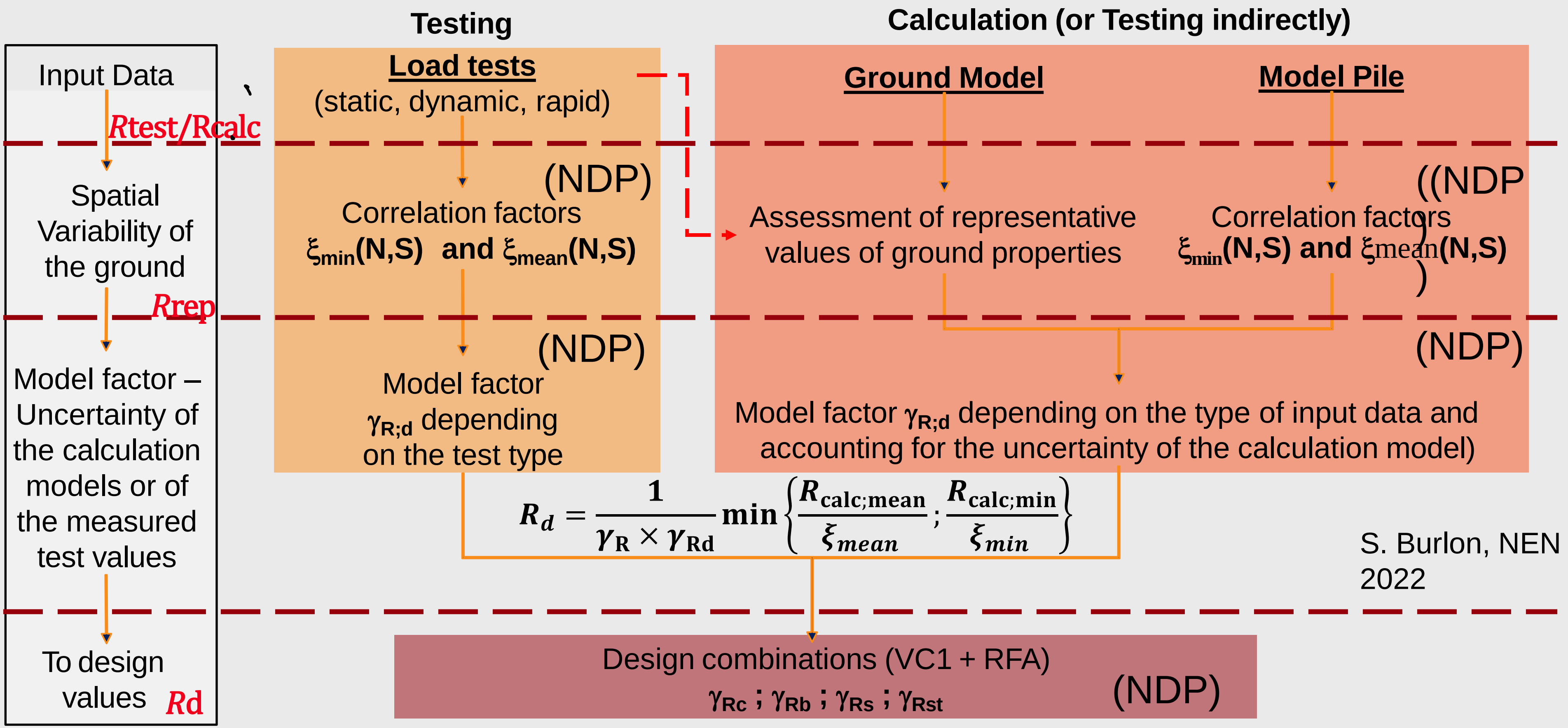
$$R_{c,d} = \frac{R_{c,rep}}{\gamma_{Rc} \cdot \gamma_{Rd}} \quad or \quad \left(\frac{R_{b,rep}}{\gamma_{Rb} \cdot \gamma_{Rd}} + \frac{R_{s,rep}}{\gamma_{Rs} \cdot \gamma_{Rd}} \right)$$

$$R_{t,d} = \frac{R_{t,rep}}{\gamma_{Rst} \cdot \gamma_{Rd}}$$

$R_{c,rep}$, $R_{b,rep}$, $R_{s,rep}$, $R_{t,rep}$ can be determined

By caluclation	**from ground parameters - ‘ground model’** (qs and qb based on C_u, c and φ , p_l*, q_c, N_{SPT}, etc. or empirical tables)	$R_{rep} = R_{cal}$
	from N field test profiles - ‘model pile’ (N CPTs, N PMTs, N SPTs, etc. or empirical tables)	$R_{rep} = \min\left\{\frac{R_{\text{calc;mean}}}{\xi_{mean}} ; \frac{R_{\text{calc;min}}}{\xi_{min}}\right\}$
By testing	**from tests** ◦ static pile load tests ◦ dynamic impact or rapid load tests (ULS in compression only)	$R_{rep} = \min\left\{\frac{R_{\text{test;mean}}}{\xi_{mean}} ; \frac{R_{\text{test;min}}}{\xi_{min}}\right\}$
Prescriptive rules	According to the given rules	

CONCEPT FOR MODEL AND CORRELATIONS FACTORS ADJUSTED



CONCEPT FOR MODEL AND CORRELATIONS FACTORS ADJUSTED

$$R_d = \frac{1}{\gamma_R \times \gamma_{Rd}} \min\left\{\frac{R_{calc;mean}}{\xi_{mean}}; \frac{R_{calc;min}}{\xi_{min}}\right\}$$

$$R_d = \frac{1}{\gamma_R \times \gamma_{Rd}} \min\left\{\frac{R_{test;mean}}{\xi_{mean}}; \frac{R_{test;min}}{\xi_{min}}\right\}$$

Static load tests

Correlation Factor	Number of tests							
	1	2	3	4	5	7	10	≥20
ξmean	1.4	1.35	1.33	1.31	1.29	1.27	1.25	1.19
ξmin	1.4	1.27	1.23	1.20	1.15	1.12	1.08	1.06

Rapid load load or dynamic impact tests

Correlation Factor[a]	Correlation Factor	Number of tests							
		1	2	3	4	5	7	10	≥ 20
Rapid Load Test	ξ_{mean}	1,4	1,36	1,32	1,29	1,28	1,25	1,23	1,19
	ξ_{min}	1,4	1,28	1,23	1,19	1,15	1,13	1,1	1,06
Dynamic Impact Test	ξ_{mean}	1,4	1,36	1,32	1,29	1,28	1,25	1,23	1,19
	ξ_{min}	1,4	1,28	1,23	1,19	1,15	1,13	1,1	1,06

Model pile method

Correlation Factor[a,b]	Coefficient of variation (CoV)	Number of tests or profiles							
		1	2	3	4	5	7	10	≥ 20
ξ_{mean}	≤ 12 %	1,4	1,35	1,33	1,31	1,29	1,27	1,25	1,19
ξ_{min}	n/a	1,4	1,27	1,23	1,20	1,15	1,12	1,08	1,06

CONCEPT FOR MODEL AND CORRELATIONS FACTORS ADJUSTED

$$R_d = \frac{1}{\gamma_R \times \gamma_{Rd}} \min\left\{\frac{R_{calc;mean}}{\xi_{mean}}; \frac{R_{calc;min}}{\xi_{min}}\right\}$$

$$R_d = \frac{1}{\gamma_R \times \gamma_{Rd}} \min\left\{\frac{R_{test;mean}}{\xi_{mean}}; \frac{R_{test;min}}{\xi_{min}}\right\}$$

Calculation model uncertainty

Verification by		Model factor γ_{Rd}	
Ground Model Method	Confirmed by suitability tests	1.2	
	Extensive comparable experience without site-specific Control Tests	1.3	
	Serviceability Control Tests	1.4	
	No pile load tests and limited comparable experience	1.6	
		Compressive resistance	**Tensile resistance**
Model Pile Method	Pressuremeter test	1.15	1,4
	Cone penetration test,	1.1	1.1
	Profiles of ground properties based on other field or laboratory tests	1.2	1.2

Testing method uncertainty

Verification by		Model factor γRd		
		Fine soils	**Coarse soils**	**Rock mass**
Static load tests		1.0	1.0	1.0
Rapid load tests (multiple load cycles)		1.4	1.2	1.2
Rapid load tests (single load cycle)		1.4	1.2	1.2
Dynamic impact tests (signal matching)	Shaft resist.	1.5	1.2	1.2
	End resist.	1.4	1.25	1.25
Dynamic impact tests (multiple blow)	Shaft resist.	1.5	1.2	1.2
	End resist.	1.4	1.2	1.2
Dynamic impact tests (closed form solutions)	Shaft resist.	Not permitted	Not permitted	Not permitted
	End resist.	Not permitted	1.3	1.3
Wave equation analysis		Not permitted	1.6	1.5
Pile driving formulae		Not permitted	1.8	1.7

CONCEPT FOR MODEL AND CORRELATIONS FACTORS ADJUSTED

$$R_d = \frac{1}{\gamma_R \times \gamma_{Rd}} \min \left\{ \frac{R_{calc;mean}}{\xi_{mean}} ; \frac{R_{calc;min}}{\xi_{min}} \right\}$$

Different sets of partial factor γ_R

Additionally pile design should be validated using **site specific testing**

(strong connection with ISO 22477)

Verification of	Partial factor on	Symbol	Material factor approach (MFA) – both combinations		Resistance factor approach (RFA)			
			(a)	(b)	Pile class	Ground Model Method	Model Pile Method	Design by testing
Axial tensile resistance	Actions; Effect of actions	γF ; γE	Not Used		All	VC1		
	Ground properties	γM				Not factored		
	Shaft resistance in tension	γRst			Full displ.	1,2	1.15	1.25
					Partial displ.	1,2		1.25
					Replacement	1,3		1.25
					Unclassified	1,5	1.4	1.25
Transverse resistance	Actions and effects of-actions	γF; γE	VC4 or VC1	VC3	All	VC1	not used	not used
	Ground properties	γM	M1	M2		Not factored		
	Transverse resistance	γRtr	Not factored			1,3		

C.7 AXIAL MICROPILE RESISTANCE FROM PMT PROFILES

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- The representative value of unit shaft friction $q_{s,rep}$

$$q_{s,rep} = \min\left(k_{s,PMT}(a_{PMT}p_{LM}^{*} + b_{PMT})(1 - e^{-c_{PMT}p_{l}}); q_{s,max}\right)$$

- The representative value of unit base resistance $q_{b,rep}$ (but for micropiles usually not taken into account)

$$q_{b,rep} = k_{b,PMT}\frac{1}{z_1 + 3z_2}\int_{-z_1}^{3z_2} p_{LM}^{*}(z)dz$$

- ks,PMT and kb,PMT depend on pile type and ground type
- aPMT, bPMT, cPMT depend on ground type
- P*LM is the PMT net limit pressure (MPa) at a depth z;

Parameter	Fine soil	Coarse soil	Chalk	Marl/ marly limestone	Weathered rock masses
$ks_{,PMT}$	2.70	2.90	2.40	2.40	2.40
$kb_{,PMT}$	1.15	1.1	1.45	1.45	1.45
$q_{s,max}$ (kPa)	200	380	320	320	320

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Current EN 1997-1	EN 1997-3:2024x
from static load tests results	
(DA1.C2) Fcd=10.2MN Rc;d = 1.15MN, → **9 (8.9) piles** are needed	(RFA) Fcd=12.9MN Rc;d = 1.57MN, → **9 (8.2) piles** are needed
from ground test profiles (CPT)	
(DA1.C2) Fcd=10.2MN Rc;d = 0.96MN, → **11 (10.6) piles** are needed	(RFA) Fcd=12.9MN Rc;d = 1.16MN, → **12 (11.1) piles** are needed

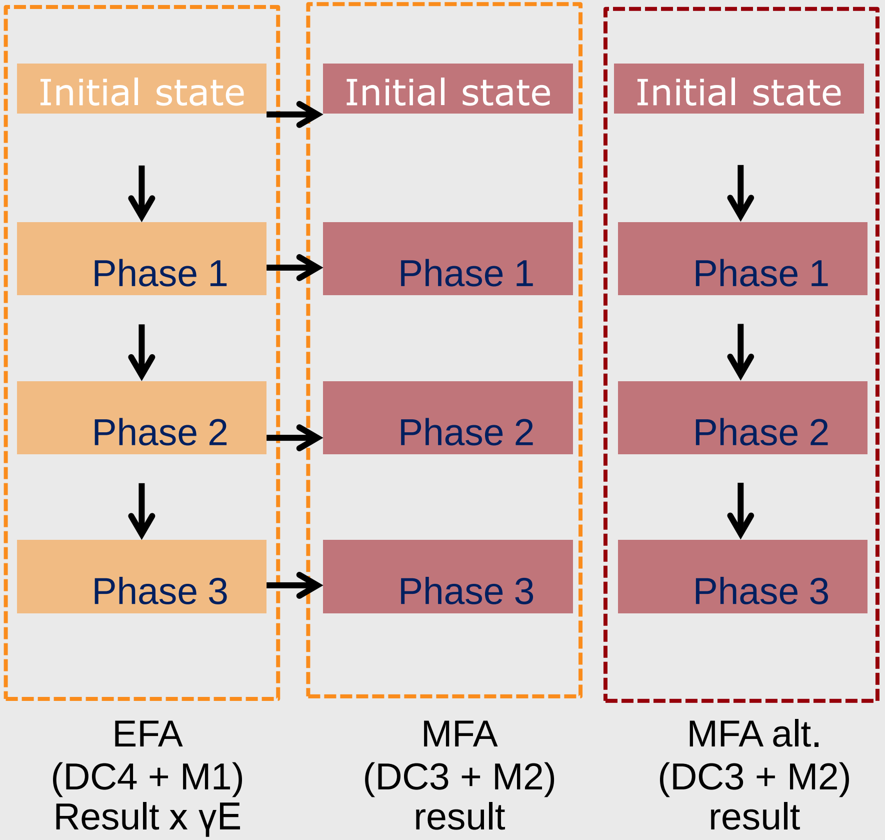
- One Design Case to be checked instead of having to evaluate multiple Design Approaches
- Additional factors, a new „design path", but the outcome is comparable
- The new correlation factors could provide slightly more conservative characteristic values > 5 piles
- Individual datasets shall comply with CoV ≤ 12%; if not datasets should be split into datasets with less variation

Based on: Patrick Ijnsen, NEN Webinar 19.10.2022

2nd generation of EC7 provides rules for numerical models

- **EFA** using characteristic values and applying partial factor on effects of action
- **MFA recommended** with modelling excursion to invoke design values (factored parameters) at critical stage, involves a procedure such as strength reduction
- **MFA alternative** using design values (factored parameters from start)

Dual check for all problem types



SUMMARY

- Pile design acc. to prEN 1997:202x is an evolution, no revolution
- Harmonisation of all design aspects, incl. materials, execution, testing
- New topics: pile groups, piled rafts, numerical calculations
- Micropiles are explicilty in the scope of prEN 1997:202x
- prEN 1997:202x specifies basic requirements for analysis and verification of piled foundations, not specific calculation models
- EC7 shall be combined with national experience and NDP
- Where not restricted by National Annex, EC7 remains flexible for project-specific choices - **useful for projects outside of Europe.**
- **A modern framework for state-of-the-art pile design**

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