Master‘s Thesis Defense

“Model validation of geogrid-back anchored working platform for construction of offshore wind turbines“

Suleiman Spingher

Lehrstuhl für Grundbau, Boden- und Felsmechanik
Fakultät für Bau- und Umweltingenieurwissenschaften
Ruhr-Universität Bochum

Gescher, 02.11.2018

Index

1. Motivation

Anchoring sheetpiles with geogrids:

- „New“ way of anchoring, poor practical experience
- Complex material behaviour of geogrids and complex interaction between geogrid and soil
  - Elastic-viscoplastic behavior of geogrids

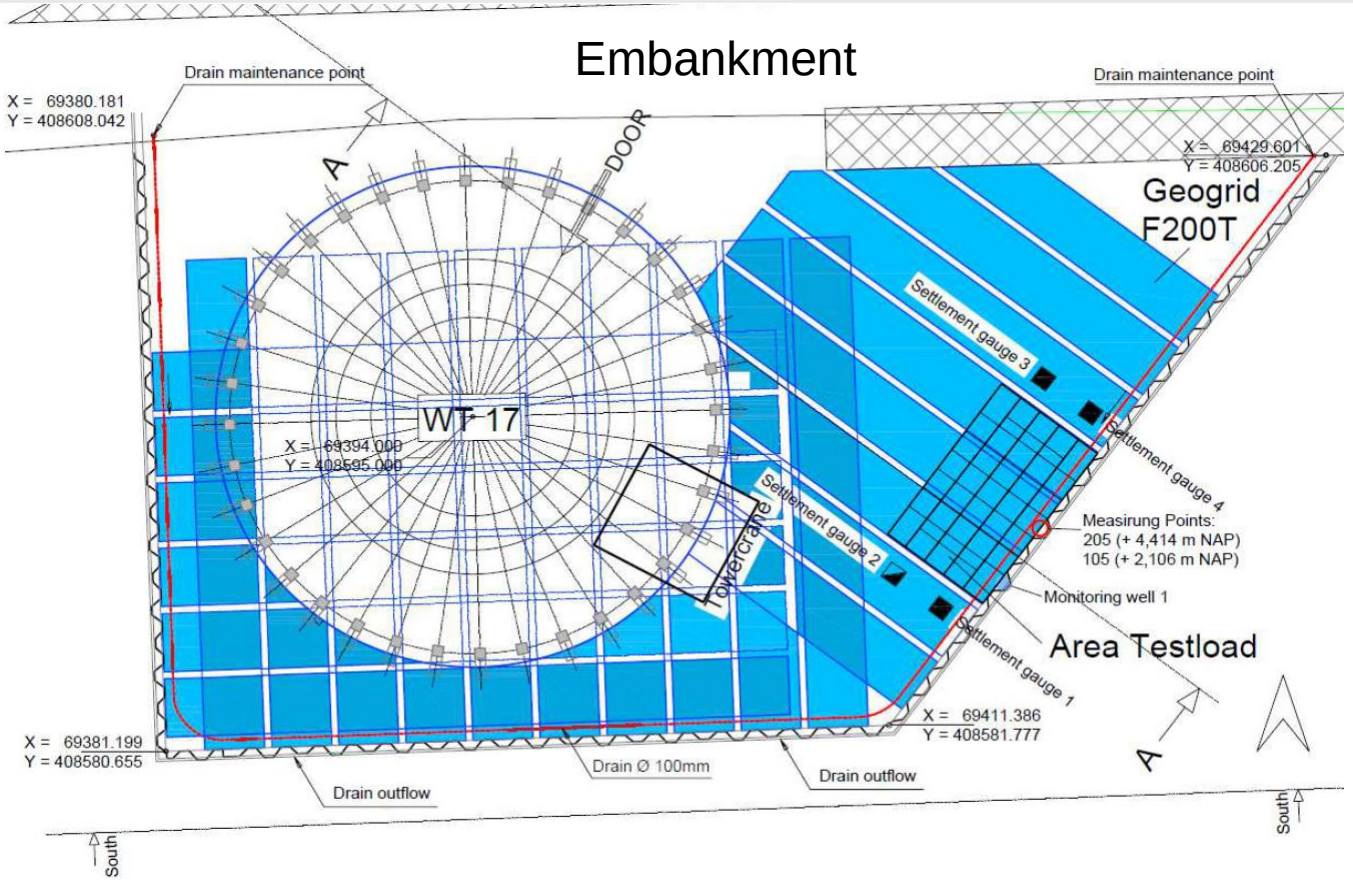
    → loss of tensile strength by time due to creep
- Structual behaviour not well known
- Prediction of structual behavior is uncertain
- Thesis:
  - Forecasting and verifying the structural behavior
  - Validation of measurement results by creating a numerical model in PLAXIS-2D
  - Parameter variation of the numerical model in order to determine the parameters of great influence

Geogrid anchoring of a sheetpile,Windpark Krammer WT17

2. Windpark Krammer

Design of wind turbines:

- Foundation next to the embankment within a sheetpile construction
- Sheetpiles back-anchored with geogrids
- Critical construction phase: heavy crane on a working platform for assembling the wind turbines within the sheetpile construction → anchored sheetpile construction has to bear very high loads



Top view of WT17 and location of testload (Ratio Survey 2018, modified)

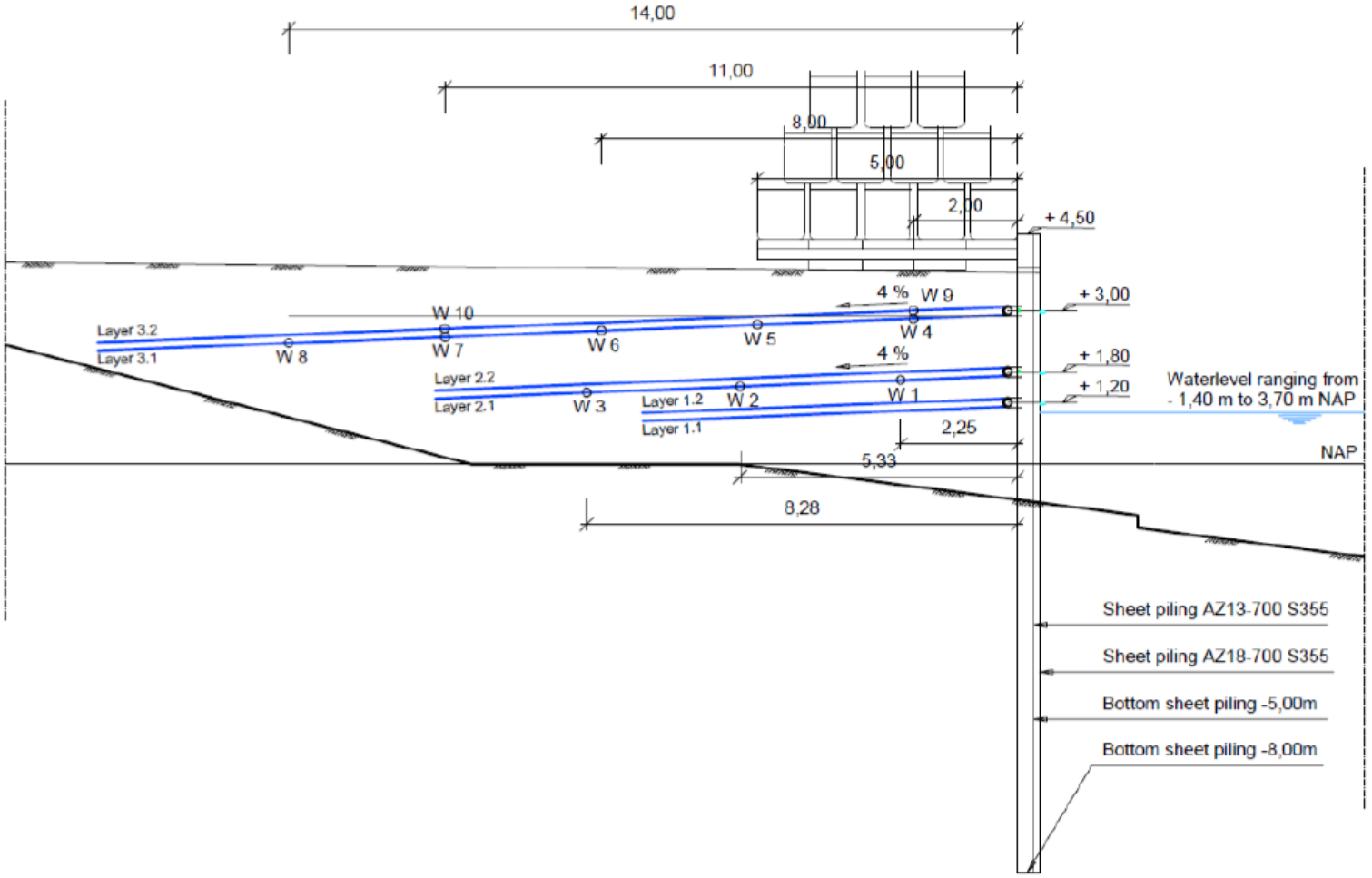
2. Windpark Krammer

Design of wind turbines:

- Foundation next to the embankment within a sheetpile construction
- Sheetpiles back-anchored with geogrids
- Critical construction phase: heavy crane on a working platform for assembling the wind turbines within the sheetpile construction → anchored sheetpile construction has to bear very high loads

Looking in south direction from the embankment

2. Windpark Krammer



Cross section of WT17 and location of geogrids and strain gauges (GeoTec Solutions, modified)

2. Windpark Krammer

Anchoring:

- 3 layers of geogrids (+1,20 m NAP, +1,80 m NAP, +3,00 m NAP) with 4% inclination
- Each layer curled up around a deflector roll (15 cm diameter) and filled with ~ 15 cm sand inbetween

Anchored geogrids

2. Windpark Krammer

Anchoring:

- Installation of the strain gauges and covering the geogrids with sand except the front part (~ 2,5 m)
- Applying prestress by pushing the deflection roll a few centimeters towards the sheetpiles
- Covering the front part with sand and compressing the whole sand layer

Applying prestress

2. Windpark Krammer

Monitoring:

- Before using the heavy crane: simulation of the heavy crane by a testload (wooden platform with three layers of sandbags)
- Monitoring of sheetpile deformations, geogrid strains and testload settling:
  - Before applying testload
  - After applying testload
  - After removing testload

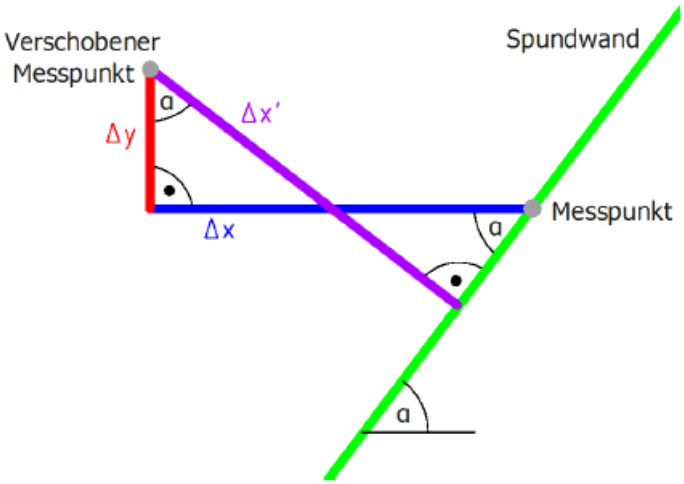
Testload and settling points

2. Windpark Krammer

Monitoring: sheetpile displacements

- Measuring displacements of fixed points on the sheetpiles via GPS
- 2 fixed points of importance: no. 105 (+ 4,414 m NAP and no. 205 (+ 2,106 m NAP) → highest bearing expected
- GPS measuring accuracy ± 2 – 3 mm
- Displacements in 3 directions
- Transformation of 3D displacements into 2D for better comparison with numerical results
- Transformation for x- and y-displacements only, z-displacement remains the same
- Horizontal displacements of particular interest, vertical displacements negeltable

$$x' = \frac{\Delta y}{\cos \alpha} + (\Delta x - \Delta y \tan \alpha) \sin \alpha$$



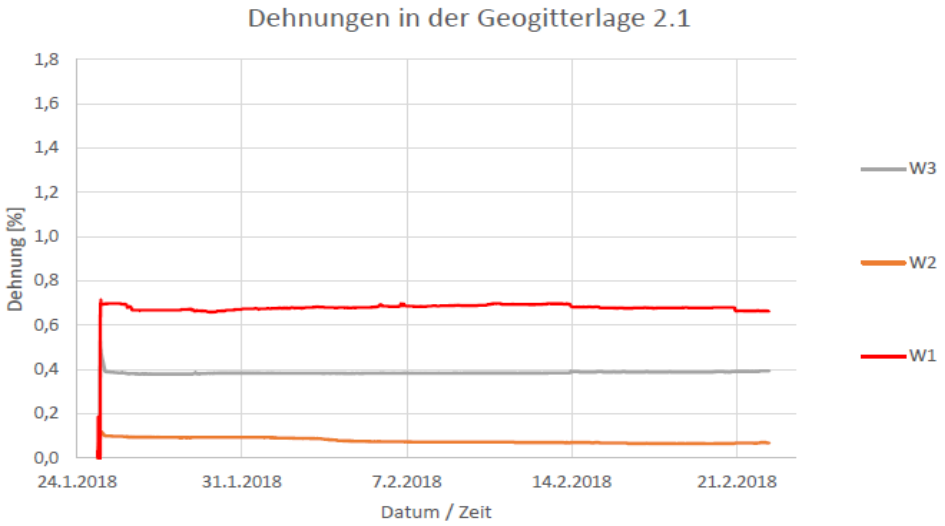
Transformation of displacements

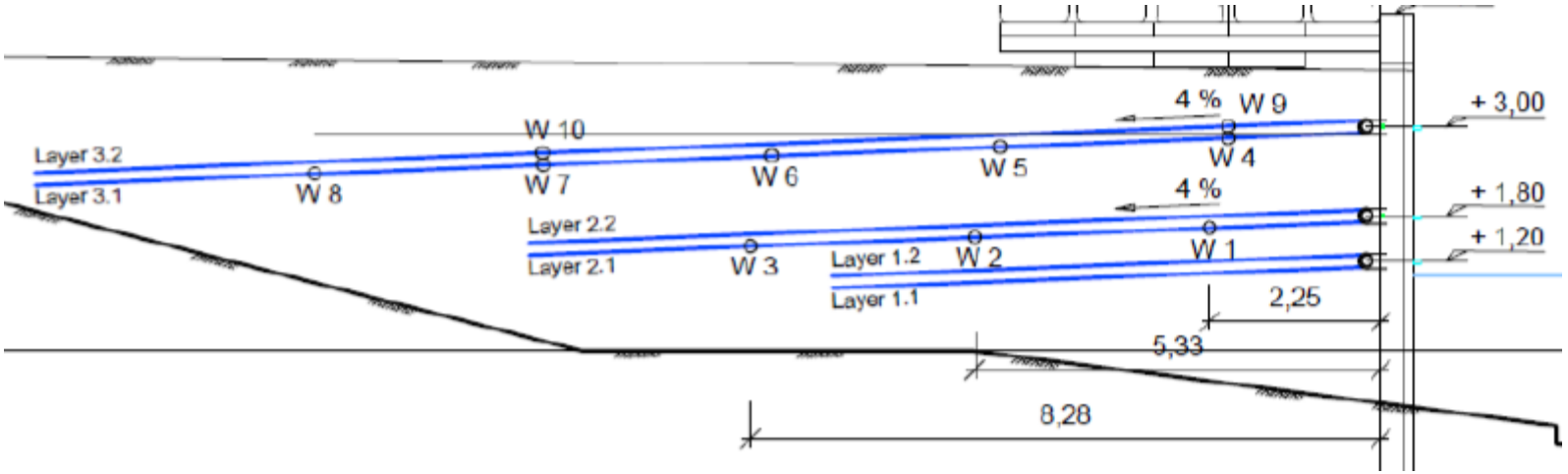
Datum	Transformierte Verschiebungen [mm]			
	Punkt 205 (4,414 m NAP)		Punkt 105 (2,106 m NAP)	
	Δx' [mm]	Δz [mm]	Δx' [mm]	Δz [mm]
25.01.2018	-	-	-	-
29.01.2018 - 1	-3,6	0	-0,6	0
29.01.2018 - 2	-4,4	-3	-0,8	0
02.02.2018	-1,8	-2	0,8	-3
06.02.2018	1,8	0	4,2	0
13.02.2018	-1,8	-2	1,8	-2
15.02.2018	-2,6	0	-0,6	0

4. Windpark Krammer

Monitoring: geogrid strains

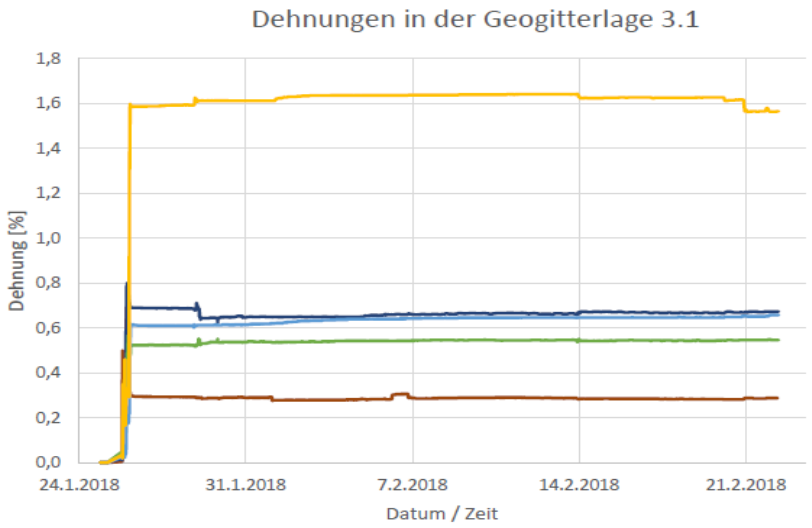
- Installation of strain gauges in layer 2.1, 3.1 and 3.2 by HUESKER Synthetic
- 3 time periods of importance:
  - Prestressing (25.012018 & 26.01.2018)
  - applying testload (29.01.2018)
  - removing testload (14.02.2018)

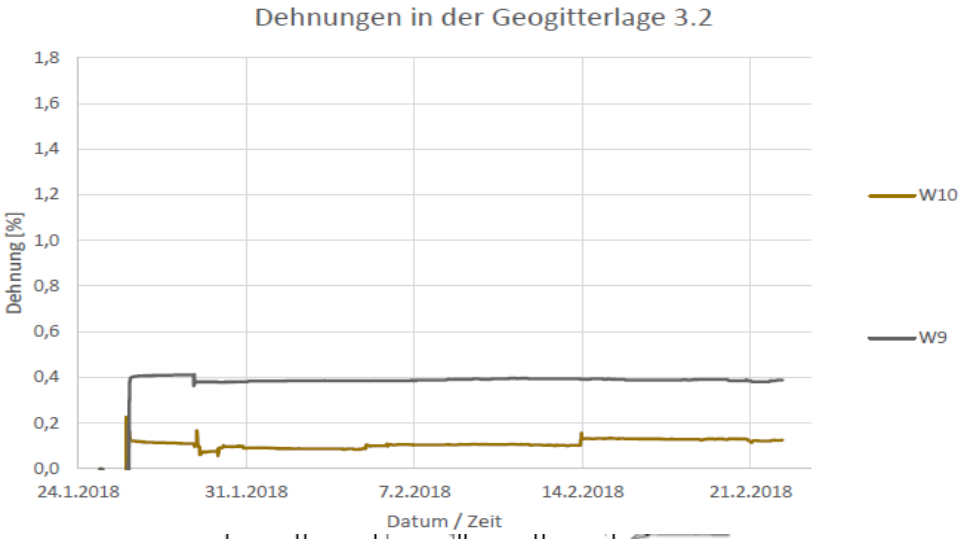


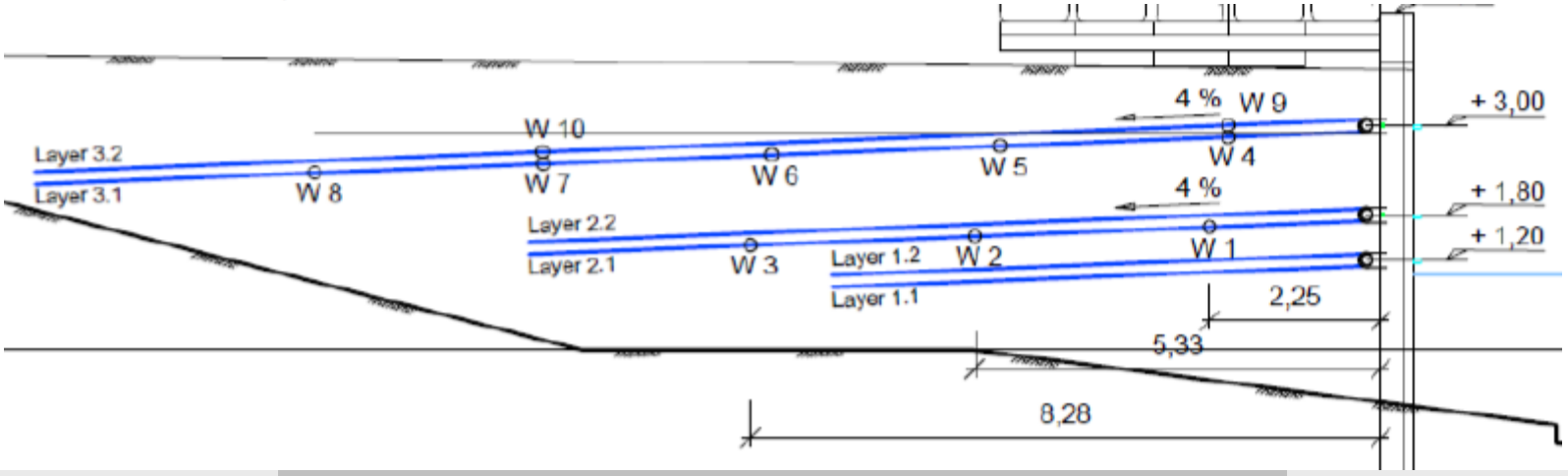


4. Windpark Krammer

Monitoring: geogrid strains



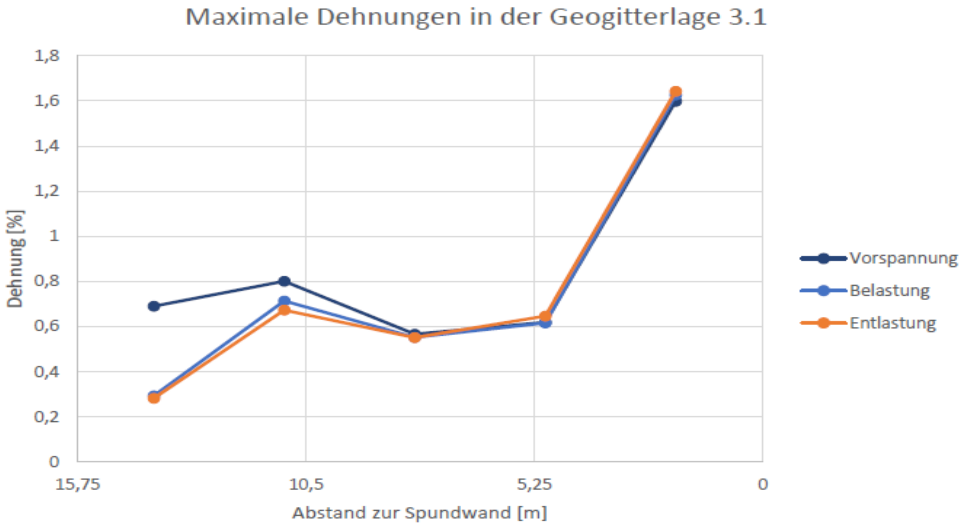


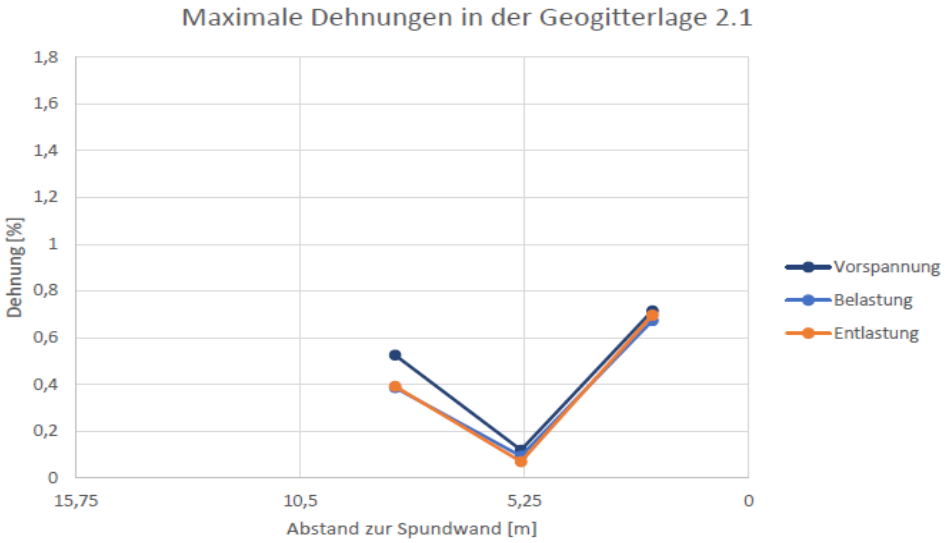


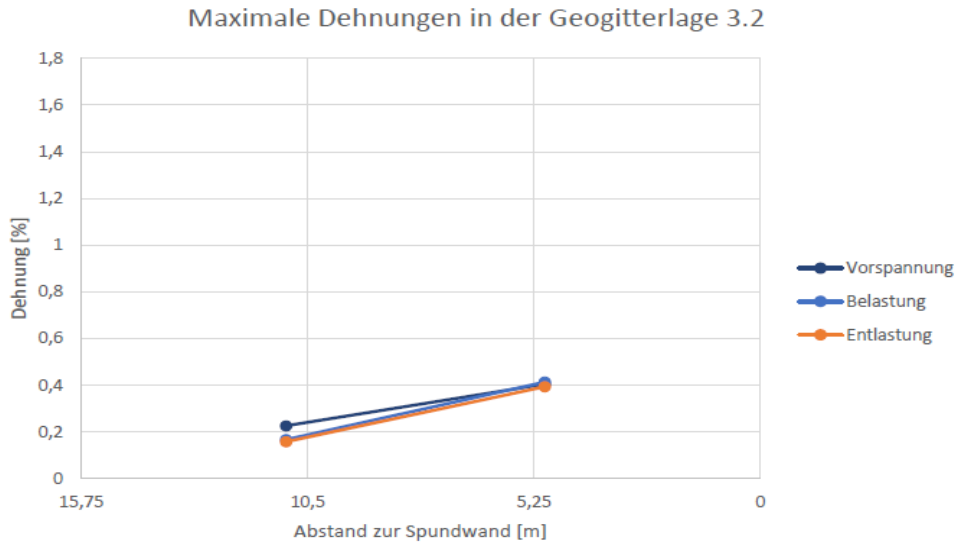
2. Windpark Krammer

Monitoring: geogrid strains

- Maximum strains vs. distance to sheetpile for each time period
- Maximum strains occur after prestressing
- After prestressing no significant change in strain magnitude



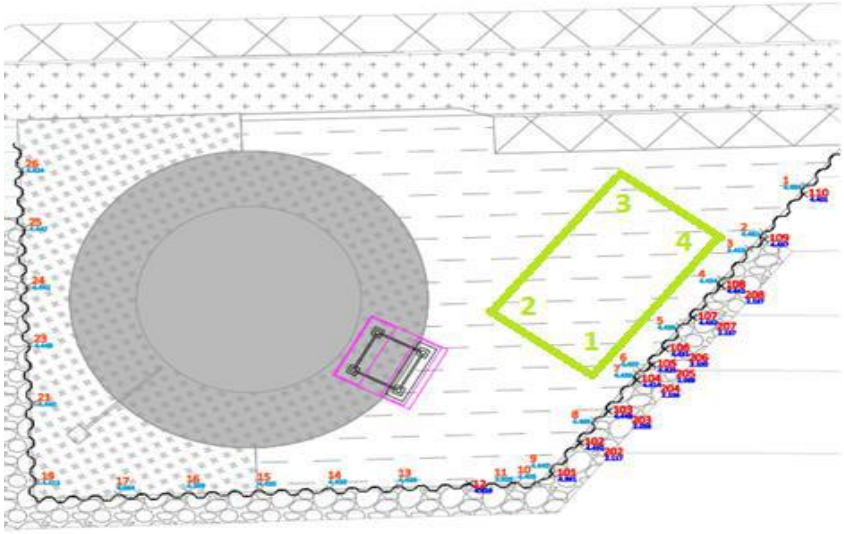




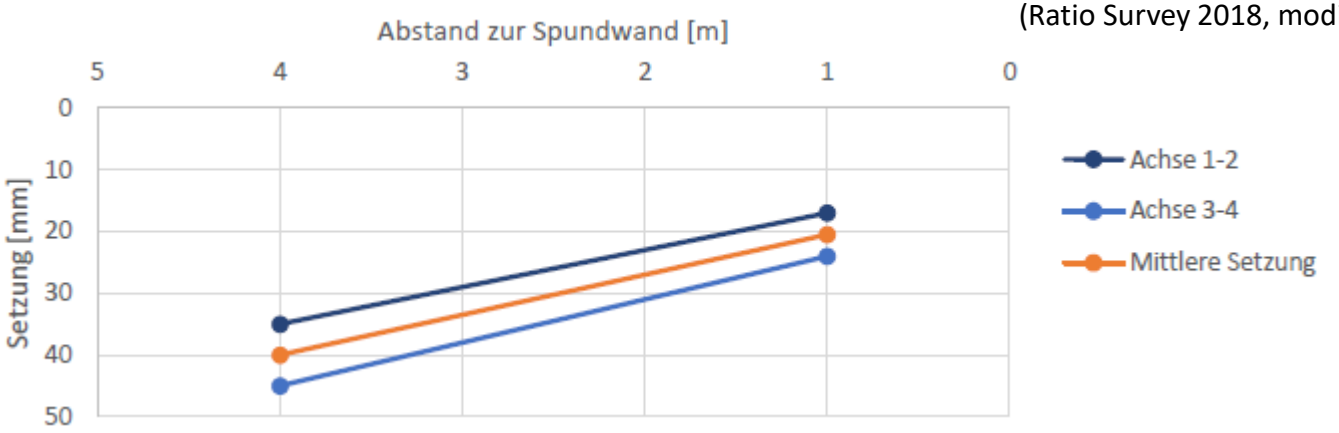
2. Windpark Krammer

Monitoring: testload settling

Datum	Eckpunkt	Setzung [mm]
29.01.2018	1	-10
	2	-27
	3	-34
	4	-18
06.02.2018	1	-14
	2	-32
	3	-42
	4	-22
13.02.2018	1	-17
	2	-35
	3	-45
	4	-24



Location of testload and settling points
(Ratio Survey 2018, modified, not to scale)

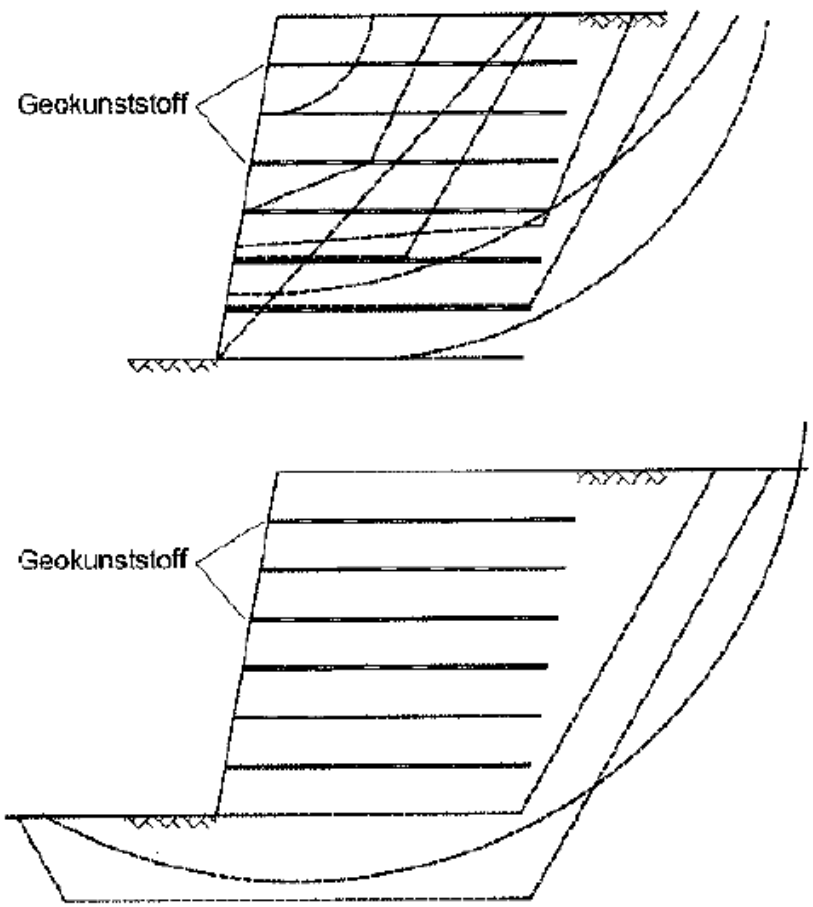


3. Prognosis of the structual behaviour

- Geogrids as anchoring elements:
  - Characteristics of reinforcement elements (“plain” geogrids) and grouted anchors
  - Forecasting the structual behavior by comparing “plain” geogrids and grouted anchors individually
  - Of particular interest:
    - Lastabtrag (Übersetzung)
    - Failure mechanism
    - Horizontal earth pressure on sheetpile

- Main prognoses: (Übersetzung in Arbeit)
  - Lastabtrag über gesamte Länge durch Erdwiderstand an den Querzuggliedern und Oberflächenreibung
  - Bruchmechanismus: Auflast bewirkt besseren Verbund → globales Versagen unwahrscheinlich → lokales Versagen/Scherfugen und/oder Andeutung eines Bruchmechanismus (tiefe Gleitfuge)
  - Geogitter als Verankerungselemente → Erddruckkonzentrationen in den Verankerungspunkten und Erddruckentlastungen zwischen den Verankerungen gemäß EAB
  - Vorspannung → steiferes System → geringere Verschiebungen und Setzungen, jedoch höherer Erddruck als aktiver Erddruck

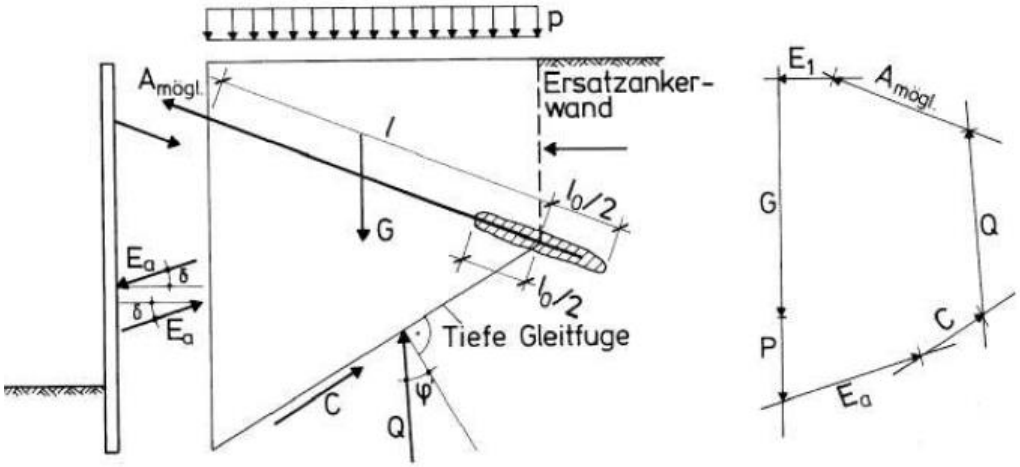
3. Prognosis of the structual behaviour



Possible failure mechanisms for geogrids as reinforcing elements (EBGEO 2010)

- Main prognoses: (Übersetzung in Arbeit)
  - Lastabtrag über gesamte Länge durch Erdwiderstand an den Querzuggliedern und Oberflächenreibung
  - Bruchmechanismus: Auflast bewirkt besseren Verbund → globales Versagen unwahrscheinlich → lokales Versagen/Scherfugen und/oder Andeutung eines Bruchmechanismus (tiefe Gleitfuge)
  - Geogitter als Verankerungselemente → Erddruckkonzentrationen in den Verankerungspunkten und Erddruckentlastungen zwischen den Verankerungen gemäß EAB
  - Vorspannung → steiferes System → geringere Verschiebungen und Setzungen, jedoch höherer Erddruck als aktiver Erddruck

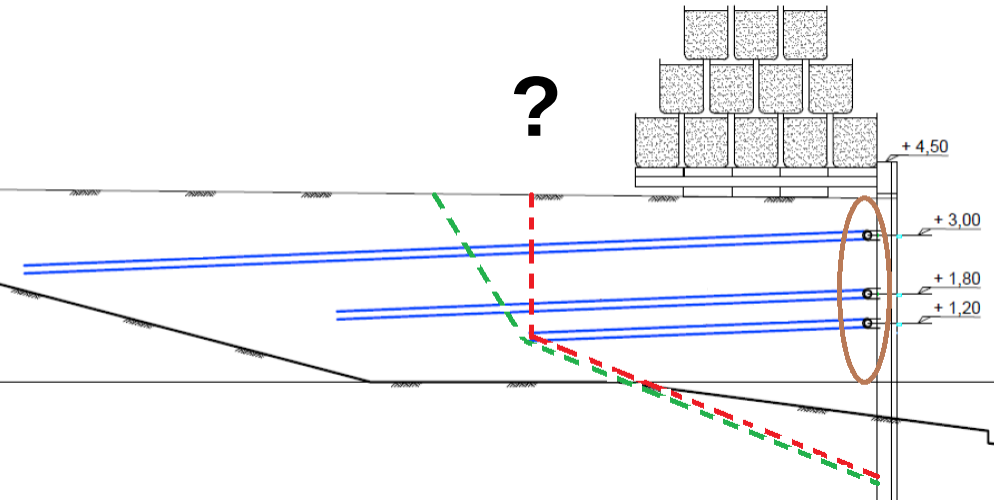
3. Prognosis of the structual behaviour



Failure mechanisms for a grout anchor (Grundbauskript RUB, 2012)

- Main prognoses: (Übersetzung in Arbeit)
  - Lastabtrag über gesamte Länge durch Erdwiderstand an den Querzuggliedern und Oberflächenreibung
  - Bruchmechanismus: Auflast bewirkt besseren Verbund → globales Versagen unwahrscheinlich → lokales Versagen/Scherfugen und/oder Andeutung eines Bruchmechanismus (tiefe Gleitfuge)
  - Geogitter als Verankerungselemente → Erddruckkonzentrationen in den Verankerungspunkten und Erddruckentlastungen zwischen den Verankerungen gemäß EAB
  - Vorspannung → steiferes System → geringere Verschiebungen und Setzungen, jedoch höherer Erddruck als aktiver Erddruck

3. Prognosis of the structual behaviour

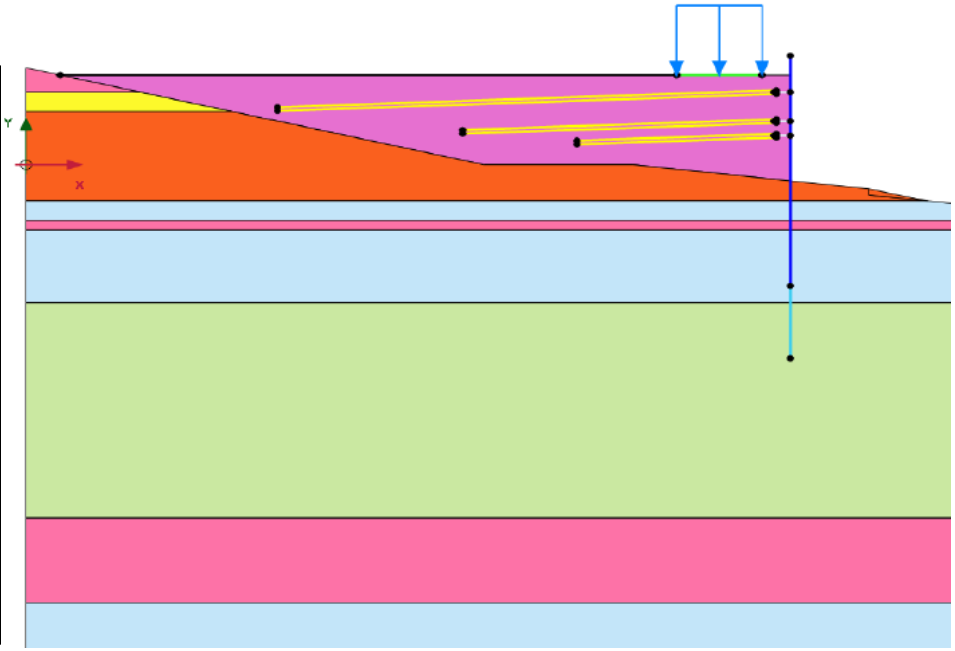


Failure mechanisms of sheetpile back-anchored with geogrids

- Main prognoses: (Übersetzung in Arbeit)
  - Lastabtrag über gesamte Länge durch Erdwiderstand an den Querzuggliedern und Oberflächenreibung
  - Bruchmechanismus: Auflast bewirkt besseren Verbund → globales Versagen unwahrscheinlich → lokales Versagen/Scherfugen und/oder Andeutung eines Bruchmechanismus (tiefe Gleitfuge)
  - Geogitter als Verankerungselemente → Erddruckkonzentrationen in den Verankerungspunkten und Erddruckentlastungen zwischen den Verankerungen gemäß EAB
  - Vorspannung → steiferes System → geringere Verschiebungen und Setzungen, jedoch höherer Erddruck als aktiver Erddruck

4. Numerical model

Parameter aus Tabelle 5.1							Parameter für das HS-Modell			Zusätzliche Parameter für das HS-SS-Modell		Interface-Wert
GOK (NAP) [m]	Bodenart	γ [kN/m³]	γsat [kN/m³]	c'k [kPa]	φ'k [°]	Ψ = 30° - φ [°]	E50,ref [kN/m²]	Eoed,ref [kN/m²]	Eur,ref [kN/m²]	G0,ref [kN/m²]	γ0.7 [-]	R [-]
+4,00	Schluff, stark sandig	20	20	0	27	0	15000	15000	45000	75000	0,0001	1
+3,00	Sand, mitteldicht	18	20	0	32	2	40000	40000	120000	200000	0,00015	1
+2,20	Sand, dicht	19	21	0	35	5	75000	75000	225000	375000	0,0002	1
-1,50	Sand, locker	17	19	0	25	0	15000	15000	45000	75000	0,0001	1
-2,30	Schluff, stark sandig	20	20	0	27	0	15000	15000	45000	75000	0,0001	1
-2,70	Sand, locker	17	19	0	25	0	15000	15000	45000	75000	0,0001	1
-5,70	Sand, mitteldicht	18	20	0	32	2	45000	45000	135000	225000	0,00015	1
-14,60	Schluff, stark sandig	20	20	0	27	0	15000	15000	45000	75000	0,0001	1
-18,1	Sand, locker	17	19	0	25	0	15000	15000	45000	75000	0,0001	1
+3,70	Bewehrte Erde	18	20	7	42,5	12,5	50000	50000	150000	250000	0,00025	0,67



Introduction:

- Soil parameters obtained from:
  - existing model (simulation of foundation construction by Dr. Lavasan)
  - Shear tests and triaxial tests of the reinforced soil
- System geometry according to cross section of WT17
- 9 soil layers according to CPT results
- Material model: HS small strain ($\gamma_{0.7}$ für Erfahrungswerte)
- Remaining parameters, e. g. sheetpile stiffness, from online sources

4. Numerical model

Parameter variation:

- Variation of parameters which are not well known
- Capillary cohesion may vary due to weather conditions
- Stiffness of reinforced soil influenced by compaction force
- Verbundbeiwert between RS and GG/SP estimated
- Prestress magnitude estimated by measured geogrid strains

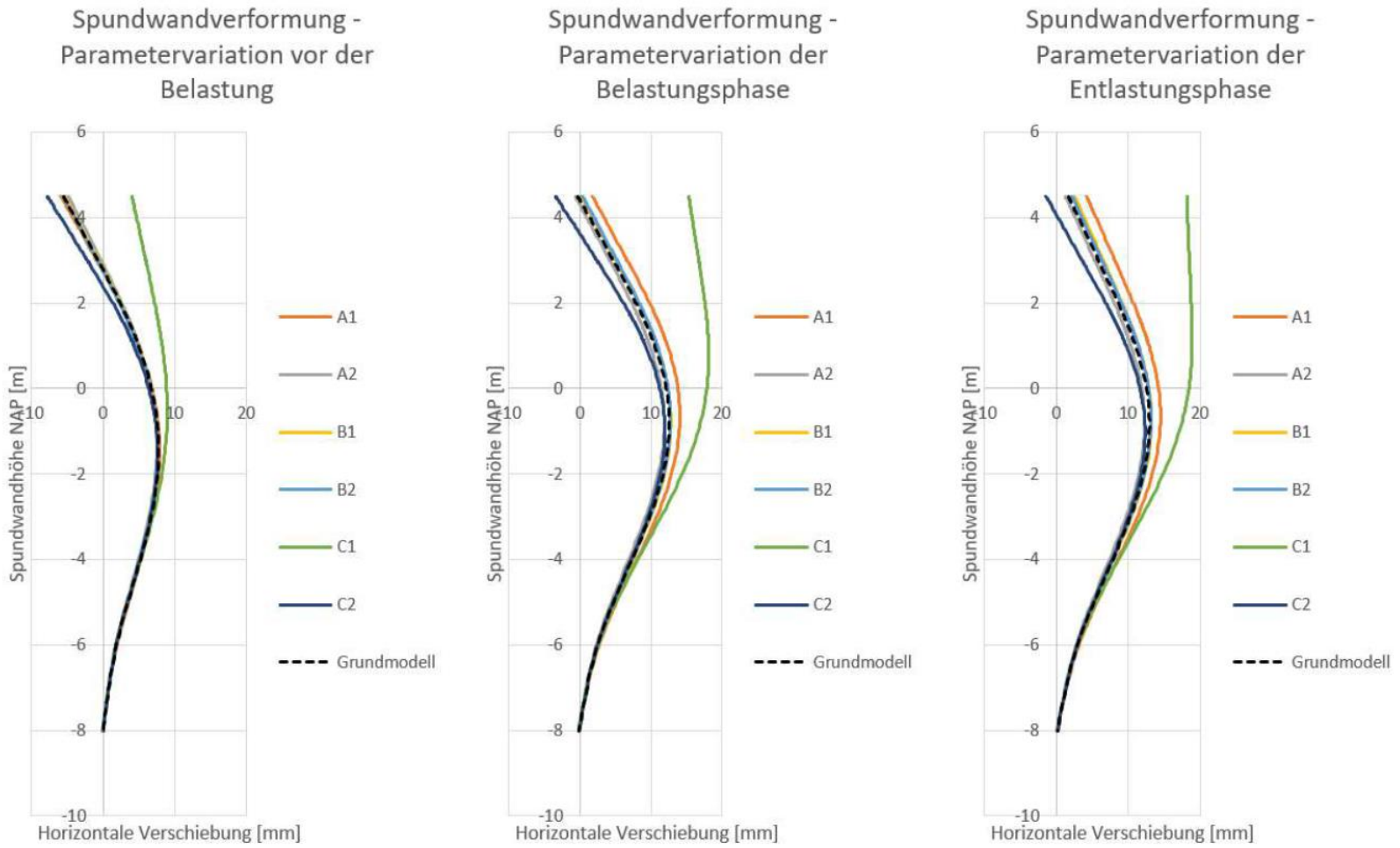
Reinforced Soil:

- Enggestufter, sehr schwach schluffiger und sehr schwach mittelsandiger Feinsand
- Mean water content: 11,83%
- Mean proctor density: 1600 kg/m³
- Friction angle: between 40 ° to 44,5°
- Capillary cohesion: between 6 to 7 kN/m²

Parametervariation	c [kN/m²]	E [kN/m²]	$R_{inter,GG}$ [-]	$R_{inter,SW}$ [-]	P [kN/m]
A1	3,5	40.000	-	-	-
A2	10	60.000	-	-	-
B1	-	-	0,9	0,6	-
B2	-	-	0,8	0,53	-
C1	-	-	-	-	0
C2	-	-	-	-	25/22,5/50
Grundmodell	7	50.000	1	0,67	20/18/40

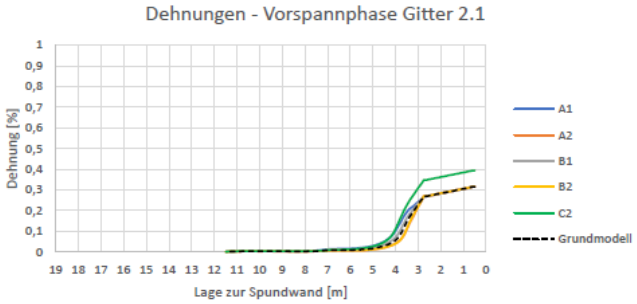
4. Numerical model

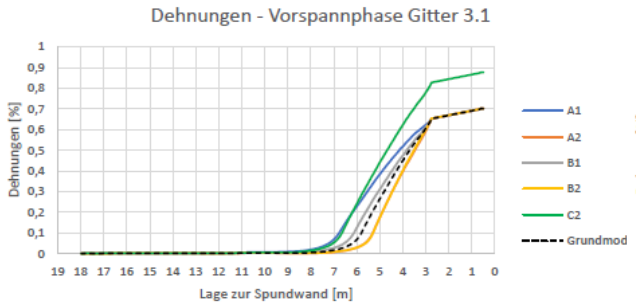
Horizontal sheetpile displacements

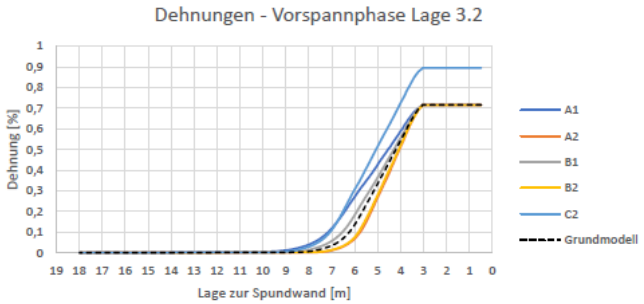


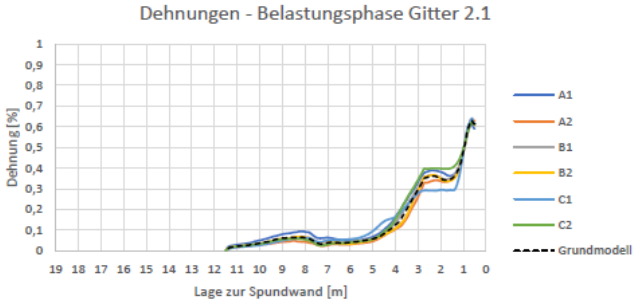
4. Numerical model

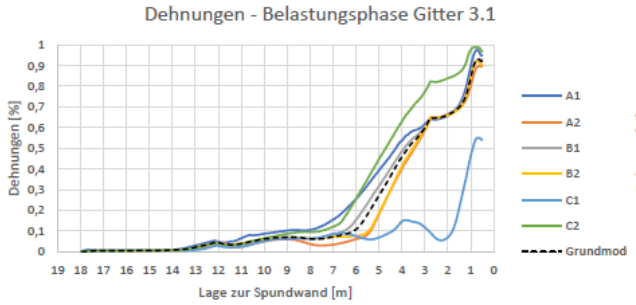
Geogrid strains

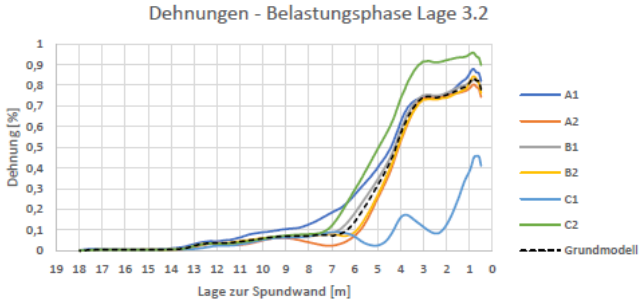


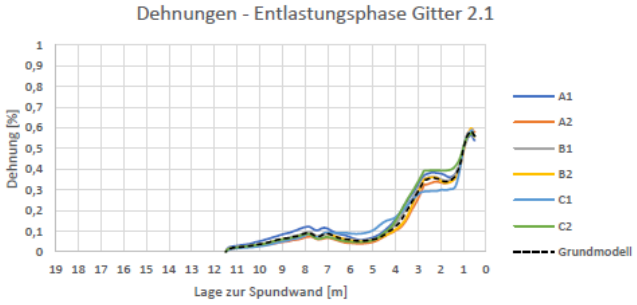


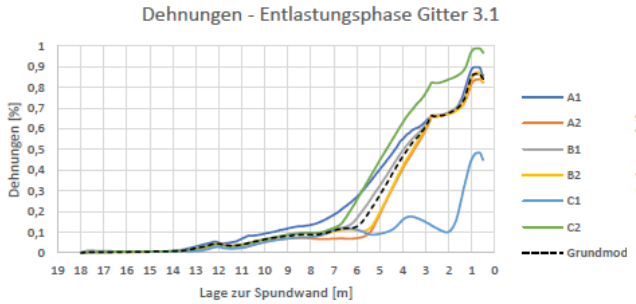


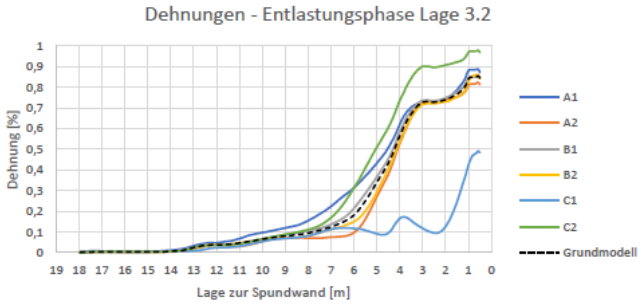










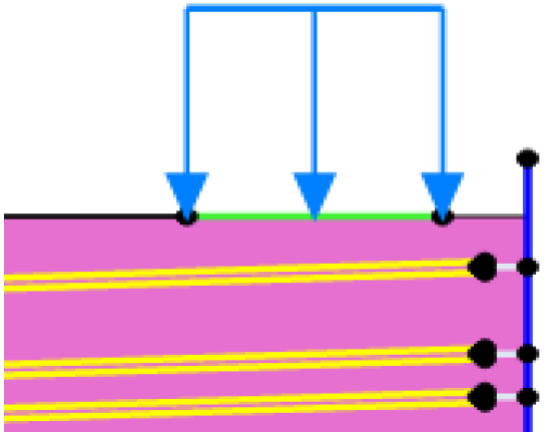


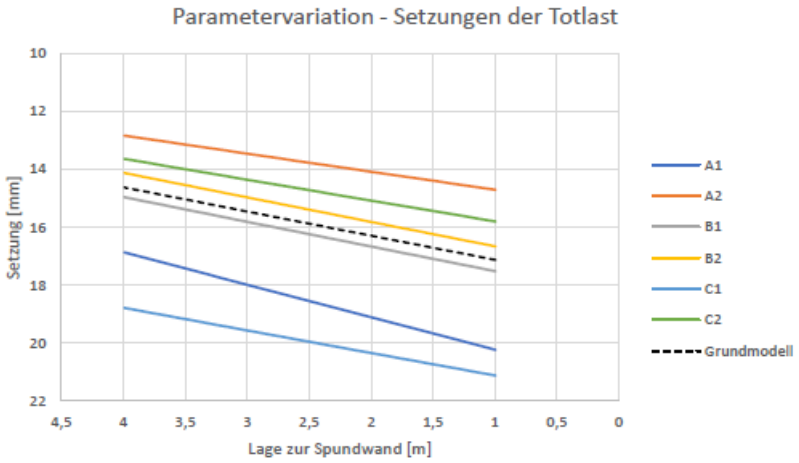
4. Numerical model

Testload Settling

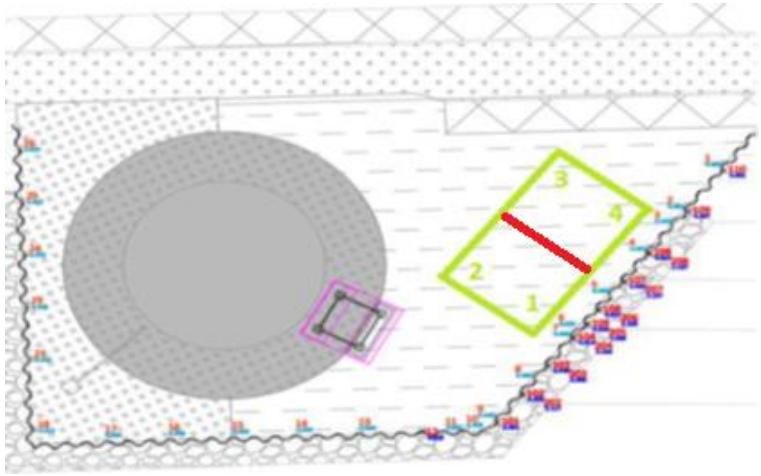
- Settling ranges from 14,7 mm to 17,1 mm
- Highest Settling for C1 (no prestress):

  18,1 mm to 21,1 mm
- Lowest settling for A2 (cohesion +43% and stiffness +20%): 12,8 mm to 14,7 mm
- Neglectable settling difference for B1 & B2 (-10% and -20% of R_{inter})



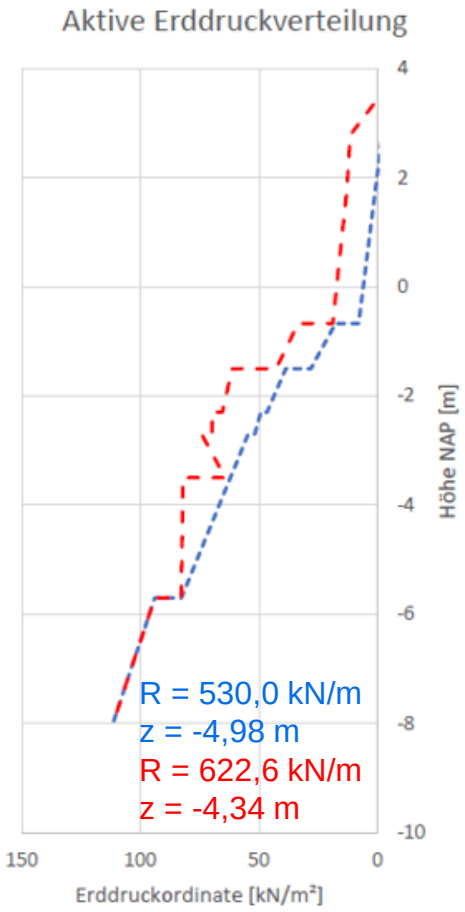


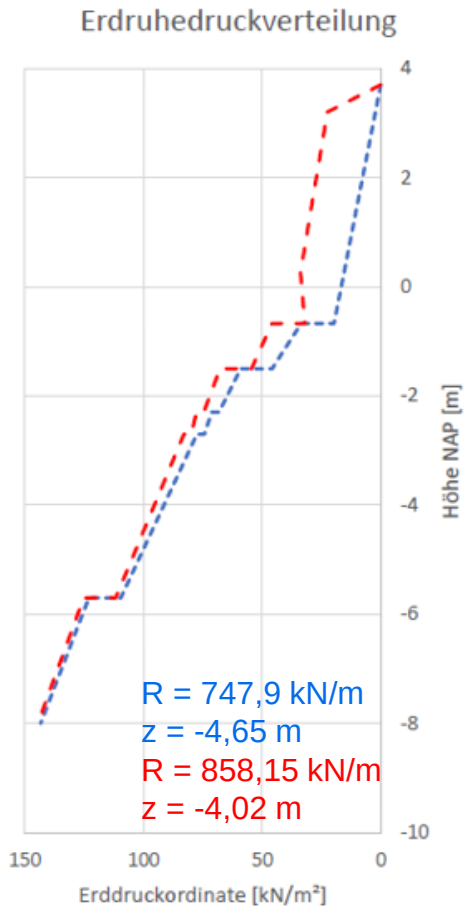
≙

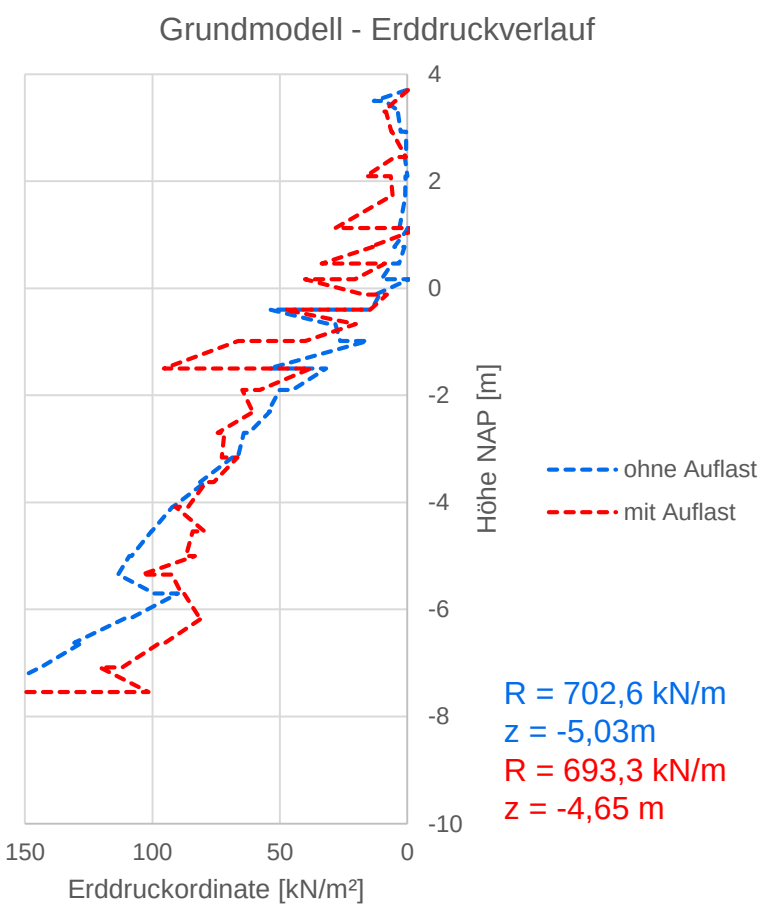


4. Numerical model

Horizontal earth pressure without geogrids: Coulomb vs. PLAXIS



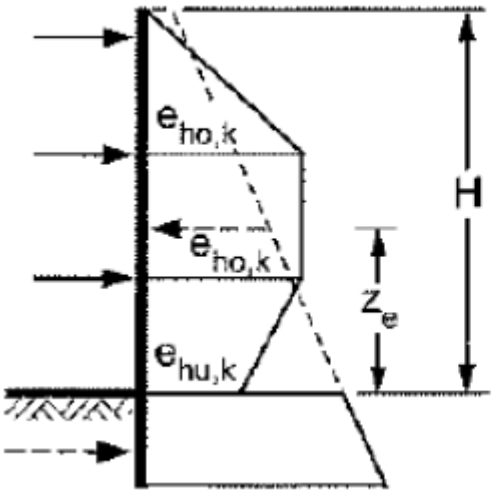




4. Numerical model

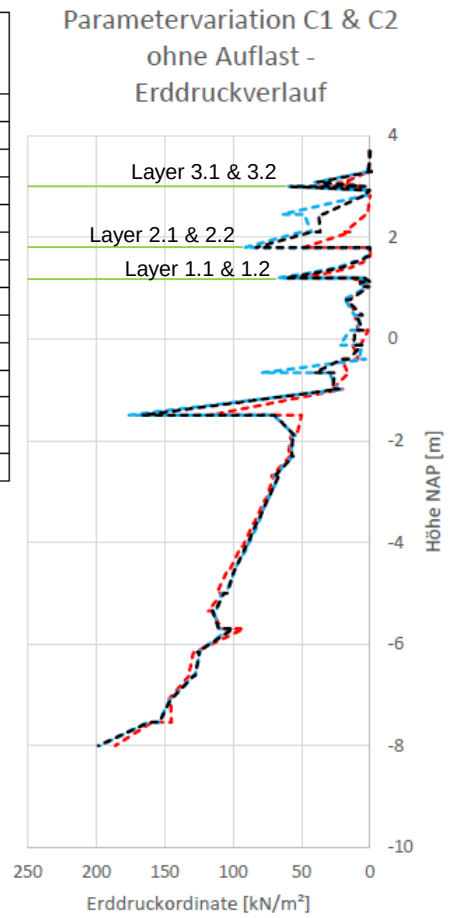
Horizontal earth pressure: main model and parameter variation C1 (no prestress) and C2 (+25% more prestress)

	Parametervariation	Resultierender Erddruck E [kN/m]	z [m NAP]
Ohne Auflast	Grundmodell	808,9	-4,32
	A1	805,1	-4,34
	A2	815,1	-4,29
	B1	808,2	-4,32
	B2	797,1	-4,39
	C1	758,0	-4,70
	C2	828,4	-4,20
Mit Auflast	Grundmodell	860,5	-4,10
	A1	853,9	-4,13
	A2	858,3	-4,12
	B1	865,4	-4,12
	B2	833,4	-4,22
	C1	814,0	-4,36
	C2	869,4	-4,05



$$e_{ho,k} = 2e_{hu,k}$$

$$z_e = 0{,}4H - 0{,}5\,H$$



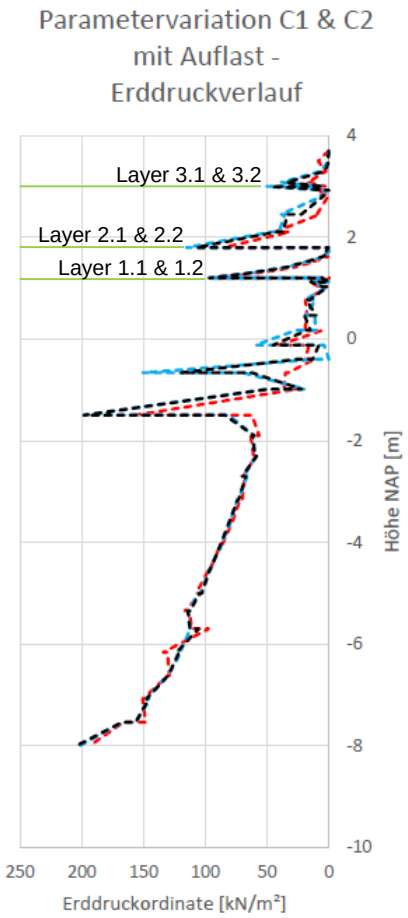
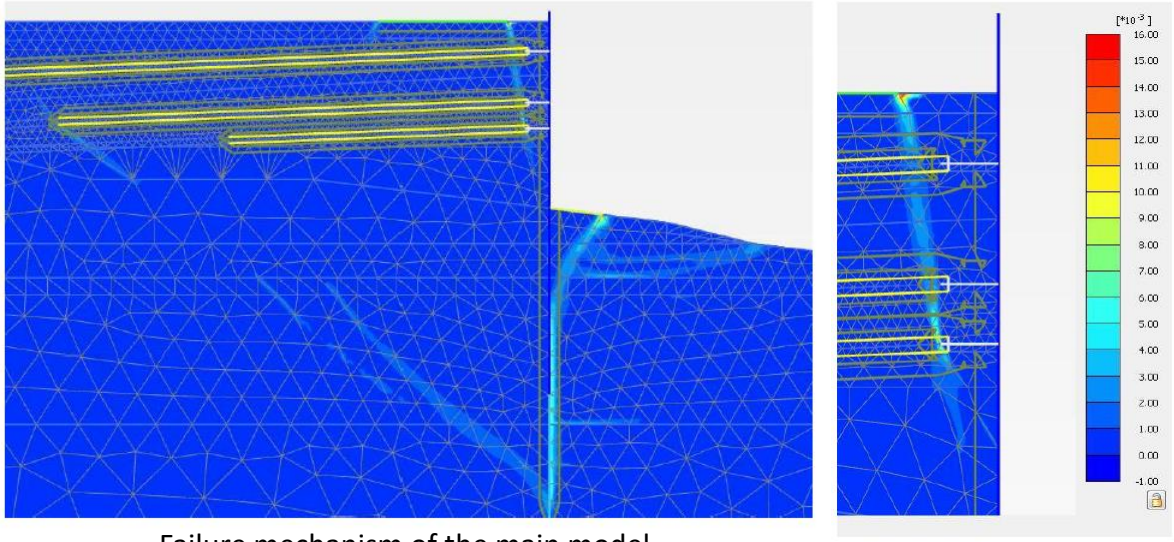


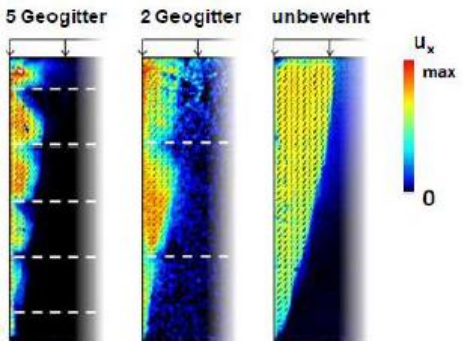
Abbildung 5.20: Einfluss der Parametervariationen C1 und C2 auf die Erddruckverteilung an der Spundwand (rot: C1 – ohne Vorspannung, blau: C2 – mit Vorspannung, schwarz: Grundmodell)

4. Numerical model

Failure mechanism



Failure mechanism of the main model

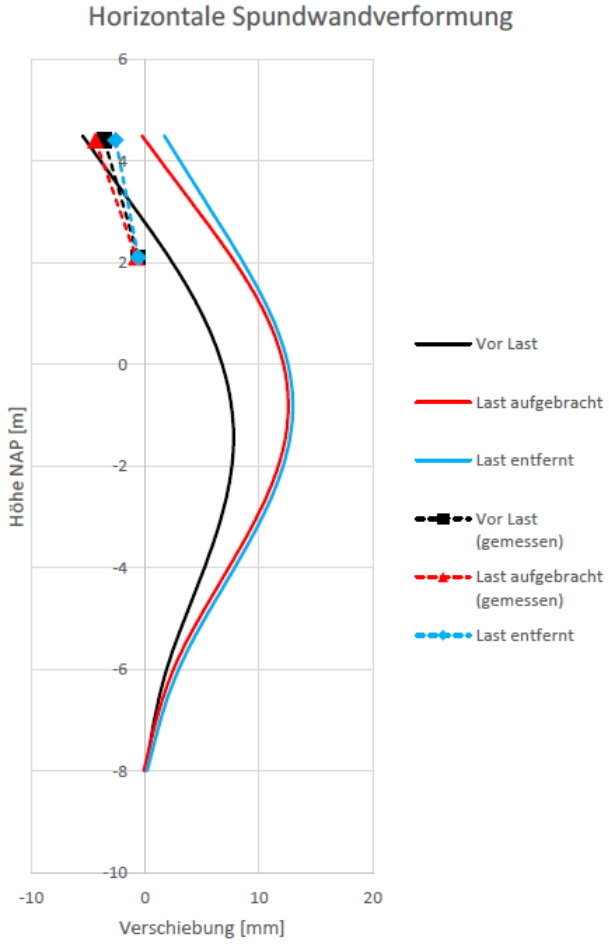


Failure mechanism of non reinforced soil, 2 geogrid layers and 5 geogrid layers (Ruiken, 2013)

- No global failure mechanism
- Partial shear bands only
- Local failure in non-reinforced area / anchor area
- → almost complete Bruchkörper
- Bruchkörper according to Ruikens (2013) evaluation of the influence of geogrinds on horizontal earth pressure and failure mechanism

5. Comparison: monitoring and numerical results

Sheetpile displacements

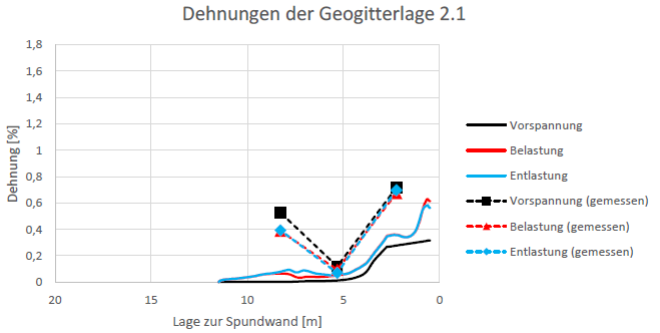


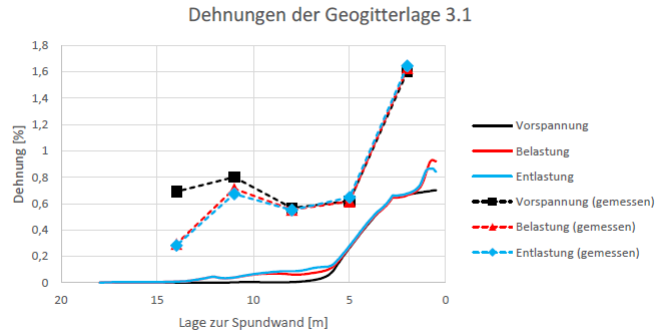
- Almost no displacements during monitoring for all phases
- Most displacements before applying the testload in PLAXIS
- After applying and removing the testload almost no difference in displacements in PLAXIS
- Displacements during monitoring barely higher than expected measuring error (± 2 – 3 mm)
- → useful data for comparison?
- Comparison difficult due to lack of reference points (only 2 points for comparison)
- Possible reasons for measured displacements:
  - Influence of soil filling one side of the sheetpile profile → stiffer structural behavior?
  - 2 kinds of sheetpiles (high stiffness and low stiffnes) → mean stiffness for numerical model accurate?

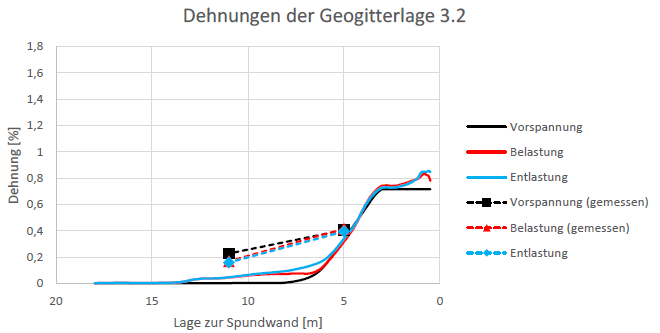
5. Comparison: monitoring and numerical results

Geogrid strains

- Highest strains while prestressing for all layers
- After prestressing almost no difference in strains
- Layer 2.1: … Fortsetzung folgt

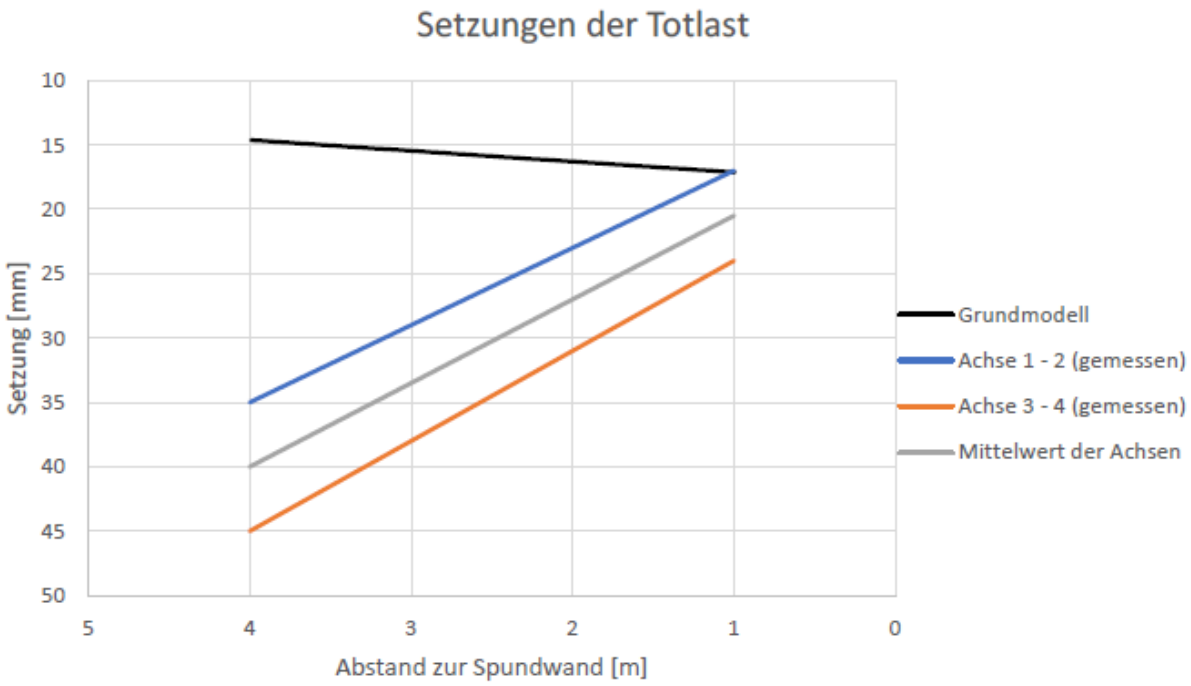






5. Comparison: monitoring and numerical results

Testload settling



6. Conclusions