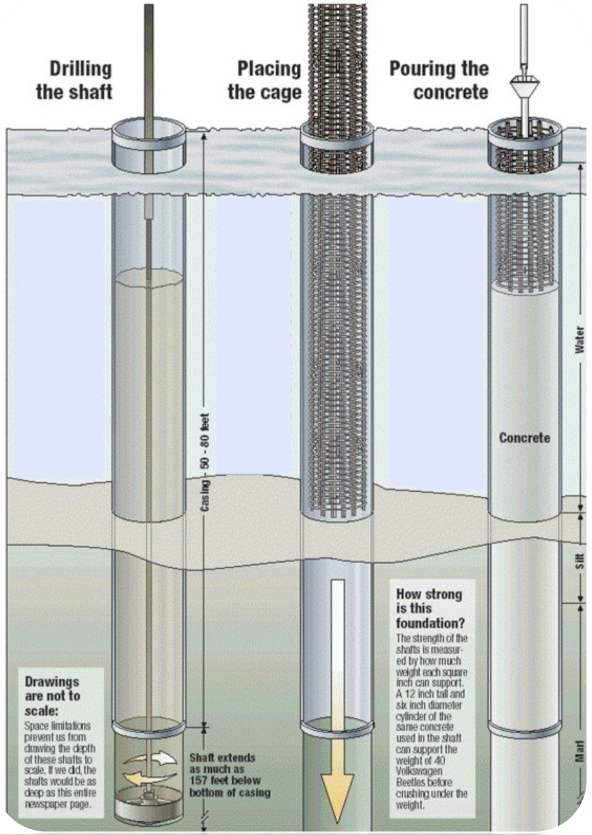
Knowledge Sharing Section

Federation of Myanmar Engineering Societies



Technical Aspects of Design and Construction of Pile Foundation:

Pile-Soil Interaction Analysis

Presented by:
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PE-0038 (Geo), ACPE-00564 (Civil)

Seminar: : Geotechnical Engineering, Technical Division, Fed. MES

Date: *: 9 am to 12:00 noon, 17-10-2022, Saturday*

17-12-2022 Webinar အခမ်းအနားအစီအစဉ်

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Objectives of Presentation

- *Knowledge shearing* to geotechnical design and construction engineers based on my past experiences: (Case Studies)
- Different types of geomaterials *behave* differently for deep foundation. Therefore, different design methods for estimation of deep foundation capacity (foundation of building or bridge etc.), testing and construction methods should be considered for *the site specific conditions*.

Scope of Presentation:

1. Introduction
2. Review on theoretical back Ground
3. Technical Aspects of Pile Foundation Design

   (Soil-Structure Interaction (SSI) Analysis, Case studies)
4. Technical Aspects of Pile Installation (Construction)
5. Reliability Assessment of Pile Foundation
5. Conclusion

1.Introduction

1.Introduction

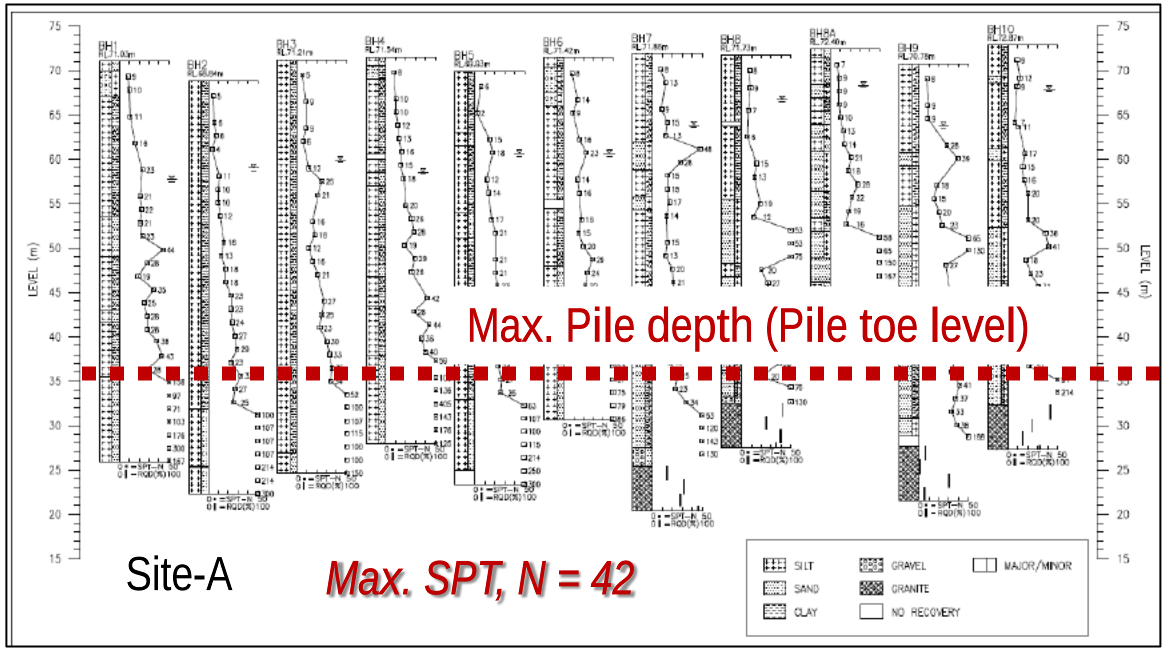
Current issues for the use of a Pressed / Spun Piles foundation

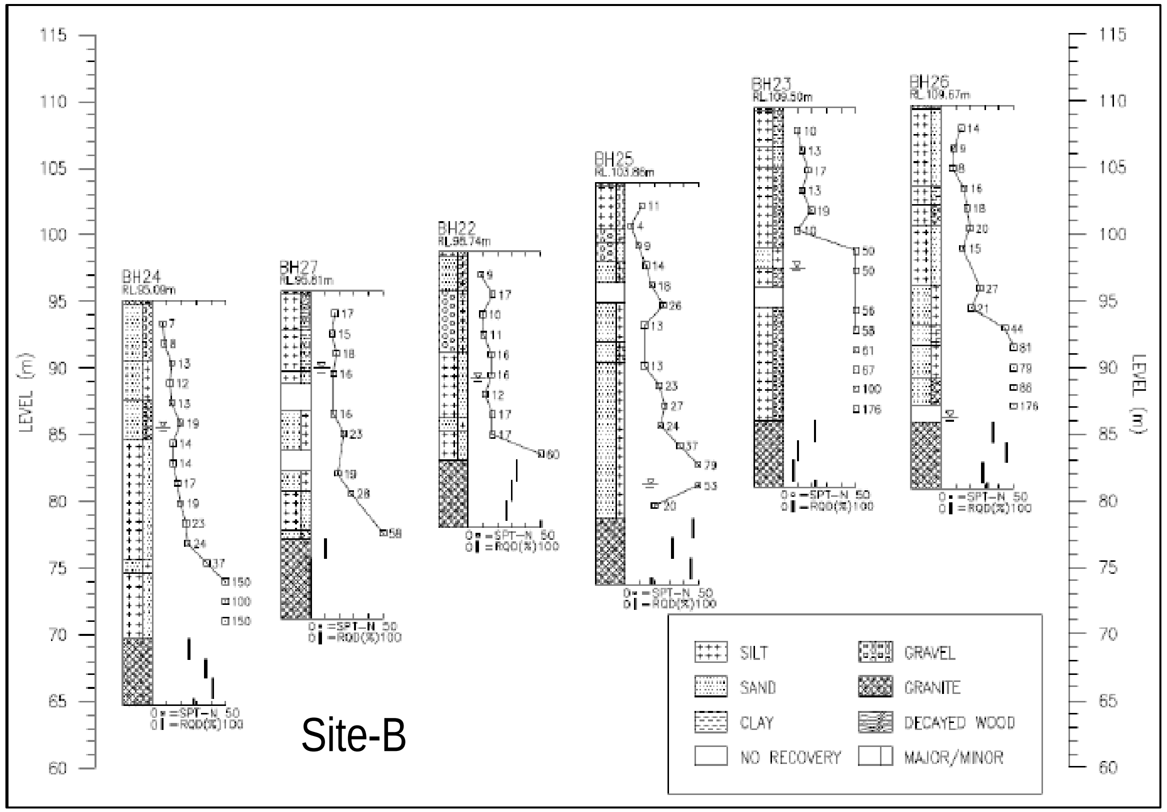
1. How many storeys can be used the pressed / Spun piles foundation?
2. The differences of the actual working capacity (depth) with predicted capacity (depth), Why?
3. How many percent of shortage of the pile length during actual pilling work?

The function of a pile foundation:

1. to transmit the load of a structure through a material or stratum of poor bearing capacity,
2. to resist lateral loads
3. to eliminate objectionable settlement
4. to transfer loads from a structure through easily eroded soils in a scour zone / liquefaction to a stable underlying bearing stratum
5. to anchor structures subjected to hydrostatic uplift or overturning
6. to function as a fender to absorb wear and shock.
7. to improve the load-bearing capacity of the soil in some instances
8. to serve as a retaining structure when installed in groups or in a series of overlapping (cast-in-place) piles.

Ground Response due to loading and unloading





31 Storey Condominium

- ϕ450 mm, 100 mm thks Spun Pile, Working Load, 1520 kN
- ϕ500 mm, 110 mm thks Spun Pile, Working Load, 2300 kN

45 Storey Condominium

- ϕ450 mm, 80 mm thks Spun Pile, Working Load, 1600 kN
- ϕ500 mm, 90 mm thks Spun Pile, Working Load, 2100 kN
- ϕ500 mm, 100 mm thks Spun Pile, Working Load, 2800 kN

Pile Load Test Results

Pile Diameter (mm)	Pile Length (m)	Settlement (mm)		Remarks
		Working Load	2*Working Load	
Site A				
450*	10.5	6.36	12.89	-
500	37.0	4.53	11.89	-
500*	20.6	9.23	20.46	20m preboring
Site B				
450	12.0	3.04	6.96	-
500	17.7	7.82	17.81	-
500	22.6	5.39	12.77	-
500	9.5	5.41	15.03	-
500*	6.5	8.32	19.73	-
600	17.7	4.82	12.16	-
600*	20.7	5.57	13.05	-
600	14.5	9.88	21.28	-

- Pile Axial Capacity (Geotechnical capacity)
- Mostly, uniform soil layer
- Low Seismicity

PILE DESIGN FOR DEEP FOUNDATION

Current Practice of Common Pile Design in Myanmar:

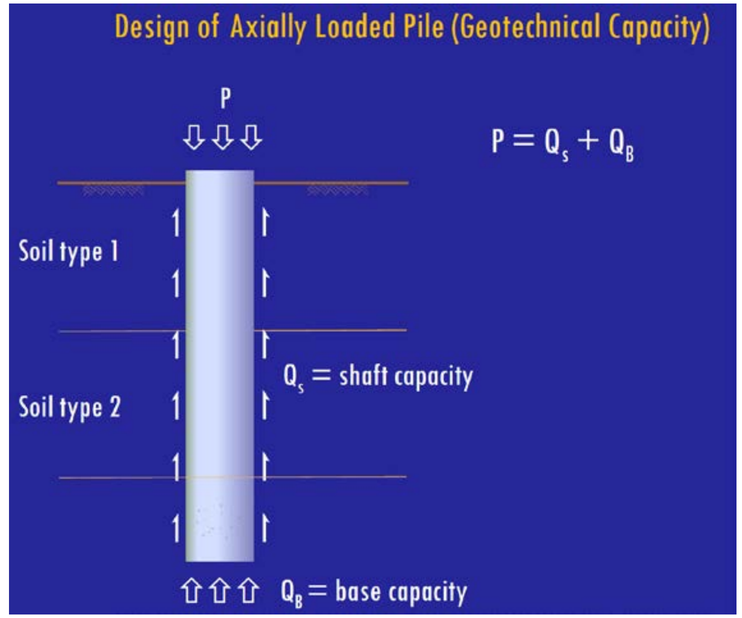
Rules and Current Practices:

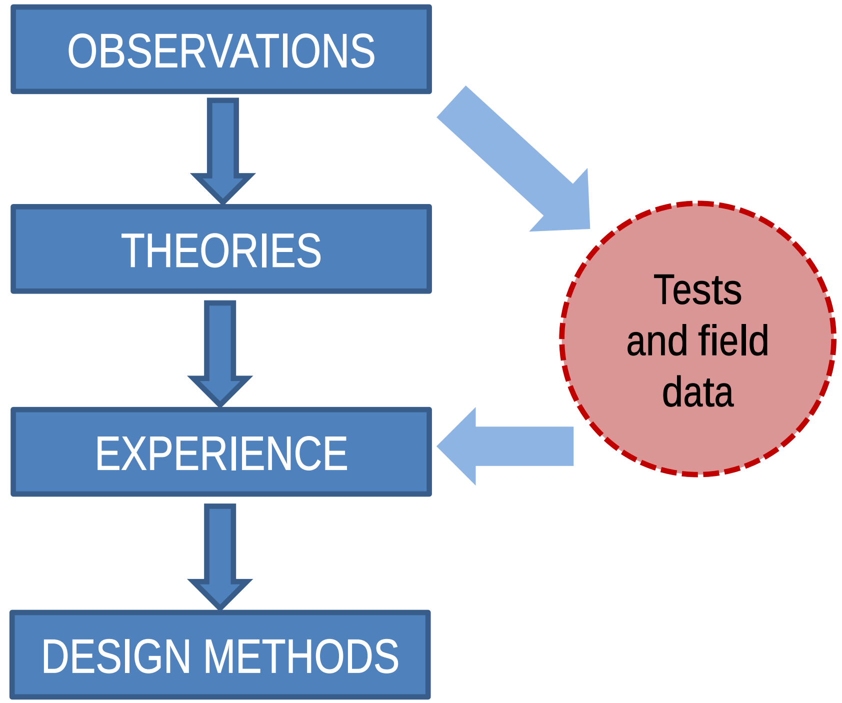
1. Code of Practice for Foundations (MNBC 2020)
2. Pile Design were derived based on experience and different piling layouts have been applied without geological and geotechnical consideration (geological and geotechnical models for a project).
3. Some rules may be conservative and are not considered based on soil and rock mechanics (CP4, ROT, Method using c and phi, etc).
4. The acceptance of design capacities for a project are adopted from the Pile Load **Tests** ***(ULT and WLT, 1% of Total numbers of working Piles)***
5. Long term capacities of *individual piles* were not considered for a entire project (settlement and capacities).

- ❑ Ground Conditions in Myanmar are very complex and can cause the challenging problems depending on the local geological condition of the project.
- ❑ For Sensitive Building, more detail should be considered in foundation design.
- ❑ More economic design may be feasible using rational design methods

Rational Design Approaches:

1. Code of Practice for Foundations (MNBC 2020)
2. Proper site study prior to design (actual geological and hydrological conditions)
3. Characterization of site by means of filed test, in-situ test and laboratory test.
4. Adequate site investigation to provide the soil models (nos. of boring)
   - Geological model and
   - Geotechnical model
5. Analysis of geological and geotechnical inputs (For long-term, GBR)
6. Pile testing to verify the design assumption.
7. Proper Calculation Methods for prediction of Non-testing Capacity of Pile
8. Design analysis using the geomechanics and/or correlation of empirical formulas.
9. Analysis and Design of Individual Pile Group and Pile Foundation for Reliability using Appropriate Methods.





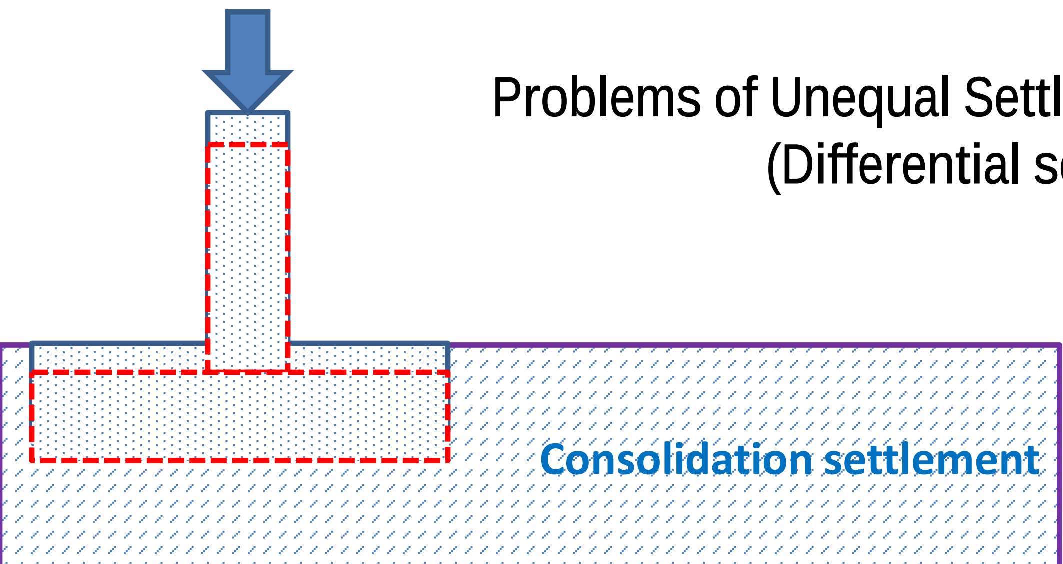
Concept of O'Neill:

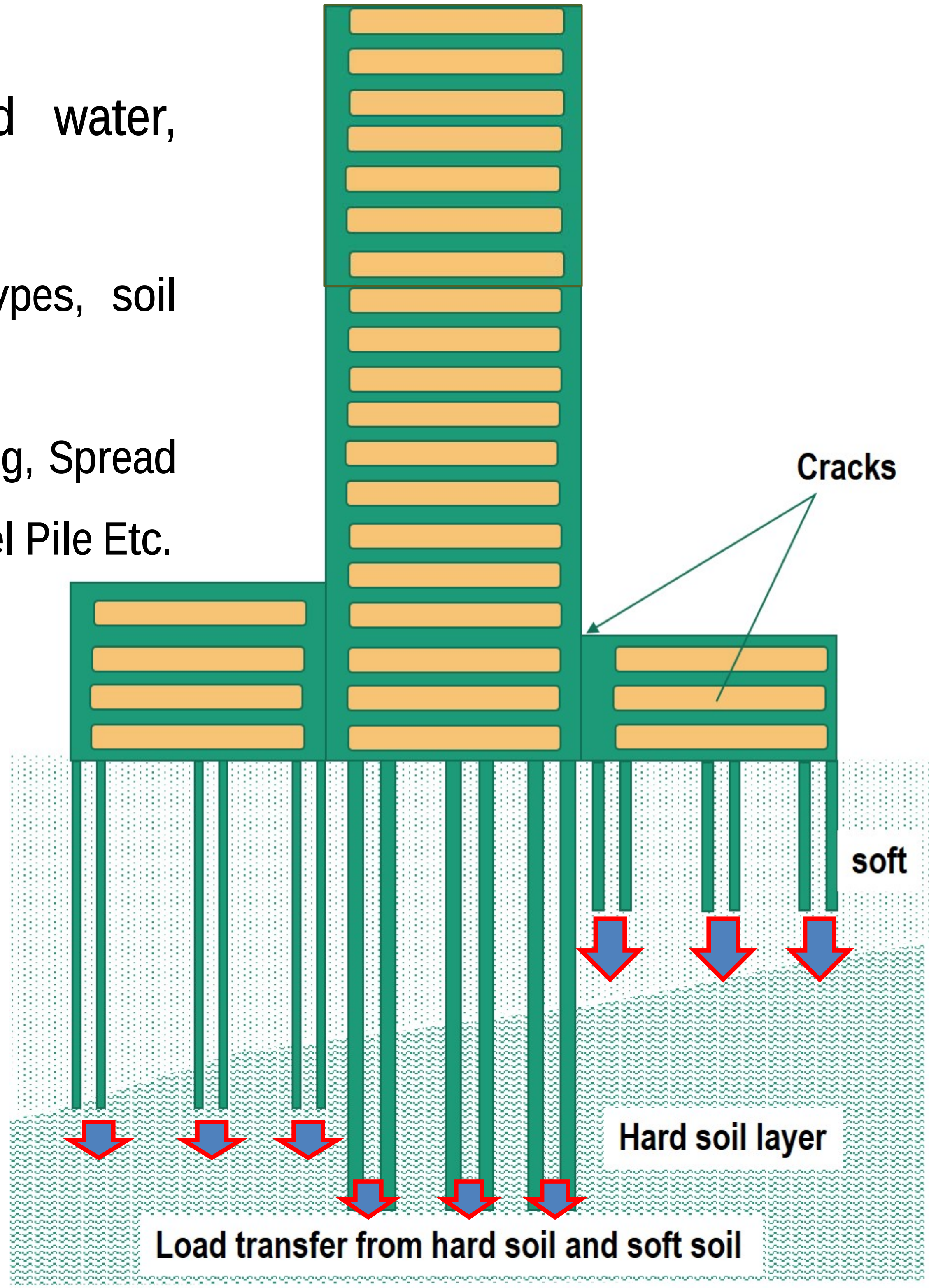
Observations, Theoretical Modeling, Application of Experience, and Design Method development in Foundation Engineering

Changes of geotechnical capacity for long-term loading in Design Consideration:

1. Different Geomorphology (Physical features, ground water, floodplain etc.)
2. Different geological and geotechnical conditions (soil types, soil properties, etc.)
3. Different types of foundation (Isolated Footing, Strap Footing, Spread Footing, Bored Pile, Pressed Pile, Driven Pile, Spun Pile, Steel Pile Etc.
4. Loads, Pile layout and Pilling Pattern
5. Different depth, and
6. Different pile sizes and spacing

Problems of Unequal Settlement of Pile Capacity (Differential settlement)





2.Review on Theoretical Background

2. Review on Theoretical Background

Soil Properties:

Site Investigation and Soil failure Theories:

❖ Strength and Deformation Behavior

The Purpose of Site Investigation

1. *The site investigation is* at providing sufficient reliable subsurface information for most economical, satisfactorily safe foundation for the proposed structures.

2. *The site investigation should* reveal sufficient subsurface information for the design and construction of a stable foundation safe from both collapse and detrimental (allowable) movements.

❖ Geotechnical Requirements

Geotechnical Study	*Key Model*	*Relative (100% total)*		*Key data*	*Comments*
		Effort	*Benefit*		
Desktop study	Geological model	<5%	~20%	Geological setting, existing data, site history, aerial photographs and terrain assessment.	Minor SI costs (site reconnaissance) with significant planning benefits.
Definition of needs		<5%	~20%	Justify investigation requirements and anticipated costs.	Safety plans and services checks. Physical, environmental and allowable site access.
Preliminary investigation	Geological and geotechnical model	15%	~20%	Depth, thickness and composition of soils and strata.	Planning/Preliminary Investigation of ~20% of planned detailed site investigation.
Detailed site investigation	Geotechnical model	75%	~20%	Quantitative, and characterisation of critical or founding strata.	Laboratory analysis of 20% of detailed soil profile.
Monitoring/ Inspection		<10%	~20%	Instrumentation as required. QA testing.	Confirms models adopted or requirements to adjust assumptions. Increased effort for observational design approach.

Geotechnical categories (GC) of investigation

Geotechnical category		GC1	GC2	GC3
Examples		▪ Sign supports ▪ Walls < 2m ▪ Single or 2-storey building ▪ Domestic buildings; Some roads	▪ Industrial/commercial buildings ▪ Roads > 1 km ▪ Small/medium bridges	▪ Dam, Tunnels, Ports ▪ Large bridges and buildings ▪ Heavy machinery foundation ▪ Off-shore platform, Deep excavation
1	Nature and size of construction	Size of construction - simple conventional loadings	Conventional structures – no abnormal loadings.	Large or unusual structures.
2	Surroundings	No risk of damage to neighboring buildings, utilities, etc.	Risk of damage to neighboring structures	Extreme risk to neighboring structures.
3	Ground conditions	Straightforward. Does not apply to refuse, uncompacted fill, loose or highly compressible soils	Routine procedures for field and laboratory testing.	Specialist testing
4	Ground water conditions	No excavation below water table require	Below water table, Lasting damage cannot be caused without prior warning	Extremely permeable layers.
5	Seismicity	Non-Seismic	Low seismicity	High Seismic areas
6	SI Cost = % of capital cost	0.1%–0.5%	0.25%–1%	0.5%–2%
7	Type of study	Qualitative investigation may be adequate.	Quantitative geotechnical studies.	Two stage investigation required.
8	Minimum level of expertise	Graduate civil engineer or engineering geologist under supervision by an experienced geotechnical specialist.	Experienced Geotechnical engineer/ Engineering geologist.	Specialist geotechnical Engineer with relevant experience.

Driven Pile, Jack in Pile Foundation:

1. In the past, ***Driven Pile, Jack in Pile**s* have usually been designed ***structurally for axial loads only using an allowable stress Design (ASD) approach.***
2. *The allowable stresses had been set primarily to assure pile drivability*.
3. For tall building and heavy loading building foundation, ***Load and Resistance Factor Design (LRFD) approach*** should be conducted.
4. The piles must be analyzed for *combined horizontal and axial loads which* requires a change in the evaluation procedure.
5. A combined bending and axial load analysis of the structural behavior of the pile must be made. A pile foundation must be installed to meet the design requirements for;
   a. compressive,
   b. lateral and
   c. uplift capacity.
5. *The required ultimate capacity or a predetermined length is established by the designer*.
6. *For displaced piles (Driven and Pressed piles), Pile driveability is a very important aspect of the process and must be considered during the design phase*. (geological condition such as, the soils containing BIM, Gravel, etc.)

Ref: NHI Courses No. 132021 and 132022, Design and Construction of Driven Pile, Foundations, Displaced Piling Works

Some of Empirical Equations for determining the pile friction bearing capacity using n_s results

$$q_s = n_s N$$

- q_s is the limit skin friction stress at a given depth
- n_s is the skin friction factor proposed by researchers

Key Technical Note:

q_s = skin friction which is mechanical property

N = SPT value which is the physical property of soil (depending on the several factors)

No	References	Equation	n_s (kPa)	Type of Installation Pile
1	Bazaraa and Kurkur [17]	$q_s = 0.67\,N$ if $D \leq 0.5$ m. else $q_s = 1.34\,N$	0.67 if $D \leq 0.5$ m, 1.34 for the other D values (where D is pile diameter in m)	Bored
2	Decourt [18]	$q_s = 10\,(N/3+1)$	-	Bored
3	Lopes and Laprovitera [19]	$q_s = 1.62\,N$ $q_s = 1.94\,N$	1.62 in sand 1.94 in silty sand	Bored
4	Meyerhof [20]	$q_s = 1\,N$ $q_s = 2\,N$	1 2	Bored Driven
5	Shioi and Fukui [21]	$q_s = 1\,N$ $q_s = 2\,N$	1 2	Bored Driven
6	Aoki and Veloso [22]	$q_s = 2\,N$ $q_s = 2.28\,N$	2.00 in sand 2.28 in silty sand	Bored
7	Reese and O'Neill [23]	$q_s = 3.3\,N$	3.3	Bored
8	Robert [24]	$q_s = 1.9\,N$	1.90 1.90	Bored Driven

Ref: Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur, Malaysia

Methods for Predicting Axial Displaced Pile Capacity

1. *The ratio of predicted capacity (Q_P) to measured capacity (Q_M) was used as the metric to quantify* how well or poorly a predictive method performs.
2. Statistics for each of the predicted methods were used to quantify the accuracy and precision for several pile driving formulas.

The predicted capacities are compared with measured pile capacity as determined from *a static load test*. The predicted capacity (Q_P) divided by the measured capacity (Q_M) is the metric used to quantify the accuracy of a prediction.

1. A value of Q_P/Q_M equal to 1 represents *perfect agreement*,
2. A value of Q_P/Q_M equal to 1.5 means the method over-predicts capacity by 50%.
3. Values of Q_P/Q_M less than one represent under-prediction of capacity.

Key Technical Note:

Mean, *standard deviation, and the coefficient of variation for Q_P/Q_M are used as measures of the accurac*y and precision for the methods.

Pile Group Capacity

The pile group capacity may be less than the sum of the capacities of the individual piles

$$P_{ug} \neq n\, P_{up}$$

where, P_{ug} is the ultimate capacity of the pile group;

P_{up} is the ultimate capacity of an individual pile, and

n is the number of piles in the pile group.

It is common to not allow for any increase in capacity due to densification effects. However, pile group capacity losses are an effect which engineers must be careful to account for. Pile group capacity loss is by convention calculated using ***a pile group efficiency factor, ε.***

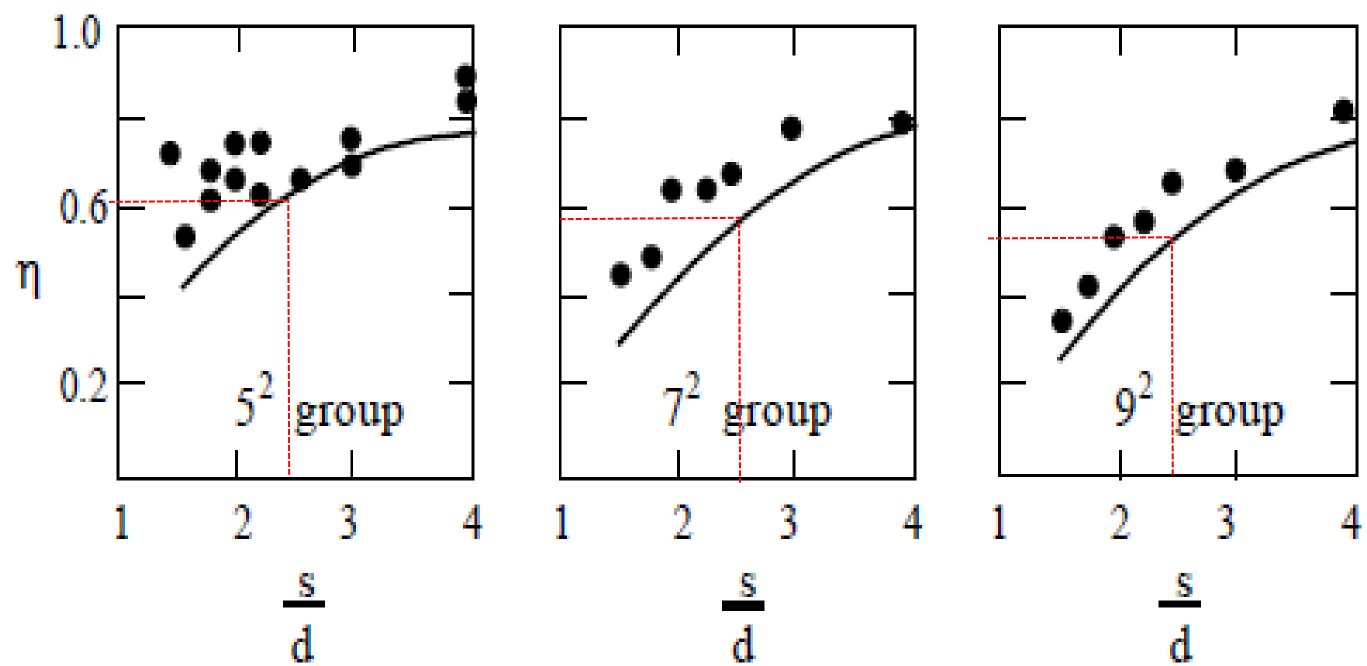
$$P_{ug} = \varepsilon\, n\, P_{up}$$

The efficiency and pile group settlement can vary considerably. Major factors affecting efficiency are:

1. soil type,
2. pile group size and
3. the ratio of pile diameter to spacing.

Important Technical Note:

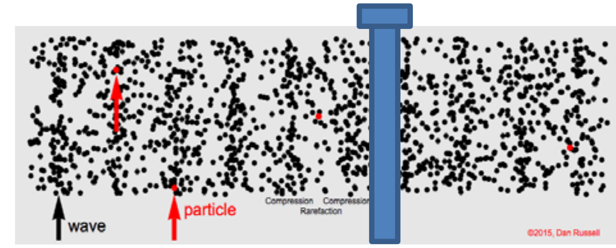
- Numbers of Pile for a Pile Group
- Depend on predetermined pile cap thickness, pile capacity is not significant increased the numerically, if > 60 Nos. (ref: Researches)



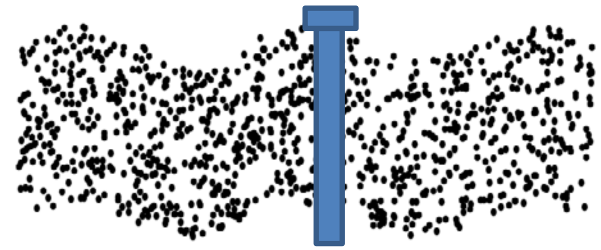
Pile-Soil Interaction

The pile may experience two distinct phases of initial Pile-soil interaction.

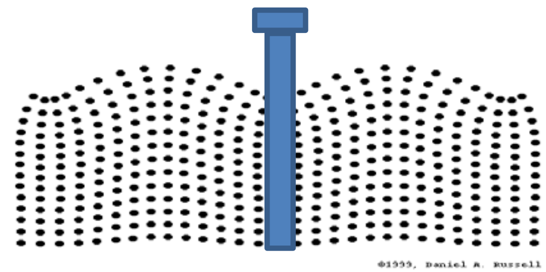
1. When the earthquake happens and before the superstructure starts oscillating, the piles may be forced to follow the soil motion, depending on the flexural rigidity (EI) of the pile. Here, ***the soil and pile may take part in kinematic interplay and the motion of the pile may differ substantially from the free field motion. This may induce bending moments in the pile.***
2. As the superstructure starts to oscillate, inertial forces are generated. These inertia forces are transferred as lateral forces and overturning moments to the pile via the pile-cap. The pile-cap transfers the moments as varying axial loads and bending moments in the piles. Thus the piles may experience additional axial and lateral loads, which ***cause additional bending moments in the pile.***



P- wave



S- wave

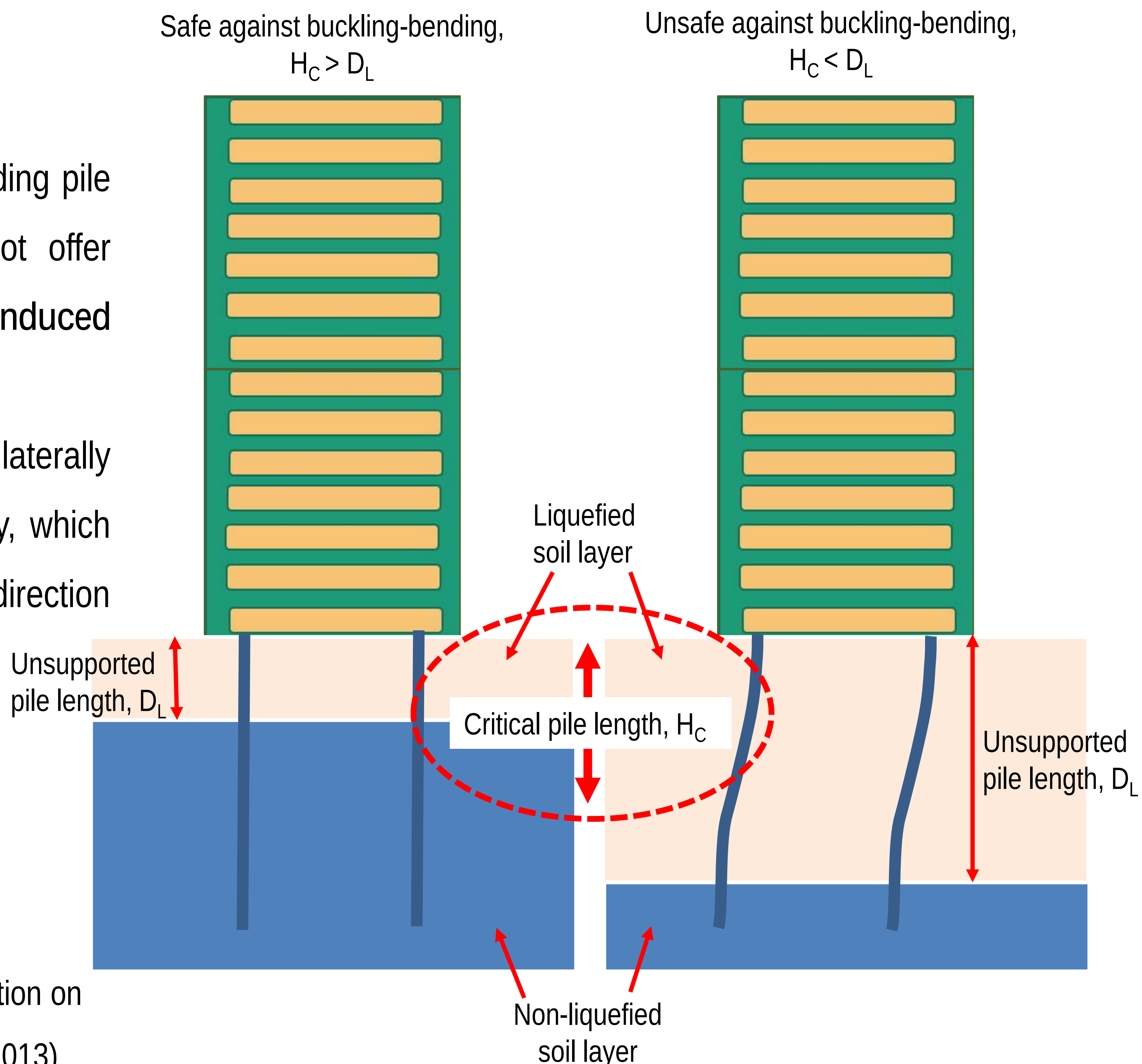


Surface-wave

Foundation Failure

(A) Buckling Failure

1. The buckling failure occurs when the soil surrounding pile loses its effective confining stress and may not offer sufficient lateral support **during earthquake-induced liquefaction.**
2. The pile is a slender element which behaves as a laterally unsupported column susceptible to axial instability, which may cause that the pile buckles sideways in the direction of least elastic bending stiffness *under axial load*.

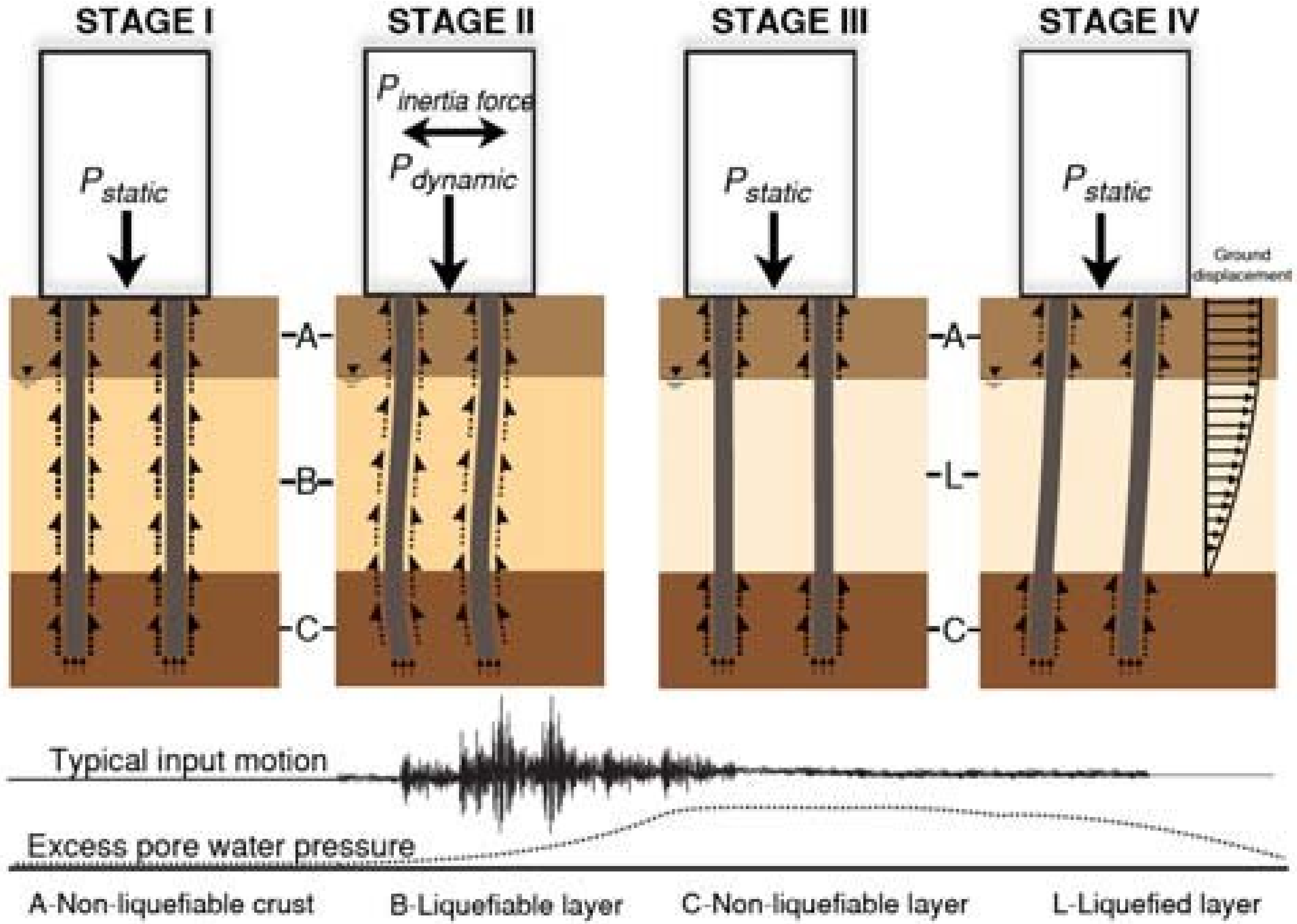


Ref: Scheme showing the effect of bending-buckling interaction on the response of pile foundation (Bhattacharya and Goda 2013)

Buckling Failure of Pile in liquefaction soil

Buckling instability where the piles are treated as beam-columns i.e., axially loaded slender columns carrying lateral loads.

The piles are treated as unsupported columns in the liquefiable zones.



Key Technical Note:

1. There may be a wrong consideration in design. The piles are in free standing column condition when they are surrounded by soft soil even in fairly stiff soil. We shall consider that such a long member have every risk of buckling when they are loaded axially.
2. Special analysis or analytical calculation should be made for this case. Example as below: Checking the buckling Capacity of Pile if pile encountered in liquefaction depth.

Buckling failure

The buckling load of the pile in absence of the soil may be estimated (Euler critical buckling), and represents ***the maximum axial force at which the pile* becomes unstable** and the deflection becomes infinitely large (Bhattacharya and Goda 2013).

$$P_{cr} = \frac{\pi^2 EI}{L_{eff}^2}$$

Where EI is the stiffness of the pile material and

L_{eff} is the effective length of the pile, which depends on the fixity conditions of the element ends.

In the case of an axially loaded pile in liquefiable soil,

$L_{eff}=\alpha_1(h_L+L_h)$ (Bhattacharya and Madabhushi, 2008)

where L_h is the length of the pile in free air/water,

h_L is the depth of liquefiable soil layer and

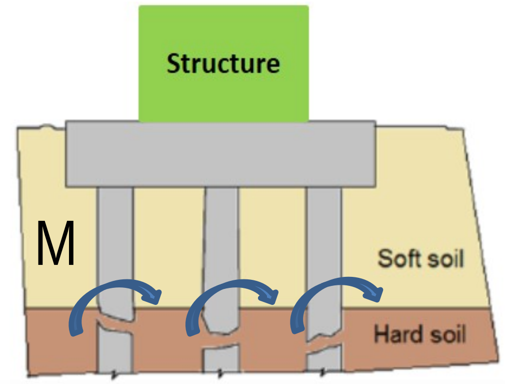
α_1 is the effective length multiplier which is a function of the boundary condition of the pile at the top and bottom of the liquefiable layer.

Case ID in Fig. 4d	Boundary condition of the pile at the top and bottom of the liquefied layer		Effective length	Buckling load of each pile	Example
	Top	Bottom			
Case 1	Fixed [$\theta = 0, \delta = 0$]	Fixed [Sufficient embedment at the dense layer] [$\theta = 0, \delta = 0$]	$L_{eff} = 0.5L_0$	$\frac{4\pi^2 EI}{L_0^2}$	Pile groups with raked piles Large non-liquefied crust which will not slide
Case 2	Free to translate but restrained against rotation–sway frame [$\theta = 0, \delta \neq 0$]	Pinned [Insufficient embedment at the dense layer] [$\theta \neq 0, \delta = 0$]	$L_{eff} = 2L_0$	$\frac{\pi^2 EI}{4L_0^2}$	NFCH building, Hamada (1992a,b)
Case 3	Free to translate but restrained against rotation–sway frame [$\theta = 0, \delta \neq 0$]	Fixed [Sufficient embedment at the dense layer] [$\theta = 0, \delta = 0$]	$L_{eff} = L_0$	$\frac{\pi^2 EI}{L_0^2}$	Most cases fall under such category
Case 4	Fixed in direction but free to rotate [$\theta \neq 0, \delta = 0$]	Fixed [Sufficient embedment at the dense layer] [$\theta = 0, \delta = 0$]	$L_{eff} = 0.7L_0$	$\frac{2\pi^2 EI}{L_0^2}$	Pile groups with raked piles. Improper pile-pilecap connection
Case 5	Fixed in direction but free to rotate [$\theta \neq 0, \delta = 0$]	Pinned [Less embedment at the dense layer] [$\theta \neq 0, \delta = 0$]	$L_{eff} = L_0$	$\frac{\pi^2 EI}{L_0^2}$	Pile groups with raked piles. Improper pile-pilecap connection
Case 6	Free i.e. unrestrained against rotation and displacement [$\theta \neq 0, \delta \neq 0$]	Fixed [Sufficient embedment at the dense layer] [$\theta = 0, \delta = 0$]	$L_{eff} = 2L_0$	$\frac{\pi^2 EI}{4L_0^2}$	Piles in a row such as the Showa Bridge piles

Bending-buckling interaction

(B) Bending Failure due to different soil stiffness

Bending Failure Theories (Tokimatsu, Suzuki, and Sato 2005)



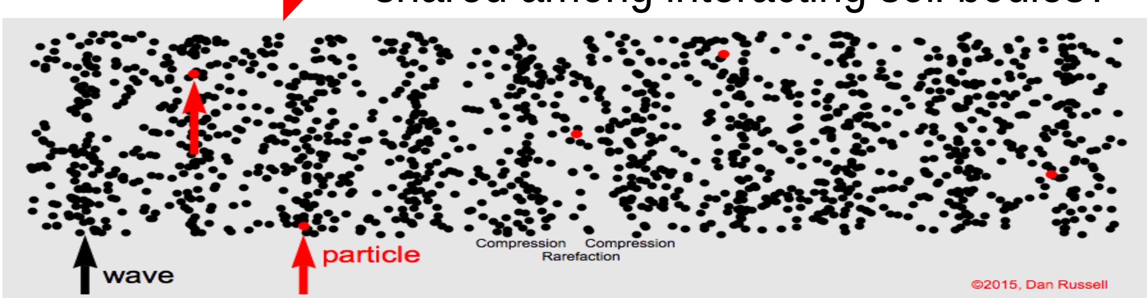
Pile failure at Stiffness Contract

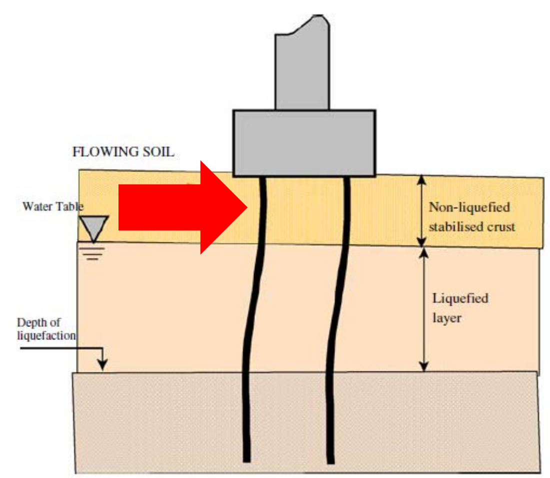
This mechanism of failure assumes that the soil pushes the pile element. Lateral loads due to the inertia of the superstructure and/or kinematic loads due to lateral spreading of the soil may induce bending failure in piles.

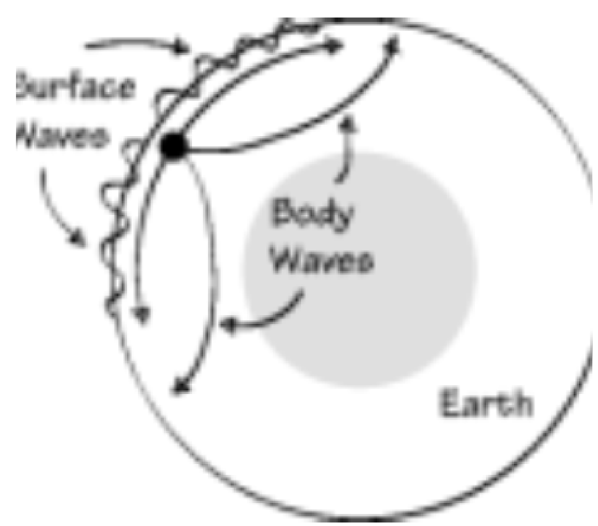
Prior to the development of pore water pressure, the inertia force from the superstructure may dominate. After that , there are two cases;

1. ***AT the start of the earthquake shaking***, the soil is subjected to a flow liquefaction at a particular depth which causes a lateral soil flow and the pile bending moments will be developed due to the summation of inertia and kinematic loads.
2. ***At the end of the shaking***, the lateral soil flow will continue until the full dissipation of pore pressures. The bending moment is then only generated due to kinematic forces. a significant effect on pile performance particularly when permanent displacements occur in laterally spreading soil
3. ***Near Sources,*** If earthquake source is less than 10 km, both vertical and horizontal force shall be considered in design (records; USGS- about 40 %).

How the momentum and energy are shared among interacting soil bodies?

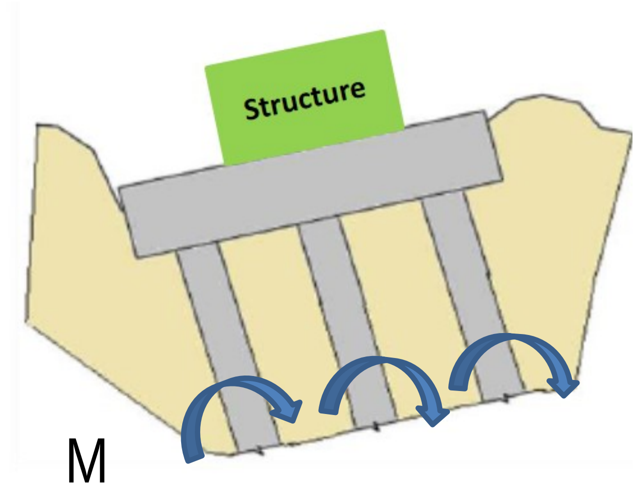






(C) Bending Capacity or Tension Pullout Failure

Lateral loads due to the inertia of the superstructure and/or kinematic loads due to lateral spreading of the soil may induce bending failure in piles.



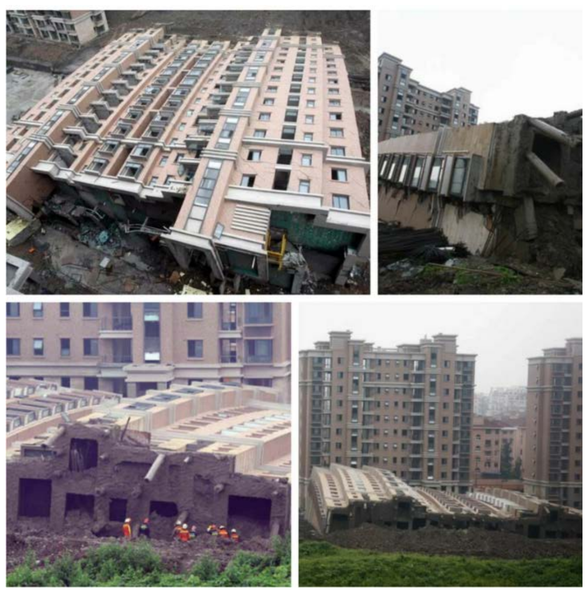
Bending capacity or tension pullout failure

Technical Note:

1. The failure mechanism assumes that the soil pushes the pile element.
2. Largest bending moment is developed due to lateral soil pressure at ***the interface of soft and firm stiff soil layer.*** (ref; Inspection report)

Technical Question;

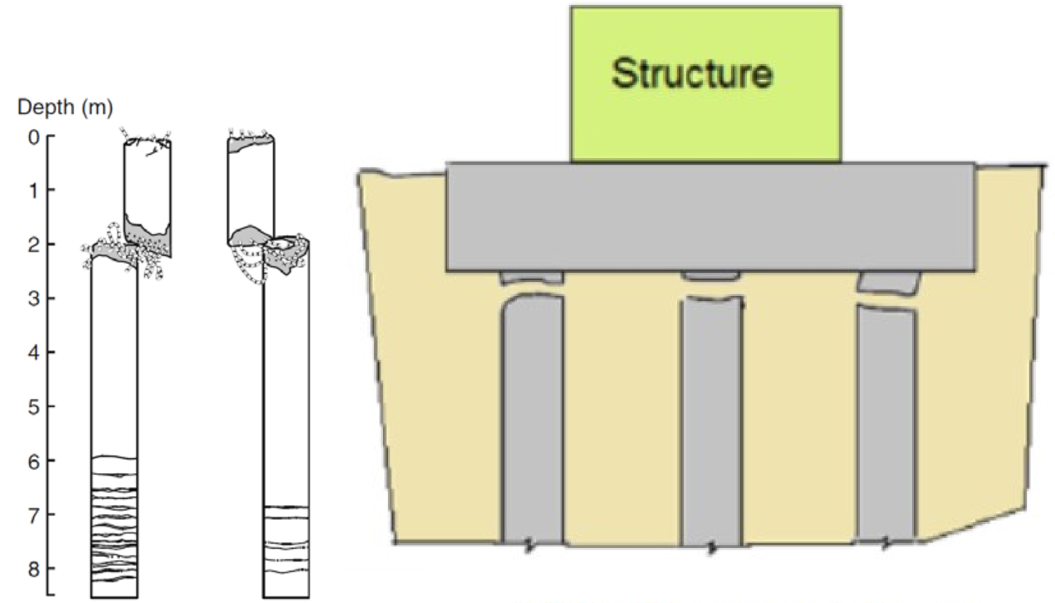
1. How do you think?
2. Accident or incident?



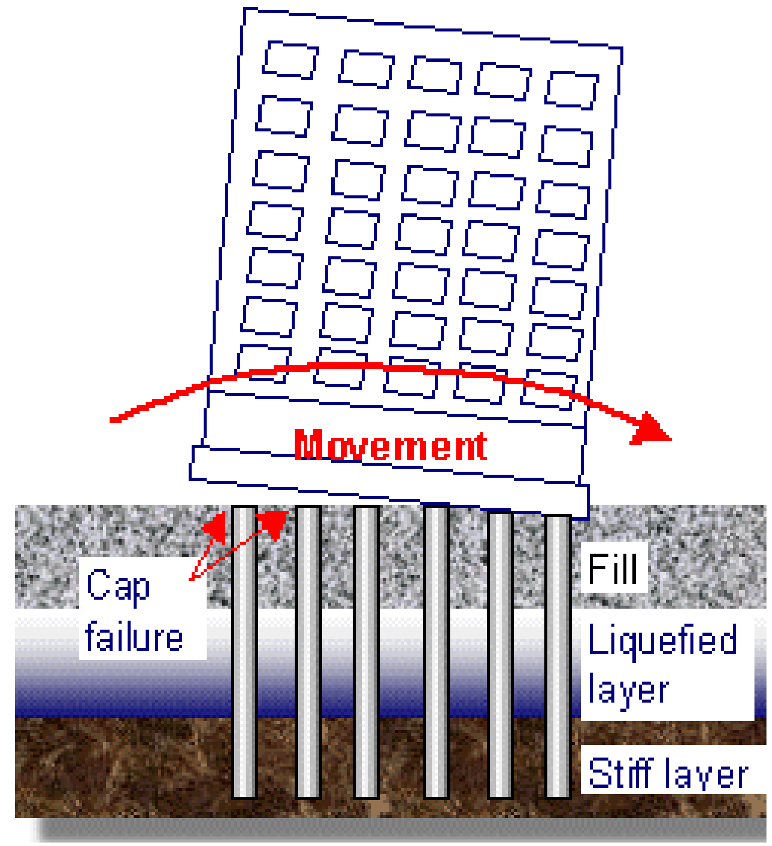
Foundation failure on apartment building, Shanghai, 2009

(D) Shear Failure of Piles

Lateral loads due to the seismic load and inertia of the superstructure and/or kinematic may induce shear failure in pile tip.



Pile flexure/shear failure at head



Technical Note:

1. It can be seen in case study where high shear stress is occurred due to earthquake force.
2. The shear capacity of pile shall be checked depending on the site conditions (soil type, geomorphology etc.) and lateral load.
3. Sometimes, it is the critical factor, especially for pressed pressed pile and spun pile foundation.

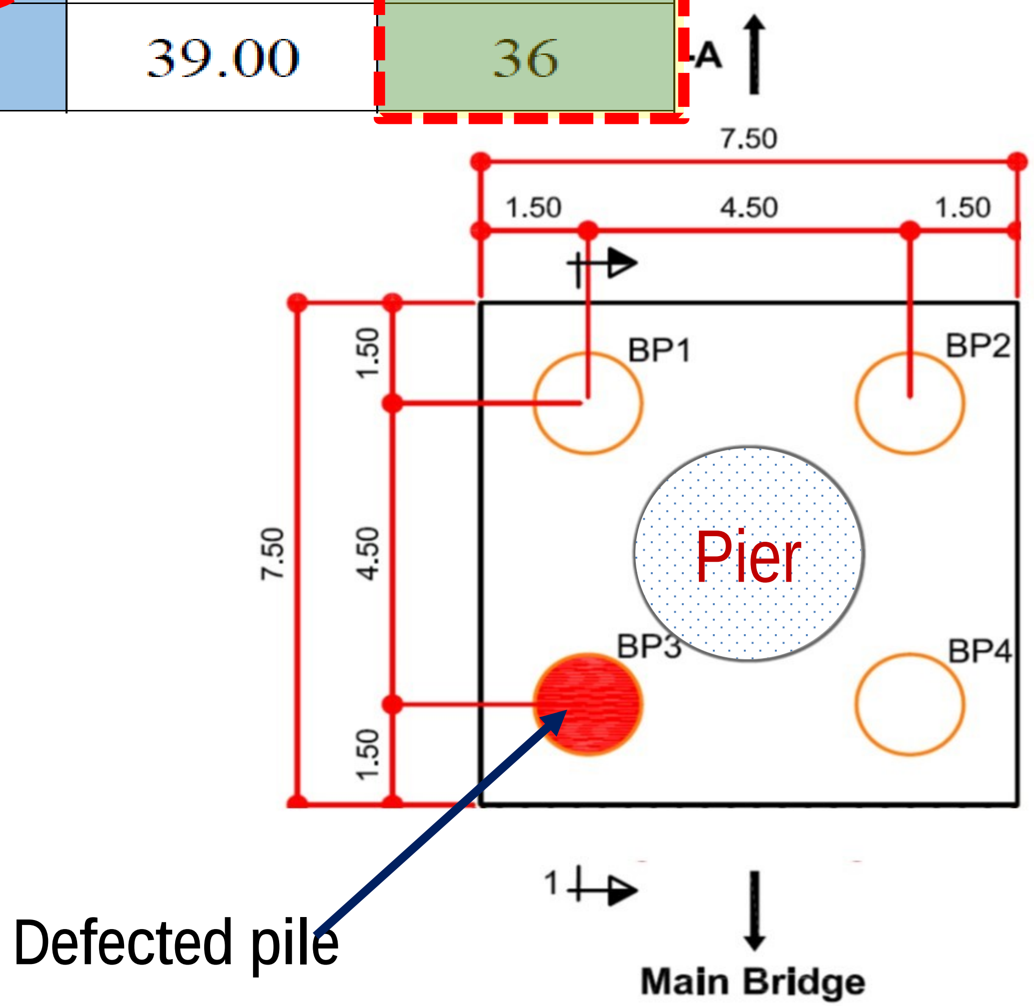
Ref: Static and dynamic behavior of pile supported structures in soft soil

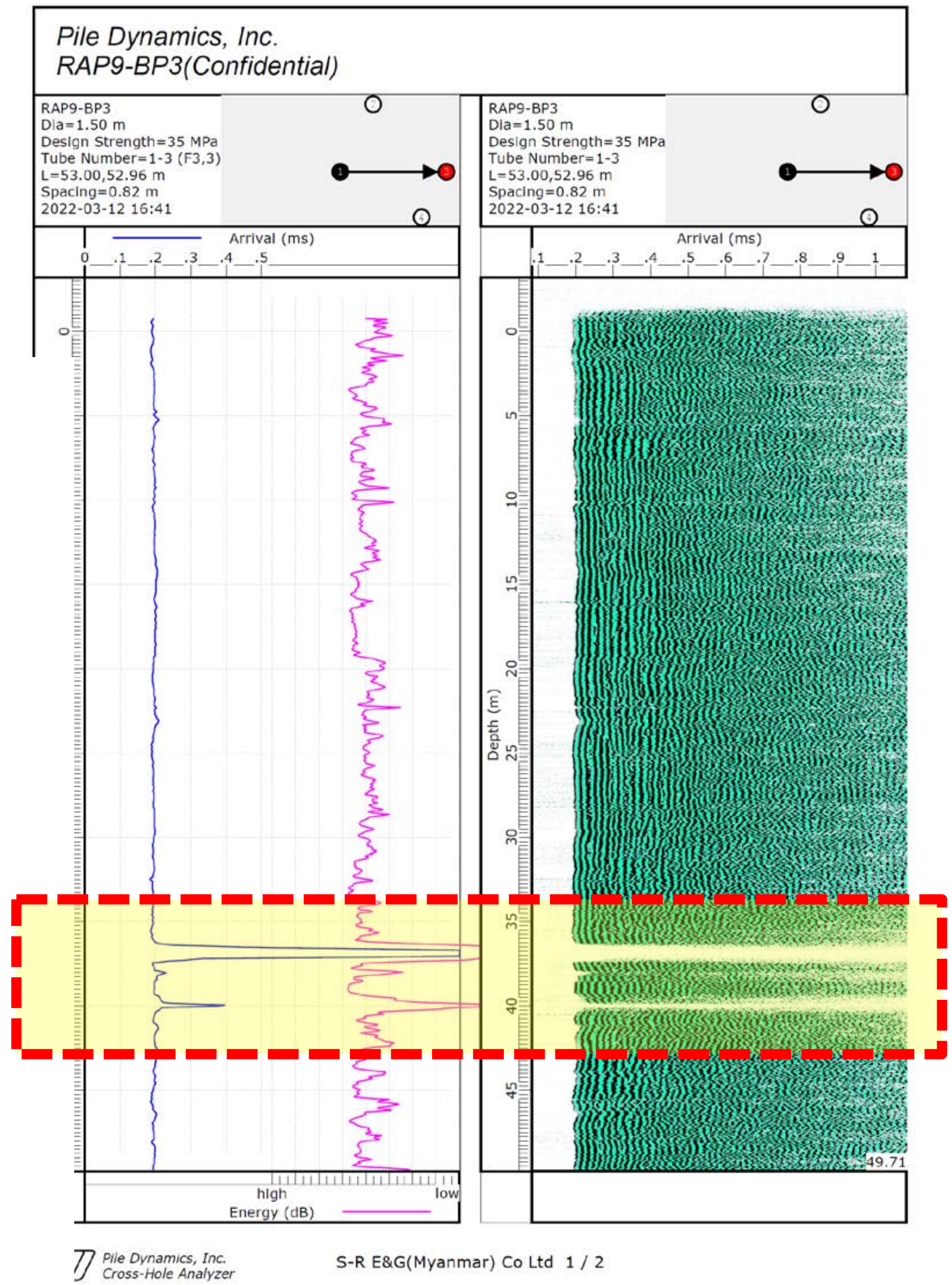
3. Technical Aspects of Pile Foundation Design (Soil-Structure Interaction (SSI) Analysis)

Case Study – 1: Unequal Pile Capacity for a Pile Group for Normal Loading Condition

Dala Bridge Pier *(4 Nos. of Group Pile)*

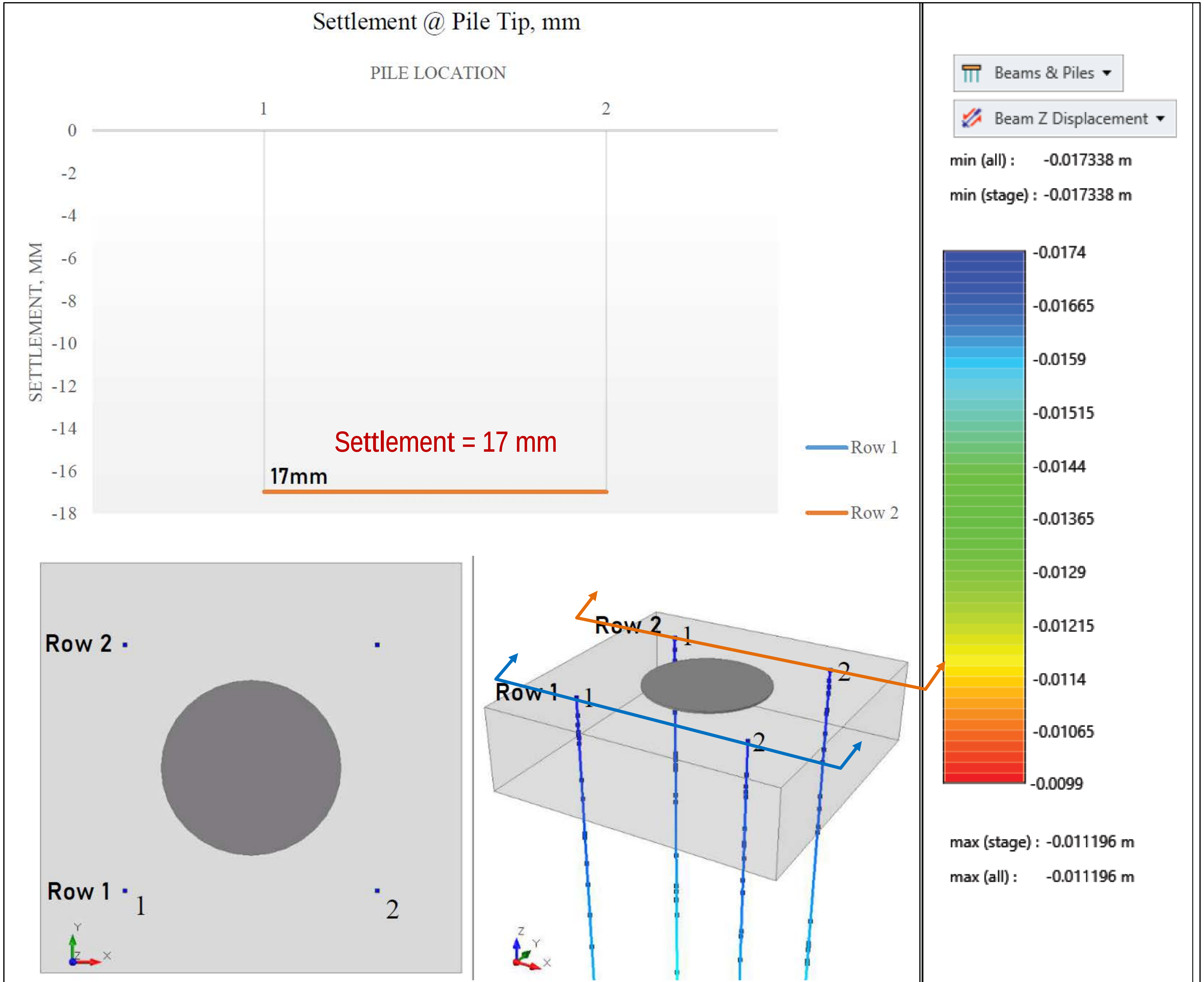
Avg., ton	Q_{all}, ton	@Depth below surface (m)	Length of pile (m)
767.18	767	54.00	50
288.08	288	39.00	36





Settlement of Pile Cap

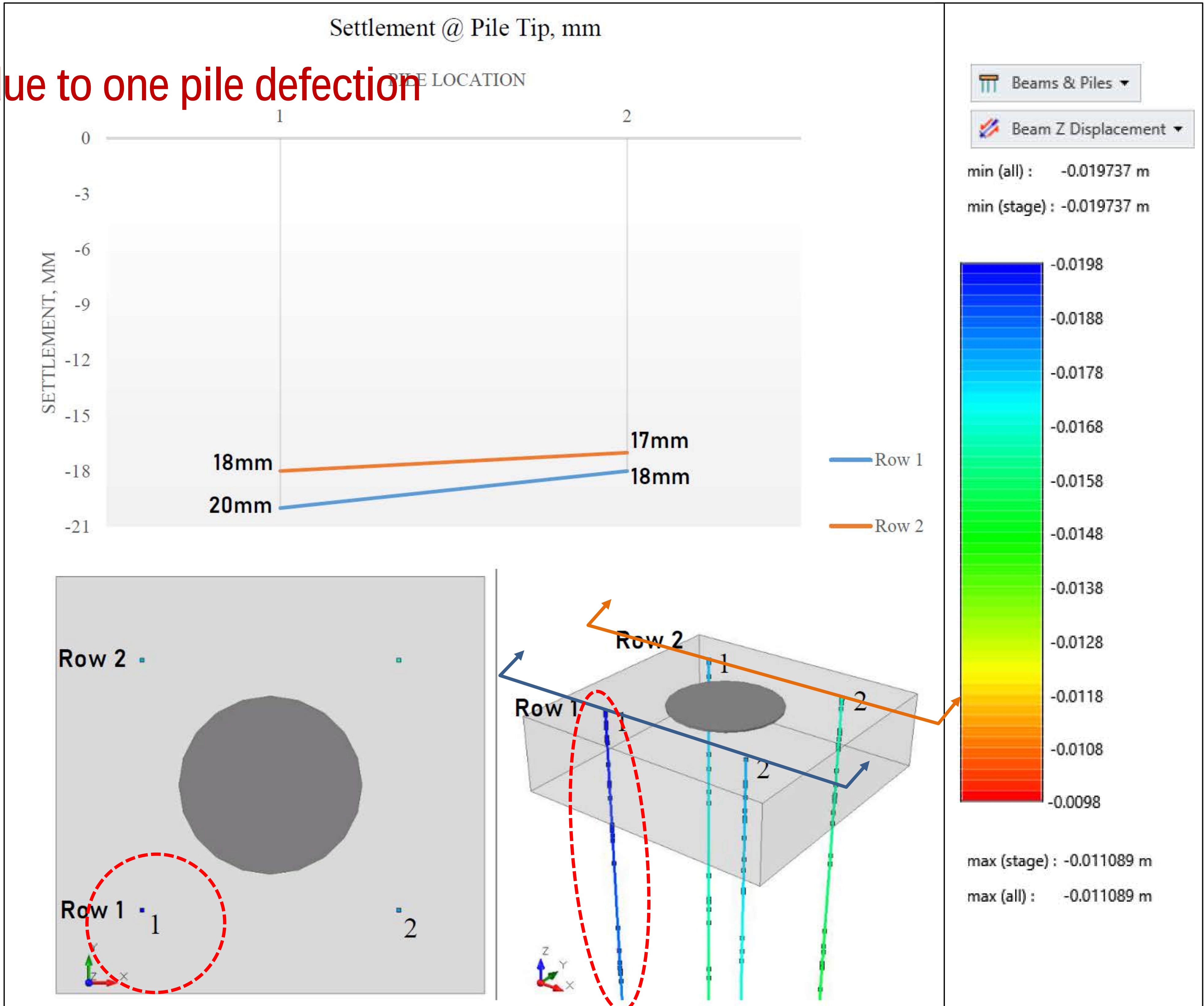
- Max. Settlement at full loading 17 mm



Analysis of Bridge Foundation (Design piles)

Settlement of Pile Cap due to one pile defection

1. Max. Settlement at full loading = 20 mm
2. Max. Settlement at full loading = 18 mm

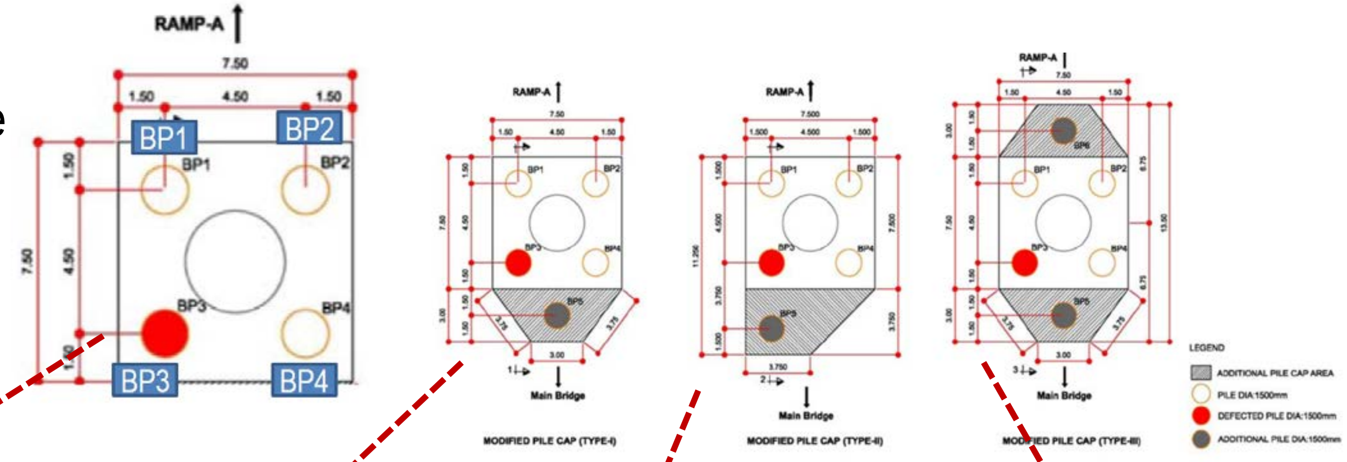


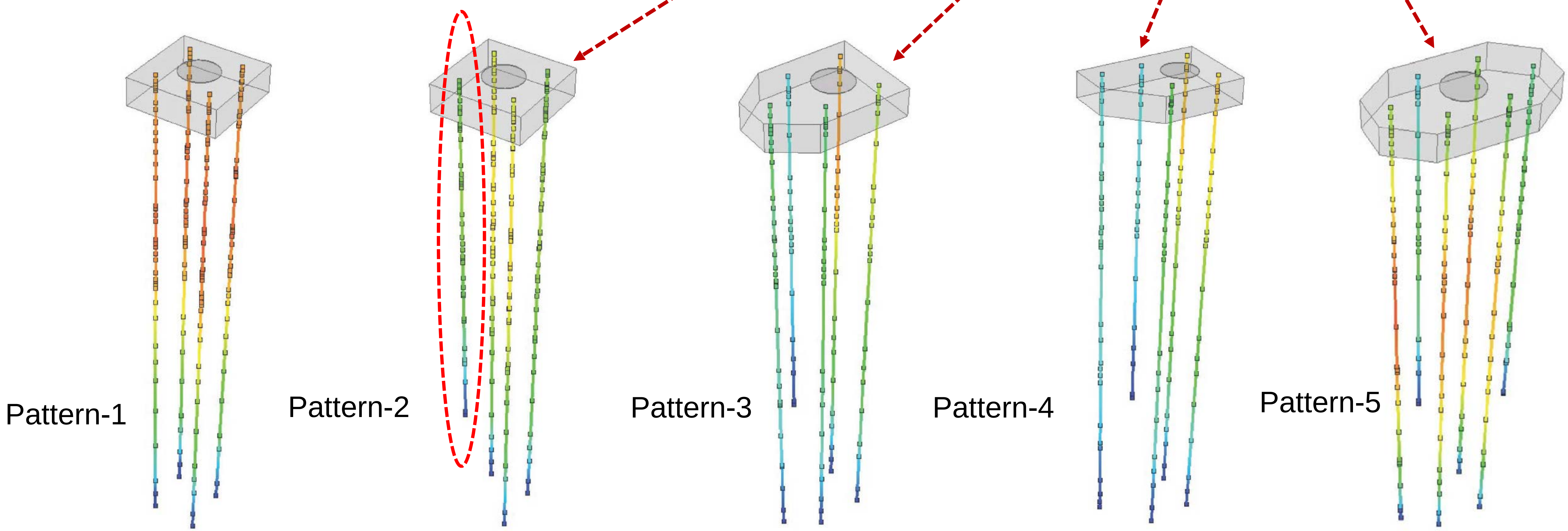
Analysis of Bridge Foundation (Defected pile)

Remedial Measures for Pile Group

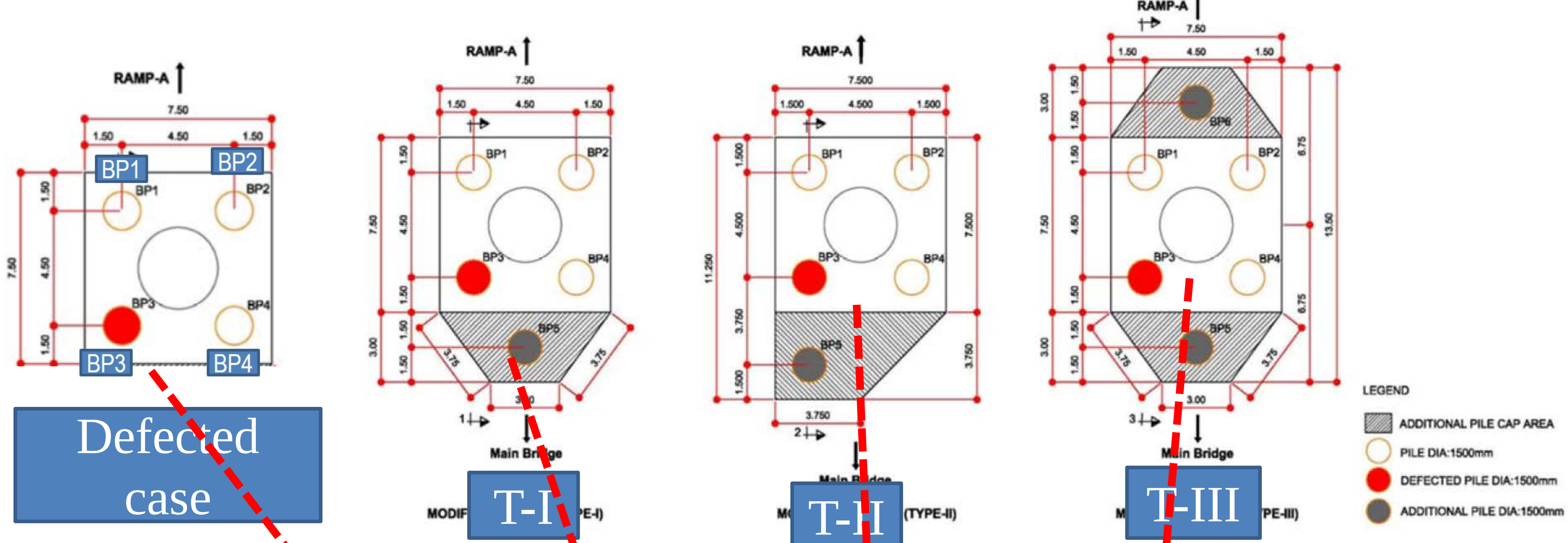
Pile Geotechnical capacities, settlements of individual pile and pile cap settlements were designed for five pilling patterns:

1. Pattern-1: Settlement and pile capacity as built drawing
2. Pattern-2: Settlement and pile capacity including defected pile
3. Pattern-3: Modified design for piling type-1 (T-I)
4. Pattern-4: Modified design for piling type-2 (T-II)
5. Pattern-5: Modified design for piling type-3 (T-III)





Note: Pile spacing and patterns were considered as per ASSHTO



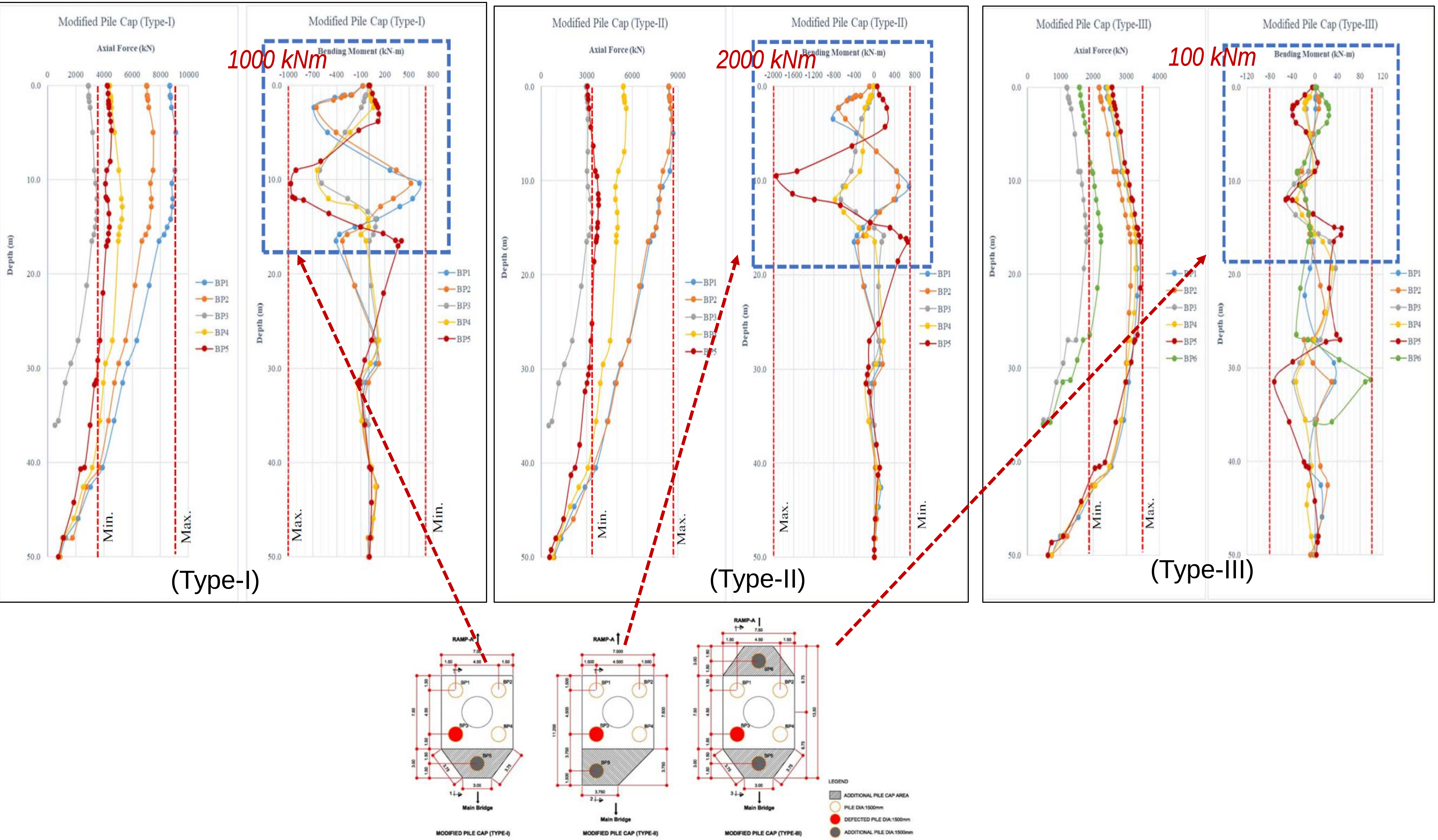
Design Capacity of Pile =767 ton (based on three predicted methods)

Table (4.2) Summary of Analysis Results for Structural Capacities of Piles (Five cases for pilling layout pattern)

Pile No.	Design*		Defected Case		Remedial Measure (T-I)		Remedial Measure (T-II)		Remedial Measure (T-III)		Length, m	Remark
	Axial Force, kN	Bending Moment, kN-m	Axial Force, kN	Bending Moment, kN-m	Axial Force, kN	Bending Moment, kN-m	Axial Force, kN	Bending Moment, kN-m	Axial Force, kN	Bending Moment, kN-m		
BP1	7622	354	8326	497	9072	687	8679	820	3333	35	50	-
BP2	7574	343	7007	490	7486	652	8574	714	3127	30	50	-
BP3	7591	419	6609	260	3499	612	3343	662	1805	51	36	Defected pile
BP4	7704	407	8284	319	5275	640	5584	775	3283	34	50	-
BP5	-	-	-	-	4522	971	3786	1946	3428	72	50	Additional pile
BP6	-	-	-	-	-	-	-	-	2229	99	36	Additional pile

Remark: * As built design for un-defected pile group

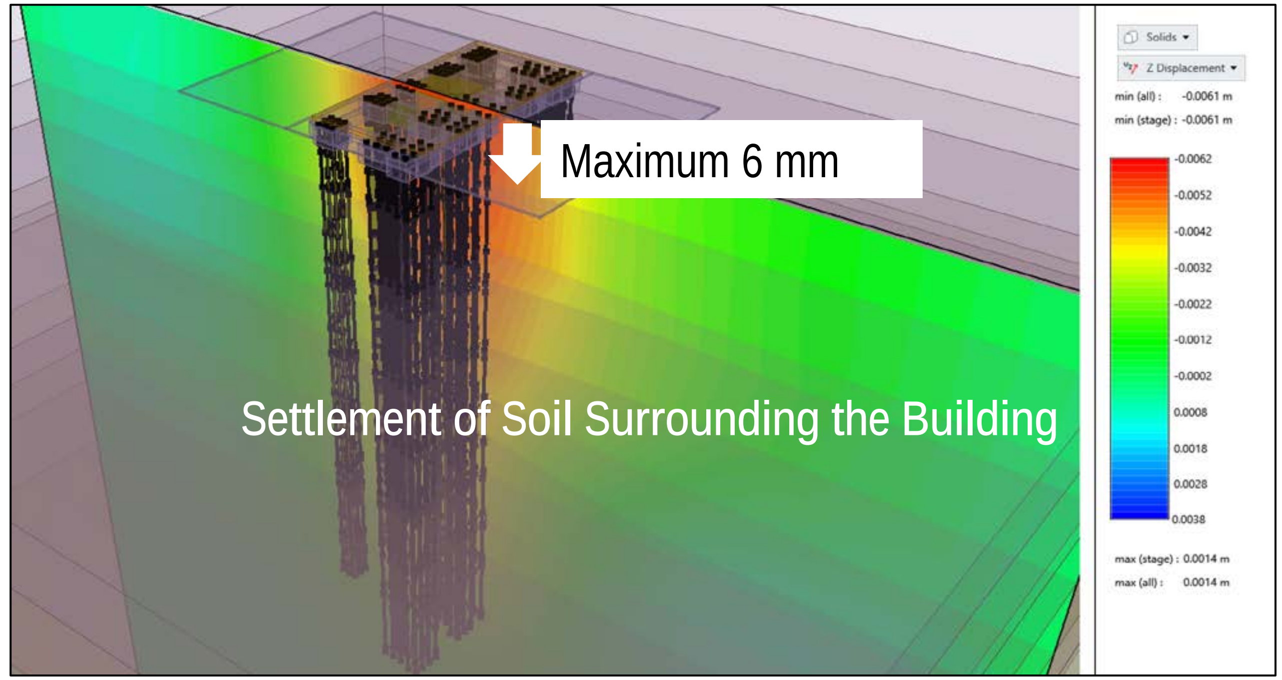
Axial force and Bending Moment on Piles



Case Study – 2:
Pile-Soil Interaction for different thickness of Soil layer, 8th Storeys Building, Tarmwe Project

Pile-Soil Interaction Analysis in

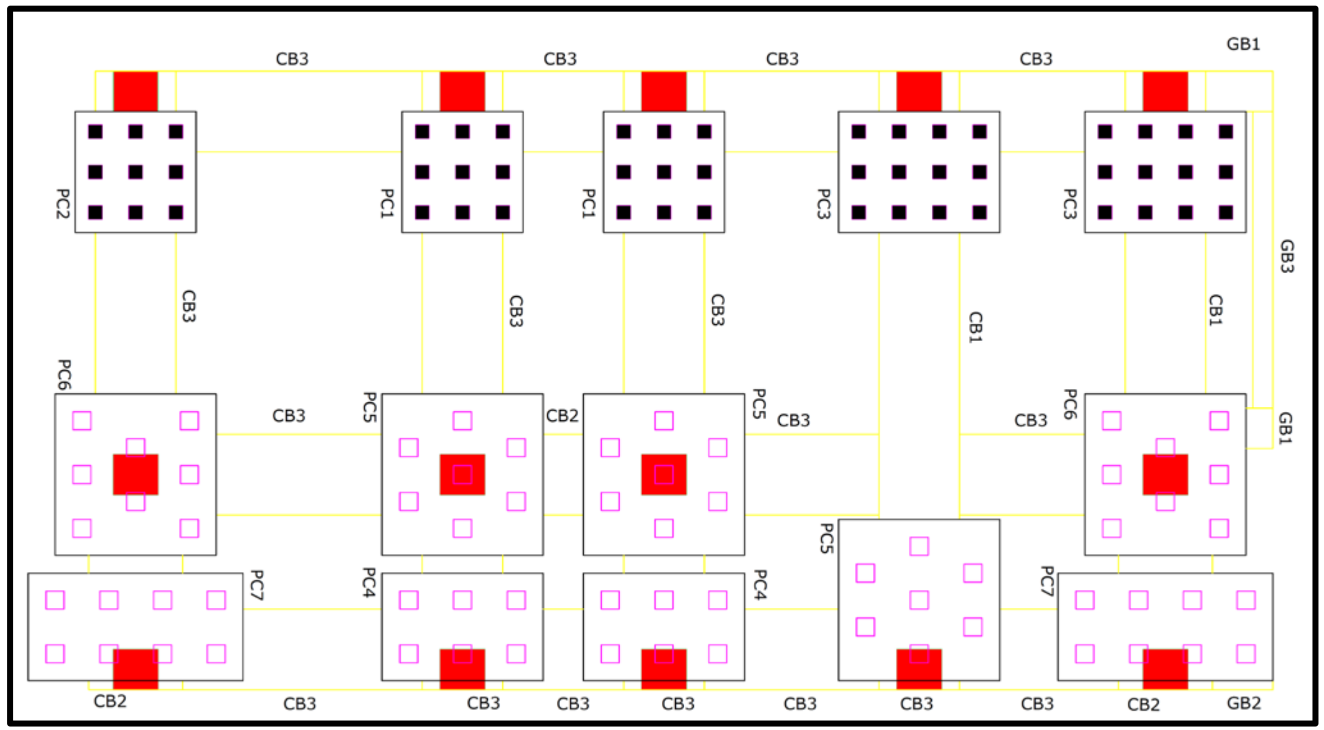
Normal Full Loading Condition



Piling Pattern

- Pile Cap Thickness 900 mm
- Pile Spacing = 600 mm c/c
- Pile size = 200 x 200 mm

- Mini. settlement of pile = 5 mm
- Max. settlement of pile = 6 mm

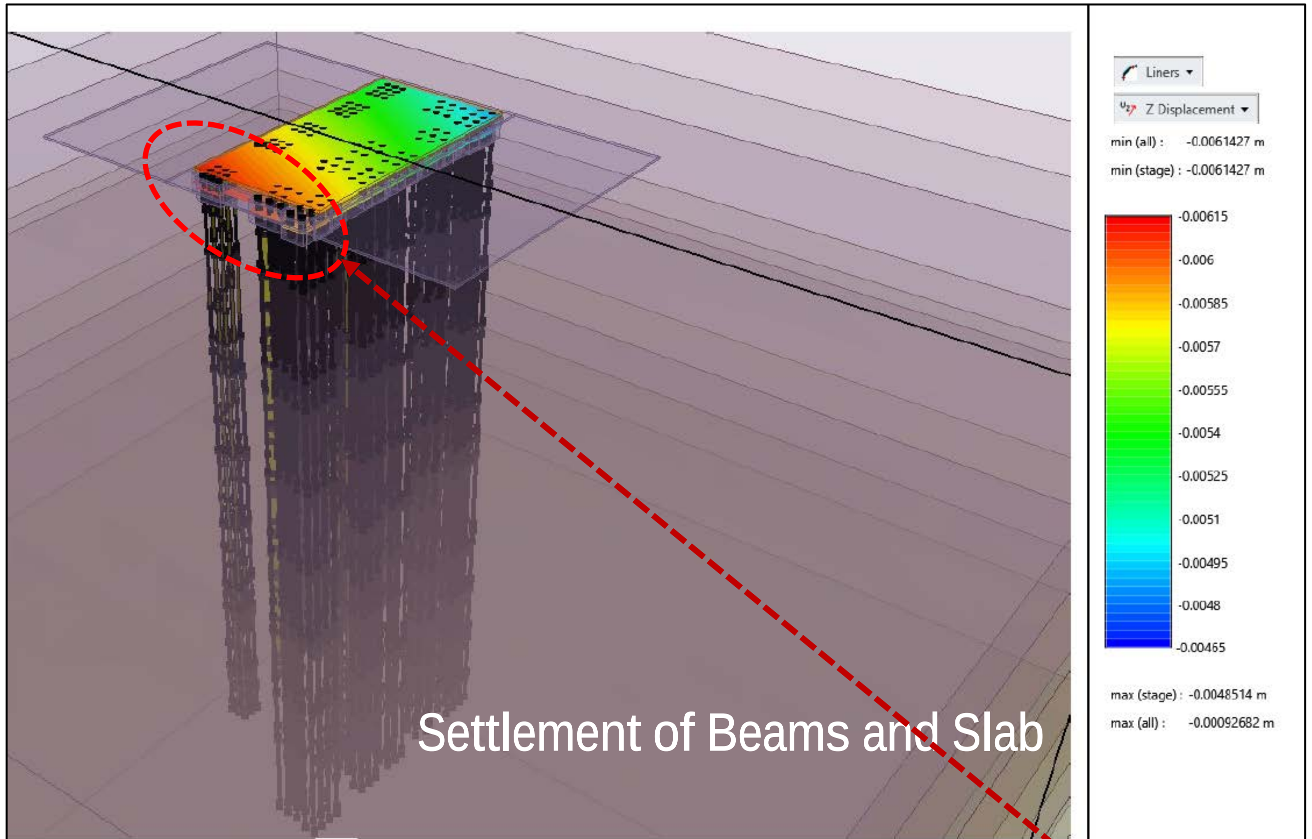


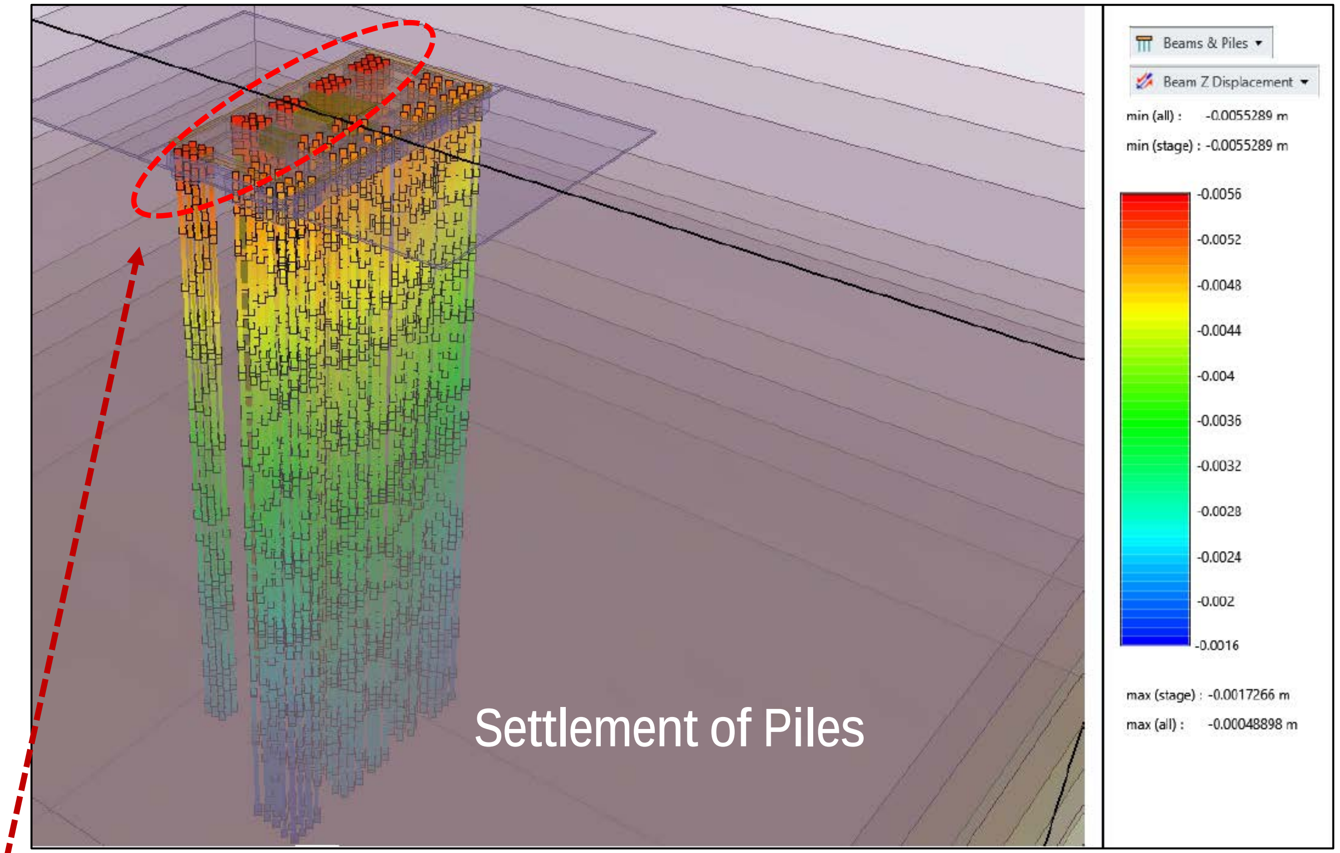
Pilling Pattern and Column Location

8th Storeys Building

8th Storeys Building, Tarmwe Project

Pile-Soil Interaction Analysis when Full Loading Condition is occurred.





Technical Note and Evaluation:

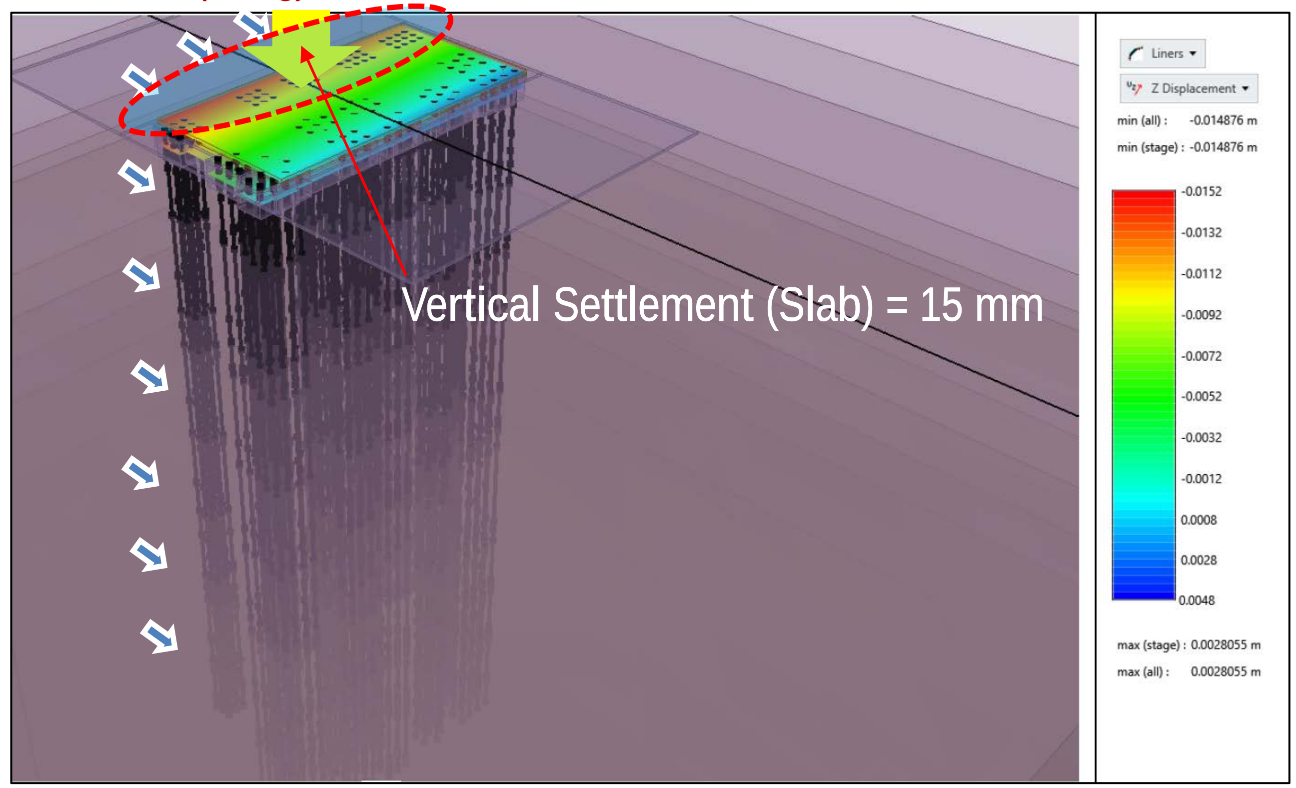
1. Different Building settlements due to different soil layers. (See red dotted line)
2. Settlement will be happened depended on the different soil properties and different pile lengths of individual pile.
3. Test pile is only represented on the piles with similar conditions of soil layer. Therefore, 99 % of non-testing pile shall be checked with the tested pile and predicted capacity of pile.

2.2. Seismic Loading - Case Study for 8th Storey Building- of Tarmwe Project

Pile-Soil Interaction Analysis:

using Pseudo Static Analysis Method for Earthquake Loading

Seismic load principal direction (0.25g)



Displacements during Seismic Loading:

1. Maximum vertical settlement ***(slab)*** = 15 mm
2. Maximum horizontal movement ***(slab)*** = 41 mm
3. Maximum horizontal movement ***(Pile tip)*** = 43 mm
4. Maximum horizontal movement ***(pile toe)*** = 13 mm

Technical Evaluation:

For the specific site condition and building layout, Technical consideration requires for;

1. Pile structural capacity during seismic (bending, Shear and axial load)
2. Pile geotechnical capacity during seismic loading
3. Settlements and movements

Soil Liquefaction induced Damages

Soil liquefaction, its causes and Solution?

Seismic Loading for 8th Storey Building

Pile-Soil Interaction Analysis

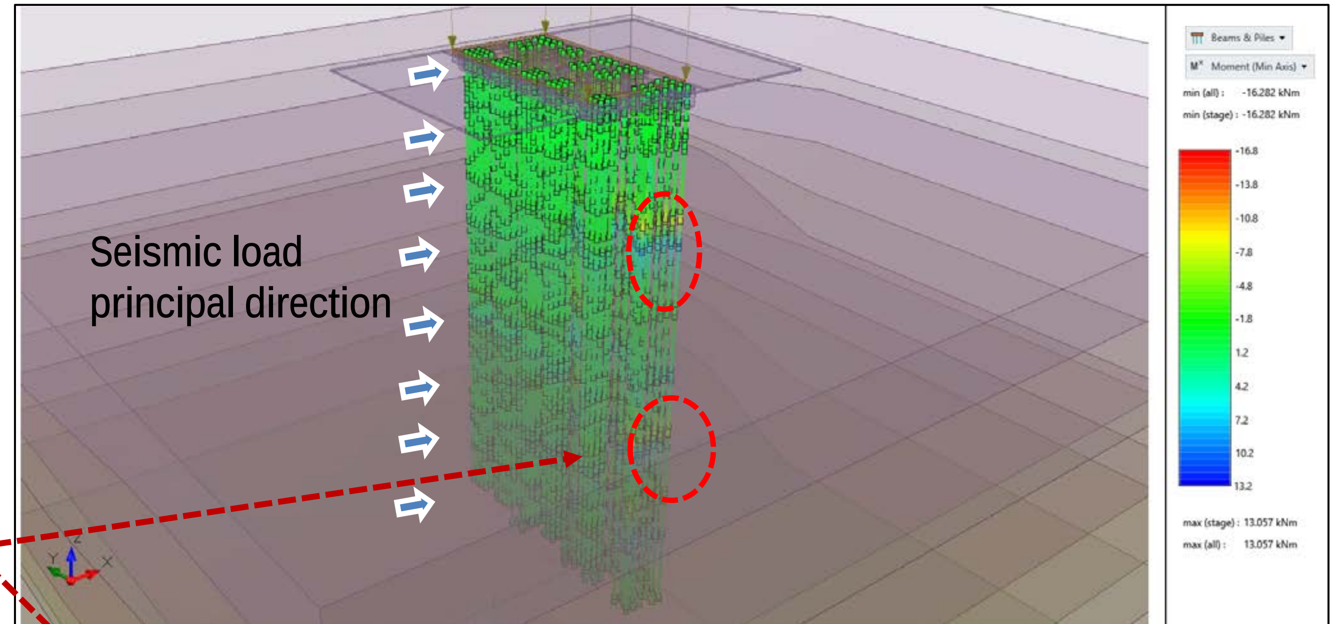
using Pseudo Static Analysis Method

It is adopted as the lateral force at the 30 m of upper layer of soil and not considered vertical force for far source earthquake.

Technical Evaluation:

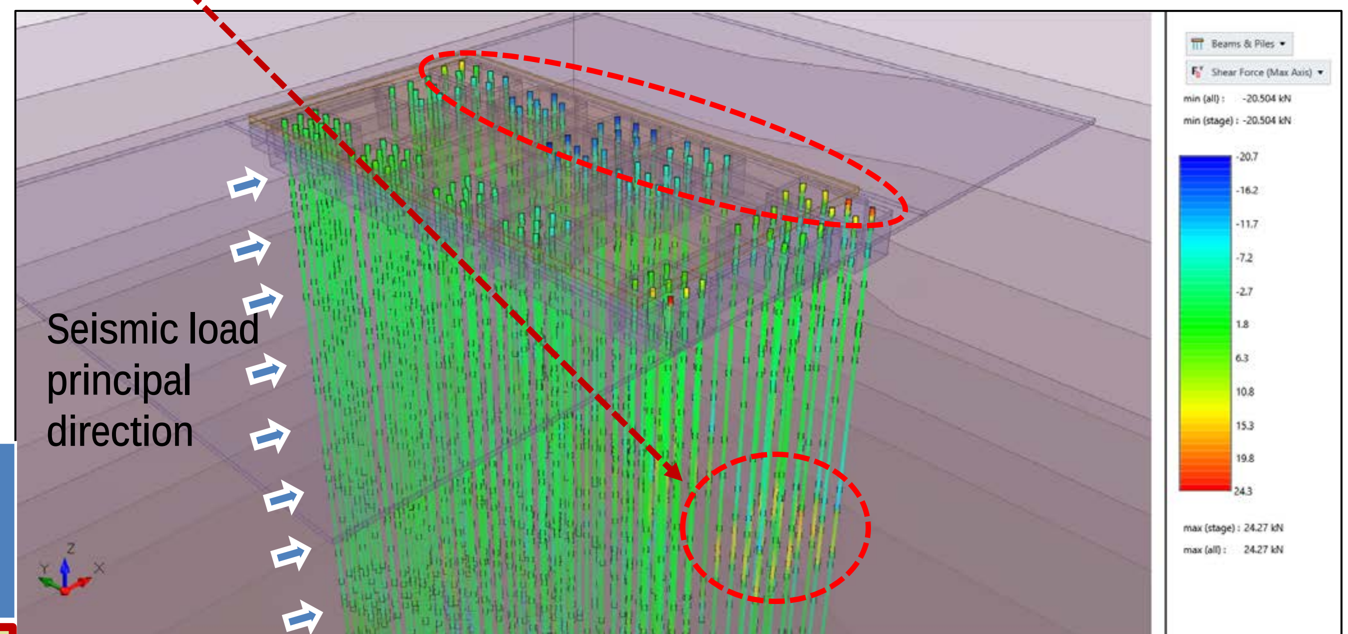
1. Red dotted lines show that the maximum bending moment and shear of pressed piles will be happened.
2. The BM and SF will be depended on *the stiffness of different soil layers and seismic load.*
3. Design should be considered within the safety factor for capacity of pressed piles *(especially at joints)*
4. *Pile size selection shall be selected based on capacities (Axial load, BM and shear force)*

	Description	Qty.	Load factor	Design capacity
1	Max. Bending moment, kNm	16.28	1.6	26.05
2	Max. Shear Force, kN	24.27	1.6	38.83



Bending Moment on individual pile

Maximum Moment on individual pile = 16.28 kNm



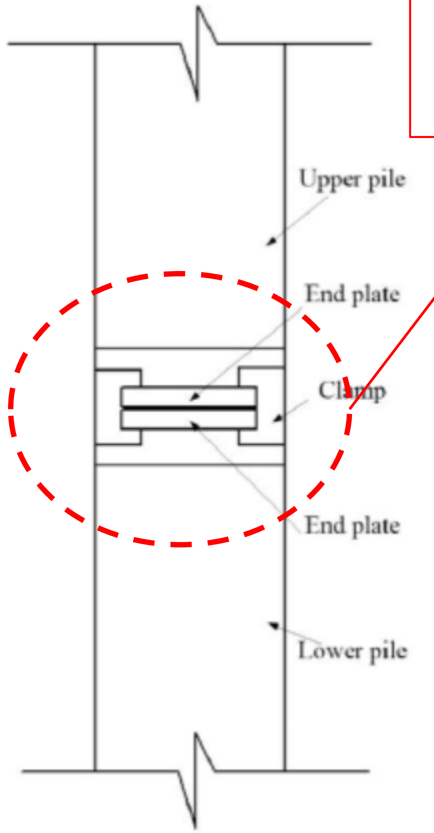
Shear force on individual pile tip

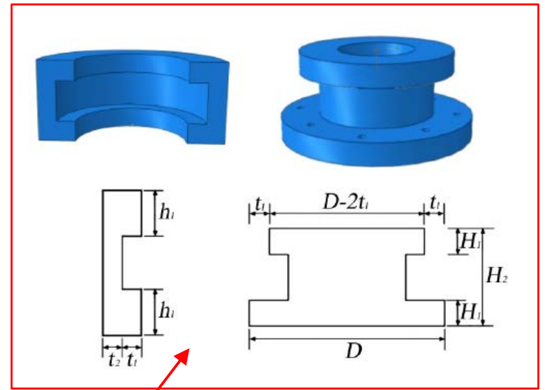
Maximum shear force on individual pile = 24.27 kN

To check the resistance for Bending Moment of Pile Connection

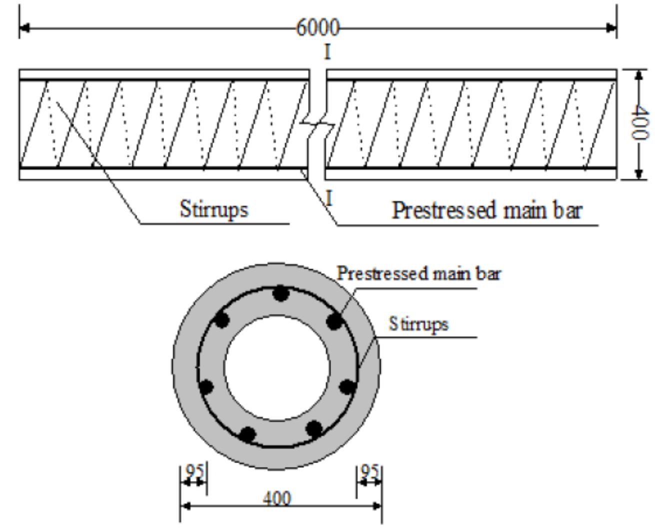
Pre-stressed high-strength concrete (PHC) pipe Piles

Bending Moment of Pile, Dia. 400 mm

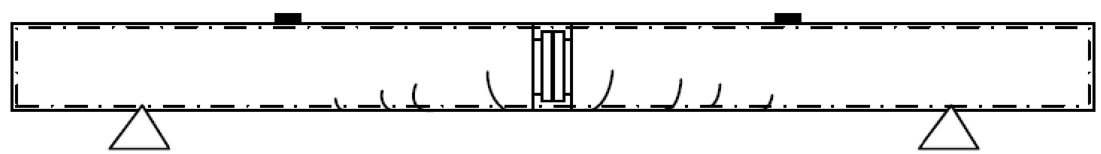




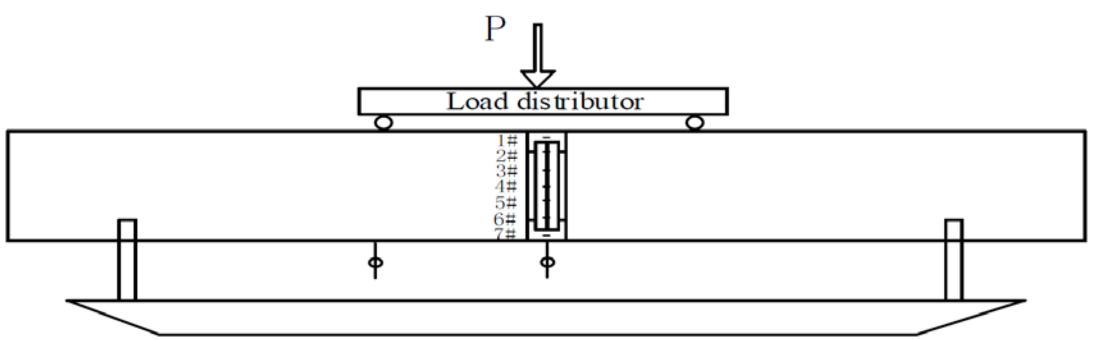
Schematic diagram of PH
pipe pile hoop connection



Schematic diagram of the reinforcement of PHC pipe pile (*pile diameter=400 mm*)



Crack pattern



Schematic diagram of loading device

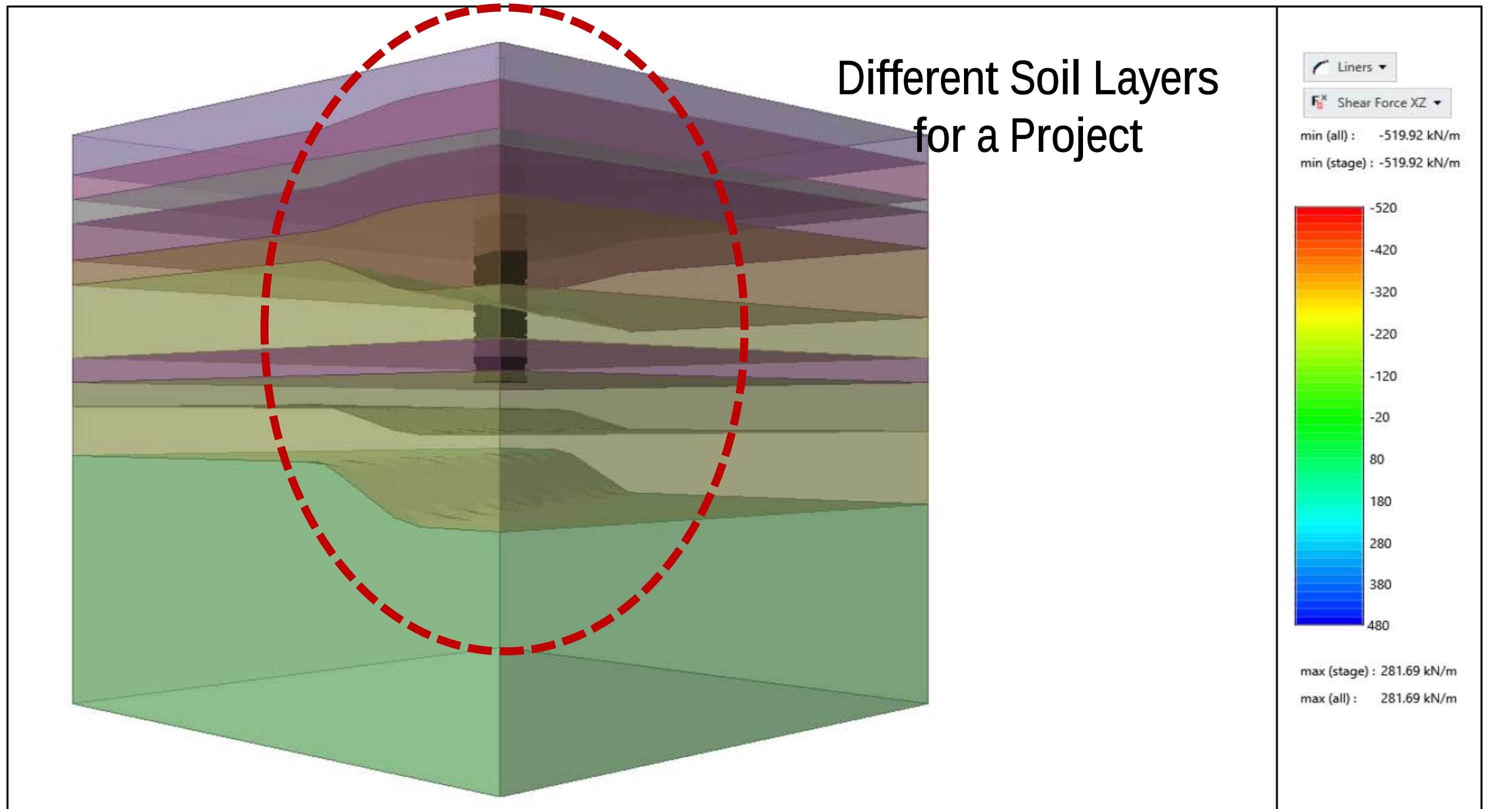
- When the bending moment of the pure bending section reaches *99 kNm*, a vertical crack appears on the left and right sides of the joint.
- The *width and length of the cracks are 0.64 mm and 240 mm*, respectively, at the time of damage.

Coffee Break

10 minutes

Case Study-3A

Analysis of a Pile Groups in ***Different Soil Layers and Large Numbers of Piles***

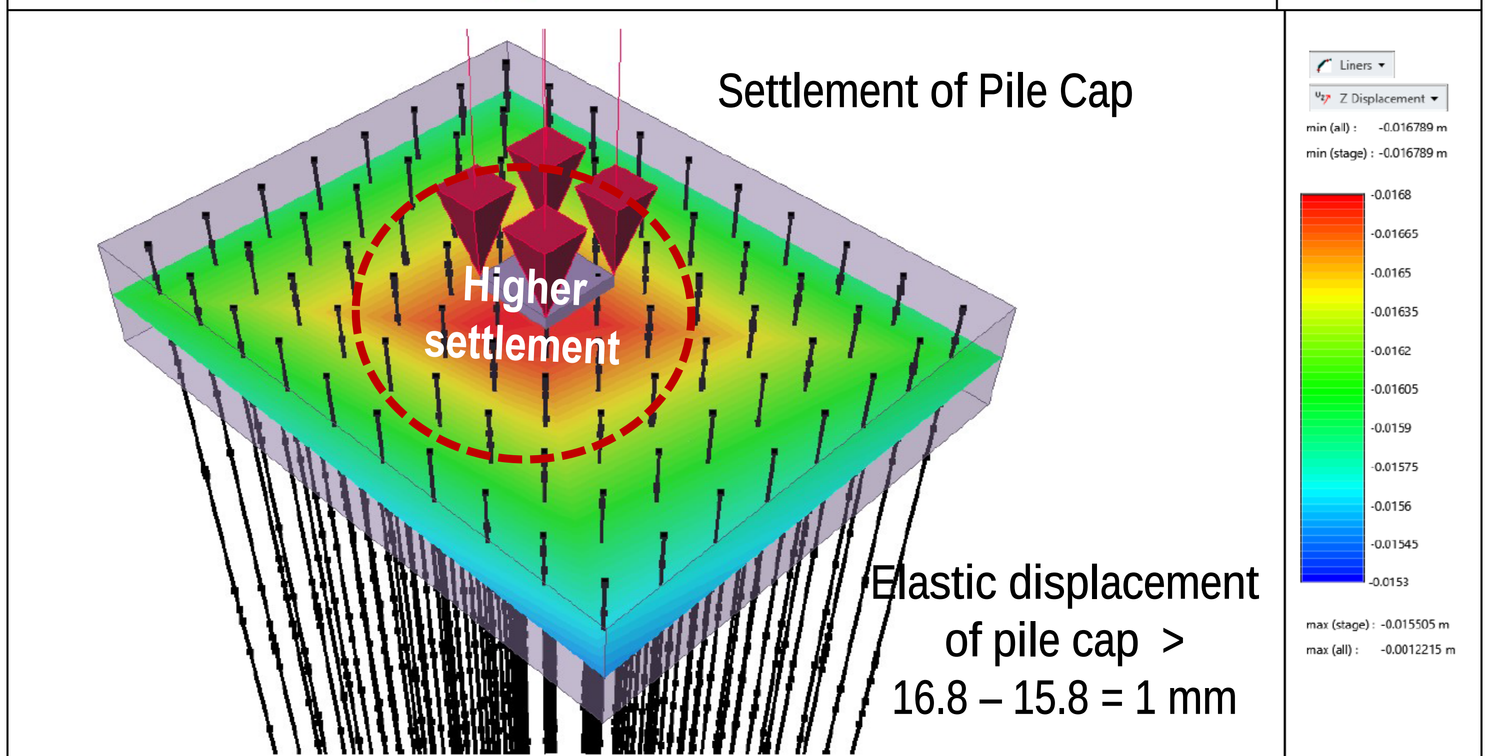


Capped pile groups

1. The modulus of subgrade reaction is not an intrinsic soil property for heavy load and considered on the overall effect of the soil .
2. Linear Soil Behavior

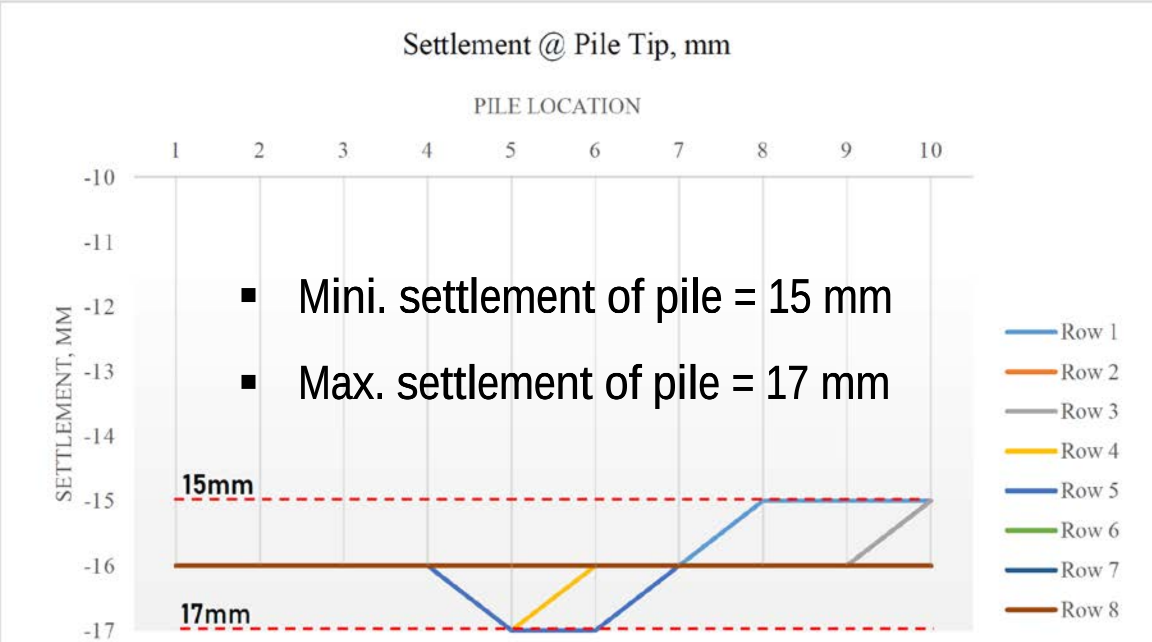
Technical Aspects:

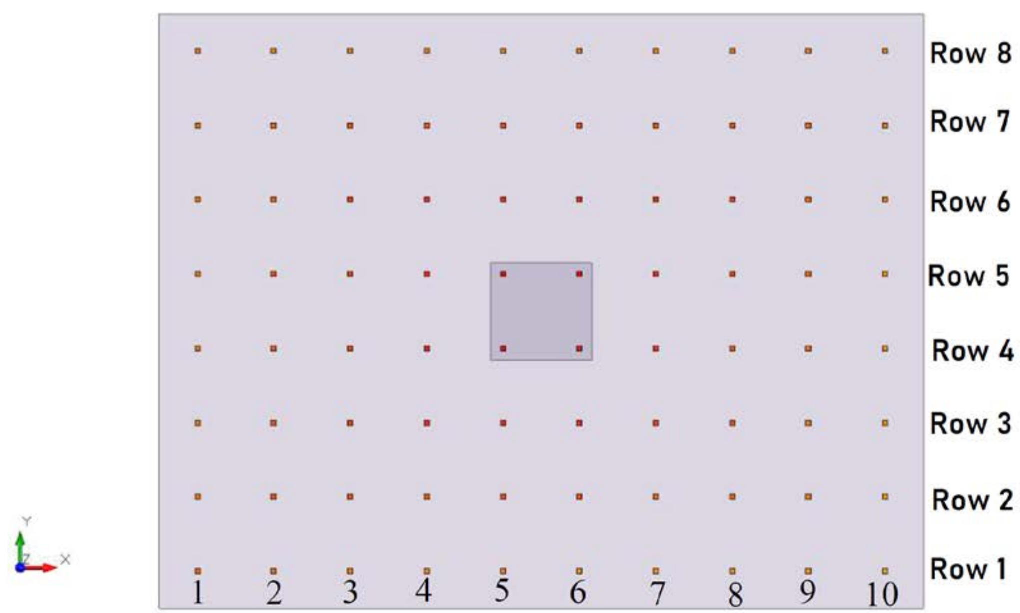
1. The distribution of load between piles in a group is of basic importance in design.
2. Load-deformation coupling- Pile-soil interaction is a three-dimensional problem, and each of the load components has deformation-coupling effects, i.e. there is an interaction between the axial and lateral response of the piles

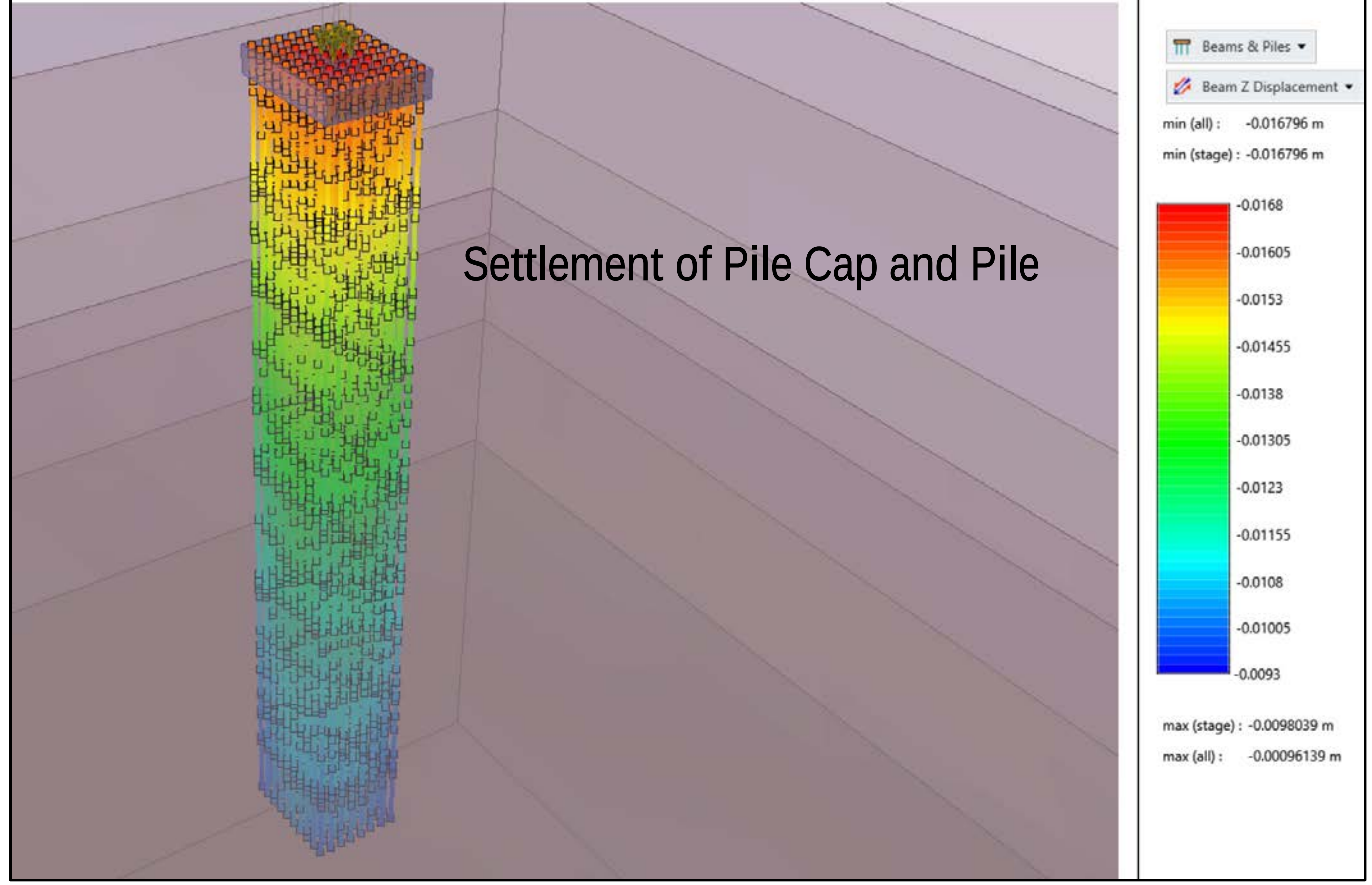


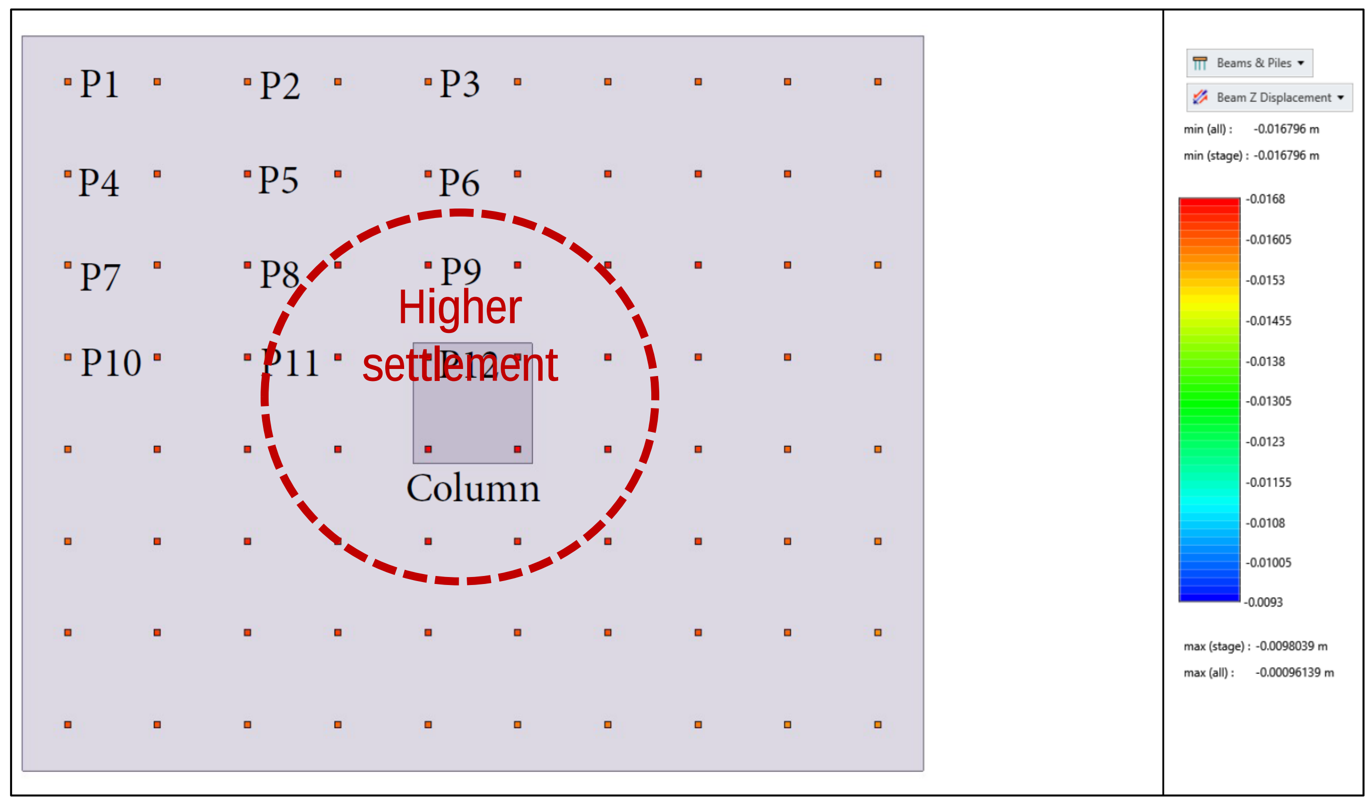
Settlement of Pile Cap and Pile Tip:

- Mini. settlement of pile = 15 mm
- Max. settlement of pile = 17 mm



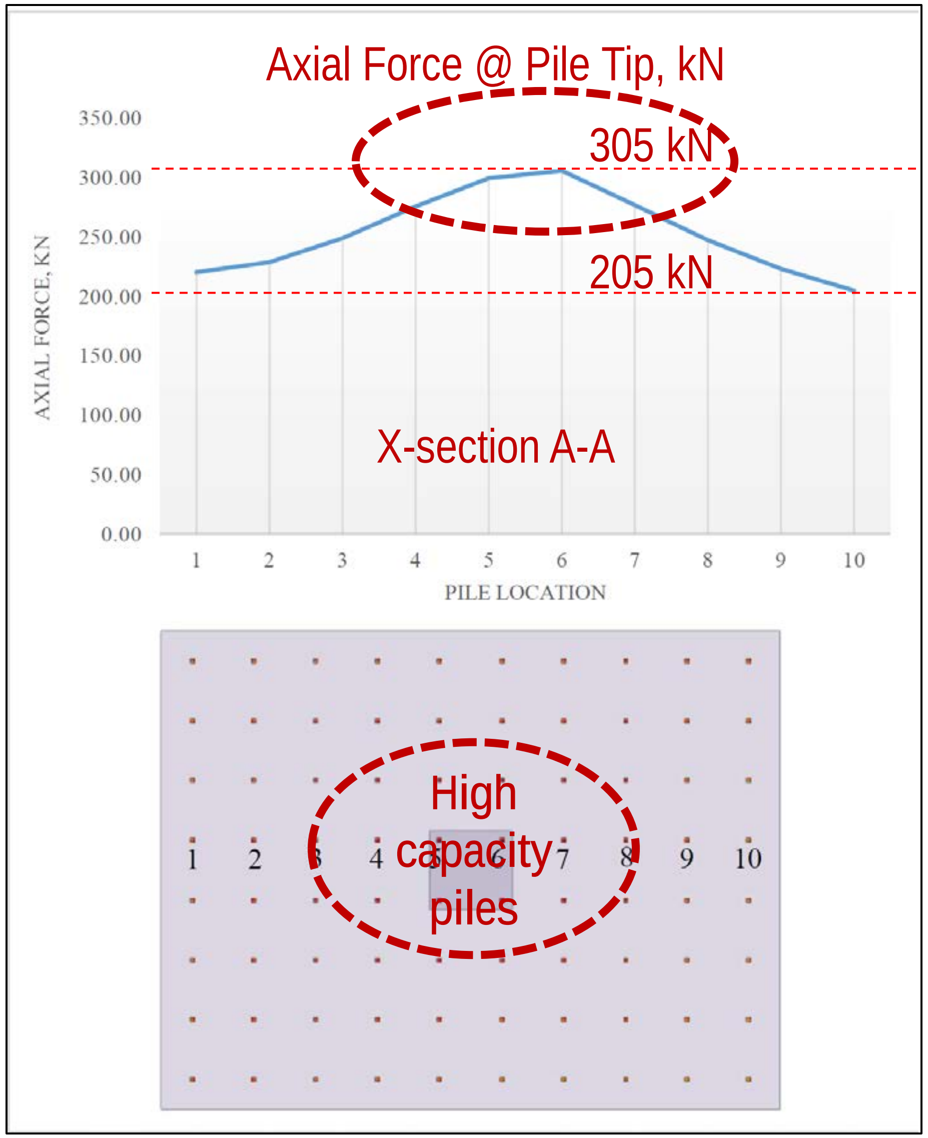


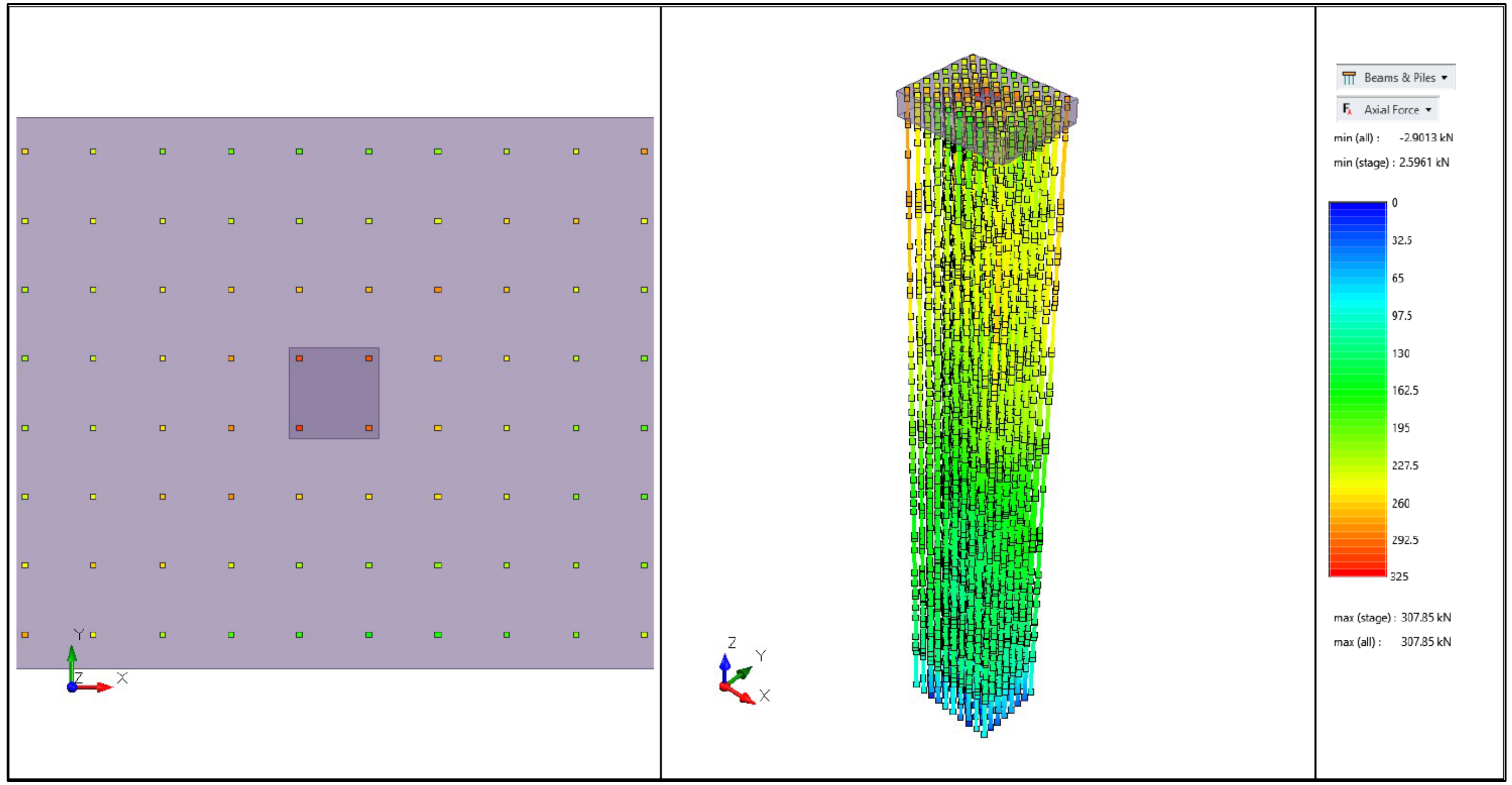


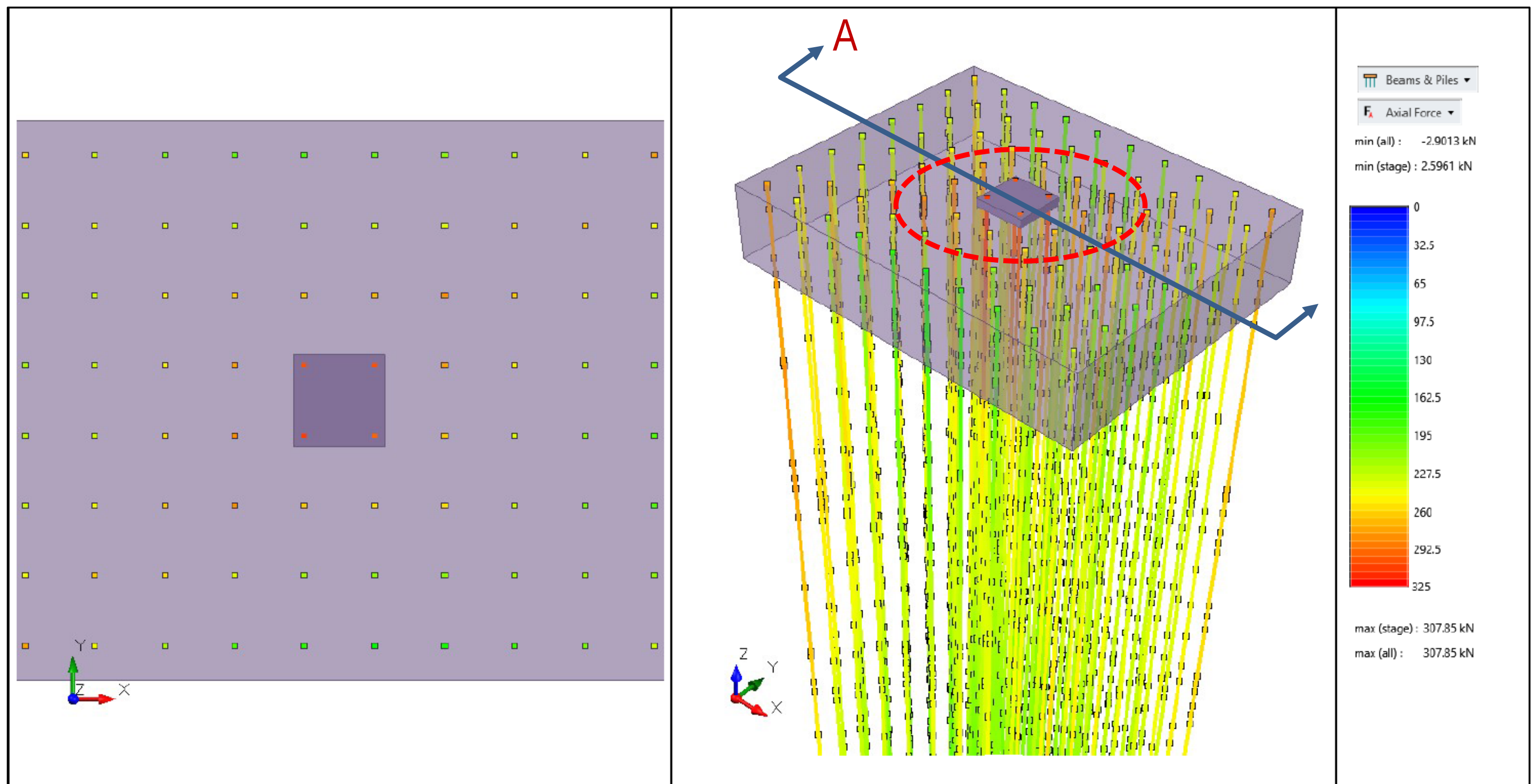


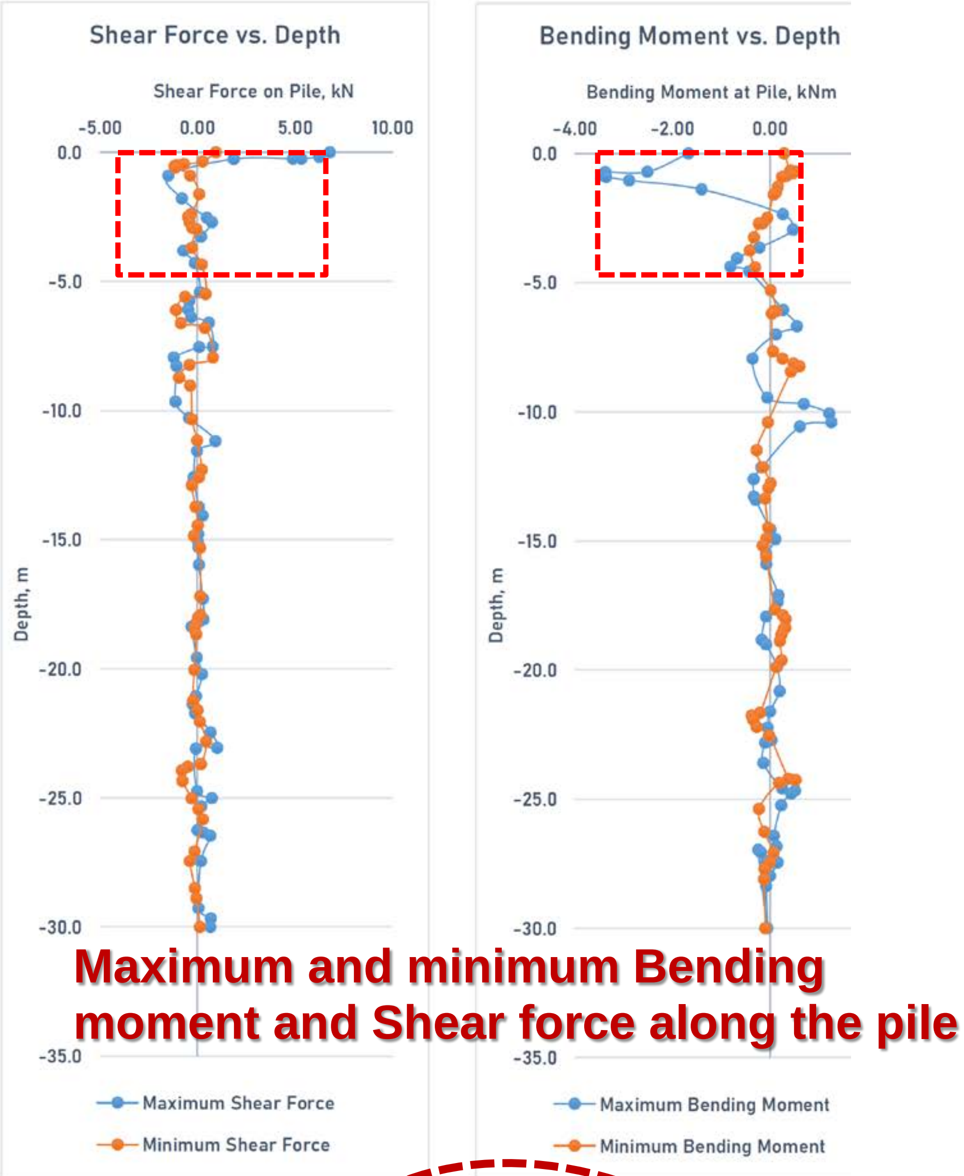
Variation of Pile Axial Force at Pile Tip

- Pile Cap Thickness = 900 mm
- Pile Spacing = 460 mm c/c
- Pile size = 200 x 200 mm
- Design capacity = 35 ton = 350 kN

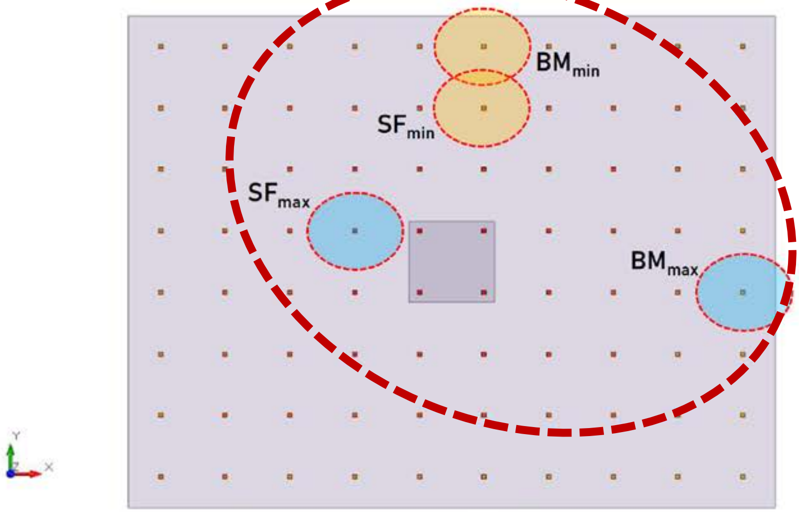


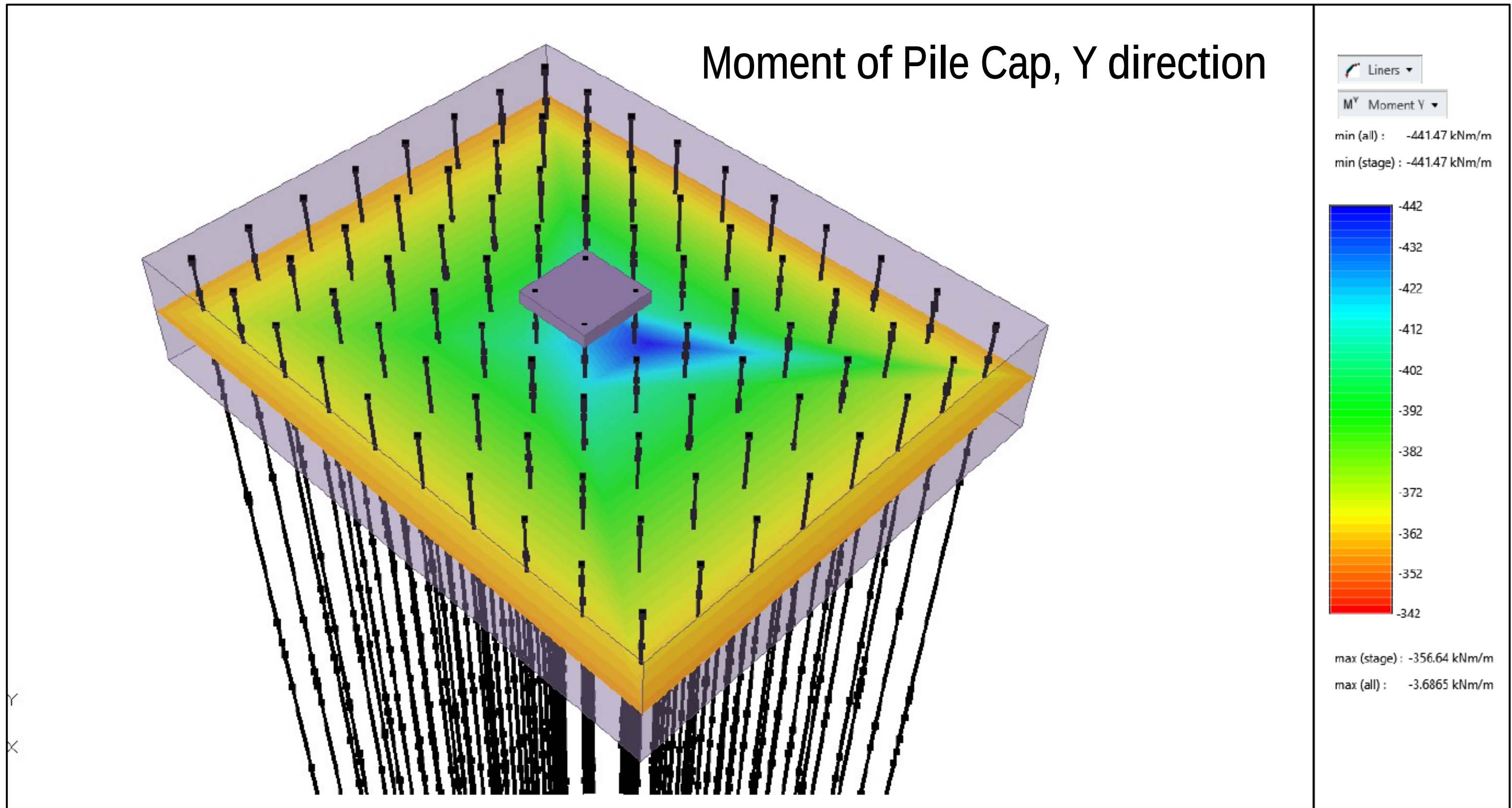


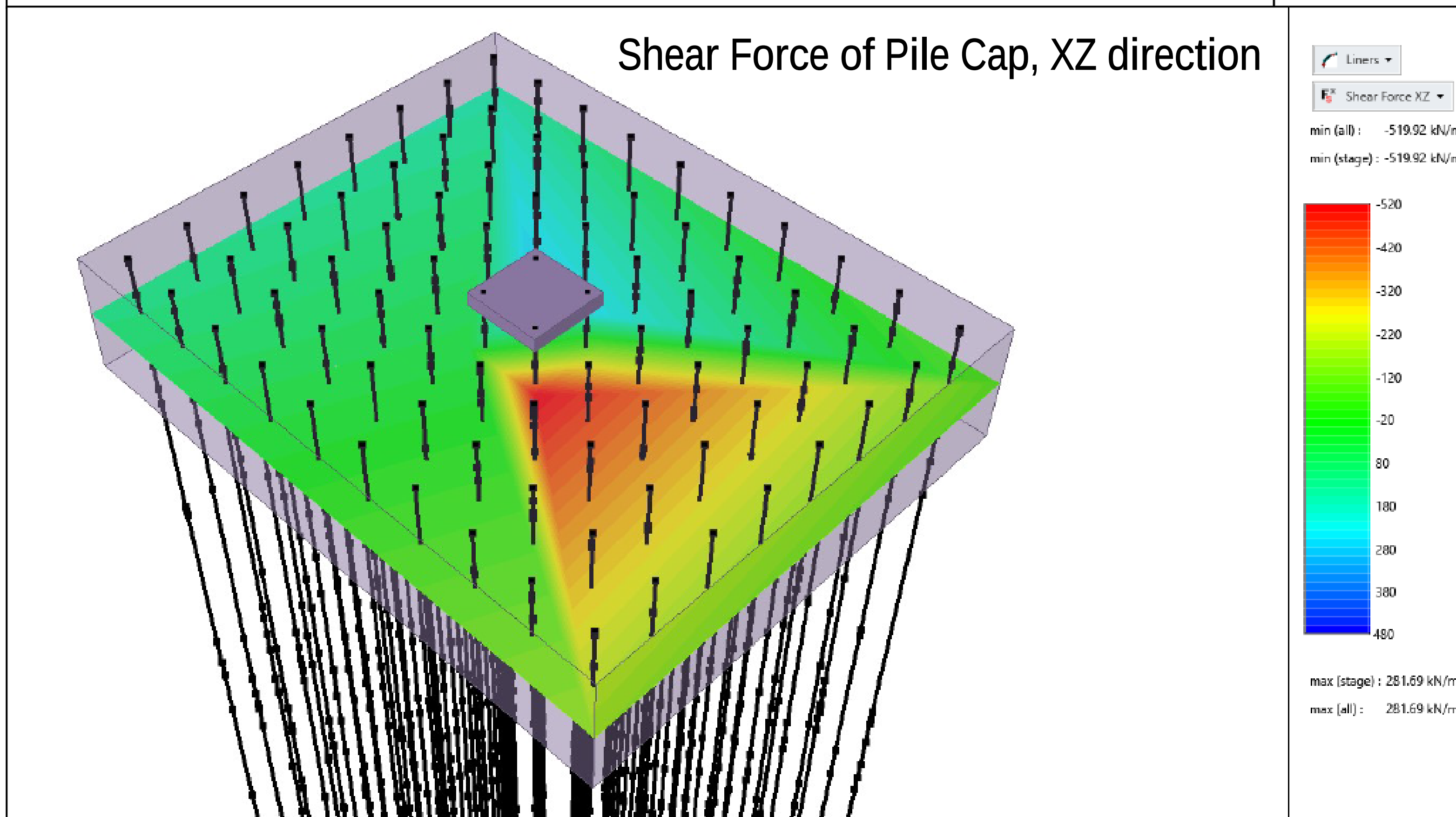




Maximum and minimum Bending moment and Shear force along the pile



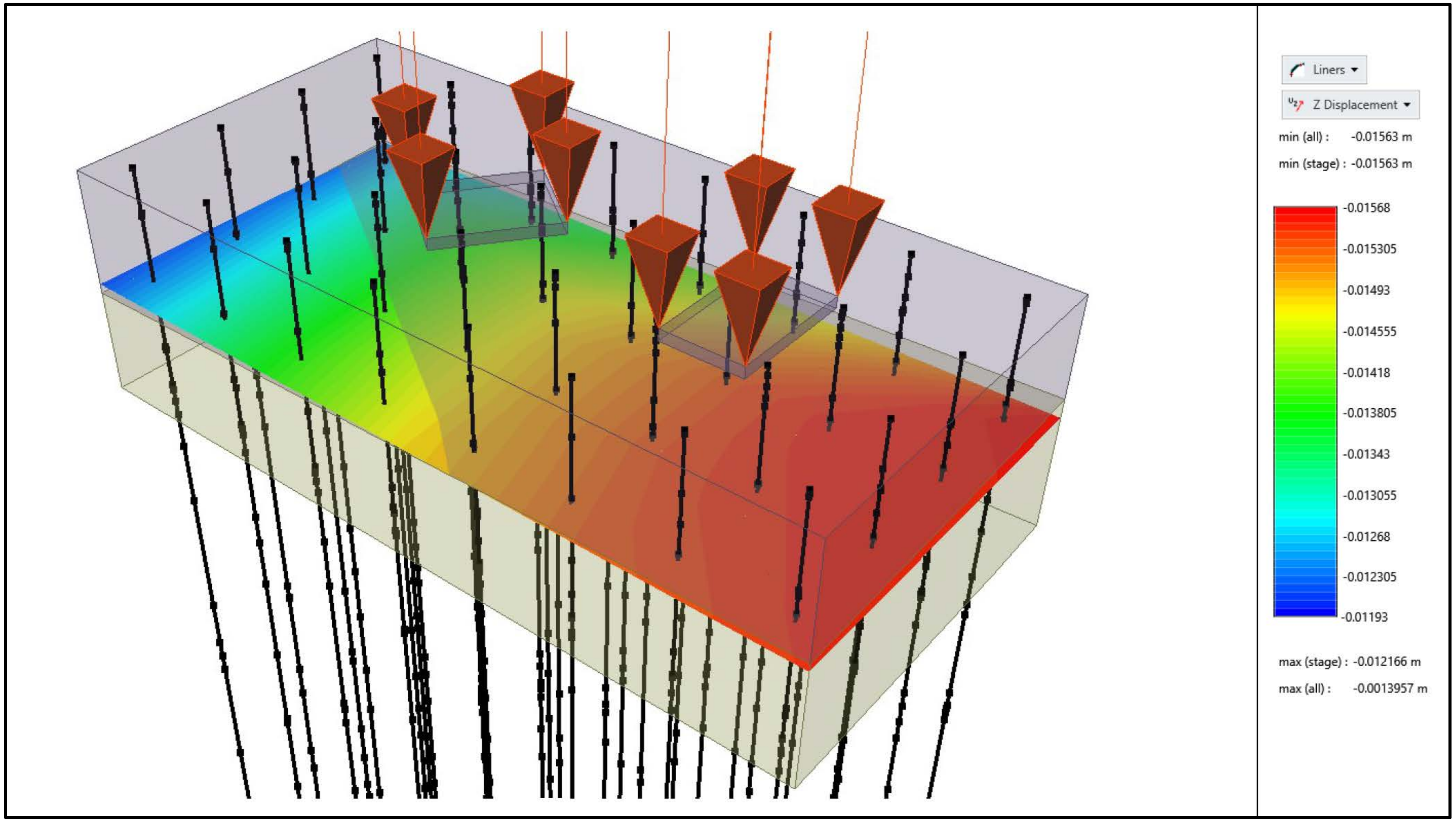




Case Study-3b

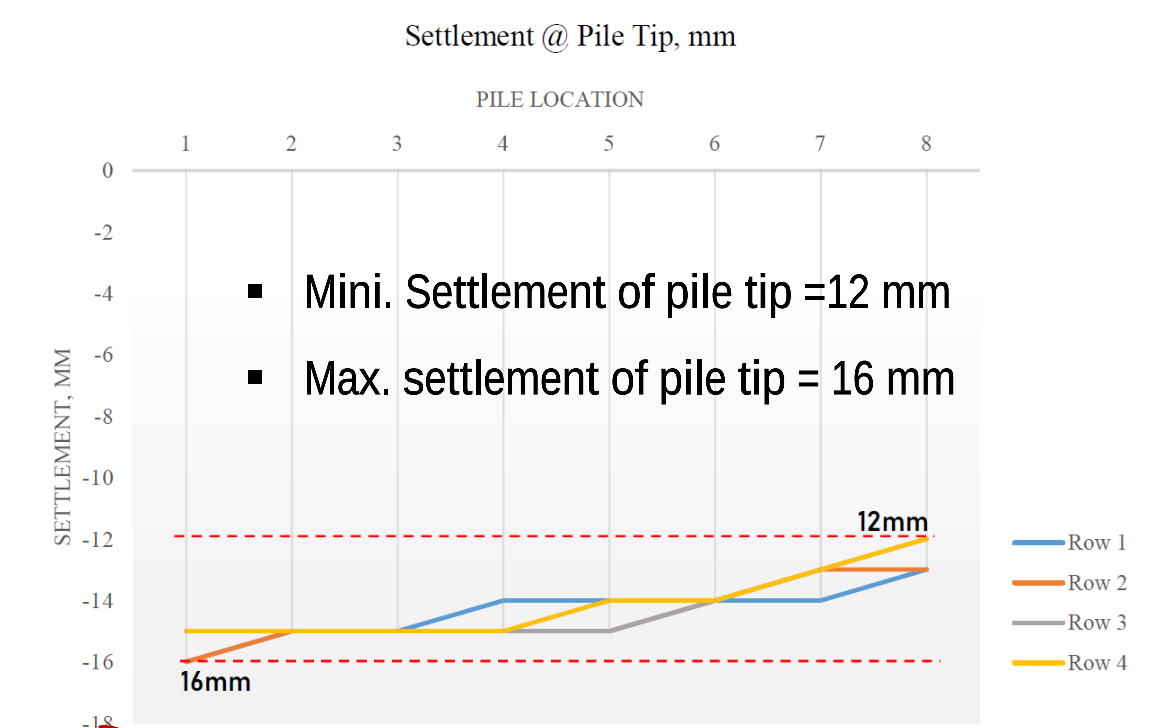
Soil-Structure interaction for Unsymmetrical loading on pile cap

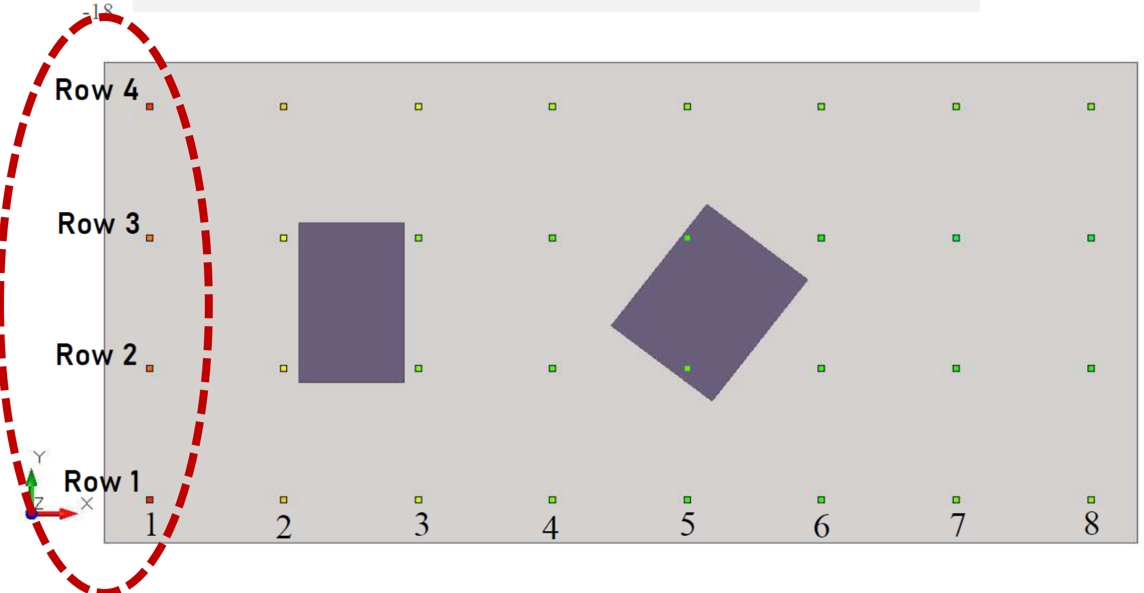
Variation of Settlement at Pile Cap

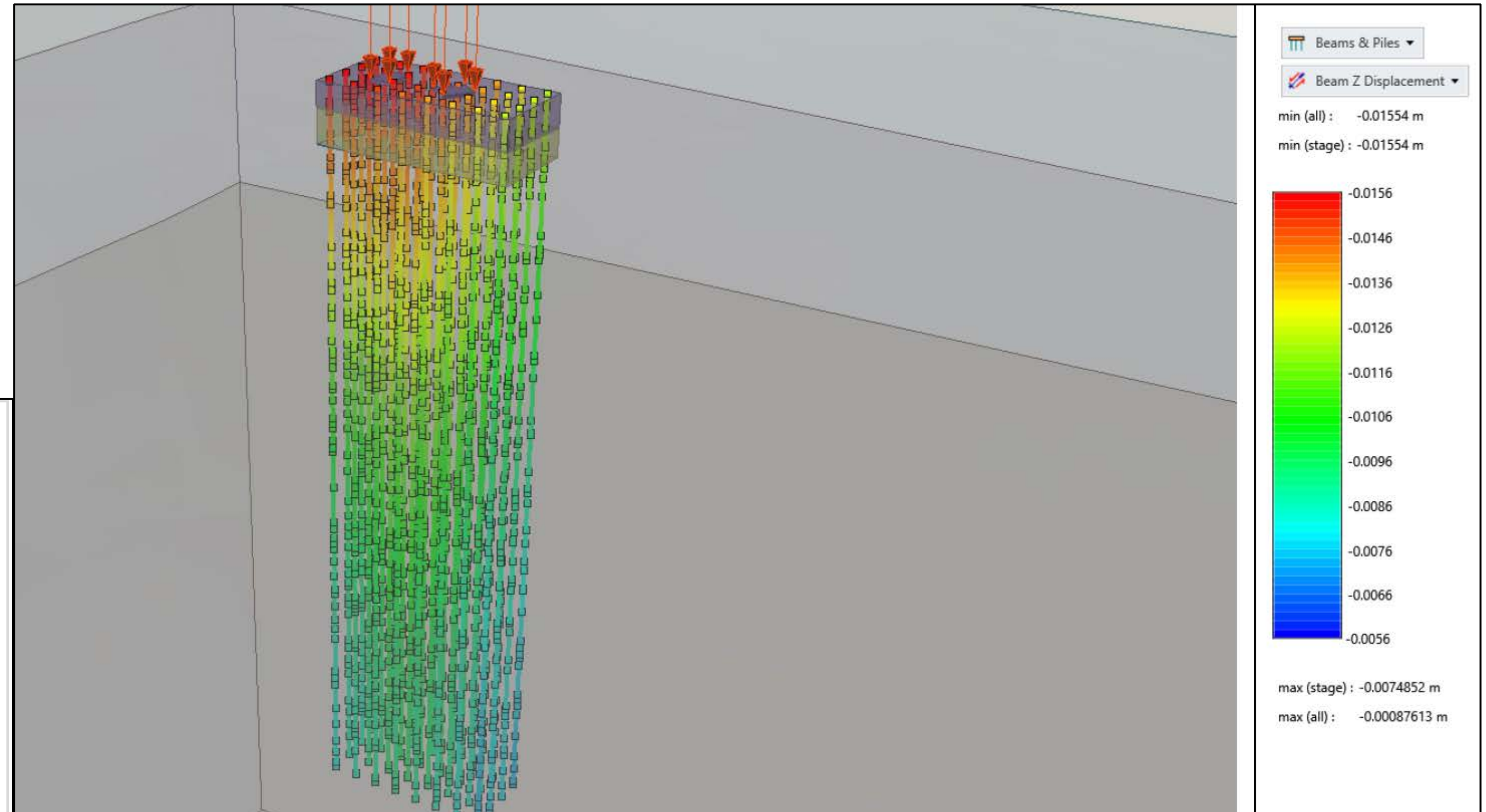


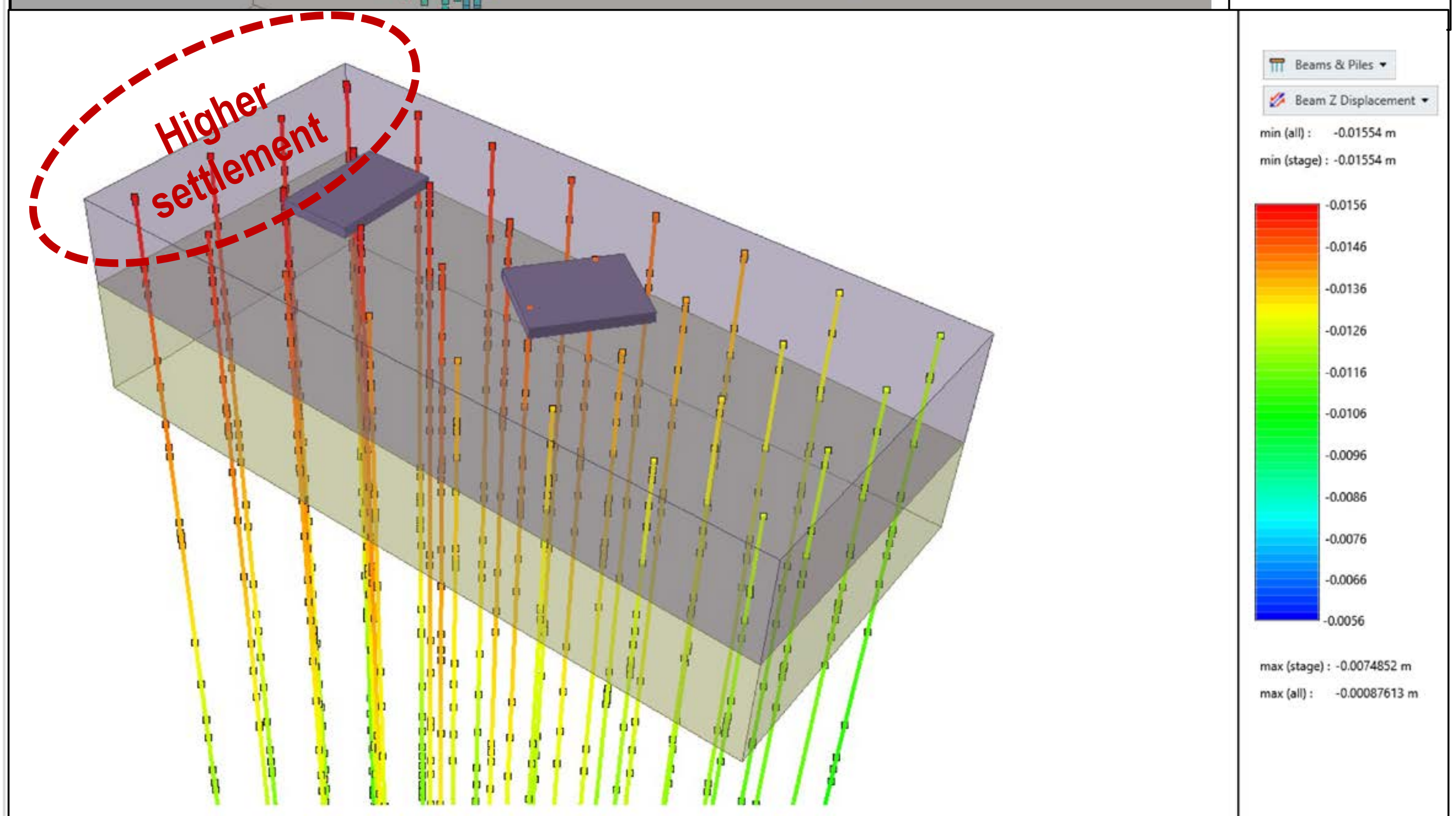
- Mini. Settlement of pile tip =12 mm
- Max. settlement of pile tip = 16 mm

Variation of Settlement at Pile Tip



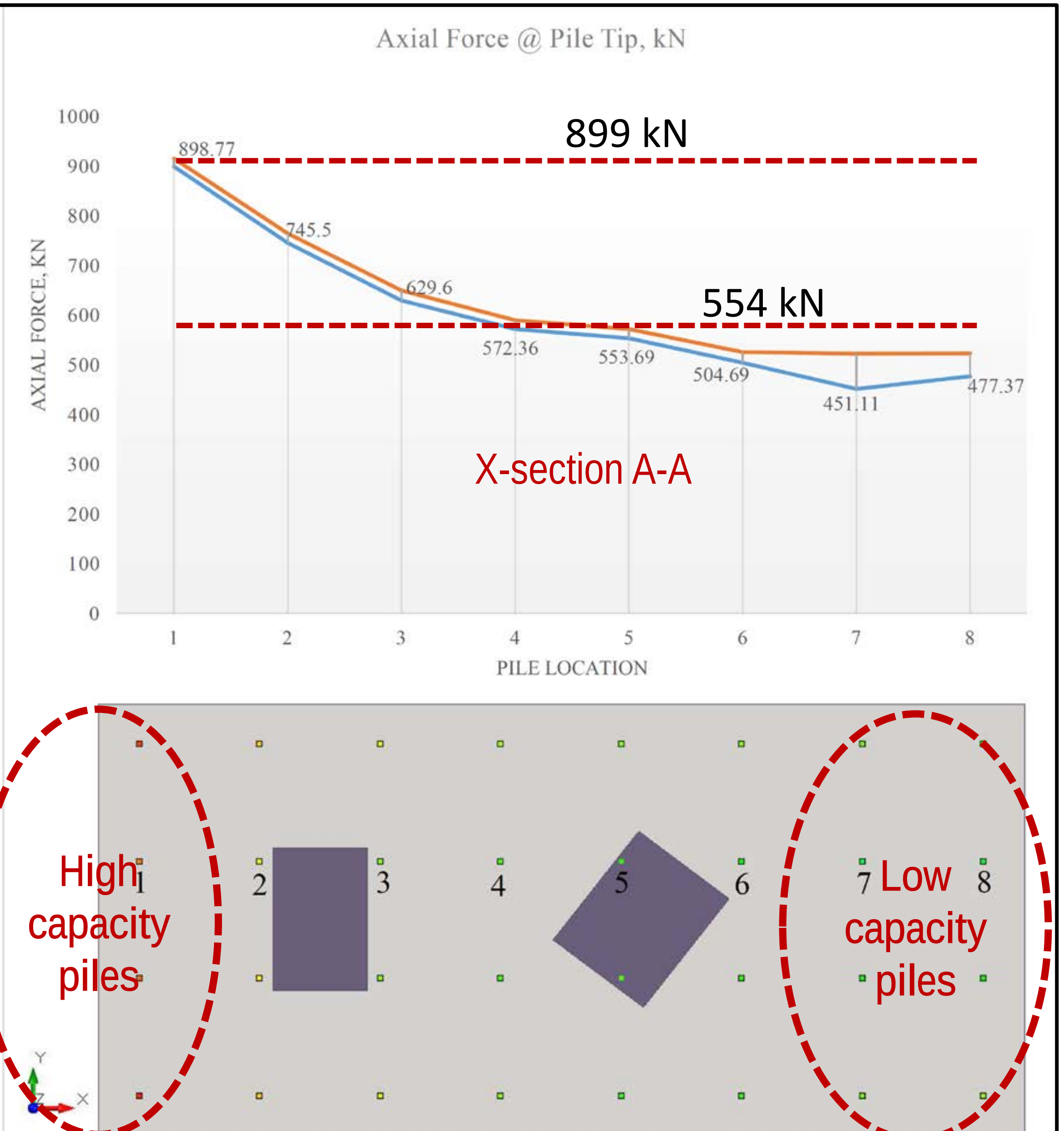


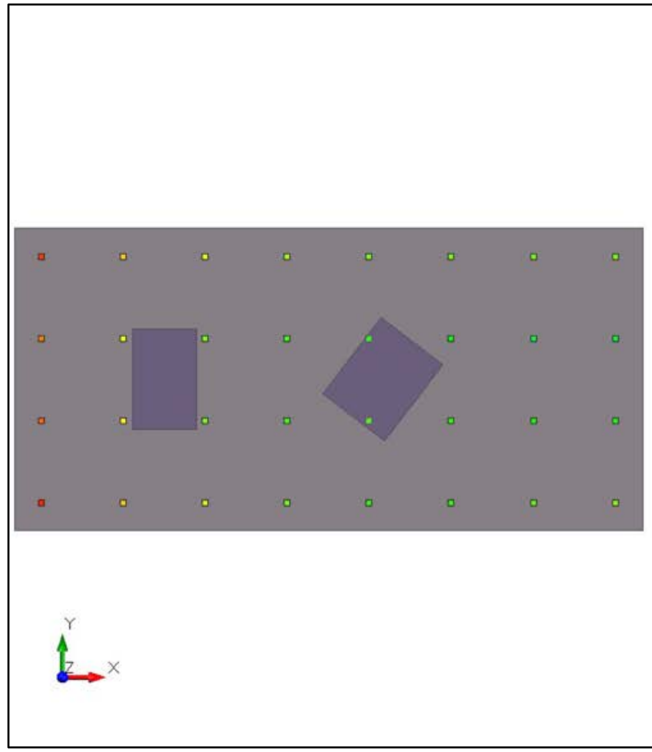


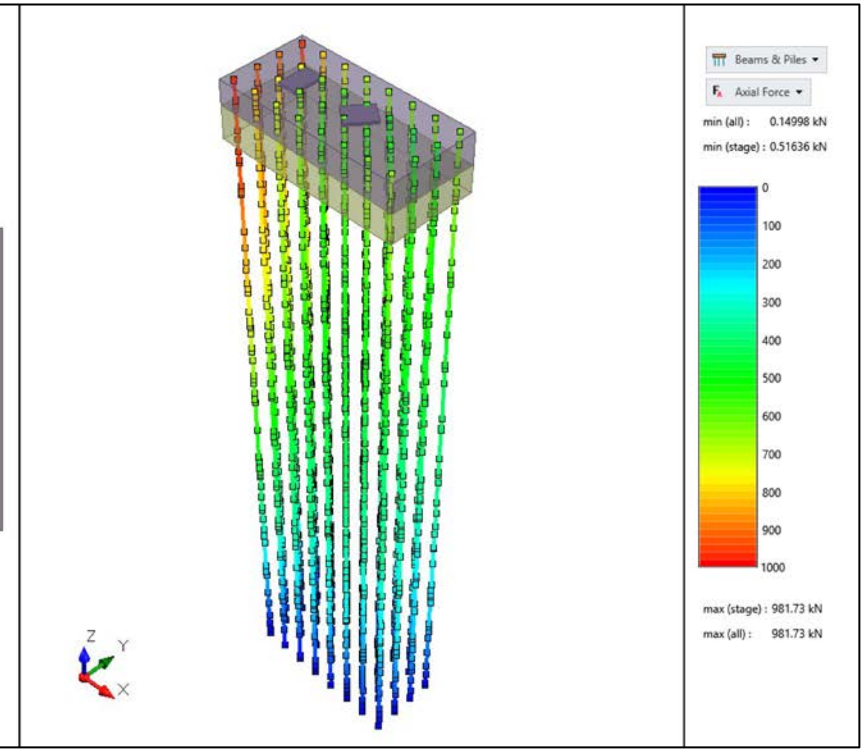


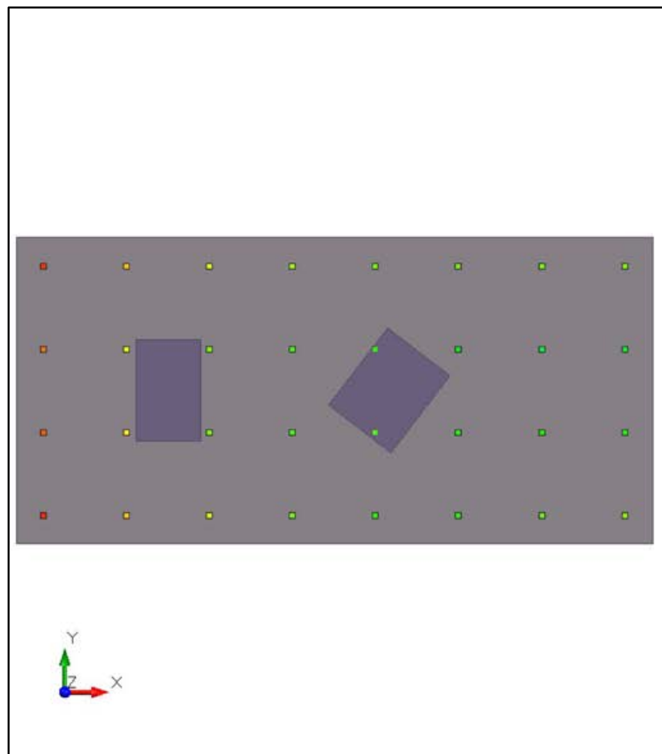
Variation of Pile Axial Force at Pile Tip

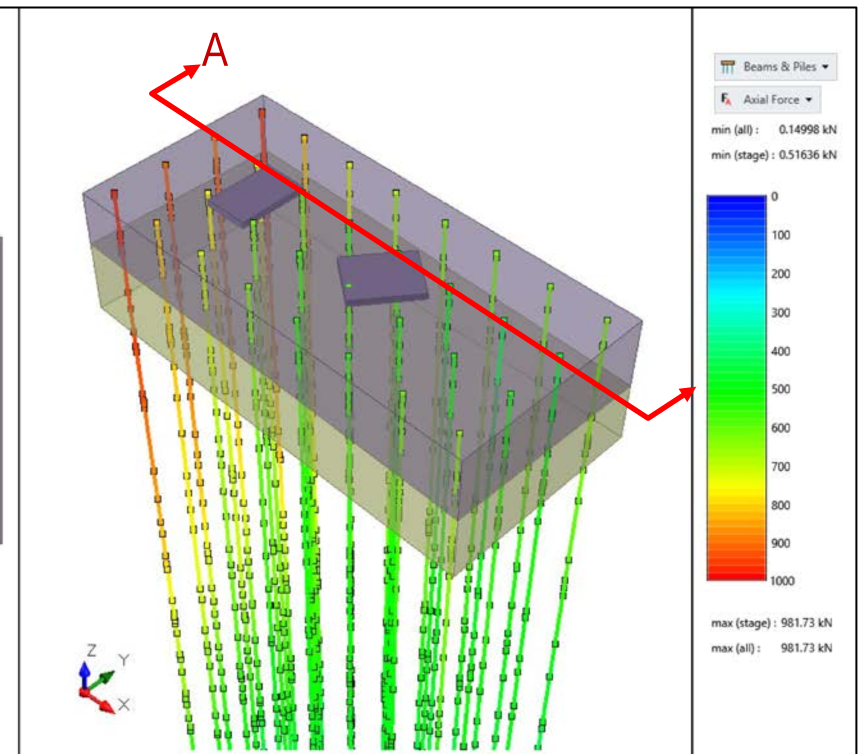
- Pile Cap Thickness = 2130 mm
- Pile Spacing = 914 mm c/c
- Pile size = 305 x 305 mm
- Design capacity = 100 ton = 1000 kN



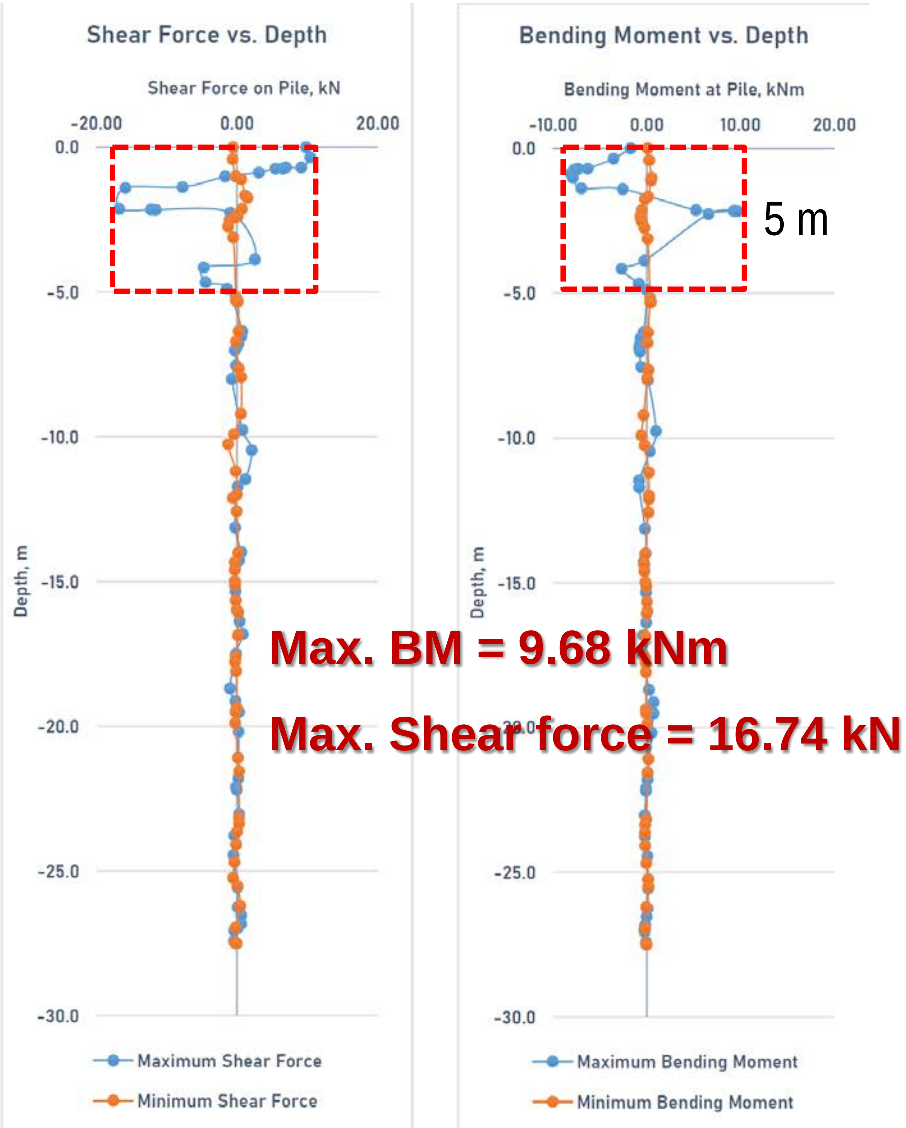






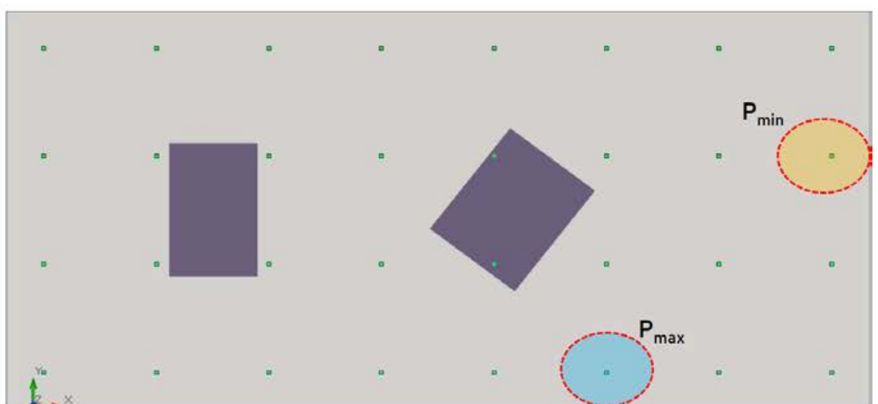


Maximum and minimum Bending moment and Shear force along the pile

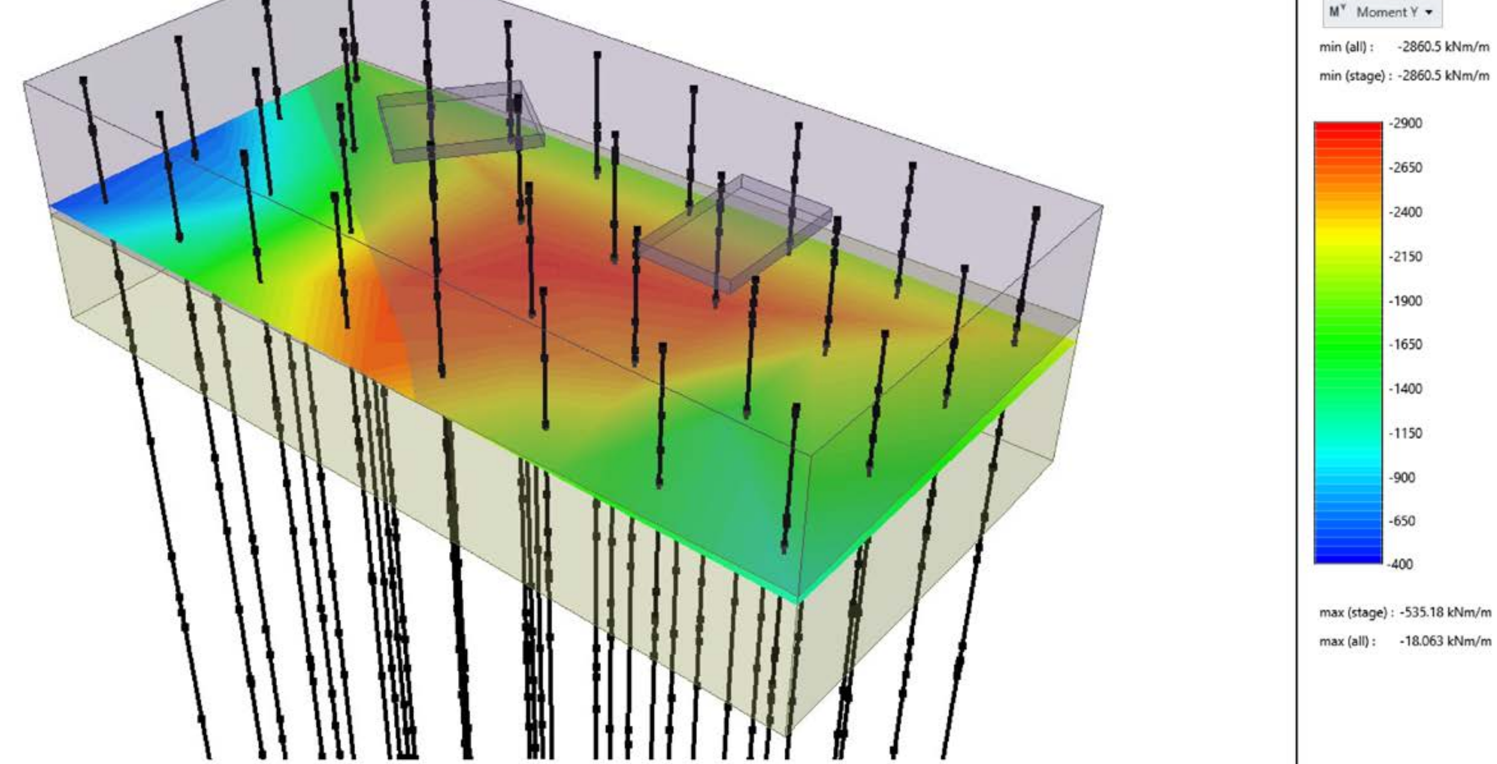


Max. BM = 9.68 kNm

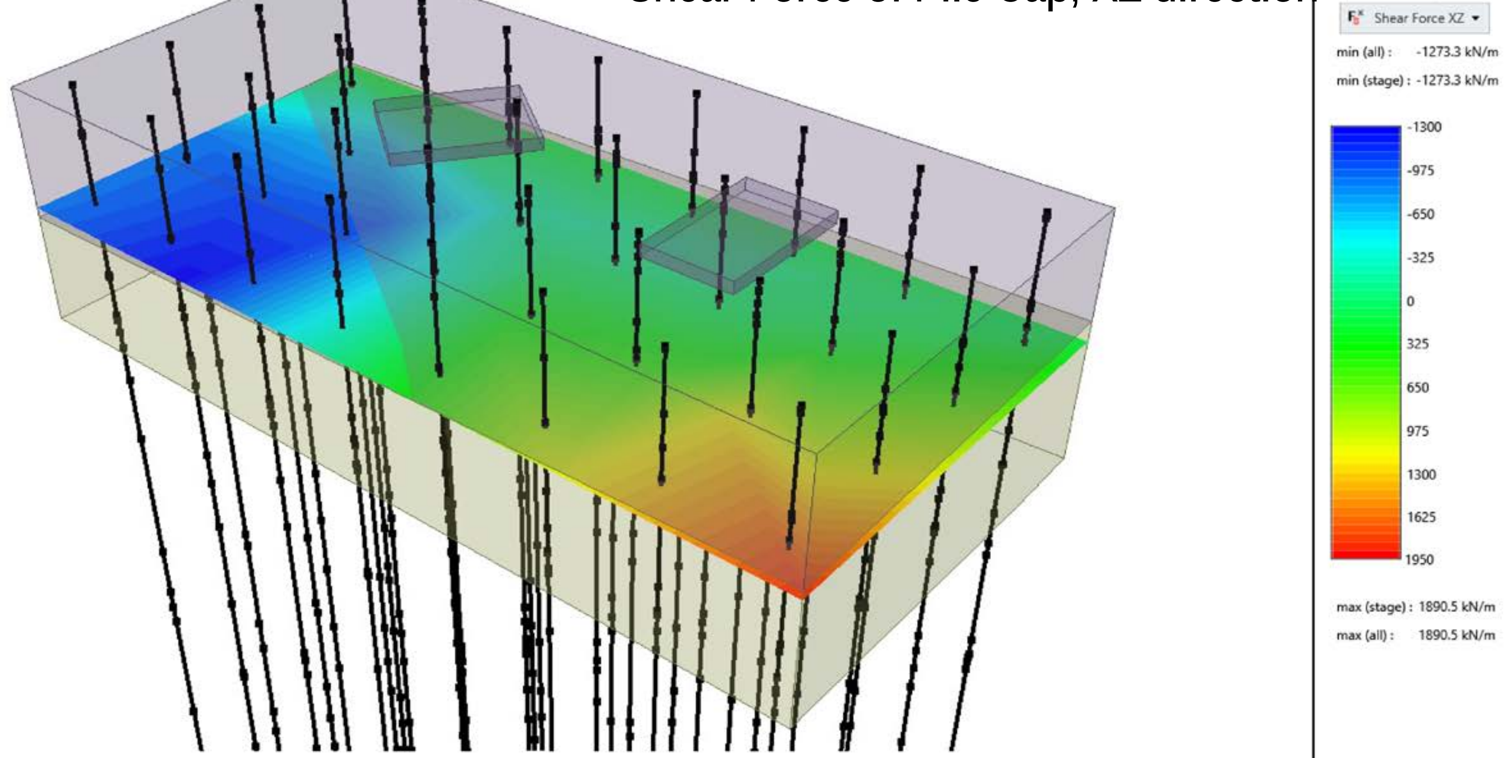
Max. Shear force = 16.74 kN



Moment of Pile Cap, Y direction



Shear Force of Pile Cap, XZ direction



Case Study-5

Pile Capacity and Settlement in Design Limit

Pile Capacity and Settlement:

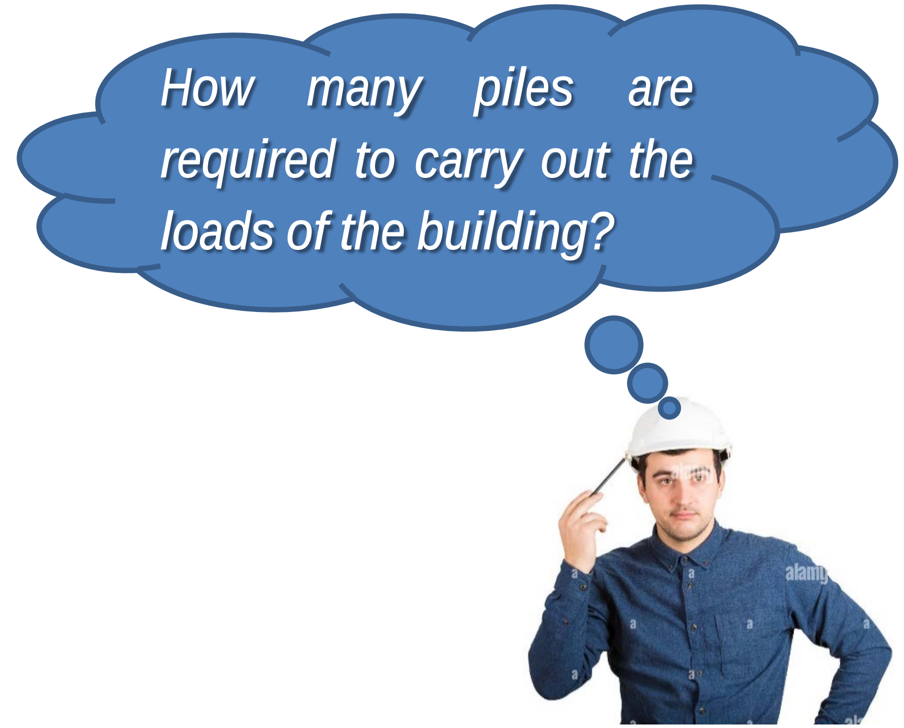
1. Traditionally, Engineers engaged in a pile group design have asked themselves.

How many piles are required to carry out the loads of the building?

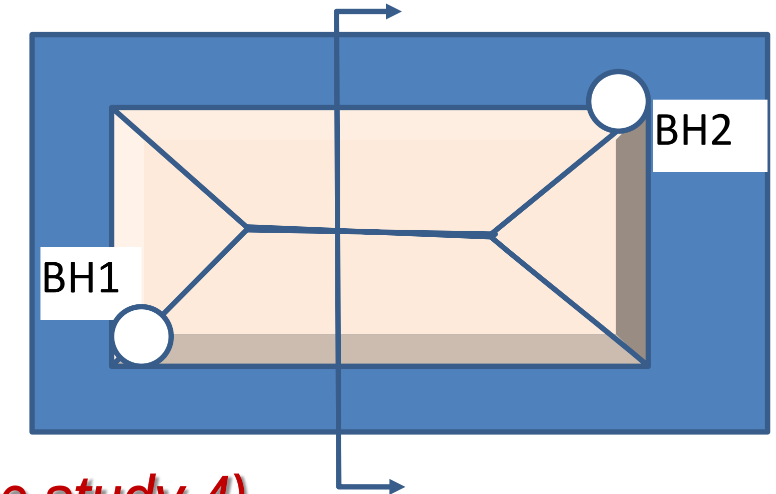
2. When settlement is the controlling factor in the choice of piles, designers should consider the question.

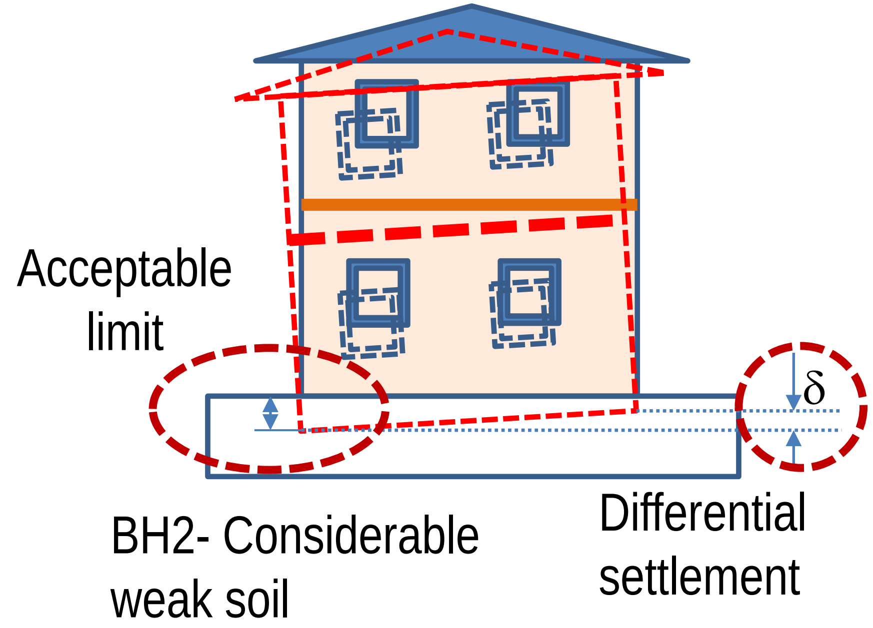
How many piles are required to reduce and/or control the settlement? (Using conventional methods or analysis for pile group settlement).

Still now, ***Capacity-based design*** is used where settlement control is not significant for ordinary building, but more cost and sometimes more or less design life.

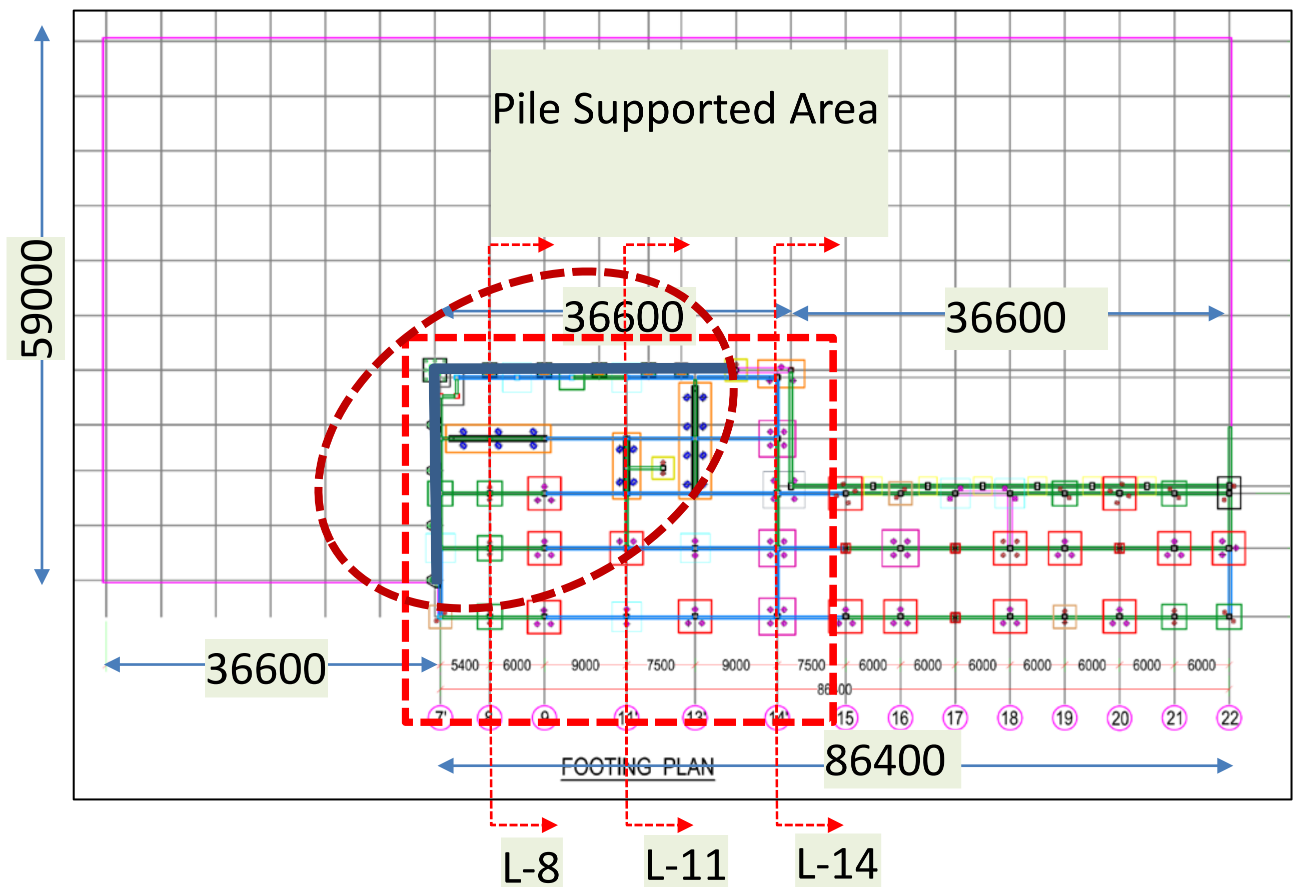


- Wrong Concept of soil parameters on foundation design





- Mistake of foundation design *(Case study-4)*



Connected the Plinth Beam both Pile support and footing

4.2.4.2 Number and location of borings

Site investigation shall be carried out to sufficient extent to establish adequate information for the significant soil strata and ground variation. Location of borings shall be determined by registered geotechnical professional and/or design professional. Number of borings shall be as follows:

1. Minimum of 2 borings for every project.

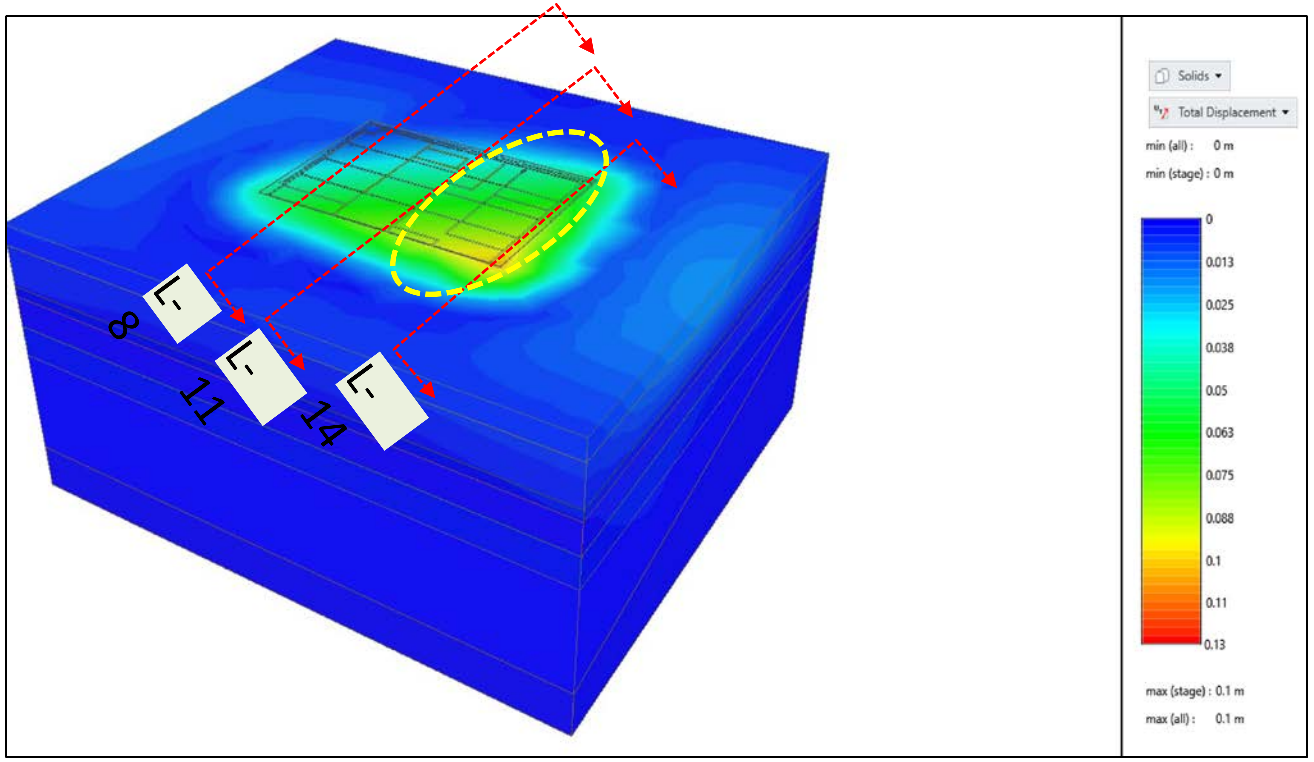
4.7.4.1.1 Design loads

Footings shall be designed for the most unfavorable effects due to the combinations of loads specified in Section 3.2.1. The dead load is permitted to include the weight of foundations, footings and overlying fill. Reduced live loads, as specified in Sections 3.2.3.9 and 3.2.3.11, are permitted to be used in the design of footings.

4.8.12 Settlement analysis

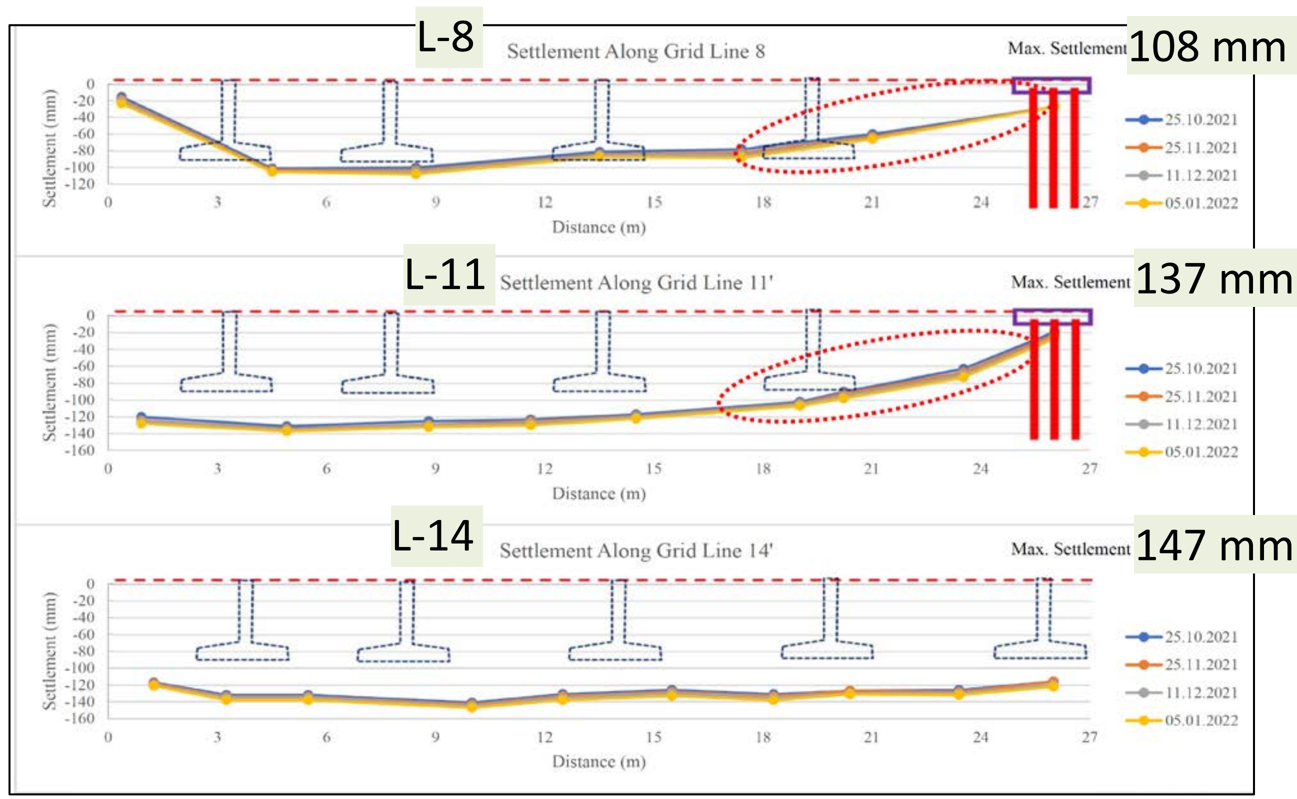
The settlement of piers, individual piles or groups of piles shall be estimated based on approved methods of analysis. The predicted settlement shall cause neither harmful distortion of, nor instability in, the structure, nor cause any stresses to exceed allowable values.

Results of Settlement Analysis (not included construction settlement (primary settlement))



Days	Years	Max. settlement (mm)	Further settlement, mm
400	1.10	78	-
700	1.92	87	9
1500	4.11	99	21
2000	5.48	100	22

Maximum settlement = 100 mm



Technical remarks:

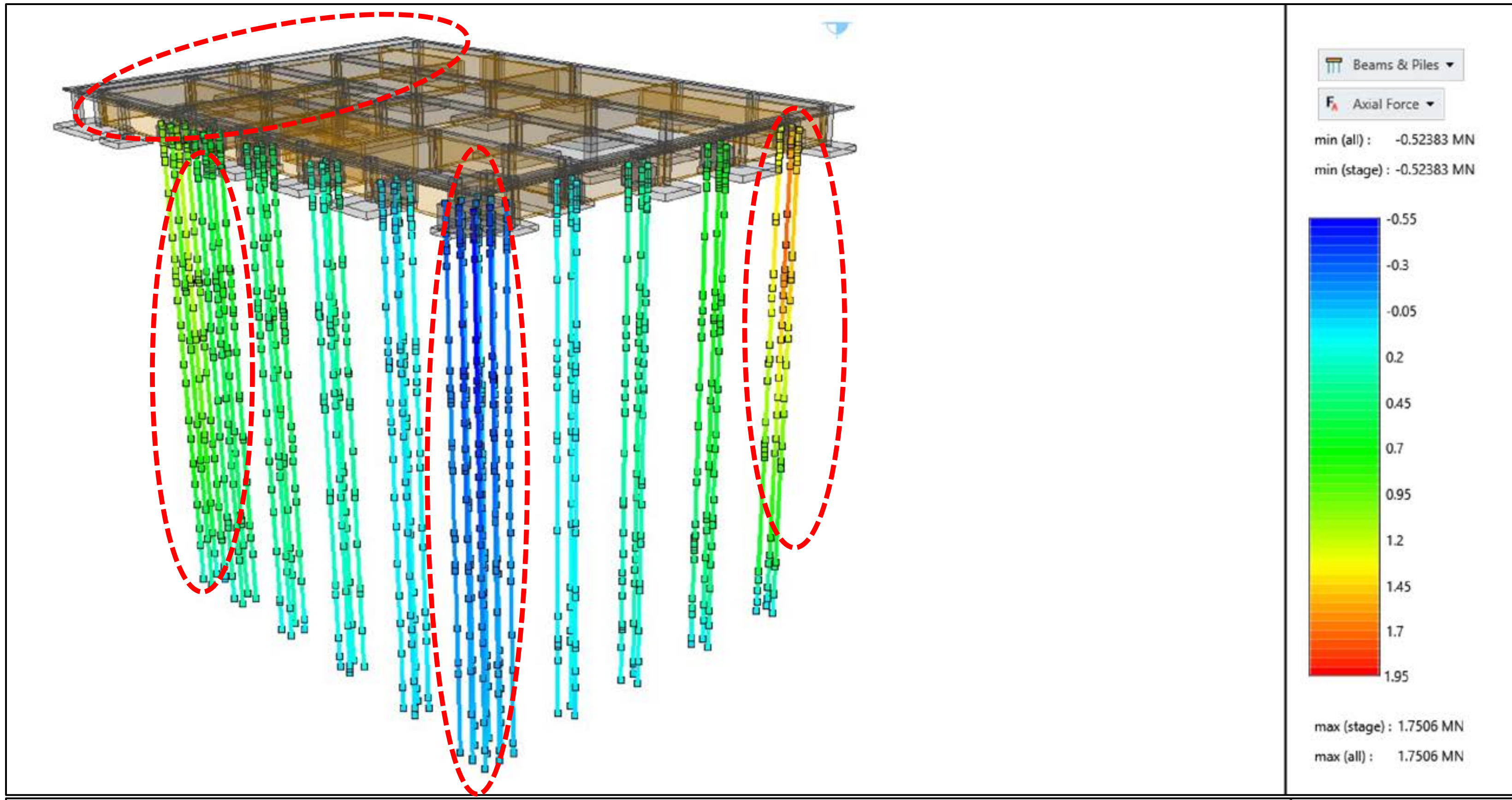
1. Different settlements were occurred due to different stiffness of soil and pile supports.
2. Tension piles have been developed.
3. Higher compression piles were happened due to the unequal settlement.

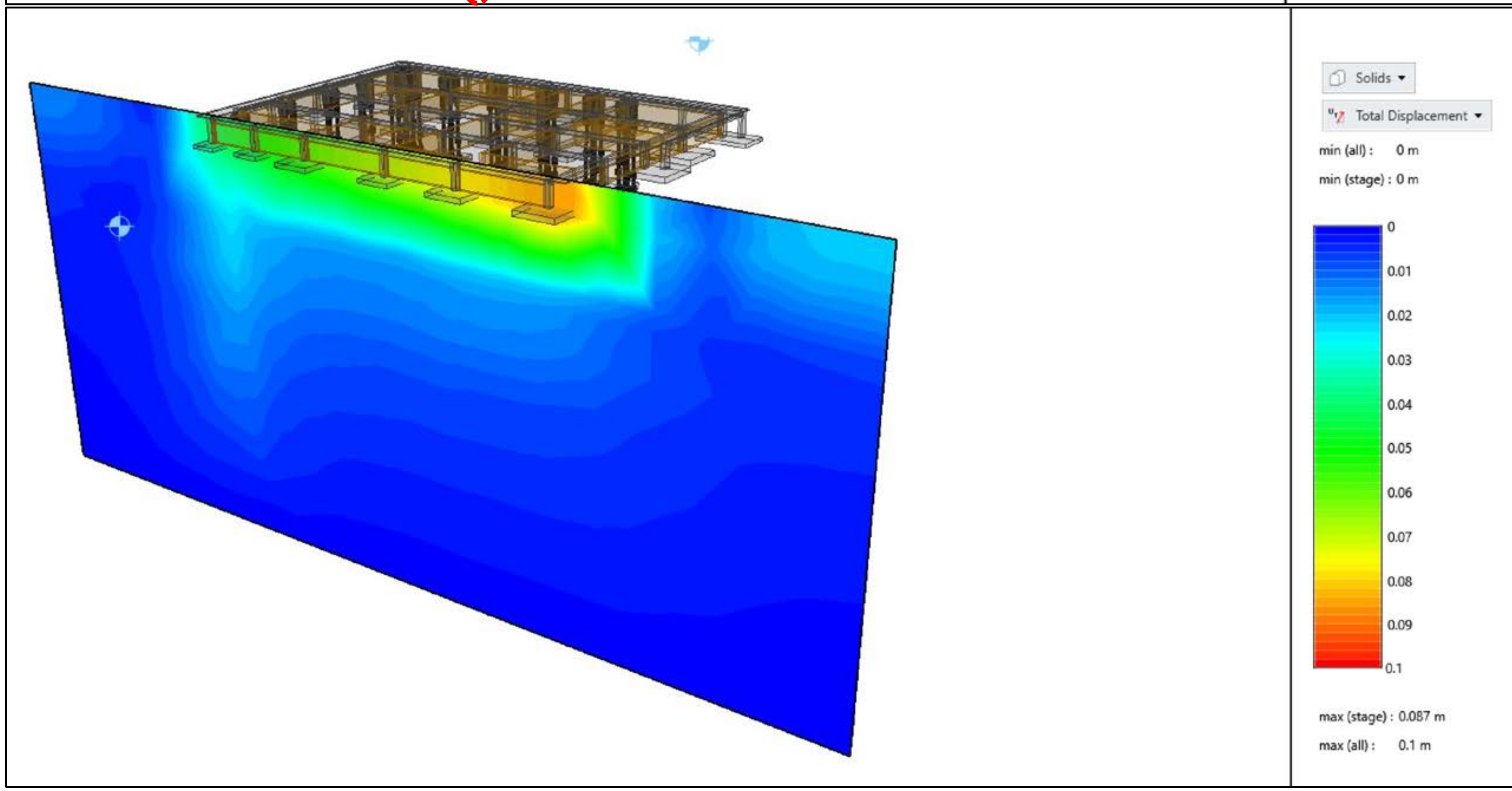
Effects:

1. Excessive distortion settlement was happened near the combination of pile and footing support.
2. Crack were found at the floor and wall.
3. Some of structure members were damaged.
4. The function of doors is disturbed.

Rehabilitation:

1. Prevention of further settlement (ground treated by Jet Grout Column (JGC)
2. All structures and non-structure member are repaired as per analysis results.





Technical Remarks for Design & Construction of Pile foundation (Summarized Note)

Pile foundation type selection should be considered that at least the following basic factors (not limited);

1. Must be designed the required pile size to meet the structural capacities (Axial, Bending and shear), especially for tall and heavy buildings in Seismic prone regions.
2. Must be included the determination of pile length in liquefaction zone and technically feasibility of pilling work to achieve the required capacities.
3. Must be designed to achieve the accuracy of pile capacity assessment for sensitive buildings.
4. Must be considered for construction issues (for ex. If the building included the basement construction except open basement excavation method)
5. Must be analysed properly for soil conditions (For ex. Very stiff soil, very dense soil, Block in Matric (BIM) soil, displaced pile has some limitations and may be damaged or deviated the piles during pilling work).
6. Must be considered the environmental factors.

4. Technical Aspects of Pile Installation

(Construction)

2. Construction Phase

General Technical Aspects of Driven/Pressed Piles Installation

1. Knowledgeable construction supervision and inspection is the key to proper installation of piles. State-of-the-art designs and detailed plans and specifications must be coupled with good construction supervision to achieve desired results (piling sequence, piling method etc.).

2. According to technical requirement, the pressed pile depth shall be fulfilled the pile predetermined pile depth (result of static load test pile). Note: in some countries- some percent of allowable limit is adopted based on past experiences.

3. Post construction review of pile driving results versus predictions regarding pile driving resistances, pile length, field problems, and load test capacities is essential.

4. It must be clearly understood that *the static analysis based on the subsurface exploration information usually has the function of providing an estimate of the pile length prior to going to the field*. The final driving criterion is usually a load and holding time that is established after going to the field and the individual pile penetrations may vary depending on the soil variability.

5. *Pile driveability for pressed pile is a very important aspect of the process and must be considered during the design phase*. If the design is completed, a contractor is selected, and *then the piles cannot be driven, large costs can be generated*. It is absolutely necessary that the *design and construction phases be linked in a way* that does not exist elsewhere in construction.

Pile driveability

Pile driveability depend on:

1. Characteristics of soil layers (Physical properties such as texture, structure, porosity, density, consistence, aggregate stability, Soil type)
2. Dynamic stiffness of soil (Dynamic stiffness of soil > Static stiffness)
3. Densify due to pile layout pattern

Before final design, three methods used to evaluate pile drivability which include:

1. Wave equation analysis
2. Dynamic testing and analysis
3. Static loads tests

Pre-boring Method

Pre-bored method is used for following matters:

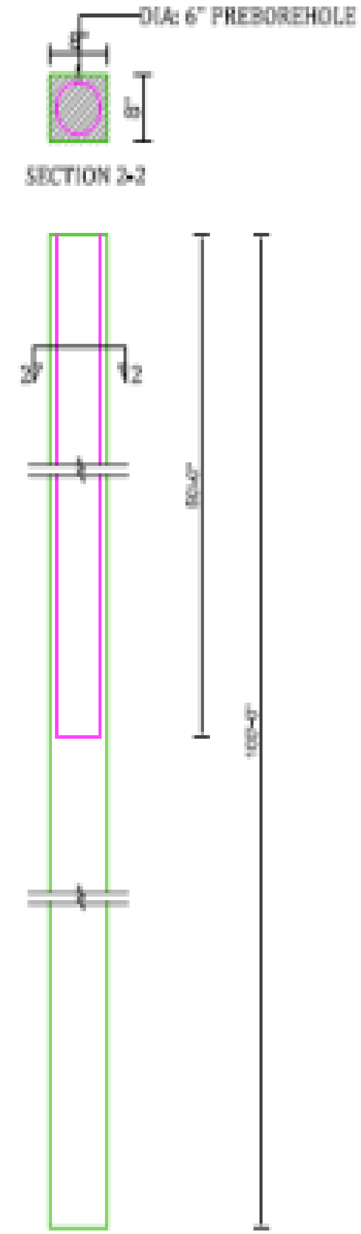
a. To assure the pre-determined depth of pressed pile.

b. To prevent the soil movement and vibration effects on environment

c. To prevent the disturbed on soil properties around the piles.

Specification:

1. For large ground heave or movement will be occurred due to press piling. Therefore, pro-boring method should be used for this condition.
2. In order to achieve the effectiveness of skin friction of piles, the size of pre-bore shall not be larger than the predetermined pre-bored size *(less than 70% of pile size area).*
3. Pre-bored length should be determined based on soil porosity, required load and depth.



DETAIL OF PRE-BORING AND PRESS PILING

Pre-bored size and length

Factors Affecting Skin Friction during Bored Piles Installation

- Reduction in friction angle
  - ✓ Presence of weak materials at pile/soil interface (e.g. bentonite filter cake)
  - ✓ Loosened/disturbed soil
  - ✓ Slaking on bore hole wall
- Reduction in confining stress in bored piles
  - ✓ Stress relief
  - ✓ Arching effect
  - ✓ Loosening of soil due to poor construction control
- Construction Time

1. Technical Aspects for QA/QC during pile construction

In the View of Changes of Geotechnical Design Parameters

O'Neill (1999) found that details of pile installation can produce resistances that differ by ***a factor of 3 to 10***.

1. Stress relief
2. Moisture migration from the concrete to the geomaterial
3. Borehole roughness
4. Borehole smear

← Geological conditions (Engineering geological data and geotechnical data)

Construction drilling fluids

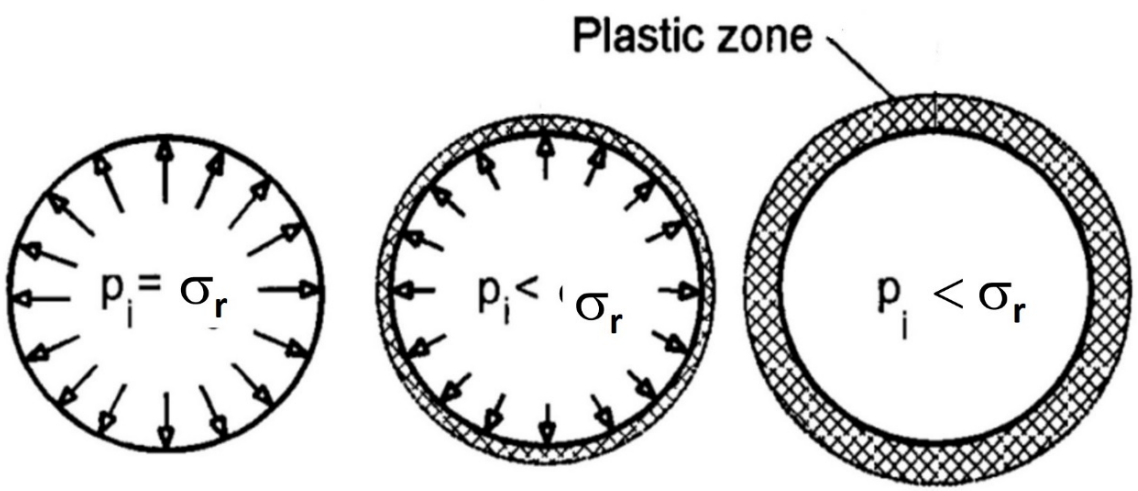
←
1. Excessive filter cake from bentonite mineral slurry
2. Synthetic polymer drilling fluids (hydrolyzed polyacrylamide)

Temporary casing

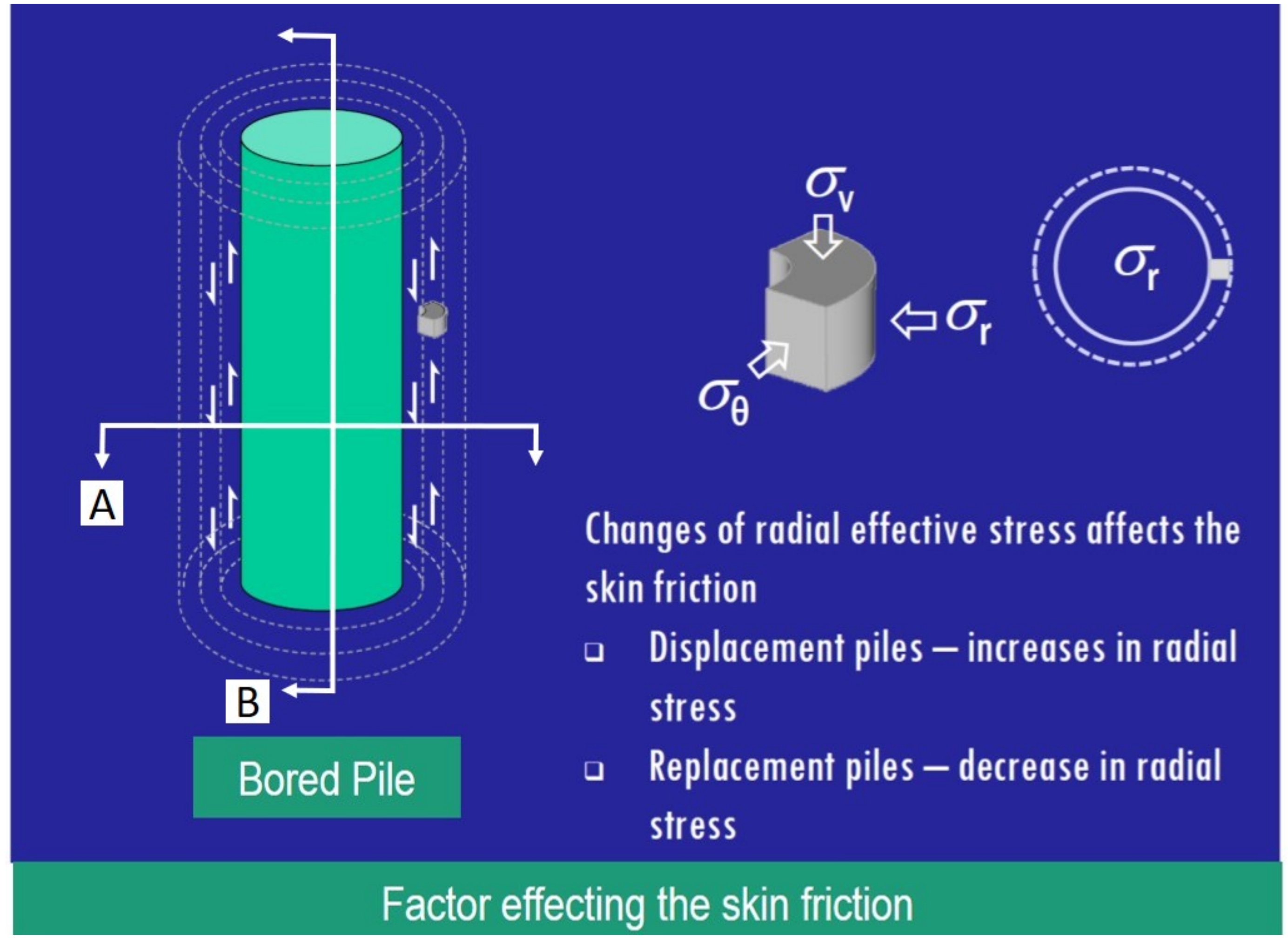
←
1. Tendency for higher in situ lateral stresses and/or densification from installation of the casing in advance of excavation in cohesionless soil.
2. However, significantly reduced side shear capacity for piles constructed using casing advanced ahead of the excavation in a cohesive soil due to a reduction in sidewall roughness (hydrolyzed polyacrylamide)

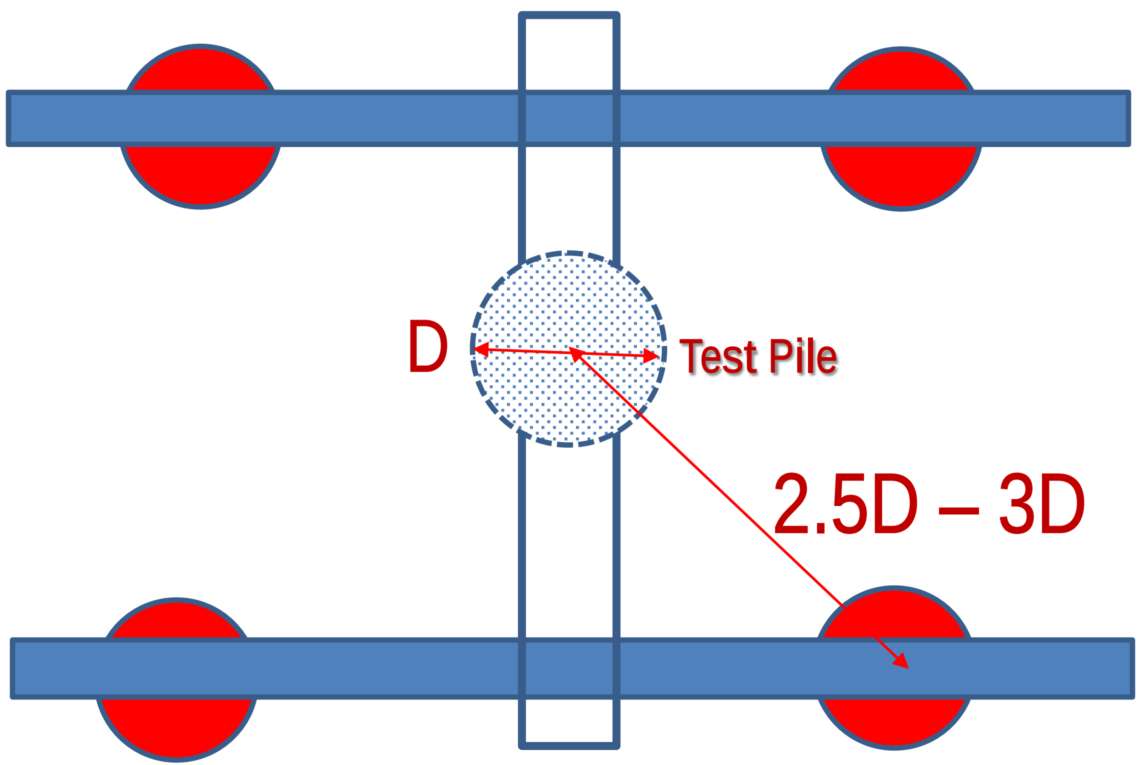
Soil/concrete interface immediately adjacent to the Bored Pile

Effect of clear spacing on pile capacity in pile load test



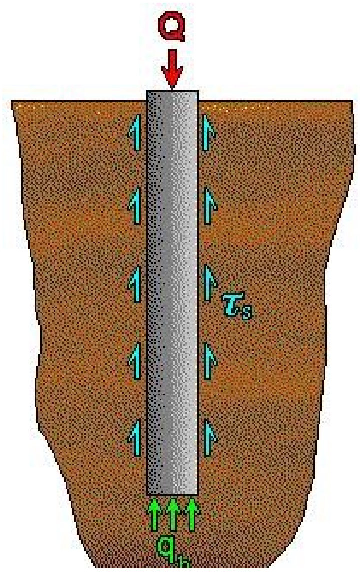
Section-A

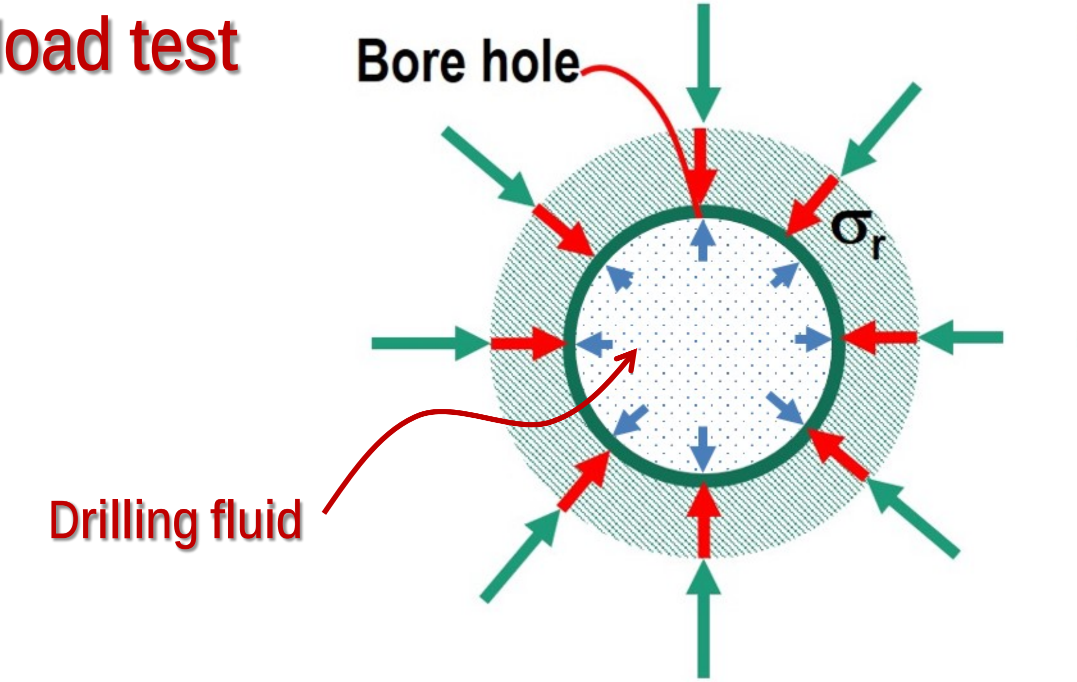


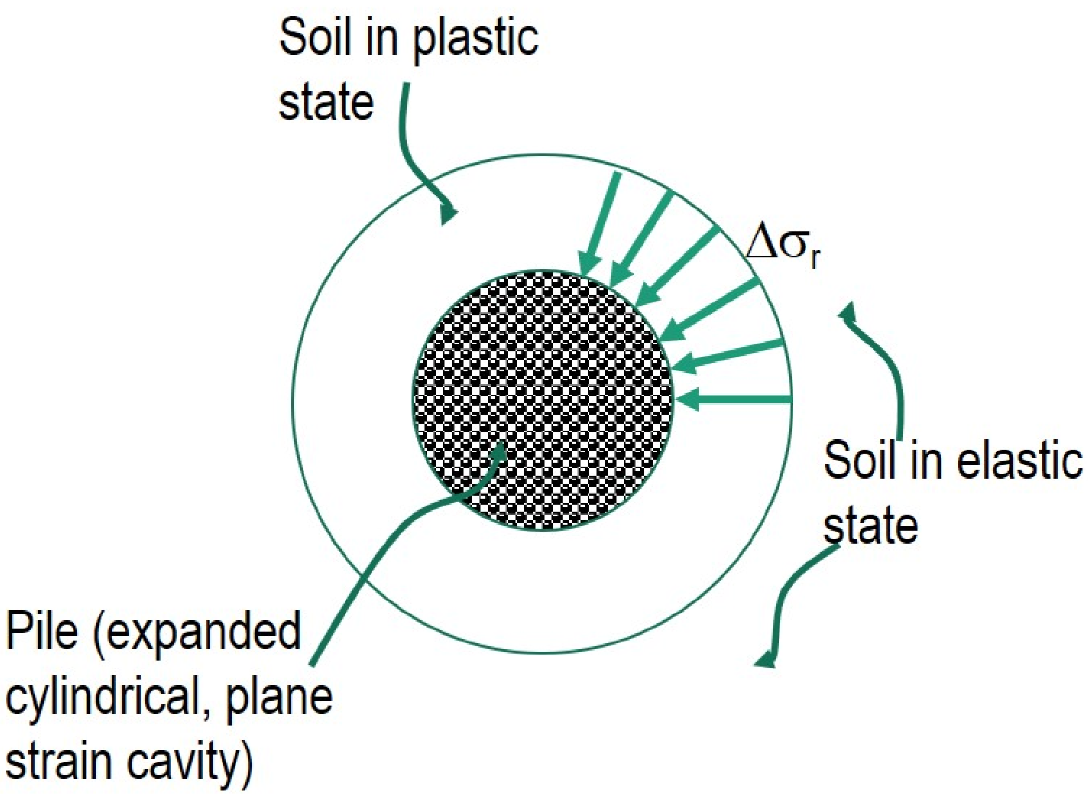


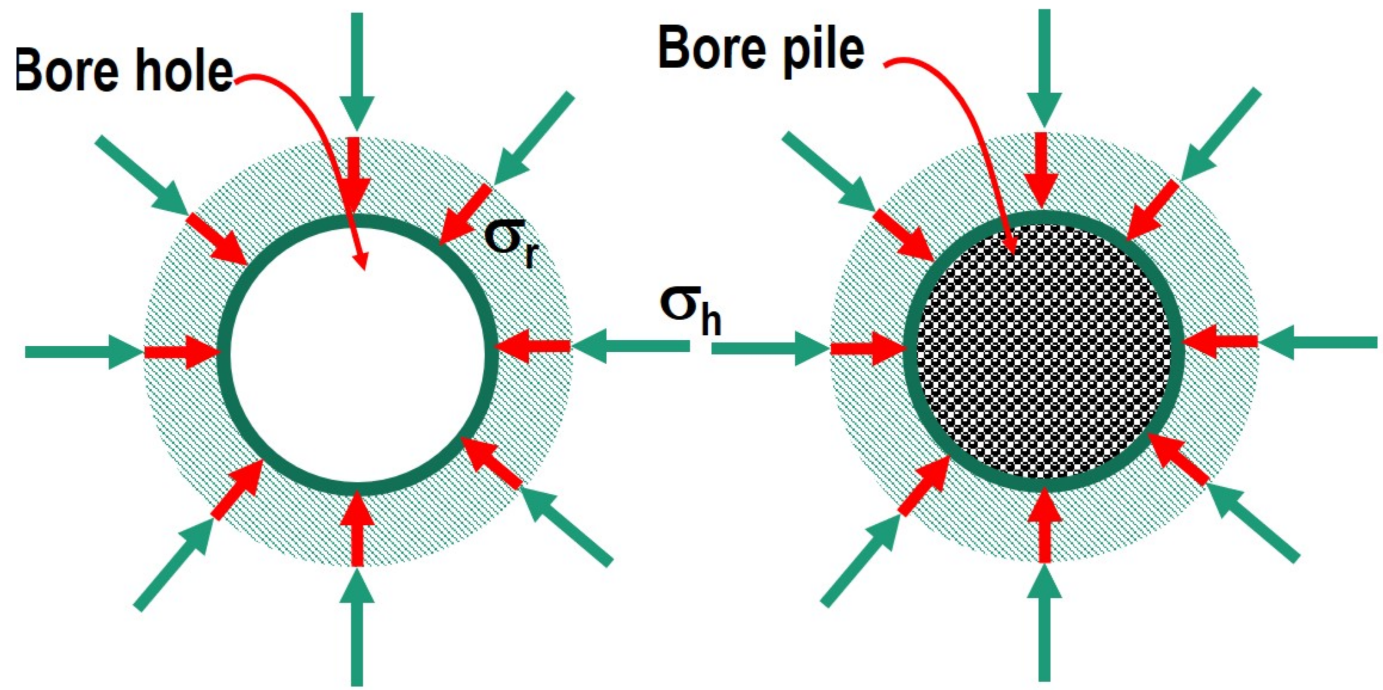
Pile Load Test

Effect of clear spacing on pile capacity in pile load test



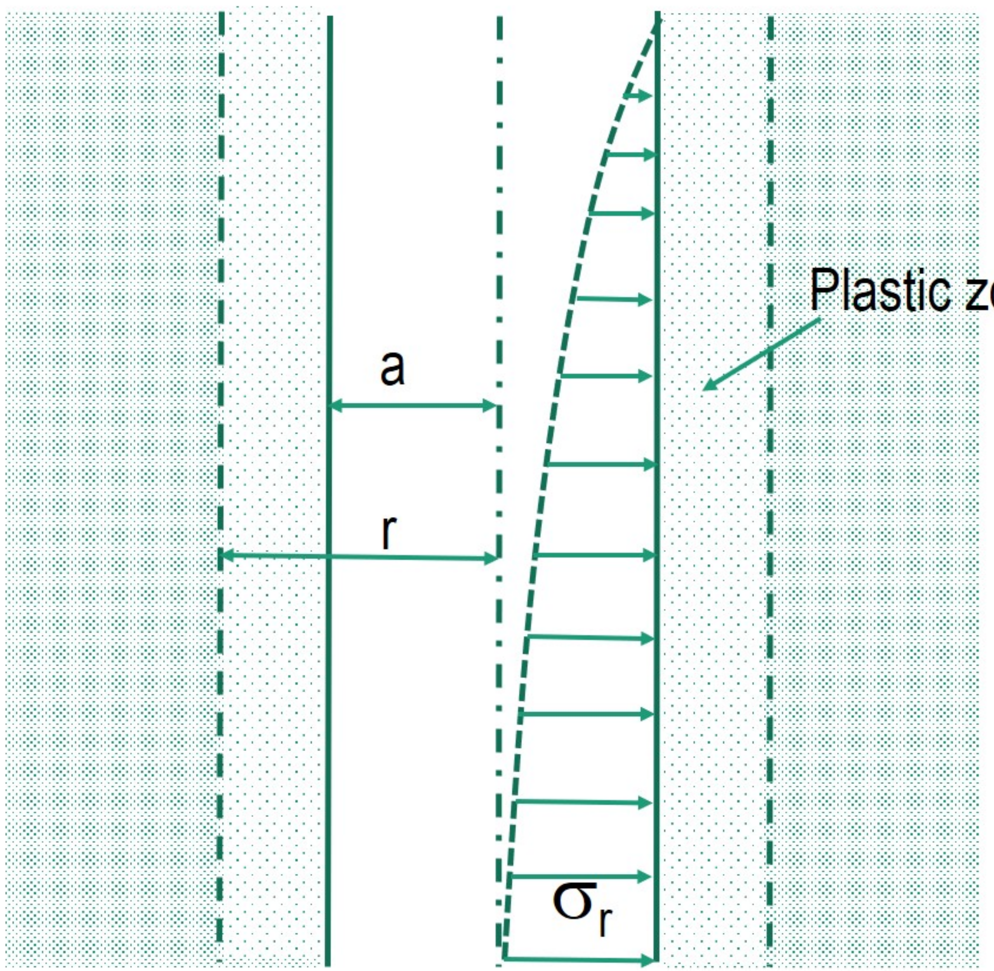


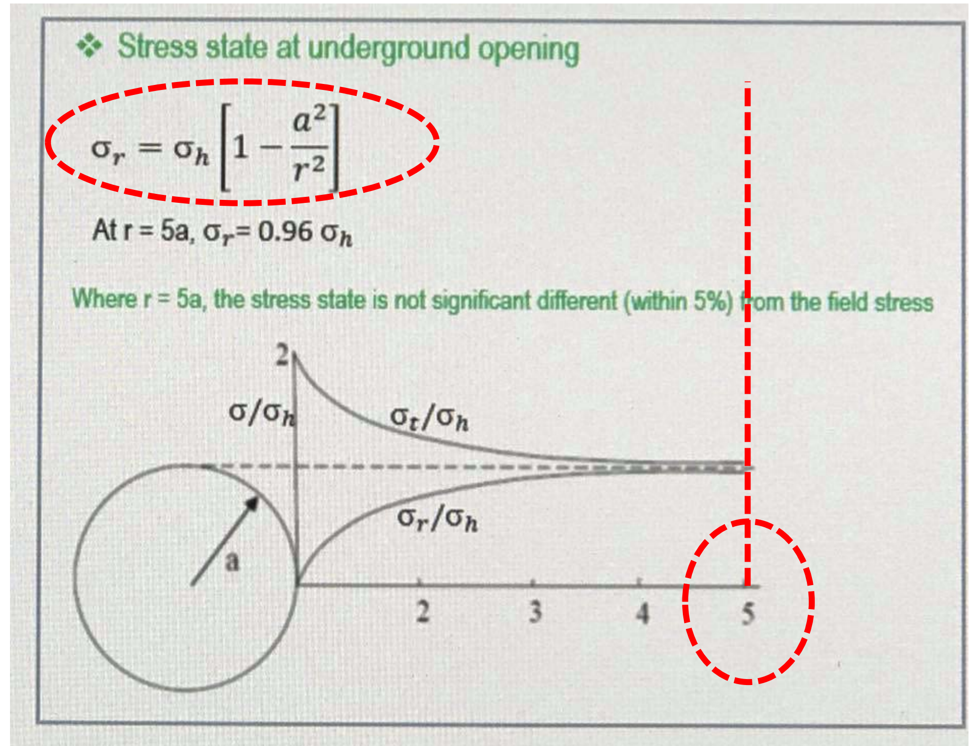




Stress relief or deformation of soil around bore hole

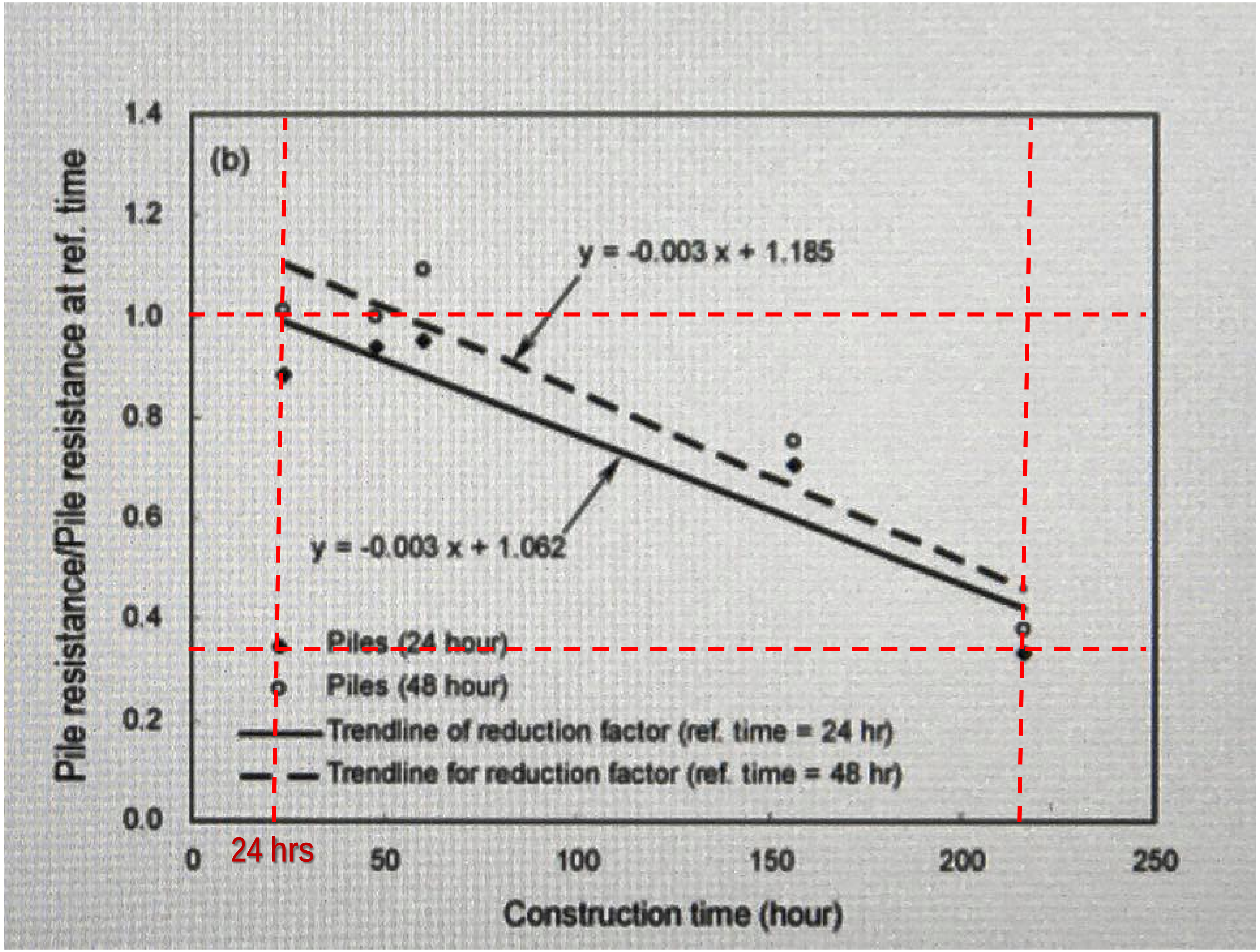
Effect of clear spacing on pile capacity in pile load test





No.	Clear spacing bet. piles	% of effect on skin friction of bore pile
1	1D	25%
2	2D	12%
3	3D	6%
4	4D	4%
5	5D	0%

Duration of pile construction Vs Pile Resistance

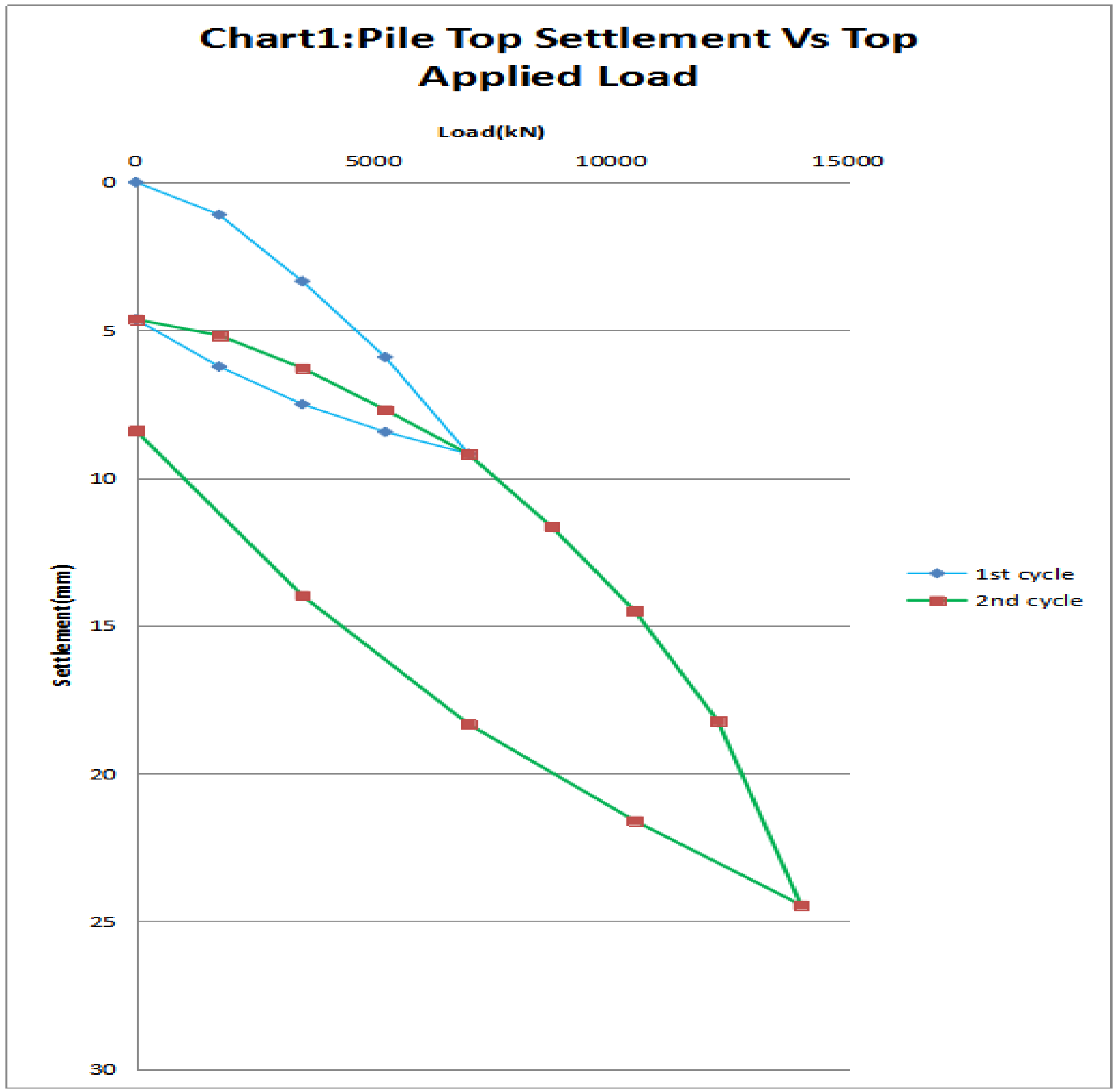


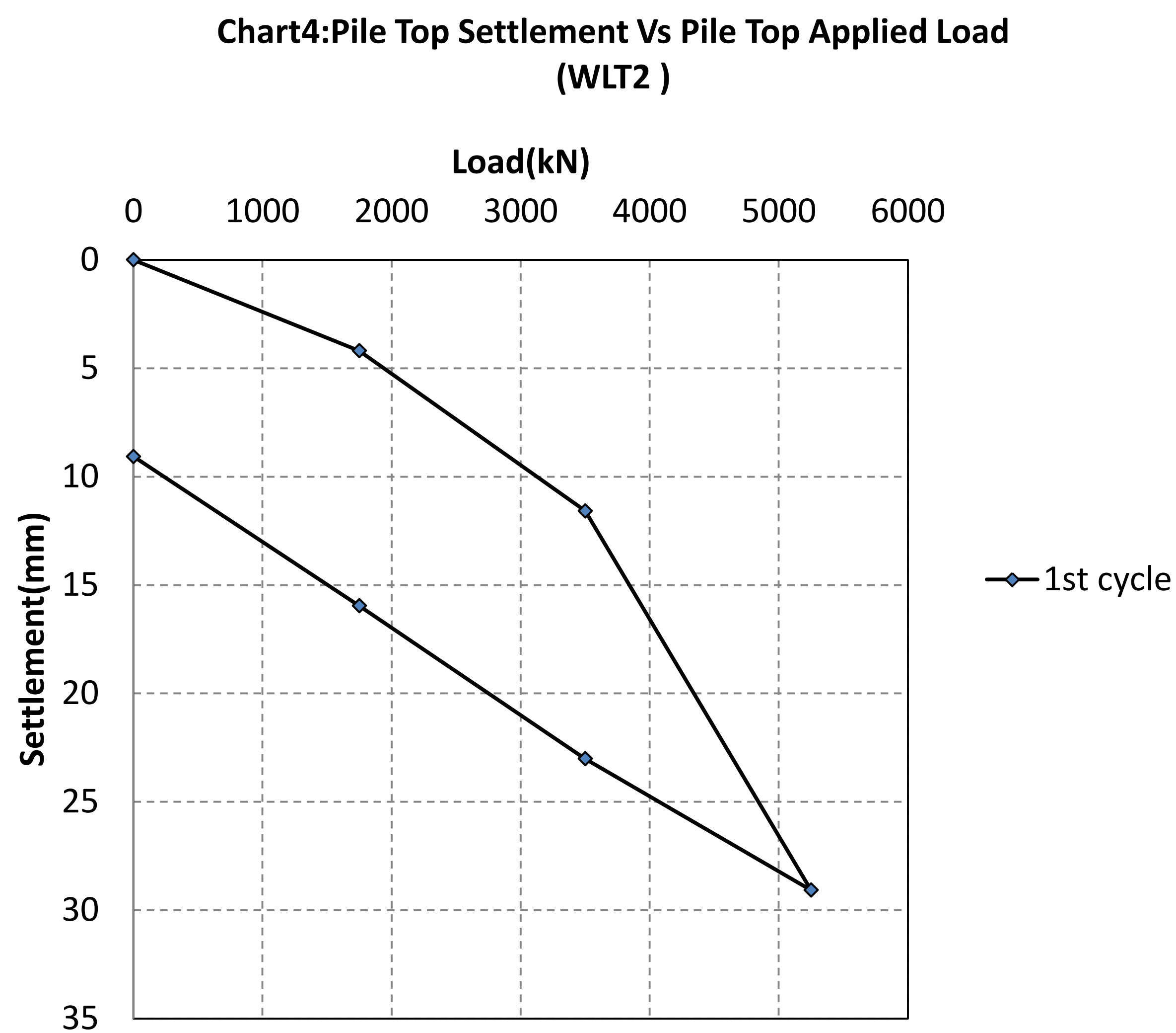
Case Study:

- Two numbers of working pile load tests at a site
- Working Load = 7,000 kN

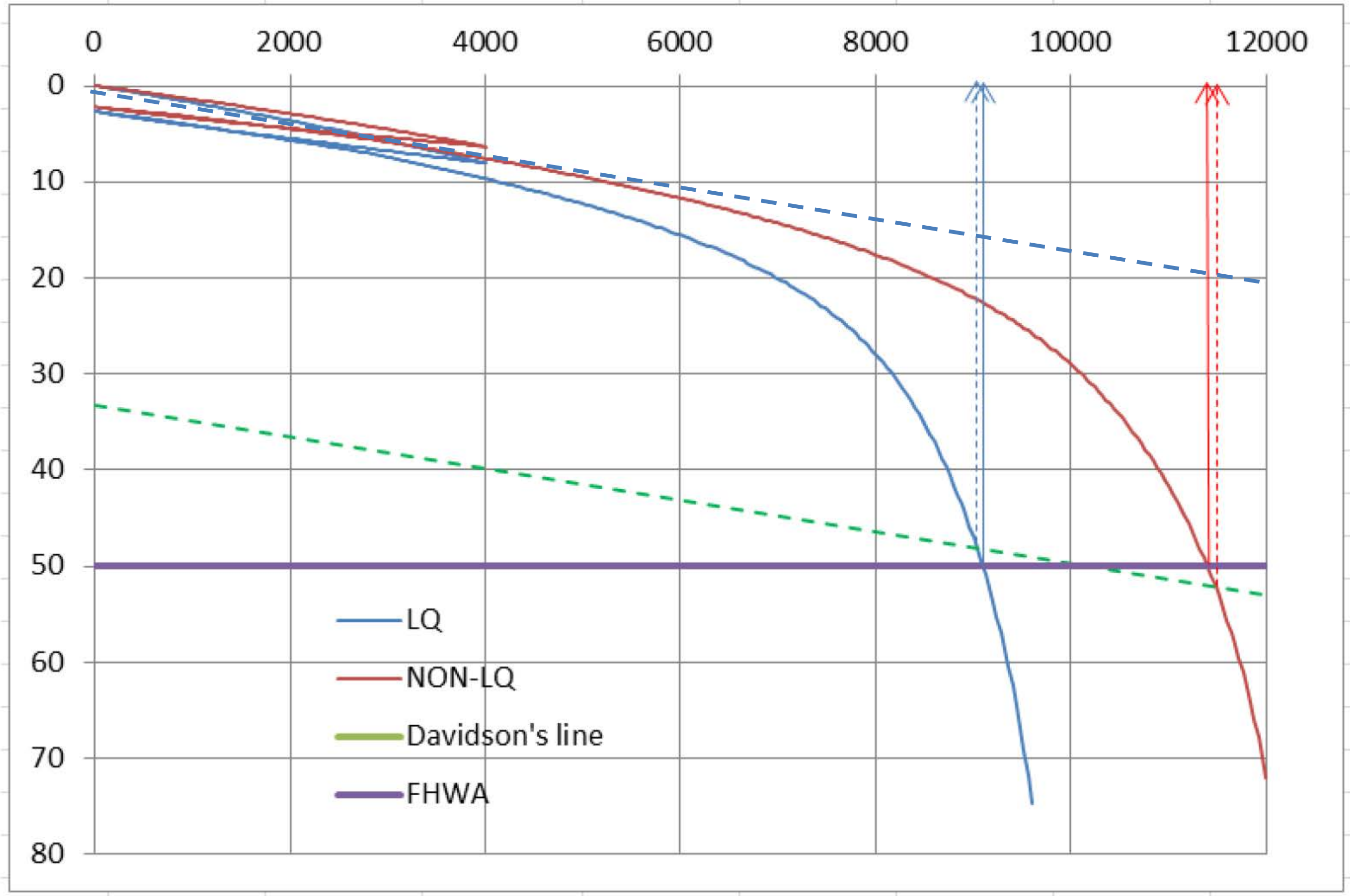
Load test failed

- Construction time – 36 hours
- Not proper base cleaning
- Borehole smear





Evaluation of Safety Factor for Test Results (Non-testing piles with/without Liquefaction)



Case Study:

1. Using Davidson's method (intersection of simulated curve with line, S = PL/EA + D/30)
2. FHWA method – Sec. 2.3.4 LRFD for Deep Foundation (Load at S = D/20 = 50 mm)

Minimum nominal pile capacity shall be 9000 kN in case of LQ and 11170 kN in case of NON-LQ, resulting in the safety factor of FS = 9000/4000 = 2.25 in case of LQ, and 2.79 for NON-LQ .

Remark: Davidson's method intersection may change according to modification.

Method for estimation of pile capacity from static load test

Nominal pile capacity can be determined from two following methods

Method 1: AASHTO-2012, Sec.10.7.3.8.2

Case 1: D≥900mm: Load at settlement of PL/EA + D/30

Case 2: D≤600mm: Load at settlement of PL/EA + D/120+4mm (1973)

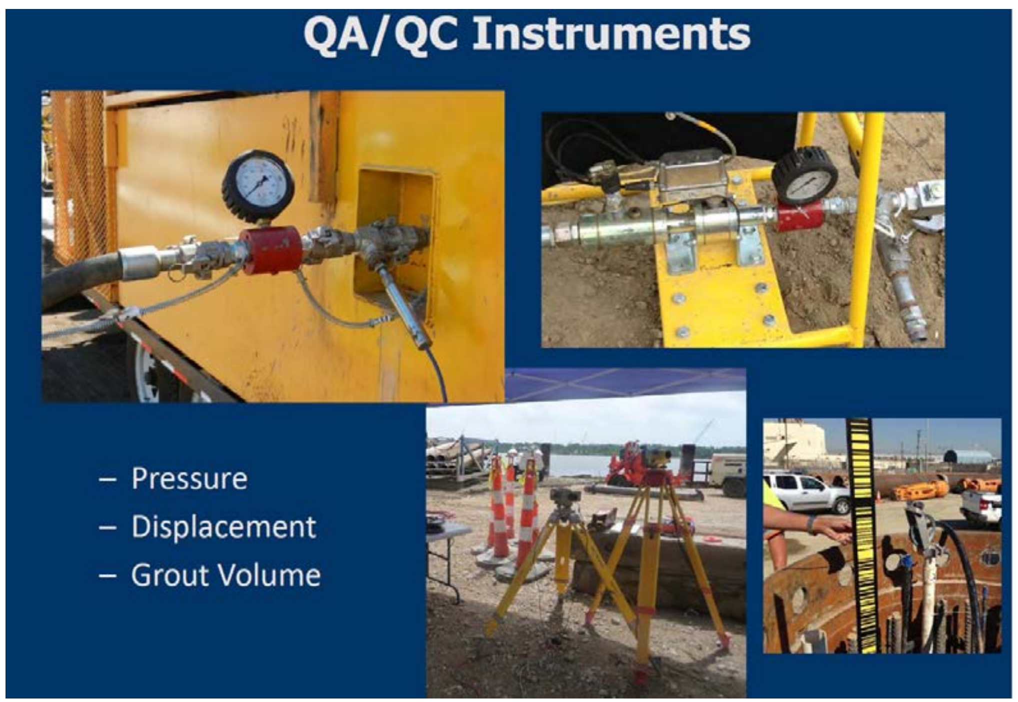
Case 3: D=800mm: Load at settlement of PL/EA + D/1240+4/3mm

2. QA/QC for Acceptance criteria of post-grouted piles

The criteria to be determined during post-grouting are:

1. Grout pressure,
2. Bore pile uplift (*Vertical displacement of pile top, 3 mm – 6 mm or according to results PLT test)*, and
3. Grout volume

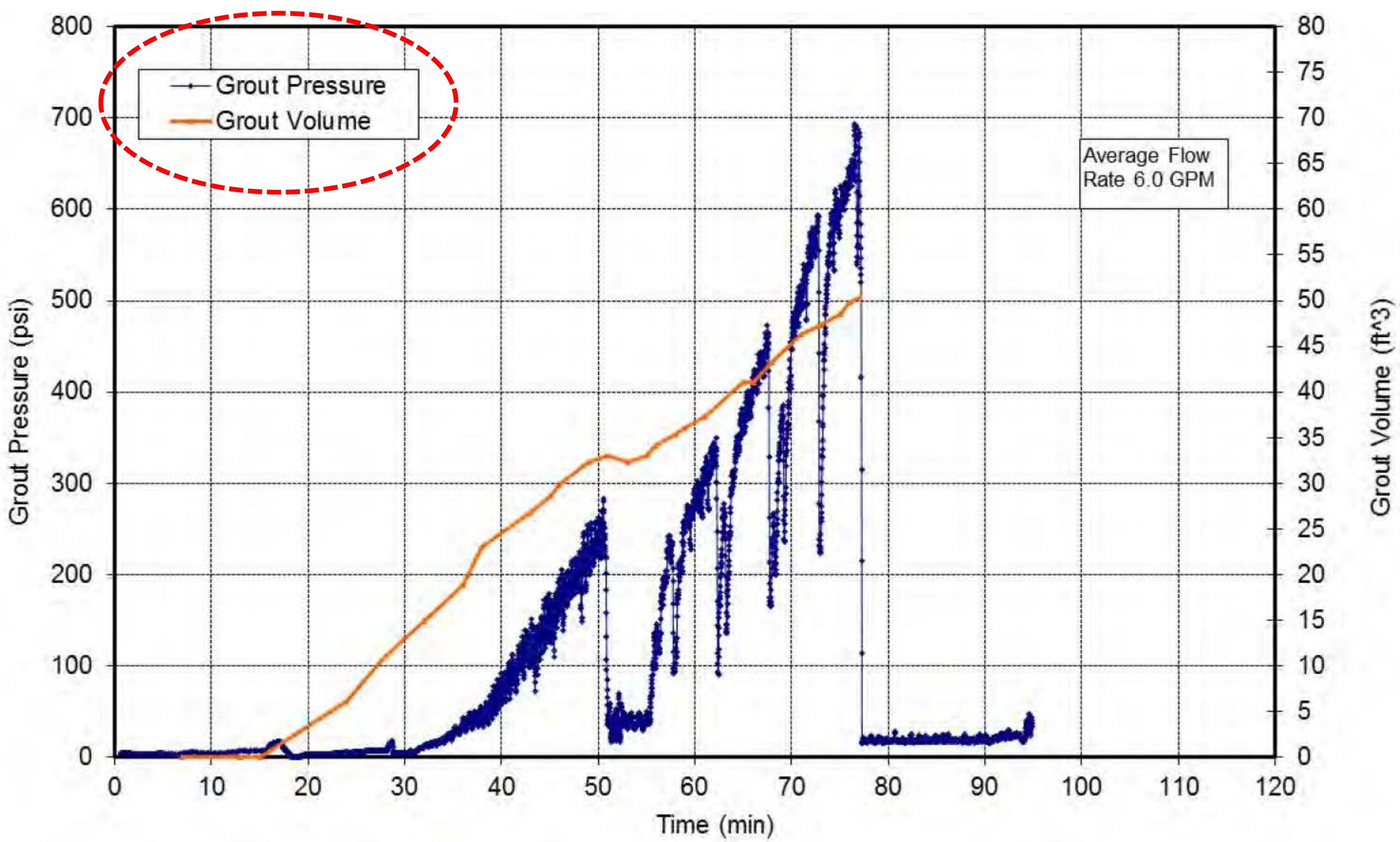
- Parameter monitoring trends must be stable during post-grouting.
- If grout pressure and shaft uplift criteria are met, the post-grouting work should be acceptable.



QA/QC Measurements during Grouting

- **Grout Pressure**
- **Upward displacement**
- **Grout Volume**
- **Strain gauges (optional)**
- **Multi-Axis plots (Real time monitoring)**
- **By experienced person who can interpret data in the field and make decision immediately**

Grout Pressure and Grout Volume



Grout Mix Design:

- Portland cement and water (no Sand)
- W/C = 0.4 – 0.75
- Admixtures sometimes
- Typical strength requirement, 2000 psi-2500psi
- Sampling and testing as per ACI

5. Reliability Assessment of Pile Foundation

Reliability-based Deep Foundation Design

(Serviceability and Ultimate Limit States)

Modern geotechnical design codes are transferring towards *Load and Resistance Factor Design (LRFD) methodologies*. Where the geotechnical system supports a structure, the load factors are generally determined by the structural codes.

The geotechnical resistance factors, typically determined by *calibration with traditional working stress* (or allowable stress) design, *have yet to be clearly defined in geotechnical design codes*.

Working Stress Design (WSD) method (Allowable Stress Design (ASD))

$$Q \leq Q_{all} = \frac{Q_{ult}}{FS} = \frac{R_n}{FS}$$

Where Q = design load;

Q_{all} = allowable design load; and

Q_{ult} = ultimate geotechnical pile resistance

R_n = resistance of the element or the structure

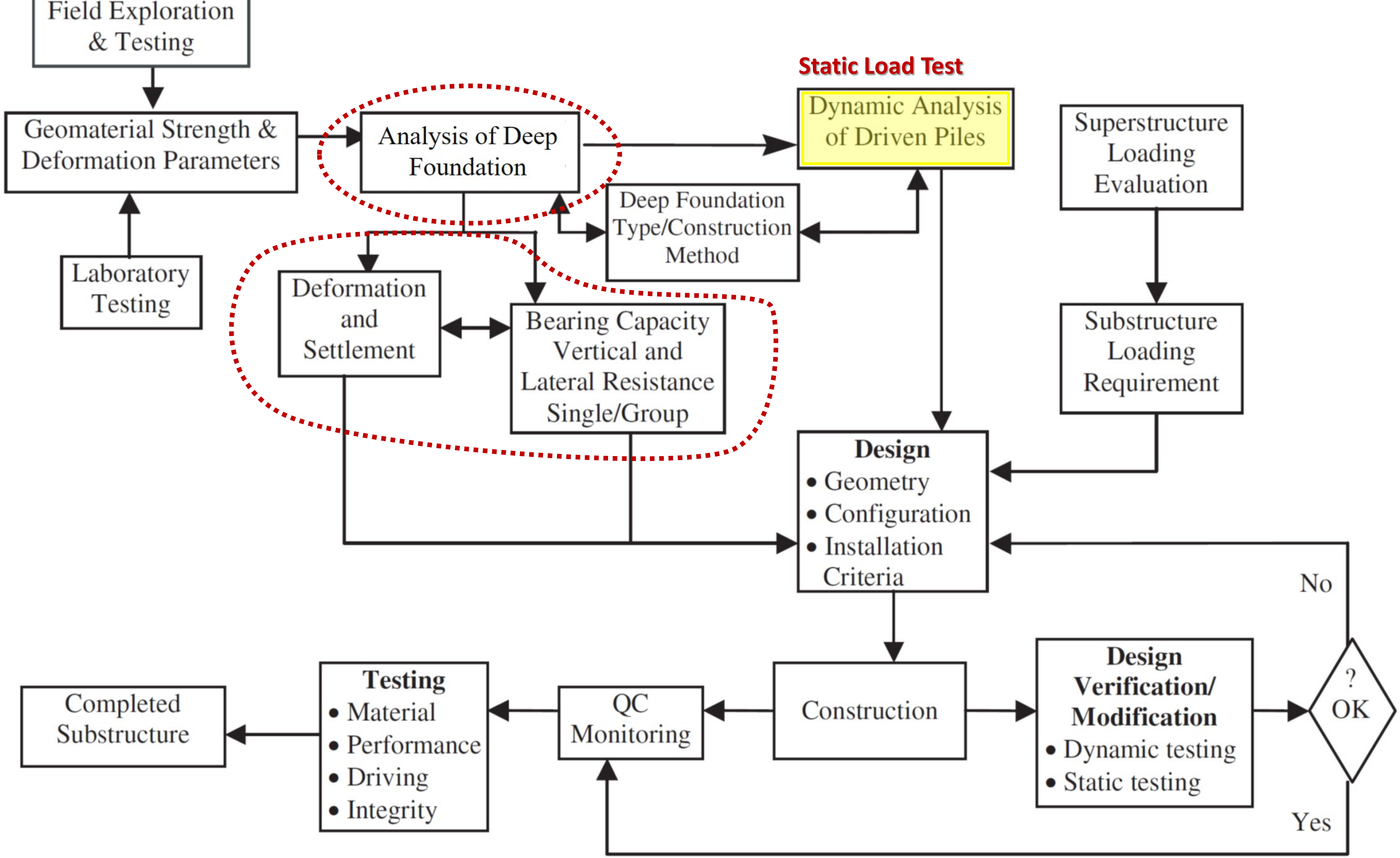
For Ultimate Limit State (ULS), Factored resistance ≥ Factored load effects

For Serviceability Limit State (SLS), Deformation ≤ Tolerable deformation to remain serviceable

1. **Factors of Safety.** Factors of safety represent reserve capacity which a foundation or structure has against collapse for a given set of loads and design conditions. Uncertain design parameters and loads, require a higher factor of safety than required when the design parameters are well known.

2. **Load and Resistance Factor Design (LRFD) is a reliability based design philosophy**, which explicitly takes into account the *uncertainties that occur in the determination of loads and strengths.*

3. **Soil-Structure Analysis.** The functional significance and economic considerations of the structure will determine the type and degree of the foundation exploration and testing program. For critical structures the foundation testing program should clearly define the necessary parameters for the design of the pile foundation, such as soil types and profiles, soil strengths, etc.



Design and construction process for deep foundations

6. Conclusion

Some of the critical aspects of the design & construction process which require coordination are:

1. Evaluation of ***geotechnical data and Geotechnical model*** of subsurface soil layers.
2. Lateral resistance of soil
3. Determination of loading conditions, loading effects, potential failure mechanisms, and other related features of the analytical models.
4. Preliminary and final selection of pile type.
5. Allowable deflections at the ground line and fixity of the pile head.
6. Pile spacing and Pile arrangement.
7. Required pile length and pile capacity (axial, bending and shear capacities).
    a. Maximum stresses during handling, driving, and service loading (for pressed piles, spun pile).
    b. Static Load testing and monitoring programs.
8. Driveability or drillability of the pile to the selected capacity and depth.
9. Appropriate design analysis for the reliability of pile foundation must be required ***for tall, heavy and sensitive buildings, especially in earthquake prone regions.***
10. Technical Management in construction work (QA/QC in ground preparation, piling, concreting etc.)

Thanks all!!

WELCOME AND INVITE YOUR SUGGESTIONS

FOR MY PRESENTATION