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CENTRIFUGE MODELING OF AXIAL BEHAVIOR OF HELICAL PILES IN SAND – DATA REPORT FOR NI01

BY
NAVEEL ISLAM
LIJUN DENG
RICK CHALATURNYK

DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING
SCHOOL OF MINING AND PETROLEUM ENGINEERING
UNIVERSITY OF ALBERTA

Centrifuge Modeling of Axial Behavior of Helical Piles in Sand –

Data Report for NI01

Naveel Islam, Lijun Deng and Rick Chalaturnyk

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1 Introduction

The test program NI01, is the first part of the test series to study the axial behavior of helix piles in sand using the centrifuge modeling technique. NI01 was aimed to 1) develop the pile instrumentation and centrifuge modeling technique for helical piles in silica sand; 2) investigate the axial load distribution and internal load transfer mechanism within the piles for compression and tensile loading 3) investigate the effect of helices and inter helix spacing on the axial responses within the piles.

Five types of aluminum model helical piles were fabricated for the test: including one smooth pile without helix, one single-helix pile and three double-helix piles with spacing ratio of 1.5, 2.5 and 3.5, was fabricated with better controlled pitch size of the helices. The shaft diameter, *d*, was 12.7 mm (0.5 in), the helix diameter, *D*, was 38.1 mm (1.5 in), and the embedment of the piles was 150 mm. The pitch of a helix defined as the opening size of the helix of 12.7 mm is set to be scaled from the pitch size of a prototype pile at 254 mm. Table 1 lists the dimensions of all the model piles. Fig. 1 shows the schematics of the model piles and Fig. 2 presents the fabricated photos of the piles. The dimensions were considered from standard practice. The model soil box was prepared with silica sand (Sil-3) supplied by Sil Industrial Minerals in Edmonton, Alberta. The model sand box was prepared with air pluviation of sand with a portable travelling pluviator (PTP). The relative density of the deposited sand was estimated from the developed calibration chart relating to the height of fall of sand in the model box.

Axial strain gauges were installed at various sections of the pile to measure the axial load distributions. Torque strain gauges were placed on a collar assembly at the top of the pile to measure the developed torque. The model piles were axially loaded to 0.33 mm/min in compression and 10 mm/min in tension up to a maximum normalized displacement of 20% of the helix diameter. The readings were measured using an HBM Data Logger MX1615 B and later read through the computer program CATMAN.

Tests were conducted on the 2-m- radius Broadbent centrifuge at UAlberta. The centrifugal acceleration was set at a 20 g scale for the tests. Model scale factors of the analyzed parameter are listed in Table 2.

Table 1. Dimensions of the model piles

Pile Code	Number of helices	L (mm)	d (mm)	D (mm)	P (mm)	E (mm)	H_b (mm)	S (mm)	S/D
P0	0	273.1	12.7	38.1	12.7	228.6	150		
P1	1							N.A.	N.A.
P2	2							57.2	1.5
P3	2							95.2	2.5
P4	2							133.4	3.5

Note: d = shaft diameter; D = helix diameter; P = pitch of helix; E = length of pile from soil surface to tip; H_b = length of pile from soil surface to leading edge of bottom helix; S = spacing of two helices

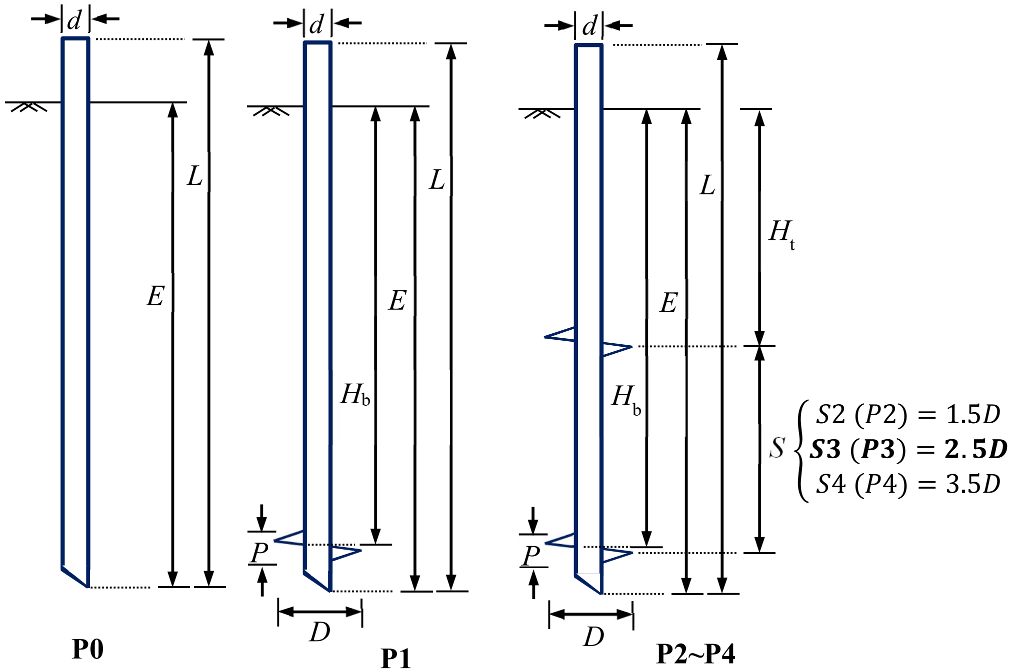


Figure 1. Schematic Diagram of the Model Helical Piles (P0 to P4)

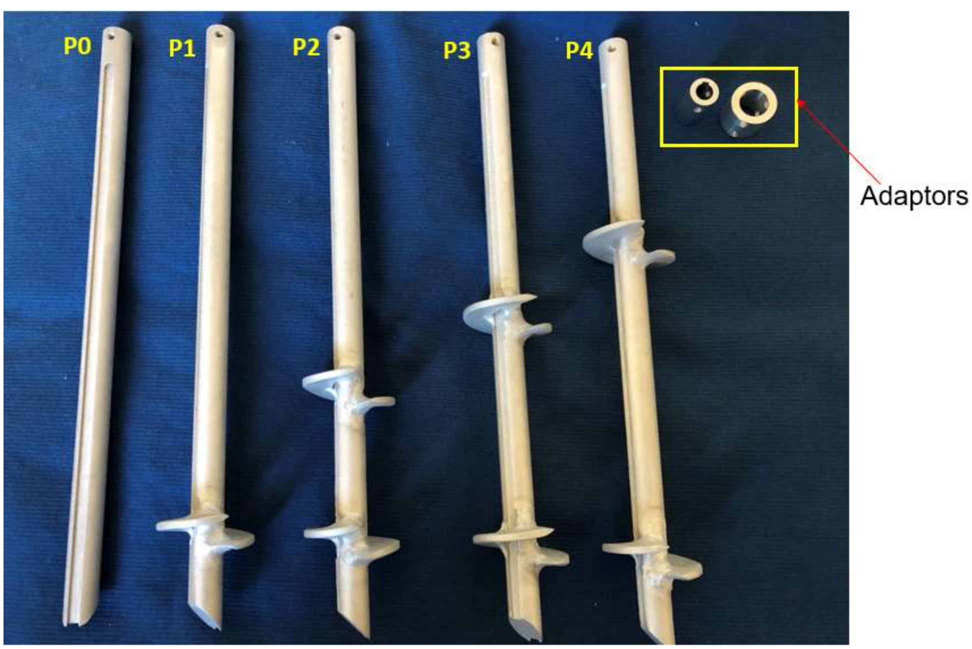


Figure 2. Fabricated Model Piles & Adaptors (P0 to P4)

Table 2. Selected scale factors (prototype/model) of centrifuge modeling tests

Term	Force	Dimension	Stress
Scale Factor	400	20	1

2 Centrifuge Testing Program

2.1 Test matrix

Table 3 shows the summary of the test matrix with the model pile dimensions corresponding to each test type. The test program NI01 was sub divided into two parts, NI01a and NI01b. In NI01a, five model piles were tested in compression in a model silica sand box and later in NI01b, four model piles were tested in tension on a newly pluviated model silica sand box. Figure 3& 4 shows the test layout plan and cross sections for NI01a and NI01b. Five model piles were tested in compression at NI01a; and four model piles were tested in tension in NI01b. The piles were designated as PXL, where P stands for pile, X stands for pile number, and L stands for loading type (C for Compression and T for Tension). The smooth pile without helix is denoted as P0C, and helix piles, as P1C to P4C.

Table 3. Summary of Test Matrix and Pile Dimensions in Model and Prototype Scale Unit

Tests Plan	Test Loading Type	Scale	Pile Test ID	No. of helices	Shaft dia. d (mm)	Helix Dia. D (mm)	Pile Length L (mm)	Helix Spacing S (mm)	Lower Helix Embedment E (mm)	$S_r = (S/D)$
NI01a	Compression	Model Scale Unit	P0C	0	12.7	38.1	271.8	NA.	150	NA.
			P1C	1	12.7	38.1	271.8	NA.	150	NA.
			P2C	2	12.7	38.1	271.8	57.2	150	1.5
			P3C	2	12.7	38.1	271.8	95.2	150	2.5
			P4C	2	12.7	38.1	271.8	133.4	150	3.5
		Prototype Scale Unit	P0C	0	254	762	5436	N.A.	3000	N.A.
			P1C	1	254	762	5436	N.A.	3000	N.A.
			P2C	2	254	762	5436	1144	3000	1.5
			P3C	2	254	762	5436	1905	3000	2.5
			P4C	2	254	762	5436	2668	3000	3.5
NI01b	Tension	Model Scale Unit	P0T	0	12.7	38.1	271.8	NA.	150	NA.
			P1T	1	12.7	38.1	271.8	NA.	150	NA.
			P2T	2	12.7	38.1	271.8	57.2	150	1.5
			P3T	2	12.7	38.1	271.8	95.2	150	2.5
		Prototype Scale Unit	P0T	0	254	762	5436	N.A.	3000	N.A.
			P1T	1	254	762	5436	N.A.	3000	N.A.
			P2T	2	254	762	5436	1144	3000	1.5
			P3T	2	254	762	5436	1905	3000	2.5

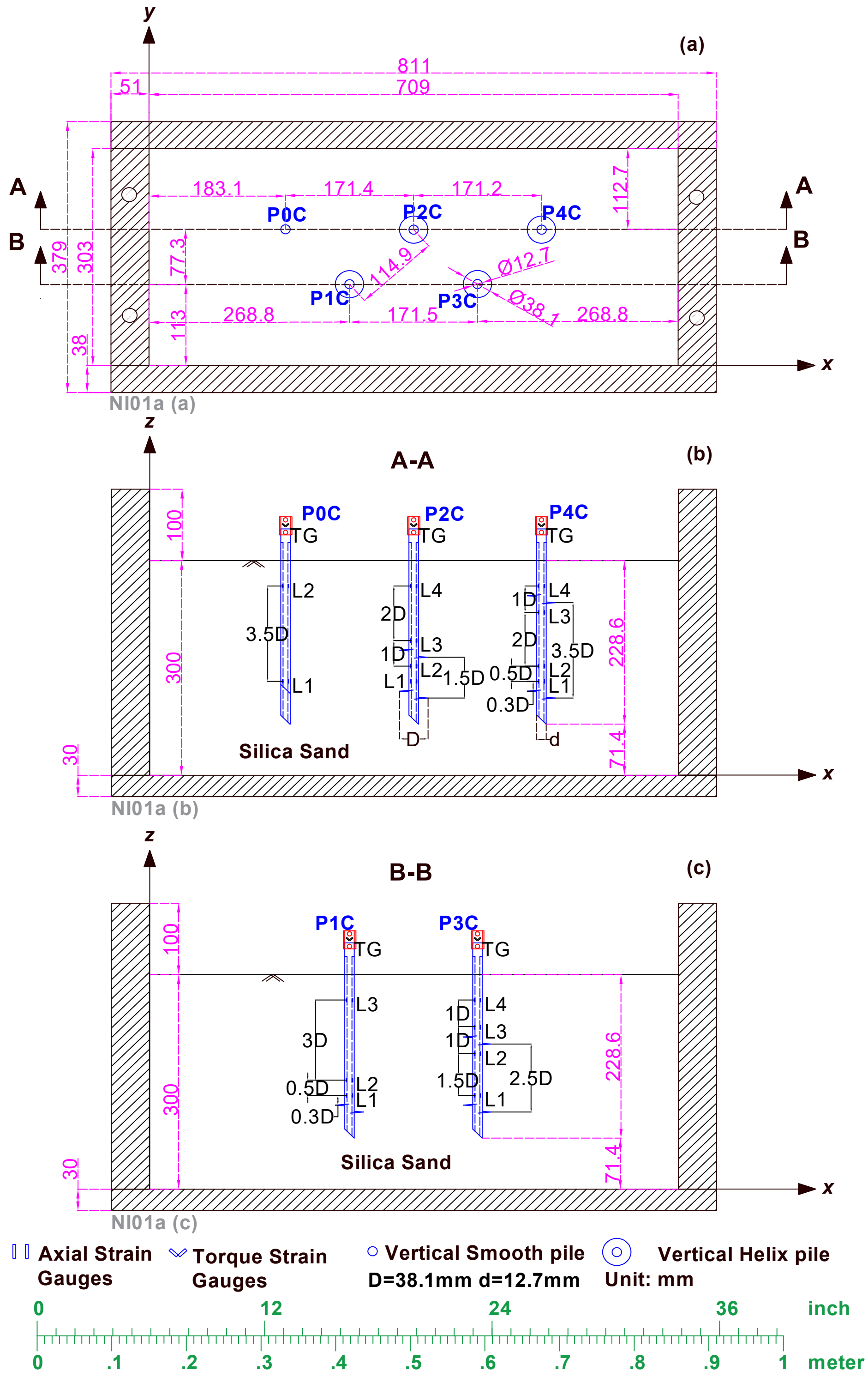


Figure 3. (a) Layout plan of test NI01a (Compression); (b) Cross-sectional profile at A-A section; and (b) Cross-sectional profile at B-B section. All dimensions are in model scale.

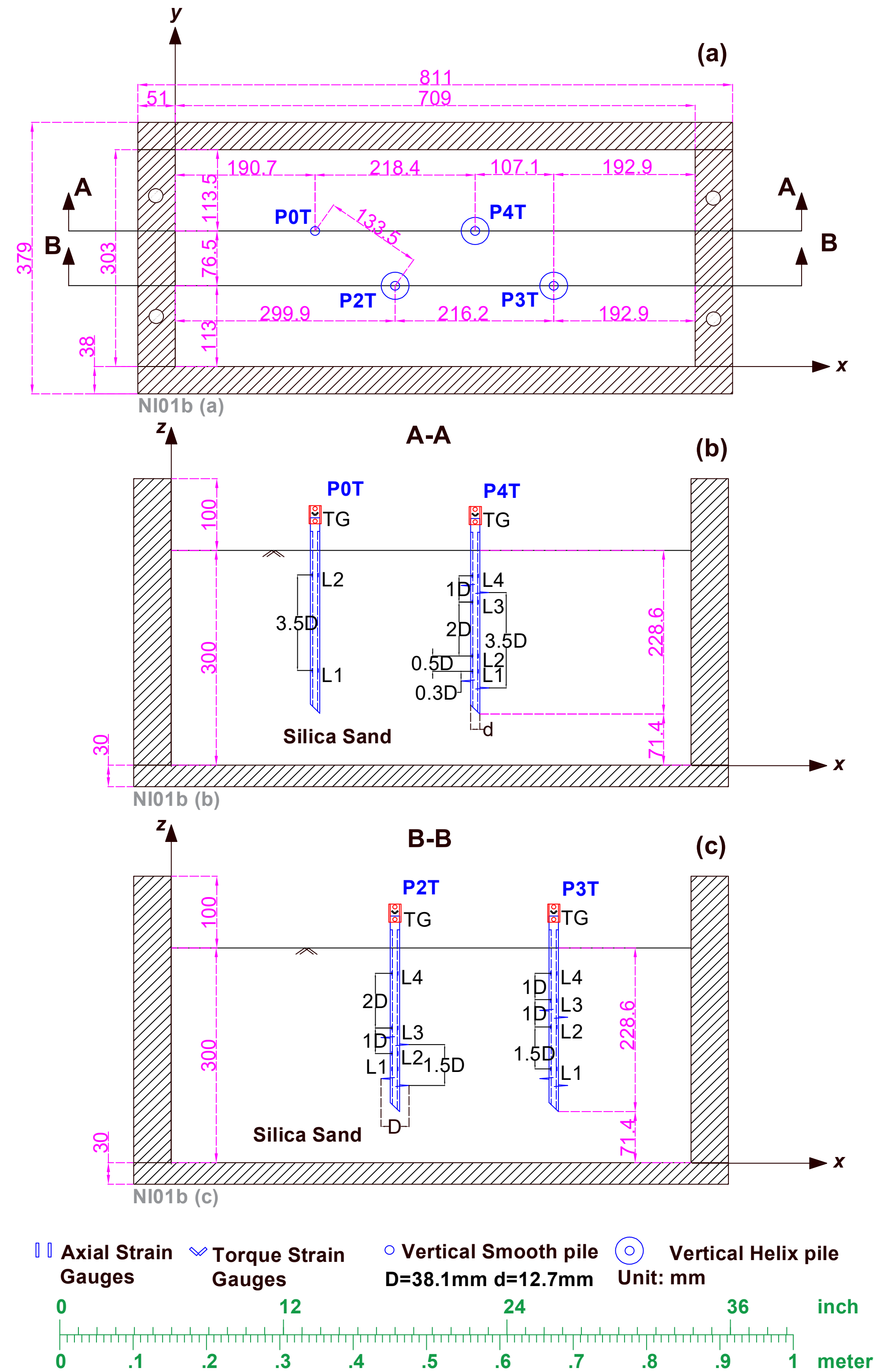


Figure 4. (a) Layout plan of test NI01b (Tension); (b) Cross-sectional profile at A-A section; and (b) Cross-sectional profile at B-B section. All dimensions are in model scale.

2.2 Soil Properties

The model test was performed upon dry silica sand (Sil-3) supplied by Sil Industrial Minerals in Edmonton, Alberta. The geotechnical properties of Sil-3 sand are summarized in Table 4. The minimum and maximum density of the Sil 3 sand was measured following ASTM D4254-16 and ASTM D4253-16e1 respectively. The tested particle size distribution (PSD) of Sil-3 sand is shown in Fig. 3. From the PSD, the estimated, d_{50} = 0.29 mm, C_u = 1.5 mm and C_c = 1.08 mm, indicates uniform distribution of grain sizes. As per Schiavon et al. 2016, effective model sand for centrifuge test of helix piles should carry uniformly distributed grain sizes, should not contain a lot of fine sand dust and maintain the ratio of the effective helical radius of the model helix piles (r_h) to the average grain size (d_{50}) of the sand, r_h/d_{50} greater than 58. Hence, for Sil- 3 as model sand, the r_h of the model piles was kept greater than 16.82 mm (discussed in the following section). The direct shear test on the Sil-3 sand is shown in Fig. 6. Table 5 shows the estimated parameter for the direct shear test.

Table 4. Geotechnical properties of model silica sand

Term	Value
Specific Gravity (G_s) (Correlated)	2.65
Average Bulk density (ρ), Mg/m^3	1.61
Constant Volume Friction angle (φ_{cv}), deg.	31.7
Maximum Dry Density (ρ_{max}), Mg/m^3	1.73
Minimum Dry Density (ρ_{min}), Mg/m^3	1.52
Minimum void ratio (e_{min})	0.53
Maximum void ratio (e_{min})	0.74

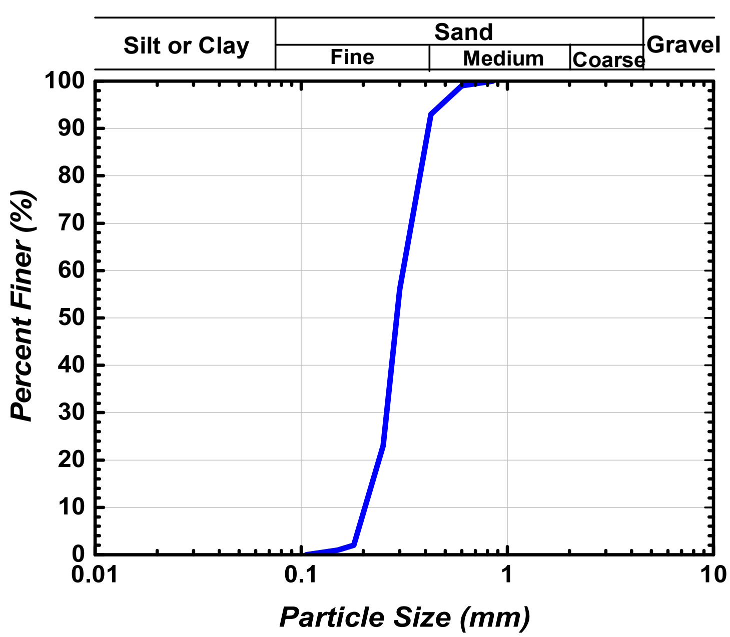


Figure 5. Particle size distribution of model silica sand

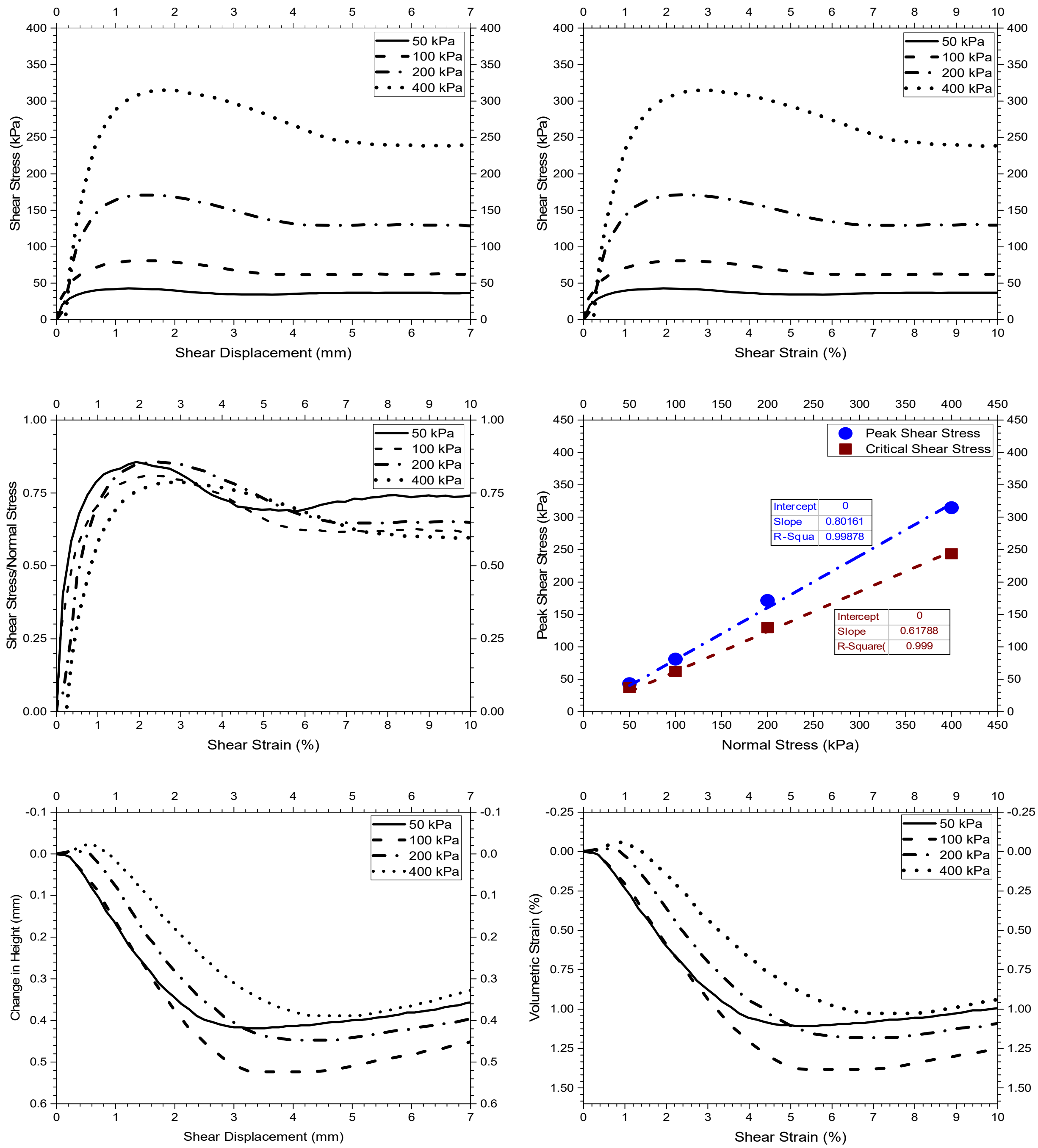


Figure 6. Direct Shear test results on Sil 3 Sand (strain rate: **0.76 mm/min**)

Table 5. Estimated Shear Strength parameters of Sil 3 sand from the direct shear test

Cohesion intercept condition	Estimated c' and φ'
With zero intercept for cohesion	$c' = 0\ kPa$ and $\varphi' = 38.7°$
	$c'_{cv} = 0\ kPa$ and $\varphi'_{cv} = 31.2°$
Without zero intercept for cohesion	$c' = 6.2\ kPa$ and $\varphi' = 37.9°$
	$c'_{cv} = 5.9\ kPa$ and $\varphi'_{cv} = 30.8°$

2.3 Soil model construction

The soil model was constructed in an aluminum container. The container measures internally, 709.2 mm (length), ×300 mm (width) × 400 mm (height) with wall thickness ≥ 30 mm. The box was designed for a maximum centrifugal acceleration of 50 g scale unit. To reduce the gross weight in-flight, all the walls were made of aluminum. The model sand deposition was controlled with a portable traveling pluviator (PTP) setup to allow uniform density deposition of sand at each layer in the model box.

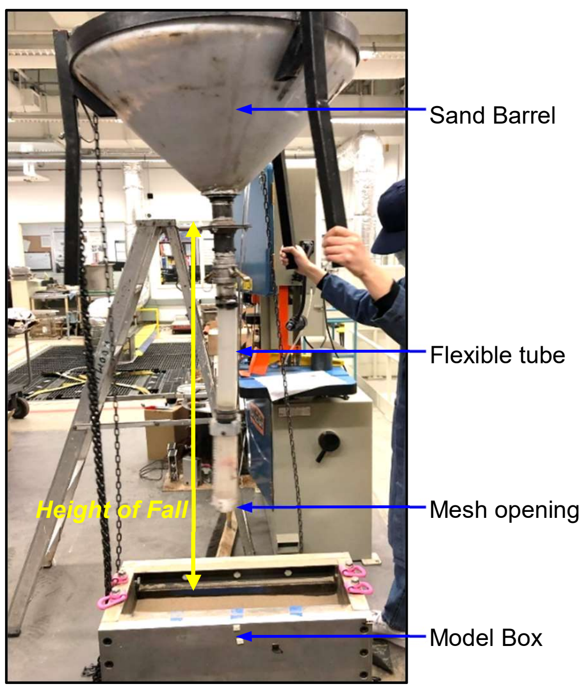


Figure 7. Portable traveling sand pluviator setup

Figure 7. shows the various components of the portable travelling pluviator (PTP) setup for the Sil-3 sand deposition in the model box. The configuration of PTP is similar to the stationary/portable travelling pluviator (PTP) as reported in literature (e.g. Dave and Dasaka 2012, Gade and Dasaka 2016, Hakhamaneshi et al. 2016 and Taeseri et al. 2018). The height of fall and the mesh size can be adjusted to control the density of the sand in the model box. The PTP was used to calibrate the Height of Fall against the relative density,

varying the deposition height between 110 -150 mm and changing the mesh size opening for 5 mm and 100 mm. Figure 8. shows the calibration assembly for the PTP using a density mould.

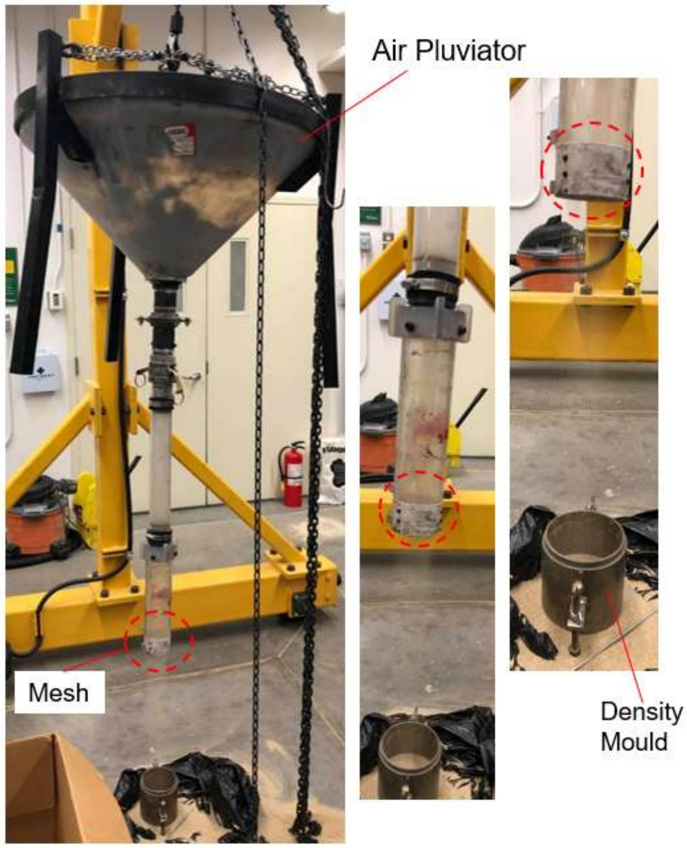


Figure 8. Calibration Assembly for the Portable Travelling Pluviator

Figure 9. presents the calibration chart developed to ascertain the relationship between the relative density of sand with the height of fall of sand from the PTP to the model box for mesh openings of 5 mm and 10 mm, respectively. The height of fall varied between 110 cm to 150 cm to deposit the sand in a density mold. Later, the relative density of sand for each calibration test was determined. As observed in Fig. 9, the relative density ranged between 72 to 100 % for 10 mm mesh opening and 46 to 86 % for 5 mm mesh opening. For test NI01, the relative density was fixed at 55%, which corresponds to a height of fall of 114 cm at the PTP.

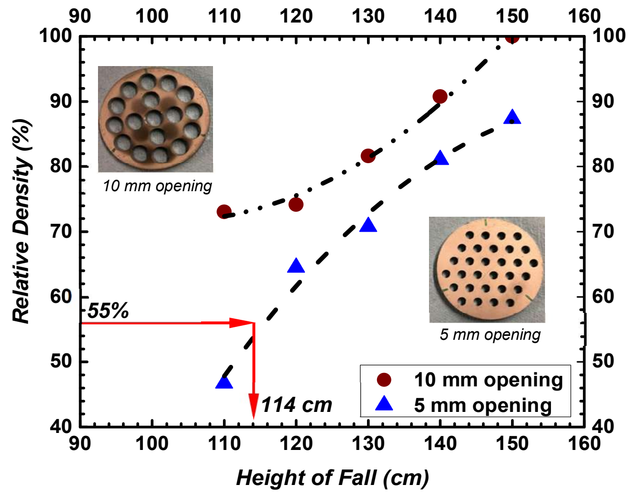


Figure 9. PTP calibration chart for the relationship between the relative density of sand with Height of fall for two mesh openings.

Figure 10 shows the schematic of the plan view of the model soil box showing the path of motion of the PTP during preparation of the sand bed.

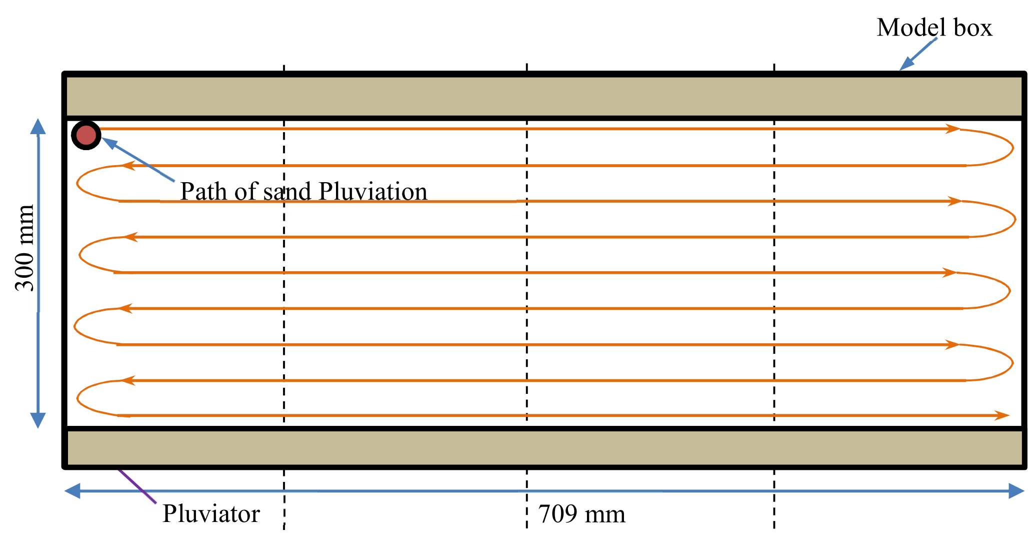


Figure 10. Plan view of plain strain model box showing path of sand Pluviation.

Figure 11 shows the photos of sand pluviation in the model box.

(a) Ongoing Pluviation

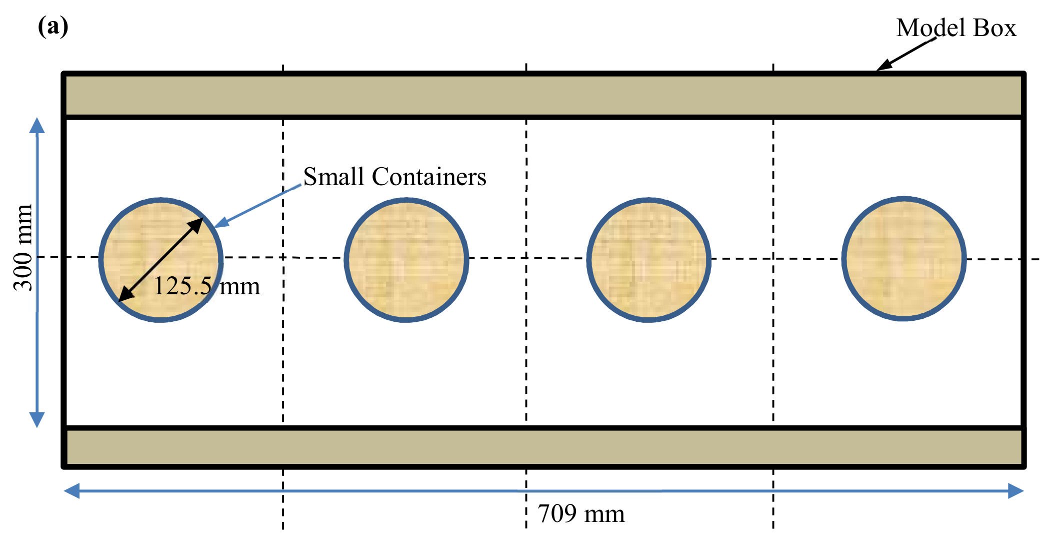
(b) Pluviation in Layers

(c) Completed Pluviation

Figure 11. Pluviation of sand in the model box

The quality of deposition of sand in the model box was verified using the small container method (see Choi et al. 2010 and Tabaroei et al. 2017). A total of 12 small containers (four in each layer) were selected to estimate the density on it along the course of travel of the PTP maintaining a uniformity in the height. The configuration and the dimensions of the containers are shown in Fig. 12.

(a)



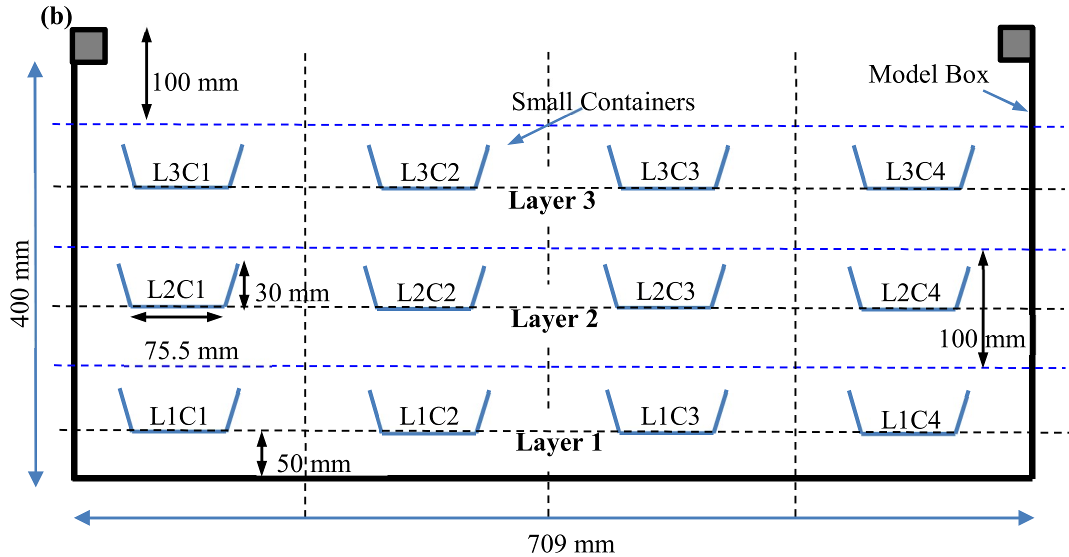


Figure 12. Location of molds (small containers) to perform calibration test (a) Plan View (b) Side view on the model box

Figure 13. shows the photos of the measurement and placement of the model box in the container. Figure 14 summarizes the estimated relative density (D_r) from the containers. The measured average $D_r = 54.3$ % which is in closer approximation to the desired density 55%.

Figure 13. Photos of the measurement and placement of the container in the model box.

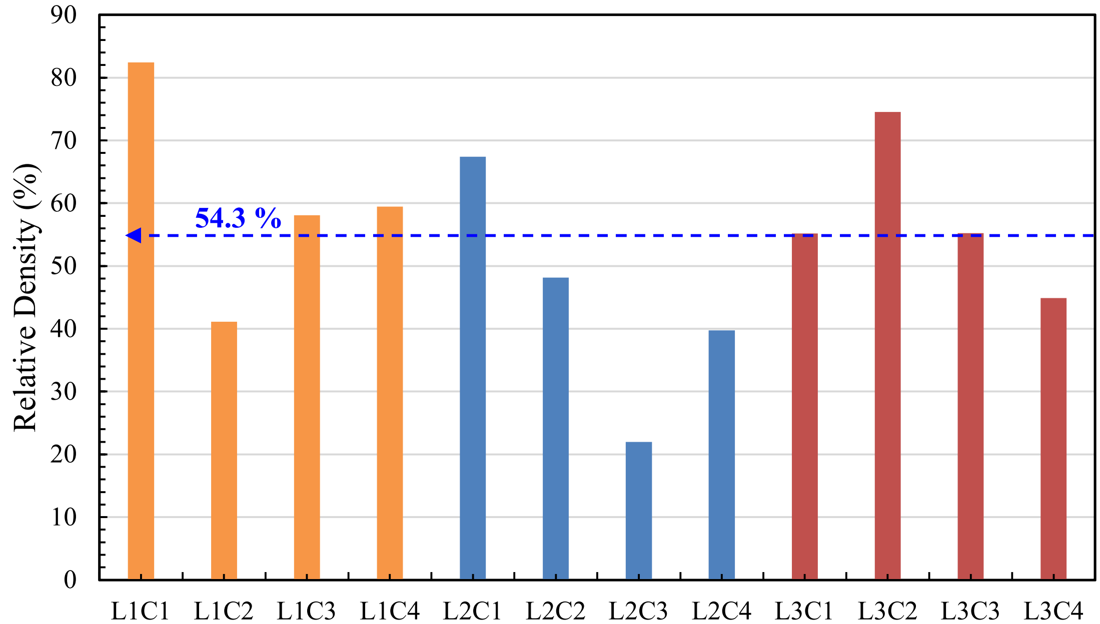


Figure 14. Comparative Sand Density of Small Containers in the Model Box

The average relative density was also measured from the weight of the strong box before and after the pluviation of sand. The measured average relative density was 49.7% for an average soil bulk density of 1.61 gm/cm^3.

2.4 Model Pile Instrumentation

In the present research, model piles are instrumented with axial strain gauges and torsional strain gauges for measuring the internal axial forces during pile loading tests and the torque during pile installation. Table 6 shows the description of the strain gauges and Fig. 15 shows the configuration of the gauges. The gauges were ordered from the supplier Terracene International (made by Micro Measurements VPG) that are universal general-purpose type with strain ranges of ± 3%.

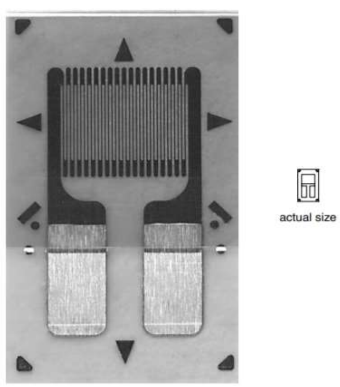
As per the precision Strain Gauges handbook from the supplier, the terminologies: **CEA** indicates Universal general purpose strain-gages. Constantan grid completely encapsulated in polyimide, with large, rugged copper-coated tabs. The following number **13** (Item a) or **06** (Item b) designates the approximate thermal expansion coefficient in ppm/°F of the structural material on which the gage is to be used. The following number, **062** designates the active gage length in Mils [0.001 in (0.0254 mm)]. **UW** or **UV** stands for grid and tab geometry and the number at the end indicates the resistance in Ohms.

Two types of strain gauge circuits will be adopted. For torque measurement, a full Wheatstone bridge consisting of two pads of strain gauges was used; the gauge model is CEA-06-062UV-350. Two strain gauges, on a base pad, were placed at the 45 and 135º rosette, with respect to the pile cross-sectional plane. The full-bridge configuration will compensate the effects of temperature, pile axial strain, and bending moment on the pile.

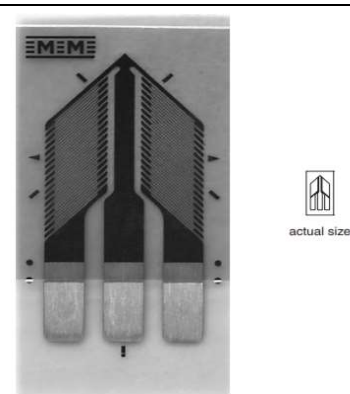
For axial strain measurement, a half Wheatstone bridge circuit consisting of two active single gauges will be adopted. The gauge model is CEA-13-062UW-350. The gauges are placed on two grooves cut into the pile shaft. The active gauges are wired to two dummy gauges on the data acquisition box. The locations of strain gauge stations are determined with the consideration of anticipated load distribution, so that the axial load transfer mechanism along the shaft and helical plates can be inferred.

Table 6. Description of the Strain Gauges

Items	Description of the Strain Gauges
a	CEA-13-062UW-350
b	CEA-06-062UV-350



a) Strain Gauge, CEA-13-062UW-350



b) Strain Gauge, CEA-06-062UV-350

Figure 15. Strain Gauge Configuration

The arrangement of the approximate locations of the strain gauges are presented in Figure 16. In order to protect the strain gauges from any potential damages from moist invasion or physical abrasion, especially for these axial gauges embedded in soil, the following techniques are adopted:

- Two grooves, 5 mm wide and 4.75 mm deep, were excavated along the shaft on the opposite sides.
- Axial strain gauges were then glued to the bottom of the grooves. To prevent moisture attack and electric leakage, the strain gauges were covered with VPG M-B coating and Teflon tapes, and then the grooves were carefully filled with epoxy (shown in Fig 16 a)
- The surfaces of the cured epoxy will eventually be smoothed with #240 sand papers and polished with soft cloth.

Calibration of the strain gauges were performed using the HBM data logger MX 1615B to convert the electronic signals into engineering units. The analyzed results and setup for calibration are presented in Appendix A.

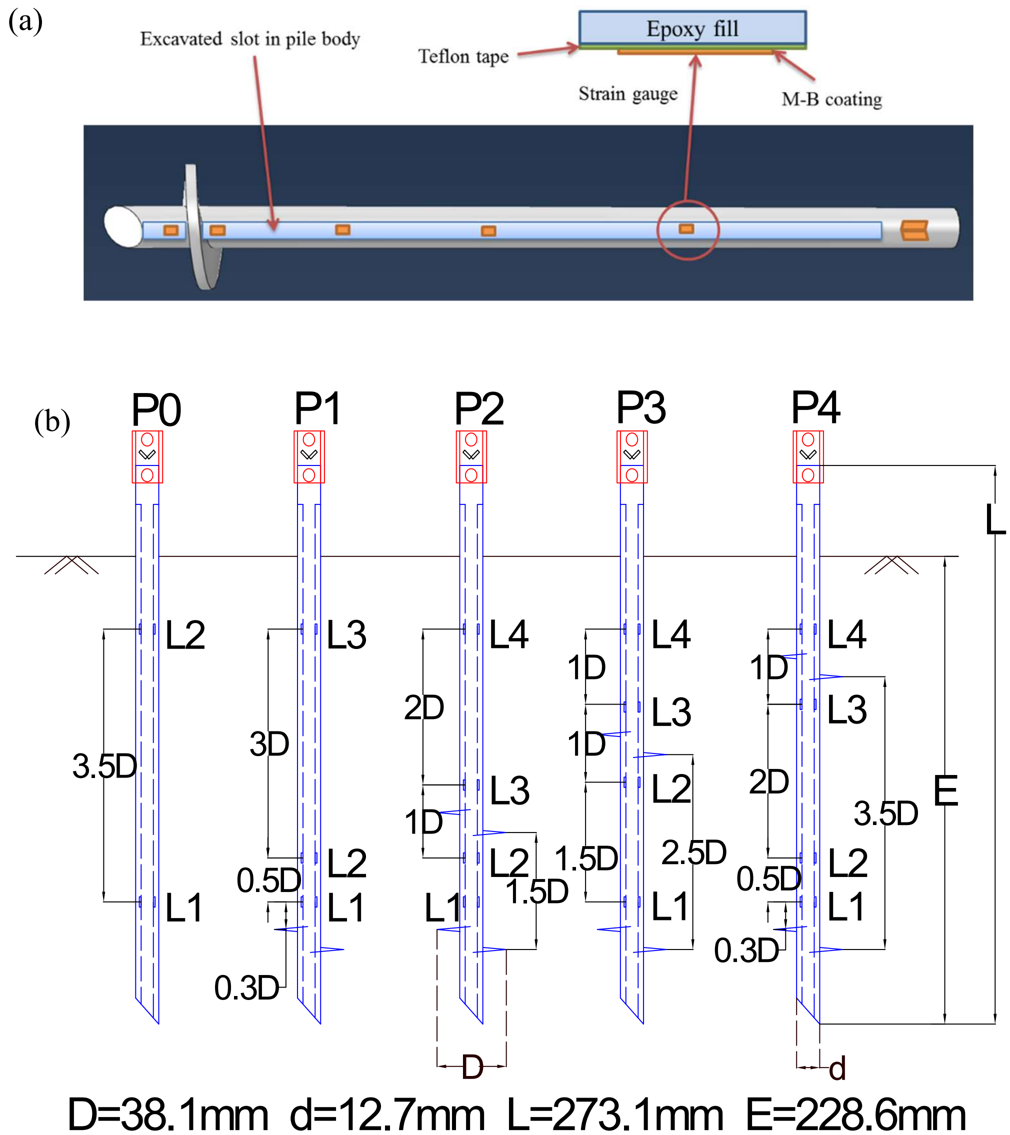
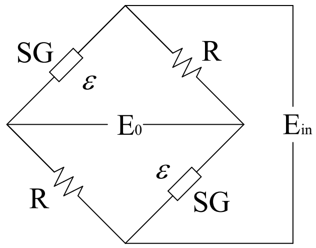
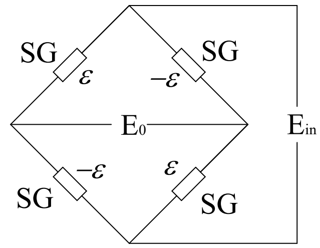


Figure 16. a) Approximate locations of strain gauge stations and protection technique and b) Position of strain gauges (L1-L4) and Torque Gage (TG) on the model piles.

Figure 17 presents the Wheatstone bridge connections for the axial and torque strain gauges as in the model connection assembly.



a) Axial



b) Torque

Figure 17. a) Half bridge circuit for axial strain measurement, where SG = axial strain gauge on pile shaft and R = complementary resistor embedded in the data logger and b) Full bridge circuit for torque measurement.

2.5 Calibration of Gear Motor

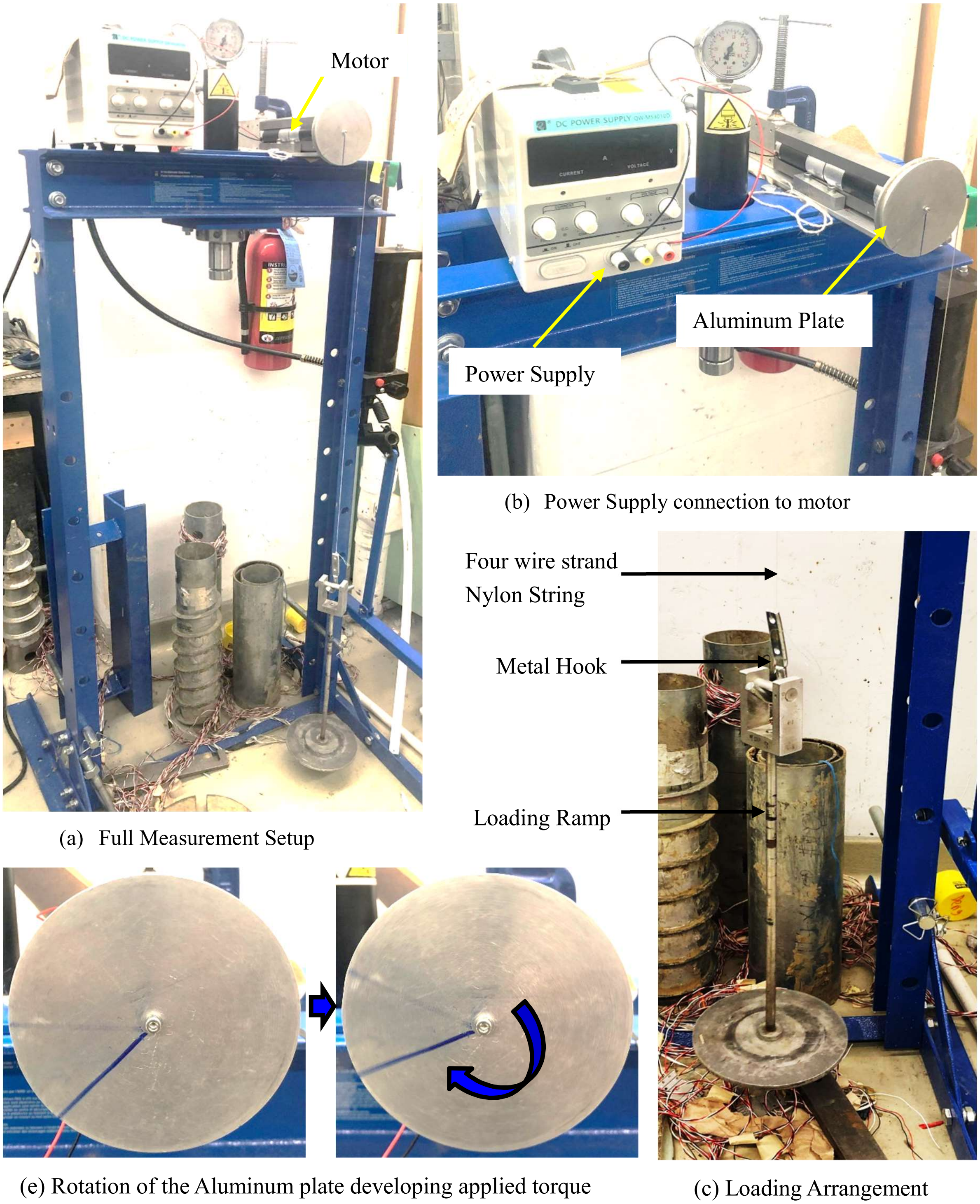
A slender gear motor is required that can simulate the pile installation during the motion of the centrifuge at high g level and that can fit the working space of the test setup. Hence, a slender gear motor, MMP S17-400A-12V manufactured by Midwest Motion Products, was selected for installing model piles in flight (see in Figure 18).

(a) Plan View

(b) Cross Sectional View

Figure 18. Slender gear motor, MMP S17-400A-12V (by Midwest Motion Products)

Prior to use, the motor needs to be calibrated such that it can fulfill the recommended output speed (in rpm) of installing the pile as practiced in field for the variation of soil resistances.



(a) Full Measurement Setup

(b) Power Supply connection to motor

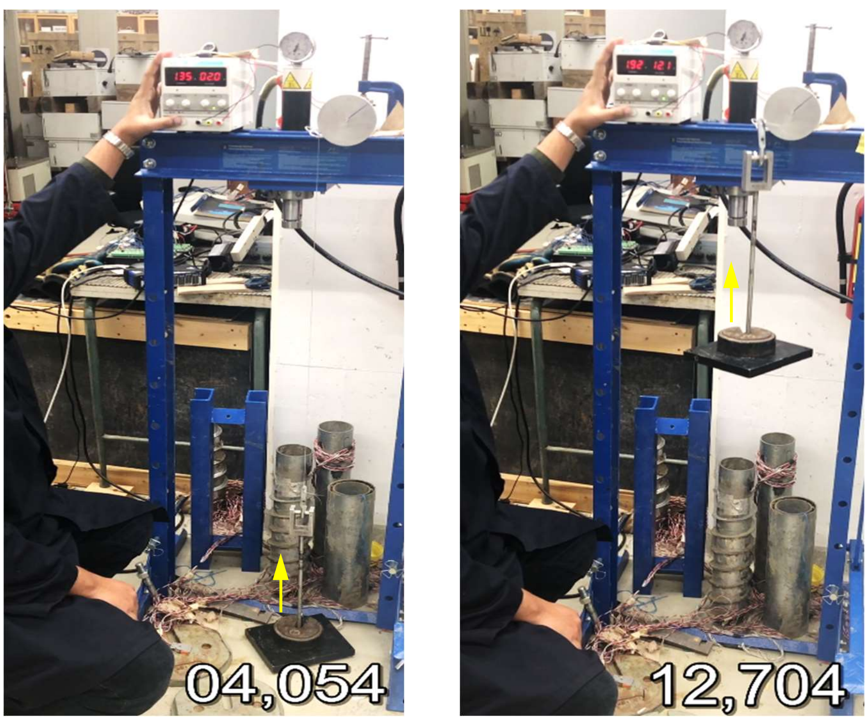
(c) Loading Arrangement

(e) Rotation of the Aluminum plate developing applied torque

Figure 19. Photos showing measurement setup for output speed of the motor to applied torque.

Tsuha et al. (2007, 2012), Schiavon et al. (2016) adopted a motor speed of 5.3 rpm during the anchor installation and pullout in dense sand both at 1g and 22g. According to Perko

(2009), typical rotation rates range from 10 to 30 rpm. As per AB Chance's (2012) guide to model specification, the helical anchors are usually installed with a rotation rate ranging from 5 to 20 rpm to provide a continuous and smooth advance into the soil. Li and Deng (2021) adopted a rotation rate of 22.5 rpm overall during the helix pile installation at 20g. The motor is calibrated by adopting variable torque combinations mounted with an aluminum circular plate and connected with a DC power supply that can generate variable voltage outputs. The applied torques (in N-m) simulates the nature of soil resistances. Figure 19 shows the photos of the setup used for the measurements. A circular aluminum plate (of diameter = 92.58 mm) was fixed onto the shaft of the motor, and a four-strand nylon string was tied on the edge of the plate to add variable dead weights (ref to Fig 19 (a-c)). A total number of fourteen load combinations were adopted and hanged to the nylon string in the vertical direction for the motor to uplift each of them (see Fig 19 (e)). The rotations were measured using a camera and later counting the elapsed time over three complete revolutions of the aluminum plate for each of the torque combinations. Figure 20 shows a screenshot from the measurement of time (in milliseconds). Correlations of output motor speed (rpm) against applied torque (Nm) for variable power supply voltage is shown in Figure 21.



(a) Start time (in milliseconds) (b) Stop Time (in milliseconds)

Figure 20. Measurements of output speeds against variable torque combinations for 3 complete revolutions of the aluminum plate.

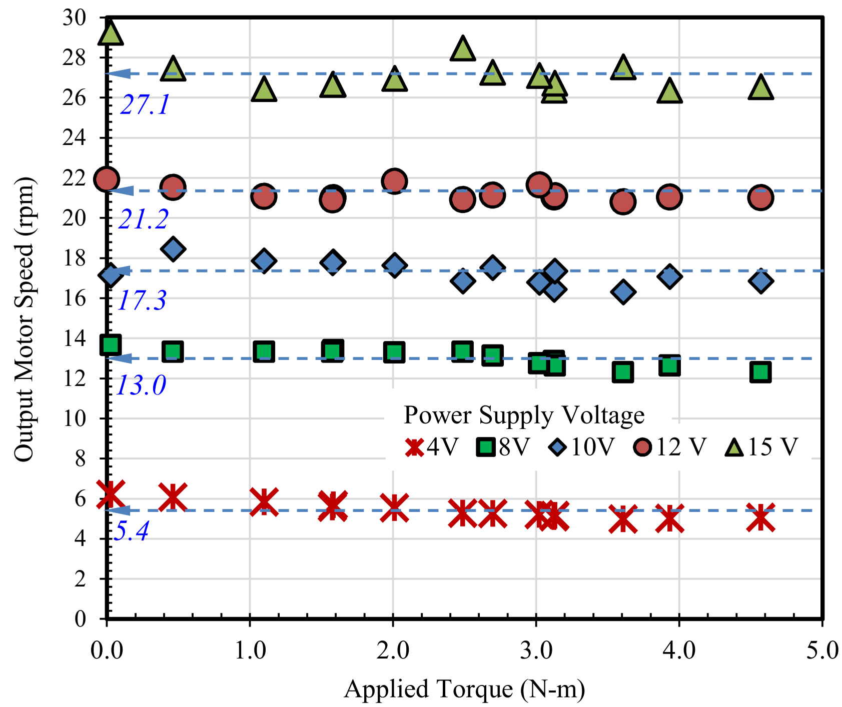


Figure 21. Motor output speeds against applied torques for changed power supply voltage.

As observed in Figure 21, the speed of the motor is maintained constant at 5.4, 13.0, 17.3, 21.2 and 27.1 rpm overall regardless the magnitude of torque (from 0 to 4.6 N-m) for power supply voltage of 4V, 8V, 10 V, 12 V and 15 V respectively.

2.6 Centrifuge Model Box Configuration

Figure 22 shows the model assembly on the centrifuge with its various components. Figure 23 shows the connection assembly to the centrifuge data logger placed alongside the model box in the loading arm.

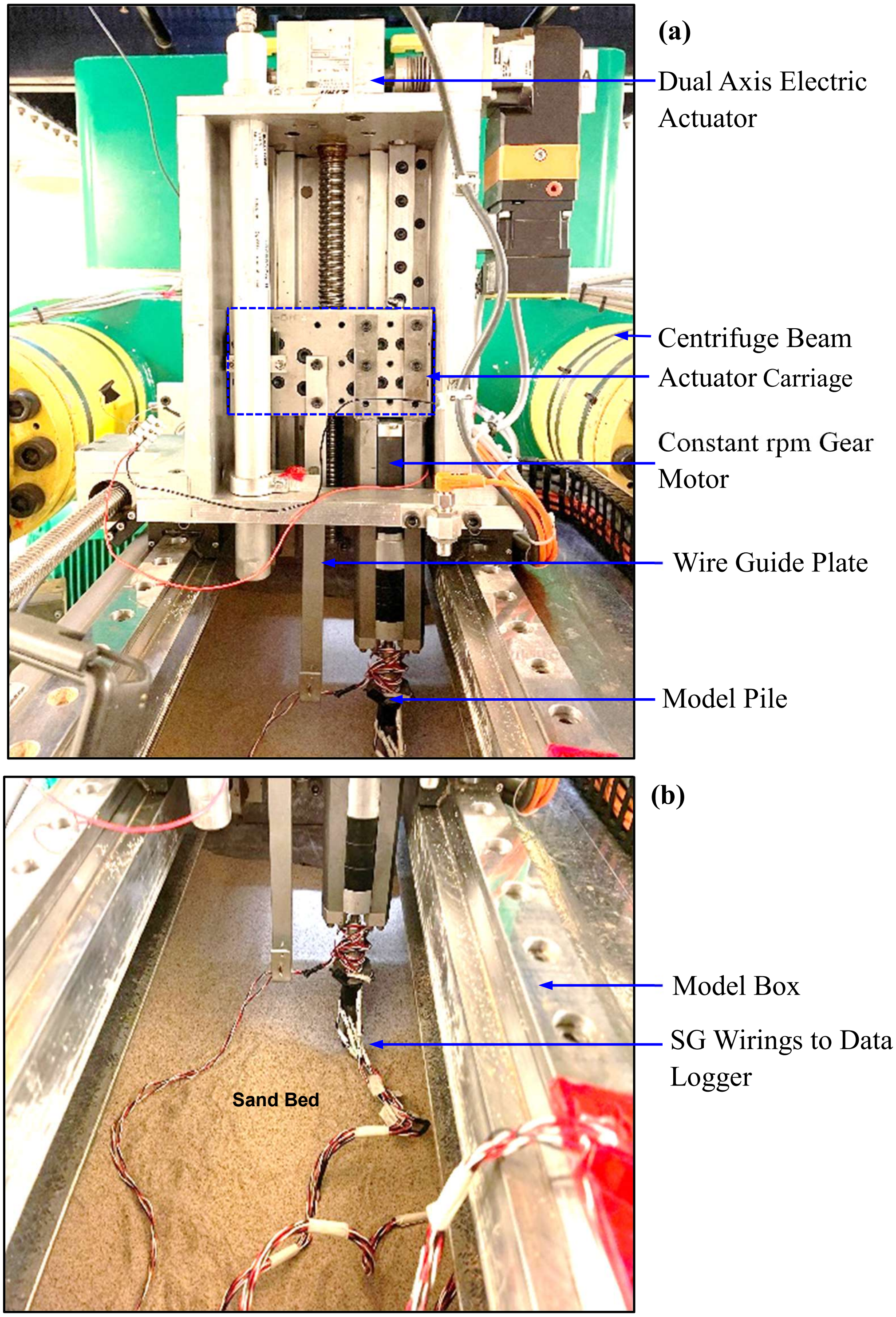


Figure 22. Centrifuge Model Assembly.

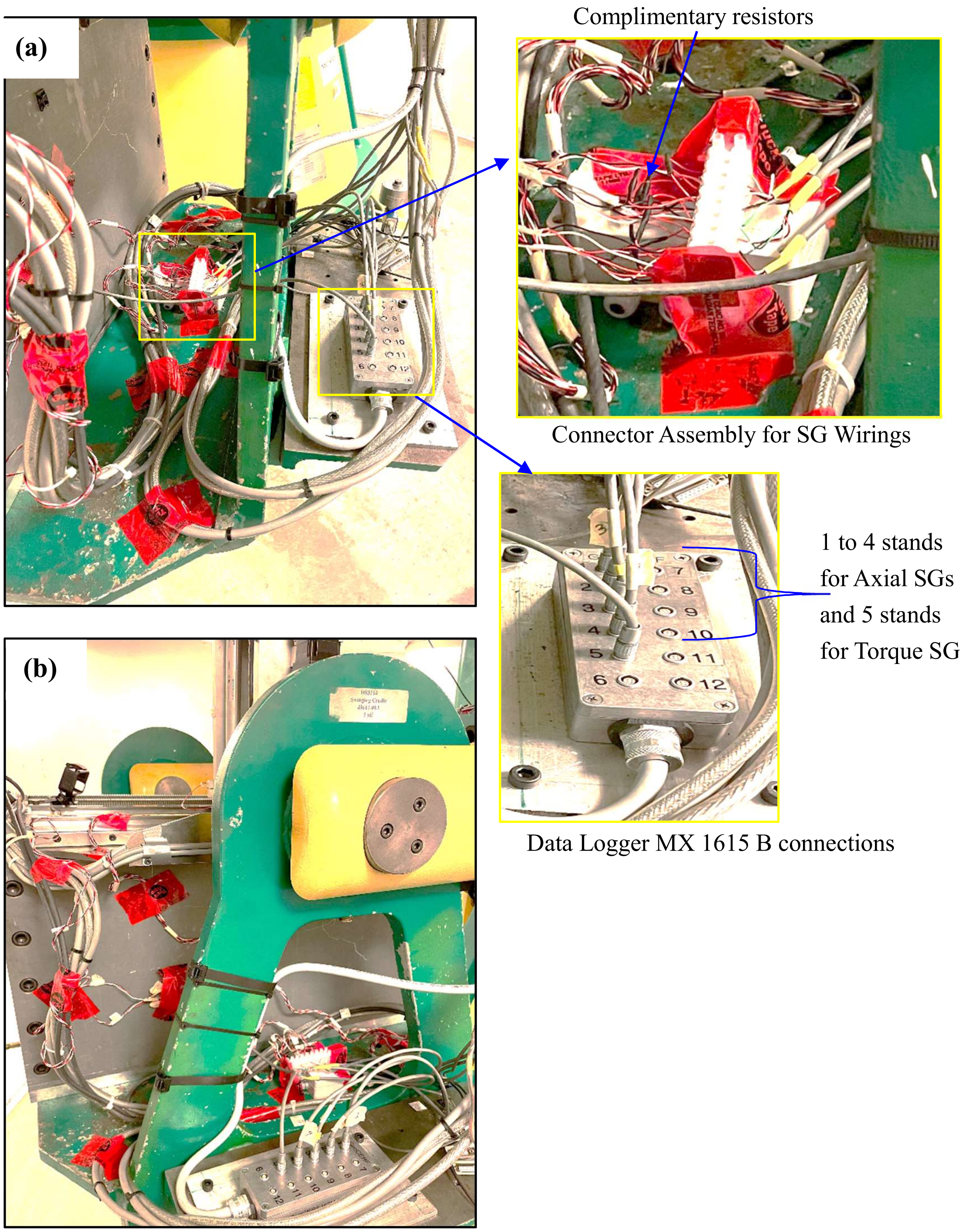


Figure 23. Wire Connections on the Centrifuge Assembly to the Centrifuge Datalogger; (a) Front view and (b) Side view

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3 Test and Loading Sequence

The test and loading sequence were arranged based on the test matrix. In the test sequence, the actions at each day with the time and date were recorded and presented in a tabular format. Table 7 and Table 8 shows the test sequence for NI01a and NI01b respectively.

Table 7. Test sequence for NI01a centrifuge model test

Day Count	Date	Time	Work/St	Action
1	8 Mar 22 Tuesday	10:00 am to 4:30 pm	1	Air pluviation of sand in model box
2	9 Mar 22 Wednesday	10:00 am to 1:00 pm		
		1:30 pm to 4:30 pm	2	Lowering of model box in the swinging table Loading setup arrangement
3	10 Mar 22 Thursday	10:00 am to 1:00 pm	3	Wirings and connections check Safety check of centrifuge testing for NI01A
		1:30 pm to 4:30 pm	4	Installation and Monotonic Compression on P0C
4	11 Mar 22 Friday	10:00 am to 1:00 pm	5	Installation and Monotonic Compression on P1C
		1:30 pm to 4:30 pm	6	Installation and Monotonic Compression on P2C
5	14 Mar 22 Monday	10:00 am to 1:00 pm	7	Installation and Monotonic Compression on P3C
		1:30 pm to 4:30 pm	8	Installation and Monotonic Compression on P4C
6	15 Mar 22 Tuesday	10:00 am to 1:00 pm	9	Lowering of loading setup and uplifting of model box
		1:30 pm to 4:30 pm		Clear of sand from the model box, taking out of installed piles, retrieval of data from the data logger for NI01A test

Table 8. Test sequence for NI01b centrifuge model test

Day Count	Date	Time	Work/St	Action
1	16 Mar 22 Wednesday	10:00 am to 4:30 pm	1	Air pluviation of sand in model box
2	17 Mar 22 Thursday	10:00 am to 1:00 pm		
		1:30 pm to 4:30 pm	2	Lowering of model box in the swinging table Loading setup arrangement
3	18 Mar 22 Friday	10:00 am to 1:00 pm	3	Wirings and connections check Safety check of centrifuge testing for NI01B
		1:30 pm to 4:30 pm	4	Installation and Monotonic Compression on P0T
4	21 Mar 22 Monday	10:00 am to 1:00 pm	5	Installation and Monotonic Compression on P1T
		1:30 pm to 4:30 pm	6	Installation and Monotonic Compression on P2T
5	22 Mar 22 Tuesday	10:00 am to 1:00 pm	7	Installation and Monotonic Compression on P3T
		1:30 pm to 4:30 pm	8	Lowering of loading setup and uplifting of model box
6	23 Mar 22 Wednesday	10:00 am to 1:00 pm	9	Sand from the model box, taking out of installed piles, retrieval of data from the data logger for NI01B test
		1:30 pm to 4:30 pm		

Table 8 and Table 9 shows the loading sequence for NI01a and NI01b respectively. In the loading sequence, the power supply voltage, pile installation rpm, actuator speed and the loading rate were recorded for each pile type.

Table 9. Loading sequence for NI01A centrifuge model test

Test ID	Pile type	Load type	Power supply voltage (V)	Pile Installation rpm (1g)	Actuator speed (mm/sec)	Loading rate (mm/min)	g level
P0C	P0	Compression	12	21.2	4.487	0.33	20
P1C	P1	Compression	12	21.2	4.487	0.33	20
P2C	P2	Compression	12	21.2	4.487	0.33	20
P3C	P3	Compression	12	21.2	4.487	0.33	20
P4C	P4	Compression	12	21.2	4.487	0.33	20

Table 10. Loading sequence for NI01B centrifuge model test

Test ID	Pile type	Load type	Power supply voltage (V)	Pile Installation rpm (1g)	Actuator speed (mm/sec)	Loading rate (mm/min)	g level
P0T	P0	Tension	12	21.2	4.487	10	20
P1T	P1	Tension	12	21.2	4.487	10	20
P2T	P2	Tension	12	21.2	4.487	10	20
P3T	P3	Tension	12	21.2	4.487	10	20

4 Recorded Data

The data was recorded in HBM Data Logger and arranged on the folder titled Centrifuge Test NI01 in the format shown in Table 11.

Table 11. Organization of data files

Test ID	Pile ID	SG Station ID	Data file	Description
NI01a P0Torque	P0	IT 1g	NI01A_P0_1gTorque	Install. torque
NI01a P0Torque	P1	IT 1g	NI01A_P1_1gTorque	Install. torque
NI01a P0Torque	P2	IT 1g	NI01A_P2_1gTorque	Install. torque
NI01a P0Torque	P3	IT 1g	NI01A_P3_1gTorque	Install. torque
NI01a P0Torque	P4	IT 1g	NI01A_P4_1gTorque	Install. torque
NI01b P0Torque	P0	IT 1g	NI01B_P0_1gTorque	Install. torque
NI01b P0Torque	P1	IT 1g	NI01B_P1_1gTorque	Install. torque
NI01b P0Torque	P2	IT 1g	NI01B_P2_1gTorque	Install. torque
NI01b P0Torque	P3	IT 1g	NI01B_P3_1gTorque	Install. torque
NI01a P0Axial	P0	L1-L2	NI01A_P0_Axial	Axial Compressive
NI01a P1Axial	P1	L1-L3	NI01A_P1_Axial	Axial Compressive
NI01a P2Axial	P2	L1-L4	NI01A_P2_Axial	Axial Compressive
NI01a P3Axial	P3	L1-L4	NI01A_P3_Axial	Axial Compressive
NI01a P4Axial	P4	L1-L4	NI01A_P4_Axial	Axial Compressive
NI01b P0Axial	P0	L1-L2	NI01B_P0_Axial	Axial Tensile
NI01b P1Axial	P1	L1-L3	NI01B_P1_Axial	Axial Tensile
NI01b P2Axial	P2	L1-L4	NI01B_P2_Axial	Axial Tensile
NI01b P3Axial	P3	L1-L4	NI01B_P3_Axial	Axial Tensile

Note: IT 1g= Installation torque at 1g; L1-L2, L3 or L4 identifies the axial strain gauges station from the tip of the pile and up.

5 Processed Results

The results are processed in MATHCAD and are presented in details in Appendix B. Figure 24 shows the photos from the model box after installations of the pile and after the spin for loading.

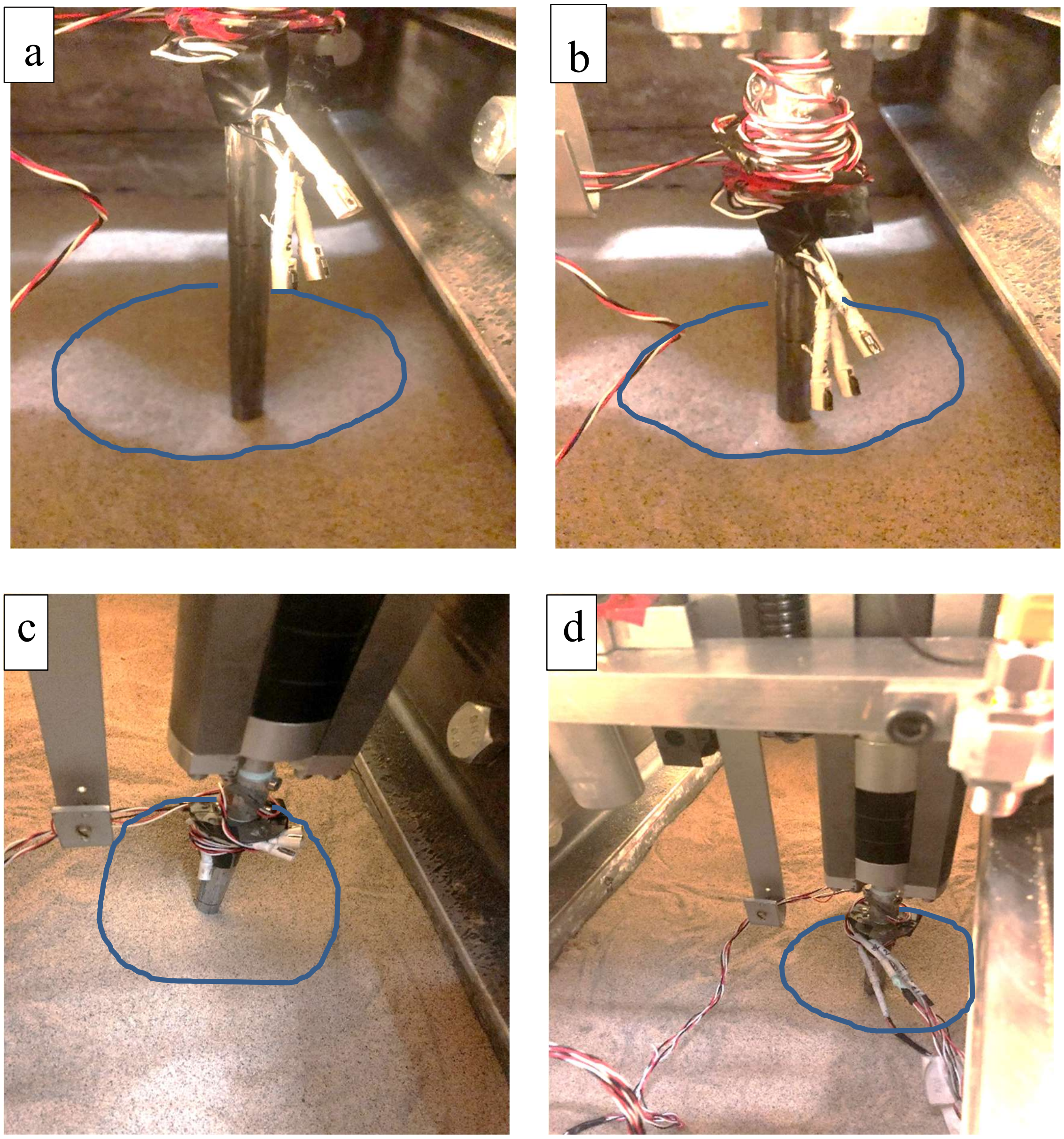

Figure 24. (a)-(b) Showing Caving of soil during pile installation at 1g; (c)-(d) Showing soil caving after loading at 20g.

6 Limitations

The model piles were installed at 1g due to the limitation on the capacity of the installation gear motor in the development of adequate torque. The specified maximum gear motor continuous torque was 16 N-m with a gear head efficiency of 70% that leads to a torque value of 11.2 N-m. Even at 1g, all of the piles reached the maximum capacity at about halfway distance within the pile installation. The estimated torque at 1 g (in model scale) was about 15.5 N-m and at 20 g (in prototype scale) was about 122.8 kN-m. A larger gear motor than can provide the required torque was again beyond the present accommodation capacity of the centrifuge assembly.

In the test of compression pile P3, the strain gauge L4 at the top did not provide the true representation of load. There could be a connection issue with the connector during the spinning of pile.

The piles were installed upto a maximum penetration depth of 20% of the diameter of the helix or the shaft. Penetrations of the piles were also made upto a depth of 70% of the diameter (D_h) which causes development of hinges on the piles and caused a mode pile to buckle. Figure 25 shows the photo of the buckled/failed pile while installed up to 70% of D_h.

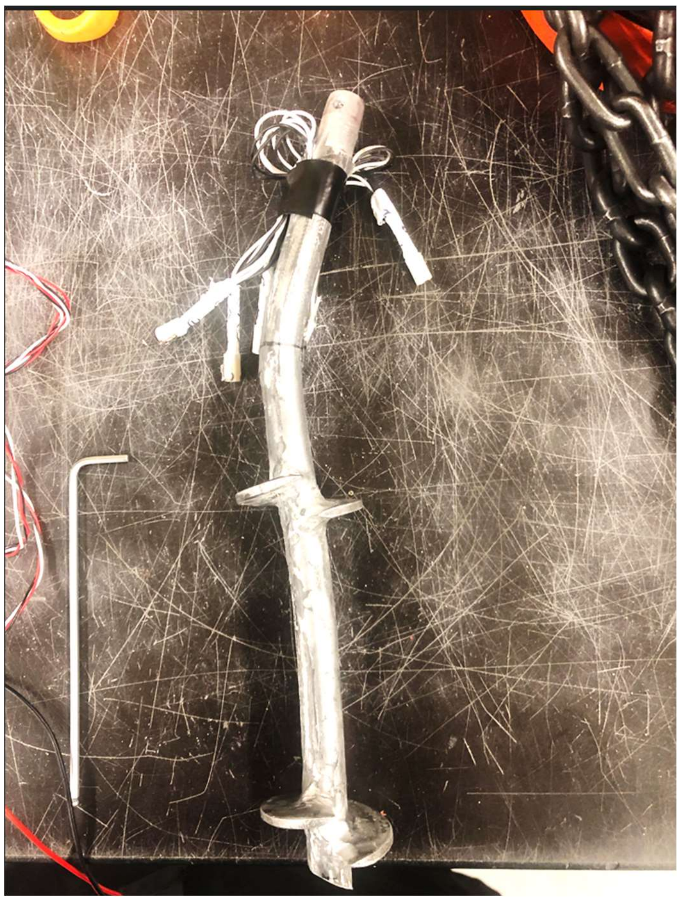

Figure 25. Failed Model Piles at higher penetration depth (70% of D_h).

The model piles were removed after each successive tests. This might not represent the true mechanism as in field.

7 Summary

NI01 centrifuge test series consists of the axial load tests on nine model piles in two separate boxes. Both smooth and helix piles were tested in compression and tension at the

GeoCerf Centrifuge facility at the University of Alberta. Among the helix piles, one single helix and three double helix piles were tested. The piles were installed in dry Sil-3 sand. The report summarizes the test results, axial strain gauge installation, instrumentation, and calibrations of the setup. A calibration chart was developed for a portable traveling pluviator for preparing the sand bed within the model box at a definite relative density. All the model piles were installed at a 1 g model scale and later tested at 20 g acceleration. A caving of soil was observed at the ground surface surrounding each pile. Appendix A presents the detailed results for the calibrations of the axial and torque strain gauges. Appendix B presents the results from the centrifuge tests for all the model piles tested.
The results presented here are from an ongoing project of helical pile research in the sand at the University of Alberta. The tests were conducted recently and are therefore considered preliminary for the current stage. Detailed interpretation will be presented in the following report and publications.

8 Future Tests and Modifications

In the following NI02 and NI03 test series the following additions and modifications will be adopted:

-The model piles will be attempted to be pre installed rather than installing it at 1 g.
-The model piles after each tests will be left in place rather than removal.
-Colored sand will be deposited in layers so as to visualize the soil disturbance surrounding the piles by excavating the portions and lubricating the sands with WD 40.

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Appendix A Calibration of Strain Gauges for Axial and Torque Measurements

Appendix B Data Conversion and Processing Sheet

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

1. Calibration of Axial Strain Gauges

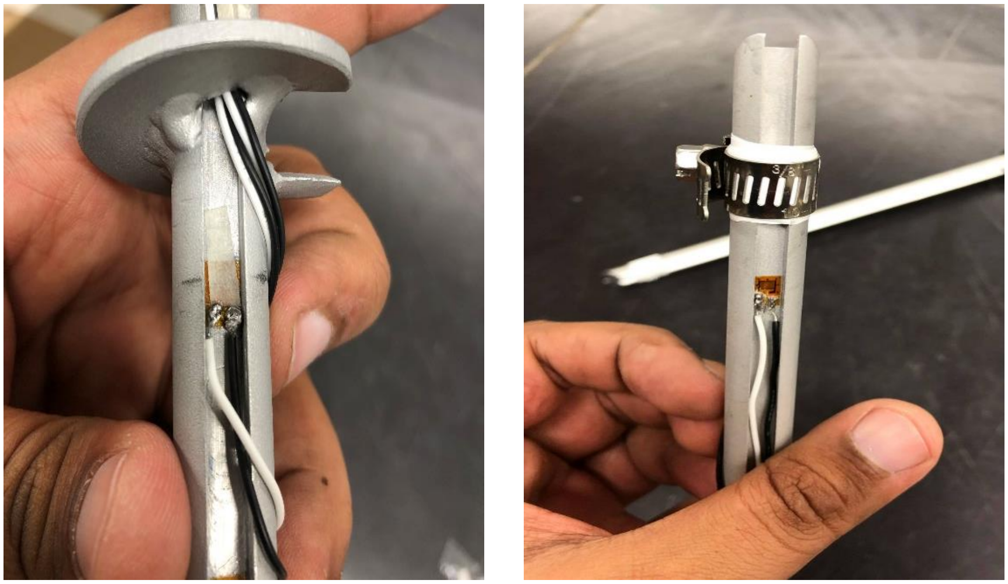
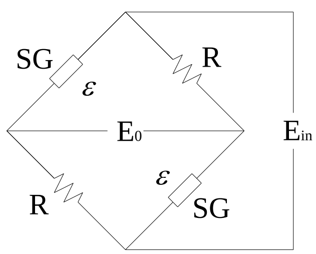


Figure A 1. Installed axial strain gages

The axial strain gauge Half bridge circuit is shown in Figure A2:



a) Axial

Figure A 2. Half bridge circuit for axial strain measurement, where SG = axial strain gauge on pile shaft and R = complementary resistor embedded in the data logger

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

Analytical Calculations,

Young's Modulus of the Aluminum,

$$E_{al} := 70 \cdot GPa$$

Diameter of the pile head,

$$d_{X\_pile} := 12.7\ mm$$

Cross sectional area of the pile head,

$$A_{X\_pile} := \pi \cdot \frac{(d_{X\_pile})^2}{4} = 126.677\ mm^2$$

Groove width,

$$b := 5\ mm$$

Groove depth,

$$h := 3.27\ mm$$

Arc angle,

$$\theta := 2 \cdot \text{acos}\left(\frac{\frac{b}{2}}{\frac{d_{X\_pile}}{2}}\right) \cdot \frac{180}{\pi} = 133.63$$

Cross sectional area at the strain gage location,

$$A_{SG\_pile} := 2 \cdot \frac{1}{2} \cdot \left(\frac{d_{X\_pile}}{2}\right)^2 \cdot \left(\left(\frac{\pi}{180} \cdot \theta\right) - \sin\left(\theta \cdot \frac{\pi}{180}\right)\right) + \left(2 \cdot \sqrt{\left(\left(\frac{d_{X\_pile}}{2}\right)^2 - \left(\frac{b}{2}\right)^2\right)} - (2 \cdot h)\right) \cdot b = 90.529\ mm^2$$

Poisson's ratio,

$$v := 0.3$$

Shear Modulus of the Aluminum,

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

$$G_{al} := \frac{E_{al}}{2\left(1+\nu\right)} = 26.923\ \mathbf{GPa}$$

Outer diameter of the adaptor,

$$d_{adap\_out} := d_{X\_pile} + 1.5875\ \mathbf{mm} = 14.288\ \mathbf{mm}$$

Inner diameter of the adaptor,

$$d_{adap\_in} := d_{X\_pile} = 12.7\ \mathbf{mm}$$

Polar moment of inertia of the adaptor,

$$J_{adaptor} := \pi \cdot \frac{\left(\left(\frac{d_{adap\_out}}{2}\right)^4 - \left(\frac{d_{adap\_in}}{2}\right)^4\right)}{2} = \left(1.537 \cdot 10^3\right)\ \mathbf{mm}^4$$

Output signal factor,

$$a := 200$$

Output voltage,

$$E_0 := 1 \cdot \mathbf{mV}$$

Input voltage,

$$E_{in} := 1 \cdot \mathbf{V}$$

Axial Gage Factor,

$GF_{axial} := 2.14$ <= Manufacturer

Axial Strain,

$$\varepsilon_a := 2 \cdot a \cdot \frac{E_0}{E_{in} \cdot GF_{axial}} = 0.187$$

Axial Force,

$$F := E_{al} \cdot A_{SG\_pile} \cdot \varepsilon_a = 1184.5\ \mathbf{kN}$$

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

The theoretical axial force per 1mV/V of HBM output are estimated.

Adopted Load Combinations

$$F_1 := 43.43\ N \qquad \varepsilon_1 := \frac{F_1}{E_{al} \cdot A_{SG\_pile}} = 6.853\ \frac{1}{m} \cdot \mu m$$

$$F_2 := 78.18\ N \qquad \varepsilon_2 := \frac{F_2}{E_{al} \cdot A_{SG\_pile}} = 12.337\ \frac{1}{m} \cdot \mu m$$

$$F_3 := 133.51\ N \qquad \varepsilon_3 := \frac{F_3}{E_{al} \cdot A_{SG\_pile}} = 21.068\ \frac{1}{m} \cdot \mu m$$

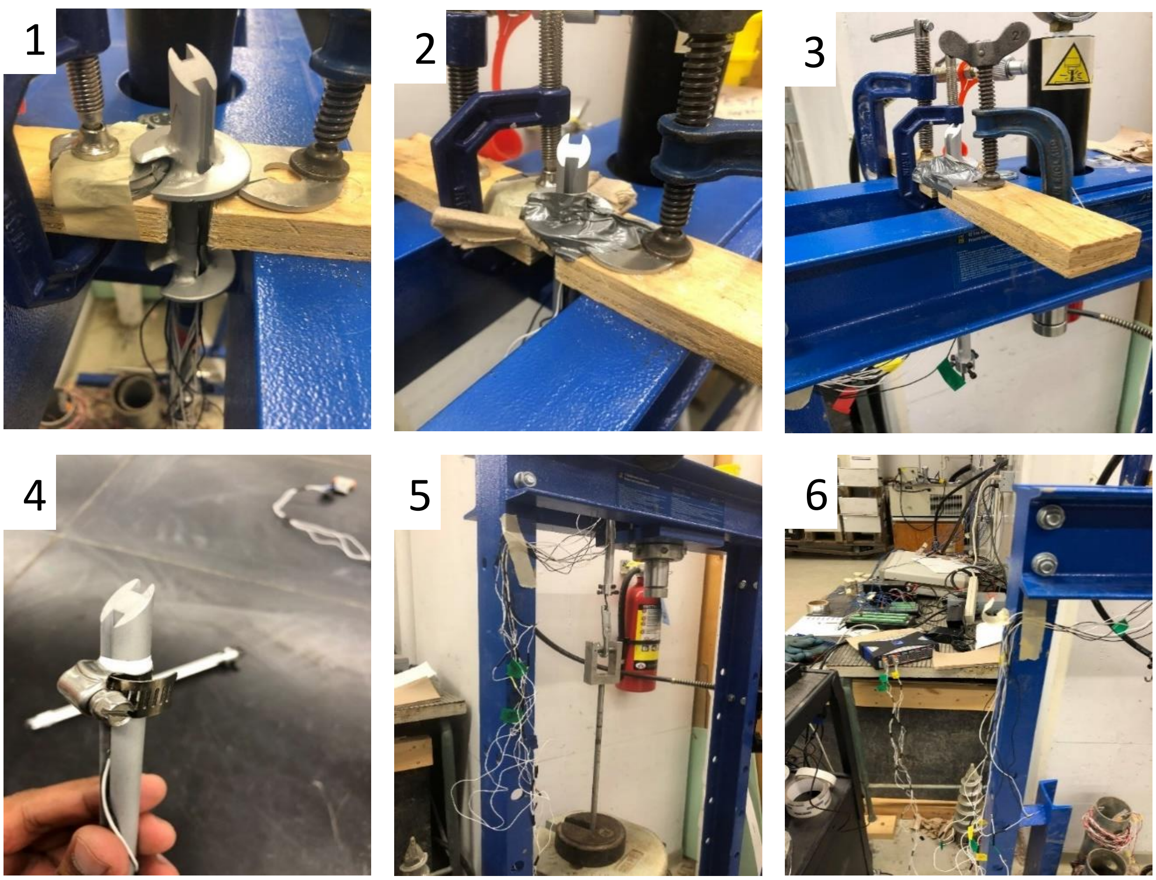


Figure A 3. Axial strain gauge calibration setup

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

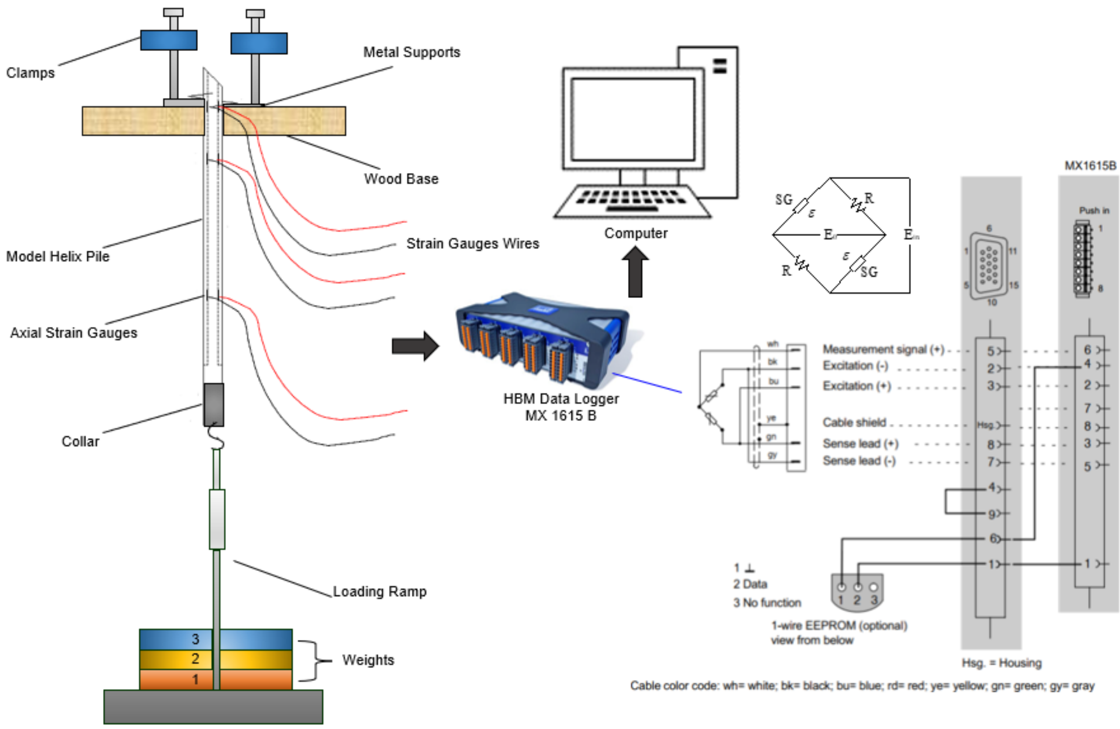


Figure A 4. Schematic calibration of axial strain gauges.

Table A 1. Calibration measurements for Axial Strain Gauges from the HBM Data Logger

Pile	Applied Load (N)	HBM Strain (μm/m)	HBM readings 10-3 (mV/V)	K_a (kN/mV/V)
P1	43.43	7.30	0.037	1190
	78.18	12.53	0.063	1248
	133.51	23.23	0.116	1149
P2	43.43	6.83	0.034	1273
	78.18	12.30	0.062	1271
	133.51	22.05	0.110	1211
P3	43.43	7.28	0.036	1194
	78.18	12.23	0.061	1278
	133.51	23.16	0.116	1153
P4	43.43	7.33	0.037	1186

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

Pile	Applied Load (N)	HBM Strain (μm/m)	HBM readings 10-3 (mV/V)	K_a (kN/mV/V)
	78.18	12.64	0.063	1237
	133.51	21.14	0.106	1263
	43.43	6.97	0.035	1246
P0	78.18	12.60	0.063	1241
	133.51	23.36	0.117	1143
			Average K_a (kN/mV/V)	**1219**

Table A 2. Summary of the axial strain gauge calibration results

SG type	Gauge Factor	Bridge type	Rosette	Excitation (V)	Calibration factor
Axial	2.14	Half	Axial	10	1219 kN/(mV/V)

2. Calibration of Torque Strain Gauges

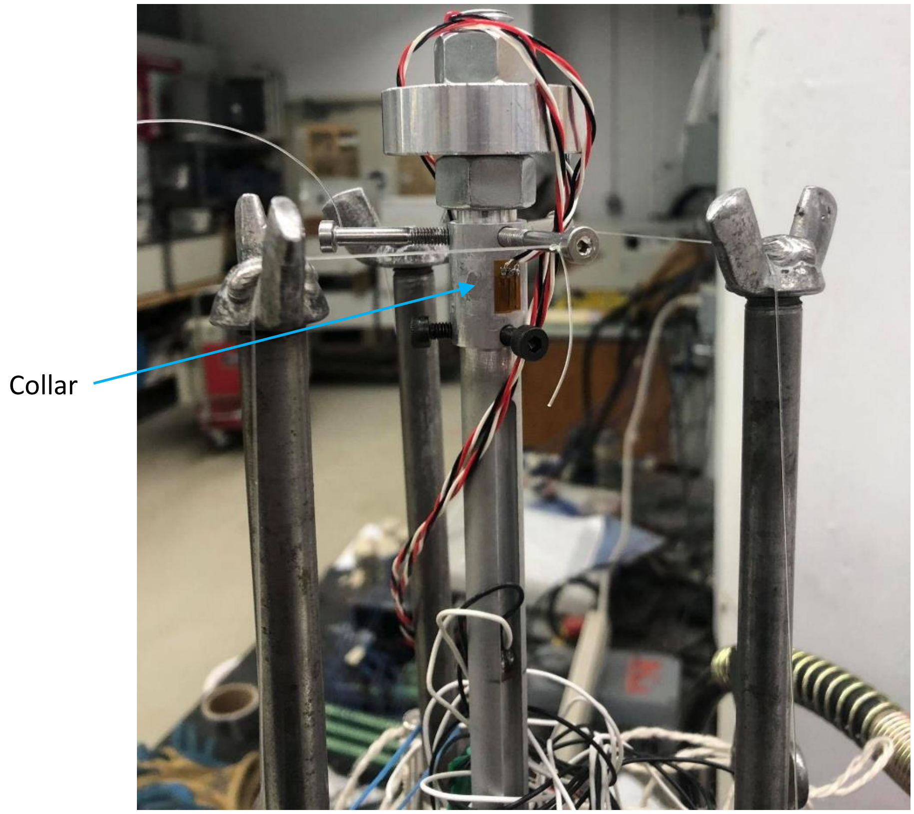


Figure A 5. Installed Torque Strain gages on the collar

Analytical Calculations

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

Young's Modulus of the Aluminum, $E_{al} := 70 \cdot GPa$

Diameter of the pile head, $d_{X\_pile} := 12.7\ mm$

Cross sectional area of the pile head, $A_{X\_pile} := \pi \cdot \frac{(d_{X\_pile})^2}{4} = 126.677\ mm^2$

Groove width, $b := 5\ mm$ Groove depth, $h := 3.27\ mm$

Arc angle, $\theta := 2 \cdot \mathrm{acos}\left(\frac{\frac{b}{2}}{\frac{d_{X\_pile}}{2}}\right) \cdot \frac{180}{\pi} = 133.63$

Cross sectional area at the strain gage location,

$$A_{SG\_pile} := 2 \cdot \frac{1}{2} \cdot \left(\frac{d_{X\_pile}}{2}\right)^2 \cdot \left(\left(\frac{\pi}{180} \cdot \theta\right) - \sin\left(\theta \cdot \frac{\pi}{180}\right)\right) + \left(2 \cdot \sqrt{\left(\left(\frac{d_{X\_pile}}{2}\right)^2 - \left(\frac{b}{2}\right)^2\right)} - (2 \cdot h)\right) \cdot b = 90.529\ mm^2$$

Poisson's ratio, $\nu := 0.3$

Shear Modulus of the Aluminum, $G_{al} := \frac{E_{al}}{2\ (1+\nu)} = 26.923\ GPa$

Outer diameter of the adaptor, $d_{adap\_out} := d_{X\_pile} + 1.5875\ mm = 14.288\ mm$

Inner diameter of the adaptor, $d_{adap\_in} := d_{X\_pile} = 12.7\ mm$

Polar moment of inertia of the adaptor, $J_{adaptor} := \pi \cdot \frac{\left(\left(\frac{d_{adap\_out}}{2}\right)^4\right)}{2} = \left(4.091 \cdot 10^3\right)\ mm^4$

Output signal factor, $a := 200$ Output voltage, $E_0 := 1 \cdot mV$

Input voltage, $E_{in} := 1 \cdot V$

Axial Gage Factor, $GF_{axial} := 2.14$ <= Manufacturer

Axial Strain, $\varepsilon_a := 2 \cdot a \cdot \frac{E_0}{E_{in} \cdot GF_{axial}} = 0.187$

Axial Force, $F := E_{al} \cdot A_{SG\_pile} \cdot \varepsilon_a = 1184.5\ kN$

Torque Gage Factor, $GF_{torque} := 2.11$ <= Manufacturer

Maximum shear strain, $\gamma_{max} := 2 \cdot a \cdot \frac{E_0}{E_{in} \cdot GF_{torque}} = 0.19$

Torque, $T := G_{al} \cdot \gamma_{max} \cdot \frac{J_{adaptor}}{\frac{d_{adap\_out}}{2}} = 2.923\ kN \cdot m$

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01
Centrifuge Tests

Adopted Torque Loads

$T_1 := 0.14\ N \cdot m$ $\qquad \gamma_{max1} := \dfrac{T_1 \cdot \dfrac{d_{adap\_out}}{2}}{G_{al} \cdot J_{adaptor}} = 9.08\ \dfrac{1}{m} \cdot \mu m$

$T_2 := 0.21\ N \cdot m$ $\qquad \gamma_{max2} := \dfrac{T_2 \cdot \dfrac{d_{adap\_out}}{2}}{G_{al} \cdot J_{adaptor}} = 13.621\ \dfrac{1}{m} \cdot \mu m$

$T_3 := 0.35\ N \cdot m$ $\qquad \gamma_{max3} := \dfrac{T_3 \cdot \dfrac{d_{adap\_out}}{2}}{G_{al} \cdot J_{adaptor}} = 22.701\ \dfrac{1}{m} \cdot \mu m$

The torque strain gauge Full bridge circuit is shown in Figure A 6.

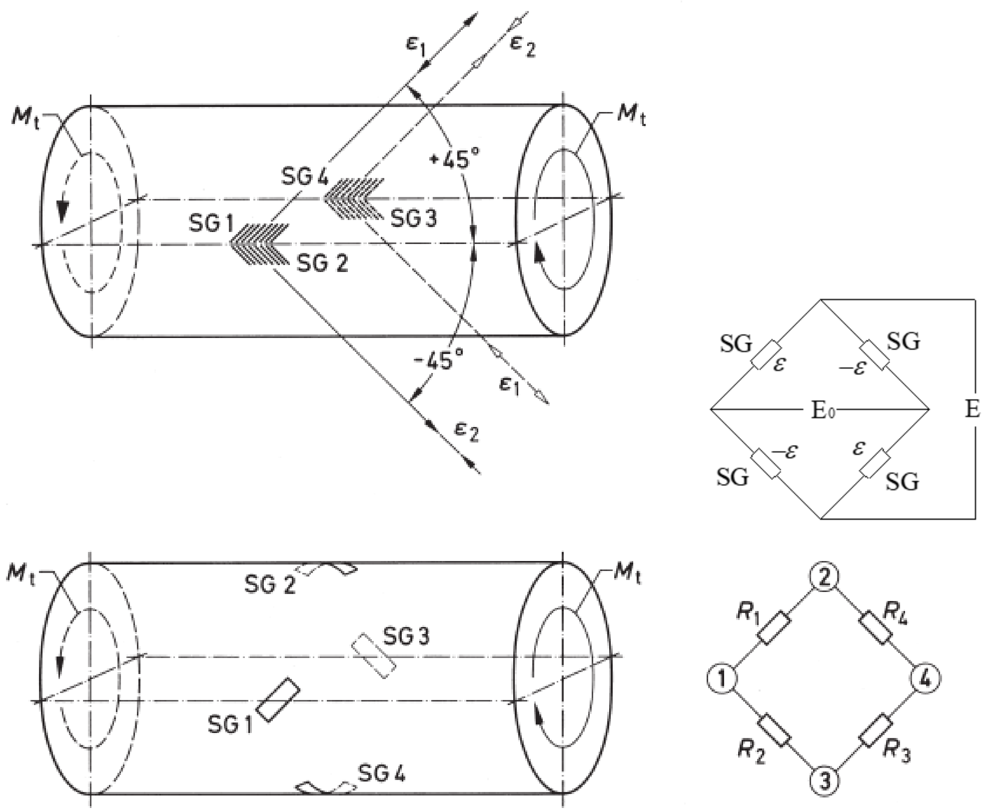


Figure A 6. Full bridge circuit for torque strain measurement, where SG = torque strain gauge on the collar over the pile shaft

For the twisted shaft,

$|\varepsilon_1| = |\varepsilon_2| = \varepsilon_{45^\circ}$

$\Rightarrow \varepsilon_1 = \varepsilon_{45^\circ}$ *then* $\varepsilon_2 = -\varepsilon_{45^\circ}$

ε_{45° = Normal strain measured by individual gauge on the torque gauge pad (at 45 deg wrt. to the longitudinal axis of the shaft)

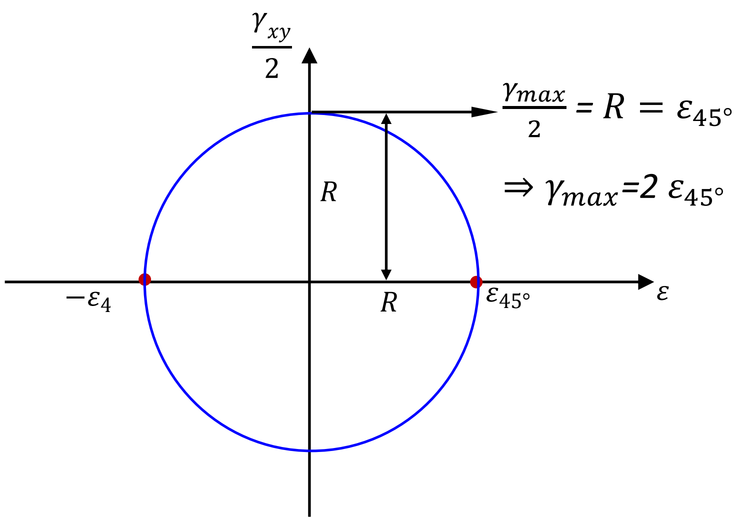


Figure A 7. Strain Mohr circle for torque strain gauge

For torque gauges, maximum shear strain induced by external torque, $\boldsymbol{\gamma_{max} = 2\ \varepsilon_{45^\circ}}$

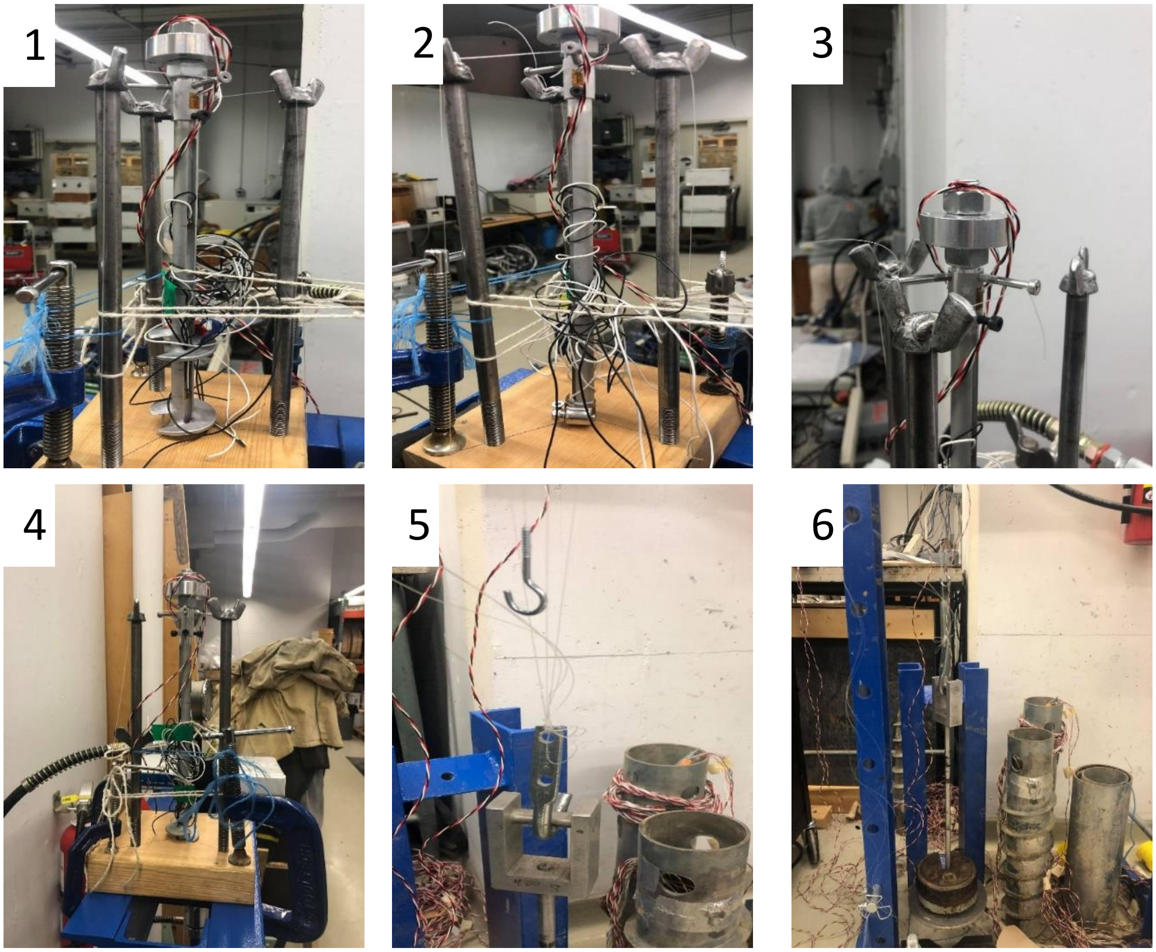


Figure A 8. Torque strain gauge calibration setup

Appendix A
Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

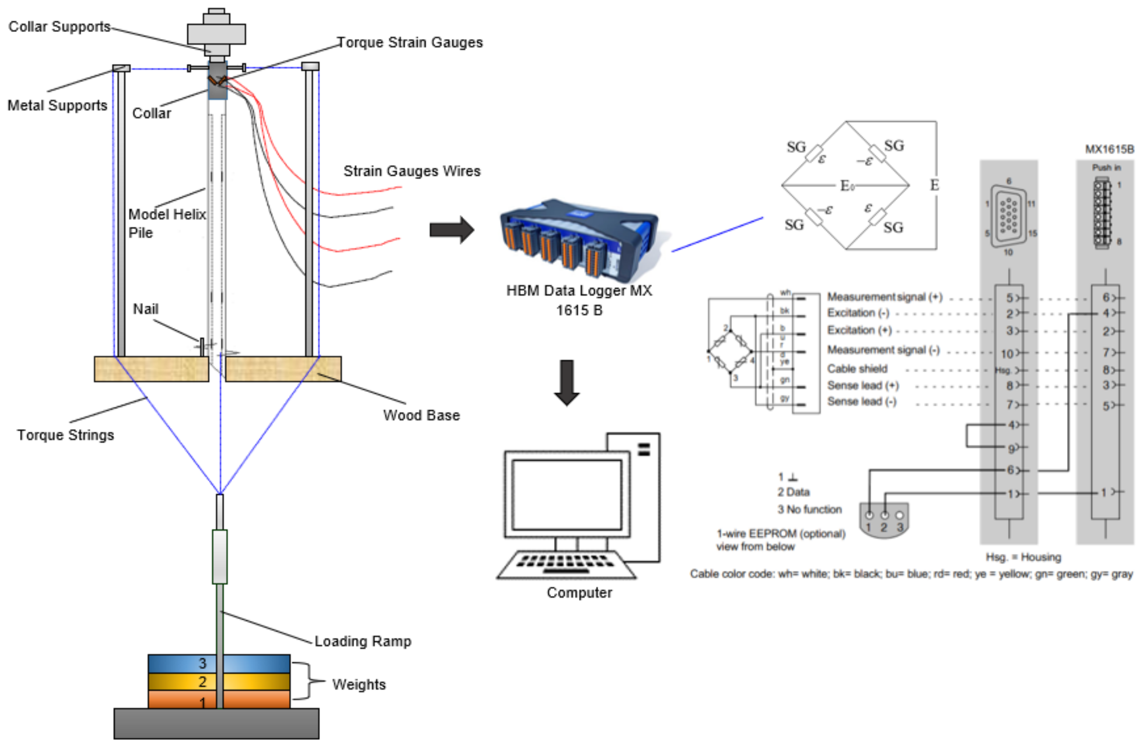


Figure A 9. Schematic of calibration setup for torque strain gauge.

Table A 3. Calibration measurements for Torque strain gauges from the HBM Data Logger

Pile	Applied Torque (N-m)	HBM Strain (μm/m)	HBM readings 10^{-3} (mV/V)	K_t (kN-m/mV/V)
P1	0.14	9.286	0.046	3.105
	0.21	13.792	0.069	2.989
	0.35	22.4	0.112	3.128
P2	0.14	9.01	0.045	3.200
	0.21	13.166	0.066	3.132
	0.35	22.991	0.115	3.047
P3	0.14	9.26	0.046	3.113
	0.21	13.218	0.066	3.119
	0.35	22.241	0.111	3.150

Appendix A

Calibration of Strain Gauges for Axial and Torque Measurements in NI01 Centrifuge Tests

Pile	**Applied Torque (N-m)**	**HBM Strain (μm/m)**	**HBM readings 10^{-3} (mV/V)**	**K_t (kN-m/mV/V)**
P4	0.14	9.178	0.046	3.141
	0.21	13.455	0.067	3.064
	0.35	22.8	0.114	3.073
P0	0.14	9.128	0.046	3.159
	0.21	13.8	0.069	2.988
	0.35	22.89	0.114	3.061

Average K_t (kN-m/mV/V) **3.098**

Table A 4. Summary of the axial strain gauge calibration results

SG type	Gauge Factor	Bridge type	Rosette	Excitation (V)	Calibration factor
Torque	2.115	Full	45°	5	3.098 kN-m/(mV/V)

Appendix B

Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

1. Introduction

The series of sheets in Appendix B contains the data conversion and processing procedures specifically for the NI01 centrifuge test series. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

$L := 271.8\ mm$	*Length of the Pile*
$d := 12.7\ mm$	*Diameter of the shaft*
$D := 38.1\ mm$	*Diameter of the helix*
$E := 169.1\ mm$	*Embedment depth of pile*
$H_b := 150\ mm$	*Depth to bottom helix*
$H_t := [150]\ mm$	*Depth to top helix*
$P_s := \pi \cdot D = 0.12\ m$	*Perimeter of the Helical Pile Shaft*
$H_{eff} := (H_b - D)$	*Effective Shaft Length*
$P := 12.7\ mm$	*Pitch of the helix*

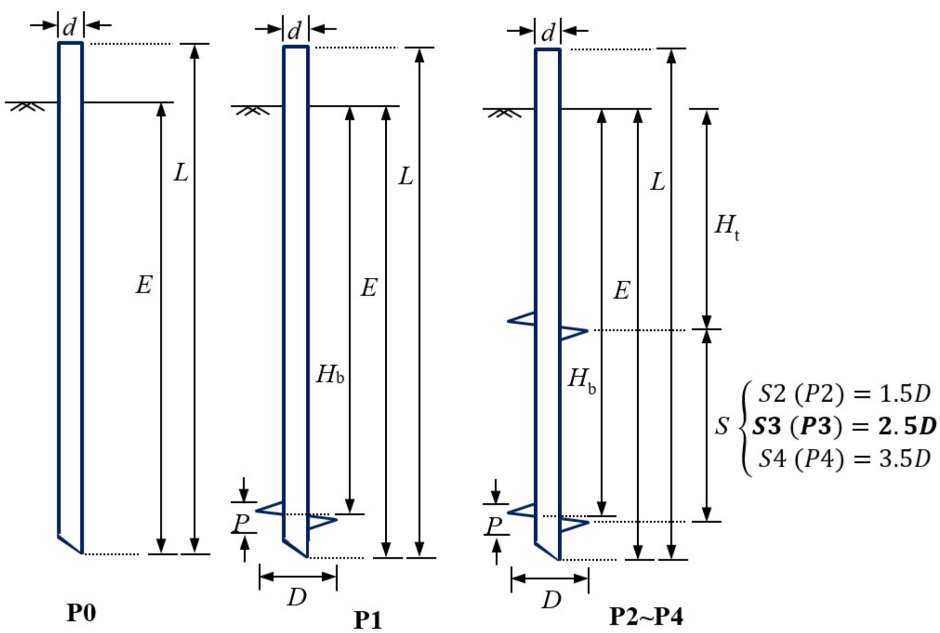


Fig B 1. Schematic of the model piles

2.1.3 Properties of Sand

$\gamma := 16.1 \, \frac{kN}{m^3}$ *Unit Weight*

$\varphi := 31.2 \, deg$ *CV Friction Angle*

$\delta := \left(\frac{3}{4} \cdot \varphi\right) = 23.4 \, deg$ *CV Dilation Angle*

2.1.4 Centrifuge Scale

$NoSGages := 4$ *1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P1=3, P2 to P4= 4*

$Nscale := 20$ *Centrifuge g-level*

$sclfac := \begin{bmatrix} 1 & 2 & 3 \end{bmatrix}$ *Centrifuge scale factor N^scale, 1 for displacement , 2 for force, 3 for Torque*

2.1.5 Loading Conditions

$CmpRate := 0.33 \, \frac{mm}{min}$ *Actuator Loading rate in compression*

$TenRate := 10 \, \frac{mm}{min}$ *Actuator Loading rate in tension*

$ActDisp := 20\% \cdot D$ *Total Actual Displacment during loading in both compression and tension*

$CmpLdTime := \frac{ActDisp}{CmpRate} = 1385.455 \, s$ *Actuator Loading time in compression*

$TenLdTime := \frac{ActDisp}{TenRate} = 45.72 \, s$ *Actuator Loading time in tension*

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“.\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$\text{RawDataCalib} = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$CmbLdAx := \text{RawDataCalib}^{\langle 0 \rangle} \, kg \cdot g$ *Load Combinations*

$CalibdataPile := \text{submatrix}(\text{RawDataCalib}, 0, \text{rows}(\text{RawDataCalib}) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V}$ *HBM Strain Gage Data*

Function for Calibration factor for all strain gages in each pile

$$CF := \left\| \begin{array}{l} \text{for } i \in 0,1..\text{rows}(CalibdataPile)-1 \\ \quad \left\| \begin{array}{l} \text{for } j \in 0,1..\text{cols}(CalibdataPile)-1 \\ \quad \left\| \begin{array}{l} k_{i,j} \leftarrow CmbLdAx_{i,0} \\ q_{i,j} \leftarrow CalibdataPile_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \qquad \left\| 0 \right. \\ \qquad \text{else} \\ \qquad \left\| \dfrac{k_{i,j}}{q_{i,j}} \right. \end{array} \right. \end{array} \right. \\ m \end{array} \right. = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{\frac{mV}{V}}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

2.2.1 Calibration of Torque Strain Gages

RawDataTorque := READEXCEL(“.\Calibration Torque S Gages HBM Centrifuge .xlsx”, “Sheet1!J34:K36”)

$$\text{RawDataTorque} = \begin{bmatrix} 0.144 & 0.022 \\ 0.206 & 0.03 \\ 0.35 & 0.052 \end{bmatrix}$$

$$CmbLdTr := \text{RawDataTorque}^{\langle 0 \rangle}\, N \cdot m$$

$$CalibdataTr := \text{RawDataTorque}^{\langle 1 \rangle} \cdot 10^{-3} \cdot \frac{mV}{V}$$

$$CFTr := \left\| \begin{array}{l} \text{for } i \in 0,1..\text{rows}(CalibdataTr)-1 \\ \quad \left\| \begin{array}{l} \text{for } j \in 0,1..\text{cols}(CalibdataTr)-1 \\ \quad \left\| \begin{array}{l} k_{i,j} \leftarrow CmbLdTr_{i,0} \\ q_{i,j} \leftarrow CalibdataTr_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \qquad \left\| 0 \right. \\ \qquad \text{else} \\ \qquad \left\| \dfrac{k_{i,j}}{q_{i,j}} \right. \end{array} \right. \end{array} \right. \\ m \end{array} \right. = \begin{bmatrix} 6.674 \\ 6.813 \\ 6.763 \end{bmatrix} m \cdot \frac{kN}{\frac{mV}{V}}$$

2.3 Axial Centrifuge Test on Piles

Five piles were tested in compression and four piles were tested in tension in two separate model boxes two ascertain the axial load transfer mechansim within the pile.

2.3.1 Axial Load vs Depth

2.3.1.1 Compression Pile P1

There were three strain gages placed within the P1 pile. The following sub sections provides the details on the load distributions:

$P := \mathrm{READEXCEL}(\text{“.\\NI01 HBM Data Corrected.xlsx”}, \text{“P1C Axial!B1:F1438”})$

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 1437 \end{array} \begin{bmatrix} 63 & 0.001 & 8.301 \cdot 10^{-4} & 7.897 \cdot 10^{-4} & 0.001 \\ 64 & 0.001 & 8.459 \cdot 10^{-4} & 7.998 \cdot 10^{-4} & 0.001 \\ 65 & 0.001 & 8.589 \cdot 10^{-4} & 8.099 \cdot 10^{-4} & 0.001 \\ 66 & 0.001 & 8.704 \cdot 10^{-4} & 8.185 \cdot 10^{-4} & 0.001 \\ 67 & 0.001 & 8.805 \cdot 10^{-4} & 8.272 \cdot 10^{-4} & 0.001 \\ 68 & 0.001 & 8.92 \cdot 10^{-4} & 8.373 \cdot 10^{-4} & 0.001 \\ 69 & 0.001 & 9.05 \cdot 10^{-4} & 8.503 \cdot 10^{-4} & 0.001 \\ 70 & 0.001 & 9.18 \cdot 10^{-4} & 8.647 \cdot 10^{-4} & 0.001 \\ 71 & 0.001 & 9.31 \cdot 10^{-4} & 8.791 \cdot 10^{-4} & 0.001 \\ 72 & 0.001 & 9.439 \cdot 10^{-4} & 8.935 \cdot 10^{-4} & 0.001 \\ 73 & 0.001 & 9.555 \cdot 10^{-4} & 9.065 \cdot 10^{-4} & 0.001 \\ 74 & 0.001 & 9.67 \cdot 10^{-4} & 9.194 \cdot 10^{-4} & 0.001 \\ & & & & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$TimeP1 := P^{\langle 0 \rangle}\, s$

$RawdataP1 := \mathrm{submatrix}(P, 0, \mathrm{rows}(P) - 1, 1, 4) \cdot \dfrac{mV}{V}$

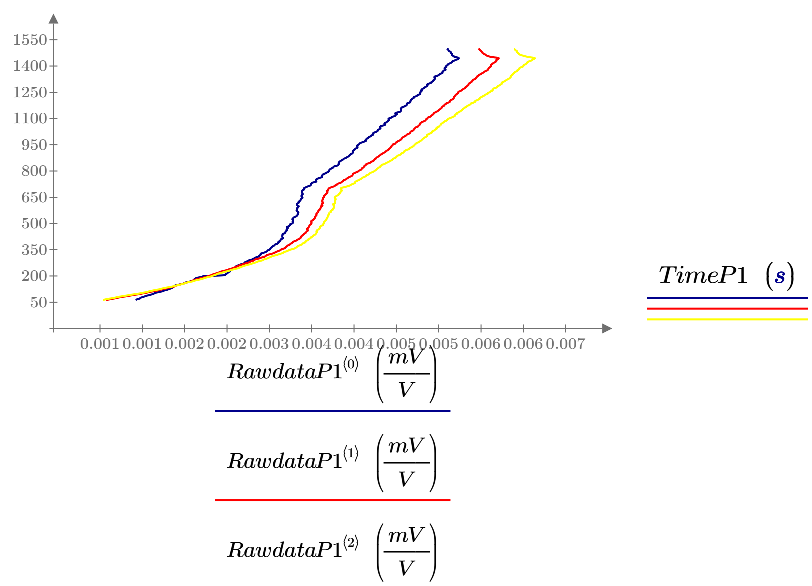


Fig B 2. Rawdata time history for compression pile P1

Appendix B
Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

Function for determining the Axial Load Distribution in each pile

$$AxlLd(Rawdata, PileNum) := \left\| \begin{array}{l} \text{for } i \in 0,1..\text{rows}(Rawdata)-1 \\ \quad \left\| \begin{array}{l} \text{for } j \in 0,1..\text{cols}(Rawdata)-1 \\ \quad \left\| \; q_{i,j} \leftarrow Rawdata_{i,j} - Rawdata_{0,j} \right. \\ SG1_{i,0} \leftarrow q_{i,0} \cdot \text{mean}(\text{submatrix}(CF,0,2,PileNum,PileNum)) \cdot Nscale^{sclfac_{0,1}} \\ SG2_{i,1} \leftarrow q_{i,1} \cdot \text{mean}(\text{submatrix}(CF,3,5,PileNum,PileNum)) \cdot Nscale^{sclfac_{0,1}} \\ SG3_{i,2} \leftarrow q_{i,2} \cdot \text{mean}(\text{submatrix}(CF,6,8,PileNum,PileNum)) \cdot Nscale^{sclfac_{0,1}} \\ SG4_{i,3} \leftarrow q_{i,3} \cdot \text{mean}(\text{submatrix}(CF,9,11,PileNum,PileNum)) \cdot Nscale^{sclfac_{0,1}} \end{array} \right. \\ \text{augment}\left(SG1^{\langle 0 \rangle}, SG2^{\langle 1 \rangle}, SG3^{\langle 2 \rangle}, SG4^{\langle 3 \rangle}\right) \end{array} \right.$$

$$LdP1 := AxlLd(RawdataP1, 1) = \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1.02 & 4.296 & 4.44 & 0 \\ 2.04 & 7.811 & 8.88 & 0 \\ 2.804 & 10.936 & 12.685 & 0 \\ 3.824 & 13.67 & 16.491 & 0 \\ 5.099 & 16.795 & 20.93 & 0 \\ 6.629 & 20.31 & 26.639 & 0 \\ 8.413 & 23.825 & 32.981 & 0 \\ 9.688 & 27.34 & 39.324 & 0 \\ 10.198 & 30.855 & 45.666 & 0 \\ 10.453 & 33.98 & 51.375 & 0 \\ 10.708 & 37.104 & 57.083 & 0 \\ & & & \vdots \end{bmatrix} kN$$

Axial Load for P1 Pile from the Raw HBM Strain Gage Data

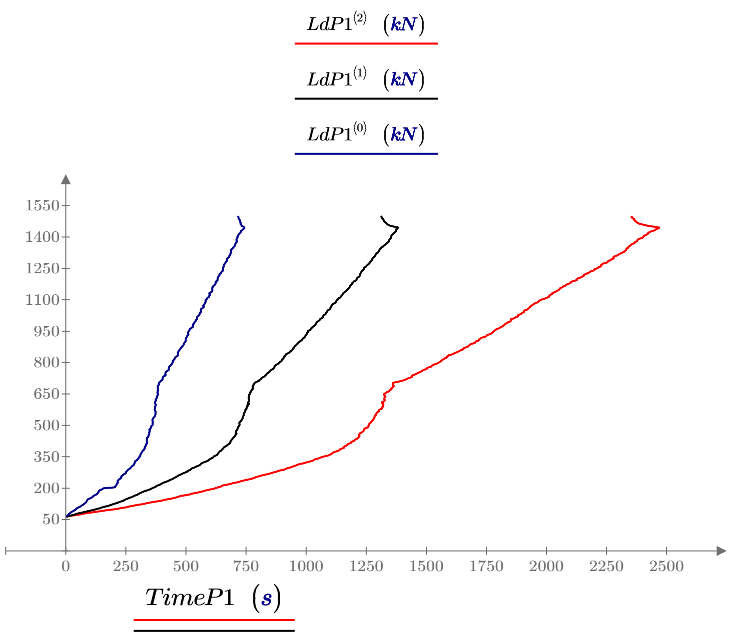


Fig B 3. Load time history for compression pile P1

Appendix B
Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

Function for determining the penetration Depth

$$percentD(TimeP) := \left\| \begin{array}{l} \text{for } i \in 0,1..\text{rows}(TimeP)-1 \\ \quad \left\| k_i \leftarrow -\left(TimeP_i - TimeP_0\right) \cdot \dfrac{CmpRate}{D} \cdot 100 \right. \\ k \end{array} \right.$$

$$DP1 := percentD(TimeP1) = \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 \\ -0.014 \\ -0.029 \\ -0.043 \\ -0.058 \\ -0.072 \\ -0.087 \\ -0.101 \\ -0.115 \\ -0.13 \\ -0.144 \\ -0.159 \\ \vdots \end{bmatrix}$$

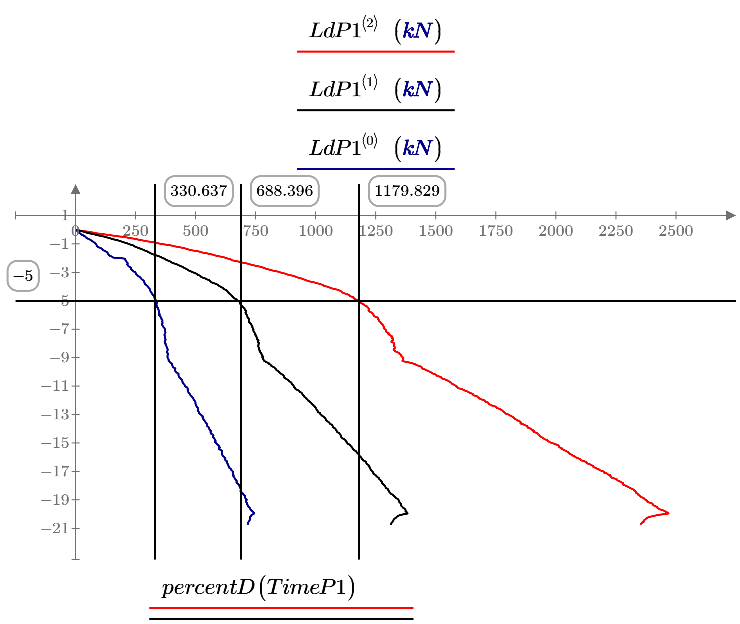


Fig B 4. Depth vs Load for compression pile P1

$$PCSGLd(LdP, DP) := \text{augment}\left(DP, \frac{LdP}{kN}\right)$$

$P1CSGLd := PCSGLd(LdP1, DP1)$ WRITEEXCEL("P1CSGLd.xlsx", $P1CSGLd$)

2.3.1.2 Compression Pile P2

There were four strain gages placed within the P2 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL(".\NI01 HBM Data Corrected.xlsx", "P2 C Axial!C1:G1574")

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 1573 \end{array} \begin{bmatrix} 63 & 2.709\cdot 10^{-4} & 4.727\cdot 10^{-4} & 4.367\cdot 10^{-4} & -0.872 \\ 64 & 2.925\cdot 10^{-4} & 4.885\cdot 10^{-4} & 4.511\cdot 10^{-4} & -0.872 \\ 65 & 3.17\cdot 10^{-4} & 5.058\cdot 10^{-4} & 4.655\cdot 10^{-4} & -0.872 \\ 66 & 3.43\cdot 10^{-4} & 5.188\cdot 10^{-4} & 4.784\cdot 10^{-4} & -0.872 \\ 67 & 3.66\cdot 10^{-4} & 5.289\cdot 10^{-4} & 4.9\cdot 10^{-4} & -0.872 \\ 68 & 3.848\cdot 10^{-4} & 5.375\cdot 10^{-4} & 5.001\cdot 10^{-4} & -0.872 \\ 69 & 4.021\cdot 10^{-4} & 5.462\cdot 10^{-4} & 5.102\cdot 10^{-4} & -0.872 \\ 70 & 4.165\cdot 10^{-4} & 5.577\cdot 10^{-4} & 5.202\cdot 10^{-4} & -0.872 \\ 71 & 4.295\cdot 10^{-4} & 5.692\cdot 10^{-4} & 5.318\cdot 10^{-4} & -0.872 \\ 72 & 4.41\cdot 10^{-4} & 5.822\cdot 10^{-4} & 5.433\cdot 10^{-4} & -0.872 \\ 73 & 4.467\cdot 10^{-4} & 5.966\cdot 10^{-4} & 5.548\cdot 10^{-4} & -0.872 \\ 74 & 4.511\cdot 10^{-4} & 6.125\cdot 10^{-4} & 5.678\cdot 10^{-4} & -0.872 \\ & & & & \vdots \\ & & & & \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$$TimeP2 := P^{\langle 0\rangle}\, s$$

$$RawdataP2 := \text{submatrix}(P, 0, \text{rows}(P)-1, 1, 4)\cdot \frac{mV}{V}$$

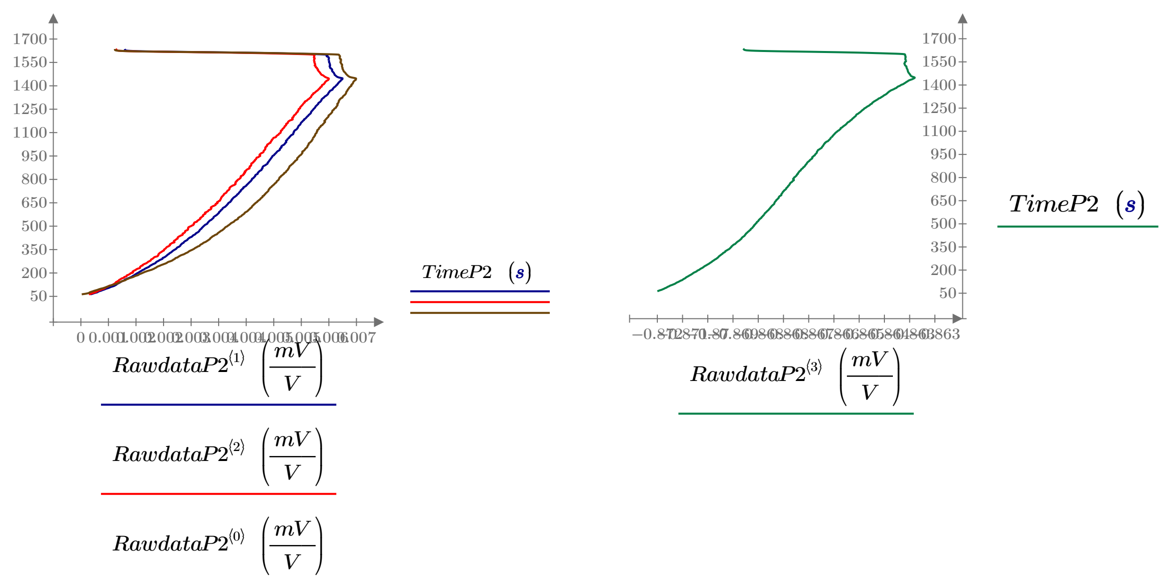


Fig B 5. Rawdata time history for compression pile P2

$$LdP2 := AxlLd(RawdataP2, 2) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \left[\begin{array}{cccc} 0 & 0 & 0 & 0 \\ 2.94 & 4.377 & 5.262 & 4.492 \\ 6.273 & 9.152 & 10.524 & 8.985 \\ 9.801 & 12.734 & 15.26 & 12.666 \\ 12.938 & 15.519 & 19.47 & 16.331 \\ 15.486 & 17.907 & 23.154 & 19.607 \\ 17.839 & 20.294 & 26.837 & 24.1 \\ 19.799 & 23.478 & 30.521 & 29.403 \\ 21.563 & 26.661 & 34.73 & 34.706 \\ 23.131 & 30.243 & 38.94 & 39.198 \\ 23.915 & 34.222 & 43.15 & 42.88 \\ 24.504 & 38.599 & 47.886 & 46.139 \\ & & & \vdots \end{array}\right] kN$$

Axial Load for P2 Pile from the Raw HBM Strain Gage Data

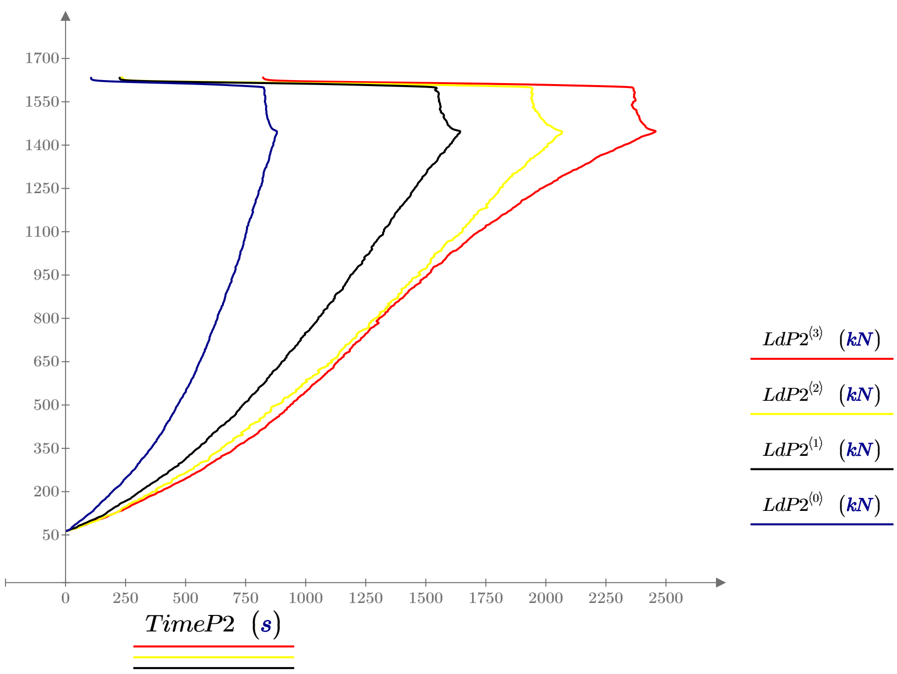


Fig B 6. Load time history for compression pile P2

$$DP2 := percentD(TimeP2) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \left[\begin{array}{c} 0 \\ -0.014 \\ -0.029 \\ -0.043 \\ -0.058 \\ -0.072 \\ -0.087 \\ -0.101 \\ -0.115 \\ -0.13 \\ -0.144 \\ -0.159 \\ \vdots \end{array}\right]$$

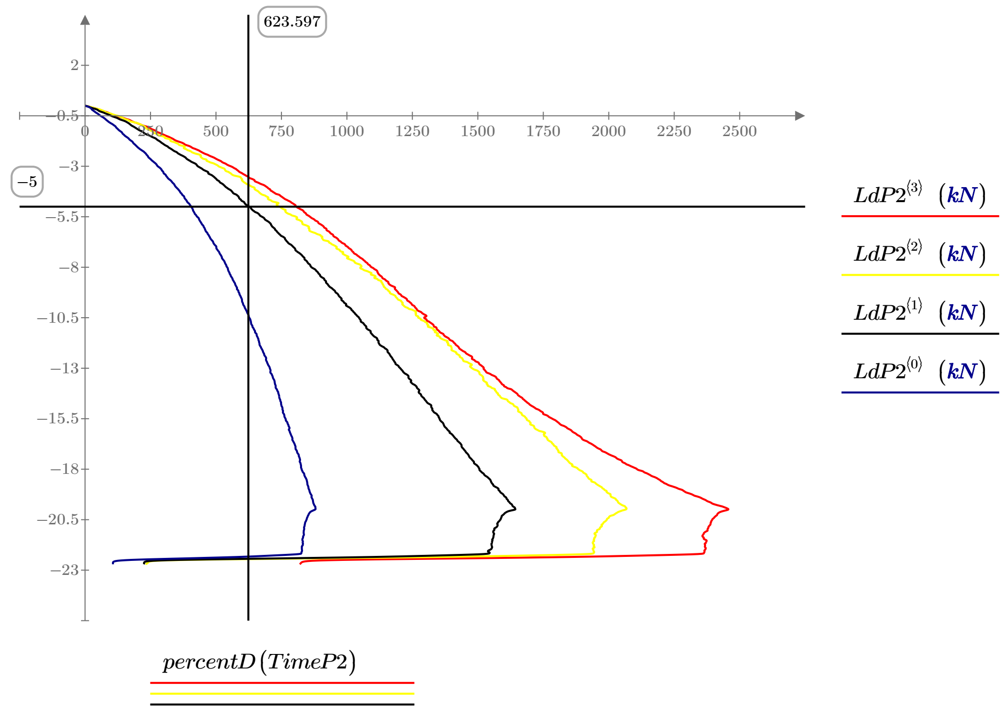


Fig B 7. Depth vs Load for compression pile P2

$P2CSGLd := PCSGLd(LdP2, DP2)$ WRITEEXCEL ("P2CSGLd.xlsx", $P2CSGLd$)

2.3.1.3 Compression Pile P3

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL (".\NI01 HBM Data Corrected.xlsx", "P3 C Axial!C1:G1531")

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 1530 \end{array} \begin{bmatrix} 63 & 7.263\cdot10^{-4} & 7.667\cdot10^{-4} & 8.56\cdot10^{-4} & 0.092 \\ 64 & 7.465\cdot10^{-4} & 7.897\cdot10^{-4} & 8.733\cdot10^{-4} & 0.092 \\ 65 & 7.71\cdot10^{-4} & 8.171\cdot10^{-4} & 8.935\cdot10^{-4} & 0.092 \\ 66 & 7.969\cdot10^{-4} & 8.459\cdot10^{-4} & 9.18\cdot10^{-4} & 0.092 \\ 67 & 8.2\cdot10^{-4} & 8.748\cdot10^{-4} & 9.425\cdot10^{-4} & 0.092 \\ 68 & 8.43\cdot10^{-4} & 9.036\cdot10^{-4} & 9.684\cdot10^{-4} & 0.093 \\ 69 & 8.647\cdot10^{-4} & 9.295\cdot10^{-4} & 9.929\cdot10^{-4} & 0.093 \\ 70 & 8.834\cdot10^{-4} & 9.526\cdot10^{-4} & 0.001 & 0.093 \\ 71 & 9.021\cdot10^{-4} & 9.756\cdot10^{-4} & 0.001 & 0.093 \\ 72 & 9.194\cdot10^{-4} & 9.958\cdot10^{-4} & 0.001 & 0.093 \\ 73 & 9.382\cdot10^{-4} & 0.001 & 0.001 & 0.093 \\ 74 & 9.555\cdot10^{-4} & 0.001 & 0.001 & 0.093 \\ & & & & \vdots \end{bmatrix}$$

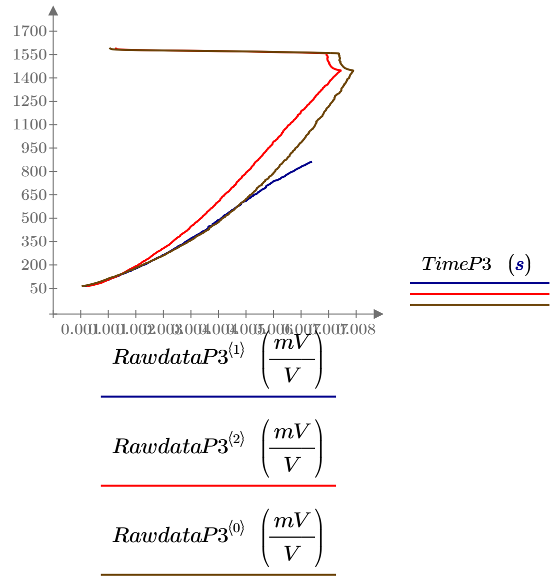
Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

Appendix B

Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

$TimeP3 := P^{\langle 0 \rangle}\ s$

$RawdataP3 := \text{submatrix}(P, 0, \text{rows}(P)-1, 1, 4) \cdot \frac{mV}{V}$



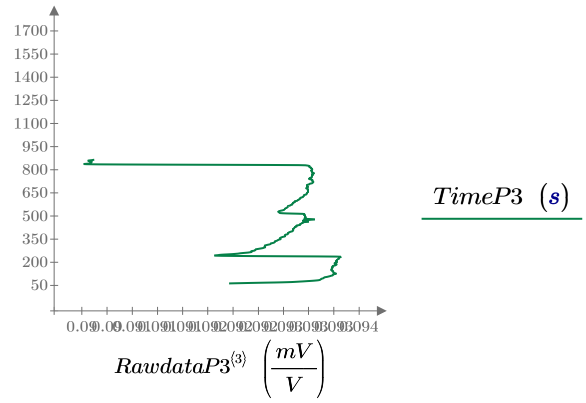


Fig B 8. Rawdata time history for compression pile P3

$LdP3 := AxlLd(RawdataP3, 3) =$

0	0	0	0	0
1	3.521	5.057	6.061	42.519
2	7.796	11.062	13.133	84.376
3	12.322	17.382	21.72	131.546
4	16.345	23.703	30.307	184.029
5	20.369	30.024	39.399	237.846
6	24.141	35.713	47.986	289
7	27.41	40.77	55.562	334.841
8	30.679	45.826	62.634	372.047
9	33.697	50.251	68.19	399.951
10	36.966	54.043	73.241	420.546
11	39.984	57.836	78.292	437.82
⋮				⋮

kN

Axial Load for P3 Pile from the Raw HBM Strain Gage Data

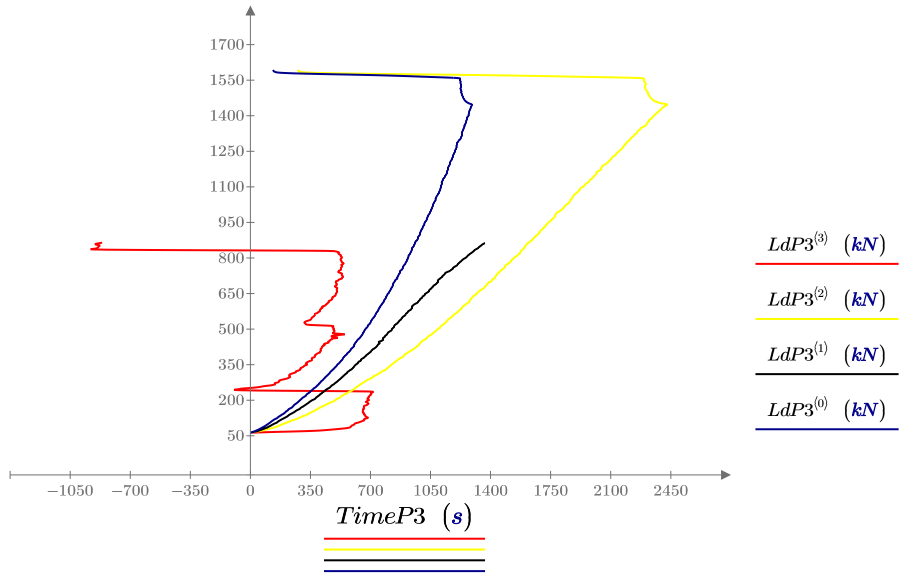


Fig B 9. Load time history for compression pile P3

$$DP3 := percentD(TimeP3) = \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 \\ -0.014 \\ -0.029 \\ -0.043 \\ -0.058 \\ -0.072 \\ -0.087 \\ -0.101 \\ -0.115 \\ -0.13 \\ -0.144 \\ -0.159 \\ \vdots \end{bmatrix}$$

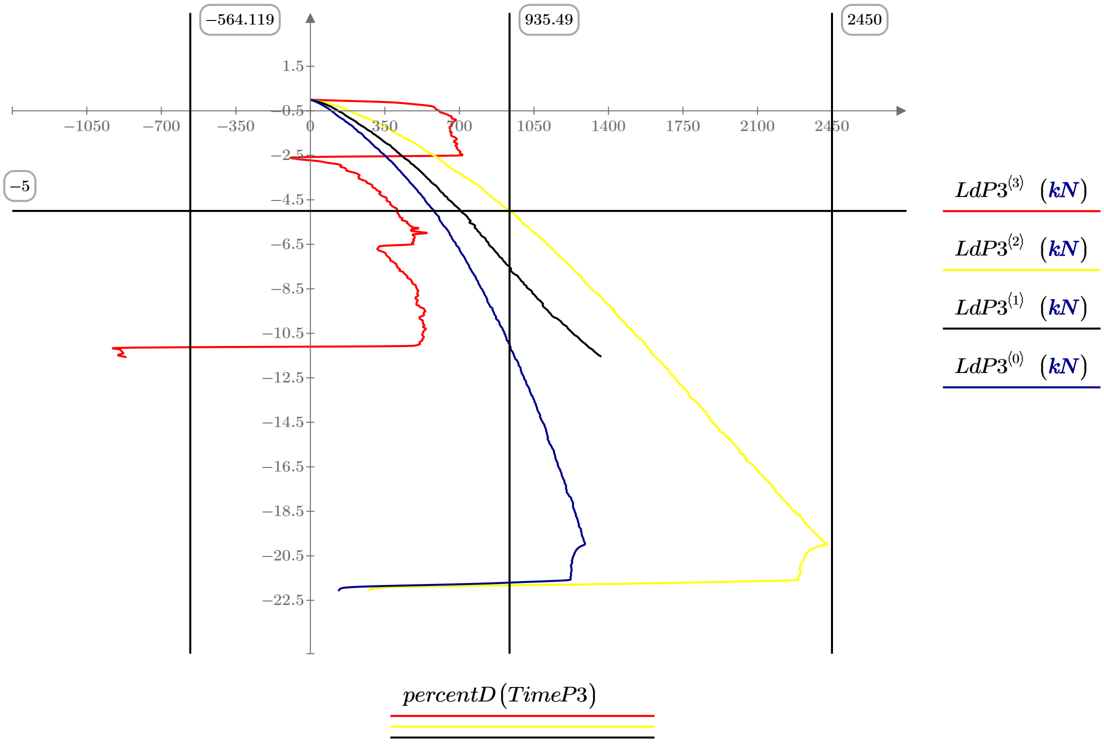


Fig B 10. Depth vs Load for compression pile P3

$P3CSGLd := PCSGLd(LdP3, DP3)$ WRITEEXCEL ("P3CSGLd.xlsx", $P3CSGLd$)

2.3.1.4 Compression Pile P4

There were four strain gages placed within the P4 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL (".\NI01 HBM Data Corrected.xlsx", "P4 C Axial!C1:G1589")

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 1588 \end{array} \left[\begin{array}{lllll} 65 & 3.502 \cdot 10^{-4} & 6.154 \cdot 10^{-4} & 5.447 \cdot 10^{-4} & 5.491 \cdot 10^{-4} \\ 66 & 3.632 \cdot 10^{-4} & 6.326 \cdot 10^{-4} & 5.606 \cdot 10^{-4} & 5.591 \cdot 10^{-4} \\ 67 & 3.79 \cdot 10^{-4} & 6.514 \cdot 10^{-4} & 5.764 \cdot 10^{-4} & 5.721 \cdot 10^{-4} \\ 68 & 3.934 \cdot 10^{-4} & 6.701 \cdot 10^{-4} & 5.909 \cdot 10^{-4} & 5.865 \cdot 10^{-4} \\ 69 & 4.078 \cdot 10^{-4} & 6.874 \cdot 10^{-4} & 6.053 \cdot 10^{-4} & 6.009 \cdot 10^{-4} \\ 70 & 4.222 \cdot 10^{-4} & 7.018 \cdot 10^{-4} & 6.197 \cdot 10^{-4} & 6.139 \cdot 10^{-4} \\ 71 & 4.367 \cdot 10^{-4} & 7.162 \cdot 10^{-4} & 6.341 \cdot 10^{-4} & 6.283 \cdot 10^{-4} \\ 72 & 4.511 \cdot 10^{-4} & 7.306 \cdot 10^{-4} & 6.499 \cdot 10^{-4} & 6.399 \cdot 10^{-4} \\ 73 & 4.684 \cdot 10^{-4} & 7.479 \cdot 10^{-4} & 6.672 \cdot 10^{-4} & 6.528 \cdot 10^{-4} \\ 74 & 4.871 \cdot 10^{-4} & 7.652 \cdot 10^{-4} & 6.831 \cdot 10^{-4} & 6.672 \cdot 10^{-4} \\ 75 & 5.058 \cdot 10^{-4} & 7.825 \cdot 10^{-4} & 6.975 \cdot 10^{-4} & 6.831 \cdot 10^{-4} \\ 76 & 5.246 \cdot 10^{-4} & 7.998 \cdot 10^{-4} & 7.119 \cdot 10^{-4} & 6.989 \cdot 10^{-4} \\ & & & & \vdots \end{array} \right]$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$TimeP4 := P^{\langle 0 \rangle}\ s$

Appendix B
Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

$$RawdataP4 := \text{submatrix}(P, 0, \text{rows}(P) - 1, 1, 4) \cdot \frac{mV}{V}$$

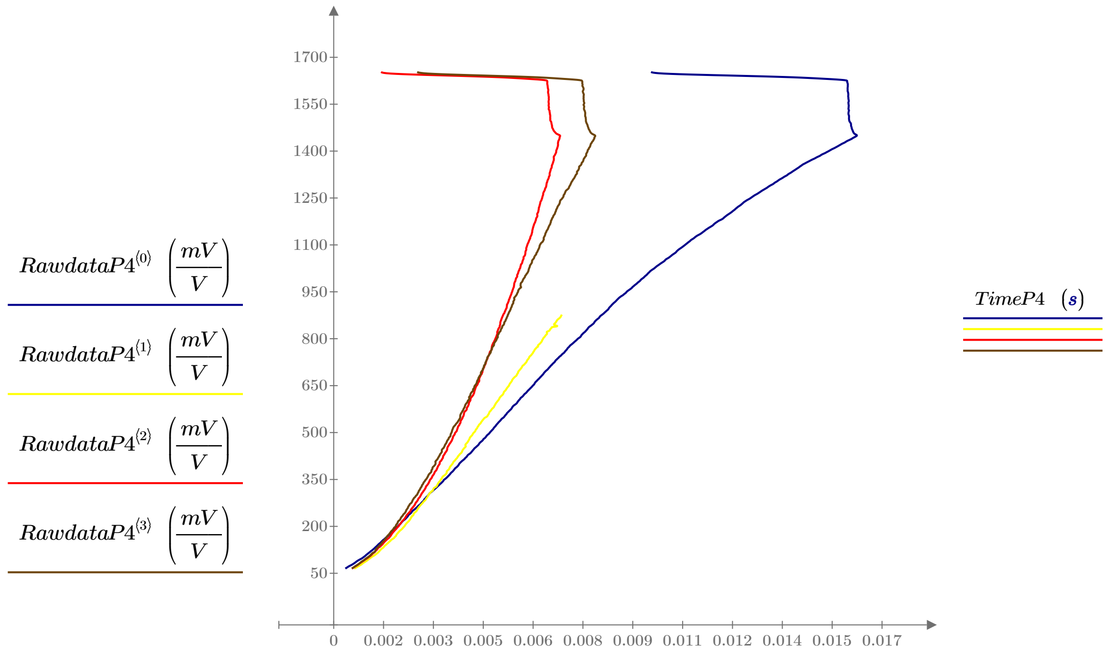


Fig B 11. Rawdata time history for compression pile P4

$LdP4 := AxlLd(RawdataP4, 4) =$

0	0	0	0	0
1	1.809	3.262	7.116	5.27
2	4.021	6.795	14.232	12.045
3	6.031	10.329	20.701	19.573
4	8.042	13.591	27.17	27.101
5	10.052	16.309	33.639	33.877
6	12.063	19.027	40.108	41.405
7	14.073	21.746	47.224	47.427
8	16.486	25.007	54.987	54.202
9	19.1	28.269	62.103	61.731
10	21.713	31.531	68.572	70.012
11	24.327	34.793	75.041	78.292
⋮				⋮

kN

Axial Load for P4 Pile from the Raw HBM Strain Gage Data

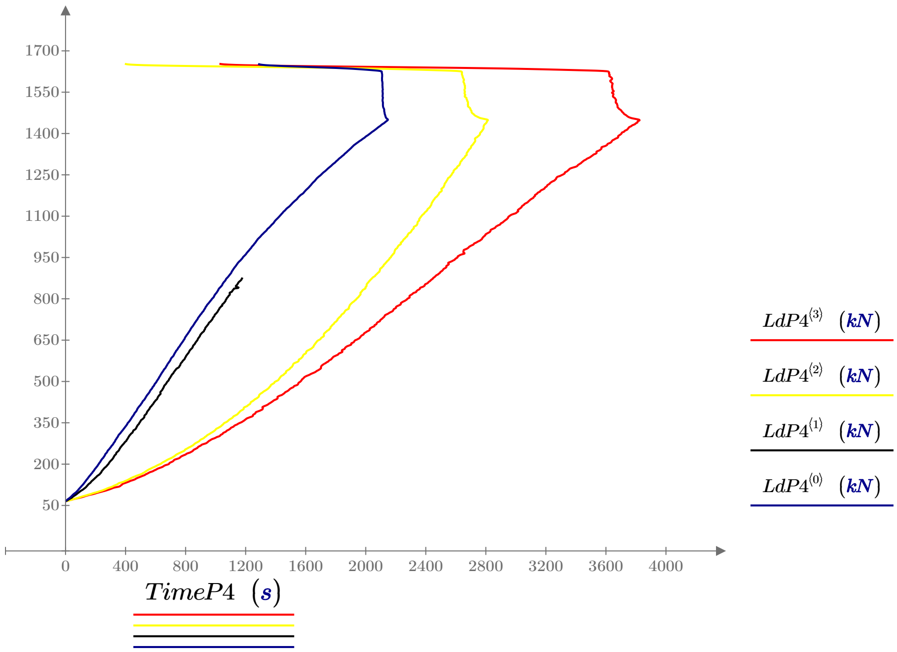


Fig B12. Load time history for compression pile P4

$$DP4 := percentD(TimeP4) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 \\ -0.014 \\ -0.029 \\ -0.043 \\ -0.058 \\ -0.072 \\ -0.087 \\ -0.101 \\ -0.115 \\ -0.13 \\ -0.144 \\ -0.159 \\ \vdots \end{bmatrix}$$

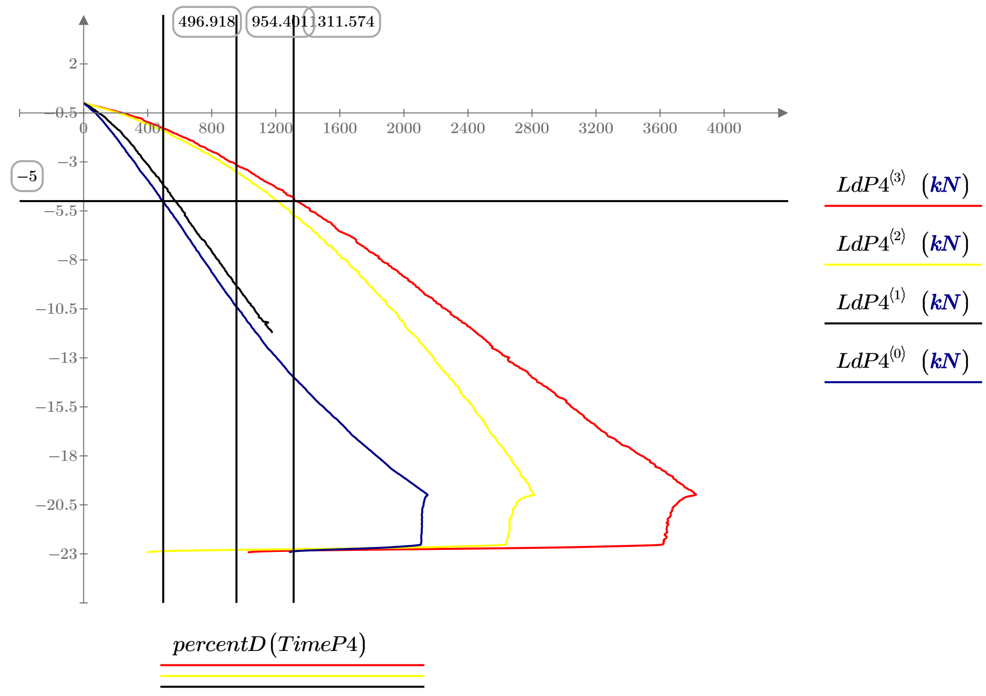


Fig B 13. Depth vs Load for compression pile P4

$P4CSGLd := PCSGLd(LdP4, DP4)$ WRITEEXCEL(“P4CSGLd.xlsx”, $P4CSGLd$)

2.3.1.5 Compression Pile P0

There were two strain gages placed within the P0 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL(“.\NI01 HBM Data Corrected.xlsx”, “P0 C Axial!B1:F1631”)

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 1630 \end{array} \left[\begin{array}{lllll} 64 & 2.666 \cdot 10^{-4} & 2.248 \cdot 10^{-4} & 0.002 & 0.002 \\ 65 & 2.652 \cdot 10^{-4} & 2.32 \cdot 10^{-4} & 0.002 & 0.002 \\ 66 & 2.623 \cdot 10^{-4} & 2.407 \cdot 10^{-4} & 0.002 & 0.002 \\ 67 & 2.623 \cdot 10^{-4} & 2.508 \cdot 10^{-4} & 0.002 & 0.002 \\ 68 & 2.652 \cdot 10^{-4} & 2.652 \cdot 10^{-4} & 0.002 & 0.002 \\ 69 & 2.68 \cdot 10^{-4} & 2.781 \cdot 10^{-4} & 0.002 & 0.002 \\ 70 & 2.738 \cdot 10^{-4} & 2.911 \cdot 10^{-4} & 0.002 & 0.002 \\ 71 & 2.796 \cdot 10^{-4} & 2.998 \cdot 10^{-4} & 0.002 & 0.002 \\ 72 & 2.868 \cdot 10^{-4} & 3.055 \cdot 10^{-4} & 0.002 & 0.002 \\ 73 & 2.911 \cdot 10^{-4} & 3.113 \cdot 10^{-4} & 0.002 & 0.002 \\ 74 & 2.954 \cdot 10^{-4} & 3.17 \cdot 10^{-4} & 0.002 & 0.002 \\ 75 & 2.998 \cdot 10^{-4} & 3.242 \cdot 10^{-4} & 0.002 & 0.002 \\ & & & & \vdots \end{array}\right]$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$$TimeP0 := P^{\langle 0 \rangle}\ s$$

$$RawdataP0 := \text{submatrix}(P, 0, \text{rows}(P) - 1, 1, 4) \cdot \frac{mV}{V}$$

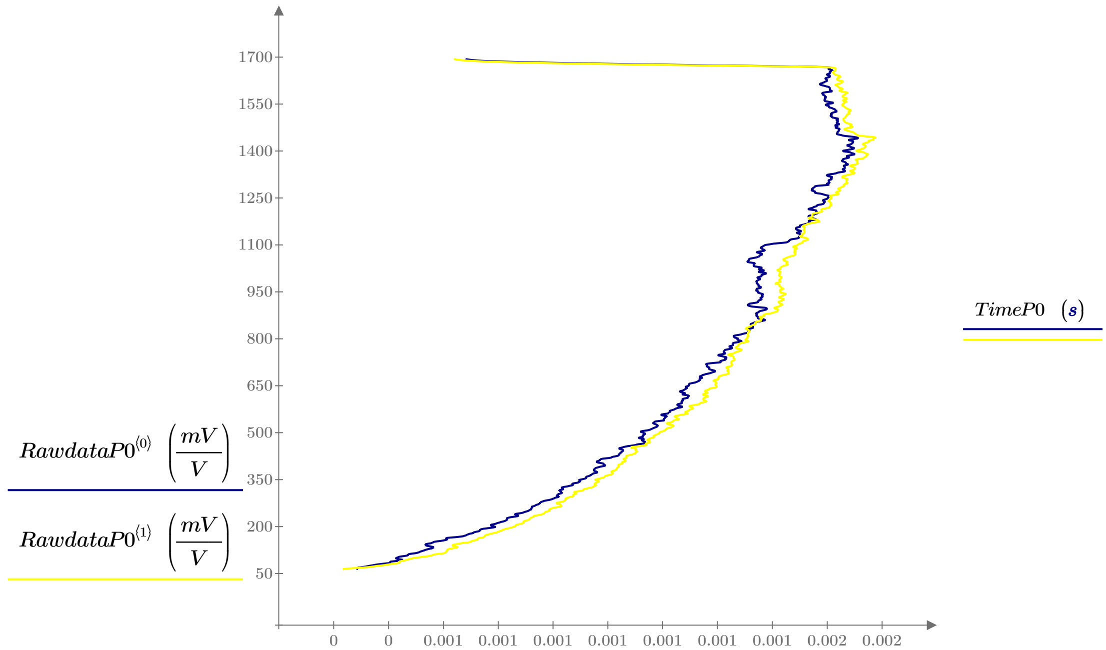


Fig B 14. Rawdata time history for compression pile P0

$$LdP0 := AxlLd(RawdataP0, 0) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.274 & 3.742 & 0 & 0 \\ -0.822 & 8.233 & 0 & 0 \\ -0.822 & 13.473 & 0 & 0 \\ -0.274 & 20.958 & 0 & 0 \\ 0.274 & 27.694 & 0 & 0 \\ 1.371 & 34.431 & 0 & 0 \\ 2.467 & 38.922 & 0 & 0 \\ 3.838 & 41.916 & 0 & 0 \\ 4.66 & 44.91 & 0 & 0 \\ 5.483 & 47.903 & 0 & 0 \\ 6.305 & 51.646 & 0 & 0 \\ & & & \vdots \end{bmatrix} kN$$

Axial Load for P0 Pile from the Raw HBM Strain Gage Data

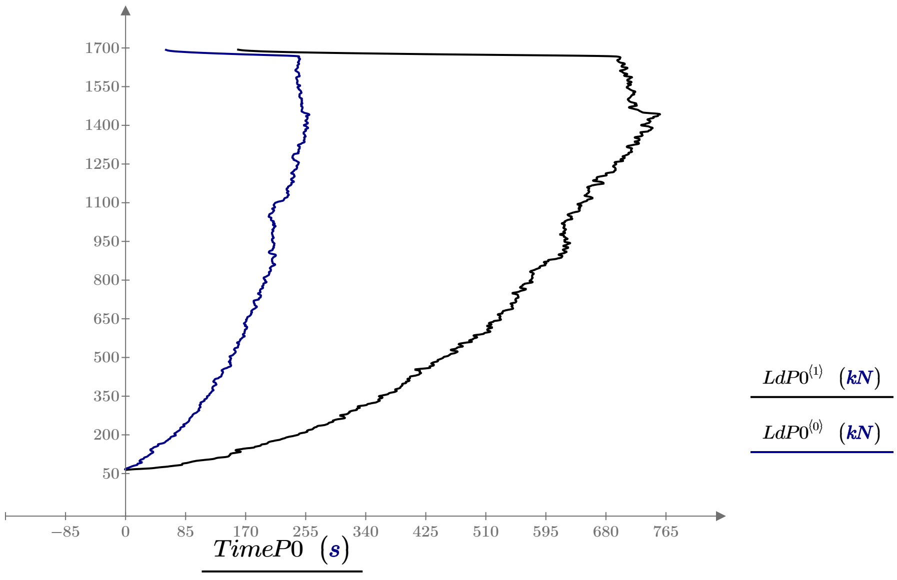


Fig B 15. Load time history for compression pile P0

Function for determining the penetration Depth

$$percentd(TimeP) := \left\| \begin{array}{l} \text{for } i \in 0,1..\text{rows}(TimeP)-1 \\ \quad \left\| k_i \leftarrow -\left(TimeP_i - TimeP_0\right) \cdot \dfrac{CmpRate}{d} \cdot 100 \right. \\ k \end{array} \right.$$

$$dP0 := percentd(TimeP0) = \begin{array}{r|l} 0 & 0 \\ 1 & -0.043 \\ 2 & -0.087 \\ 3 & -0.13 \\ 4 & -0.173 \\ 5 & -0.217 \\ 6 & -0.26 \\ 7 & -0.303 \\ 8 & -0.346 \\ 9 & -0.39 \\ 10 & -0.433 \\ 11 & -0.476 \\ \vdots & \vdots \end{array}$$

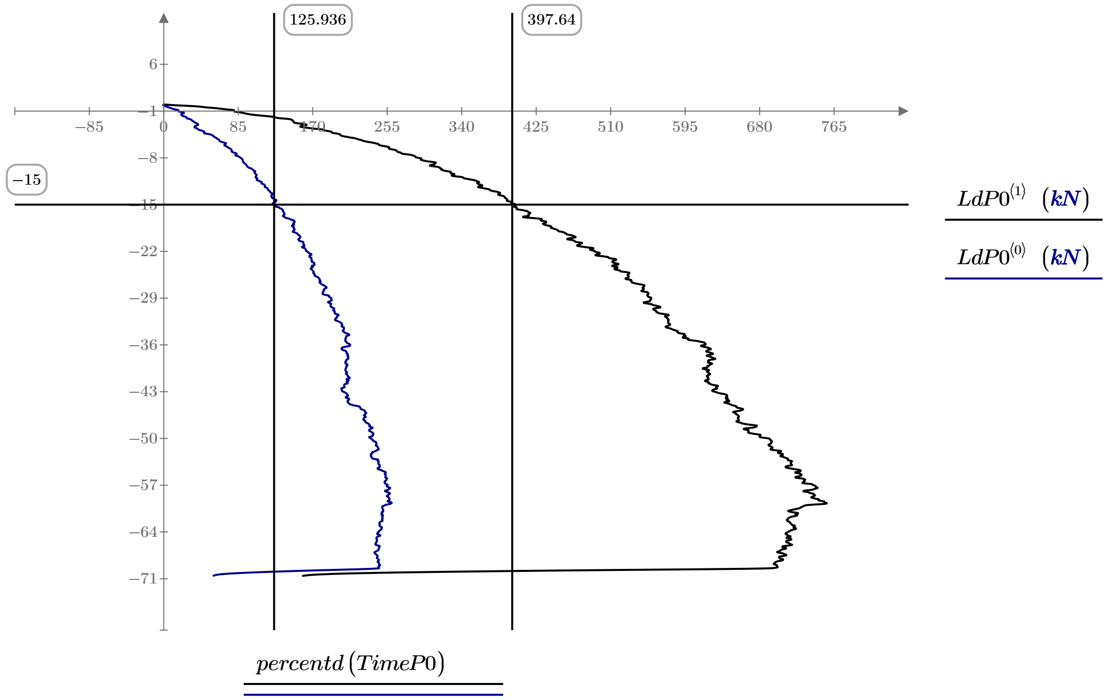


Fig B 16. Depth vs Time for compression pile P0

$P0CSGLd := PCSGLd(LdP0, dP0)$ WRITEEXCEL ("P0CSGLd.xlsx", $P0CSGLd$)

2.3.1.6 Tension Pile P1

There were three strain gages placed within the P0 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL (".\NI01 HBM Data Corrected.xlsx", "P1 T Axial!C1:G806")

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 805 \end{array} \begin{bmatrix} 111 & 4.359 & 2.732 \cdot 10^{-4} & 1.873 \cdot 10^{-4} & -0.014 \\ 112 & 4.36 & 2.631 \cdot 10^{-4} & 1.773 \cdot 10^{-4} & -0.014 \\ 113 & 4.36 & 2.458 \cdot 10^{-4} & 1.614 \cdot 10^{-4} & -0.014 \\ 114 & 4.36 & 2.228 \cdot 10^{-4} & 1.412 \cdot 10^{-4} & -0.014 \\ 115 & 4.36 & 1.997 \cdot 10^{-4} & 1.211 \cdot 10^{-4} & -0.014 \\ 116 & 4.36 & 1.752 \cdot 10^{-4} & 9.944 \cdot 10^{-5} & -0.014 \\ 117 & 4.36 & 1.522 \cdot 10^{-4} & 7.638 \cdot 10^{-5} & -0.014 \\ 118 & 4.36 & 1.248 \cdot 10^{-4} & 4.612 \cdot 10^{-5} & -0.014 \\ 119 & 4.36 & 9.308 \cdot 10^{-5} & 1.153 \cdot 10^{-5} & -0.014 \\ 120 & 4.359 & 5.561 \cdot 10^{-5} & -2.738 \cdot 10^{-5} & -0.014 \\ 121 & 4.359 & 1.382 \cdot 10^{-5} & -6.917 \cdot 10^{-5} & -0.014 \\ 122 & 4.359 & -3.086 \cdot 10^{-5} & -1.124 \cdot 10^{-4} & -0.014 \\ & & & & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$TimeP1T := P^{\langle 0 \rangle}\ s$

$RawdataP1T := \text{submatrix}(P, 0, \text{rows}(P) - 1, 1, 4) \cdot \frac{mV}{V}$

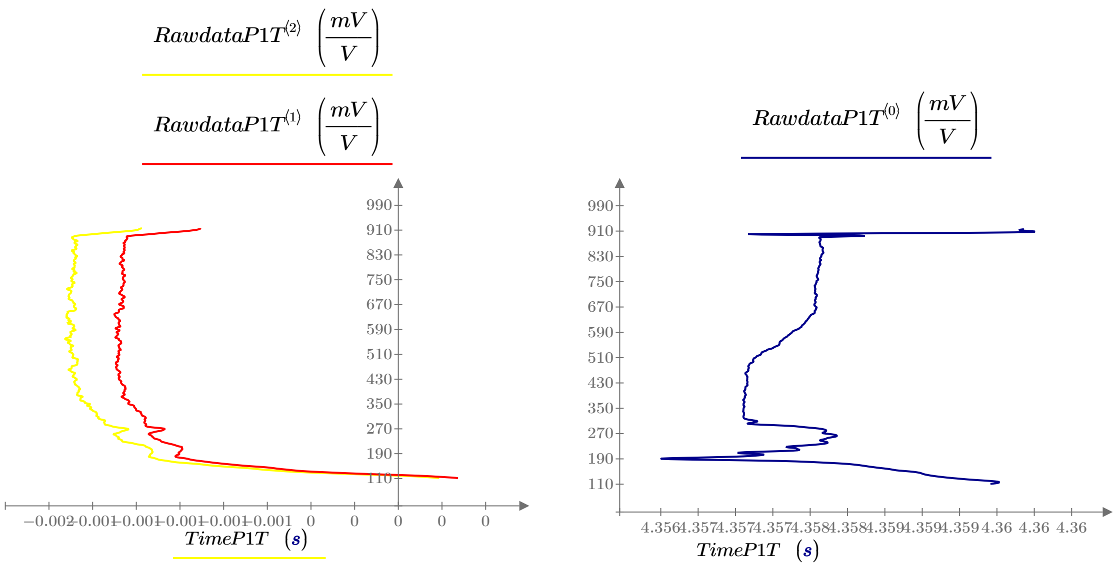


Fig B 17. Rawdata time history for tension pile P1.

$$LdP1T := AxlLd(RawdataP1T, 1) = \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 5.061 & -2.734 & -4.44 & 0 \\ 9.364 & -7.421 & -11.417 & 0 \\ 12.232 & -13.67 & -20.296 & 0 \\ 14.003 & -19.919 & -29.176 & 0 \\ 14.762 & -26.559 & -38.69 & 0 \\ 14.003 & -32.808 & -48.838 & 0 \\ 11.473 & -40.229 & -62.157 & 0 \\ 6.833 & -48.822 & -77.379 & 0 \\ 0.506 & -58.977 & -94.504 & 0 \\ -6.917 & -70.303 & -112.897 & 0 \\ -14.594 & -82.411 & -131.925 & 0 \\ & & & \vdots \end{bmatrix} kN$$

Axial Load for P0 Pile from the Raw HBM Strain Gage Data

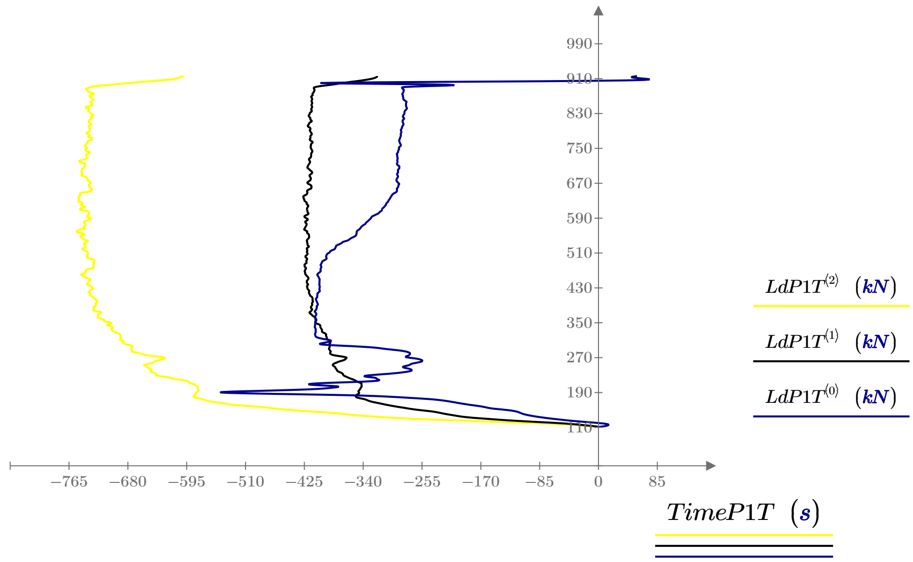


Fig B 18. Load time history for tension pile P1.

Function for determining the penetration Depth

$$percentD\_T(TimeP) := \left\| \begin{array}{l} \text{for } i \in 0, 1 .. \text{rows}(TimeP) - 1 \\ \quad \left\| k_i \leftarrow -\left(TimeP_i - TimeP_0\right) \cdot \dfrac{TenRate}{D} \cdot 100 \right. \\ k \end{array} \right.$$

$$DP1T := percentD\_T(TimeP1T) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 \\ -0.437 \\ -0.875 \\ -1.312 \\ -1.75 \\ -2.187 \\ -2.625 \\ -3.062 \\ -3.5 \\ -3.937 \\ -4.374 \\ -4.812 \\ \vdots \end{bmatrix}$$

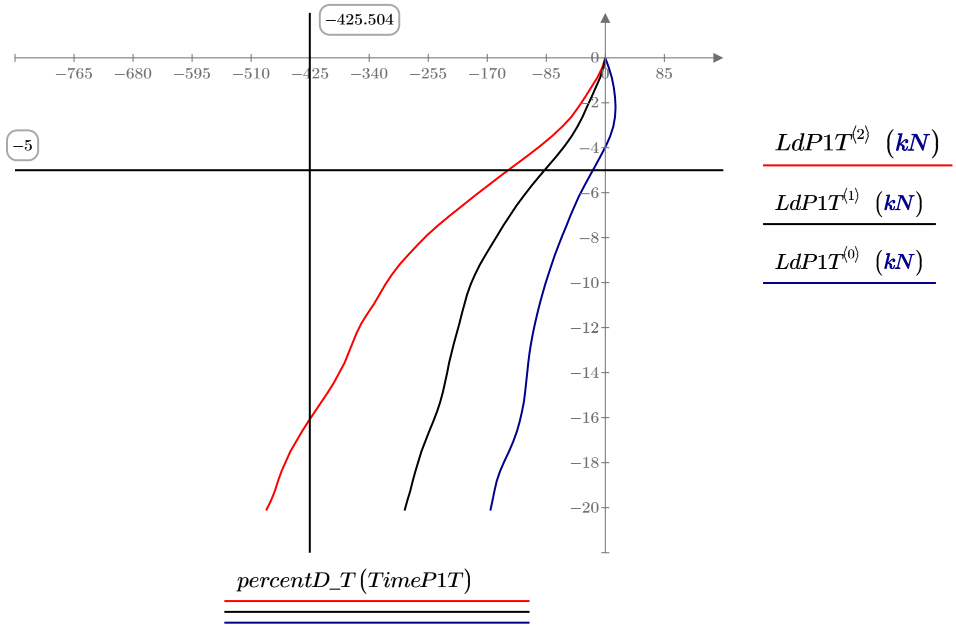


Fig B 19. Depth vs Load for tension pile P1.

$P1TSGLd := PCSGLd(LdP1T, DP1T)$ WRITEEXCEL("P1TSGLd.xlsx", $P1TSGLd$)

2.3.1.7 Tension Pile P2

There were four strain gages placed within the P2 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL(".\NI01 HBM Data Corrected.xlsx", "P2 T Axial!A280:E1221")

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 941 \end{array} \begin{bmatrix} 279 & 2.118\cdot10^{-4} & 3.142\cdot10^{-4} & 3.286\cdot10^{-4} & 2.58\cdot10^{-4} \\ 280 & 2.104\cdot10^{-4} & 3.084\cdot10^{-4} & 3.286\cdot10^{-4} & 2.536\cdot10^{-4} \\ 281 & 2.032\cdot10^{-4} & 3.012\cdot10^{-4} & 3.228\cdot10^{-4} & 2.464\cdot10^{-4} \\ 282 & 1.902\cdot10^{-4} & 2.839\cdot10^{-4} & 3.055\cdot10^{-4} & 2.291\cdot10^{-4} \\ 283 & 1.628\cdot10^{-4} & 2.522\cdot10^{-4} & 2.738\cdot10^{-4} & 1.989\cdot10^{-4} \\ 284 & 1.225\cdot10^{-4} & 2.061\cdot10^{-4} & 2.277\cdot10^{-4} & 1.571\cdot10^{-4} \\ 285 & 6.917\cdot10^{-5} & 1.499\cdot10^{-4} & 1.715\cdot10^{-4} & 1.066\cdot10^{-4} \\ 286 & 1.009\cdot10^{-5} & 8.647\cdot10^{-5} & 1.081\cdot10^{-4} & 5.188\cdot10^{-5} \\ 287 & -5.188\cdot10^{-5} & 2.162\cdot10^{-5} & 4.323\cdot10^{-5} & -5.764\cdot10^{-6} \\ 288 & -1.138\cdot10^{-4} & -4.323\cdot10^{-5} & -1.873\cdot10^{-5} & -6.485\cdot10^{-5} \\ 289 & -1.744\cdot10^{-4} & -1.023\cdot10^{-4} & -7.782\cdot10^{-5} & -1.225\cdot10^{-4} \\ 290 & -2.32\cdot10^{-4} & -1.585\cdot10^{-4} & -1.326\cdot10^{-4} & -1.801\cdot10^{-4} \\ & & & & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$TimeP2T := P^{\langle 0\rangle}\ s$

$RawdataP2T := \mathrm{submatrix}(P, 0, \mathrm{rows}(P) - 1, 1, 4) \cdot \frac{mV}{V}$

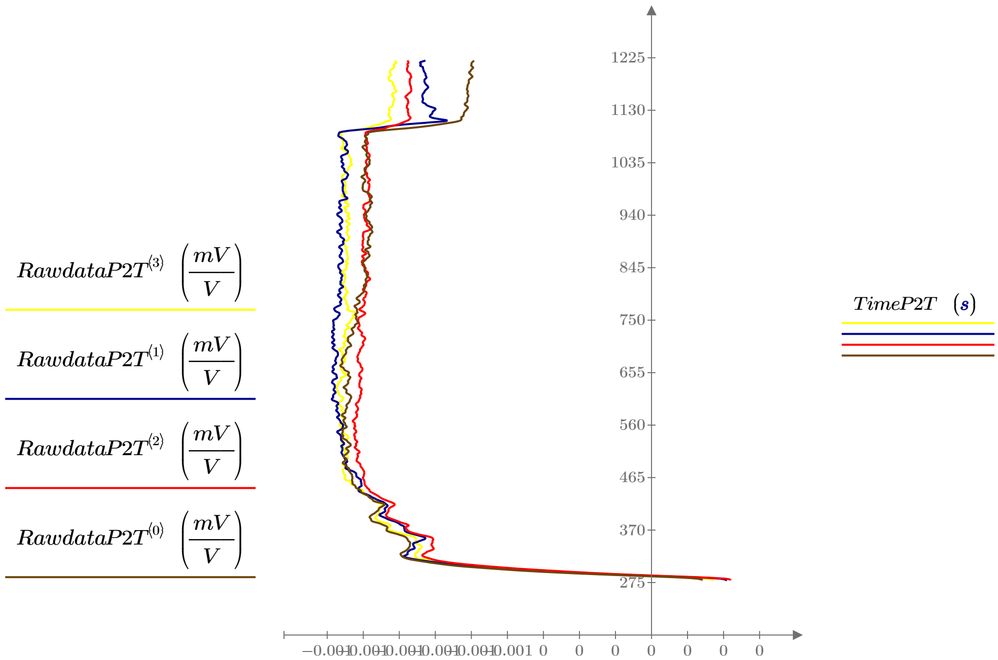


Fig B 20. Rawdata time history for tension pile P2.

$$LdP2T := AxlLd\left(RawdataP2T\,,2\right) = \begin{array}{r}0\\1\\2\\3\\4\\5\\6\\7\\8\\9\\10\\11\\\vdots\end{array}\begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.196 & -1.592 & 0 & -1.225 \\ -1.176 & -3.581 & -2.105 & -3.267 \\ -2.94 & -8.356 & -8.419 & -8.166 \\ -6.665 & -17.111 & -19.996 & -16.741 \\ -12.154 & -29.845 & -36.835 & -28.583 \\ -19.407 & -45.364 & -57.358 & -42.874 \\ -27.444 & -62.873 & -80.511 & -58.39 \\ -35.873 & -80.779 & -104.191 & -74.723 \\ -44.302 & -98.686 & -126.818 & -91.465 \\ -52.536 & -115.001 & -148.393 & -107.798 \\ -60.377 & -130.52 & -168.39 & -124.131 \\ & & & \vdots \end{bmatrix} kN$$

Axial Load for P2 Pile from the Raw HBM Strain Gage Data

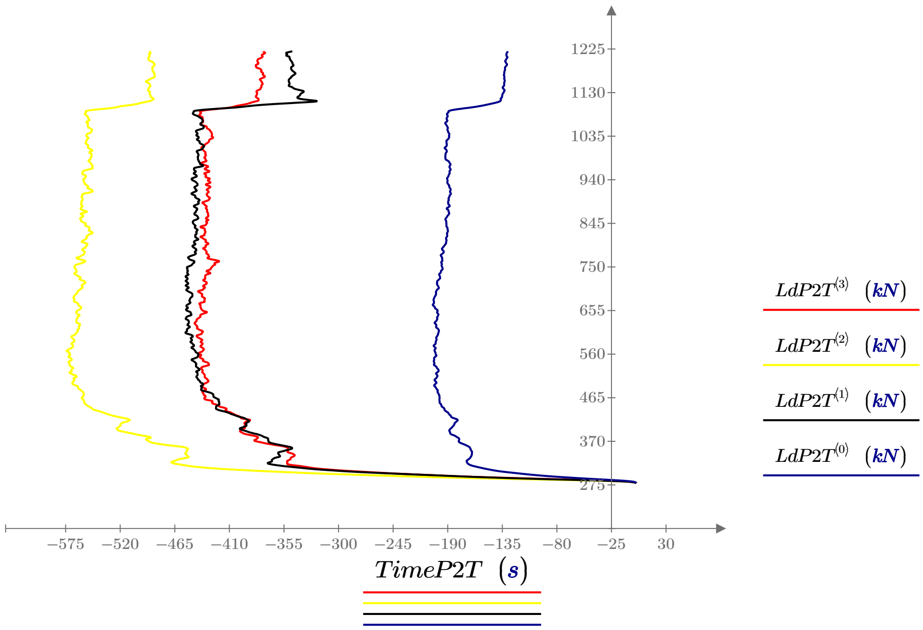


Fig B 21. Load time history for tension pile P2.

$$DP2T := percentD\_T(TimeP2T) = \begin{array}{r|l} 0 & 0 \\ 1 & -0.437 \\ 2 & -0.875 \\ 3 & -1.312 \\ 4 & -1.75 \\ 5 & -2.187 \\ 6 & -2.625 \\ 7 & -3.062 \\ 8 & -3.5 \\ 9 & -3.937 \\ 10 & -4.374 \\ 11 & -4.812 \\ \vdots & \vdots \end{array}$$

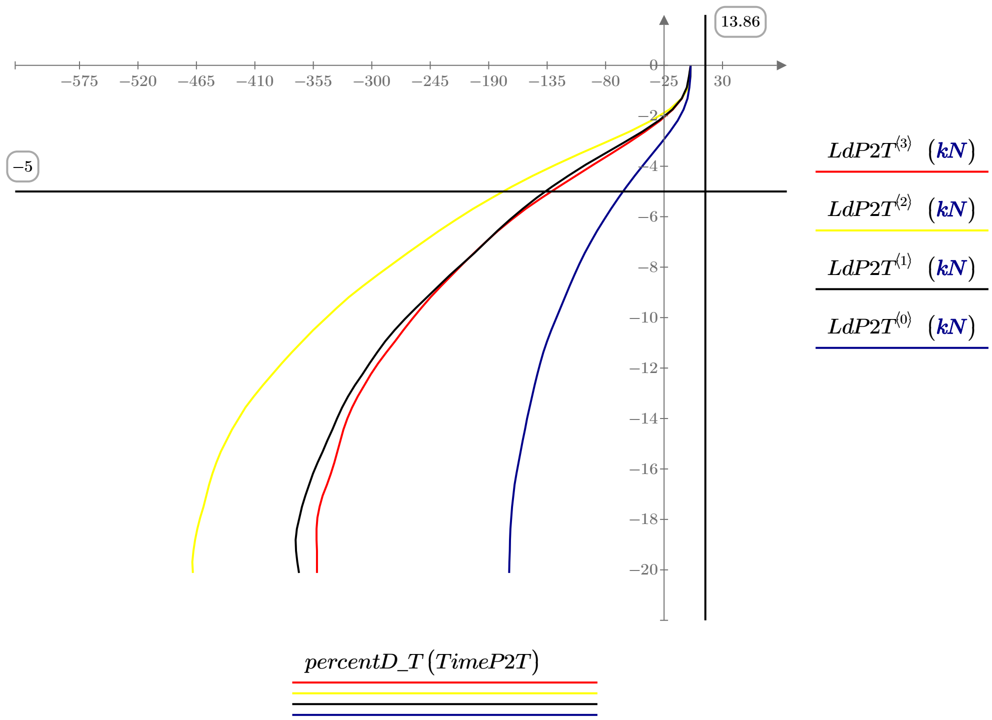


Fig B 22. Depth vs Load for tension pile P2.

$P2TSGLd := PCSGLd(LdP2T, DP2T)$ WRITEEXCEL("P2TSGLd.xlsx", $P2TSGLd$)

2.3.1.8 Tension Pile P3

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL(".\NI01 HBM Data Corrected.xlsx", "P3 T Axial!A124:E913")

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 789 \end{array} \begin{bmatrix} 123 & 5.029 \cdot 10^{-4} & 5.087 \cdot 10^{-4} & 5.303 \cdot 10^{-4} & 4.85 \cdot 10^{-4} \\ 124 & 5.001 \cdot 10^{-4} & 5.058 \cdot 10^{-4} & 5.318 \cdot 10^{-4} & 4.865 \cdot 10^{-4} \\ 125 & 4.9 \cdot 10^{-4} & 4.929 \cdot 10^{-4} & 5.231 \cdot 10^{-4} & 4.778 \cdot 10^{-4} \\ 126 & 4.669 \cdot 10^{-4} & 4.64 \cdot 10^{-4} & 4.972 \cdot 10^{-4} & 4.519 \cdot 10^{-4} \\ 127 & 4.295 \cdot 10^{-4} & 4.194 \cdot 10^{-4} & 4.539 \cdot 10^{-4} & 4.086 \cdot 10^{-4} \\ 128 & 3.761 \cdot 10^{-4} & 3.603 \cdot 10^{-4} & 3.949 \cdot 10^{-4} & 3.496 \cdot 10^{-4} \\ 129 & 3.142 \cdot 10^{-4} & 2.925 \cdot 10^{-4} & 3.271 \cdot 10^{-4} & 2.818 \cdot 10^{-4} \\ 130 & 2.45 \cdot 10^{-4} & 2.205 \cdot 10^{-4} & 2.551 \cdot 10^{-4} & 2.098 \cdot 10^{-4} \\ 131 & 1.729 \cdot 10^{-4} & 1.47 \cdot 10^{-4} & 1.83 \cdot 10^{-4} & 1.377 \cdot 10^{-4} \\ 132 & 1.009 \cdot 10^{-4} & 7.494 \cdot 10^{-5} & 1.124 \cdot 10^{-4} & 6.71 \cdot 10^{-5} \\ 133 & 3.17 \cdot 10^{-5} & 4.323 \cdot 10^{-6} & 4.323 \cdot 10^{-5} & -2.074 \cdot 10^{-6} \\ 134 & -3.459 \cdot 10^{-5} & -6.485 \cdot 10^{-5} & -2.45 \cdot 10^{-5} & -6.981 \cdot 10^{-5} \\ & & & & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$TimeP3T := P^{\langle 0 \rangle}\ s$

$RawdataP3T := \mathrm{submatrix}(P, 0, \mathrm{rows}(P) - 1, 1, 4) \cdot \frac{mV}{V}$

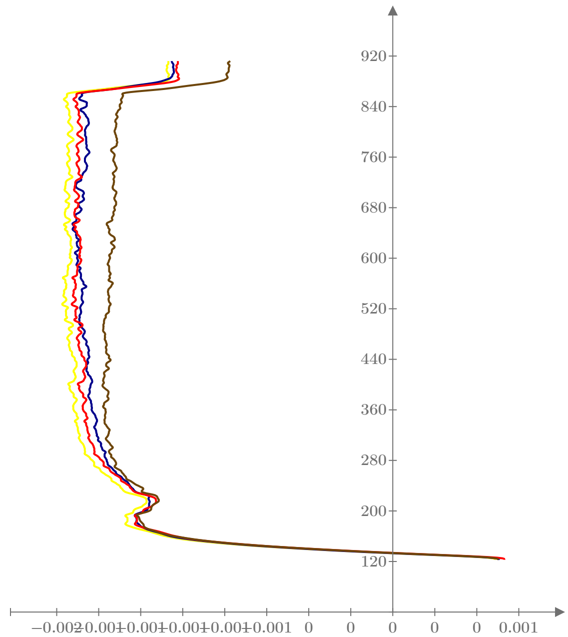


Fig B 23. Rawdata time history for tension pile P3.

$$LdP3T := AxlLd(RawdataP3T, 3) = \begin{array}{c|cccc|}
0 & 0 & 0 & 0 & 0 \\
1 & -0.503 & -0.632 & 0.505 & 0.665 \\
2 & -2.263 & -3.476 & -2.525 & -3.321 \\
3 & -6.287 & -9.797 & -11.617 & -15.28 \\
4 & -12.825 & -19.595 & -26.771 & -35.212 \\
5 & -22.129 & -32.552 & -47.48 & -62.45 \\
6 & -32.942 & -47.407 & -71.221 & -93.675 \\
7 & -45.013 & -63.209 & -96.476 & -126.893 \\
8 & -57.586 & -79.327 & -121.731 & -160.111 \\
9 & -70.16 & -95.129 & -146.482 & -192.666 \\
10 & -82.23 & -110.615 & -170.727 & -224.555 \\
11 & -93.798 & -125.785 & -194.468 & -255.781 \\
\vdots & & & & \vdots
\end{array}\ kN$$

Axial Load for P3 Pile from the Raw HBM Strain Gage Data

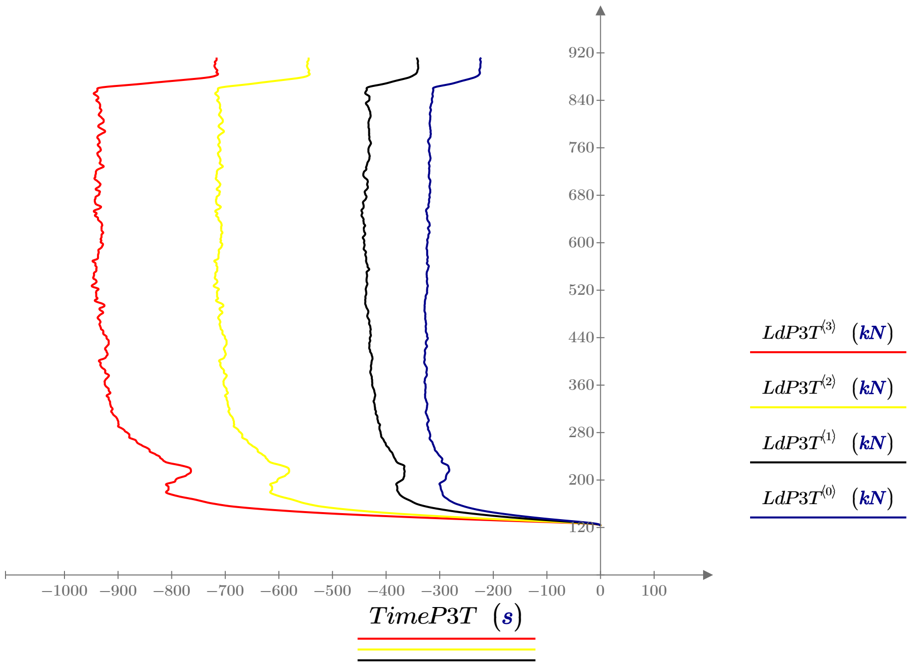


Fig B 24. Load time history for tension pile P3.

$$DP3T := percentD\_T(TimeP3T) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \begin{bmatrix} 0 \\ -0.437 \\ -0.875 \\ -1.312 \\ -1.75 \\ -2.187 \\ -2.625 \\ -3.062 \\ -3.5 \\ -3.937 \\ -4.374 \\ -4.812 \\ \vdots \end{bmatrix}$$

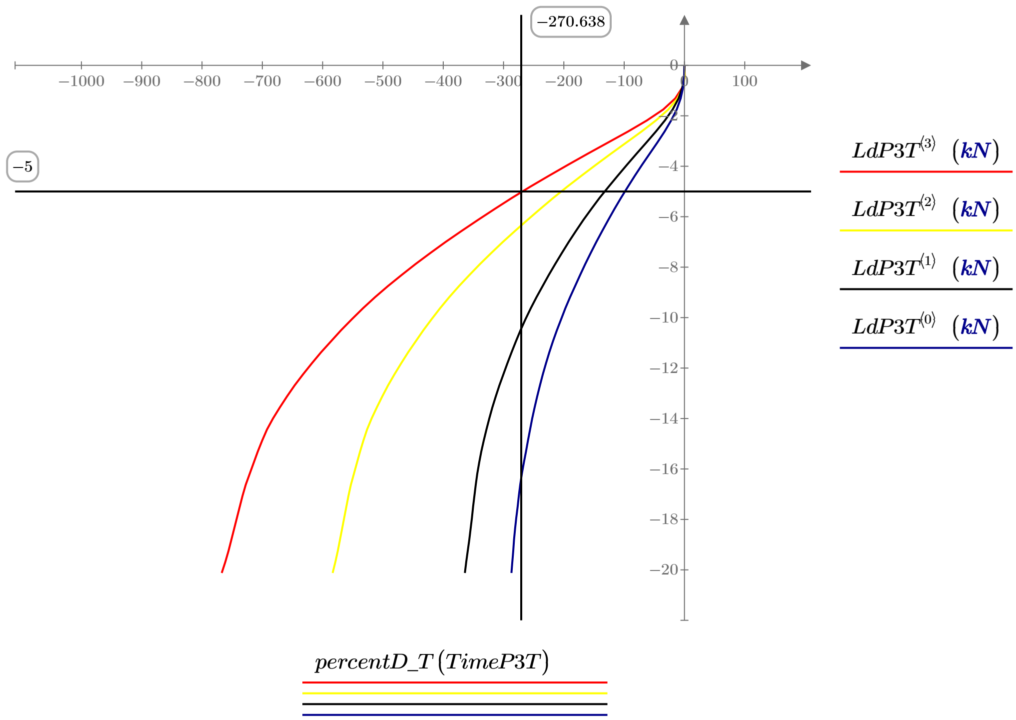


Fig B 25. Depth vs Load for tension pile P3.

$P3TSGLd := PCSGLd(LdP3T, DP3T)$ WRITEEXCEL (“P3TSGLd.xlsx”, $P3TSGLd$)

2.3.1.9 Tensione Pile P0

There were two strain gages placed within the P0 pile. The following sub sections provides the details on the load distributions:

$P :=$ READEXCEL (“.\NI01 HBM Data Corrected.xlsx”, “P0T Axial Corrected!A188:E936”)

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 748 \end{array} \begin{bmatrix} 187 & 1.657 \cdot 10^{-4} & 2.378 \cdot 10^{-4} & 0.003 & 0.003 \\ 188 & 1.657 \cdot 10^{-4} & 2.378 \cdot 10^{-4} & 0.003 & 0.003 \\ 189 & 1.657 \cdot 10^{-4} & 2.349 \cdot 10^{-4} & 0.003 & 0.003 \\ 190 & 1.657 \cdot 10^{-4} & 2.306 \cdot 10^{-4} & 0.003 & 0.003 \\ 191 & 1.643 \cdot 10^{-4} & 2.263 \cdot 10^{-4} & 0.003 & 0.003 \\ 192 & 1.6 \cdot 10^{-4} & 2.219 \cdot 10^{-4} & 0.003 & 0.003 \\ 193 & 1.513 \cdot 10^{-4} & 2.162 \cdot 10^{-4} & 0.003 & 0.003 \\ 194 & 1.355 \cdot 10^{-4} & 2.018 \cdot 10^{-4} & 0.003 & 0.003 \\ 195 & 1.124 \cdot 10^{-4} & 1.787 \cdot 10^{-4} & 0.003 & 0.003 \\ 196 & 8.214 \cdot 10^{-5} & 1.499 \cdot 10^{-4} & 0.003 & 0.003 \\ 197 & 4.756 \cdot 10^{-5} & 1.211 \cdot 10^{-4} & 0.003 & 0.003 \\ 198 & 1.585 \cdot 10^{-5} & 9.511 \cdot 10^{-5} & 0.003 & 0.003 \\ & & & \vdots & \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 to 4 stands for the Raw HBM strain gage Data

$TimeP0T := P^{\langle 0 \rangle}\ s$

$$RawdataP0T := \text{submatrix}\left(P, 0, \text{rows}(P) - 1, 1, 4\right) \cdot \frac{mV}{V}$$

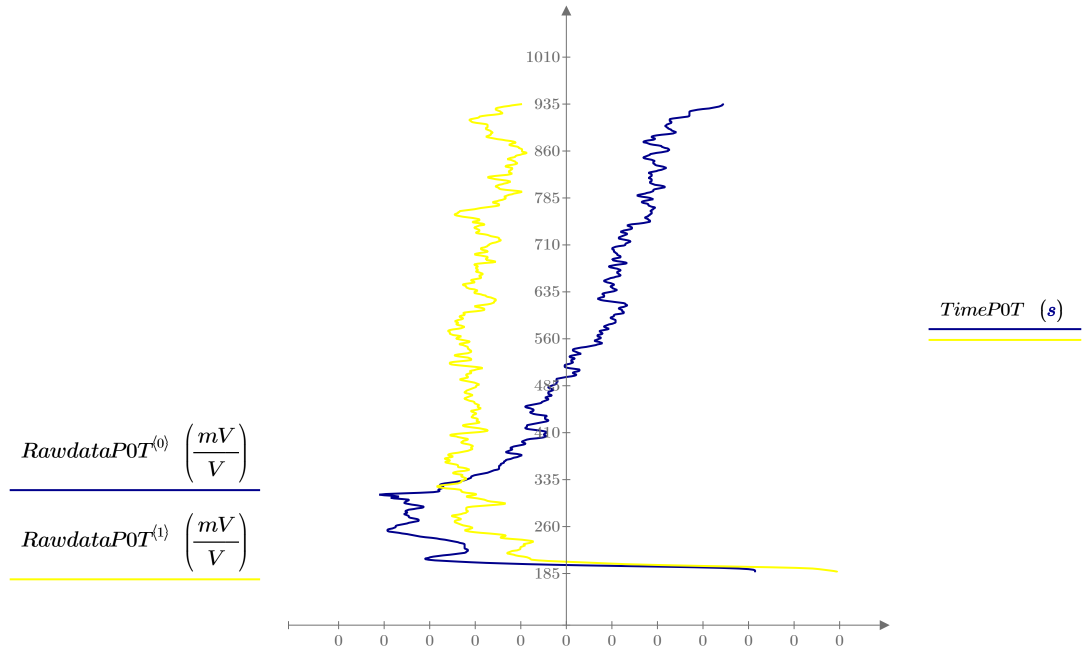


Fig B 26. Rawdata time history for tension pile P0.

$$LdP0T := AxlLd\left(RawdataP0T, 0\right) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array}\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -1.497 & 0 & 0 \\ 0 & -3.742 & 0 & 0 \\ -0.274 & -5.988 & 0 & 0 \\ -1.097 & -8.233 & 0 & 0 \\ -2.741 & -11.227 & 0 & 0 \\ -5.757 & -18.712 & 0 & 0 \\ -10.143 & -30.688 & 0 & 0 \\ -15.9 & -45.658 & 0 & 0 \\ -22.479 & -60.628 & 0 & 0 \\ -28.51 & -74.101 & 0 & 0 \\ & & & \vdots \end{bmatrix} kN$$

Axial Load for P0 Pile from the Raw HBM Strain Gage Data

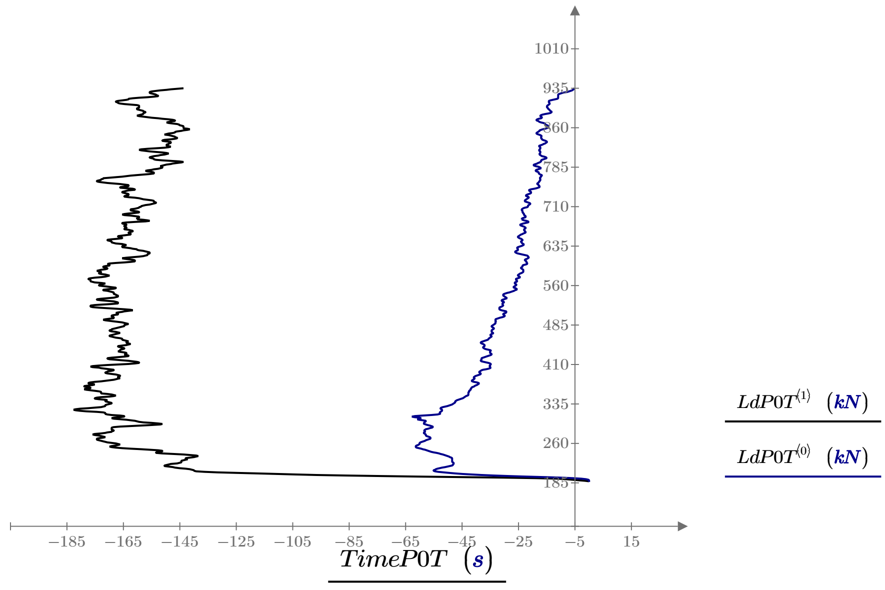


Fig B 27. Load time history for tension pile P0.

Function for determining the penetration depth

$$percentd\_T(TimeP) := \left\| \begin{array}{l} \text{for } i \in 0, 1 .. \text{rows}(TimeP) - 1 \\ \quad \left\| k_i \leftarrow -\left(TimeP_i - TimeP_0\right) \cdot \dfrac{TenRate}{d} \cdot 100 \right. \\ k \end{array} \right.$$

$$dP0T := percentd\_T(TimeP0T) = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \end{array} \left[\begin{array}{r} 0 \\ -1.312 \\ -2.625 \\ -3.937 \\ -5.249 \\ -6.562 \\ -7.874 \\ -9.186 \\ -10.499 \\ -11.811 \\ -13.123 \\ -14.436 \\ \vdots \end{array} \right]$$

748

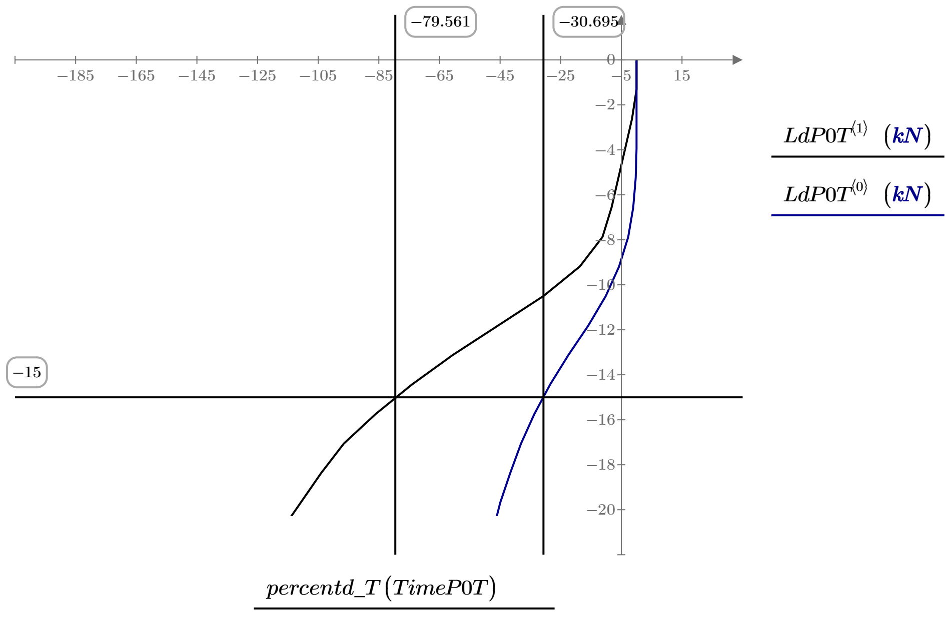


Fig B 28. Depth vs Load for tension pile P0.

$P0CSGLd := PCSGLd(LdP0, dP0)$ WRITEEXCEL("P0CSGLd.xlsx", $P0CSGLd$)

2.3.3 Skin Friction vs Depth

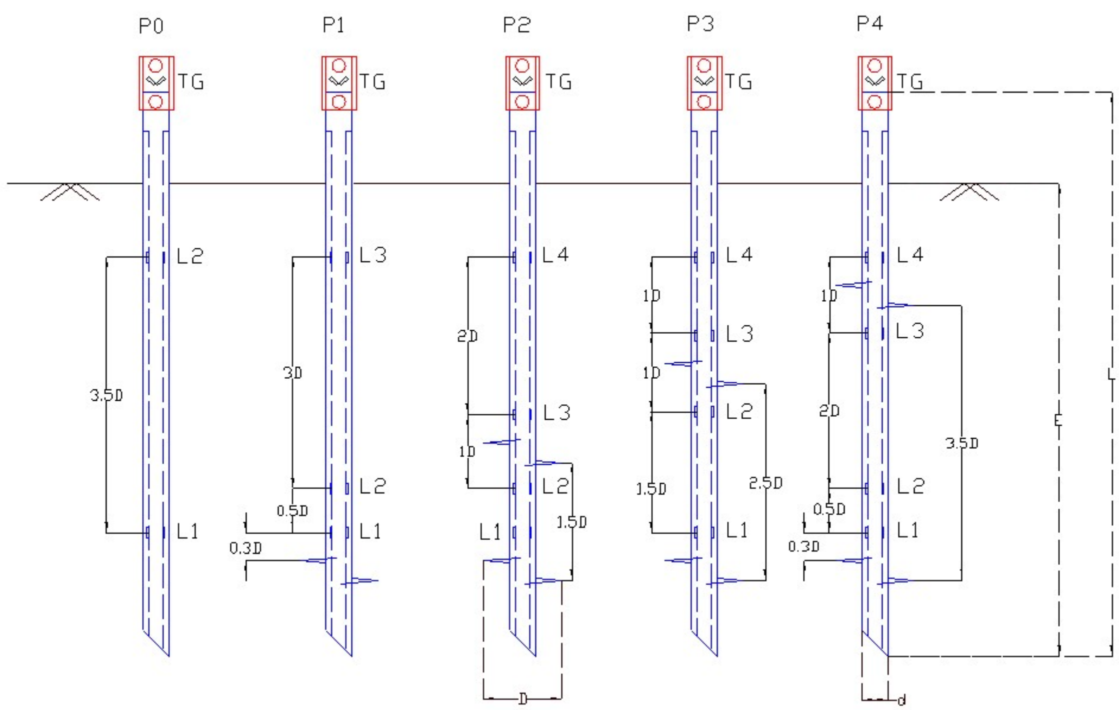


Fig B 29. Strain gauge locations in model piles.

Appendix B
Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

$$HgtShaft := \begin{bmatrix} 3.5 & 0.5 & 0.5 & 1.5 & 0.5 \\ 0 & 3 & 1 & 1 & 2 \\ 0 & 0 & 2 & 1 & 1 \end{bmatrix} \cdot D \cdot Nscale^{sclfac_{0,0}} = \begin{bmatrix} 2.667 & 0.381 & 0.381 & 1.143 & 0.381 \\ 0 & 2.286 & 0.762 & 0.762 & 1.524 \\ 0 & 0 & 1.524 & 0.762 & 0.762 \end{bmatrix} m$$

Height in the shaft segment between two stations in prototype scale. Here, colm 0-4 represents P0 to P4. Row 0 to 2 represents height between SG 1-2, 2-3 & 3-4

$$SurfArea := HgtShaft \cdot \pi \cdot d \cdot Nscale^{sclfac_{0,0}} = \begin{bmatrix} 2.128 & 0.304 & 0.304 & 0.912 & 0.304 \\ 0 & 1.824 & 0.608 & 0.608 & 1.216 \\ 0 & 0 & 1.216 & 0.608 & 0.608 \end{bmatrix} m^2$$

Surface Area of the shaft segment between two stations in prototype scale. Here, colm 0-4 represents P0 to P4. Row 0 to 2 represents surface area between SG 1-2, 2-3 & 3-4

$$SGEmbDP := -\begin{bmatrix} 0.6+3.5 & 0.6+3.5 & 0.6+3.5 & 0.6+3.5 & 0.6+3.5 \\ 0.6 & 0.6+3 & 0.6+3 & 0.6+2 & 0.6+3 \\ 0 & 0.6+3 & 0.6+3 & 0.6+2 & 0.6+3 \\ 0 & 0.6 & 0.6+2 & 0.6+1 & 0.6+1 \\ 0 & 0 & 0.6+2 & 0.6+1 & 0.6+1 \\ 0 & 0 & 0.6 & 0.6 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{sclfac_{0,0}}$$

SG embedment depth in prototype scale. Here, colm 0-4 represents P0 to P4. Row 0 to 5 represents depth to strain SG 1 to 4

Function for determining the Unit Shaft Resistance within the shaft segment

```
UntShtRes(LdP, PileNum) :=
  for i ∈ 0,1..rows(LdP) − 1
    for j ∈ 0,1..cols(LdP) − 1
      shaft12[i,0] ← (LdP[i,1] − LdP[i,0]) / submatrix(SurfArea, 0, 2, PileNum, PileNum)[0,0]
      shaft23[i,1] ← if submatrix(SurfArea, 0, 2, PileNum, PileNum)[1] = 0
                        0
                     else
                        (LdP[i,2] − LdP[i,1]) / submatrix(SurfArea, 0, 2, PileNum, PileNum)[1]
      shaft34[i,2] ← if submatrix(SurfArea, 0, 2, PileNum, PileNum)[2] = 0
                        0
                     else
                        (LdP[i,3] − LdP[i,2]) / submatrix(SurfArea, 0, 2, PileNum, PileNum)[2]
  augment(shaft12^⟨0⟩, shaft23^⟨1⟩, shaft34^⟨2⟩)
```

2.3.3.1 Compression Pile P1

$ShftResP1 := UntShtRes(LdP1, 1)$

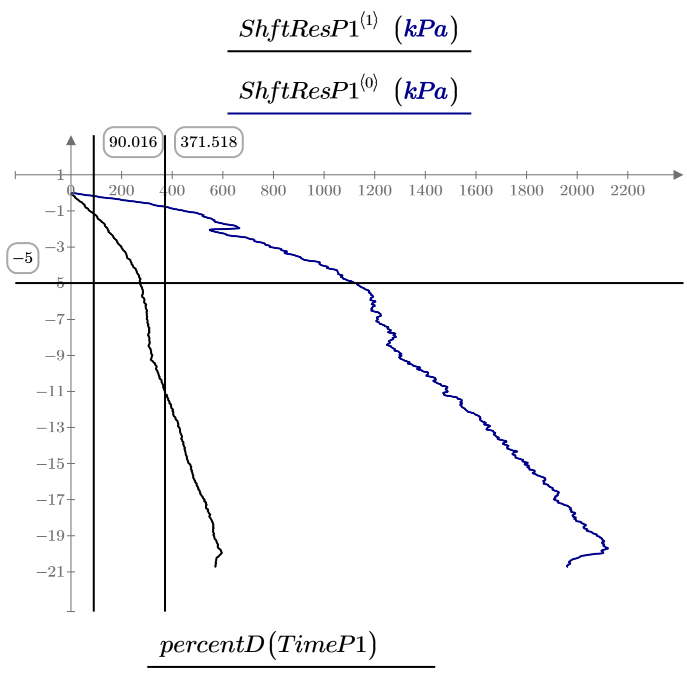


Fig B 30. Depth vs Unit Shaft Resistance for compression pile P1.

$$UltShReP1\_1 := \text{lookup}\left(-5, percentD(TimeP1), ShftResP1^{\langle 1\rangle}, \text{“near”}\right) = [272.481]\ \boldsymbol{kPa}$$

$$UltShReP1\_0 := \text{lookup}\left(-5, percentD(TimeP1), ShftResP1^{\langle 0\rangle}, \text{“near”}\right) = [1.126 \cdot 10^3]\ \boldsymbol{kPa}$$

```
ShftResplot(DP, ShftResP, PileNum) := for i ∈ 0,1..cols(ShftResP) − 1
                                          UltShReP0 ← if PileNum = 0
                                                           lookup(−15, DP, ShftResP⟨0⟩, “near”)
                                                      else
                                                           lookup(−5, DP, ShftResP⟨0⟩, “near”)
                                          UltShReP1 ← lookup(−5, DP, ShftResP⟨1⟩, “near”)
                                          UltShReP2 ← lookup(−5, DP, ShftResP⟨2⟩, “near”)
                                      combined ← if PileNum = 0
                                                      stack(UltShReP0, UltShReP0, UltShReP0, UltShReP0, UltShReP0, UltShReP0)
                                                 else if PileNum = 1
                                                      stack(UltShReP0, UltShReP0, UltShReP1, UltShReP1, UltShReP1, UltShReP1)
                                                 else
                                                      stack(UltShReP0, UltShReP0, UltShReP1, UltShReP1, UltShReP2, UltShReP2)
```

$$ShftResplotP1 := ShftResplot(DP1, ShftResP1, 1) = \begin{bmatrix} 1.126 \cdot 10^3 \\ 1.126 \cdot 10^3 \\ 272.481 \\ 272.481 \\ 272.481 \\ 272.481 \end{bmatrix} kPa$$

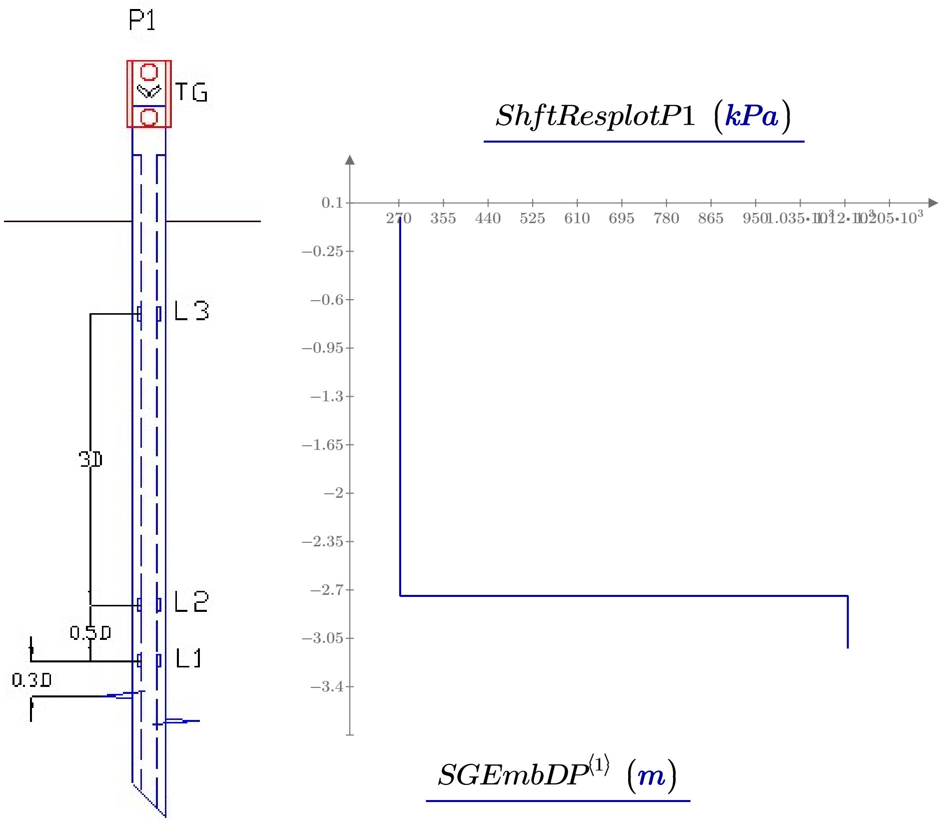


Fig B 31. Strain Gauge Depth vs Unit Shaft Resistance for compression pile P1.

2.3.3.2 Compression Pile P2

$ShftResP2 := UntShtRes(LdP2, 2)$

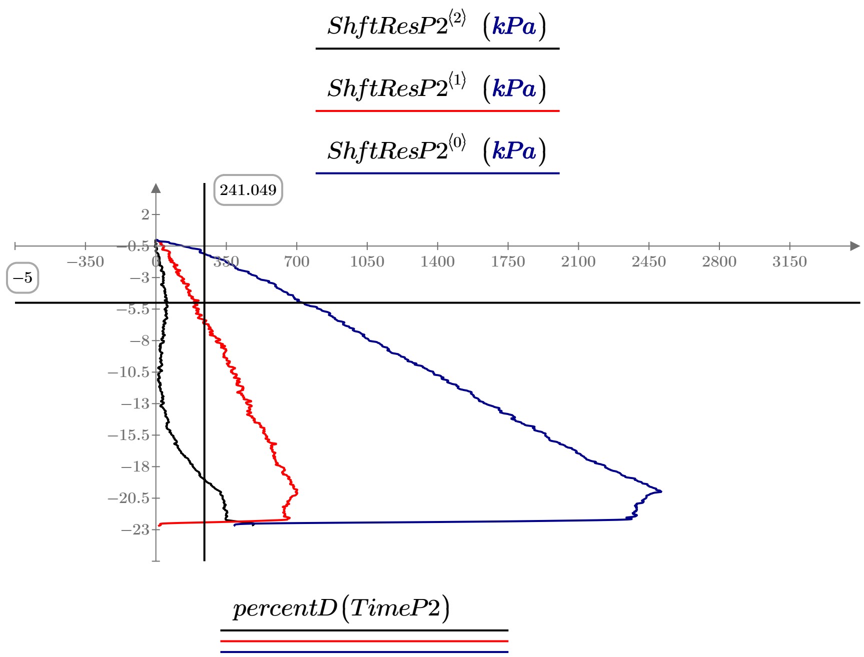


Fig B 32. Depth vs Unit Shaft Resistance for compression pile P2.

$$UltShReP2\_2 := \text{lookup}\left(-5, percentD(TimeP2), ShftResP2^{\langle 2\rangle}, \text{“near”}\right) = [53.115]\ \mathbf{kPa}$$

$$UltShReP2\_1 := \text{lookup}\left(-5, percentD(TimeP2), ShftResP2^{\langle 1\rangle}, \text{“near”}\right) = [188.642]\ \mathbf{kPa}$$

$$UltShReP2\_0 := \text{lookup}\left(-5, percentD(TimeP2), ShftResP2^{\langle 0\rangle}, \text{“near”}\right) = [729.354]\ \mathbf{kPa}$$

$$ShftResplotP2 := ShftResplot(DP2, ShftResP2, 2) = \begin{bmatrix} 729.354 \\ 729.354 \\ 188.642 \\ 188.642 \\ 53.115 \\ 53.115 \end{bmatrix}\ \mathbf{kPa}$$

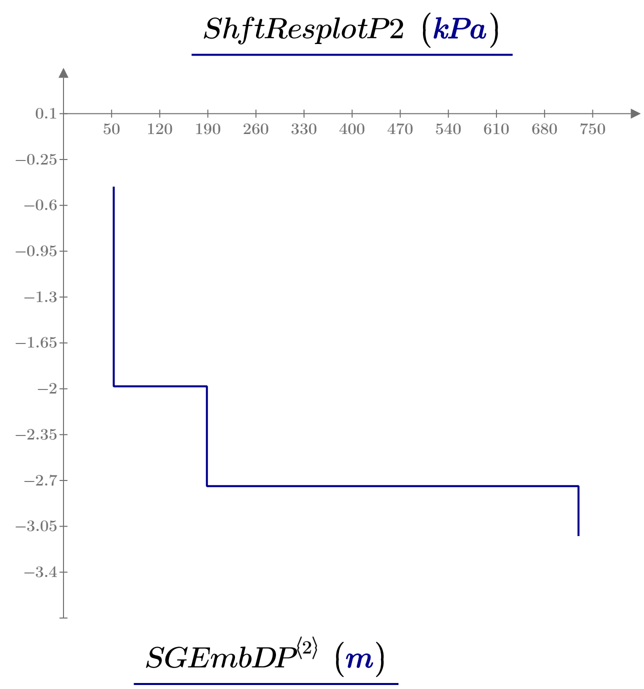


Fig B 33. Strain gauge embedment depth vs Unit Shaft Resistance for compression pile P2.

2.3.3.3 Compression Pile P3

$ShftResP3 := UntShtRes(LdP3, 3)$

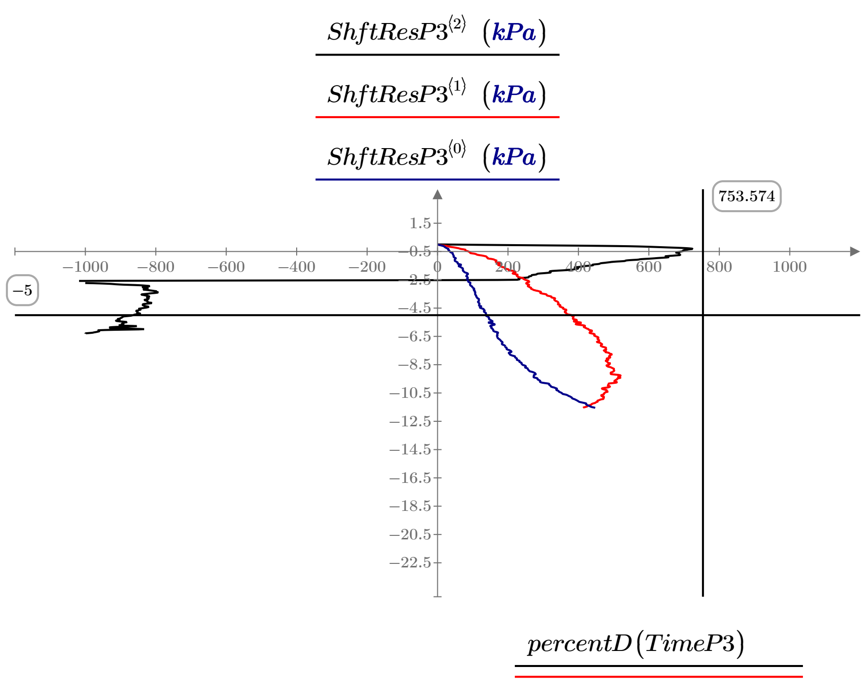


Fig B 34. Depth vs Unit Shaft Resistance for compression pile P3.

$$UltShReP3\_2 := \text{lookup}\left(-5, percentD(TimeP3), ShftResP3^{\langle 2 \rangle}, \text{"near"}\right) = [-863.797]\ kPa$$

$$UltShReP3\_1 := \text{lookup}\left(-5, percentD(TimeP3), ShftResP3^{\langle 1 \rangle}, \text{"near"}\right) = [380.013]\ kPa$$

$$UltShReP3\_0 := \text{lookup}\left(-5, percentD(TimeP3), ShftResP3^{\langle 0 \rangle}, \text{"near"}\right) = [136.52]\ kPa$$

$$ShftResplotP3 := ShftResplot(DP3, ShftResP3, 3) = \begin{bmatrix} 136.52 \\ 136.52 \\ 380.013 \\ 380.013 \\ -863.797 \\ -863.797 \end{bmatrix} kPa$$

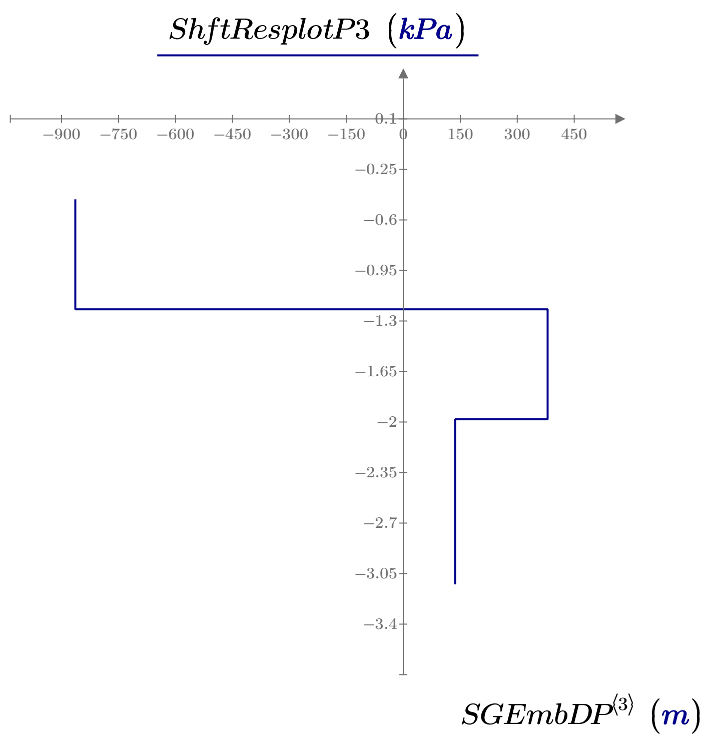


Fig B 35. Strain gauge embedment vs Unit Shaff Resistance for compression pile P3

2.3.3.4 Compression Pile P4

$$ShftResP4 := UntShtRes(LdP4, 4)$$

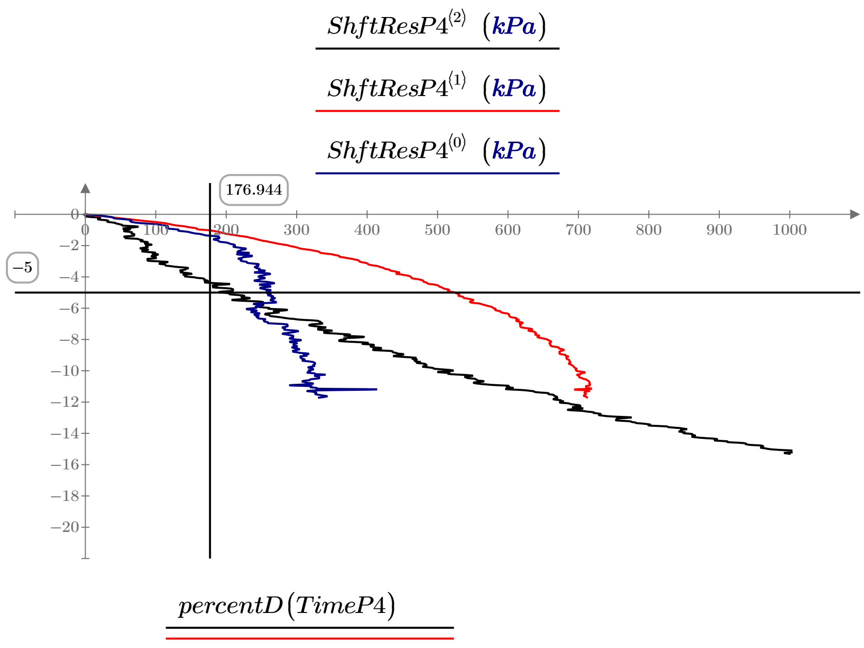


Fig B 36. Depth vs Unit Shaft Resistance for compression pile P4

$$UltShReP4\_2 := \text{lookup}\left(-5, percentD(TimeP4), ShftResP4^{\langle 2\rangle}, \text{“near”}\right) = [190.921]\ \boldsymbol{kPa}$$

$$UltShReP4\_1 := \text{lookup}\left(-5, percentD(TimeP4), ShftResP4^{\langle 1\rangle}, \text{“near”}\right) = [524.558]\ \boldsymbol{kPa}$$

$$UltShReP4\_0 := \text{lookup}\left(-5, percentD(TimeP4), ShftResP4^{\langle 0\rangle}, \text{“near”}\right) = [261.419]\ \boldsymbol{kPa}$$

$$ShftResplotP4 := ShftResplot(DP4, ShftResP4, 4) = \begin{bmatrix} 261.419 \\ 261.419 \\ 524.558 \\ 524.558 \\ 190.921 \\ 190.921 \end{bmatrix} \boldsymbol{kPa}$$

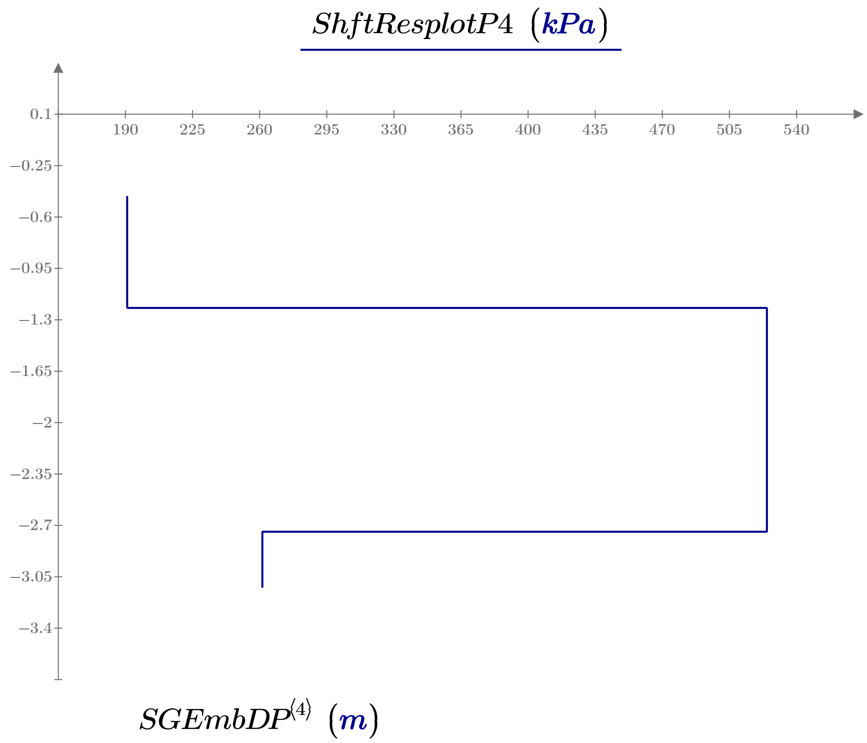


Fig B 37. Strain gauge embedment vs Unit Shaft resistance for compression pile P4

2.3.3.5 Compression Pile P0

$ShftResP0 := UntShtRes(LdP0, 0)$

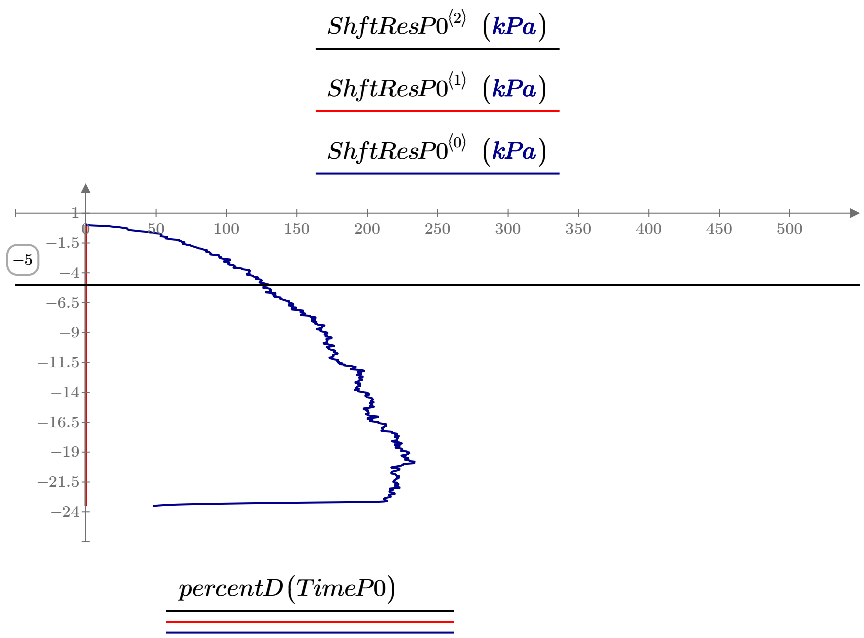


Fig B 38. Depth vs Unit Shaft Resistance for compression pile P0

$$UltShReP0\_0 := \text{lookup}\left(-15, percentd(TimeP0), ShftResP0^{\langle 0 \rangle}, \text{“near”}\right) = [130.128]\ \mathbf{kPa}$$

$$ShftResplotP0 := ShftResplot(dP0, ShftResP0, 0) = \begin{bmatrix} 130.128 \\ 130.128 \\ 130.128 \\ 130.128 \\ 130.128 \\ 130.128 \end{bmatrix} \mathbf{kPa}$$

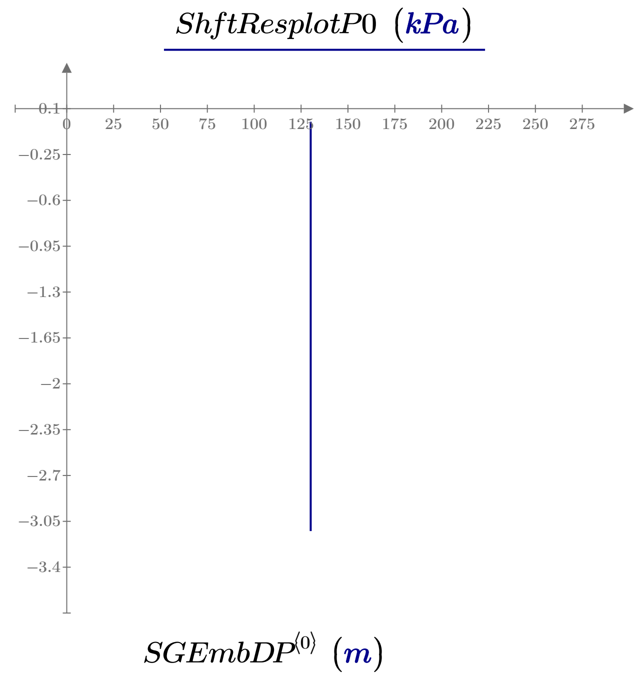


Fig B 39. Strain gauge embedment vs Unit Shaft Resistance for compression pile P0

2.3.3.6 Tension Pile P0

$ShftResP0T := UntShtRes(LdP0T, 0)$

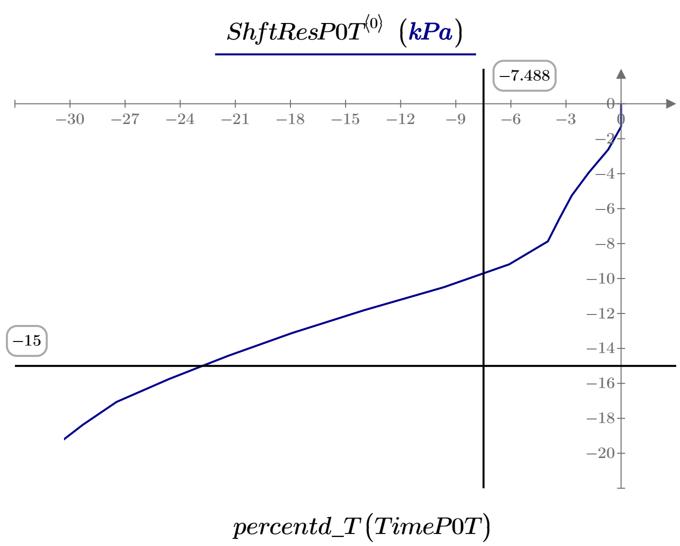


Fig B 40. Depth vs Unit Shaft Resistance for tension pile P0.

$UltShReP0T\_0 := \text{lookup}\left(-15, percentd\_T\left(TimeP0T\right), ShftResP0T^{\langle 0 \rangle}, \text{"near"}\right) = \left[-21.422\right]\ kPa$

$$ShftResplotP0T := ShftResplot\left(dP0T, ShftResP0T, 0\right) = \begin{bmatrix} -21.422 \\ -21.422 \\ -21.422 \\ -21.422 \\ -21.422 \\ -21.422 \end{bmatrix} kPa$$

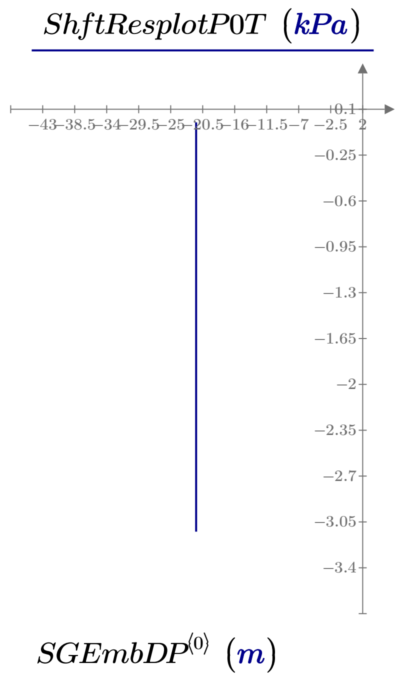


Fig B 41. Strain gauge embedment vs Unit Shaft Resistance for tension pile P0

2.3.3.7 Tension Pile P1

$ShftResP1T := UntShtRes\left(LdP1T, 1\right)$

Appendix B
Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

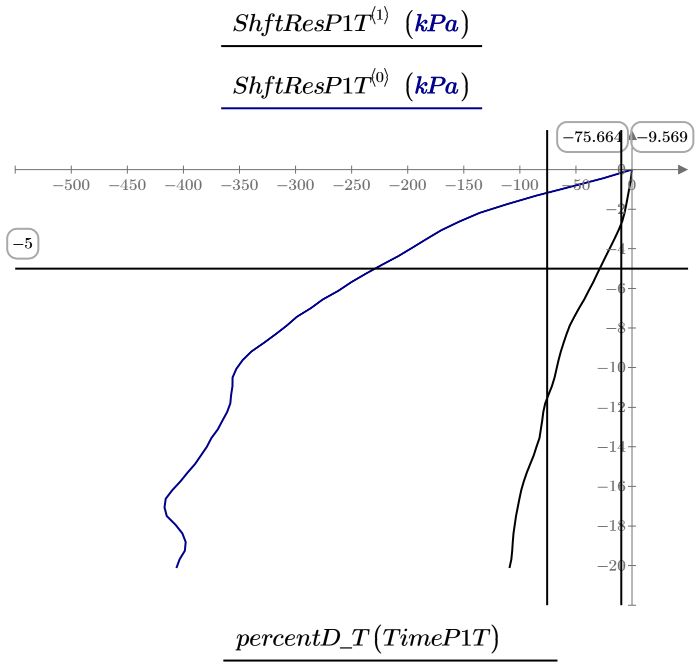
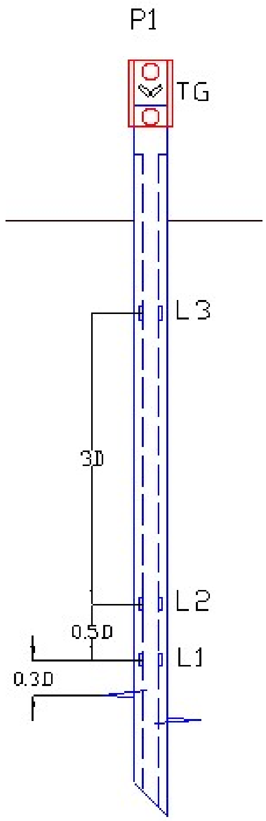


Fig B 42. Depth vs Unit Shaft Resistance for tension pile P1

$UltShReP1T\_1 := \text{lookup}\left(-5, percentD\_T\left(TimeP1T\right), ShftResP1T^{\langle 1\rangle}, \text{“near”}\right) = \left[-27.144\right]\ \boldsymbol{kPa}$

$UltShReP1T\_0 := \text{lookup}\left(-5, percentD\_T\left(TimeP1T\right), ShftResP1T^{\langle 0\rangle}, \text{“near”}\right) = \left[-223.065\right]\ \boldsymbol{kPa}$

$$ShftResplotP1T := ShftResplot\left(DP1T, ShftResP1T, 1\right) = \begin{bmatrix} -223.065 \\ -223.065 \\ -27.144 \\ -27.144 \\ -27.144 \\ -27.144 \end{bmatrix} \boldsymbol{kPa}$$



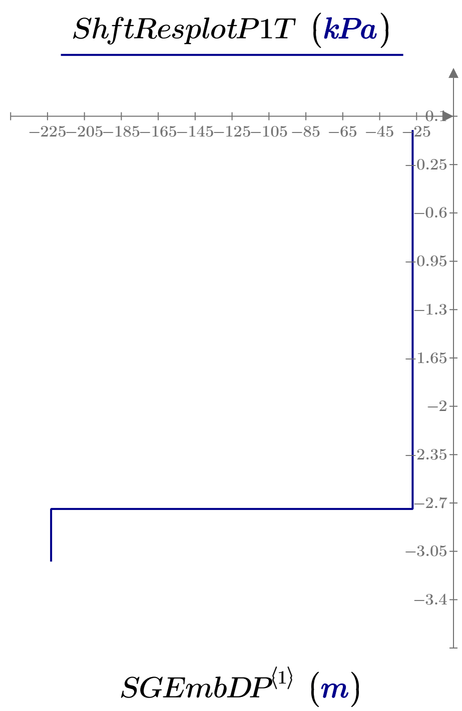


Fig B 43. Strain gauge embedment vs Unit Shaft Resistance for tension pile P1

2.3.3.8 Tension Pile P2

$ShftResP2T := UntShtRes(LdP2T, 2)$

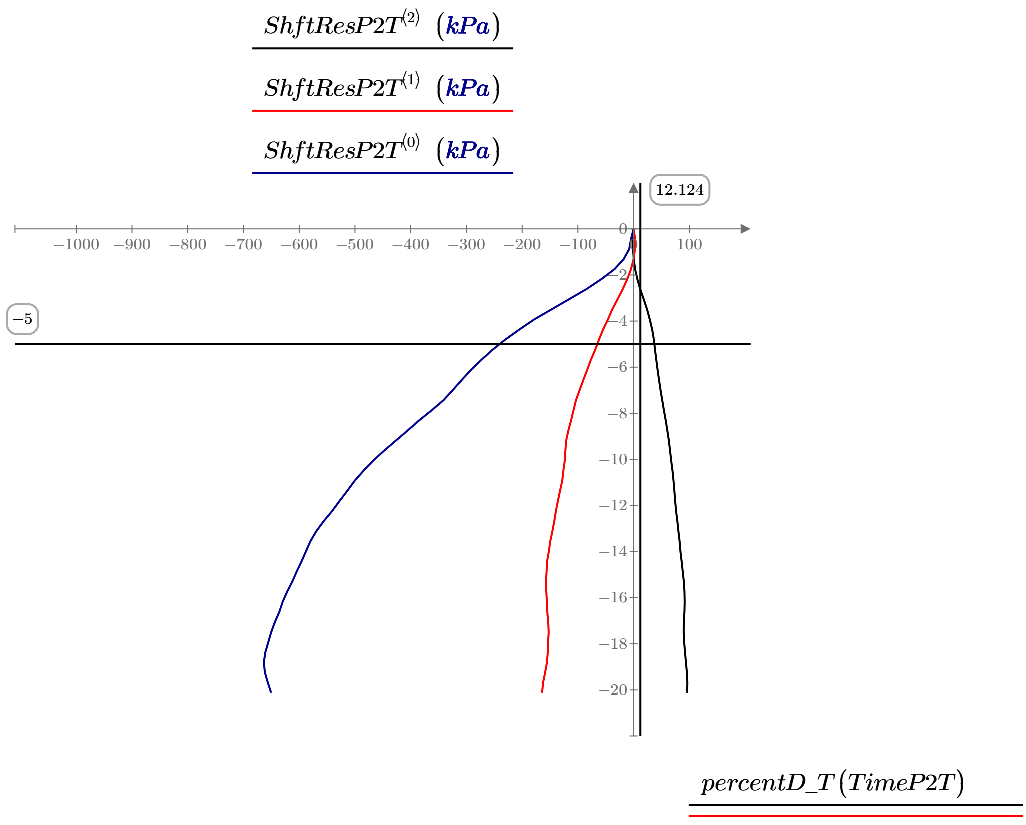


Fig B 44. Depth vs Unit Shaft Resistance for tension pile P2

$$UltShReP2T\_2 := \text{lookup}\left(-5, percentD\_T(TimeP2T), ShftResP2T^{\langle 2 \rangle}, \text{“near”}\right) = [36.394]\ kPa$$

$$UltShReP2T\_1 := \text{lookup}\left(-5, percentD\_T(TimeP2T), ShftResP2T^{\langle 1 \rangle}, \text{“near”}\right) = [-62.28]\ kPa$$

$$UltShReP2T\_0 := \text{lookup}\left(-5, percentD\_T(TimeP2T), ShftResP2T^{\langle 0 \rangle}, \text{“near”}\right) = [-230.717]\ kPa$$

$$ShftResplotP2T := ShftResplot(DP2T, ShftResP2T, 2) = \begin{bmatrix} -230.717 \\ -230.717 \\ -62.28 \\ -62.28 \\ 36.394 \\ 36.394 \end{bmatrix} kPa$$

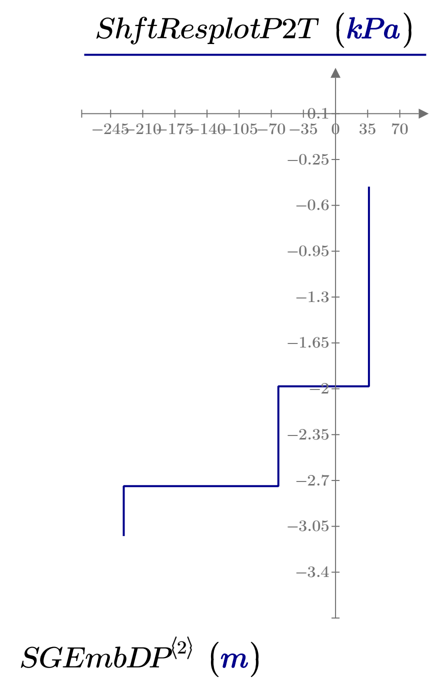


Fig B 45. Strain gague embedment vs Unit Shaft Resistance for tension pile P2

2.3.3.9 Tension Pile P3

$ShftResP3T := UntShtRes(LdP3T, 3)$

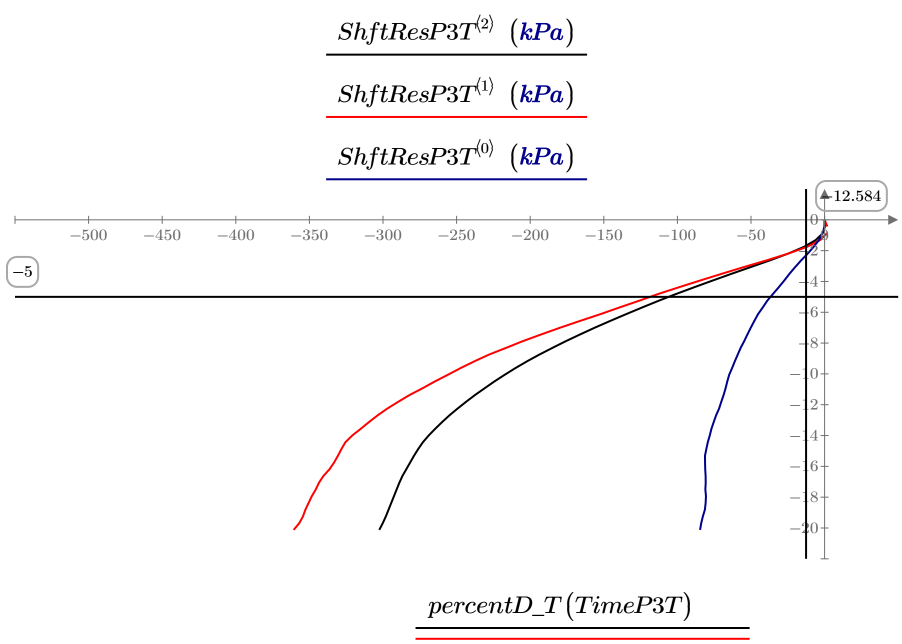


Fig B 46. Depth vs Unit Shaft Resistance for tension pile P3

$$UltShReP3T\_2 := \text{lookup}\left(-5, percentD\_T\left(TimeP3T\right), ShftResP3T^{\langle 2 \rangle}, \text{"near"}\right) = \left[-100.836\right] \; kPa$$

$$UltShReP3T\_1 := \text{lookup}\left(-5, percentD\_T\left(TimeP3T\right), ShftResP3T^{\langle 1 \rangle}, \text{"near"}\right) = \left[-112.955\right] \; kPa$$

$$UltShReP3T\_0 := \text{lookup}\left(-5, percentD\_T\left(TimeP3T\right), ShftResP3T^{\langle 0 \rangle}, \text{"near"}\right) = \left[-35.071\right] \; kPa$$

$$ShftResplotP3T := ShftResplot\left(DP3T, ShftResP3T, 3\right) = \begin{bmatrix} -35.071 \\ -35.071 \\ -112.955 \\ -112.955 \\ -100.836 \\ -100.836 \end{bmatrix} kPa$$

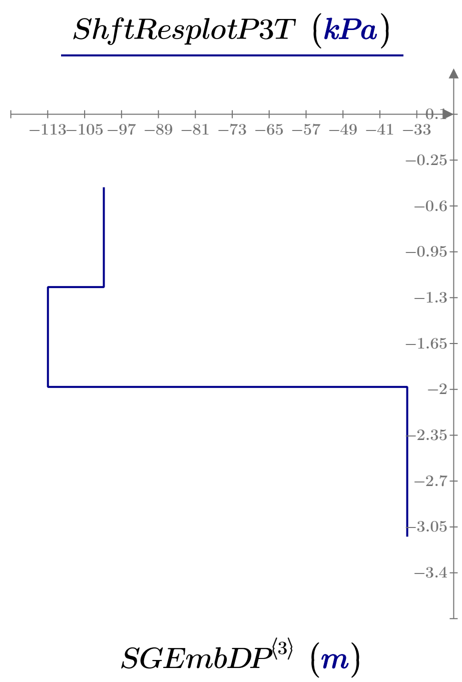


Fig B 47. Strain gauge embedment vs Unit Shaft resistance for tension pile P3

2.3.4 Coefficent of lateral earth pressure vs Depth

$$ShftResplotP\_C := \text{augment}\left(ShftResplotP0, ShftResplotP1, ShftResplotP2, ShftResplotP3, ShftResplotP4\right)$$

Utlimate Shaft resistance on the five compression piles between SGS

$$ShftResplotP\_T := \text{augment}\left(ShftResplotP0T, ShftResplotP1T, ShftResplotP2T, ShftResplotP3T\right)$$

Utlimate Shaft resistance on the four tension piles between SGS

Appendix B
Data Conversion and Processing Sheet for NI01 series of Centrifuge Tests

Function for estimating Mid depth of SGs on each piles

```
MidDSGsgmt(PileNum) :=  | shaft12 ← mean(submatrix(SGEmbDP, 0, 1, PileNum, PileNum))
                        | shaft23 ← if mean(submatrix(SGEmbDP, 2, 3, PileNum, PileNum)) = 0
                        |               || 0
                        |           else
                        |               || mean(submatrix(SGEmbDP, 2, 3, PileNum, PileNum))
                        | shaft34 ← if mean(submatrix(SGEmbDP, 4, 5, PileNum, PileNum)) = 0
                        |               || 0
                        |           else
                        |               || mean(submatrix(SGEmbDP, 4, 5, PileNum, PileNum))
                        | stack(shaft12, shaft23, shaft34)
```

Function for estimating Ks of each piles

```
Ks(ShftResplotP, PileNum) :=
  | shaft12 ← mean(submatrix(ShftResplotP, 0, 1, PileNum, PileNum)) / (mean(submatrix(SGEmbDP, 0, 1, PileNum, PileNum)) · γ · tan(δ))
  | shaft23 ← | if PileNum = 2
  |            |    || 0
  |            | else if PileNum = 3
  |            |    || 0
  |            | else
  |            |    || if mean(submatrix(SGEmbDP, 2, 3, PileNum, PileNum)) = 0
  |            |    ||     || 0
  |            |    || else
  |            |    ||     || mean(submatrix(ShftResplotP, 2, 3, PileNum, PileNum)) / (mean(submatrix(SGEmbDP, 2, 3, PileNum, PileNum)) · γ · tan(δ))
  | shaft34 ← | if PileNum = 4
  |            |    || 0
  |            | else
  |            |    || if mean(submatrix(SGEmbDP, 4, 5, PileNum, PileNum)) = 0
  |            |    ||     || 0
  |            |    || else
  |            |    ||     || mean(submatrix(ShftResplotP, 4, 5, PileNum, PileNum)) / (mean(submatrix(SGEmbDP, 4, 5, PileNum, PileNum)) · γ · tan(δ))
  | stack(−shaft12, −shaft23, −shaft34)
```

$KsP\_C := \mathrm{augment}(Ks(ShftResplotP\_C, 0), Ks(ShftResplotP\_C, 1), Ks(ShftResplotP\_C, 2), Ks(ShftResplotP\_C, 3), Ks(ShftResplotP\_C, 4))$

$KsP\_T := \mathrm{augment}(Ks(ShftResplotP\_T, 0), Ks(ShftResplotP\_T, 1), Ks(ShftResplotP\_T, 2), Ks(ShftResplotP\_T, 3))$

$MidDSGsgmtP := \mathrm{augment}(MidDSGsgmt(0), MidDSGsgmt(1), MidDSGsgmt(2), MidDSGsgmt(3), MidDSGsgmt(4))$

$Ko := \begin{bmatrix} 1-\sin(\varphi) & 1-\sin(\varphi) \end{bmatrix}$ $\qquad Kp := \begin{bmatrix} \frac{1+\sin(\varphi)}{1-\sin(\varphi)} & \frac{1+\sin(\varphi)}{1-\sin(\varphi)} \end{bmatrix}$

$K := \begin{bmatrix} 0.09 \cdot e^{0.08 \cdot \left(\varphi \cdot \frac{180}{\pi}\right)} & 0.09 \cdot e^{0.08 \cdot \left(\varphi \cdot \frac{180}{\pi}\right)} \end{bmatrix}$ Mitsch and Clemence 1985

$ProtEmbed := \begin{bmatrix} 0 & -E \cdot Nscale^{sclfac_{0,0}} \end{bmatrix} = \begin{bmatrix} 0 & -3.382 \end{bmatrix} m$ Pile Embedment in protype scale unit

$$KsP\_C = \begin{bmatrix} 10.43 & 55.073 & 35.684 & 7.676 & 12.79 \\ 0 & 24.441 & 0 & 0 & 38.003 \\ 0 & 0 & 6.253 & -147.915 & 0 \end{bmatrix}$$

$$KsP\_T = \begin{bmatrix} -1.717 & -10.914 & -11.288 & -1.972 \\ 0 & -2.435 & 0 & 0 \\ 0 & 0 & 4.285 & -17.267 \end{bmatrix}$$

$$MidDSGsgmtP = \begin{bmatrix} -1.791 & -2.934 & -2.934 & -2.553 & -2.934 \\ 0 & -1.6 & -2.362 & -1.6 & -1.981 \\ 0 & 0 & -1.219 & -0.838 & -0.838 \end{bmatrix} m$$

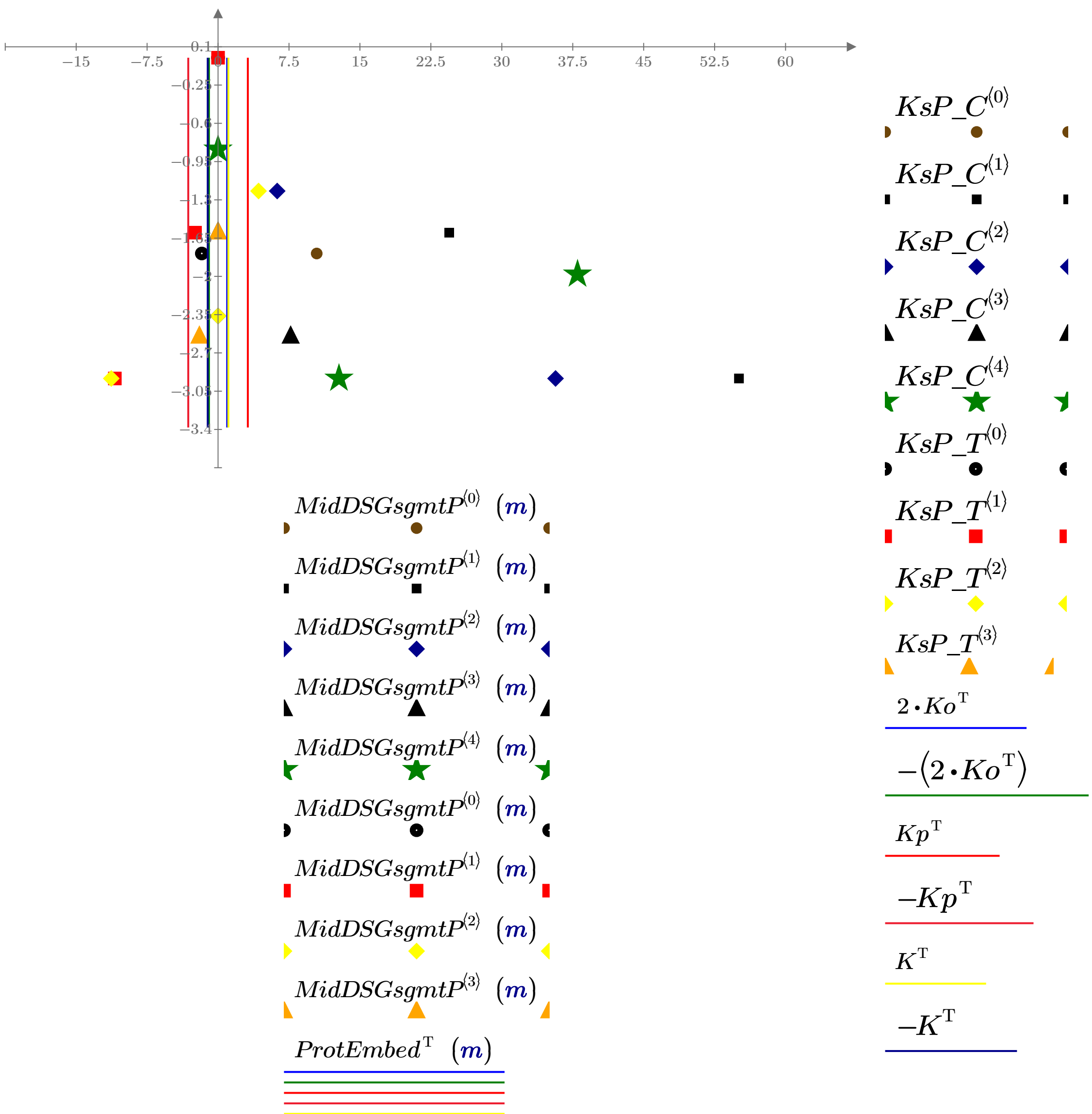


Fig B 48. Mid Depth of Strain Gauges vs Ks for all piles

2.3.4 End Bearing vs Depth

$$A_b := \pi \cdot \frac{\left(D \cdot Nscale^{sclfac_{0,0}}\right)^2}{4} = 0.456\ m^2$$

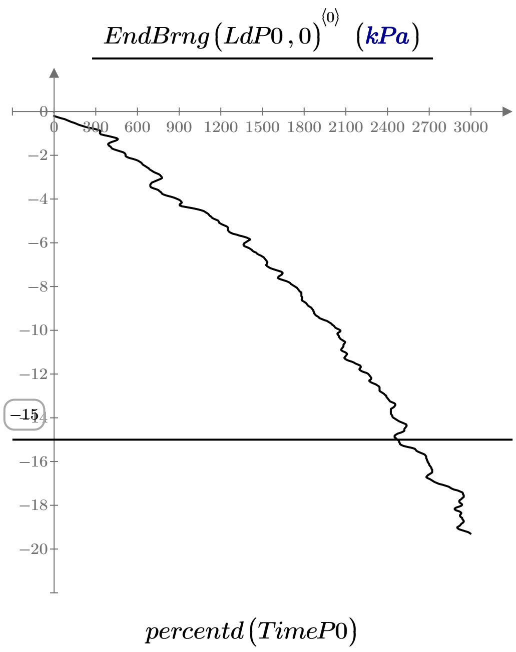
Total area at the helix in prototype scale

$$A_d := \pi \cdot \frac{\left(d \cdot Nscale^{sclfac_{0,0}}\right)^2}{4} = 0.051\ m^2$$

Total area at the shaft in prototype scale

Function for determining the end bearing

```
EndBrng(LdP, PileNum) := | for i ∈ 0,1..rows(LdP) − 1
                         |   for j ∈ 0,1..cols(LdP) − 1
                         |     q_b1[i,0] ← | if PileNum = 0
                         |                 |   (LdP[i,0]) / A_d
                         |                 | else
                         |                 |   (LdP[i,0]) / A_b
                         |     q_b23[i,1] ← | if PileNum = 2
                         |                  |   (LdP[i,2] − LdP[i,1]) / A_b
                         |                  | else if PileNum = 3
                         |                  |   (LdP[i,2] − LdP[i,1]) / A_b
                         |                  | else
                         |                  |   0
                         |     q_b34[i,2] ← | if PileNum = 4
                         |                  |   (LdP[i,3] − LdP[i,2]) / A_b
                         |                  | else
                         |                  |   0
                         | augment(q_b1^<0>, q_b23^<1>, q_b34^<2>)
```



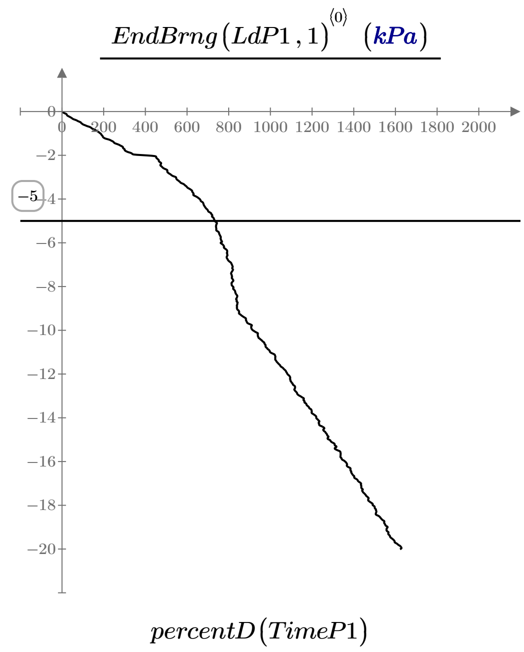
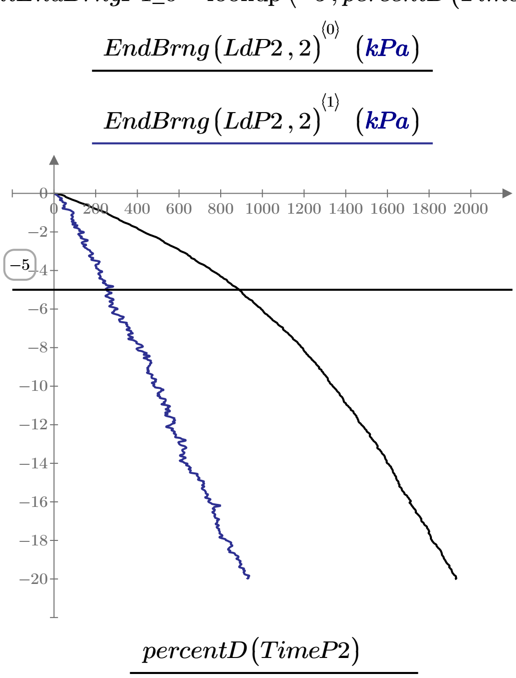


Fig B 49. Depth vs End Bearing for compression pile P0

Fig B 50. Depth vs End Bearing for compression pile P1

$$UltEndBrngP0\_0 := \text{lookup}\left(-15, percentd(TimeP0), EndBrng(LdP0,0)^{\langle 0 \rangle}, \text{"near"}\right) = \left[2.467 \cdot 10^{3}\right] \, kPa$$

$$UltEndBrngP1\_0 := \text{lookup}\left(-5, percentD(TimeP1), EndBrng(LdP1,1)^{\langle 0 \rangle}, \text{"near"}\right) = \left[731.229\right] \, kPa$$



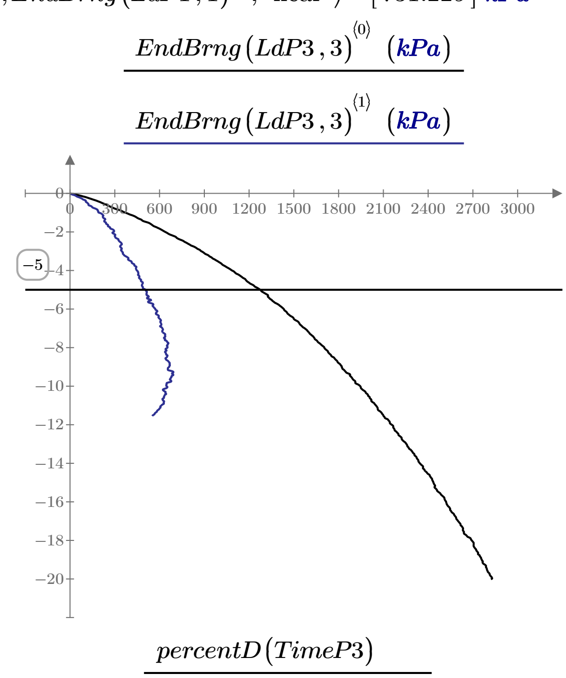


Fig B 51. Depth vs End Bearing for compression pile P2

Fig B 52. Depth vs End Bearing for compression pile P3

$$UltEndBrngP2\_0 := \text{lookup}\left(-5, percentD(TimeP2), EndBrng(LdP2,2)^{\langle 0 \rangle}, \text{“near”}\right) = [888.076]\ kPa$$

$$UltEndBrngP2\_1 := \text{lookup}\left(-5, percentD(TimeP2), EndBrng(LdP2,2)^{\langle 1 \rangle}, \text{“near”}\right) = [251.523]\ kPa$$

$$UltEndBrngP3\_0 := \text{lookup}\left(-5, percentD(TimeP3), EndBrng(LdP3,3)^{\langle 0 \rangle}, \text{“near”}\right) = [1273.785]\ kPa$$

$$UltEndBrngP3\_1 := \text{lookup}\left(-5, percentD(TimeP3), EndBrng(LdP3,3)^{\langle 1 \rangle}, \text{“near”}\right) = [506.683]\ kPa$$

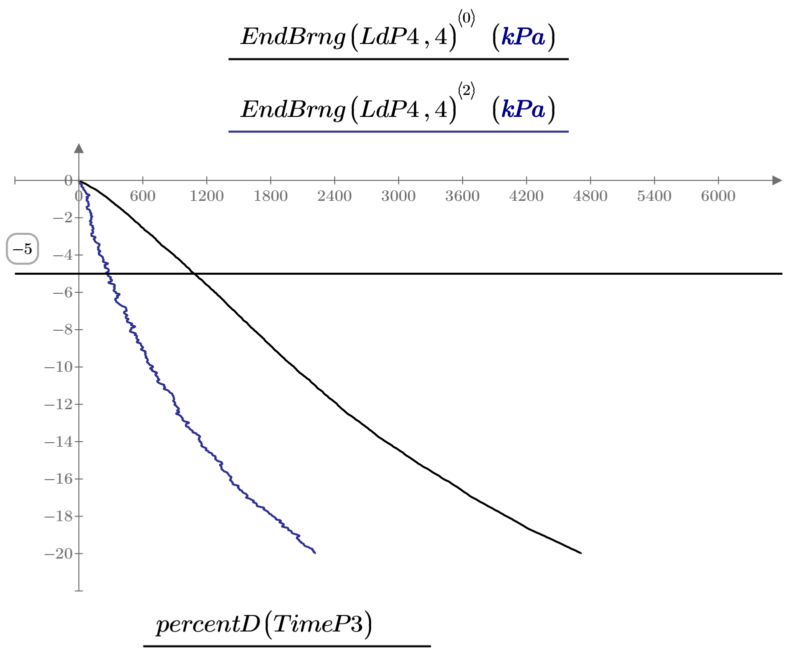


Fig B 53. Depth vs End Bearing for compression pile P4

$$UltEndBrngP4\_0 := \text{lookup}\left(-5, percentD(TimeP4), EndBrng(LdP4,4)^{\langle 0 \rangle}, \text{“near”}\right) = [1080.996]\ kPa$$

$$UltEndBrngP4\_1 := \text{lookup}\left(-5, percentD(TimeP4), EndBrng(LdP4,4)^{\langle 2 \rangle}, \text{“near”}\right) = [254.561]\ kPa$$

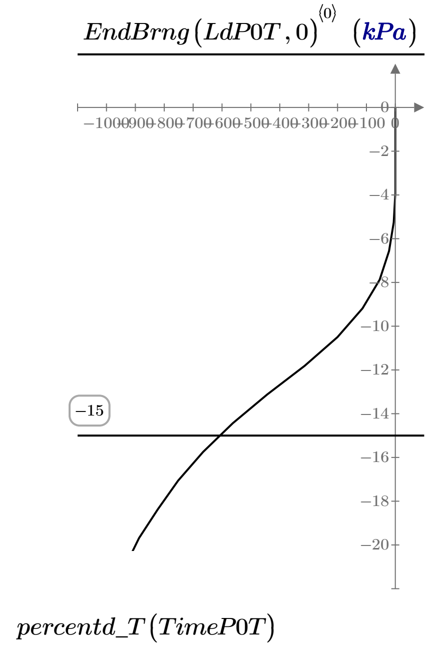


Fig B 54. Depth vs End Bearing for tension pile P0

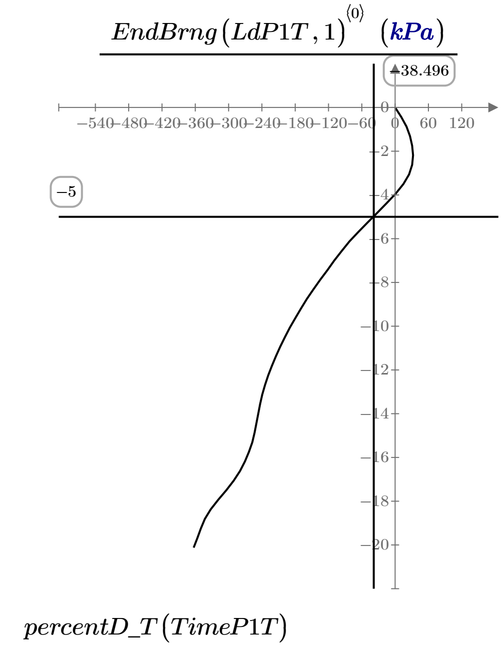


Fig B 55. Depth vs End Bearing for tension pile P1

$UltEndBrngP0T\_0 := \mathrm{lookup}\left(-15, percentd\_T(TimeP0T), EndBrng(LdP0T, 0)^{\langle 0\rangle}, \text{“near”}\right) = [-562.654]\ kPa$

$UltEndBrngP1T\_0 := \mathrm{lookup}\left(-5, percentD\_T(TimeP1T), EndBrng(LdP1T, 1)^{\langle 0\rangle}, \text{“near”}\right) = [-32.001]\ kPa$

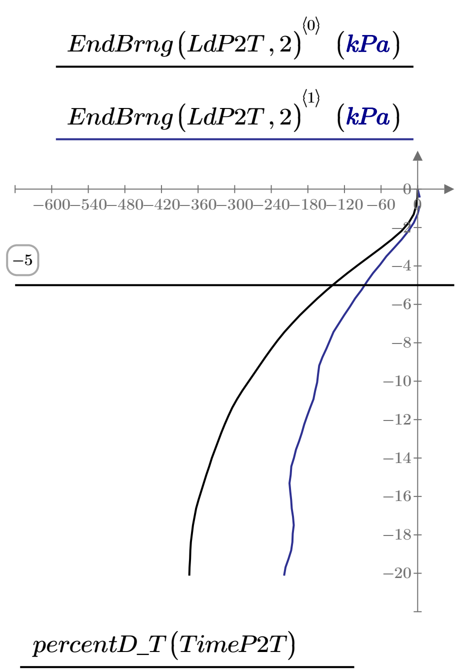


Fig B 56. Depth vs End Bearing for tension pile P2

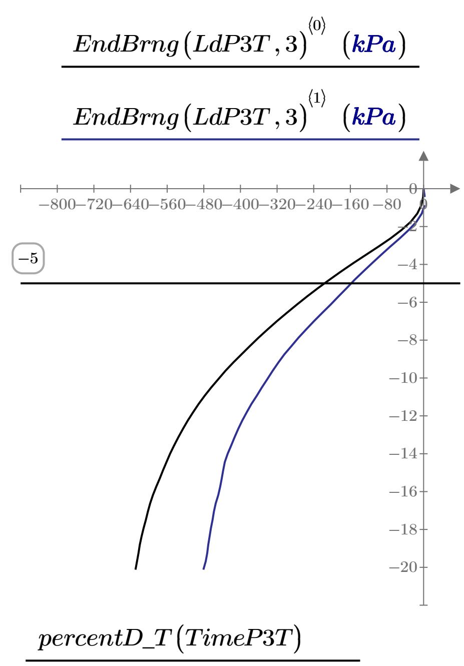


Fig B 57. Depth vs End Bearing for tension pile P3

$$UltEndBrngP2T\_0 := \text{lookup}\left(-5, percentD\_T(TimeP2T), EndBrng(LdP2T, 2)^{\langle 0 \rangle}, \text{“near”}\right) = [-132.395]\ \boldsymbol{kPa}$$

$$UltEndBrngP2T\_1 := \text{lookup}\left(-5, percentD\_T(TimeP2T), EndBrng(LdP2T, 2)^{\langle 1 \rangle}, \text{“near”}\right) = [-83.04]\ \boldsymbol{kPa}$$

$$UltEndBrngP3T\_0 := \text{lookup}\left(-5, percentD\_T(TimeP3T), EndBrng(LdP3T, 3)^{\langle 0 \rangle}, \text{“near”}\right) = [-205.68]\ \boldsymbol{kPa}$$

$$UltEndBrngP3T\_1 := \text{lookup}\left(-5, percentD\_T(TimeP3T), EndBrng(LdP3T, 3)^{\langle 1 \rangle}, \text{“near”}\right) = [-150.607]\ \boldsymbol{kPa}$$

$$HelixLoc := -\begin{bmatrix} 0.6+3.5+0.3+0.17 & 0.6+3.5+0.3+0.17 & 0.6+3.5+0.3+0.17 & 0.6+3.5+0.3+0.17 & \\ 0 & 0 & 0.6+2+0.3+0.17 & 0.6+1+0.3+0.17 & \ldots \end{bmatrix} \cdot D \cdot Nscale^{sclfac_{0,0}}$$

$$N_q(Loading) := \left\| \begin{array}{l} \text{if } Loading = \text{“Comp”} \\ \quad \left\| \begin{array}{l} P0 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP0\_0}{-HelixLoc_{0,0} \cdot \gamma}, 0\right) \\ P1 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP1\_0}{-HelixLoc_{0,1} \cdot \gamma}, 0\right) \\ P2 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP2\_0}{-HelixLoc_{0,2} \cdot \gamma}, \dfrac{UltEndBrngP2\_1}{-HelixLoc_{1,2} \cdot \gamma}\right) \\ P3 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP3\_0}{-HelixLoc_{0,3} \cdot \gamma}, \dfrac{UltEndBrngP3\_1}{-HelixLoc_{1,3} \cdot \gamma}\right) \\ P4 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP4\_0}{-HelixLoc_{0,4} \cdot \gamma}, \dfrac{UltEndBrngP4\_1}{-HelixLoc_{1,4} \cdot \gamma}\right) \end{array} \right. \\ \text{else if } Loading = \text{“Tension”} \\ \quad \left\| \begin{array}{l} P0 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP0T\_0}{HelixLoc_{0,0} \cdot \gamma}, 0\right) \\ P1 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP1T\_0}{HelixLoc_{0,1} \cdot \gamma}, 0\right) \\ P2 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP2T\_0}{HelixLoc_{0,2} \cdot \gamma}, \dfrac{UltEndBrngP2T\_1}{HelixLoc_{1,2} \cdot \gamma}\right) \\ P3 \leftarrow \text{stack}\left(\dfrac{UltEndBrngP3T\_0}{HelixLoc_{0,3}\ \gamma}, \dfrac{UltEndBrngP3T\_1}{HelixLoc_{1,3} \cdot \gamma}\right) \\ P4 \leftarrow \text{stack}(0, 0) \end{array} \right. \\ \text{augment}(P0, P1, P2, P3, P4) \end{array} \right.$$

$$N_q(\text{“Comp”}) = \begin{bmatrix} 44.002 & 13.042 & 15.84 & 22.72 & 19.281 \\ 0 & 0 & 6.678 & 19.952 & 19.392 \end{bmatrix}$$

$$N_q(\text{“Tension”}) = \begin{bmatrix} 10.036 & 0.571 & 2.361 & 3.669 & 0 \\ 0 & 0 & 2.205 & 5.931 & 0 \end{bmatrix}$$

$$HelixLoc = \begin{bmatrix} -3.482 & -3.482 & -3.482 & -3.482 & -3.482 \\ 0 & 0 & -2.339 & -1.577 & -0.815 \end{bmatrix} \; m$$

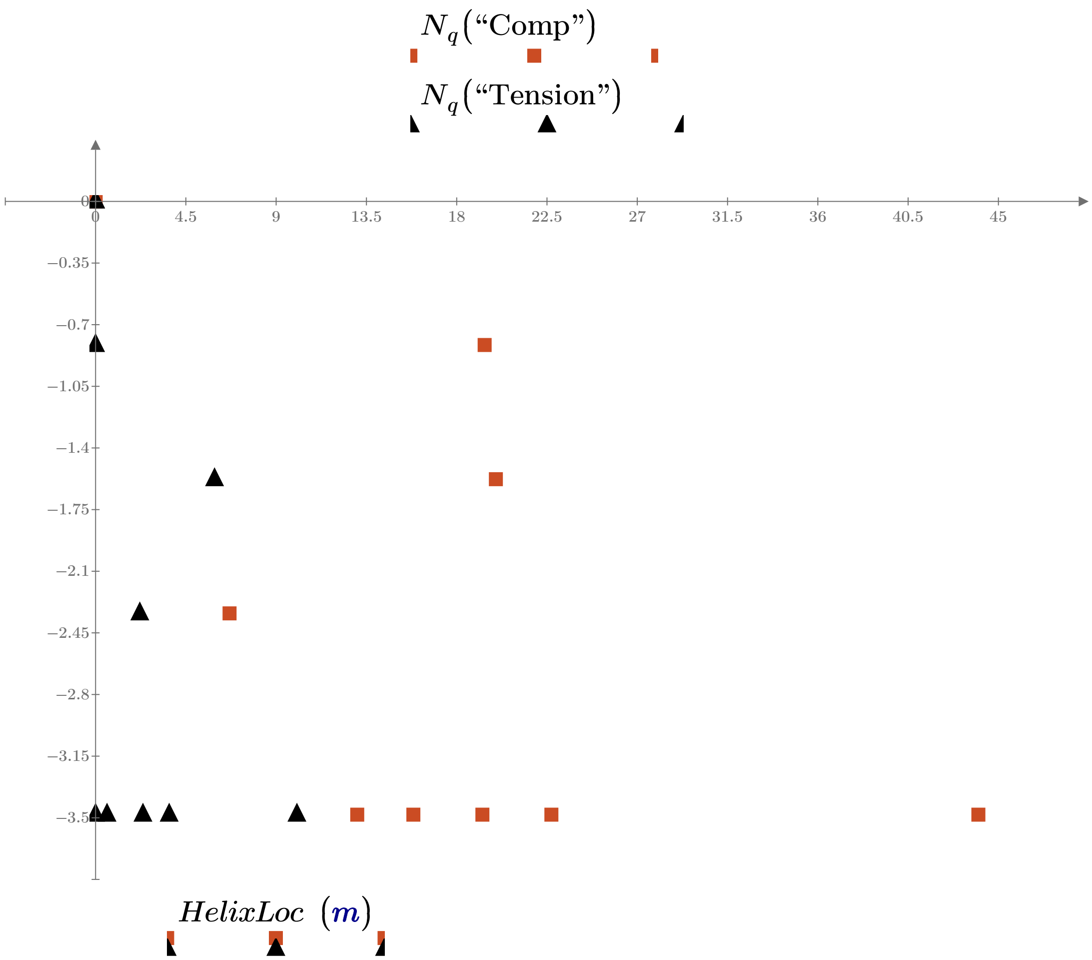


Fig B 58. Heix Depth vs Nq for all piles

2.3.5 Q vs SG Depth

Summary of plots from all nine piles:

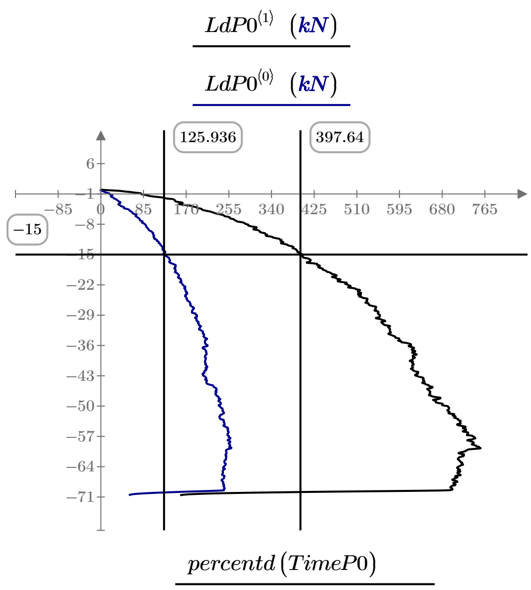


Fig B 59. Depth vs Axial Load for compression pile P0

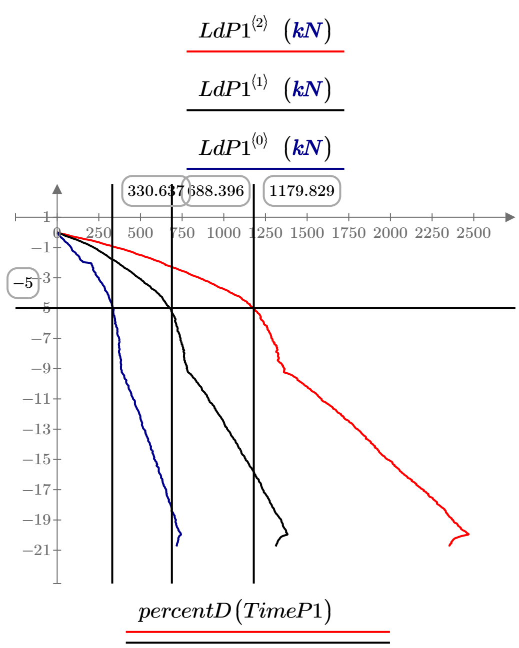


Fig B 60. Depth vs Axial Load for compression pile P1

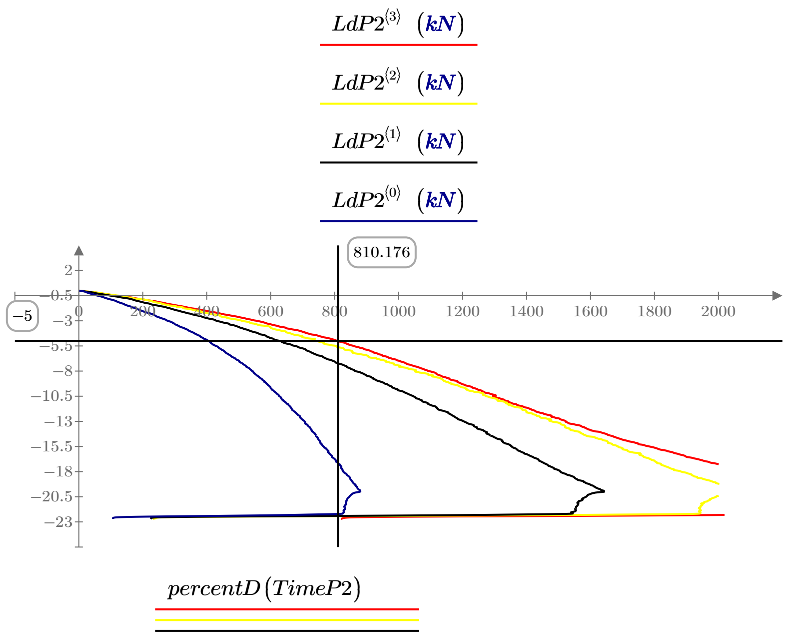


Fig B 61. Depth vs Axial Load for compression pile P2

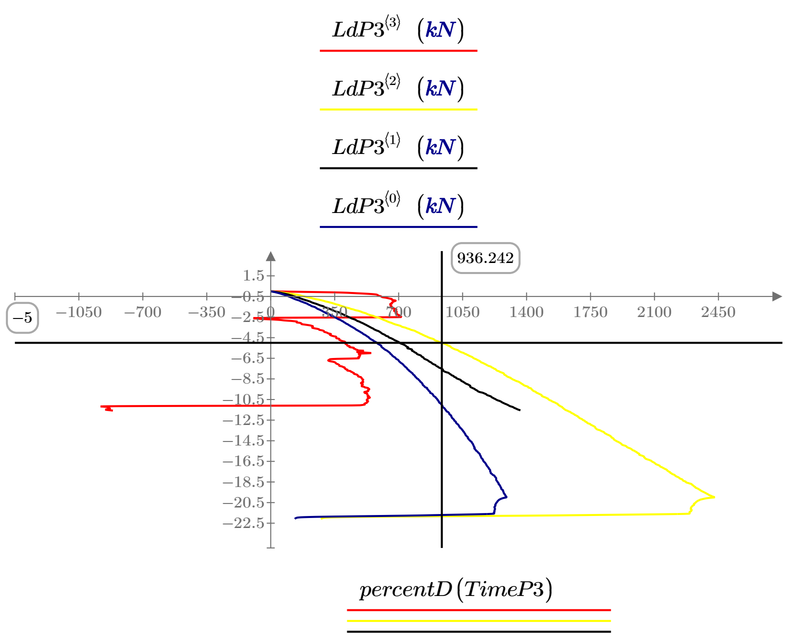


Fig B 62. Depth vs Axial Load for compression pile P3

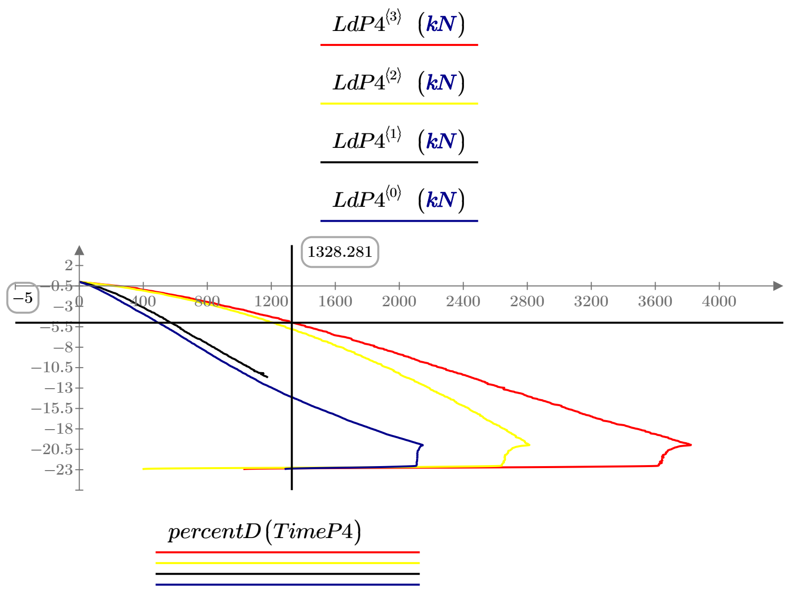


Fig B 63. Depth vs Axial Load for compression pile P4

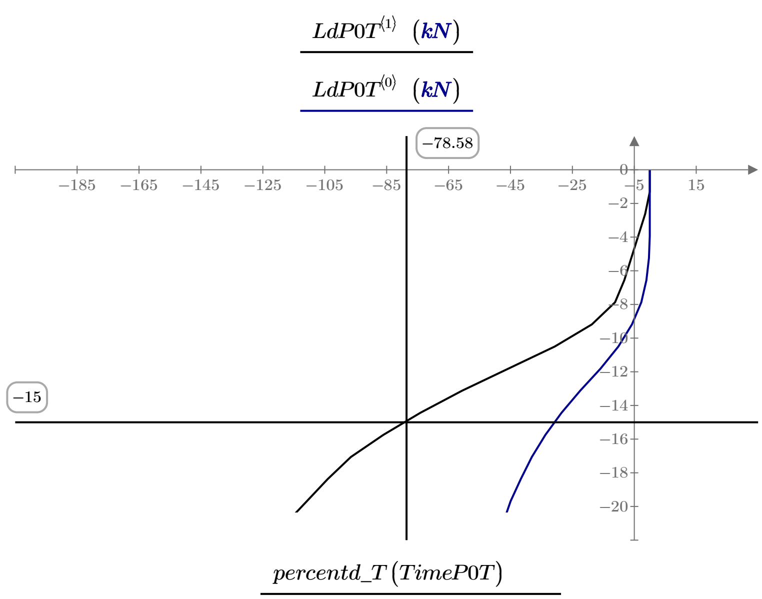


Fig B 64. Depth vs Axial Load for tension pile P0

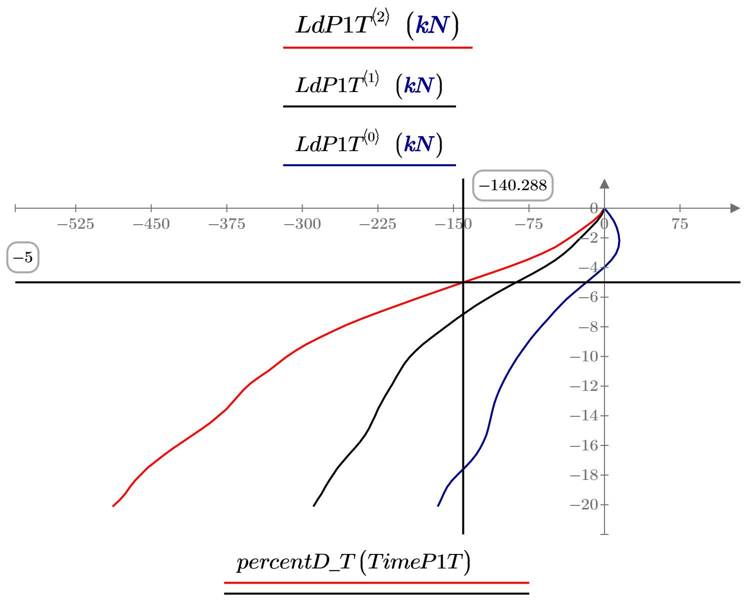


Fig B 65. Depth vs Axial Load for tension pile P1

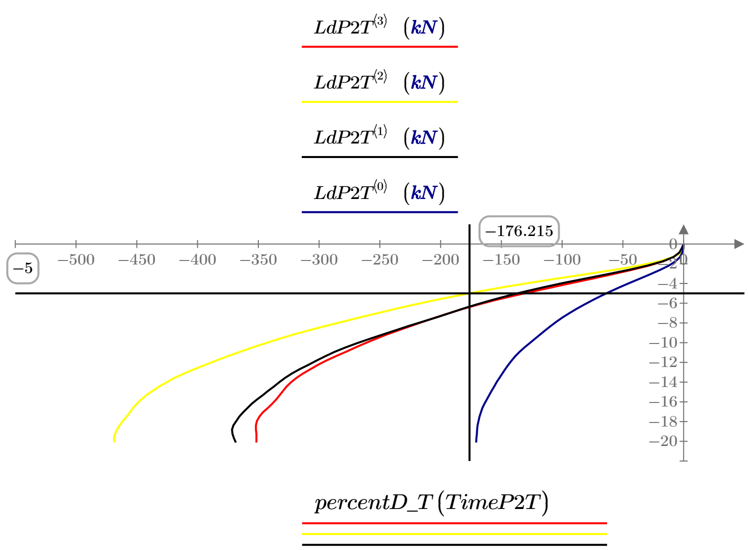


Fig B 66. Depth vs Axial Load for tension pile P2

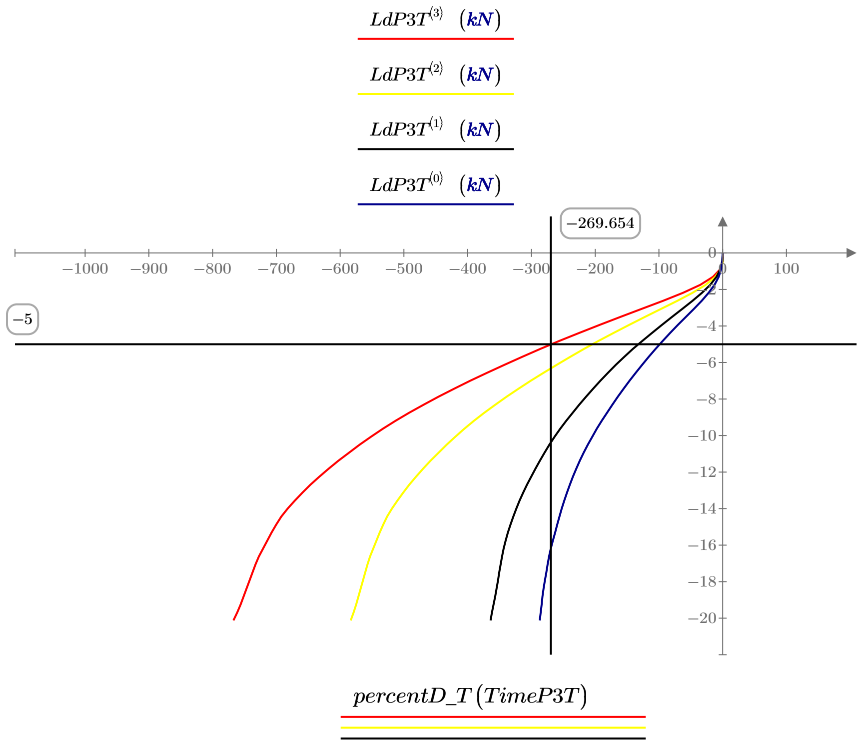


Fig B 67. Depth vs Axial Load for tension pile P3

$$SGEmbDP = \begin{bmatrix} -3.124 & -3.124 & -3.124 & -3.124 & -3.124 \\ -0.457 & -2.743 & -2.743 & -1.981 & -2.743 \\ 0 & -2.743 & -2.743 & -1.981 & -2.743 \\ 0 & -0.457 & -1.981 & -1.219 & -1.219 \\ 0 & 0 & -1.981 & -1.219 & -1.219 \\ 0 & 0 & -0.457 & -0.457 & -0.457 \end{bmatrix} m$$

SGEmbDP refers to embedment depth of SGs;
Colms 0 to 4 refers to SGS on piles P0 to P4

```
SGplotQP(DP, LdP, PileNum) := | for i ∈ 0,1..cols(LdP) − 1
                              |   | QP0 ← if PileNum = 0
                              |   |          | lookup(−15, DP, LdP⟨0⟩, "near")
                              |   |        else
                              |   |          | lookup(−5, DP, LdP⟨0⟩, "near")
                              |   | QP1 ← if PileNum = 0
                              |   |          | lookup(−15, DP, LdP⟨1⟩, "near")
                              |   |        else
                              |   |          | lookup(−5, DP, LdP⟨1⟩, "near")
                              |   | QP2 ← lookup(−5, DP, LdP⟨2⟩, "near")
                              |   | QP3 ← lookup(−5, DP, LdP⟨3⟩, "near")
                              | combined ← if PileNum = 0
                              |               | stack(QP0, QP1, QP1, QP1, QP1, QP1)
                              |             else if PileNum = 1
                              |               | stack(QP0, QP1, QP1, QP2, QP2, QP2)
                              |             else
                              |               | stack(QP0, QP1, QP1, QP2, QP2, QP3)
```

$SGplotQ\_C := \text{augment}\left(SGplotQP\left(dP0, LdP0, 0\right), SGplotQP\left(DP1, LdP1, 1\right), SGplotQP\left(DP2, LdP2, 2\right), SGplotQP\left(DP3, LdP3, 3\right), SGplotQP\left(DP4, LdP4, 4\right)\right)$

$SGplotQ\_T := \text{augment}\left(SGplotQP\left(dP0T, LdP0T, 0\right), SGplotQP\left(DP1T, LdP1T, 1\right), SGplotQP\left(DP2T, LdP2T, 2\right), SGplotQP\left(DP3T, LdP3T, 2\right)\right)$

$$SGplotQ := \text{augment}\left(SGplotQ\_C, SGplotQ\_T\right) = \begin{bmatrix} 125.006 & 333.467 & 404.995 & 580.893 & 492.974 & -28.51 & -14.594 & -60.377 & -93.798 \\ 401.94 & 675.692 & 626.737 & 705.409 & 572.452 & -74.101 & -82.411 & -130.52 & -125.785 \\ 401.94 & 675.692 & 626.737 & 705.409 & 572.452 & -74.101 & -82.411 & -130.52 & -125.785 \\ 401.94 & 1172.738 & 741.441 & 936.475 & 1210.365 & -74.101 & -131.925 & -168.39 & -194.468 \\ 401.94 & 1172.738 & 741.441 & 936.475 & 1210.365 & -74.101 & -131.925 & -168.39 & -194.468 \\ 401.94 & 1172.738 & 806.034 & 411.245 & 1326.455 & -74.101 & -131.925 & -124.131 & -255.781 \end{bmatrix} kN$$

SGplotQ refers to Qult at 5%D and 15%d for all the SGs; Colms 0 to 8 refers to P0C to P4C and P0T to P3T

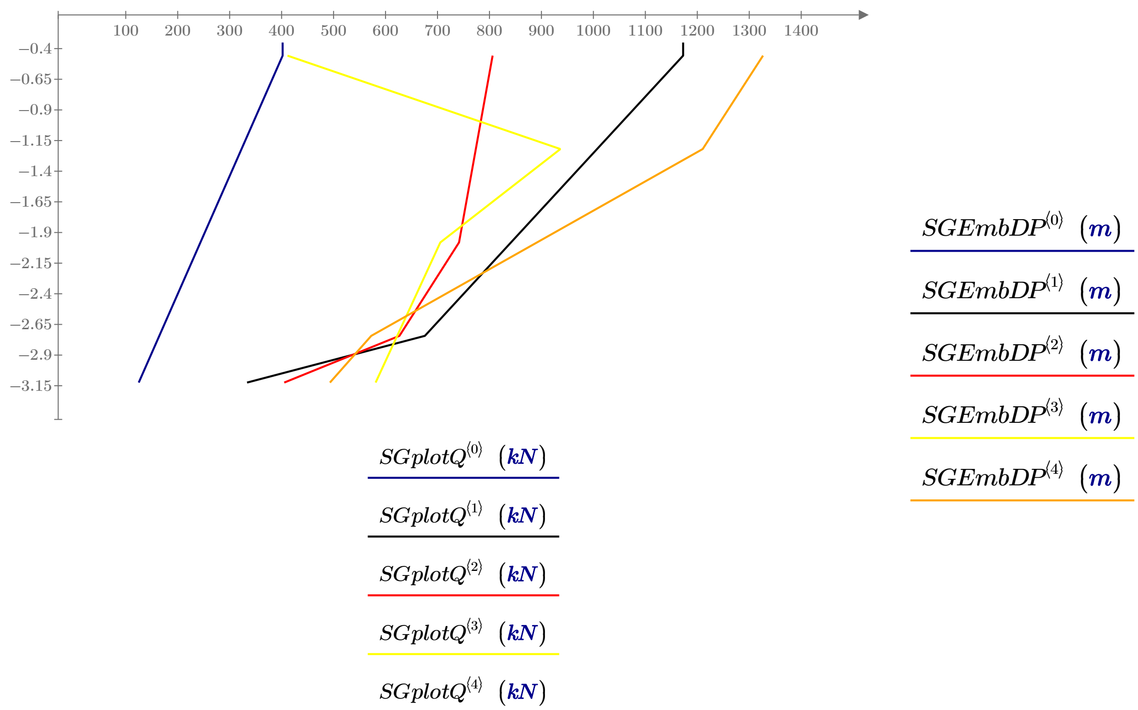


Fig B 68. SG Depth vs Axial Load for all compression piles

$SGplotQ^{\langle 0\rangle}$ to $SGplotQ^{\langle 4\rangle}$ *refers to Q of P0C to P4C*

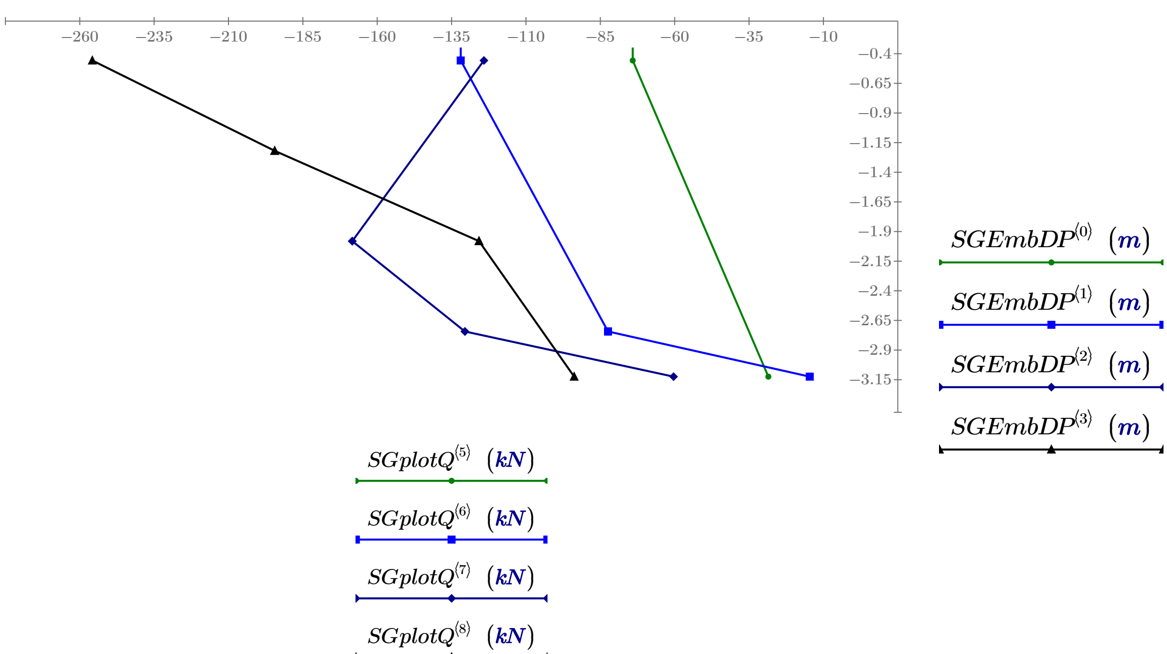


Fig B 69. SG Depth vs Axial Load for all tension piles

$SGplotQ^{\langle 5\rangle}$ to $SGplotQ^{\langle 8\rangle}$ *refers to Q of P0T to P3T*

2.4 1g Installation Torque on Piles

The installation torque was measured in 1g for the nine piles.

2.4.1 Installation Torque vs Time

2.4.1.1 Compression Pile P0

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \text{READEXCEL}\left(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P0C!A1:B149”}\right)$

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 148 \end{array} \begin{bmatrix} 0 & 2.882 \cdot 10^{-6} \\ 1 & 1.441 \cdot 10^{-6} \\ 2 & -1.441 \cdot 10^{-6} \\ 3 & -1.009 \cdot 10^{-5} \\ 4 & -1.729 \cdot 10^{-5} \\ 5 & -2.306 \cdot 10^{-5} \\ 6 & -2.594 \cdot 10^{-5} \\ 7 & -2.882 \cdot 10^{-5} \\ 8 & -2.738 \cdot 10^{-5} \\ 9 & -2.594 \cdot 10^{-5} \\ 10 & -2.306 \cdot 10^{-5} \\ 11 & -2.306 \cdot 10^{-5} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP0C := P^{\langle 0 \rangle}\ s$

$RawdataP0C := P^{\langle 1 \rangle} \cdot \frac{mV}{V}$

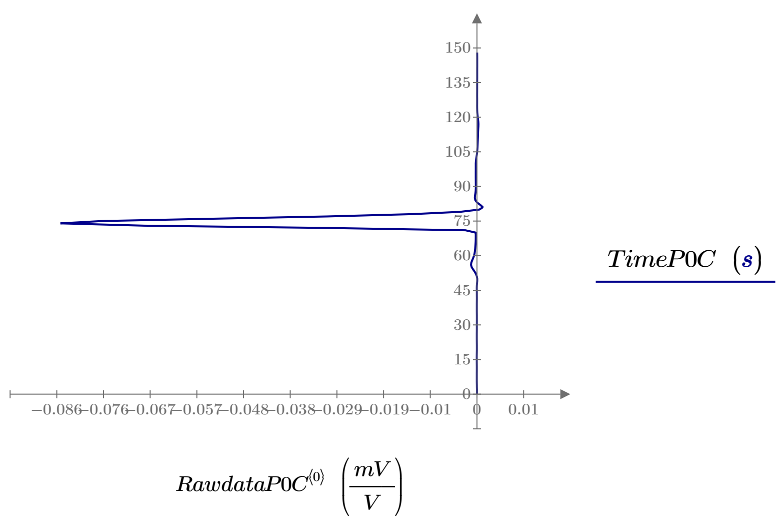


Fig B 70. Rawdata time history for installtion torque in 1g; compression pile P0

$$TorquedataP0C := RawdataP0C \cdot \text{mean}(CFTr)$$

$$\text{mean}(CFTr) = 6.75\ kN \cdot \frac{m}{\frac{mV}{V}}$$

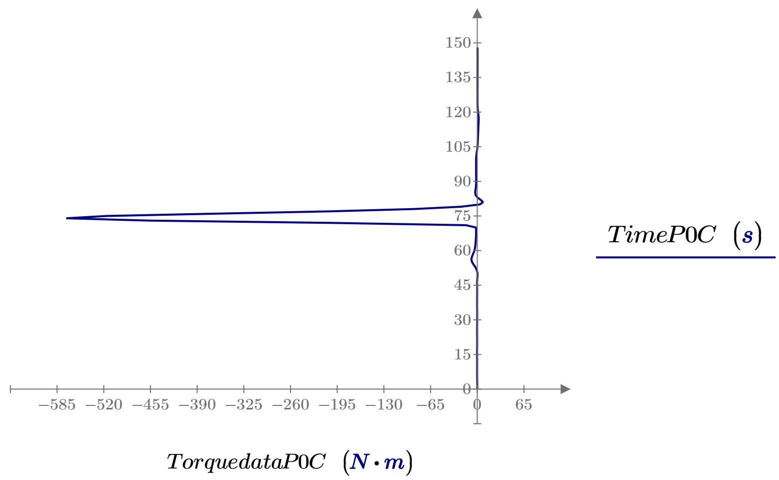


Fig B 71. Torque time history for installtion torque in 1g; compression pile P0

2.4.1.2 Compression Pile P1

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$$P := \text{READEXCEL}(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P1C!A1:B82”})$$

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 81 \end{array} \left[\begin{array}{cc} 0 & -7.206 \cdot 10^{-6} \\ 1 & -8.647 \cdot 10^{-6} \\ 2 & -1.009 \cdot 10^{-5} \\ 3 & -1.009 \cdot 10^{-5} \\ 4 & -1.009 \cdot 10^{-5} \\ 5 & -7.206 \cdot 10^{-6} \\ 6 & -5.764 \cdot 10^{-6} \\ 7 & -4.323 \cdot 10^{-6} \\ 8 & -7.206 \cdot 10^{-6} \\ 9 & -8.647 \cdot 10^{-6} \\ 10 & -1.009 \cdot 10^{-5} \\ 11 & -1.009 \cdot 10^{-5} \\ & \vdots \end{array}\right]$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$$TimeP1C := P^{\langle 0 \rangle}\ s$$

$$RawdataP1C := P^{\langle 1 \rangle} \cdot \frac{mV}{V}$$

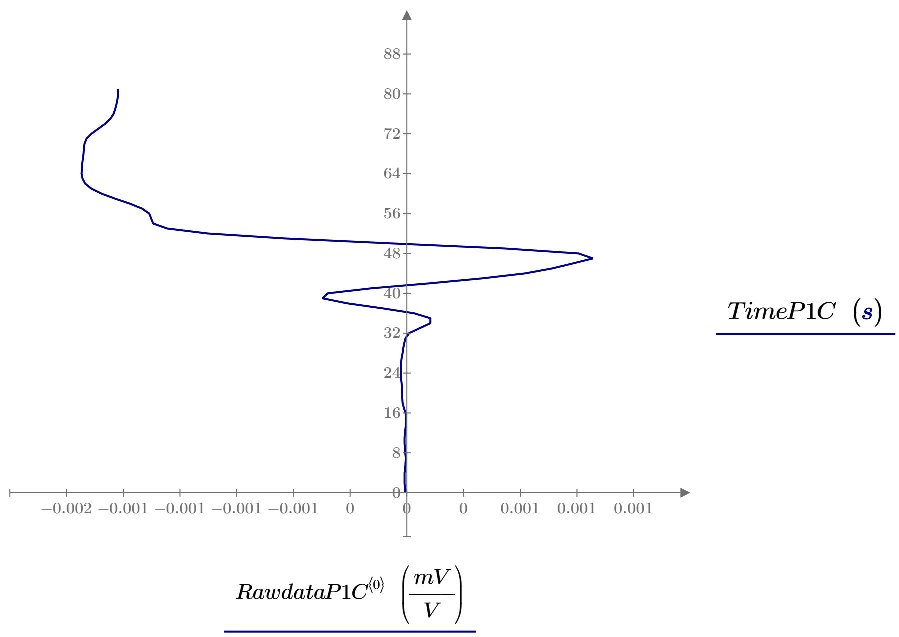


Fig B 72. Rawdata time history for installtion torque in 1g; compression pile P1

$$TorquedataP1C := RawdataP1C \cdot \mathrm{mean}(CFTr)$$

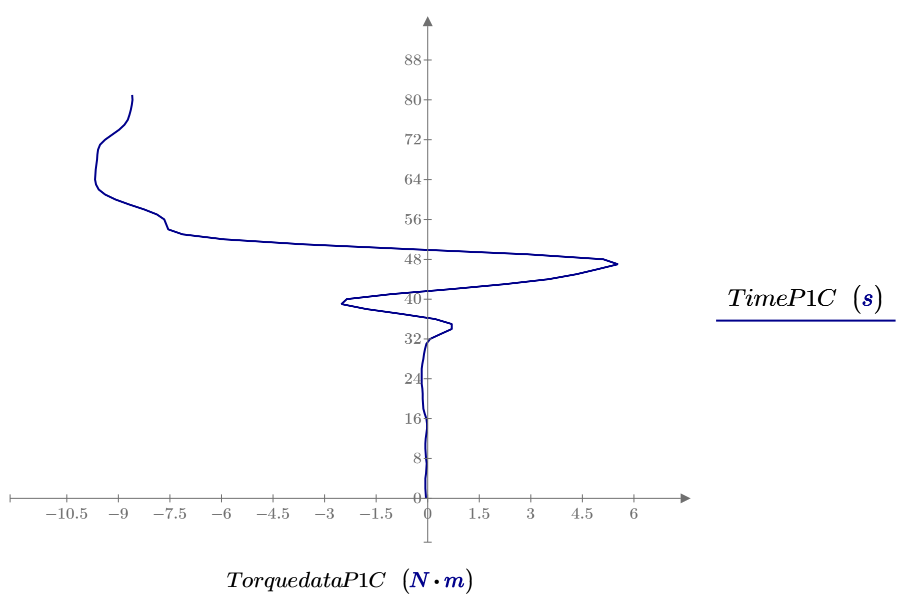


Fig B 73. Torque time history for installtion torque in 1g; compression pile P1

2.4.1.2 Compression Pile P2

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \text{READEXCEL}(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P2C!A1:B189”})$

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 188 \end{array} \begin{bmatrix} 0 & -4.323 \cdot 10^{-6} \\ 1 & -1.441 \cdot 10^{-6} \\ 2 & -3.941 \cdot 10^{-13} \\ 3 & 2.882 \cdot 10^{-6} \\ 4 & 5.764 \cdot 10^{-6} \\ 5 & 8.647 \cdot 10^{-6} \\ 6 & 1.153 \cdot 10^{-5} \\ 7 & 1.153 \cdot 10^{-5} \\ 8 & 1.009 \cdot 10^{-5} \\ 9 & 1.009 \cdot 10^{-5} \\ 10 & 1.297 \cdot 10^{-5} \\ 11 & 1.441 \cdot 10^{-5} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP2C := P^{\langle 0 \rangle} \, s$

$RawdataP2C := P^{\langle 1 \rangle} \cdot \dfrac{mV}{V}$

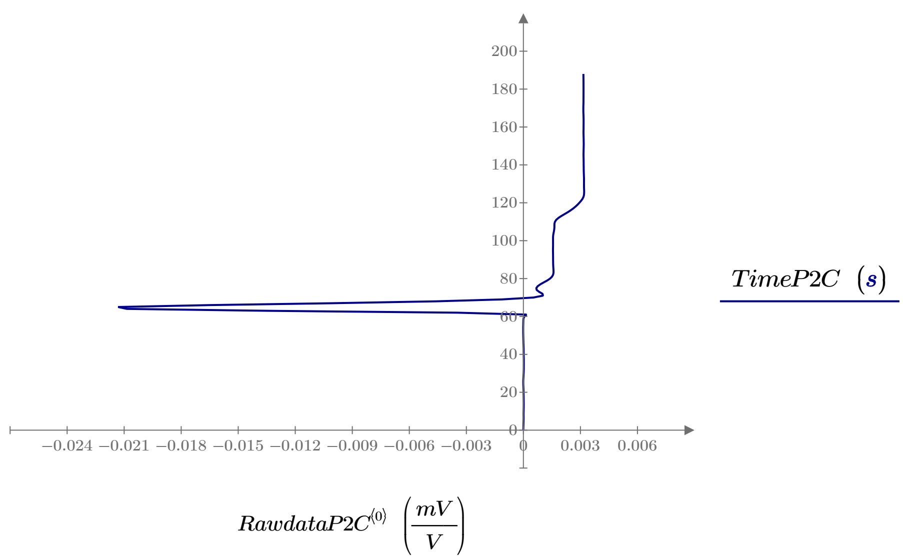


Fig B 74. Rawdata time history for installtion torque in 1g; compression pile P2

$TorquedataP2C := RawdataP2C \cdot \text{mean}(CFTr)$

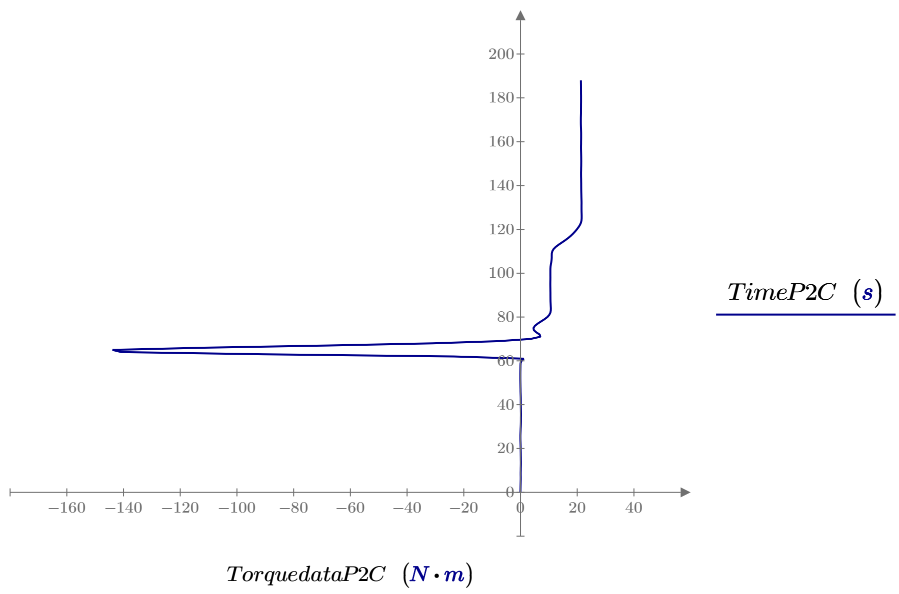


Fig B 75. Torque time history for installtion torque in 1g; compression pile P2

2.4.1.2 Compression Pile P3

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \mathrm{READEXCEL}(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P3C\_2!A1:B97”})$

$$P = \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 96 \end{array} \begin{bmatrix} 0 & -4.323 \cdot 10^{-6} \\ 1 & -4.323 \cdot 10^{-6} \\ 2 & -1.441 \cdot 10^{-6} \\ 3 & -1.441 \cdot 10^{-6} \\ 4 & -1.441 \cdot 10^{-6} \\ 5 & -2.882 \cdot 10^{-6} \\ 6 & -4.323 \cdot 10^{-6} \\ 7 & -5.764 \cdot 10^{-6} \\ 8 & -5.764 \cdot 10^{-6} \\ 9 & -4.323 \cdot 10^{-6} \\ 10 & -2.882 \cdot 10^{-6} \\ 11 & -1.642 \cdot 10^{-13} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP3C := P^{\langle 0 \rangle}\ s$

$RawdataP3C := P^{\langle 1 \rangle} \cdot \dfrac{mV}{V}$

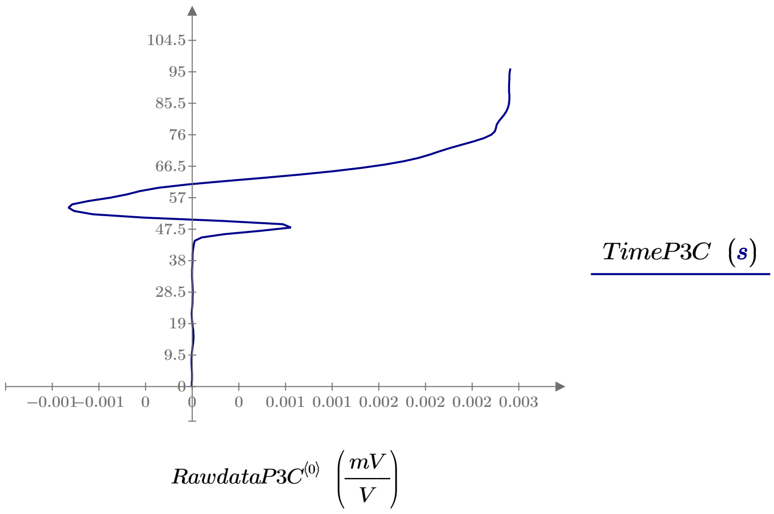


Fig B 76. Rawdata time history for installtion torque in 1g; compression pile P3

$$TorquedataP3C := RawdataP3C \cdot \mathrm{mean}\left(CFTr\right)$$

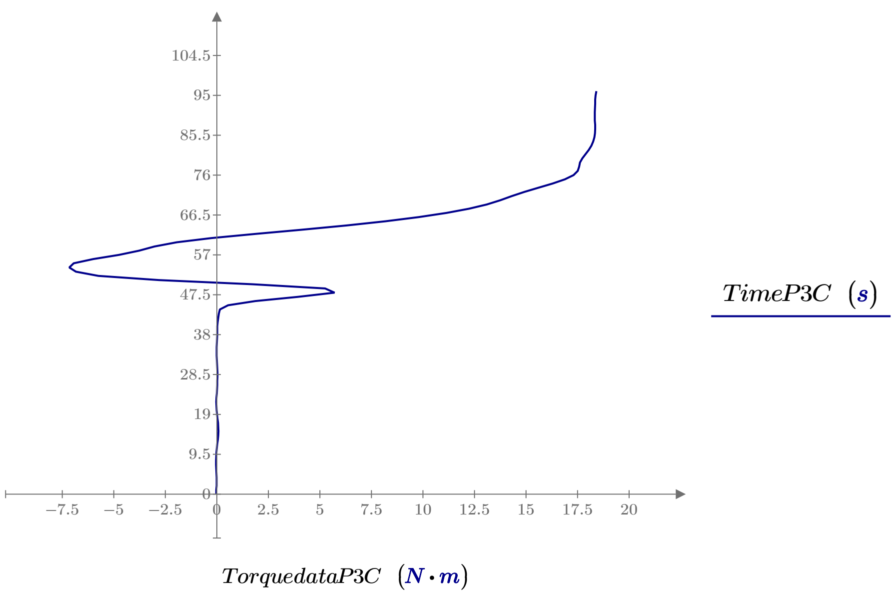


Fig B 77. Torque time history for installtion torque in 1g; compression pile P3

2.4.1.2 Compression Pile P4

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \mathrm{READEXCEL}\left(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P4C!A1:B148”}\right)$

$$P = \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 147 \end{array} \begin{bmatrix} 0 & 6.139 \cdot 10^{-4} \\ 1 & 6.154 \cdot 10^{-4} \\ 2 & 6.182 \cdot 10^{-4} \\ 3 & 6.211 \cdot 10^{-4} \\ 4 & 6.24 \cdot 10^{-4} \\ 5 & 6.269 \cdot 10^{-4} \\ 6 & 6.283 \cdot 10^{-4} \\ 7 & 6.298 \cdot 10^{-4} \\ 8 & 6.298 \cdot 10^{-4} \\ 9 & 6.298 \cdot 10^{-4} \\ 10 & 6.298 \cdot 10^{-4} \\ 11 & 6.312 \cdot 10^{-4} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP4C := P^{\langle 0 \rangle}\ s$

$RawdataP4C := P^{\langle 1 \rangle} \cdot \dfrac{mV}{V}$

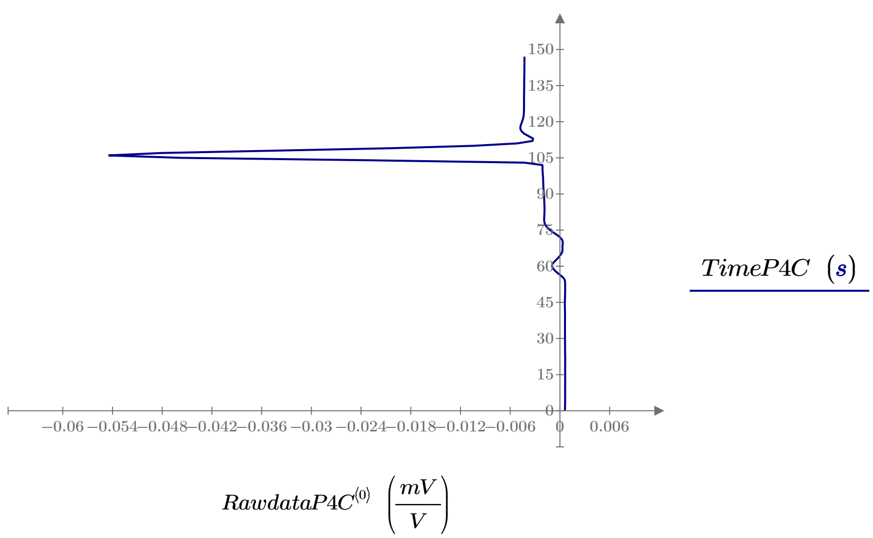


Fig B 78. Rawdata time history for installtion torque in 1g; compression pile P4

$TorquedataP4C := RawdataP4C \cdot \text{mean}(CFTr)$

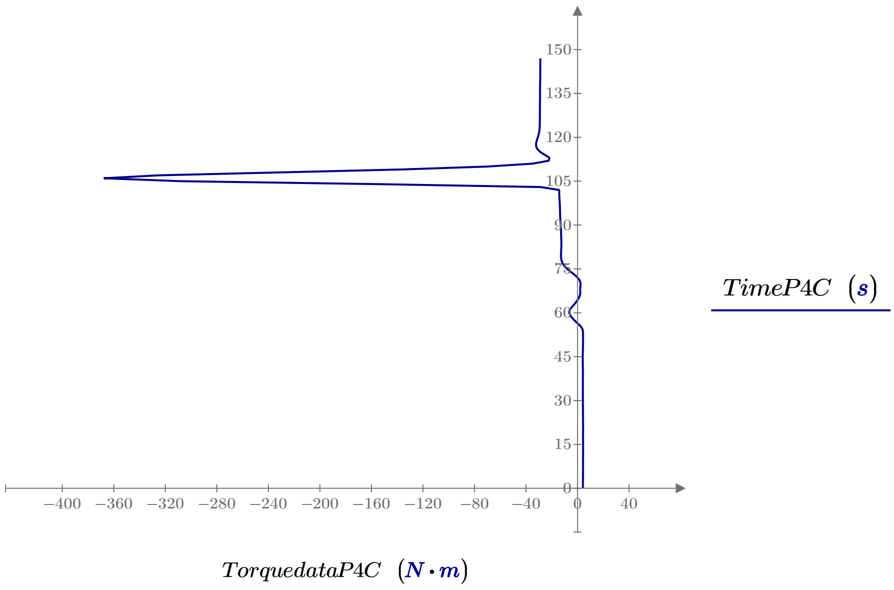


Fig B 79. Torque time history for installtion torque in 1g; compression pile P4

2.4.1.2 Tension Pile P0

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \text{READEXCEL}(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P0T!A1:B140”})$

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 139 \end{array} \begin{bmatrix} 0 & -1.009 \cdot 10^{-5} \\ 1 & -1.297 \cdot 10^{-5} \\ 2 & -1.729 \cdot 10^{-5} \\ 3 & -2.018 \cdot 10^{-5} \\ 4 & -2.162 \cdot 10^{-5} \\ 5 & -2.45 \cdot 10^{-5} \\ 6 & -2.594 \cdot 10^{-5} \\ 7 & -2.738 \cdot 10^{-5} \\ 8 & -2.882 \cdot 10^{-5} \\ 9 & -2.882 \cdot 10^{-5} \\ 10 & -2.45 \cdot 10^{-5} \\ 11 & -1.873 \cdot 10^{-5} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP0T := P^{\langle 0 \rangle}\, s$

$$RawdataP0T := P^{\langle 1 \rangle} \cdot \frac{mV}{V}$$

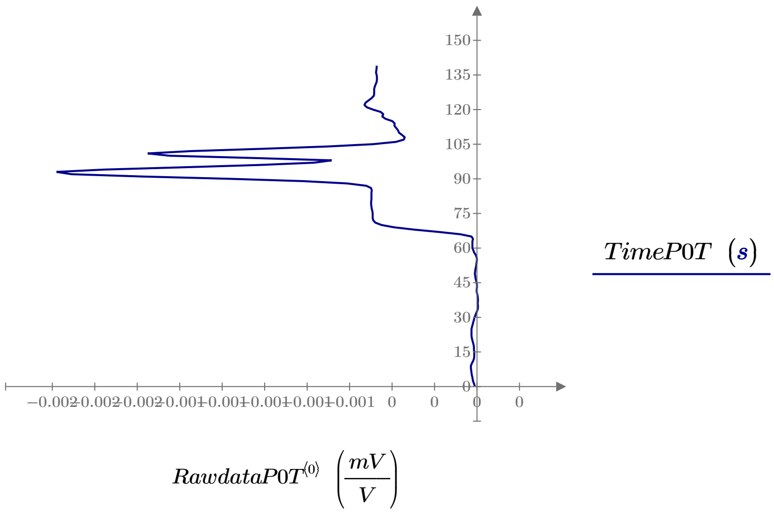


Fig B 80. Rawdata time history for installtion torque in 1g; tension pile P0

$$TorquedataP0T := RawdataP0T \cdot \text{mean}(CFTr)$$

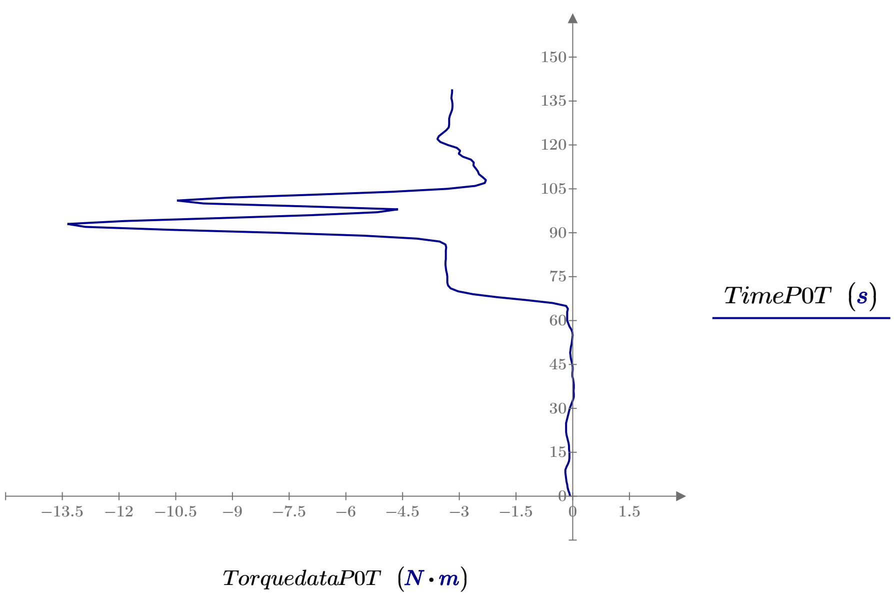


Fig B 81. Torque time history for installtion torque in 1g; tension pile P0

2.4.1.2 Tension Pile P1

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \mathrm{READEXCEL}\left(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P1T\_2!A1:B99”}\right)$

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 98 \end{array} \begin{bmatrix} 0 & 7.206 \cdot 10^{-6} \\ 1 & 5.764 \cdot 10^{-6} \\ 2 & 2.882 \cdot 10^{-6} \\ 3 & 1.441 \cdot 10^{-6} \\ 4 & 1.011 \cdot 10^{-14} \\ 5 & -1.441 \cdot 10^{-6} \\ 6 & -1.441 \cdot 10^{-6} \\ 7 & 1.441 \cdot 10^{-6} \\ 8 & 5.764 \cdot 10^{-6} \\ 9 & 1.009 \cdot 10^{-5} \\ 10 & 1.297 \cdot 10^{-5} \\ 11 & 1.441 \cdot 10^{-5} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP1T := P^{\langle 0 \rangle}\ s$

$RawdataP1T := P^{\langle 1 \rangle} \cdot \dfrac{mV}{V}$

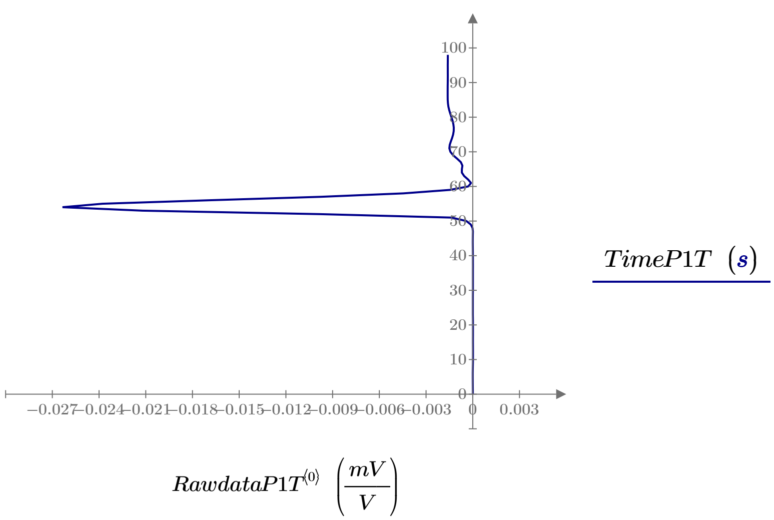


Fig B 82. Rawdata time history for installtion torque in 1g; tension pile P1

$TorquedataP1T := RawdataP1T \cdot \mathrm{mean}(CFTr)$

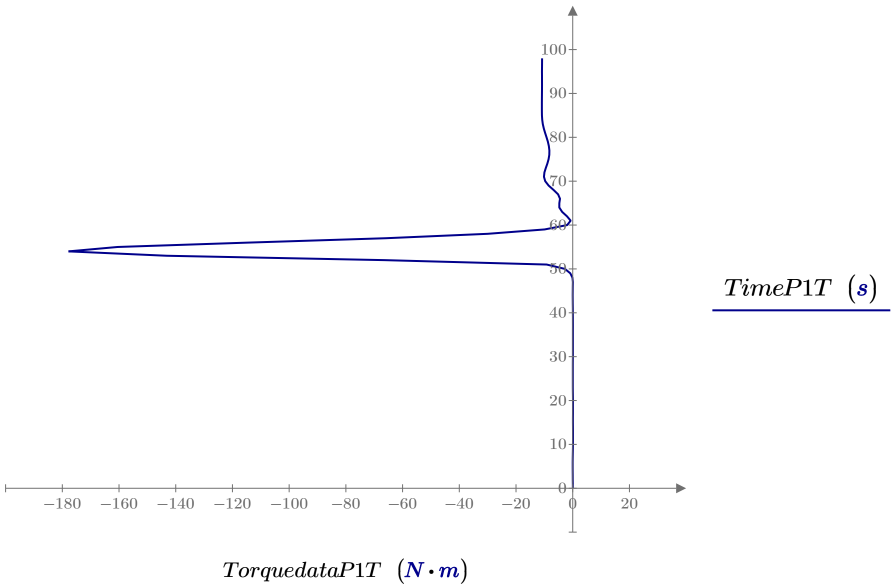


Fig B 83. Torque time history for installtion torque in 1g; tension pile P1

2.4.1.2 Tension Pile P2

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \mathrm{READEXCEL}(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P2T!A1:B237”})$

$$P = \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 236 \end{array} \begin{bmatrix} 0 & 4.9 \cdot 10^{-5} \\ 1 & 4.756 \cdot 10^{-5} \\ 2 & 4.467 \cdot 10^{-5} \\ 3 & 4.323 \cdot 10^{-5} \\ 4 & 4.179 \cdot 10^{-5} \\ 5 & 4.179 \cdot 10^{-5} \\ 6 & 4.323 \cdot 10^{-5} \\ 7 & 4.323 \cdot 10^{-5} \\ 8 & 4.467 \cdot 10^{-5} \\ 9 & 4.467 \cdot 10^{-5} \\ 10 & 4.323 \cdot 10^{-5} \\ 11 & 4.179 \cdot 10^{-5} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP2T := P^{\langle 0 \rangle}\ s$

$$RawdataP2T := P^{\langle 1 \rangle} \cdot \frac{mV}{V}$$

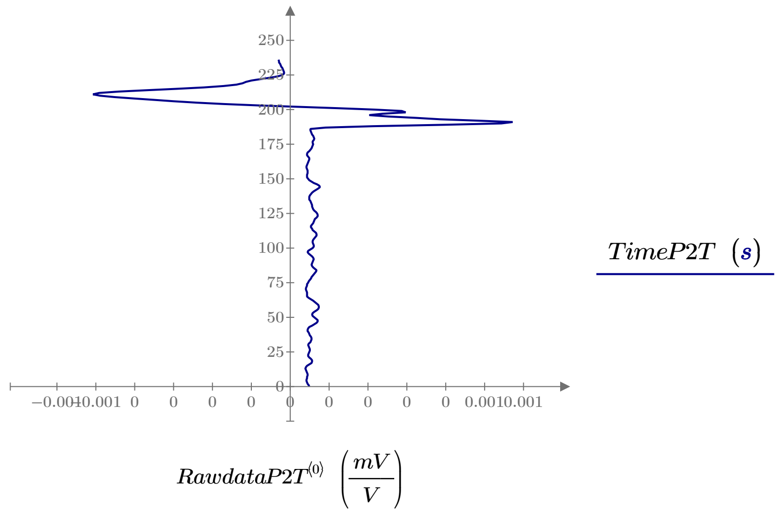


Fig B 84. Rawdata time history for installtion torque in 1g; tension pile P2

$$TorquedataP2T := RawdataP2T \cdot \text{mean}(CFTr)$$

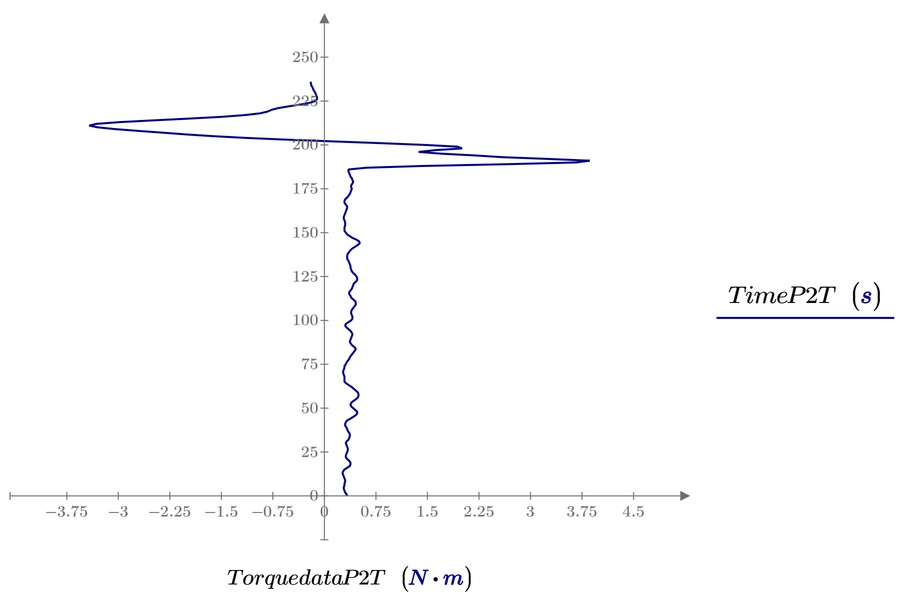


Fig B 85. Torque time history for installtion torque in 1g; tension pile P2

2.4.1.2 Tension Pile P3

The data was measured with the strain gauge placed at the collar of the pile. The section provides the details of the time history:

$P := \text{READEXCEL}\left(\text{“.\textbackslash NI01 Torque Data.xlsx”}, \text{“P3T!A1:B233”}\right)$

$$P = \begin{array}{r} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ \vdots \\ 232 \end{array}\begin{bmatrix} 0 & 4.323 \cdot 10^{-6} \\ 1 & 5.764 \cdot 10^{-6} \\ 2 & 4.323 \cdot 10^{-6} \\ 3 & 1.441 \cdot 10^{-6} \\ 4 & -2.882 \cdot 10^{-6} \\ 5 & -7.206 \cdot 10^{-6} \\ 6 & -1.153 \cdot 10^{-5} \\ 7 & -1.297 \cdot 10^{-5} \\ 8 & -1.153 \cdot 10^{-5} \\ 9 & -7.206 \cdot 10^{-6} \\ 10 & -2.882 \cdot 10^{-6} \\ 11 & 2.882 \cdot 10^{-6} \\ & \vdots \end{bmatrix}$$

Raw Data HBM Pile. The Colm 0 stands for the time, Colm 1 stands for the Raw HBM strain gage Data for torque

$TimeP3T := P^{\langle 0 \rangle}\ s$

$RawdataP3T := P^{\langle 1 \rangle} \cdot \dfrac{mV}{V}$

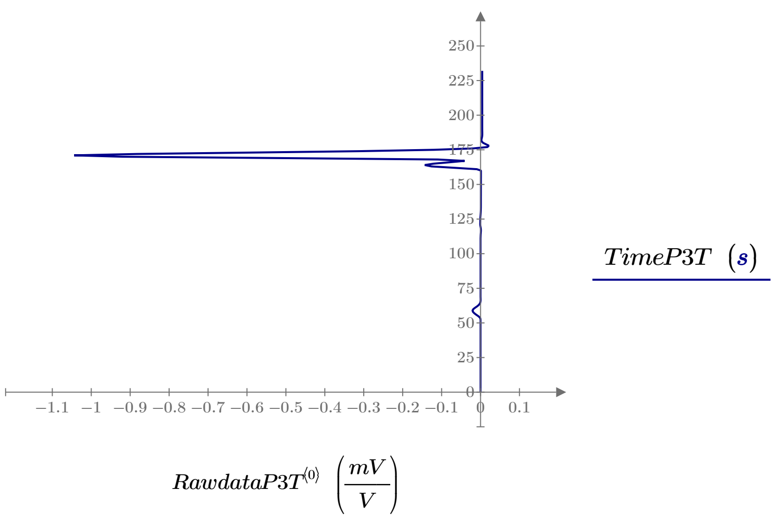


Fig B 86. Rawdata time history for installtion torque in 1g; tension pile P3

$$TorquedataP3T := RawdataP3T \cdot \text{mean}(CFTr)$$

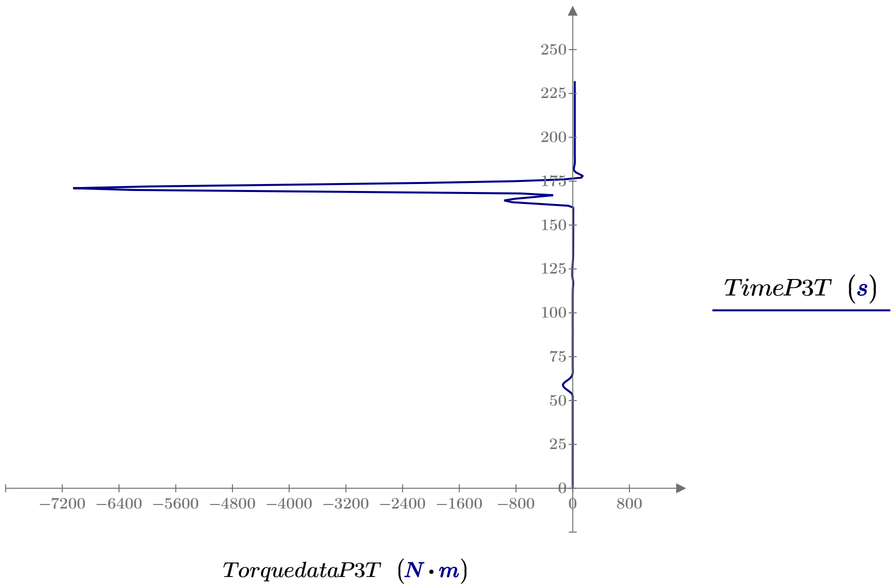


Fig B 87. Torque time history for installtion torque in 1g; tension pile P0