Behavior of monopiles in sand under cyclic lateral loading – Results of 1g model tests

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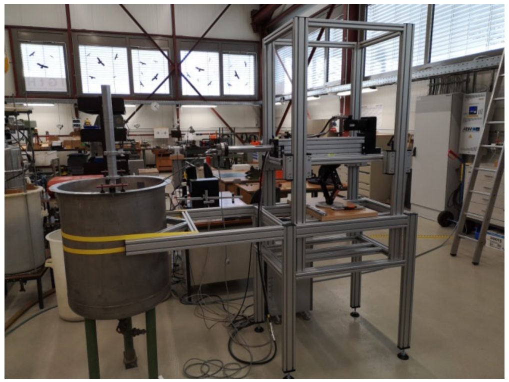
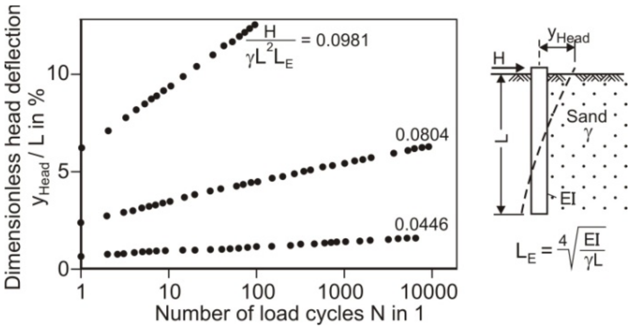
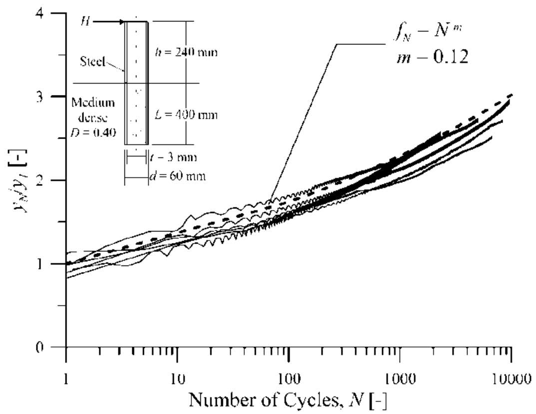


Behavior of piles under cyclic horizontal loading

Results of Hettler (1981)



Results of Peralta & Achmus (2010)



Accumulation of displacements:

$$y_N = y_1 \, f_N(N)$$

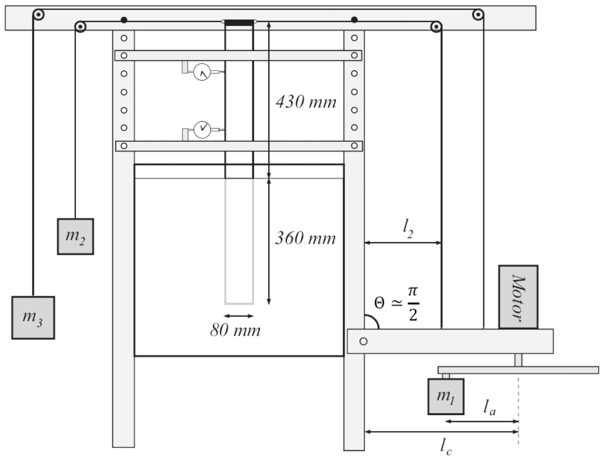
$$f_N = N^m$$

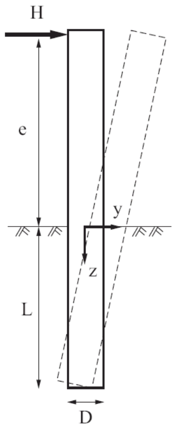
$$f_N = 1 + t \times \ln N$$

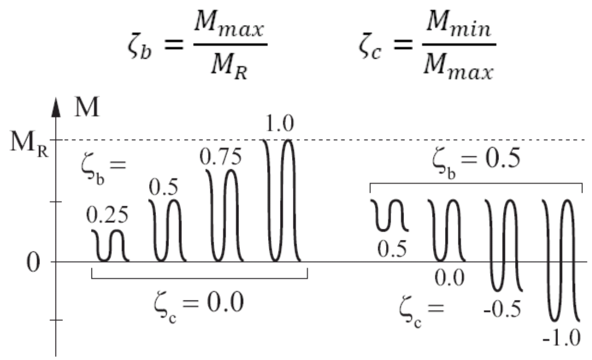
m / t are dependent on soil conditions, pile geometry (stiffness) and loading conditions

→ General empirical approach desired

Accumulation model of LeBlanc (2010)

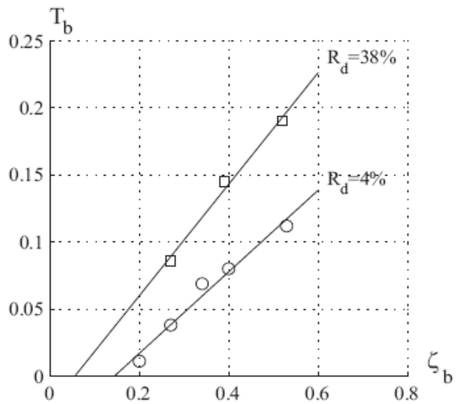


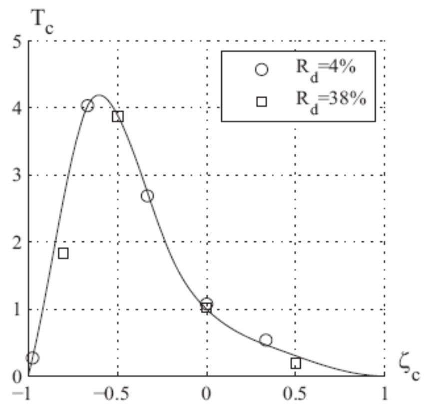




$$\Delta\theta_N = \theta_{stat}\, T_b\, T_c\, N^{\alpha}$$

Accumulation parameter $\alpha \approx 0.31$
Type of loading is considered by a function T_c
T_b depends on ζ_b and rel. density
T_c is system-independent





Model tests reported in literature - Overview

Table 1: Overview of models for cyclic displacement or rotation accumulation resulting from lateral cyclic loading

Reference	Model	Test type	Load cycles	Pile-soil-system	Model parameters
Peralta (2010)	$y_N = y_1 \cdot N^{\alpha_P}$ $y_N = y_1 \cdot (1 + t_p \cdot \ln N)$	1g 13 static 21 cyclic	10.000	D = 6 cm L/D = 3.33-8.33 h = 240 mm = const. D_r = 0.45 & 0.65	Rigid piles: $\alpha_p = 0.12$ Flexible piles: $t_p = 0.21$
LeBlanc et al. (2010)	$\theta_N = \theta_1 \cdot \left(1 + T_{b,LB} \cdot T_{c,LB} \cdot N^{\alpha_{\theta,LB}}\right)$	1g 6 static 15 cyclic	7.400–65.370	D = 8 cm L/D = 4.5 = const. h/D = 5.38 = const. D_r = 0.04 & 0.38	$\alpha_{LB} = 0.31$ $T_{b,LB}(\zeta_b, D_r = 0.38) = 0.414\,\zeta_b - 0.023$ * $T_{b,LB}(\zeta_b, D_r = 0.04) = 0.303\,\zeta_b - 0.044$ $T_{c,LB}(\zeta_c) = a\,\zeta_c^{\,4} + b\,\zeta_c^{\,3} + c\,\zeta_c^{\,2} + d\,\zeta_c + e$ **
Klinkvort & Hededal (2013)	$y_N = y_1 \cdot N^{T_{b,K\&H} \cdot T_{c,K\&H}}$	Centrifuge 5 static 12 cyclic	250-10.000	D = 2.8 cm & 4.0 cm L/D = 6 = const. h/D = 15 = const. D_r = 0.79 - 0.96	$T_{b,K\&H}(\zeta_b) = 0.61\,\zeta_b - 0.013$ $T_{c,K\&H}(\zeta_c) = (\zeta_c + 0.63)\,(\zeta_c - 1)\,(\zeta_c - 1.64)$
Li et al. (2015)	$y_N = y_1 \cdot N^{\alpha_{y,L}}$ $y_N = y_1 \cdot \left(1 + t_{y,L} \cdot \ln N\right)$ $\theta_N = \theta_1 \cdot N^{\alpha_{\theta,L}}$ $\theta_N = \theta_1 \cdot \left(1 + t_{\theta,L} \cdot \ln N\right)$	Field tests 2 static 2 cyclic	3.173-5.017	D = 34 cm L/D = 6.47 = const. h/D = 1.18 = const. $D_r \approx 1.0$	$\alpha_{y,L} = 0.085$ $t_{y,L} = 0.125$ $\alpha_{\theta,L} = 0.060$ $t_{\theta,L} = 0.080$
Truong et al. (2019)	$y_N = y_1 \cdot N^{\alpha_{y,T}}$	Centrifuge 3 static 14 cyclic	50-1.500	D = 1.1 cm & 4 cm L/D = 11.4 & 6 h/D = 2 & 3 D_r = 0.57 - 0.95	$\alpha_{y,T} = (0.3 - 0.22D_r)\left[1.2\left(1 - \zeta_c^{\,2}\right)(1 - 0.3\zeta_c)\right]$
Li et al. (2020)	$y_N = y_1 \cdot N^{T_{b,L} \cdot T_{c,L}}$	Centrifuge 2 static 18 cyclic	42-153	D = 1.8 cm L/D = 5 = const. h/D = 8 D_r = 0.5 & D_r = 0.8	$T_{b,L}(\zeta_b) = 0.07335$ $T_{c,L}(\zeta_c, D_r = 0.8) = -1.707(\zeta_c + 0.31)^2 + 0.949$ $T_{c,L}(\zeta_c, D_r = 0.5) = -1.14(\zeta_c + 0.323)^2 + 1.263$

*T_b and T_c functions fitted based on the graphical representations given in LeBlanc et al. (2010)

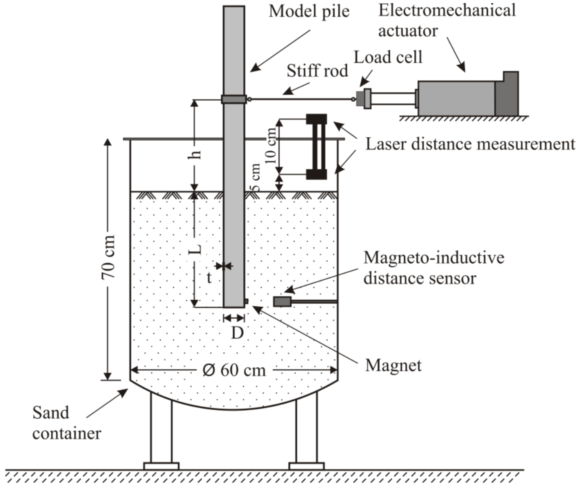
** Polynomial factors for the determination of: $T_c\,(\zeta_c \leq -0.3)$: a = 113.33; b = 288.56; c = 238.88; d = 73.48; e = 9.94

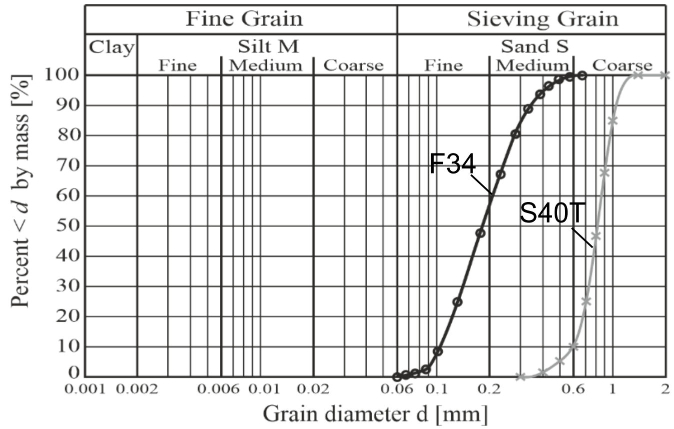
$T_c\,(\zeta_c > -0.3)$: a = 3.06; b = -6.50; c = 5.22; d = -2.76; e = 0.99

Taken from Frick & Achmus (2022)

- 1g and ng model tests
- Different accumulation models with different results
- Effects of different parameters not clear

1g model tests at IGtH/University of Hannover





Test equipment and features:

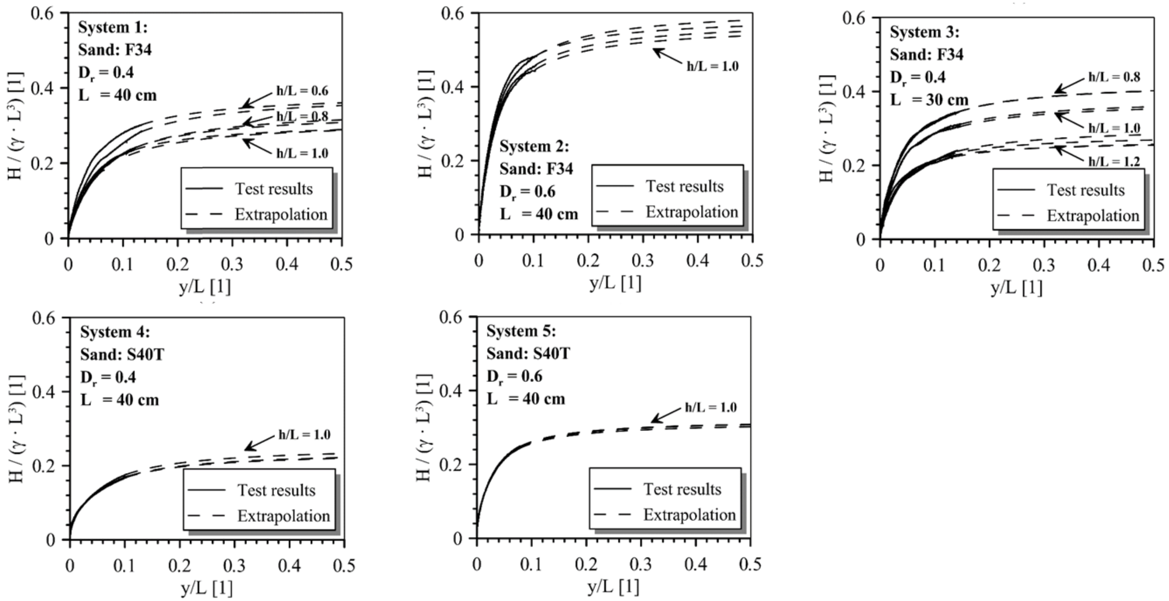
- Aluminium model pile D = 50 mm, t = 3.2 mm → almost rigid
- Two different silica sands: fine to medium sand (F34)
  coarse sand (S40T)
  → placed by air pluviation, D_r = 0.4 & 0.6
- Actuator for monotonic and cyclic loading, high precision load cell
- 2 laser distance transducers + magneto-inductive displacement transducer

Tests with monotonic loading

System	Sand type	L/D	Rel. Density D_r	Load eccentricity
1	F34	8	0.4	h/L = 0.6 / 0.8 / 1.0
2	F34	8	0.6	h/L = 1.0
3	F34	6	0.4	h/L = 0.8 / 1.0 / 1.2
4	S40T	8	0.4	h/L = 1.0
5	S40T	8	0.6	h/L = 1.0

- Variation of sand type, L/D, rel. density
  → 5 systems
- Variation of load eccentricity (systems 1 and 3)

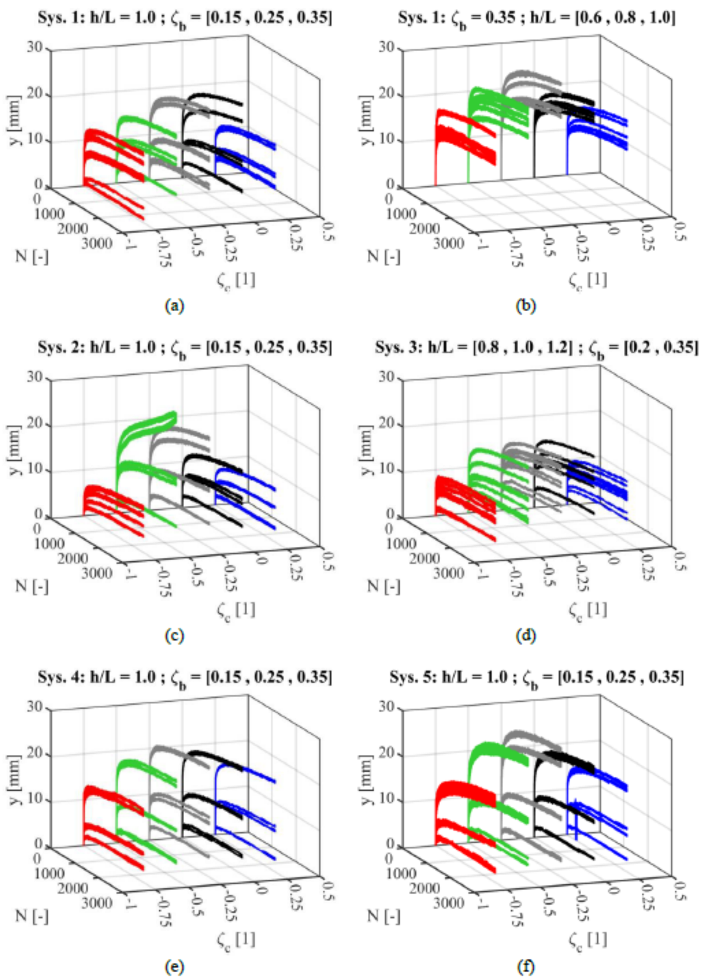
Load-displacement curves



- Good reproducibility confirmed by repeated tests
- Extrapolation of the measured curves acc. to Manoliu
  → H_{ult} taken as the asymptotic value determined by Manoliu extrapolation
  → $\zeta_b = H_{max}/H_{ult}$

Cyclic tests – Programme and results

Pile-soil system description						Load description			
System [-]	Test series	D [mm]	L/D [1]	Soil [-]	D_r [-]	h/L [1]	ζ_b [1]	ζ_c [1]	N [-]
1	1	50	8	F34	0.4	0.6	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
1	2	50	8	F34	0.4	0.8	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
1	3	50	8	F34	0.4	1.0	0.15	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
1	4	50	8	F34	0.4	1.0	0.25	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
1	5	50	8	F34	0.4	1.0	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
2	6	50	8	F34	0.6	1.0	0.15	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
2	7	50	8	F34	0.6	1.0	0.25	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
2	8	50	8	F34	0.6	1.0	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
3	9	50	6	F34	0.4	0.8	0.20	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
3	10	50	6	F34	0.4	0.8	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
3	11	50	6	F34	0.4	1.0	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
3	12	50	6	F34	0.4	1.2	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
4	13	50	8	S40T	0.4	1.0	0.15	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
4	14	50	8	S40T	0.4	1.0	0.25	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
4	15	50	8	S40T	0.4	1.0	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
5	16	50	8	S40T	0.6	1.0	0.15	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
5	17	50	8	S40T	0.6	1.0	0.25	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500
5	18	50	8	S40T	0.6	1.0	0.35	-0.75/-0.50/-0.25/0.00/0.25/1.00	2500



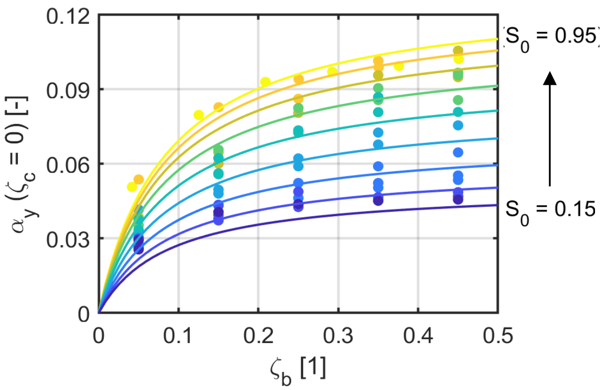
- 90 cyclic test (N = 2,500) and 18 monotonic tests
- Development of pile head displacement with cycle number for varying ζ_b- and ζ_c-values

Model approach

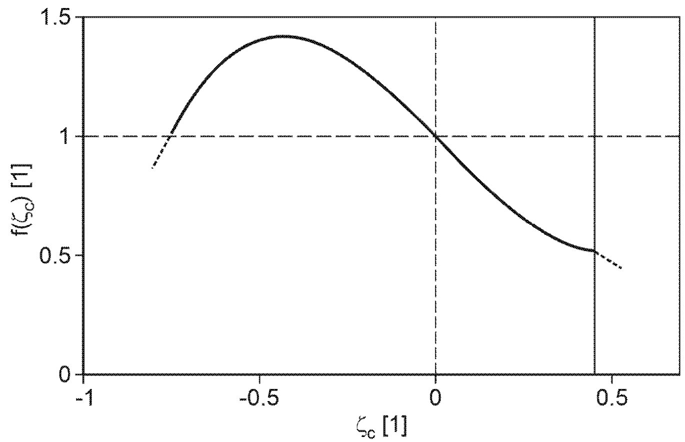
$$y_N = y_1 N^{\alpha_y}$$

$$\alpha_y = \alpha_y(\zeta_c = 0) \cdot f(\zeta_c)$$

$$f(\zeta_b, S_0)$$



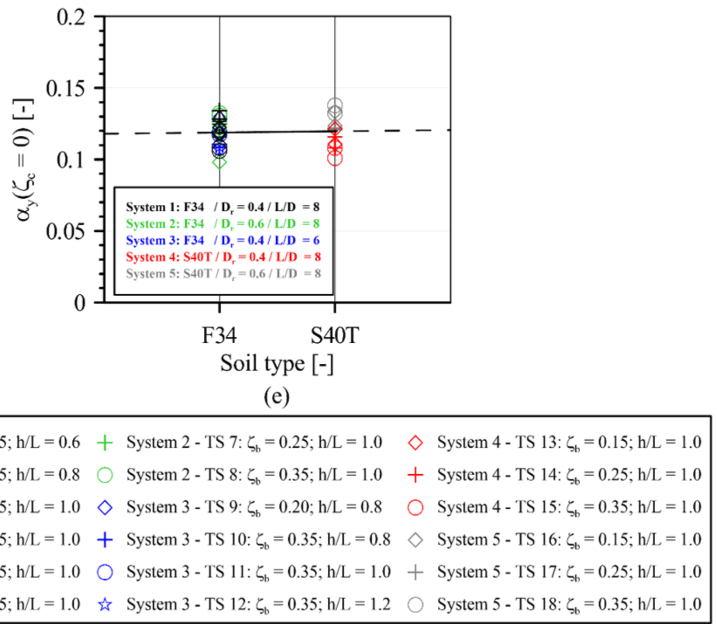
$$f(\zeta_c) = 1 - 1.4844 \cdot \zeta_c - 0.1568 \cdot \zeta_c^{\,2} + 2.4055 \cdot \zeta_c^{\,3}$$



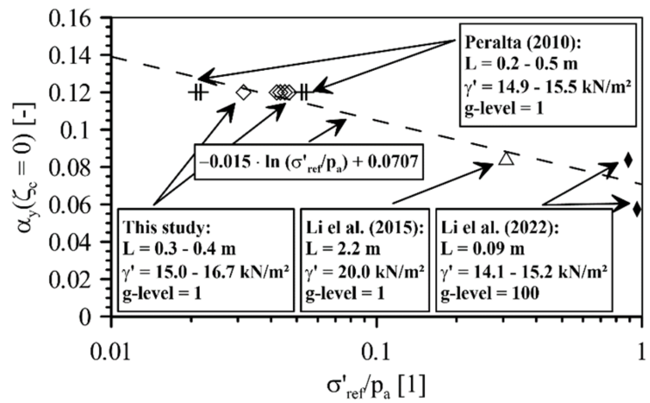
Results of the model tests with ζ_c = 0

$$y_N = y_1 \, N^{\alpha_y}$$

Model test results



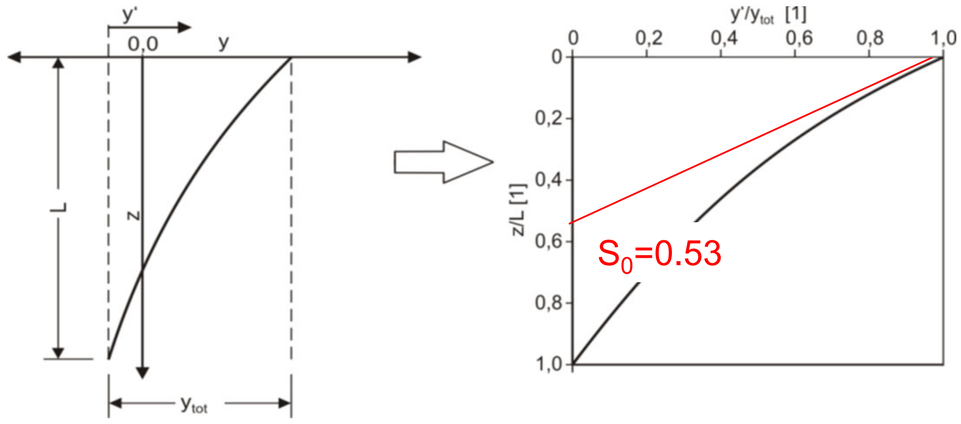
Comparison with other test results

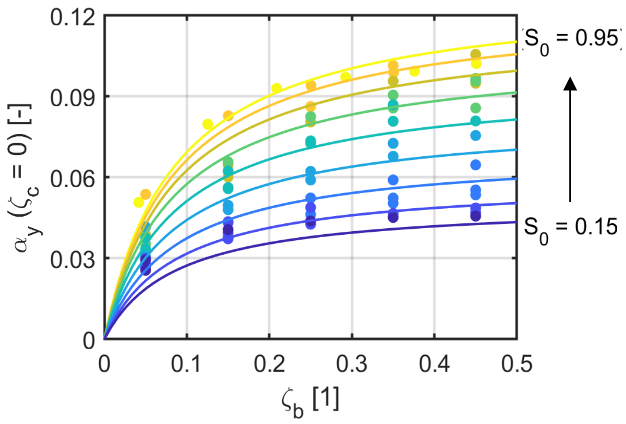


$$\alpha_y(\zeta_c = 0) = 0.0707 - 0.015 \ln \frac{\sigma'_{ref}}{p_a}$$

Extension by numerical simulations

- Stiffness Degradation Method with variation of pile-soil stiffness
- Pile-soil stiffness measure: S_0
  $0 < S_0 < 1$ ($S_0 = 1$: rigid)





Results:

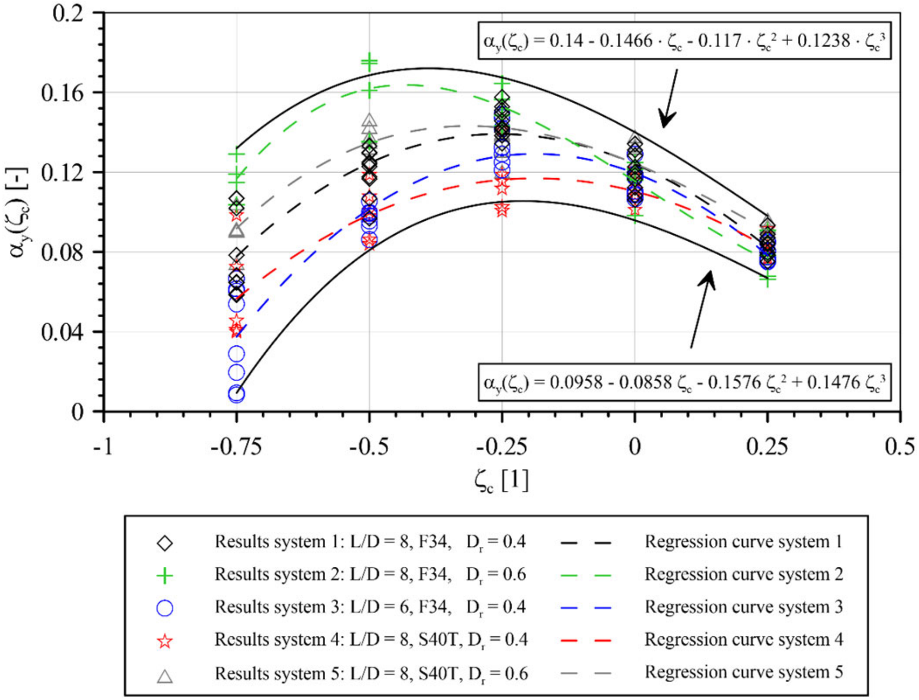
- Largest α_y-value for rigid pile and high load level
- For high load level, α_y becomes constant
  → Agreement with experimental tests
- Approach:

$$\alpha_y(\zeta_c = 0) = [-0.12 \cdot \arctan(-2.84 \cdot S_0 + 1.35) + 0.22] \cdot \left[\frac{4.5 \cdot \zeta_b}{1 + 11.54 \cdot \zeta_b}\right]$$

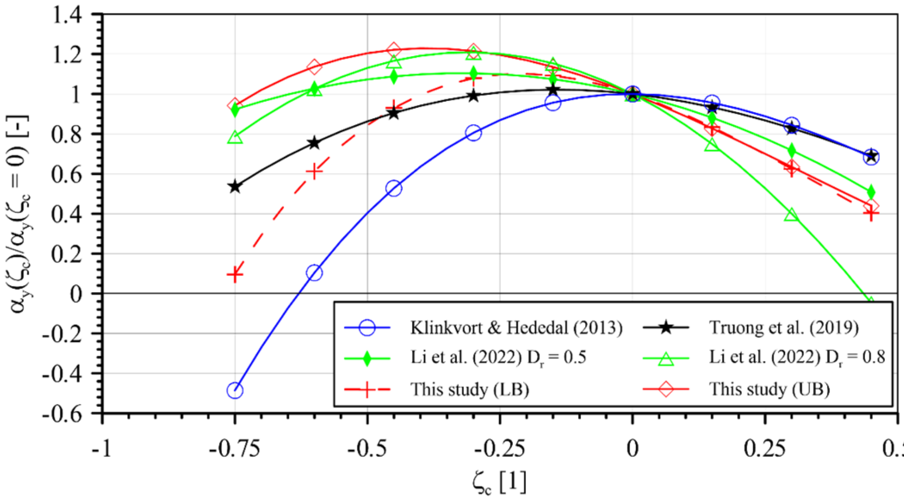
with $\zeta_b = \dfrac{H_{max}}{H(y = 0.05\ D)}$

Effect of load type (ζ_c)

Model test results



Comparison with other test results



- Greatest accumulation rate for asymmetric two-way loading (ζ_c = -0.25...-0.4)
- No clear trends (effect of D_r, L/D, soil type?)

→ Conservative approach: $f(\zeta_c) = 1 - 1.4844 \cdot \zeta_c - 0.1568 \cdot \zeta_c^{\,2} + 2.4055 \cdot \zeta_c^{\,3}$

Thanks for your attention !

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