Lessons learned from Ground Improvement projects Around the World

Frederic Masse
President
Menard Group USA
fmasse@menardusa.com

Around the world, Geotechnical Engineers face many of the same challenges

Principle 1 :
Owners don’t want to pay for a thorough geotechnical investigation incl. Lab testing -> There’s never enough information

Principle 2 : Terzaghi is our god

$$\sigma = \sigma' + u$$

Principle 3 :

- The three main issues that may lead to the use of deep foundations or ground improvement are :

SETTLEMENT / HEAVE

BEARING CAPACITY

LIQUEFACTION

To deal with these three issues, there are basically three ways :

CONSOLIDATE

Vacuum consolidation

Vertical drains

DENSIFY

Rapid impact compaction

Dynamic compaction

Vibroflotation

STRENGTHEN

Deep soil mixing

Rigid inclusions

Stone columns

Bi-modulus columns

Dynamic replacement

WICK DRAINS

- Band-Shaped plastic strip – Accelerate consolidation of compressible soils


The Art of Wick Cutting
with Jonah
US Wick Drain
Charleston 2016

VACUUM CONSOLIDATION

- Use of atmospheric pressure to simulate surcharge and accelerate consolidation

DYNAMIC COMPACTION

- Free fall of 12-20 tons weights from 50-100 ft for compaction of granular soils

RAPID IMPACT COMPACTION (RIC)

- High Frequency tamping using a 9-12 tons weight


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VIBROFLOTTATION

- High energy vibratory probe using water jets to densify clean sands

CONTROLLED MODULUS COLUMNS (CMC)

- Grouted Rigid Inclusions installed with a displacement tool

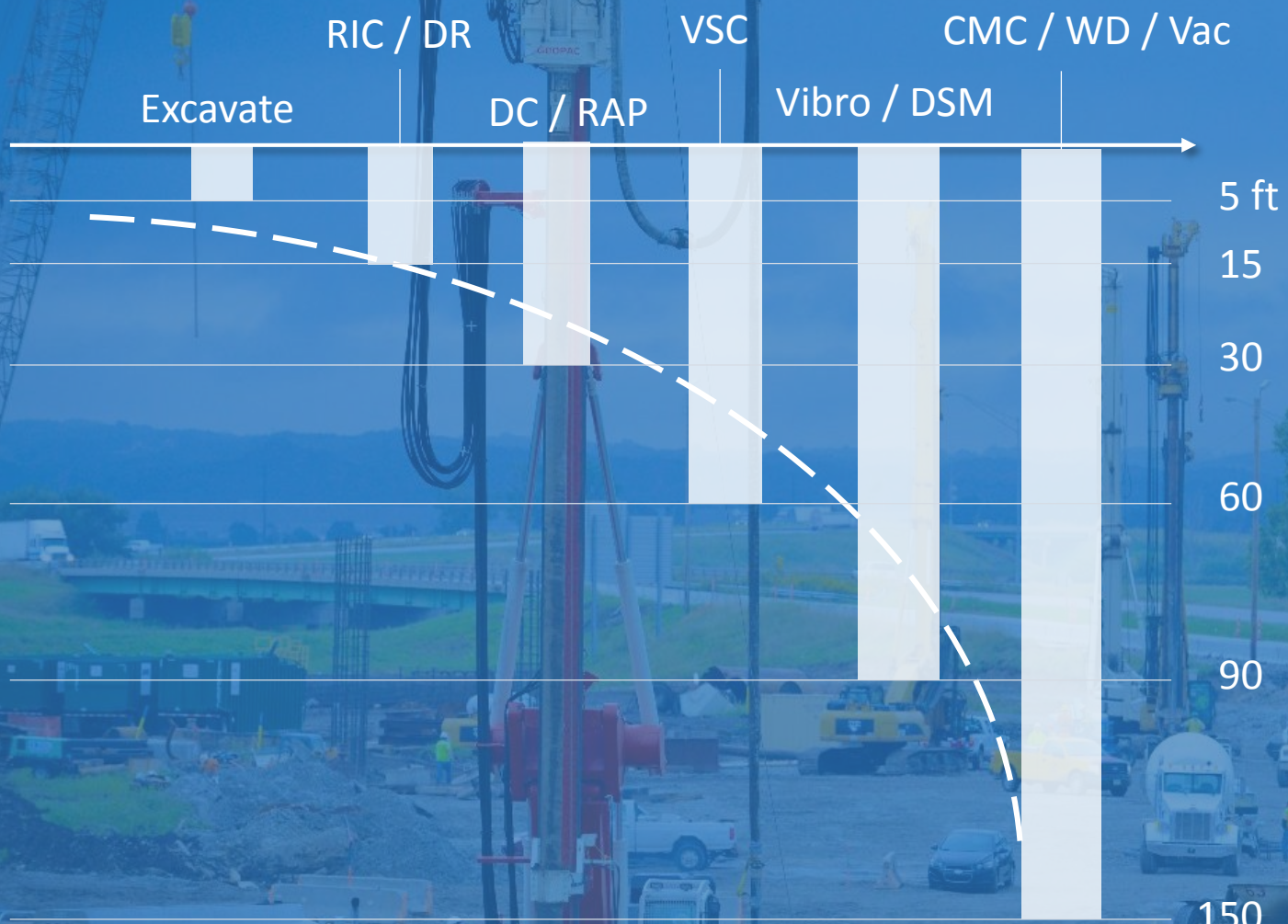
STONE COLUMNS / AGGREGATE PIERS

Columns of Vibrated Compacted Crushed Stone – Seismic mitigation

BI-MODULUS COLUMNS

- Combination of a Stone Column Installed Directly Above a Rigid Inclusion

Influence of local conditions : Depth



Influence of Local Conditions : Soil Type

Peat / Soft Organic Clays	Stiff Clays / Silts	Silty Sands / Sandy Silts	Sand / Gravel
Vacuum / Wick Drains			
	Stone Columns / Aggregate Piers		
	Dynamic Replacement		
		DC / RIC	
			Vibroflottation
	CMC Rigid Inclusions / DSM		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Project : Kimhae & Jangyoo Sewage Treatment Plant

Country : South Korea (Busan)

Summary : New plant in Greenfield with final grade raised several meters and large net new loads

Main Issues to Solve :

- Local condition : deep very soft young deposits (>45M) from NakDong River Valley
- Settlement : predicted long term settlement > 6M over 20 years due to deep soft clays
- Construction period – Fast schedule
- Lack of availability of fill material

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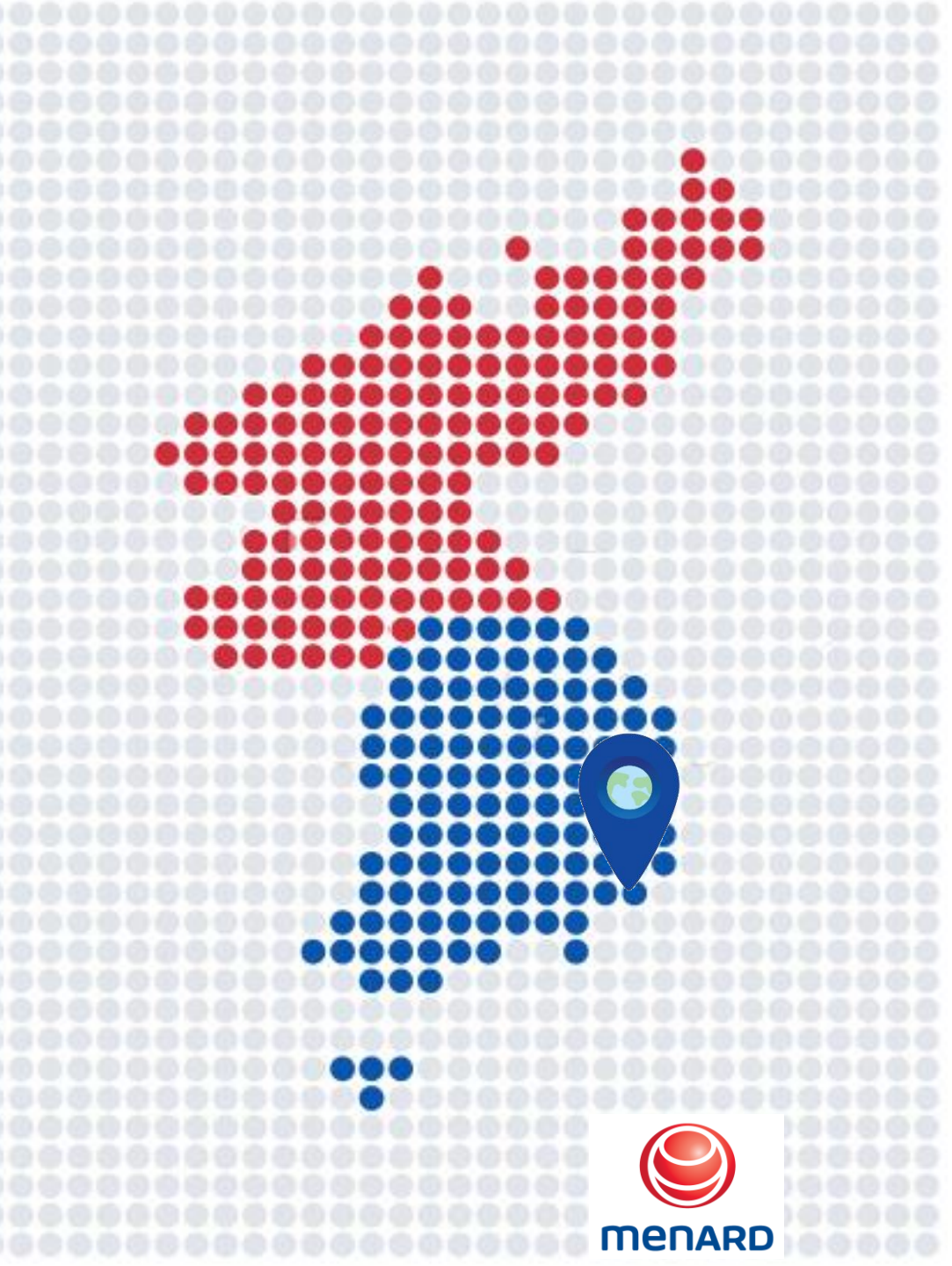
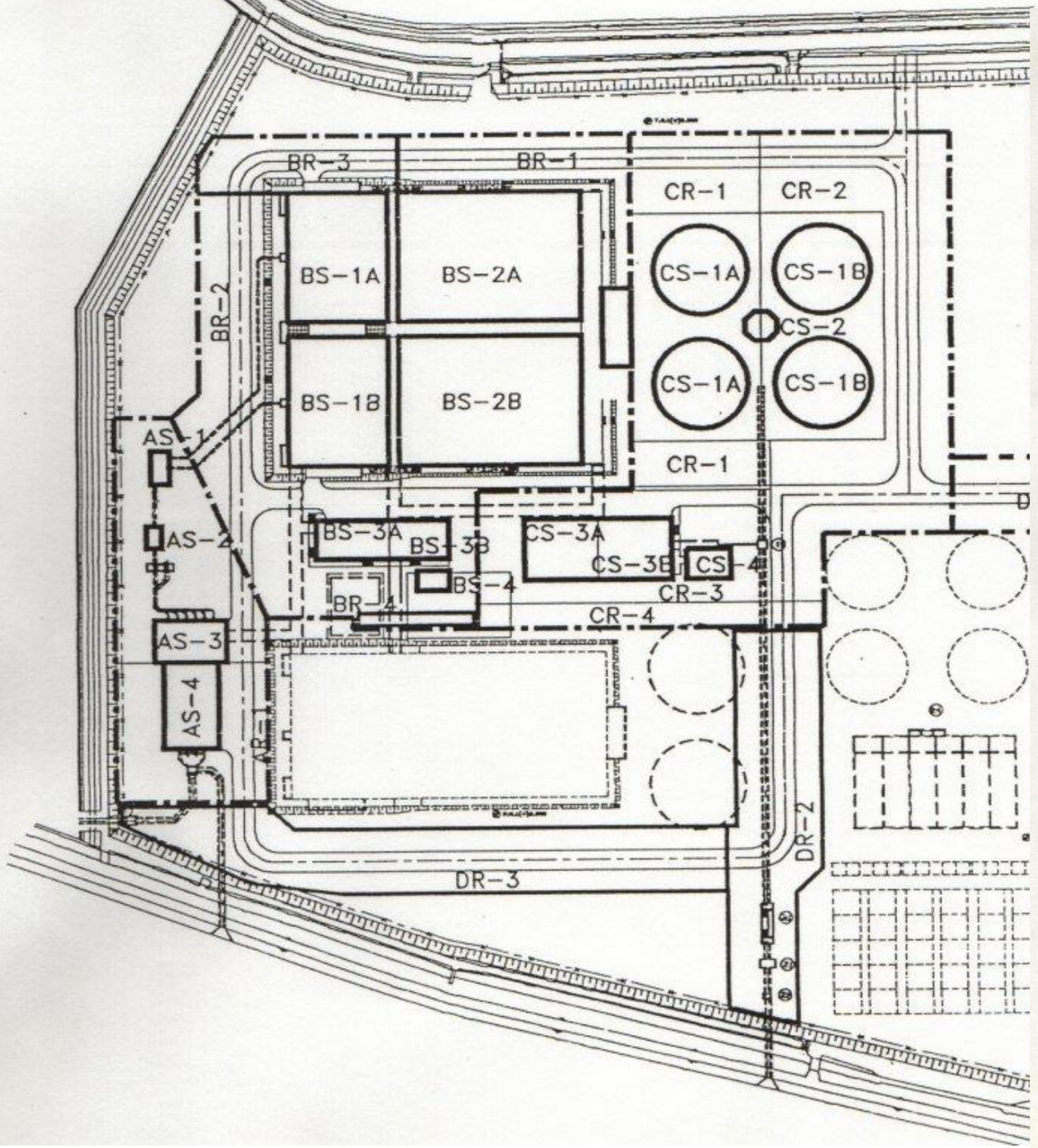
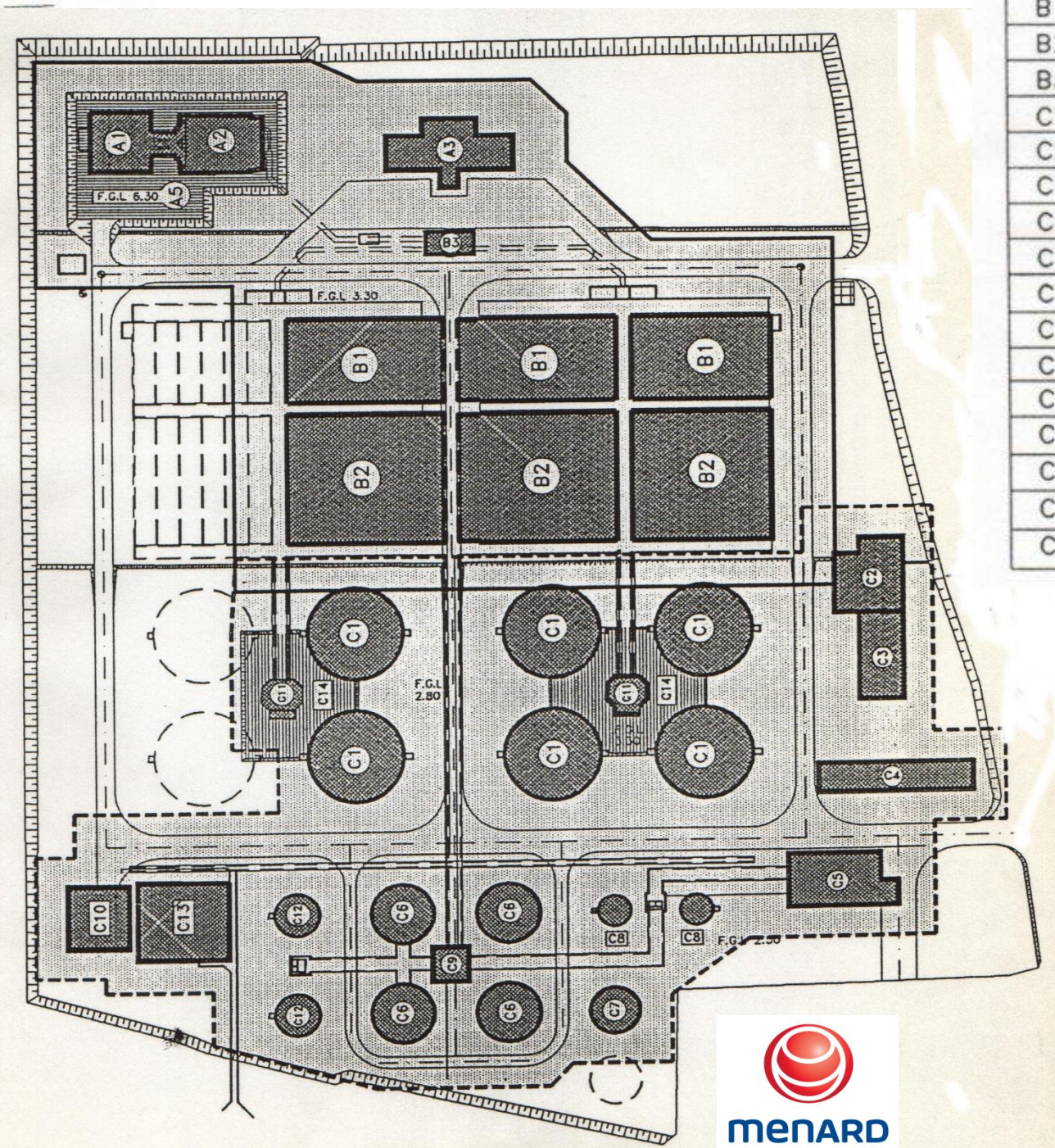
Kimhae & Jangyoo Sewage Treatment Plant




BR-3
BR-1
CR-1
CR-2
BS-1A
BS-2A
CS-1A
CS-1B
CS-2
CS-1A
CS-1B
BR-2
BS-1B
BS-2B
AS-1
CR-1
AS-2
BS-3A
BS-3B
CS-3A
CS-3B
CS-4
BS-4
CR-3
BR-4
CR-4
AS-3
AS-4
DR-2
DR-3


A1
A2
A3
A5
F.G.L 6.30
B3
F.G.L 3.30
B1
B2
C1
C14
C11
F.G.L 2.80
C4
C10
C13
C12
C6
C8
C9
C7
F.G.L 2.50

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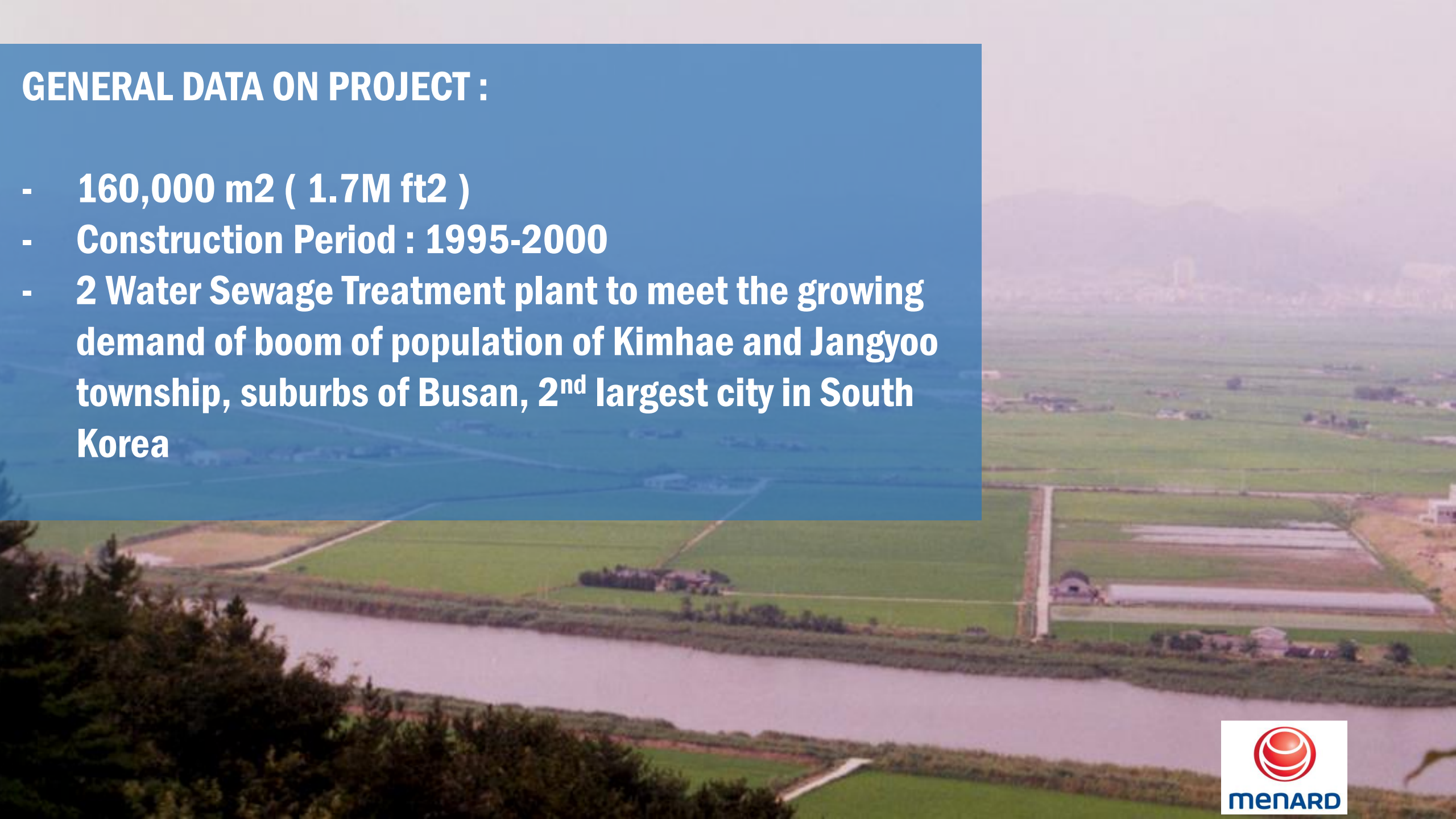
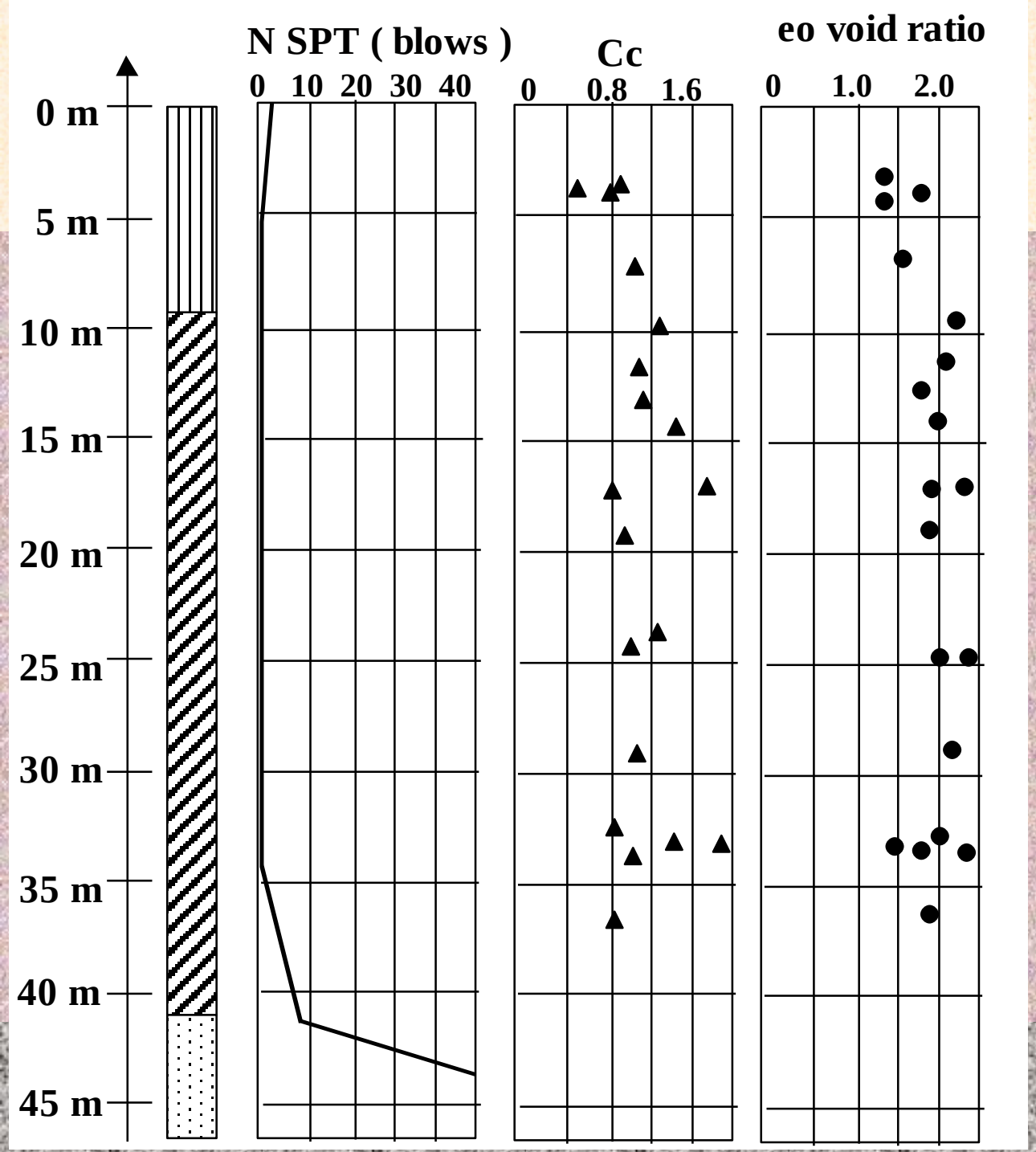


GENERAL DATA ON PROJECT :

- 160,000 m2 (1.7M ft2)
- Construction Period : 1995-2000
- 2 Water Sewage Treatment plant to meet the growing demand of boom of population of Kimhae and Jangyoo township, suburbs of Busan, 2nd largest city in South Korea



Silty Sand to Sandy Silt – 5m (17 ft)

Soft Organic clay– 40m (130 ft)

Weathered Rock

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Silty Sand to Sandy Silt – 5m (17 ft)

Soft Organic Clay– 40m (130 ft)

Weathered Rock

Main Characteristics of the Soft Clay Layer :

normally Consolidated

Water content average 75%

N(SPT) =0 to 1

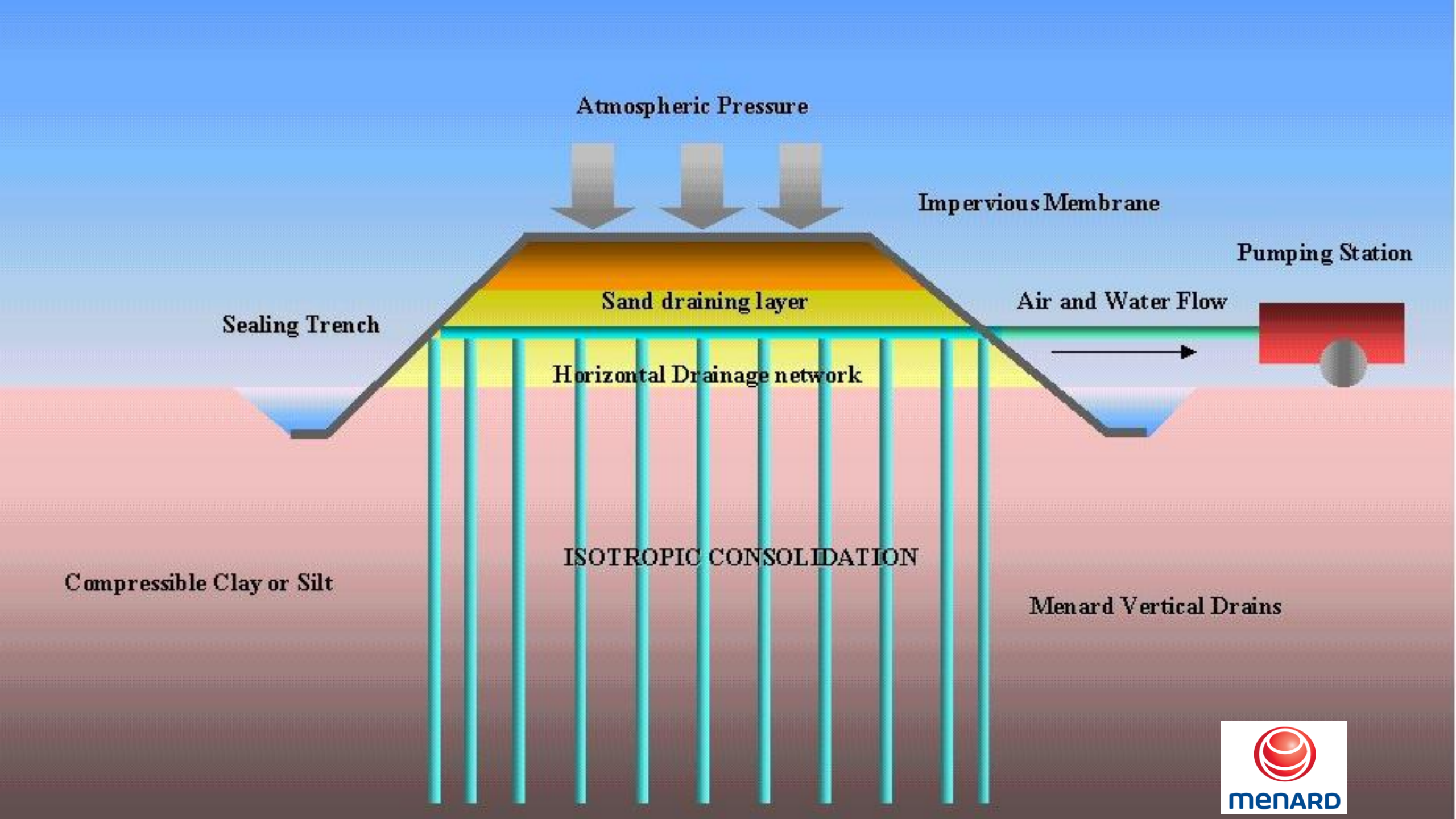
Cc = 1.21

eo = 2.012

Cv = 1.32 m2/y

Thickness between 25 and 40m (85ft to 130 ft)

Expected max settlement > 6m (15% of clay thickness)


Atmospheric Pressure
Impervious Membrane
Pumping Station
Sand draining layer
Air and Water Flow
Sealing Trench
Horizontal Drainage network
ISOTROPIC CONSOLIDATION
Compressible Clay or Silt
Menard Vertical Drains
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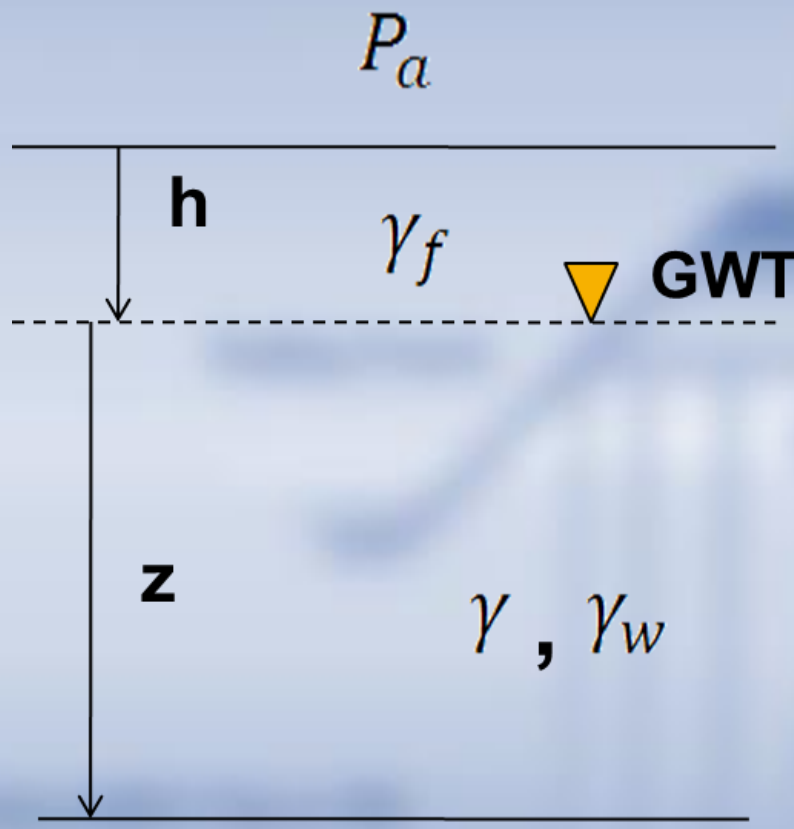

BEFORE VACUUM APPLICATION:

$$\sigma_T = \gamma z + \gamma_f h + \boldsymbol{P_a} = \sigma_t + \boldsymbol{P_a}$$
$$u_T = \gamma_w z + \boldsymbol{P_a} = u_t + \boldsymbol{P_a}$$

$$\sigma_i' = \sigma_T - u_T = \sigma_t - u_t$$
$$= \gamma' z + \gamma_f h$$

AFTER VACUUM APPLICATION:

$$\sigma_T = \gamma z + \gamma_f h + \boldsymbol{P_a} = \sigma_t + \boldsymbol{P_a}$$
$$u_T = \gamma_w z + \boldsymbol{P_a} - \boldsymbol{P_a}$$

$$\sigma_f' = \sigma_T - u_T$$
$$= \sigma_i' + \boldsymbol{P_a}$$

$$\Delta\sigma' = nP_a \rightarrow Where\ n \approx 0.7 - 0.8$$


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COMET


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START OF VACUUM / DEPRESSURE


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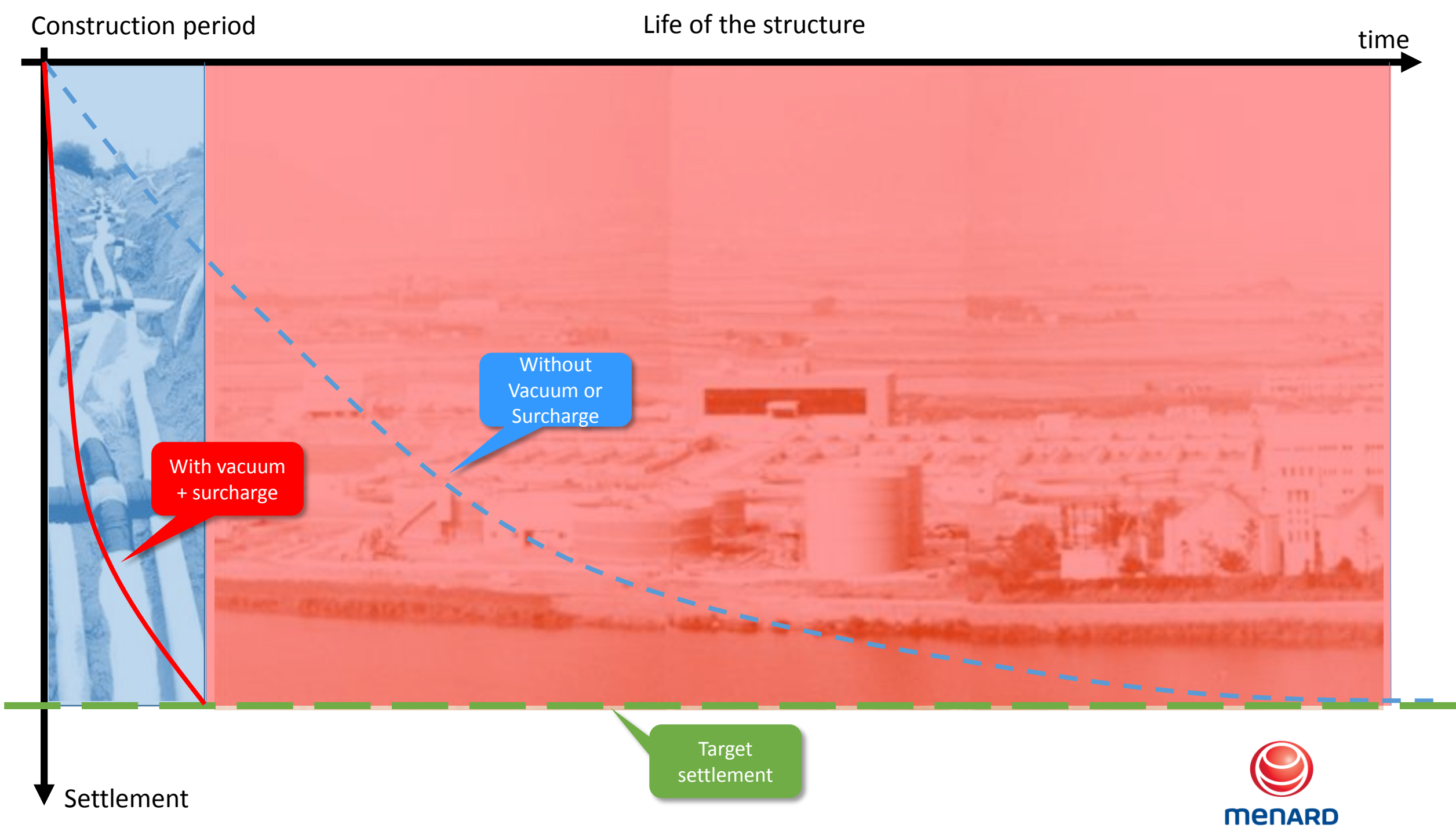

Construction period
Life of the structure
time
Without Vacuum or Surcharge
With vacuum + surcharge
Target settlement
Settlement

• SETTLEMENT ANALYSIS & VACUUM STOP DECISION PROCESS

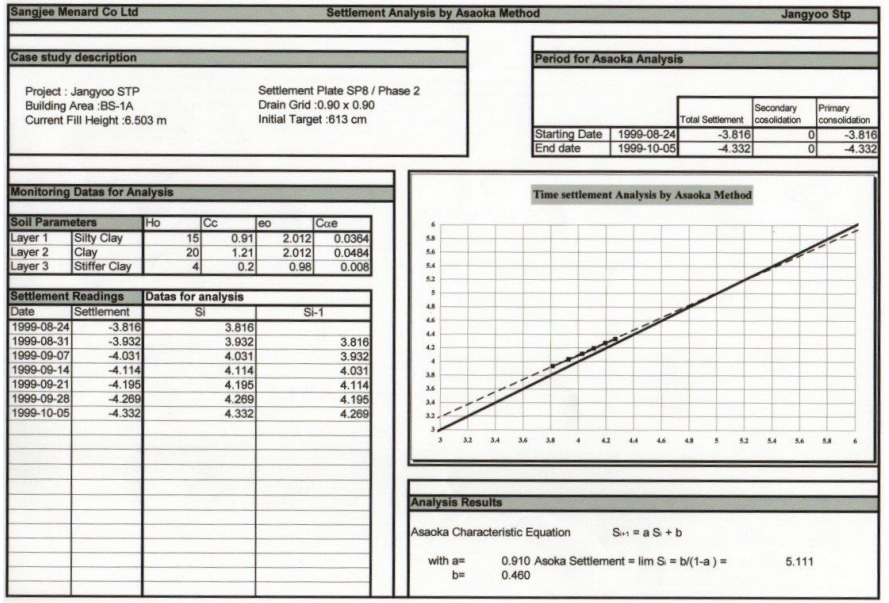
1D consolidation theory

$$\Delta\sigma'(z) = \gamma H_{fill} + \sigma_o + \gamma' \Delta H_{primarysetlement}$$

$$\Delta H_{primarysetlement} = \frac{C_c}{1+e_o}.H.\log\left(\frac{\sigma_o + \Delta\sigma'(z)}{\sigma_o}\right)$$

+

Asaoka Analysis of monitoring results



Sangjee Menard Co Ltd — Settlement Analysis by Asaoka Method — Jangyoo Stp

Case study description

Project : Jangyoo STP
Building Area :BS-1A
Current Fill Height :6.503 m

Settlement Plate SP8 / Phase 2
Drain Grid :0.90 x 0.90
Initial Target :613 cm

Period for Asaoka Analysis

		Total Settlement	Secondary cosolidation	Primary consolidation
Starting Date	1999-08-24	-3.816	0	-3.816
End date	1999-10-05	-4.332	0	-4.332

Monitoring Datas for Analysis

Soil Parameters		Ho	Cc	eo	Cαe
Layer 1	Silty Clay	15	0.91	2.012	0.0364
Layer 2	Clay	20	1.21	2.012	0.0484
Layer 3	Stiffer Clay	4	0.2	0.98	0.008

Settlement Readings		Datas for analysis	
Date	Settlement	Si	Si-1
1999-08-24	-3.816	3.816	
1999-08-31	-3.932	3.932	3.816
1999-09-07	-4.031	4.031	3.932
1999-09-14	-4.114	4.114	4.031
1999-09-21	-4.195	4.195	4.114
1999-09-28	-4.269	4.269	4.195
1999-10-05	-4.332	4.332	4.269

Time settlement Analysis by Asaoka Method

Analysis Results

Asaoka Characteristic Equation $S_{i+1} = a\,S_i + b$

with a= 0.910 Asoka Settlement = lim S_i = b/(1-a) = 5.111
b= 0.460

Calibration Coefficient

$$\beta = \frac{\Delta H_{asaoka}}{\Delta H_{theory}} = \frac{\left(\frac{Cc}{1+e_o}\right)_{actual}}{\left(\frac{Cc}{1+e_o}\right)_{soilinvestigation}}$$

Specifications

SETTLEMENT TARGET

Target reached ? Yes -> Stop vacuum
Target reached ? No -> Continue analysis

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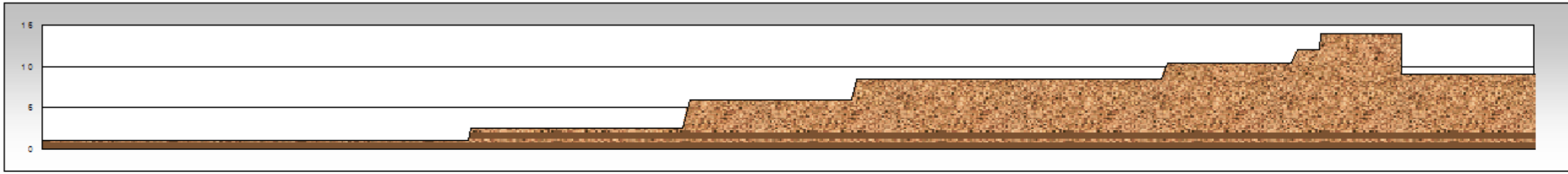
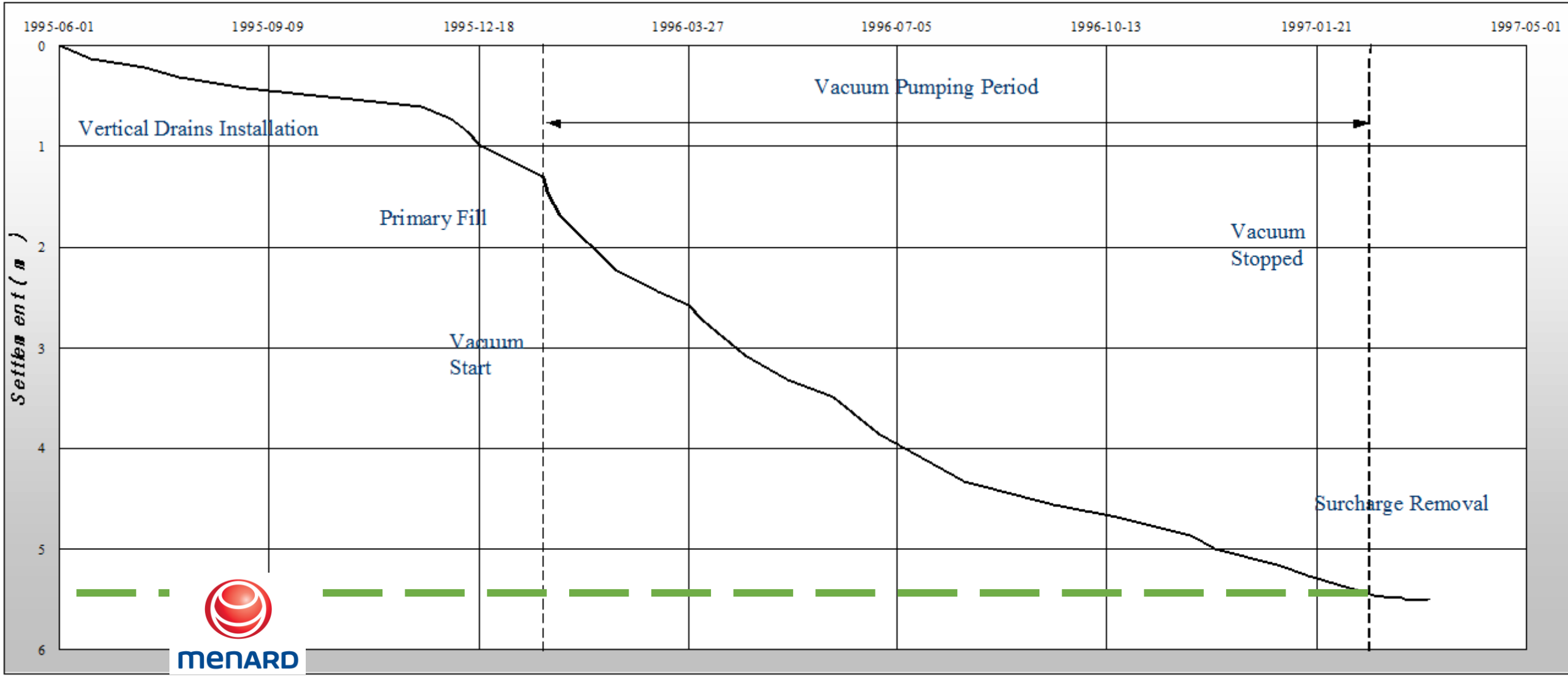

15
10
5
0


1995-06-01
1995-09-09
1995-12-18
1996-03-27
1996-07-05
1996-10-13
1997-01-21
1997-05-01
0
1
2
3
4
5
6
Settlement (m)
Vertical Drains Installation
Primary Fill
Vacuum Start
Vacuum Pumping Period
Vacuum Stopped
Surcharge Removal

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Project : Airbus A380 Assembly Plant

Country : Germany (Hamburg)

Summary : New Assembly plant on Elbe River for Airbus A380 – extension of runway

Main Issues to Solve :

- Local condition : underconsolidated river tidal deposits (Elbe River
- Settlement : predicted long term settlement > 2M over 20 years due to very compressible deposits (Muck)
- Bearing capacity / Slope Stability at edge


A380
A380


Hamburg -
Blankenese
ELBE
extension
Hahnöfer Sand
AIRBUS-
extension
Mühlenberger
Loch
Jork
Hamburg-
Finkenwerder
Alte Süderel
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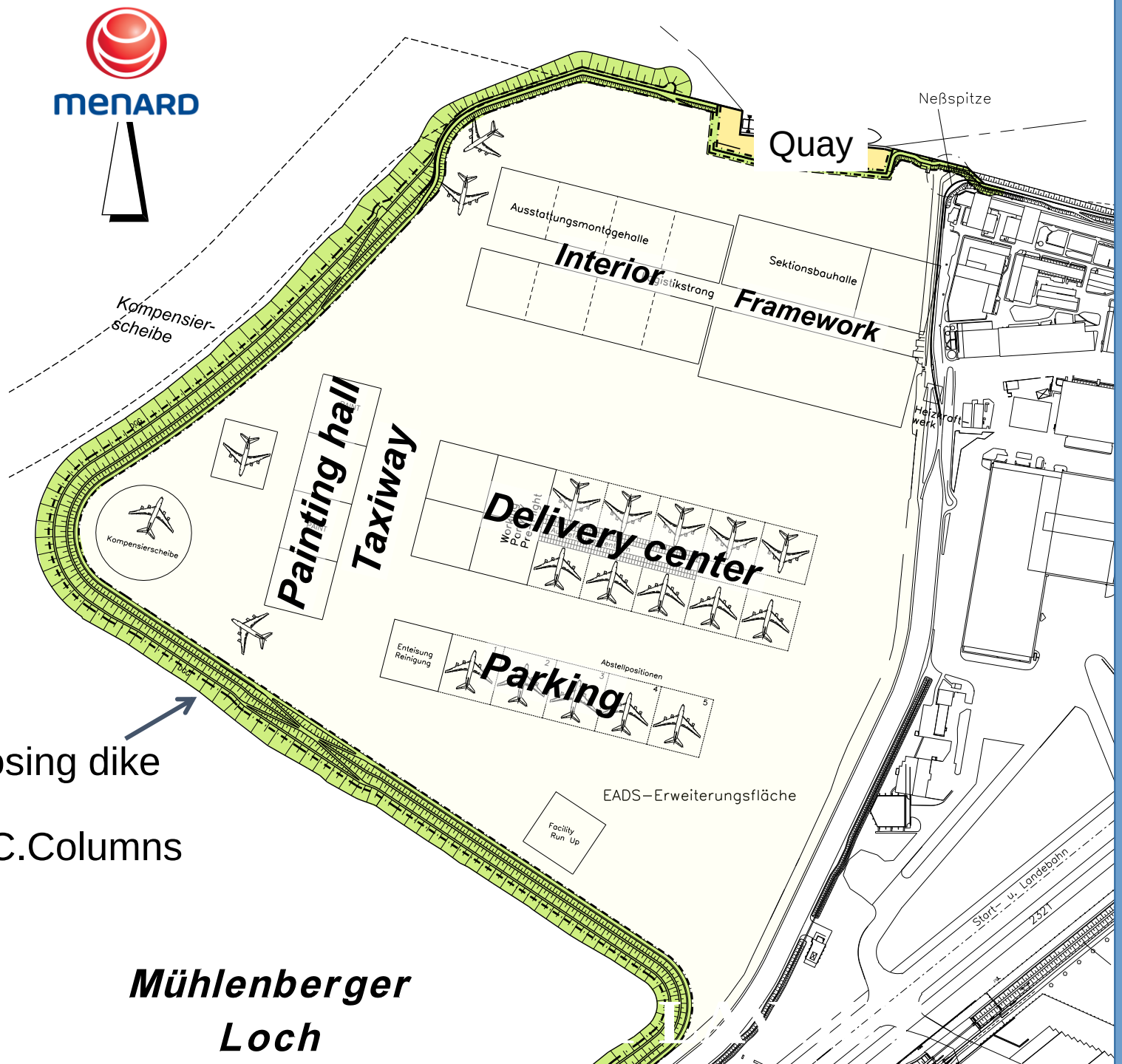
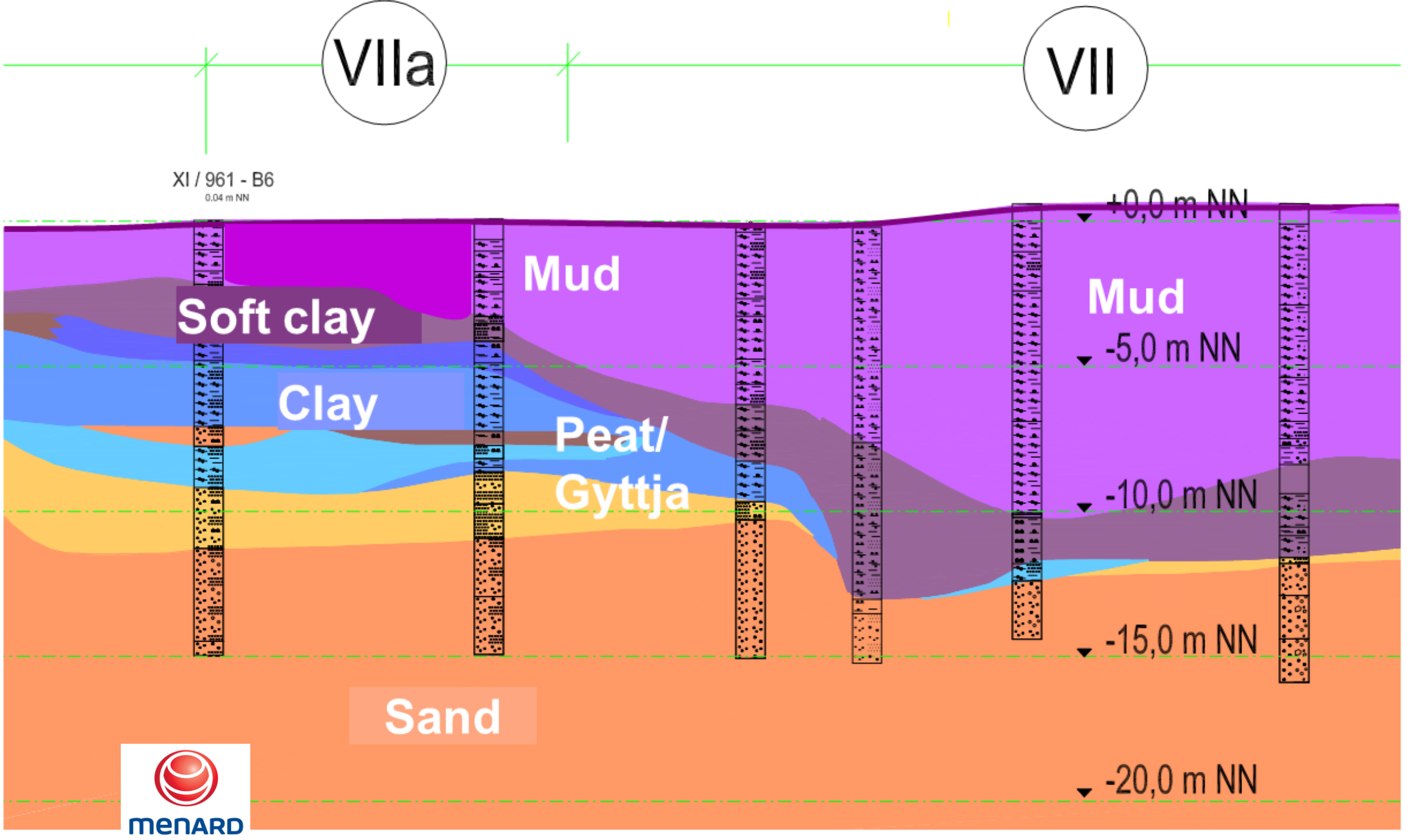


- Reclaimed Area = 170 ha (about 1.9m ft2)
- Final Assembly of Airbus A380
- Spare parts delivered by barge, plane or road to the Hamburg plant

- Containment dike on GCC
- Hydraulic sand reclamation
- Wick drains + Vaccum


VIIa
VII
XI / 961 - B6
0.04 m NN
+0,0 m NN
Mud
Soft clay
Clay
Peat/
Gyttja
Mud
-5,0 m NN
-10,0 m NN
-15,0 m NN
Sand
-20,0 m NN
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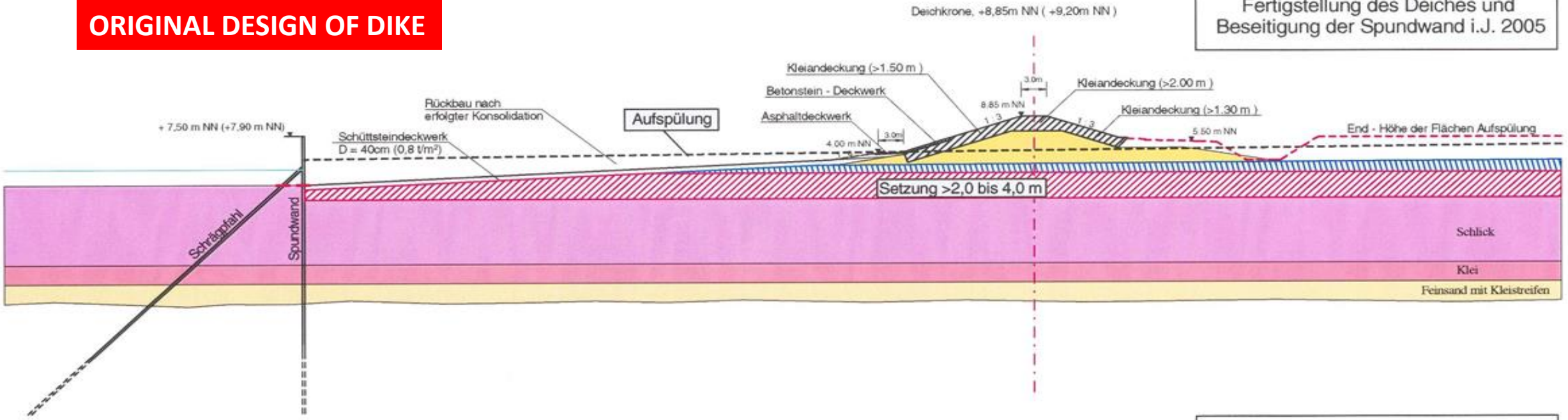
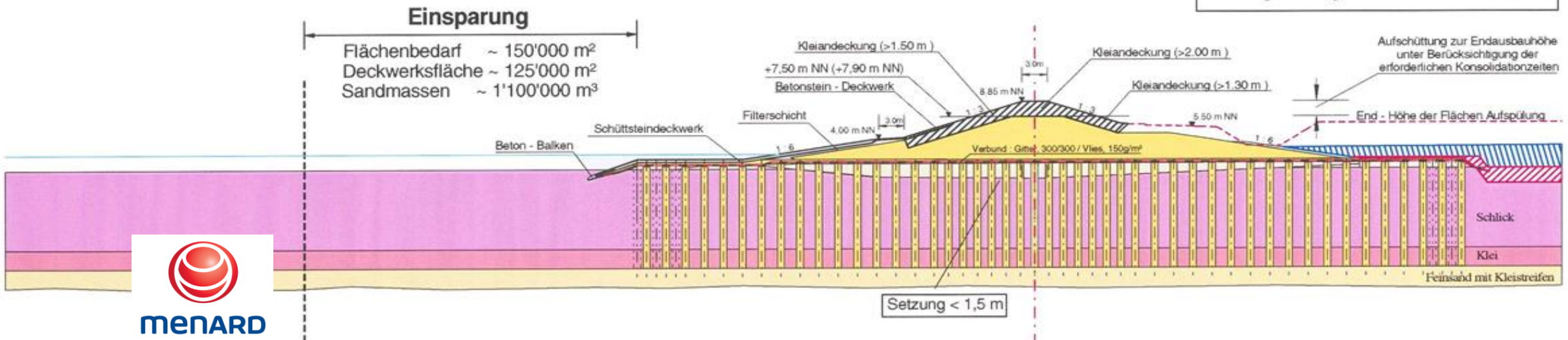
ORIGINAL DESIGN OF DIKE

Konzept der Ausschreibung:
Deich im Schutz einer temporären Spundwand
Fertigstellung des Deiches und Beseitigung der Spundwand i.J. 2005



VALUE ENGINEERING DIKE

Konzept Möbius:
Deich auf GSM - Gründung
Fertigstellung des Deiches Anf. 2002



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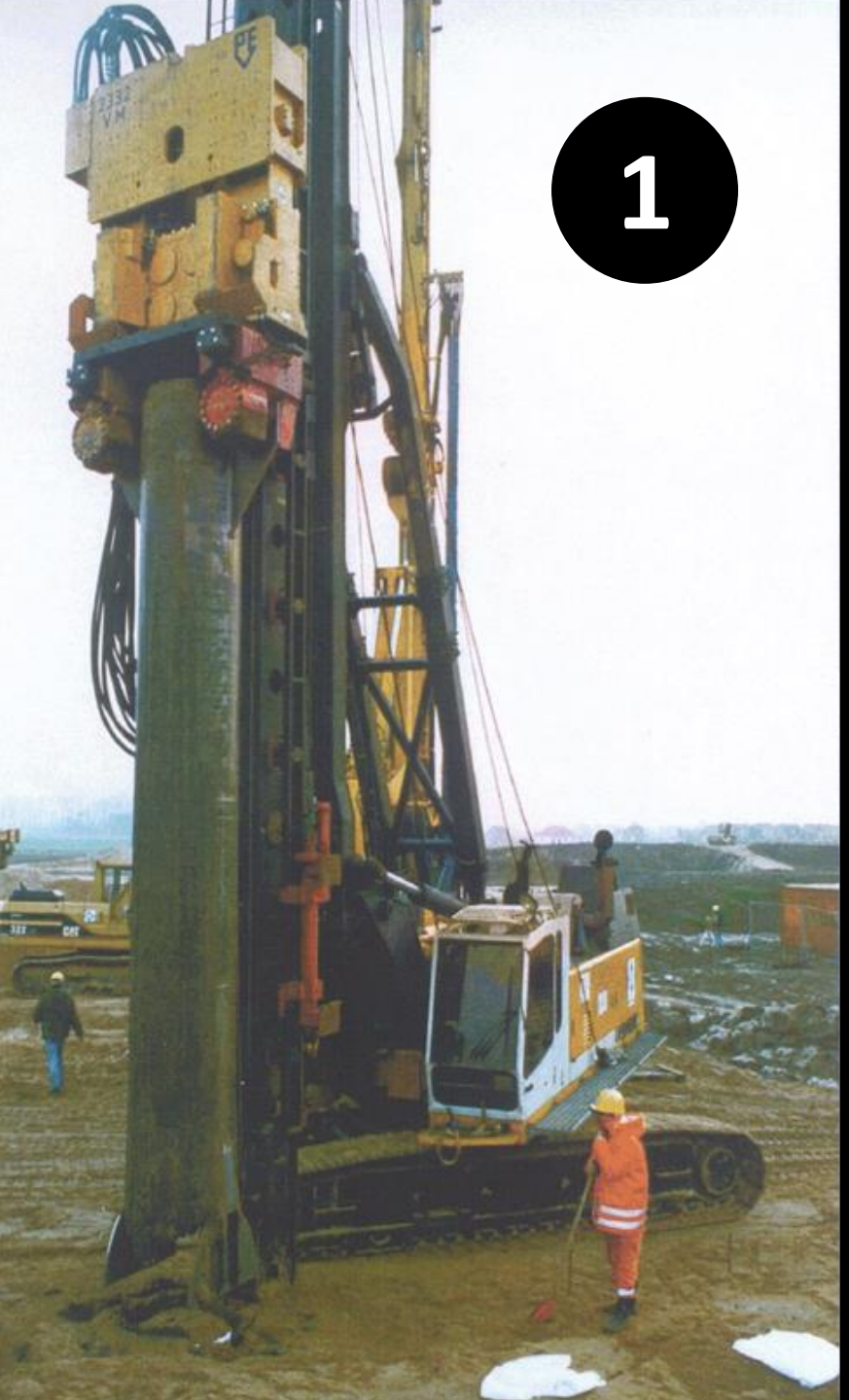
1


2


3
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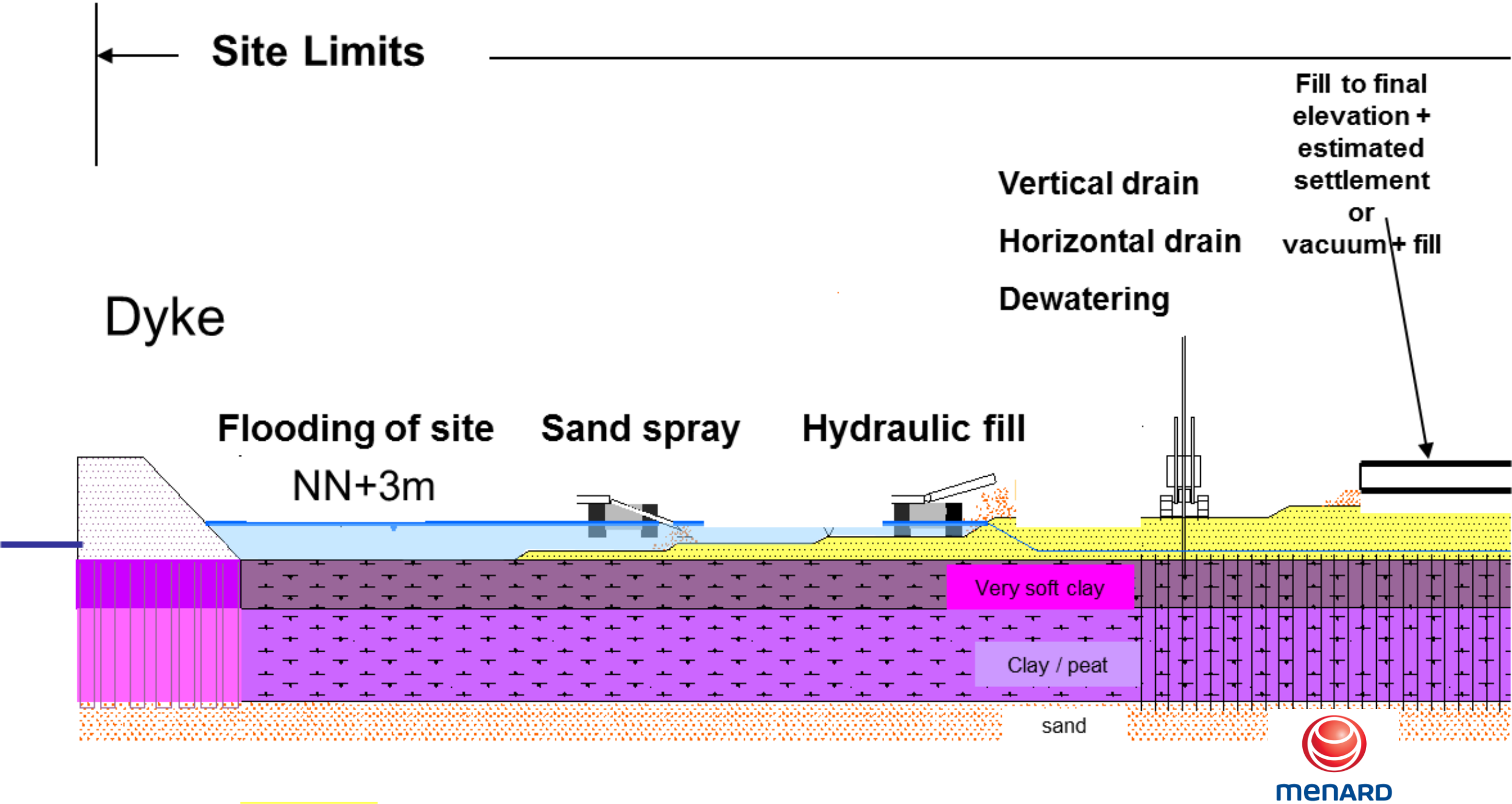
Site Limits
Fill to final elevation + estimated settlement or vacuum + fill
Vertical drain
Horizontal drain
Dewatering
Dyke
Flooding of site
NN+3m
Sand spray
Hydraulic fill
Very soft clay
Clay / peat
sand


Existing
Airbus Factory
Reclaimed area
Closing dike


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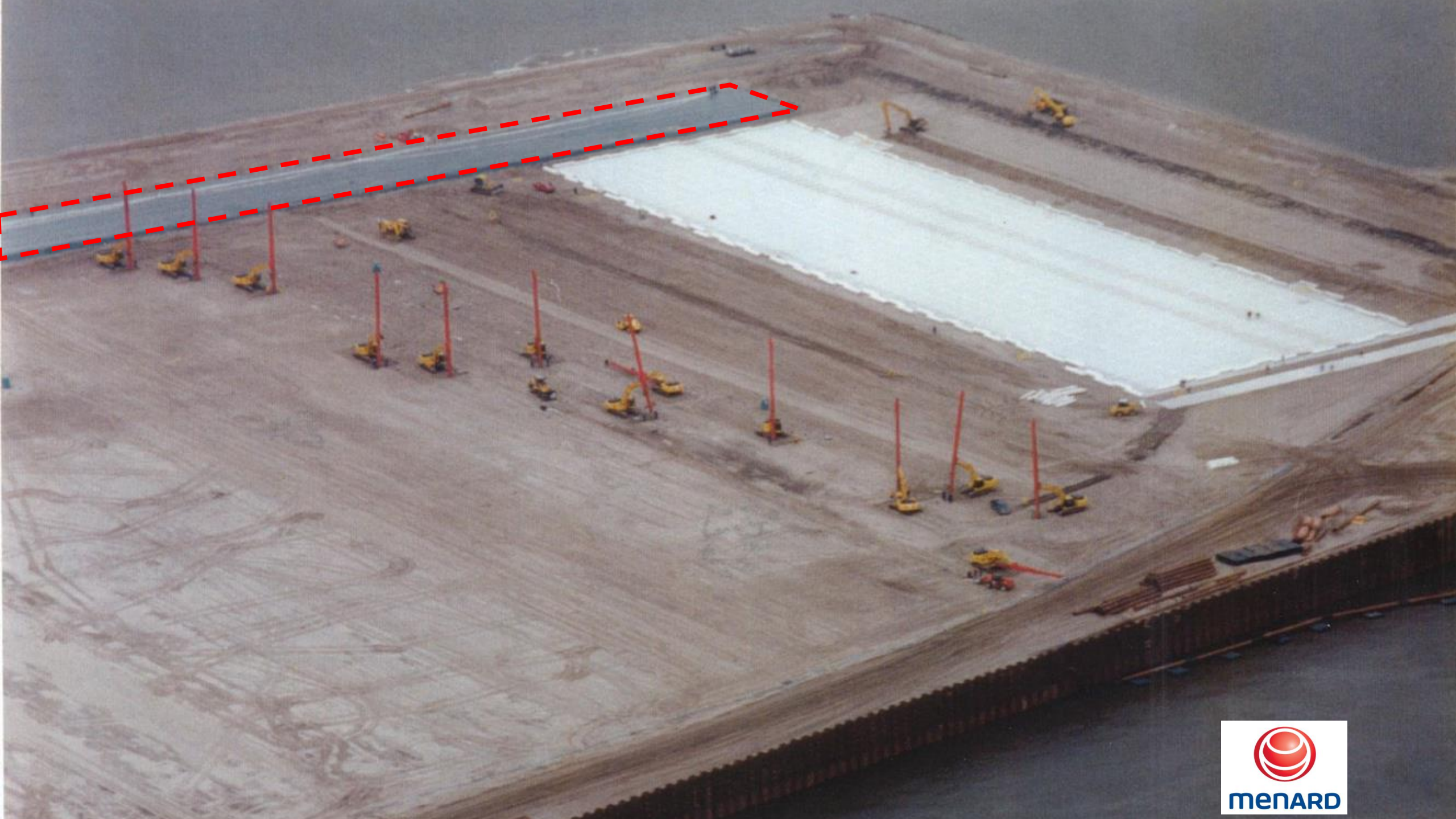
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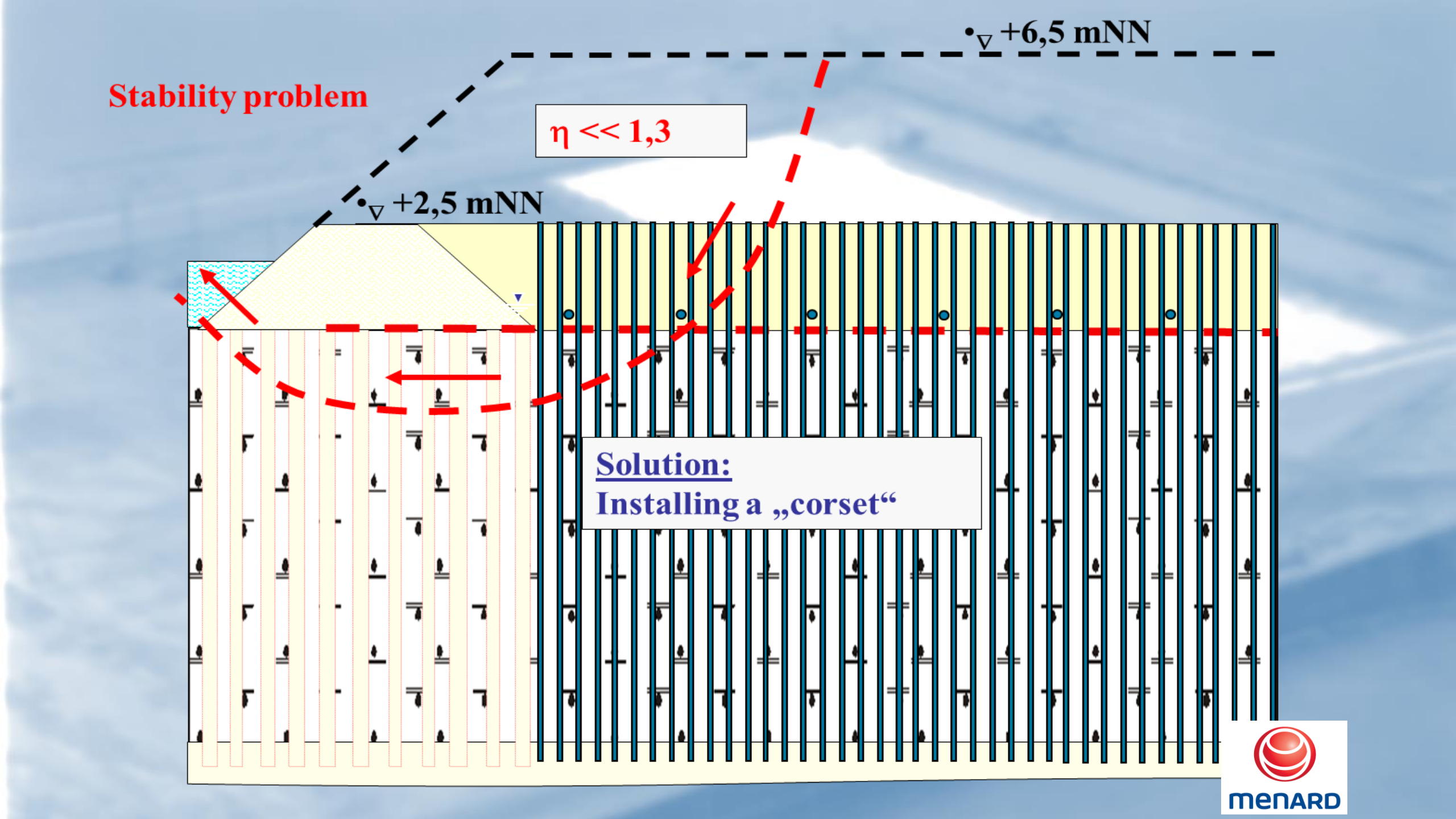
Stability problem
$\bullet_{\nabla}$ +6,5 mNN
η << 1,3
$\bullet_{\nabla}$ +2,5 mNN
Solution:
Installing a „corset“
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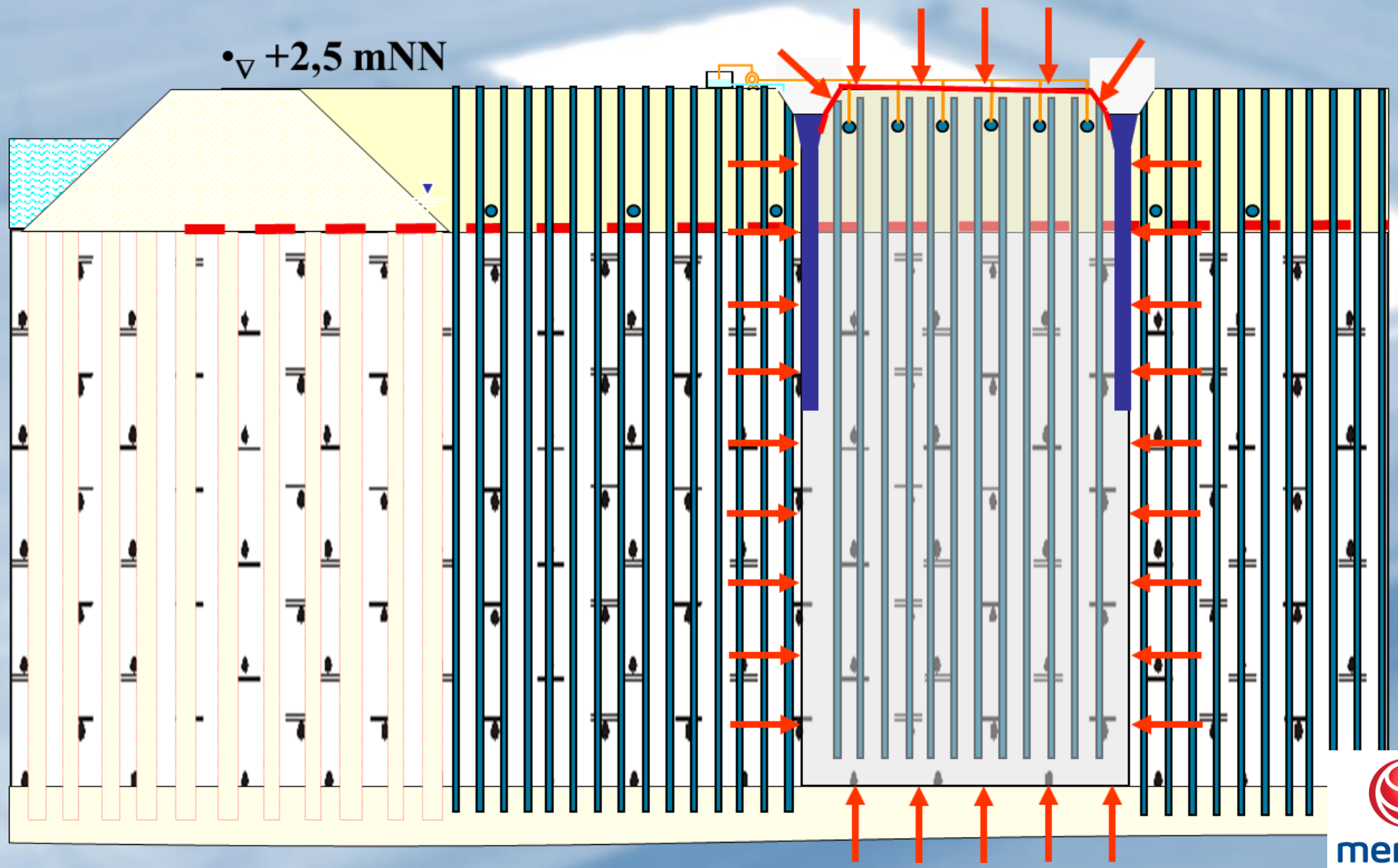
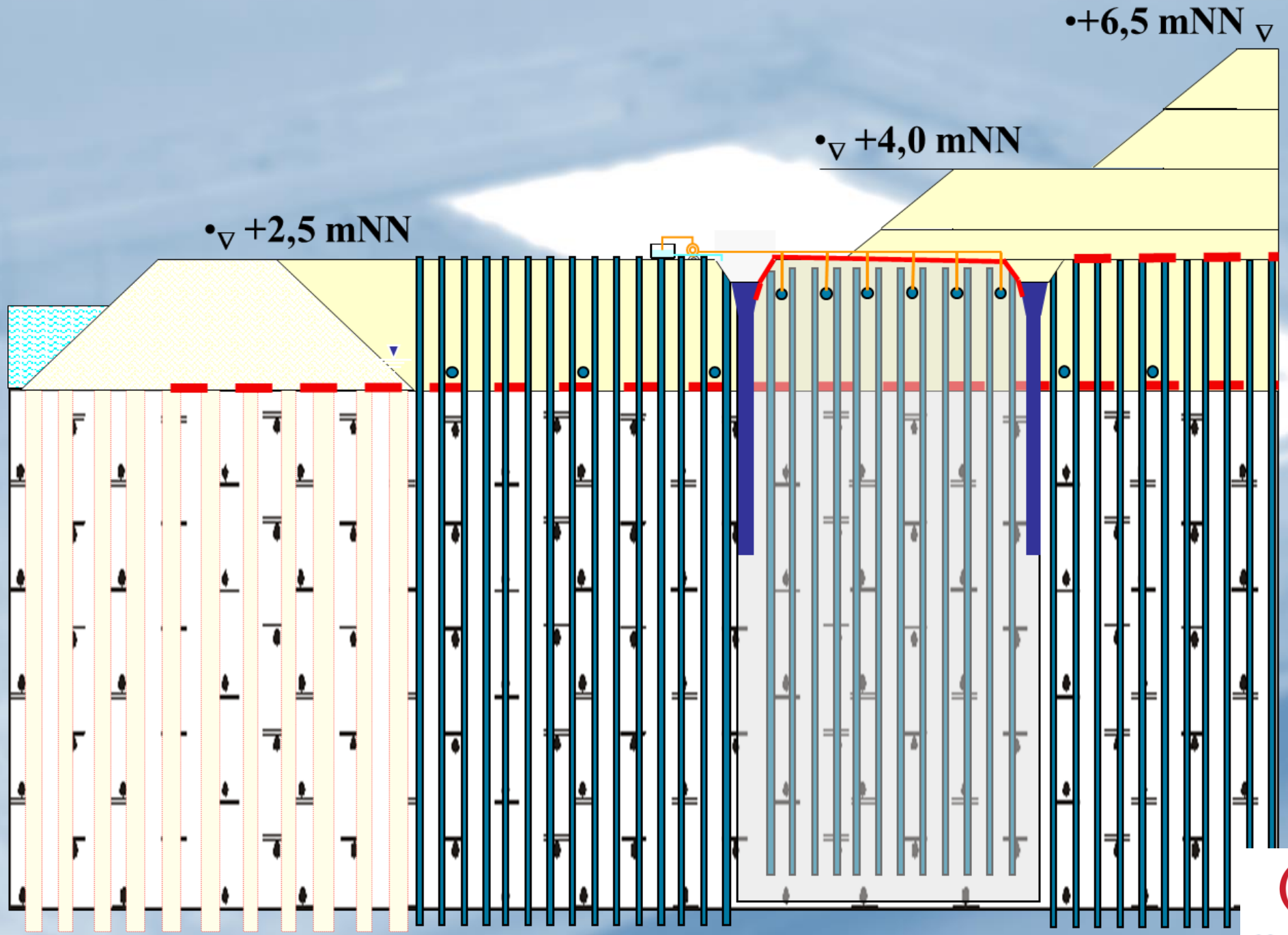
•Vacuum 70 kN/m² (0,7 bar)




•+6,5 mNN ▽
•▽ +4,0 mNN
•▽ +2,5 mNN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A380
A380

Project : King Abdulla University of Science and Technology (KAUST)

Country : Saudi Arabia (Jeddah)

Summary : New University (3M m2) built from scratch in record time in the desert

Main Issues to Solve :

- Local condition : relatively heterogeneous deposits of Sabkah (loose silt deposited by wind)
- Fast track project and project not well defined at time of ground improvement
- High water table

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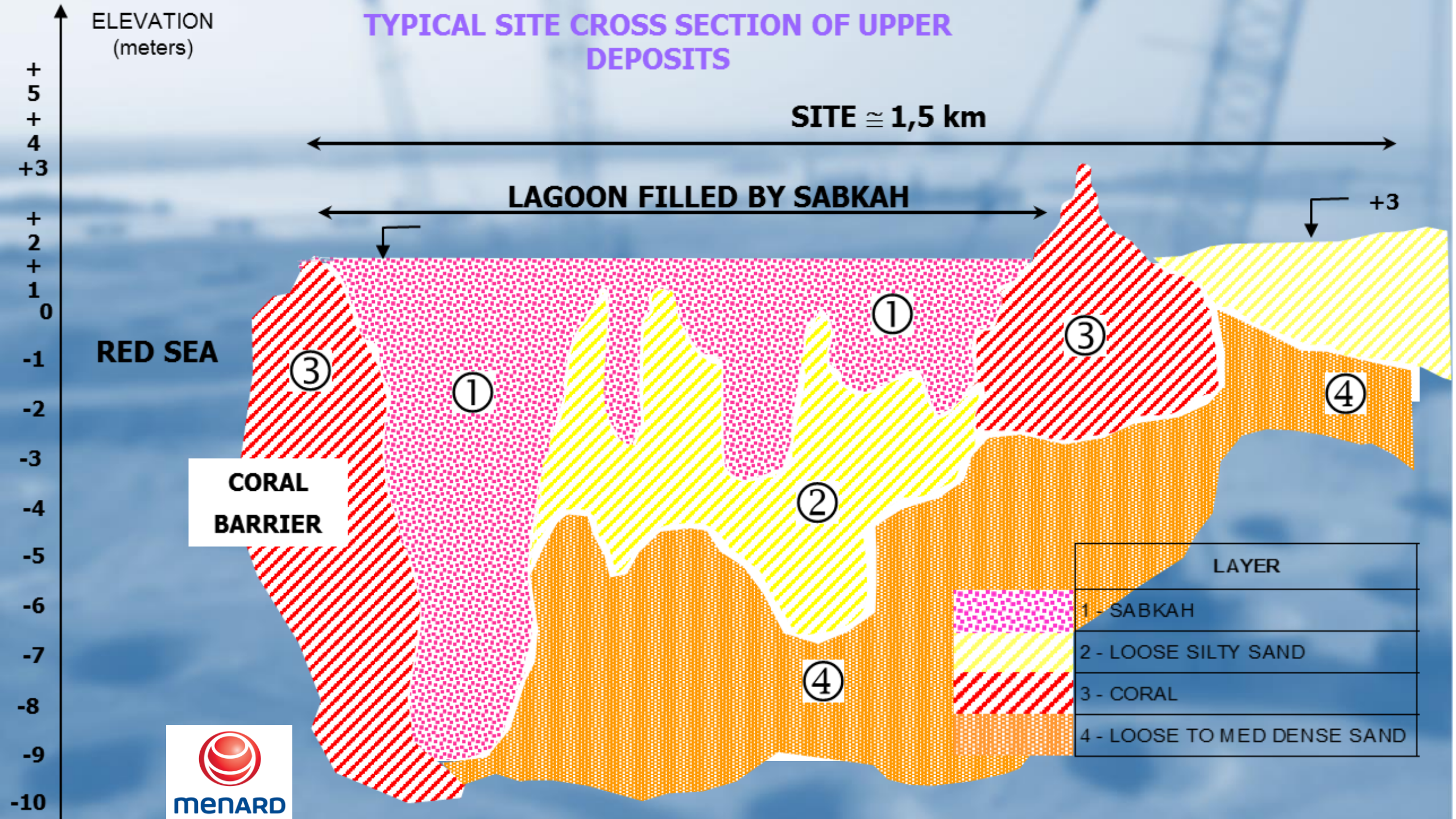
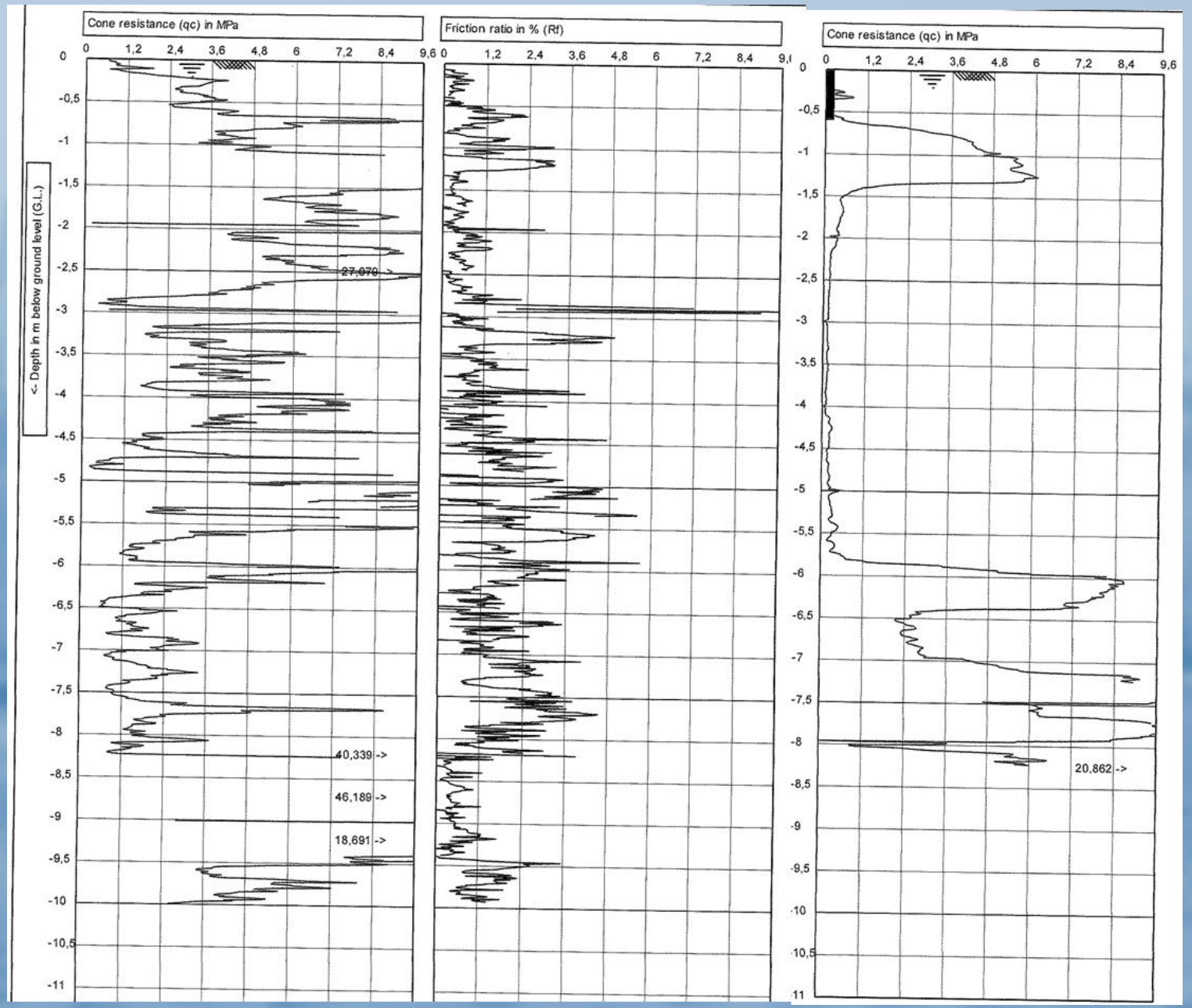
- KAUST = King Abdullah University for Science and Technology
- New university campus of 36 million m2 (i.e. 6 km x 6 km) to be completed in 26 months
- Located in the desert near Jeddah
- Includes desalination plant, wind turbines, golf course, residences, services, campus, infrastructures

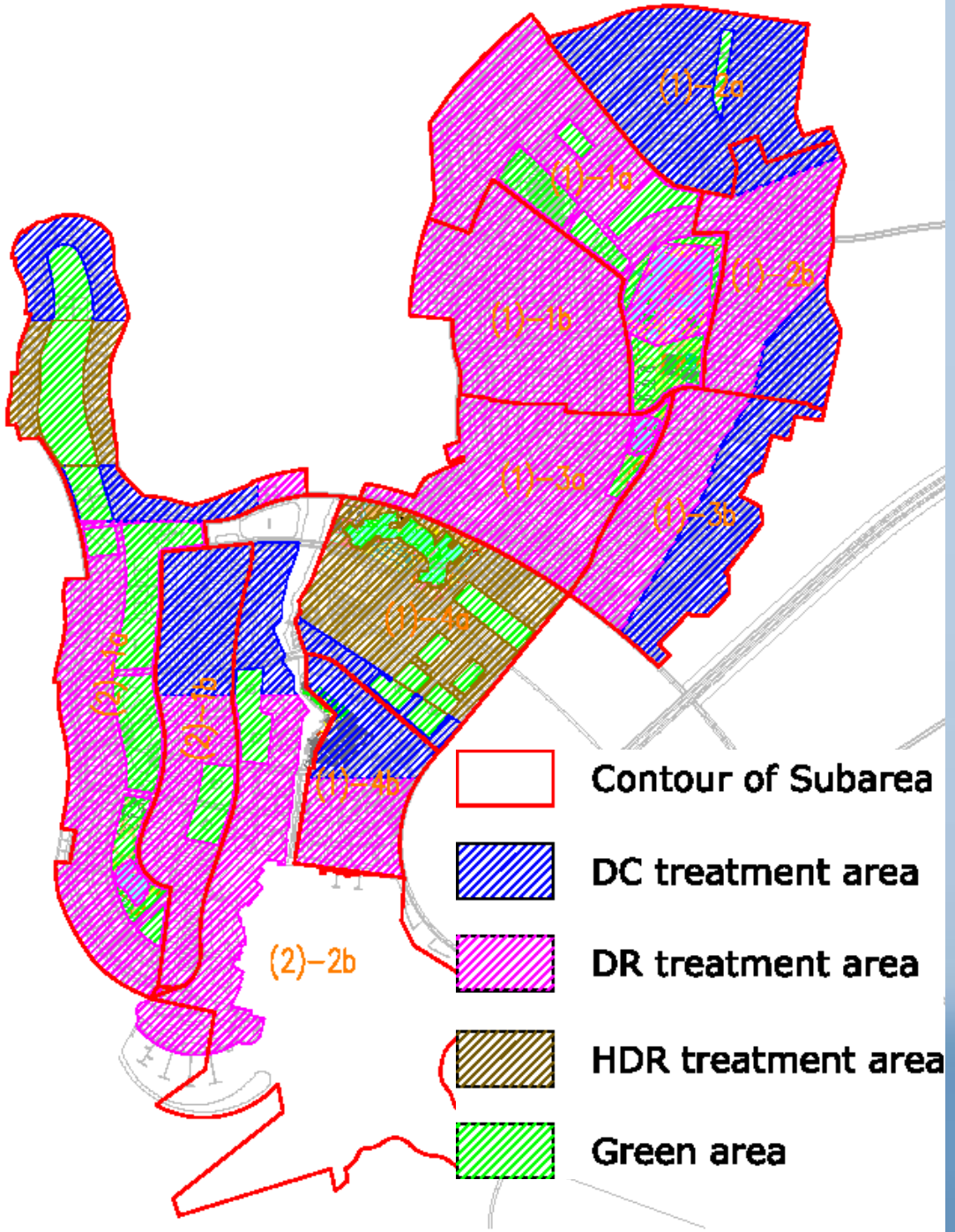
- Initial Conditions and Challenges :
  - Sabkah : saturated loose fine silty sand – wind blown . On this project, up to 5m thick at surface
  - Fast - track project : project was launched before 100% drawings – Menard needed to propose a ground improvement system without having final structural drawings and loads

TYPICAL SITE CROSS SECTION OF UPPER DEPOSITS



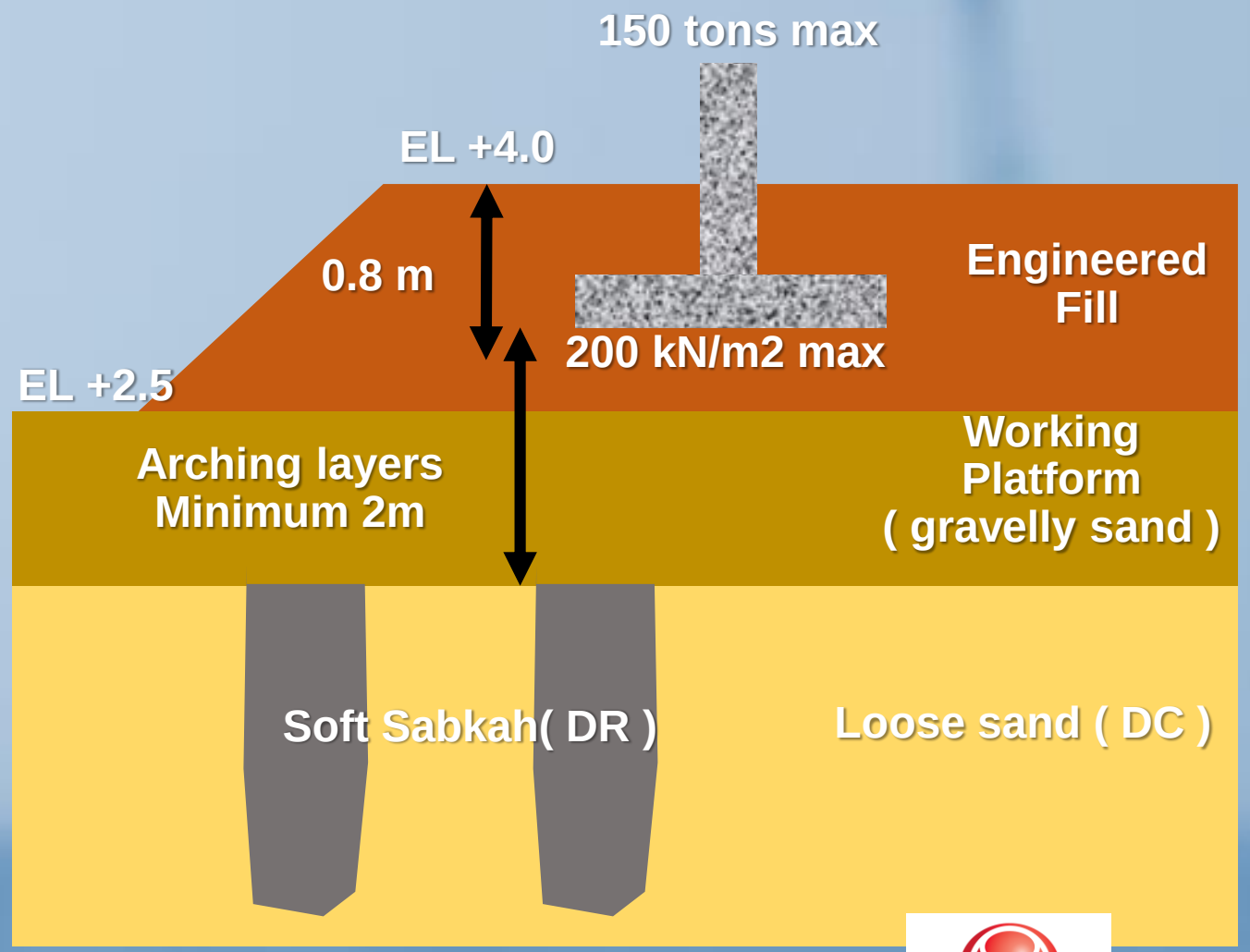
VARIATION IN SOIL PROFILE OVER 30 METERS





DESIGN CONCEPT WHEN LOCATION OF FOOTINGS UNKNOWN

Total settlement < 1 inch (25mm) – max diff 1/500 on footings



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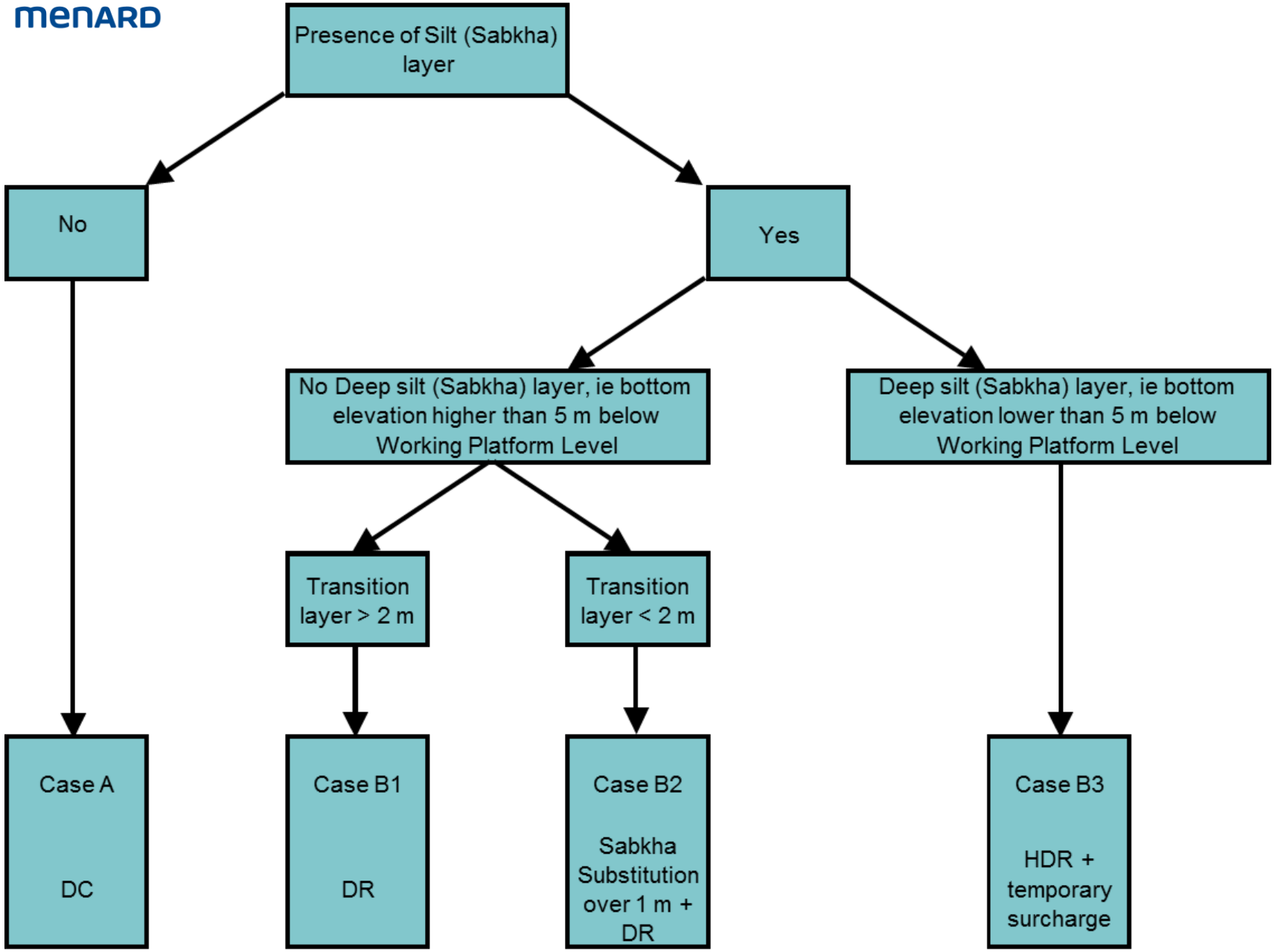

DESIGN DECISION TREE

Based on Observational Method

Selection of G.I. method is dependent on site observation during compaction and borings


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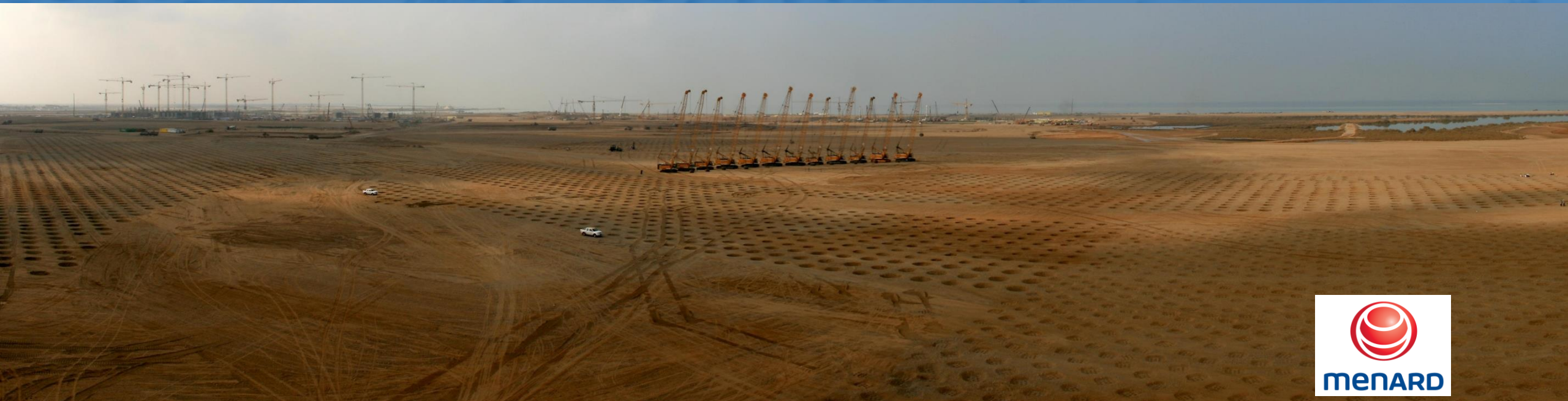
12 Cranes (LRB 855 & 885) x 2 shifts

12 to 25 tons weight depending on areas

Over 2,500,000 m2 (25,000,000 ft2) of DC/DR

Team of 100 persons on site

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11
12


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Project : Fedex Ground Sorting Facility

Country : USA (Jersey City)

Summary : New plant in Greenfield with final grade raised several meters and large net new loads

Main Issues to Solve :

- Local condition : thick deposits of varved soft clay below a layer of thick organics
- Settlement : predicted long term settlement >2ft over 20 years due to deep soft clays
- Construction period – Fast schedule
- Limited budget


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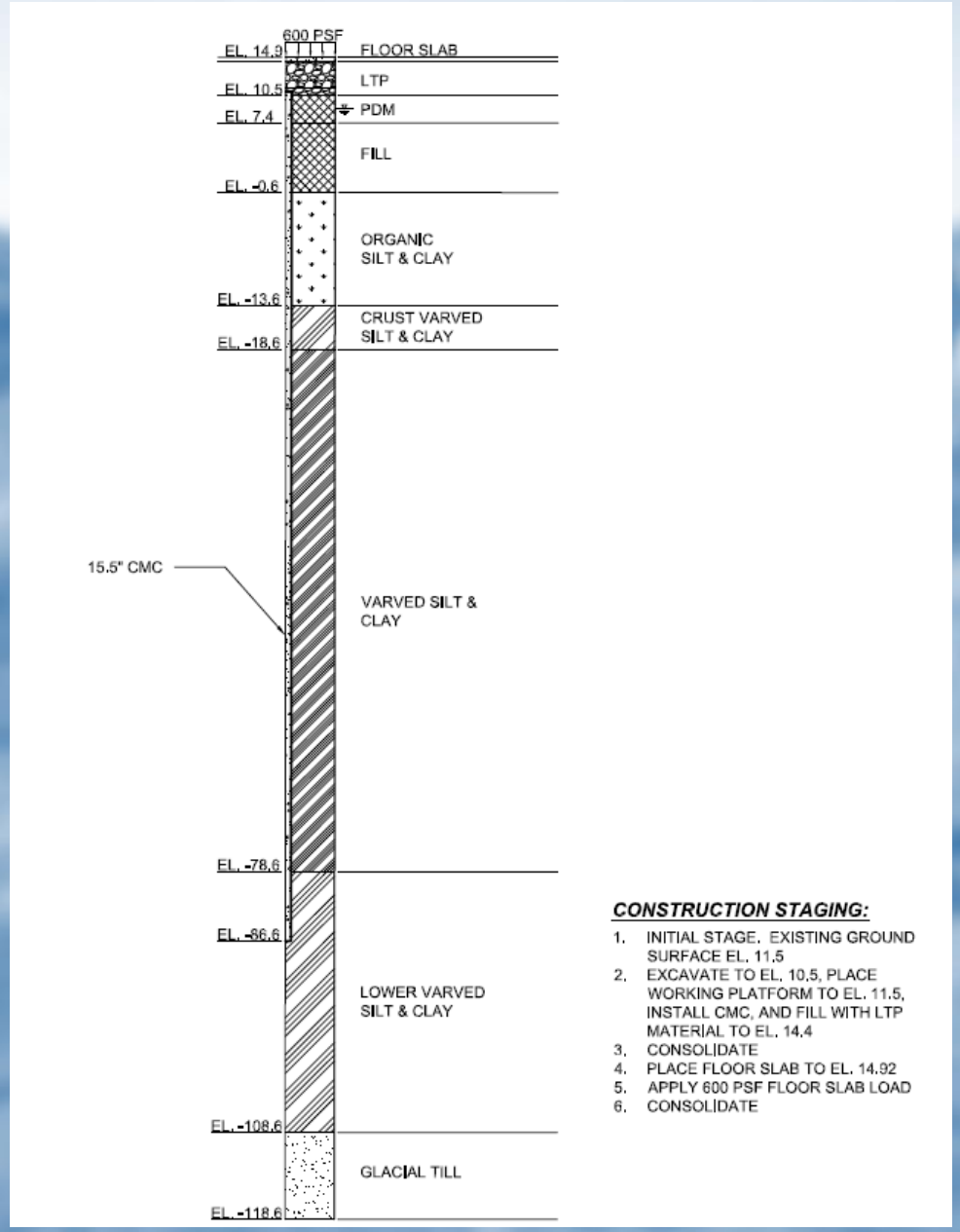


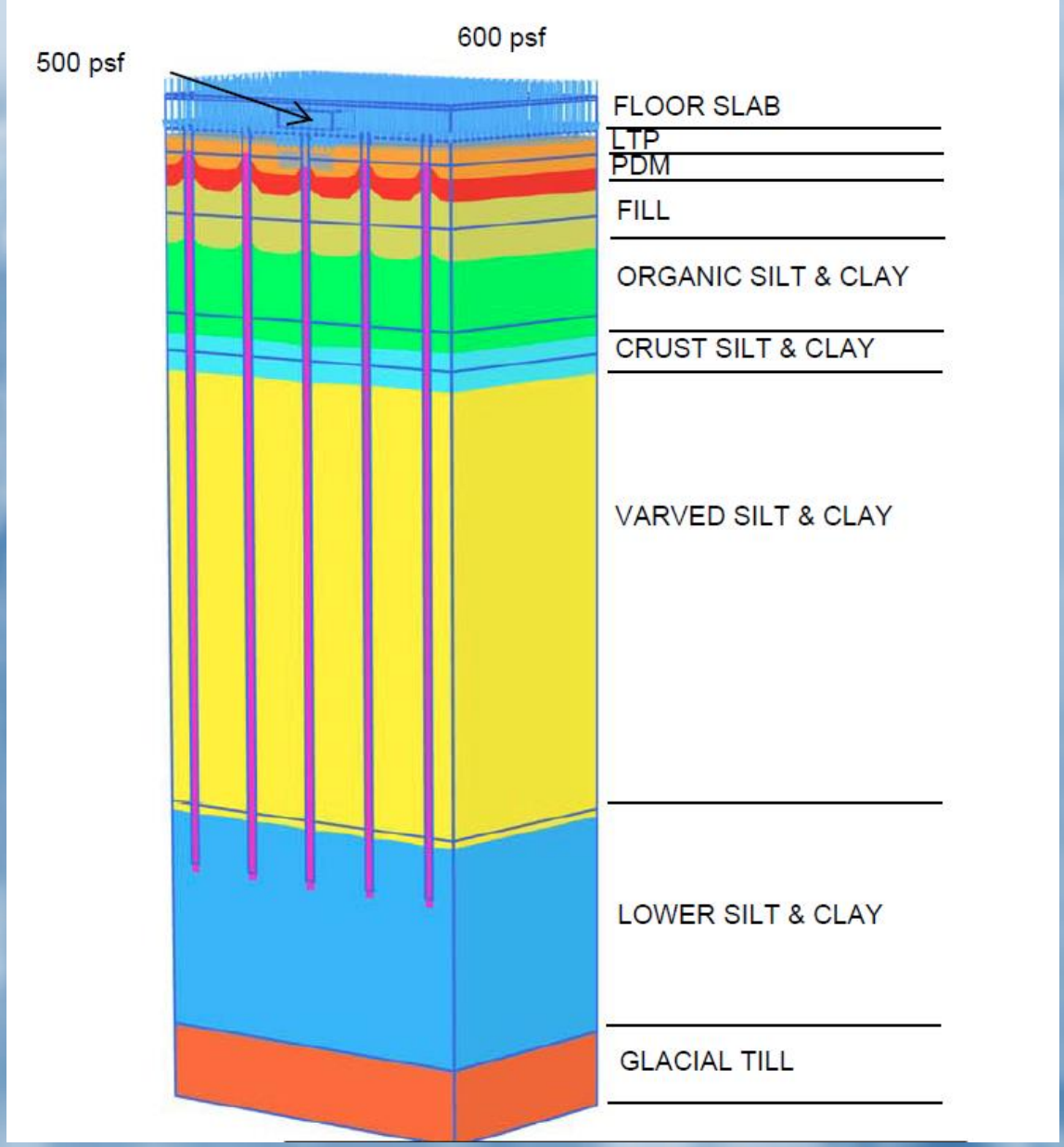
Soil profile :
Fill (with some MSW) over Organics (meadow mat) over varved silt and clays

Main Challenge was thickness of compressible soil extending beyond the capacity of classical CMC rigid inclusions elements.

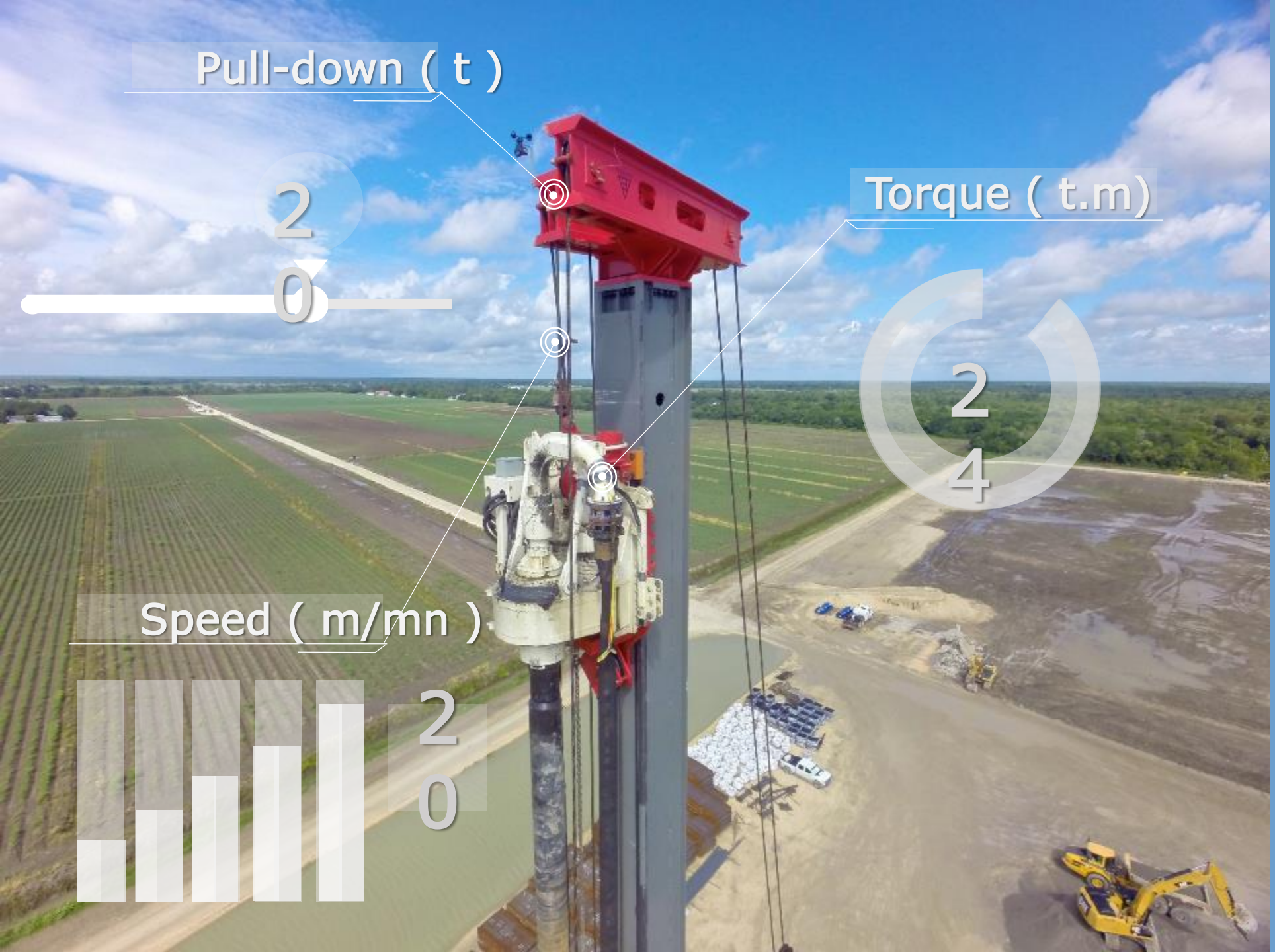
Second challenge was to limit total settlements to under 2 inches long term and differential settlement of ¾ inch between two column footings.

Differential settlement between loaded bay and unloaded bay is also to be studied

Differential between footings and slab is another focus



Depth challenge solved



Develop two custom made lead mast systems attached to crawler cranes with high torque / high pull down capacity

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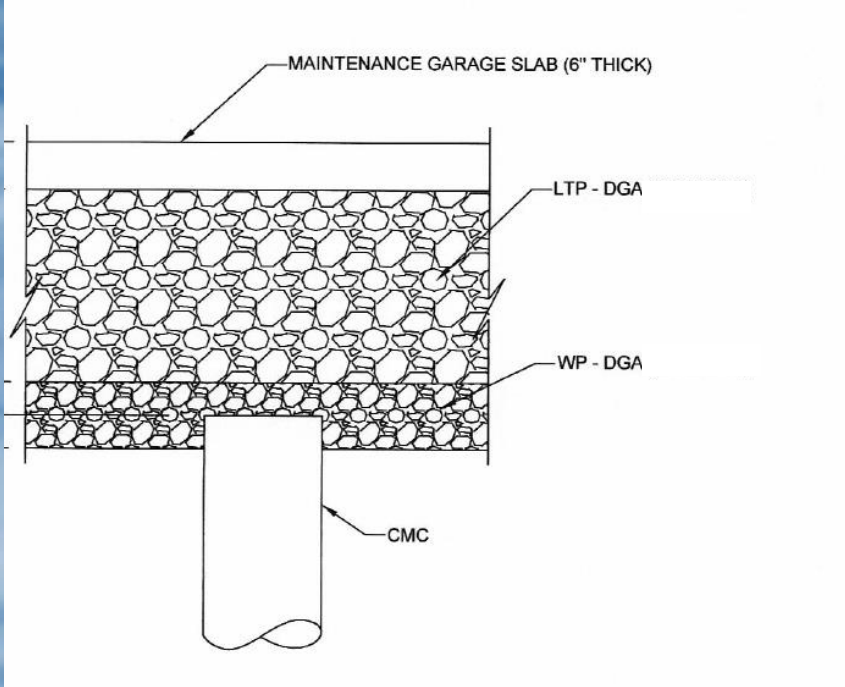
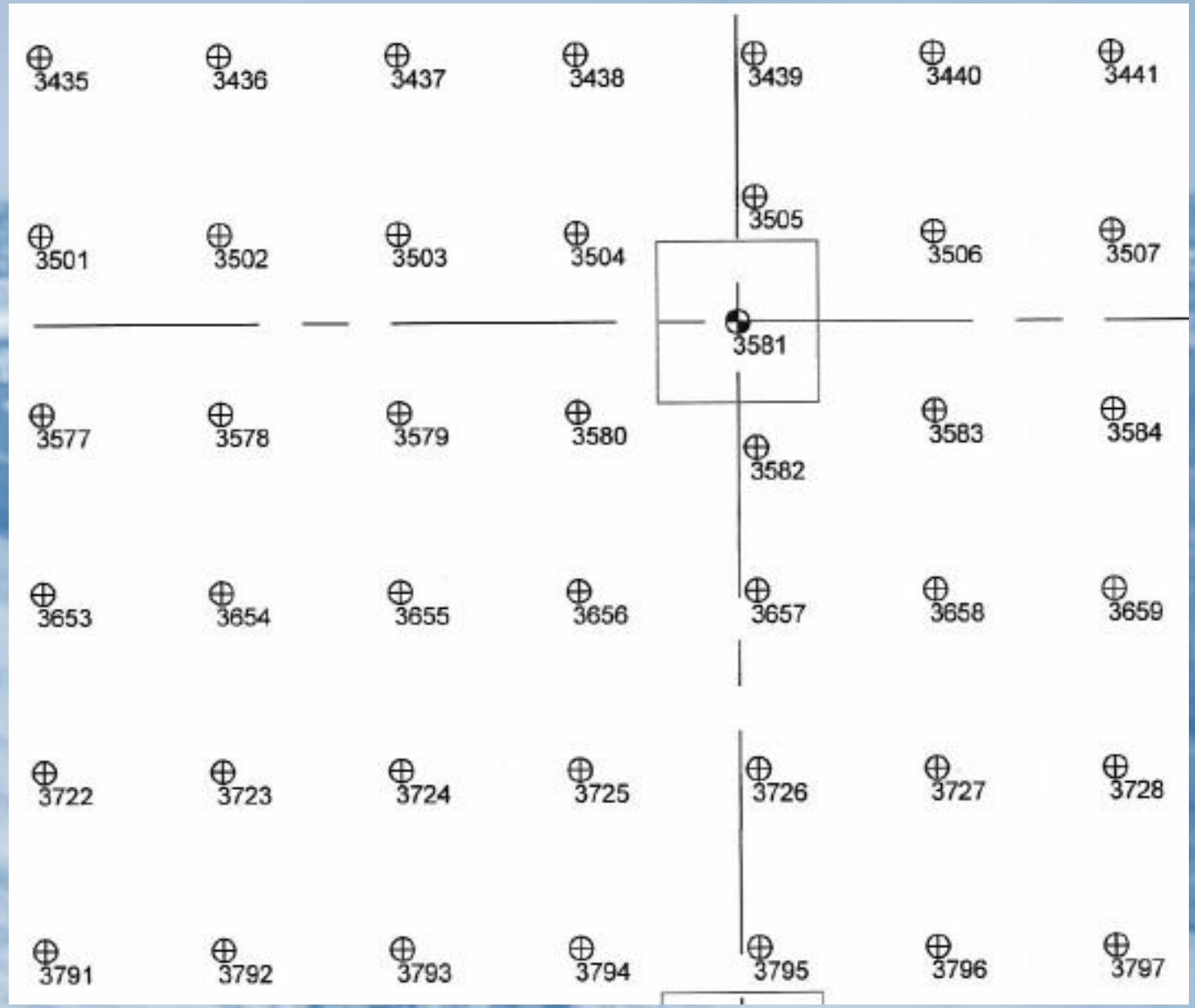
Settlement challenge solve

Combination of Global support (with one added CMC at concentrated loads) and thick LTP to spread load





Fedex NJ

- ☑ Jersey City, NJ
- ☑ warehouse
- ☑ 350,000 sf
- ☑ 600 psf floor load
- ☑ 135 ft max
- ☑ 4,150 CMC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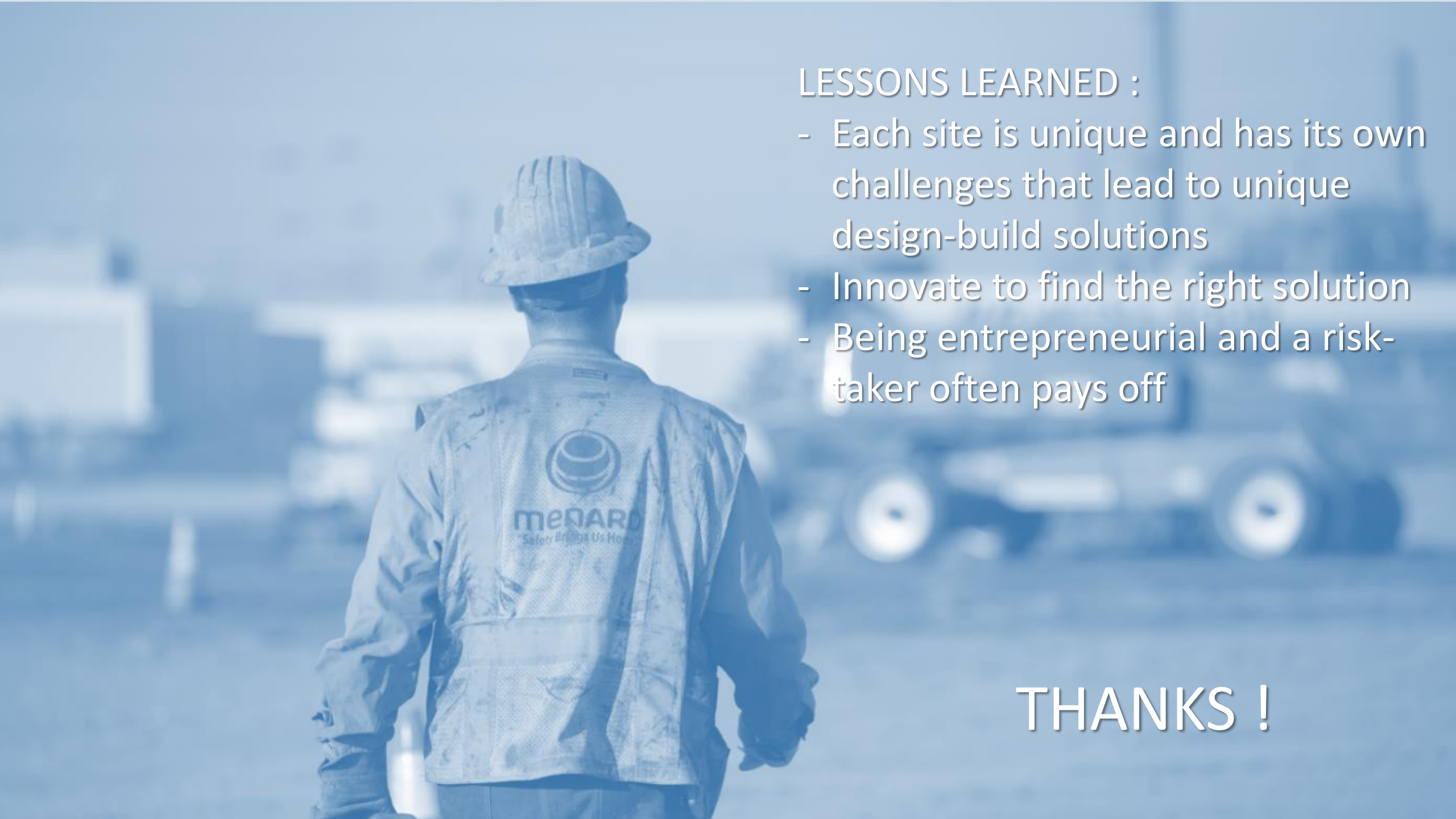

LESSONS LEARNED :

- Each site is unique and has its own challenges that lead to unique design-build solutions
- Innovate to find the right solution
- Being entrepreneurial and a risk-taker often pays off

THANKS !