One-Day Seminar Organised by
Geotechnical Engineering Technical Division, IEM
Kuala Lumpur, December 1st 2015

Ground improvement techniques with associated soil investigation and quality control

By Serge Varaksin
Vice Chairman TC 211

SIMSG ISSMGE

TC 211

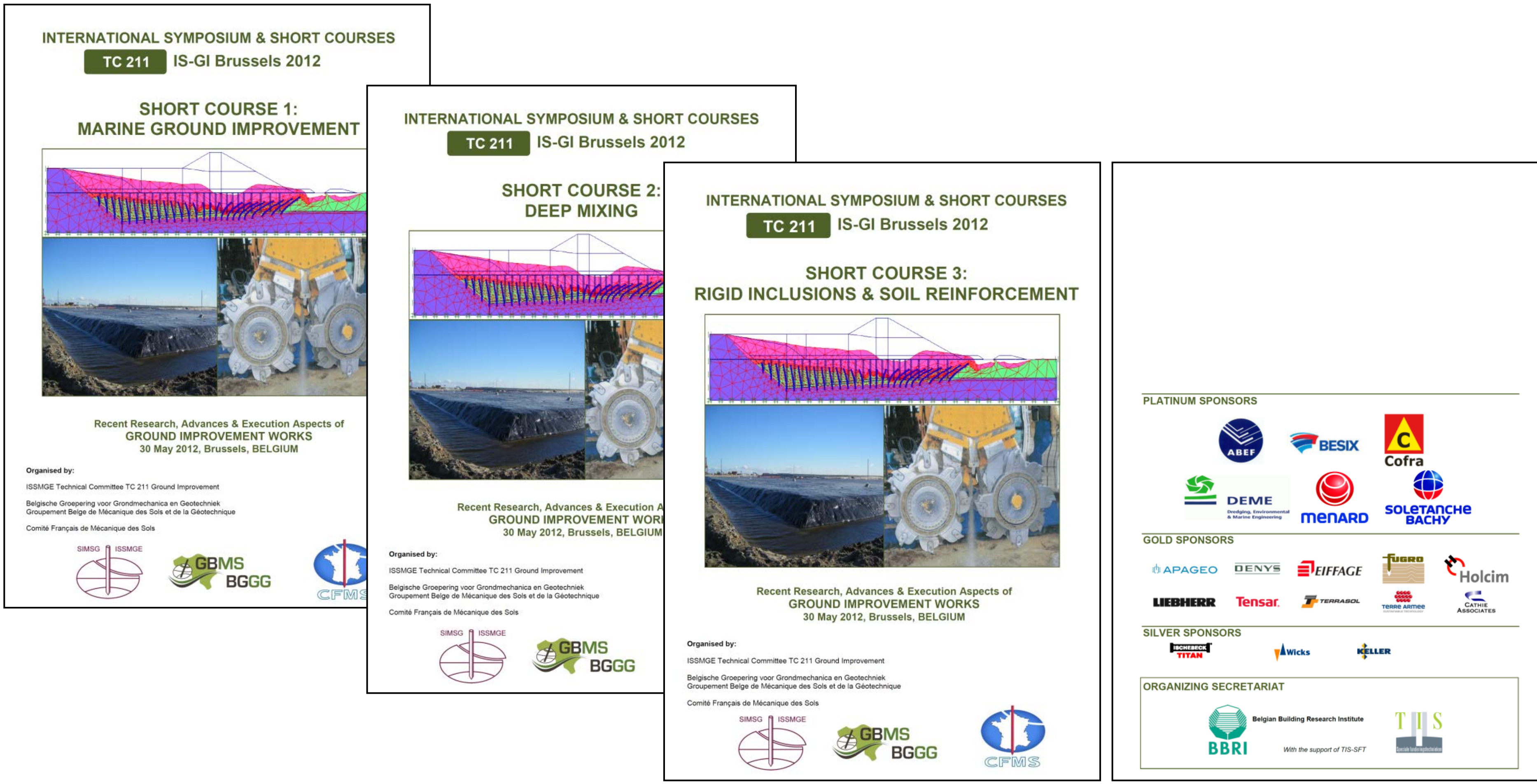
APAGEO

menARD ASIA

TC 211 IS-GI Brussels 2012

SIMSG ISSMGE GBMS BGGG CFMS

Wednesday 30 May – Short Courses : Publications



→TC 211 Workshop ICSMGE Paris 2013

Thursday 31 May & Friday 1 June - International Symposium (280 participants)

- 7 Plenary sessions
  Vibro & Impact compaction – Vertical drains,Vacuum consolidation & Preloading –
  Soil Stabilisation - Deep mixing – Rigid inclusions & Stone Columns
  Soil reinforcement in fill & in cut – Biogrout & other grouting methods
- Louis Menard lecture (P. Mengé, DEME)
- Specialty lecture by J.L. Briaud, President ISSMGE
- Technical Exhibition (16 Companies : gold & platinum sponsors)
- Banquet in the Belgian Comic Strip Centre – Horta (170 participants)

Profile participants short courses

-Participants from 36 countries – 6 continents
(B : 85 - F : 45 – other : 150)

- Contractors & Manufacturers	**: 48% *(B: 55%)***
- Design/consultants	**: 15 % *(B: 22%)***
- Research & academics	**: 33% *(B: 18%)***
- Government/owners	**: 4% (B: 5%)**

Parameters related to ground improvement

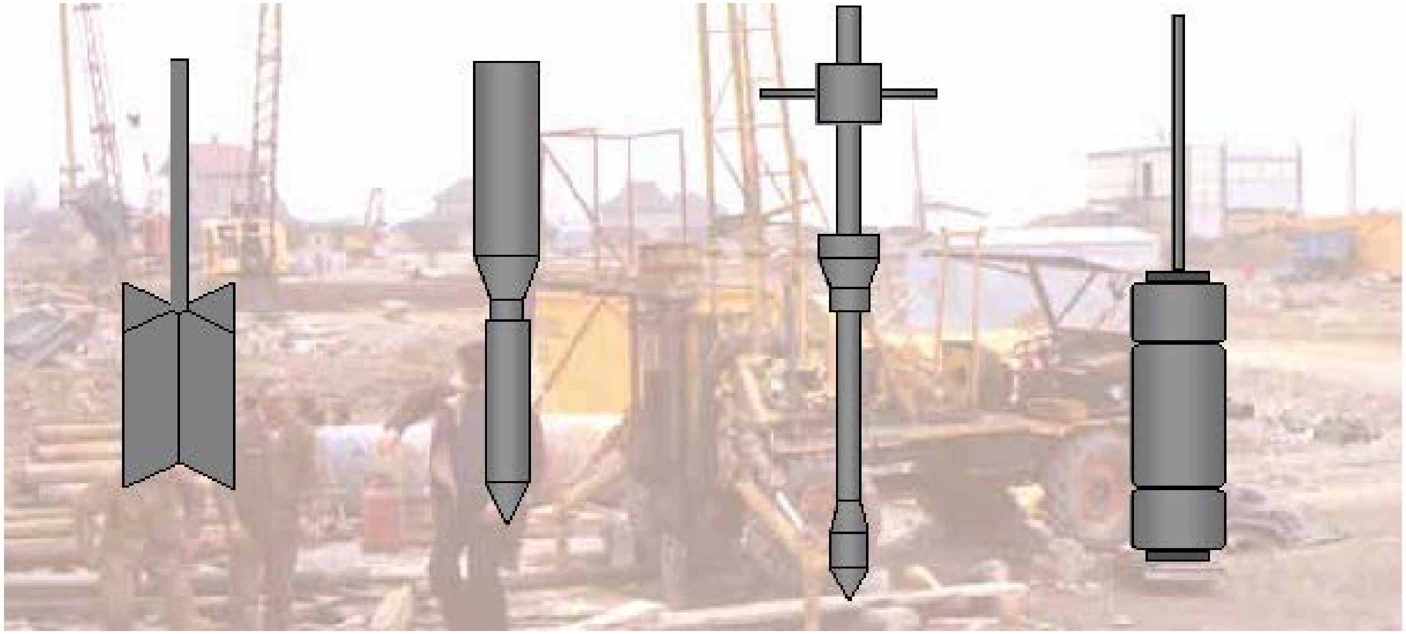
IN-SITU TEST

- Static Cone Penetration (CPT)
- Dynamic Penetration (SPT)
- Vane Test (VT)
- Menard Pressuremeter (PMT)

LABORATORY TEST

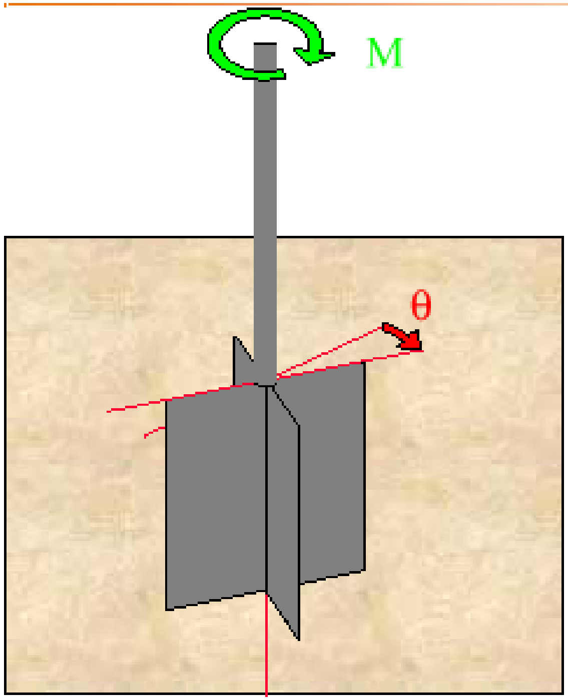
- Identification test
- Oedometer test
- Triaxial test

Parameters related to ground improvement : Differents types of in situ tests



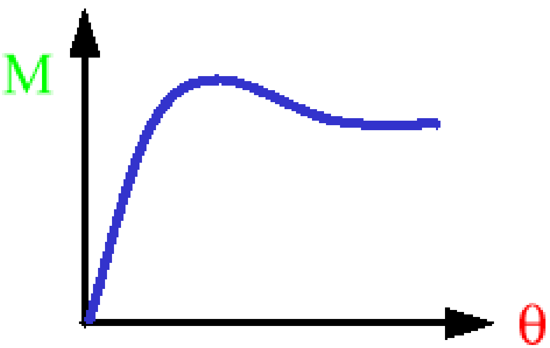
Vane test (VT)	Static Cone Penetration Test (CPT)	Dynamic Penetration Test (SPT)	Pressuremeter (PMT)

Vane Test



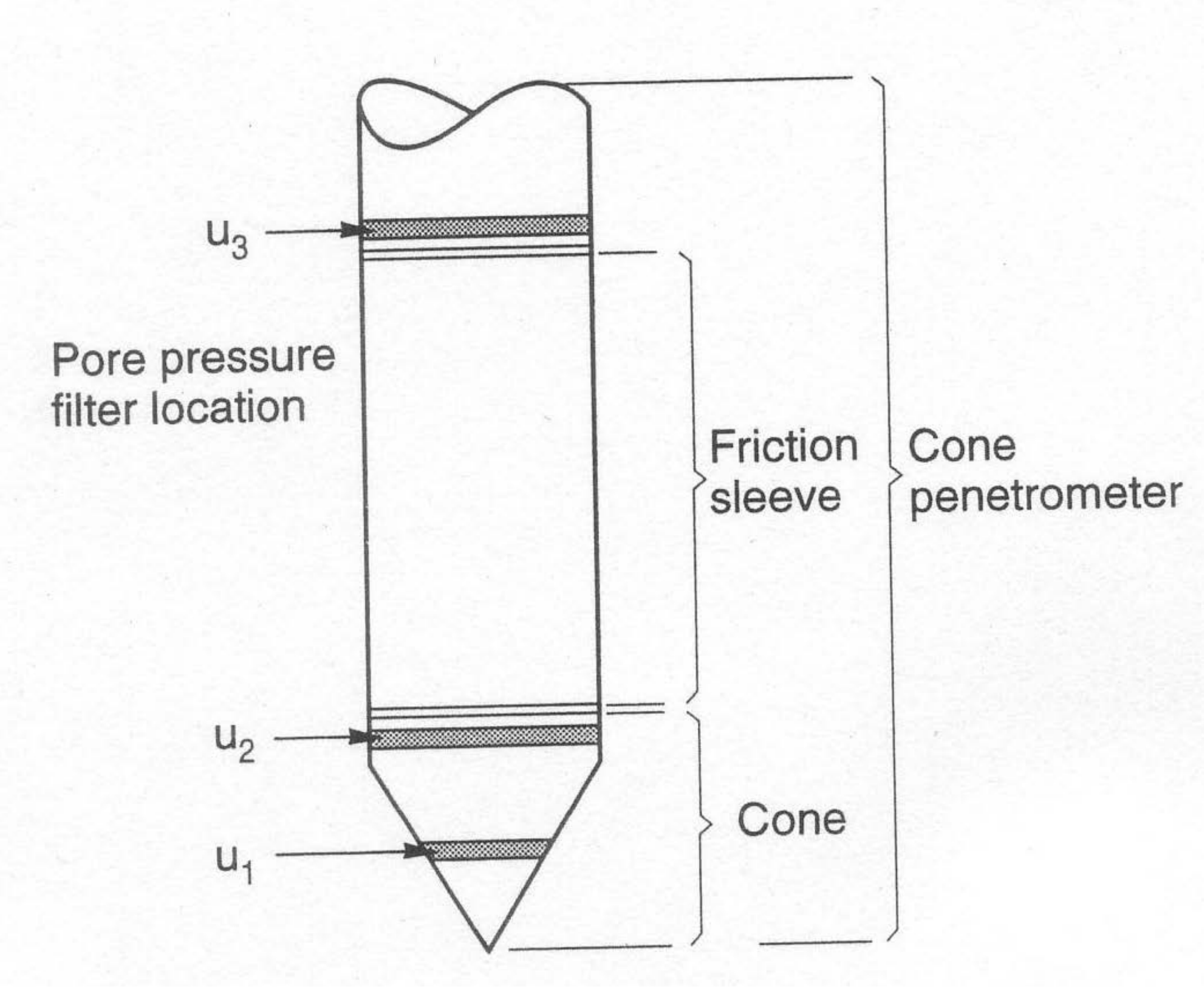
Cohesive soil

$$C_u = \frac{6M}{\pi D^2 (3H + D)}$$



➡ **Undrained cohesion of soils**

Static Penetration Test (C.P.T.)



Process of C.P.T.

- A 60º cone with face area 10cm² and 150cm² friction sleeve is hydraulically pushed into the ground (the device is pushed, rather than being driven by blows, into the soil).
- By applying a measure force to the rod, the cone is pushed into the soil at a constant speed of penetration (ranging form 1.5 to 2.5cm/s).

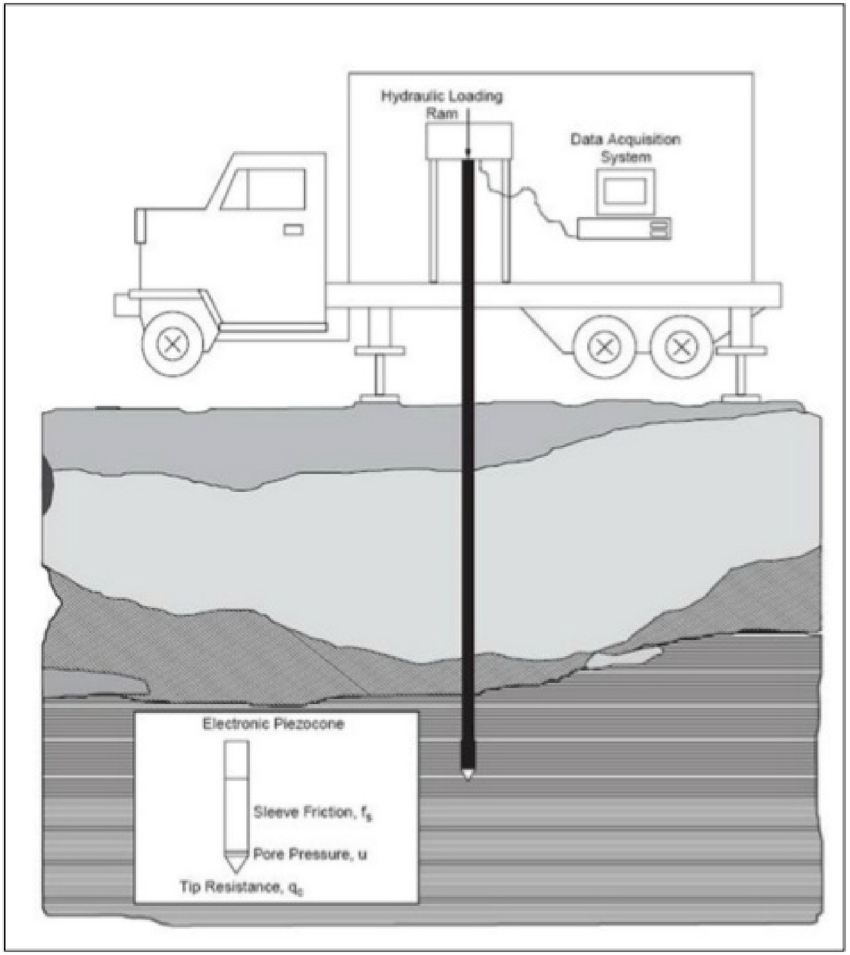


Figure 2.0 : Cone Penetration Test

Assessment of Cone Penetration Test

Advantage	Disadvantage
➢Rapid and inexpensive	➢No sample recovered
➢Reproducible result	➢Penetration depth limited to 150 – 200 feet
➢Real time measurement	➢Normally cannot push through gravel
➢Accurate, detailed subsurface stratigraphy / identification of problem soils	➢Requires special equipment and skilled operator

Static Penetration Test : Rought soil identification from CPT Test

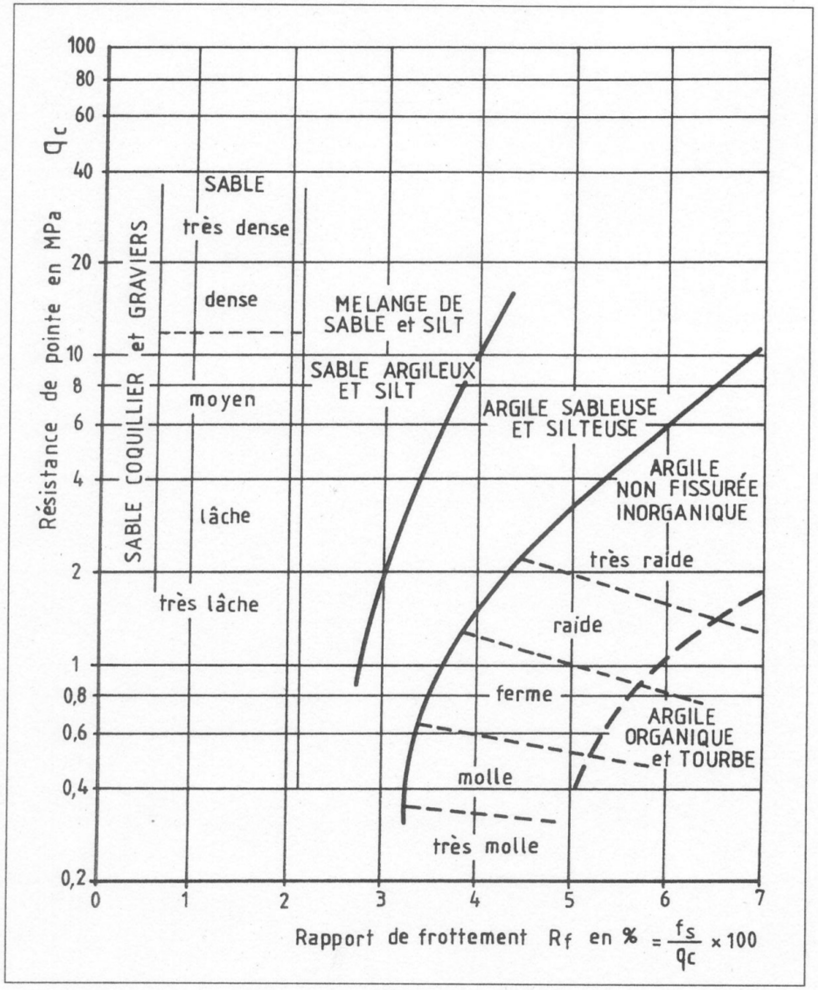
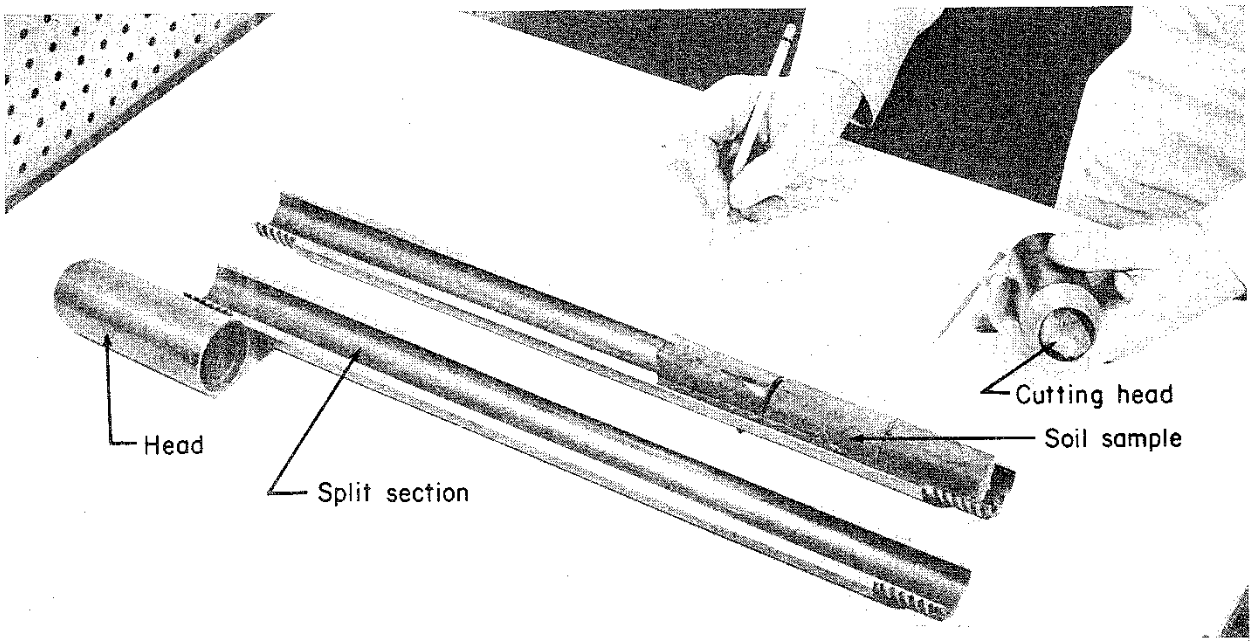
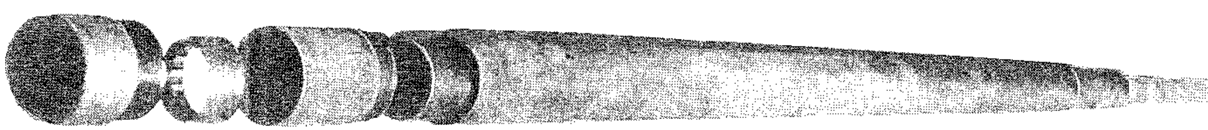


Fig. 6.14. Estimation de la nature des sols d'après q_c et R_f (Schmertmann 1969)

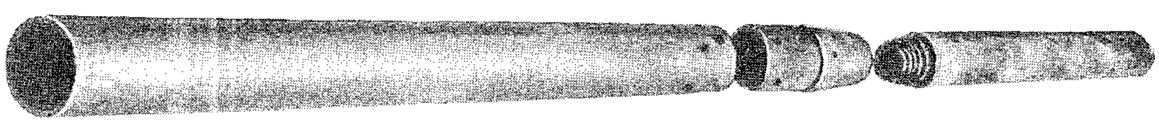
Dynamic Penetration Test
Parameters : N blows; soil identification



(d)



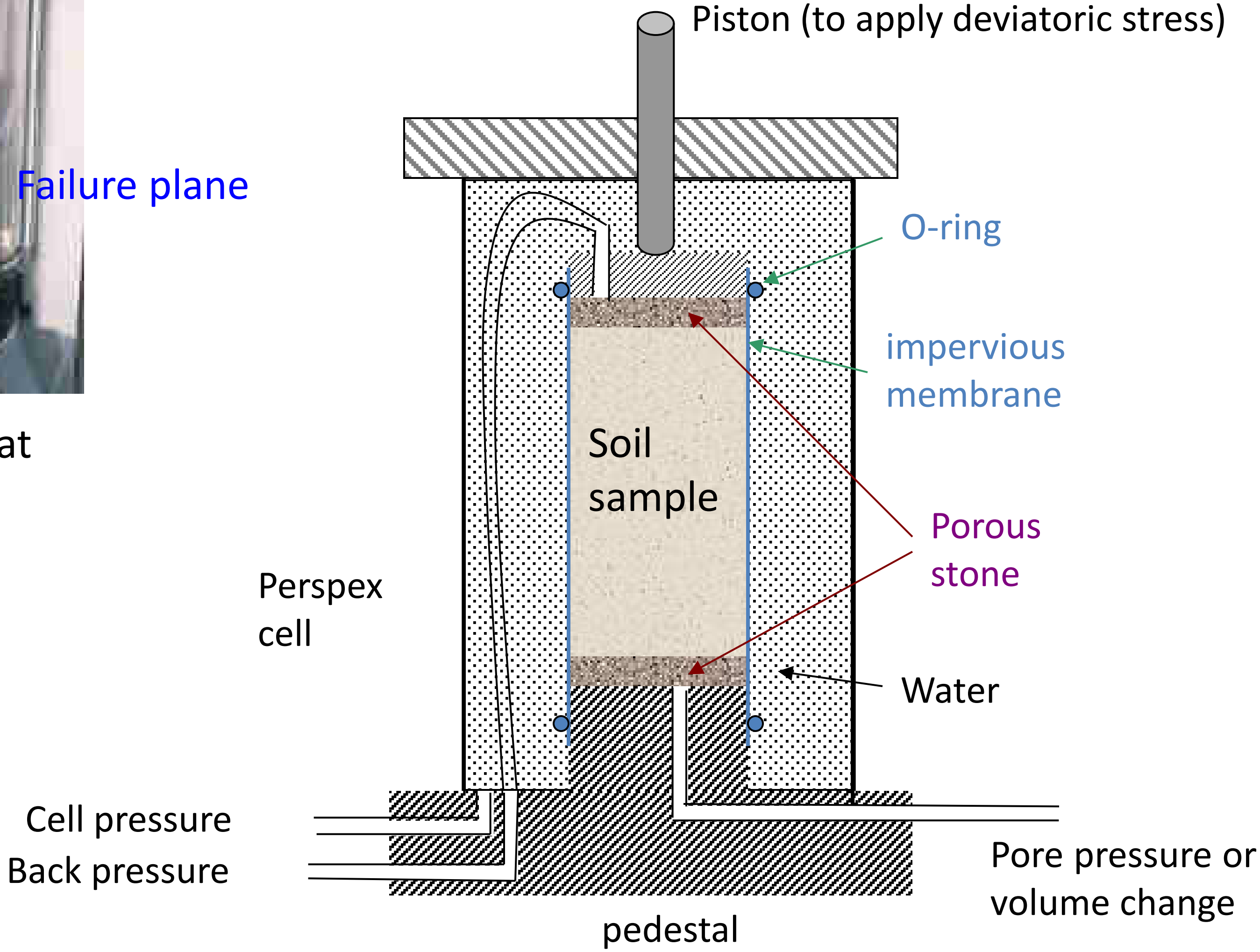
(e)



(f)

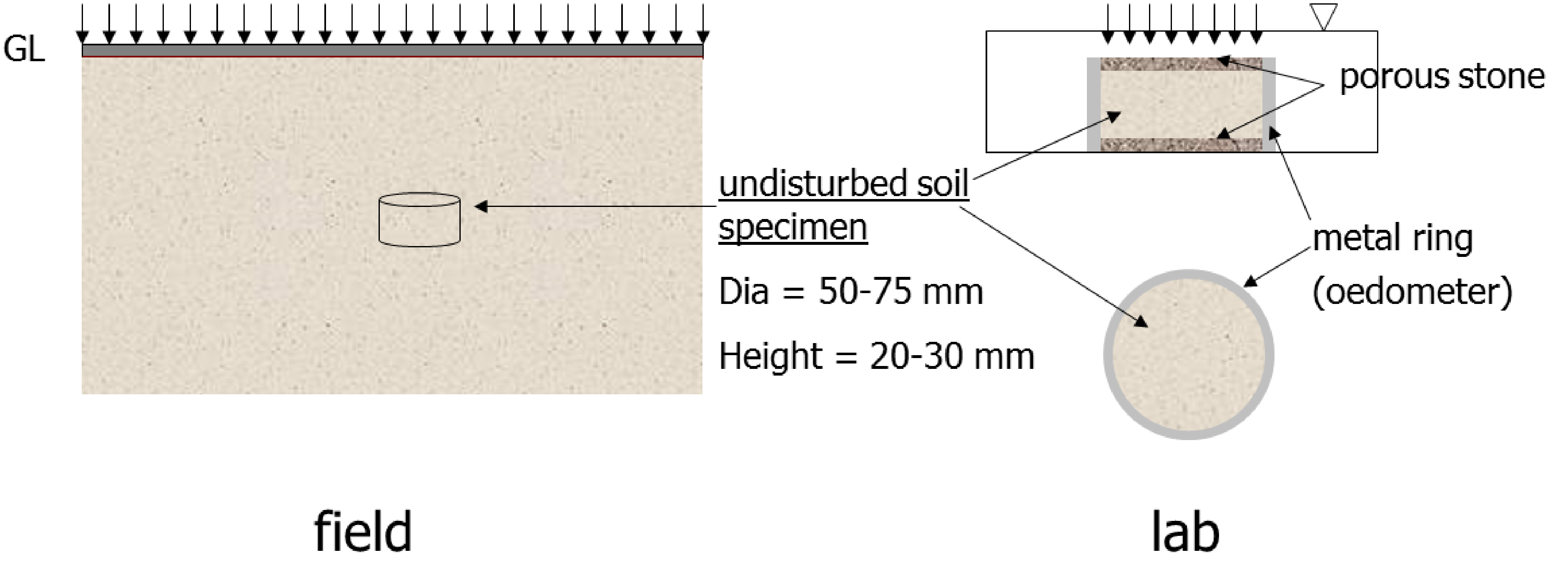
Triaxial test

Soil sample at failure



Consolidation Test: oedometer

~ simulation of 1-D field consolidation in lab.

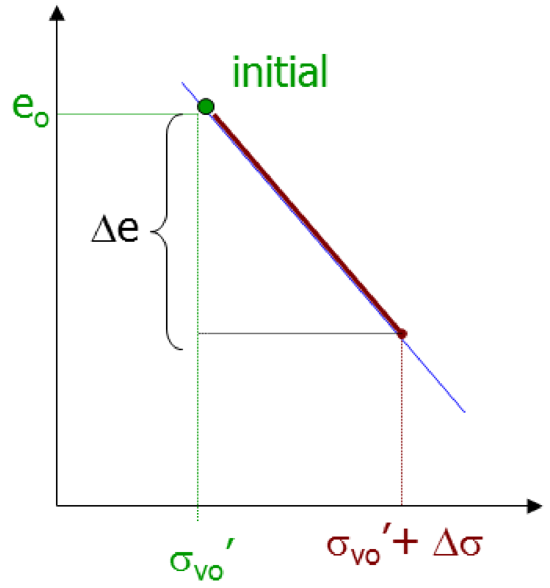


Settlement computations

~ computing Δe using e-log σ_v' plot

If the clay is normally consolidated,

the entire loading path is along the VCL.



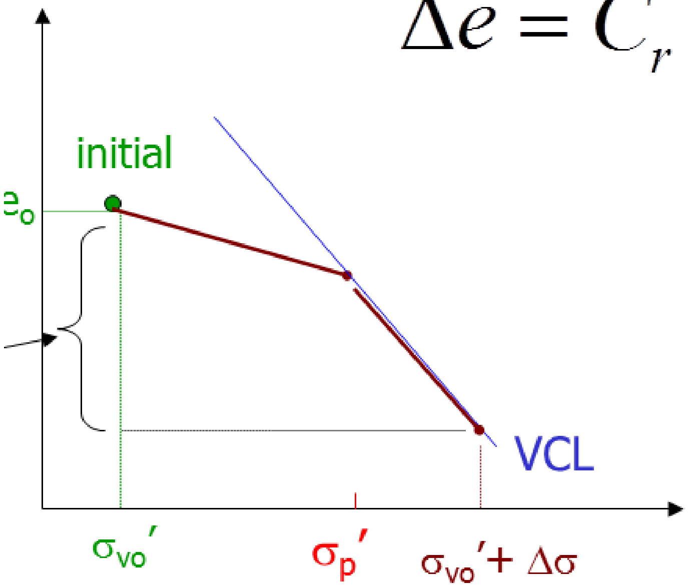
$$\Delta e = C_c \log \frac{\sigma_{vo}' + \Delta\sigma'}{\sigma_{vo}'}$$

Settlement computations

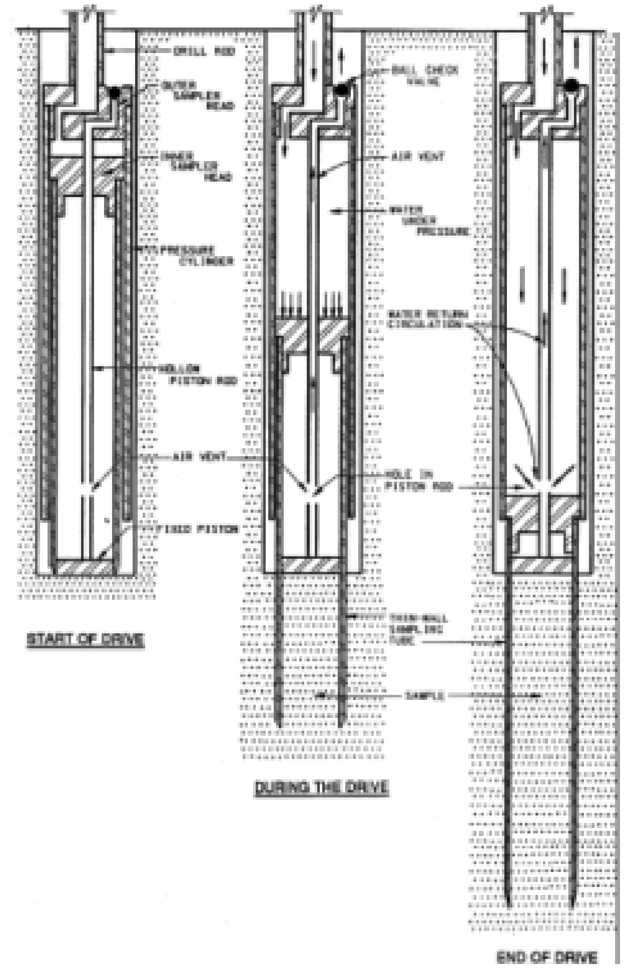
~ computing Δe using e-log σ_v' plot

If an <u>overconsolidated</u> clay becomes normally consolidated by the end of consolidation,

$$\Delta e = C_r \log \frac{\sigma_p'}{\sigma_{vo}'} + C_c \log \frac{\sigma_{vo}' + \Delta\sigma'}{\sigma_p'}$$

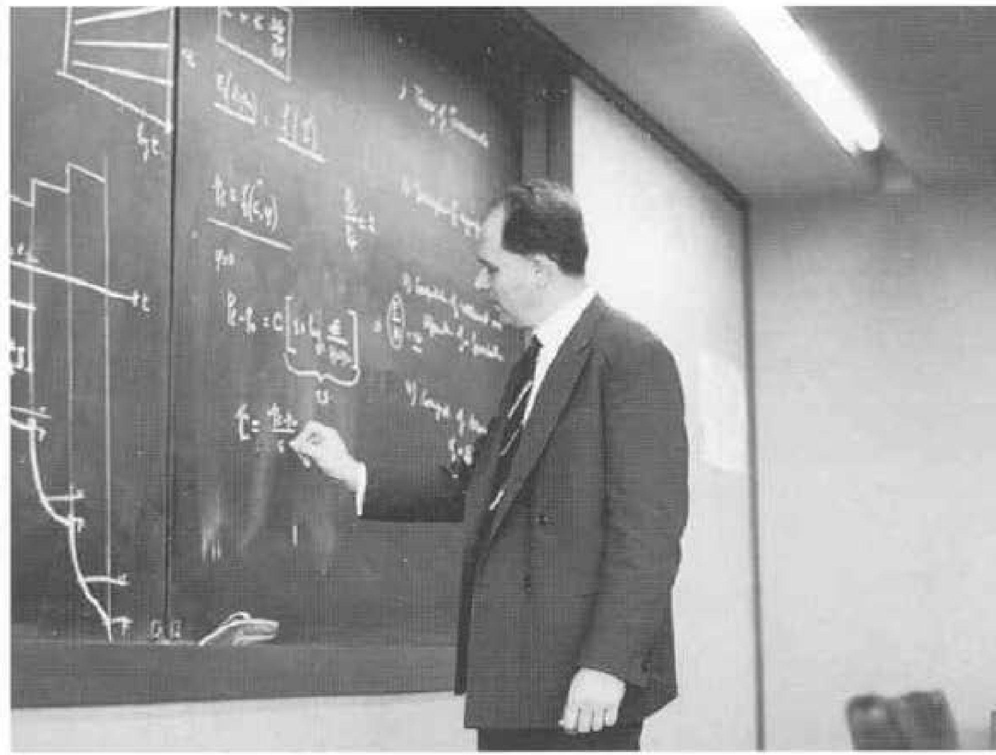


Osterberg piston sampler



Louis MENARD (1933-1978)

Courtesy of Michel Gambin

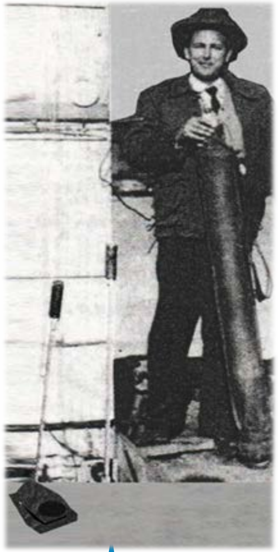


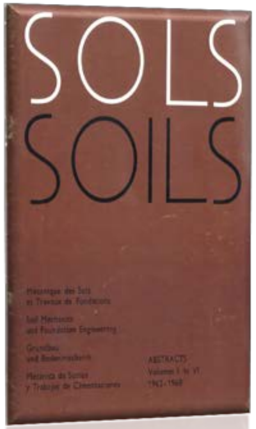
当社でプレシオメーターの講義をするメナール氏（昭和35〈1960〉年）

Courtesy of Kenji Mori

ENGINEER, INNOVATOR

PRESSUREMETERS IMPROVEMENTS WITHIN THE FIRST DECADE





1955 — **The second PMT prototype**

1967 — **D-9000** Versatile drill

1971-1975 — **G-type and GC-type Pressuremeter**

1975 — **Soil-soils** edited by Mike Gambin

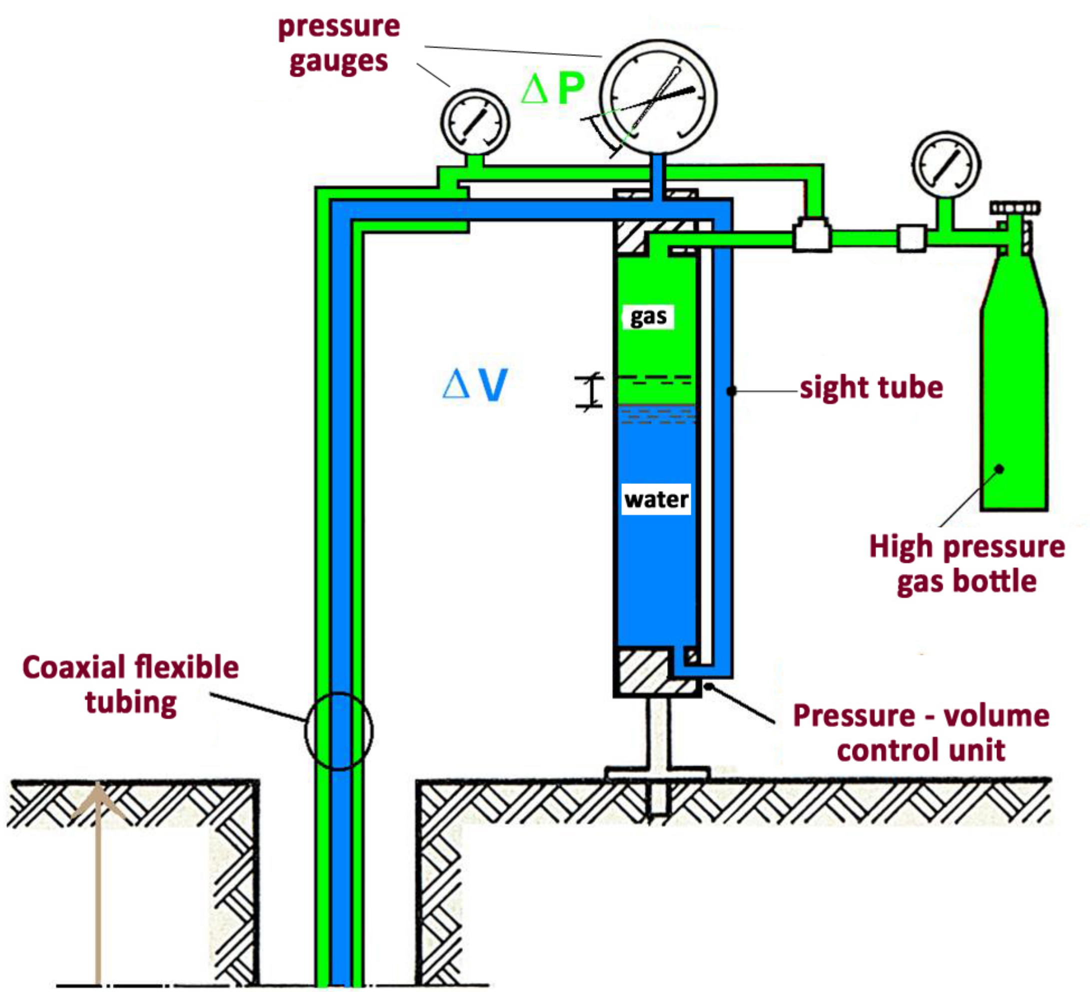
WHY PRESSUREMETER?

- Performed in previously drilled hole to any depth
- Performed in submerged sand or gravel, directly driven slotted casing or STAF® method
- Performed in fills even landfills (only possible technique)
- Provides its own reaction
- Large volume tested up to several tens of tons
- Average soil response
- Two stress-strain parameters
- Creep information
- Automatic data recording and test perfomance available
- Pressuremeter modulus (E_M) (independent from porepressure)
- Limit pressure (P_{LM}), close to failure of plate, footing or pile tip

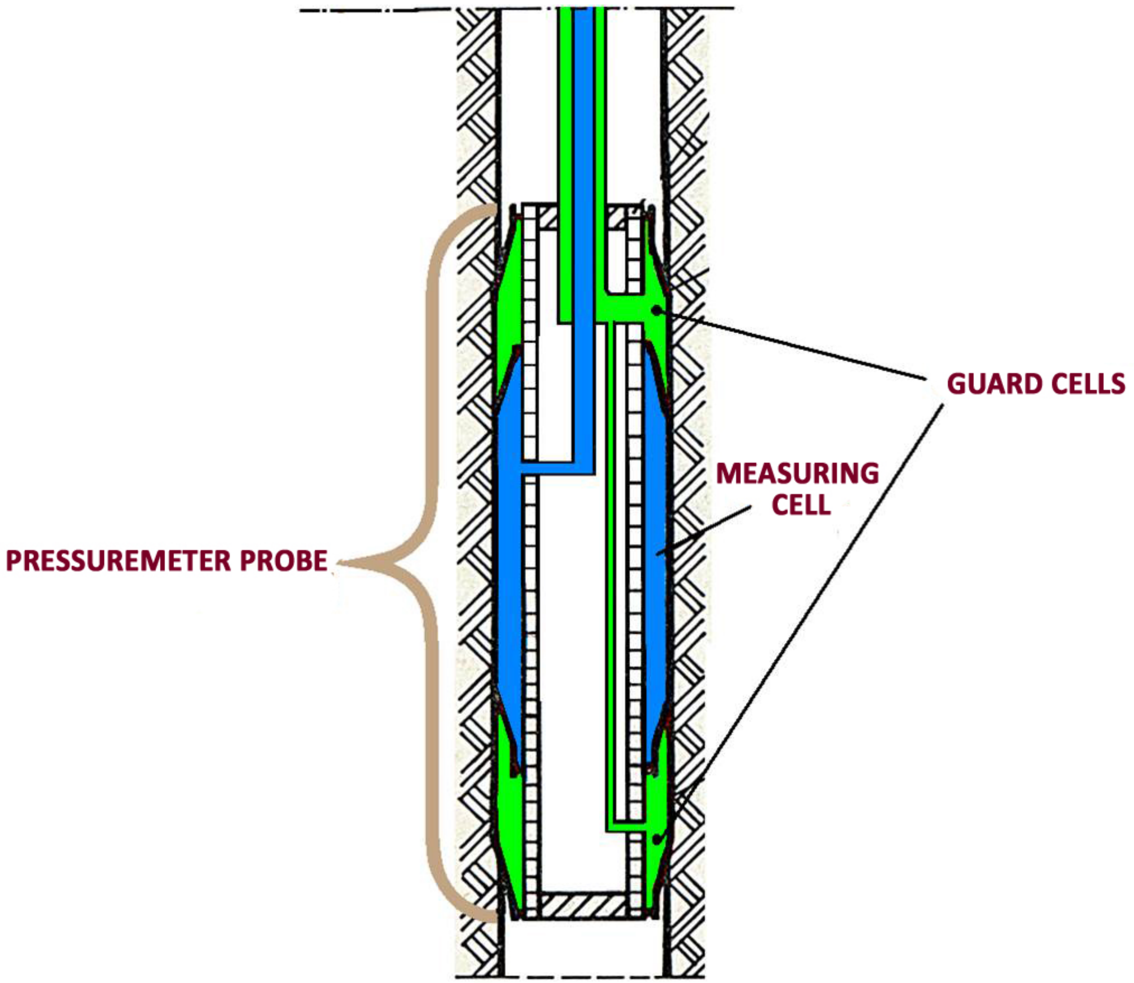
WHY STRESS CONTROLLED TESTS ?

- Strain is only consequence of stress and not its action
- Creep is available
- In construction, loading is stress controlled

General scheme of a Ménard pressuremeter

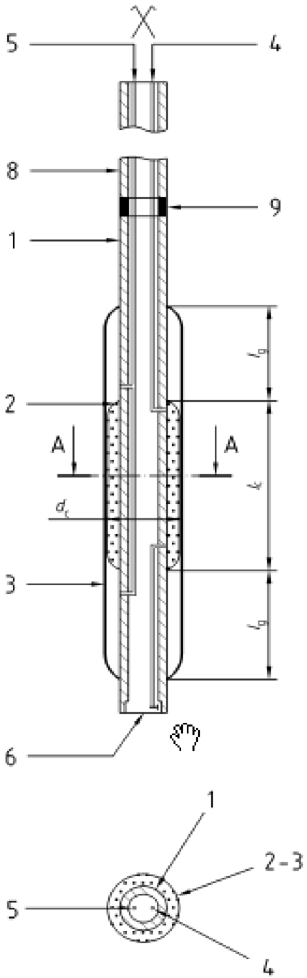


General scheme of a Ménard pressuremeter



Evolution of the pressuremeter

Detail of Ménard pressuremeter probe



<u>Type G probe :</u>
Central Cell + Flexible Cover to form 2 Guard Cells.
Central Cell Pressure is higher than in Guard Cells to balance cell membrane resistance.
Pressure lag between the Central Cell and the Guard Cells is kept constant at a given Depth

1 Hollow probe body
2 measuring cell membrane
3 external sleeve or flexible cover
4 water inlet to the measuring cell
5 gas inlet to the guard cells
6 measuring cell drain outlet
7 slotted tube
8 rods
9 probe/rod coupling

Latest state of the art

- GeoPAC® + GeoBOX

⇒ High precision and high pressure measuring tool.

⇒ Automatic piloting of the test, automatic recording and log presentation transmitted from GeoPAC® to GeoBOX® by Wifi and to the office by GPRS

⇒ Stress-controlled test (possibilities of cyclic program)

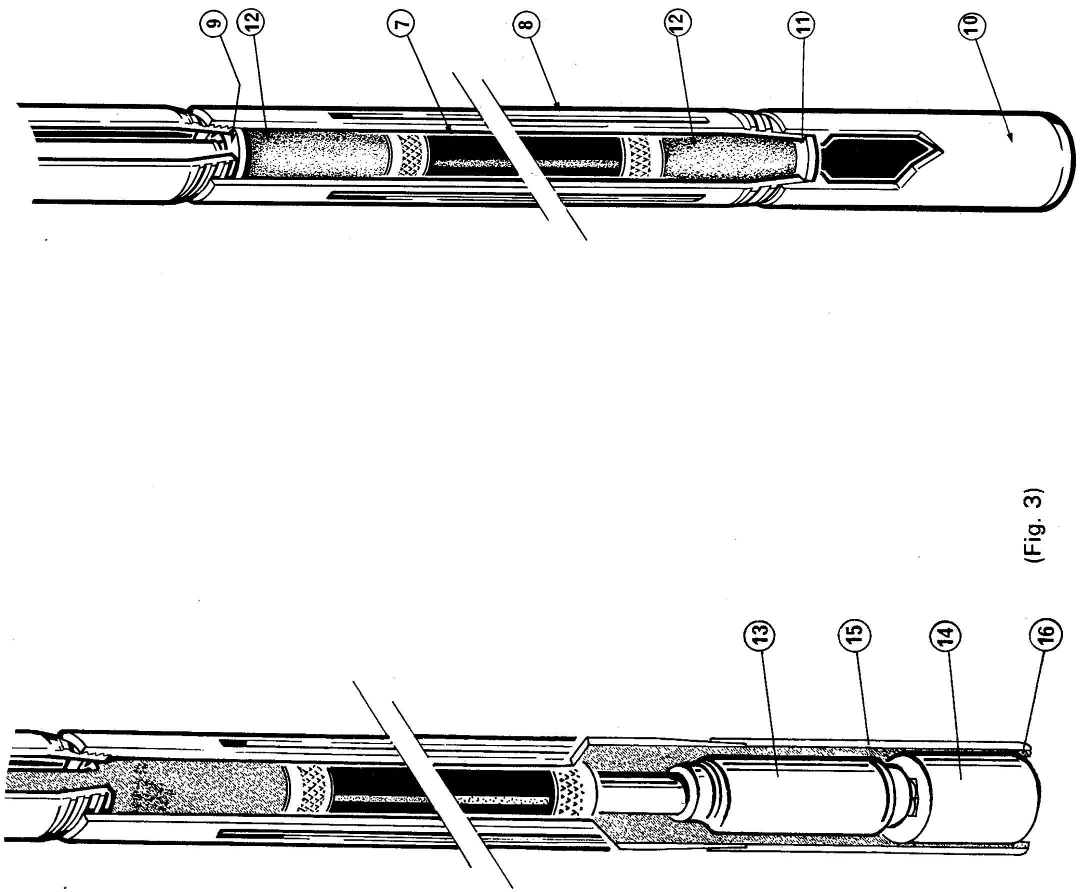
⇒ Ranges 0,1 cc to 100 Mpa

Evolution of drilling

- **Drilling methods from European norm**

- Hand auger
- Power auger
- Rotary drilling bit with bentonite injection
- Shelby tube sampler
- Slotted casing driving method
- Roto percussion
- Open slotted casing
- Recent STAF® Method (Self bored tube system)
- Self-boring pressuremeter probe under development

Slotted casing method



Cross section of a probe inside a slotted casing

The Menard Pressuremeter : typical loading tests

Typical ***load tests*** conducted on foundations :

(i) PBT; and

(ii) PMT

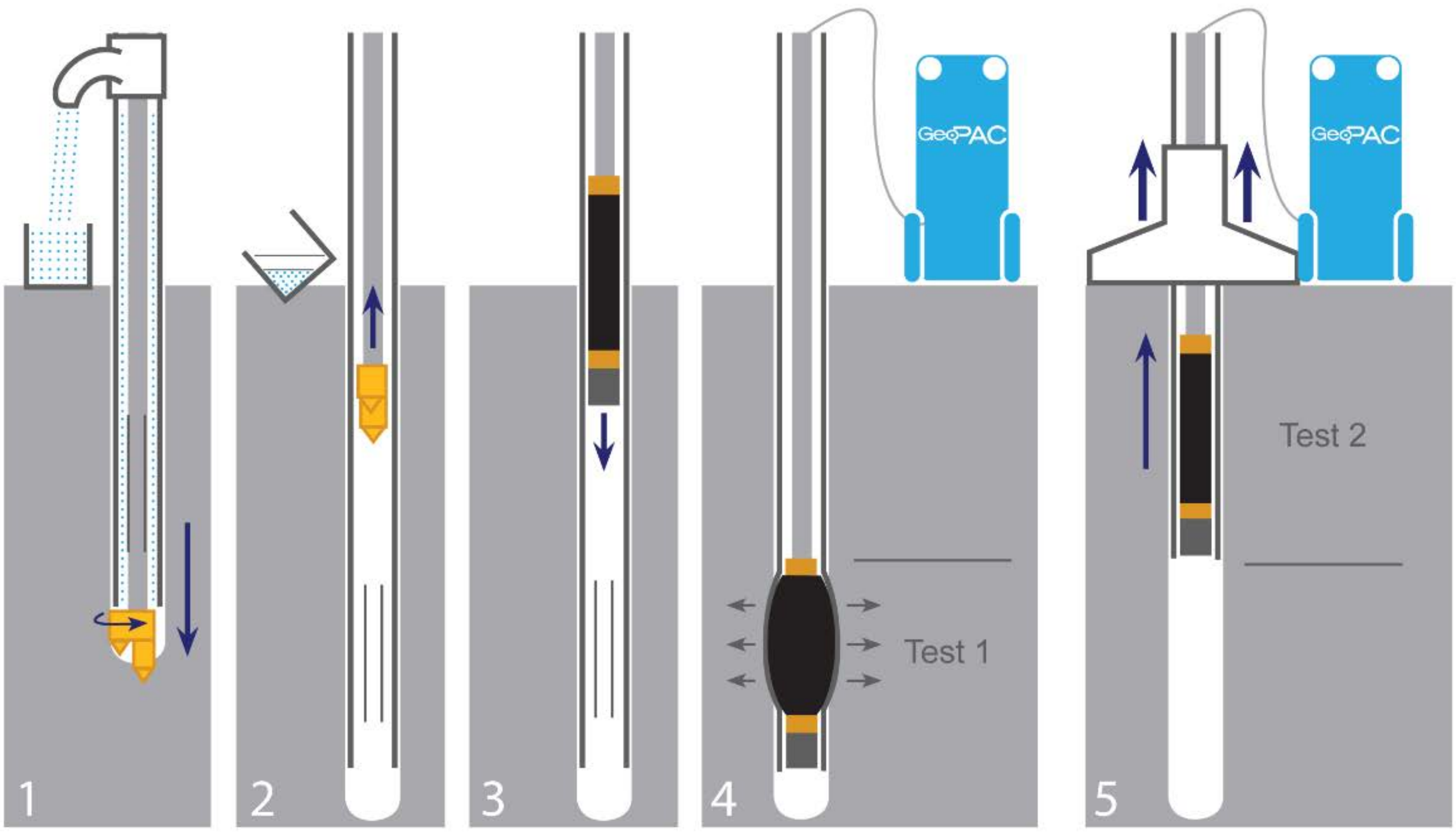
(*not CPT or SPT*)

PBT – vertical load test

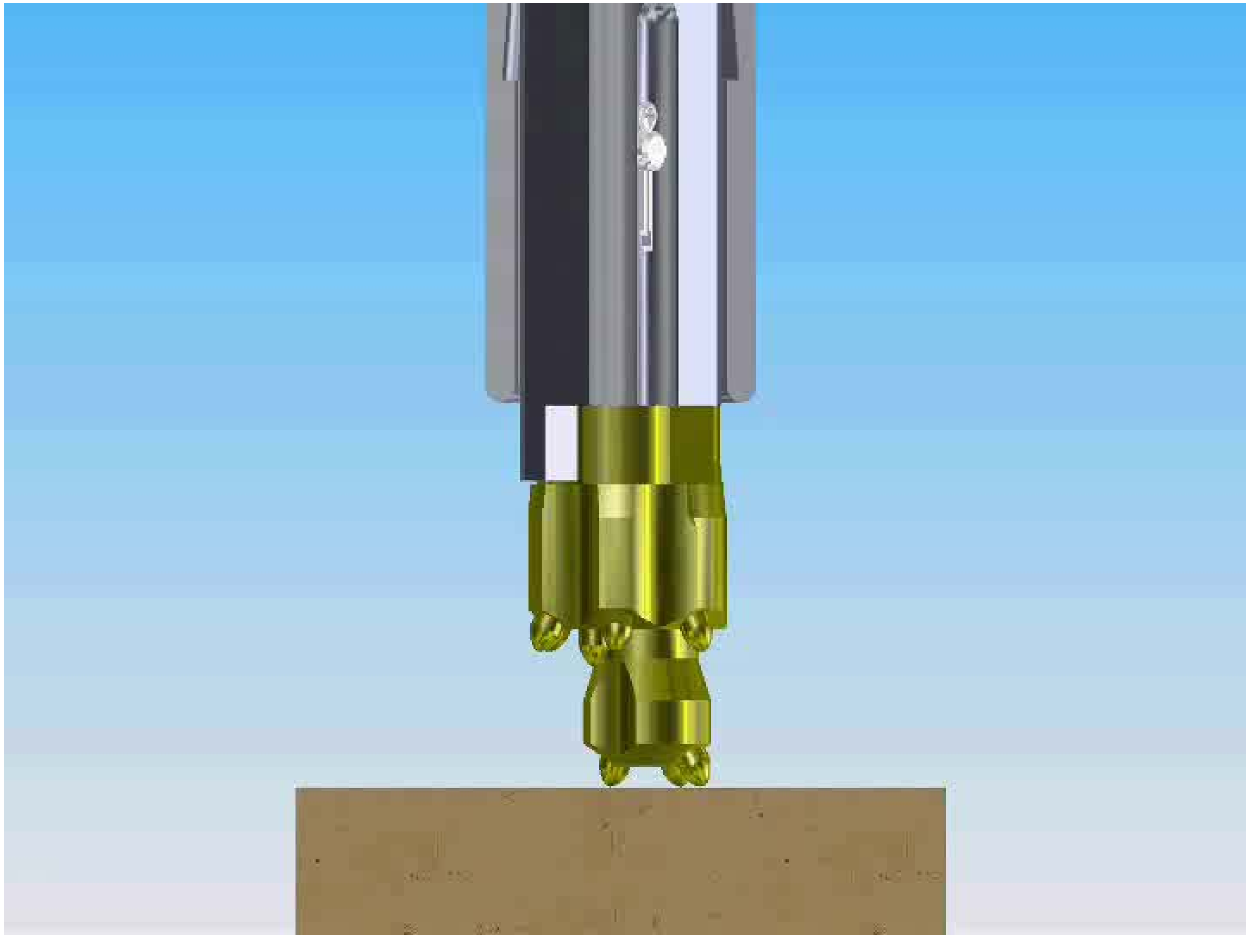
PMT – shear loading test

Self bored tube system STAF®

STAF® technique : Ménard Pressuremeter Tests inside a self-bored slotted tube

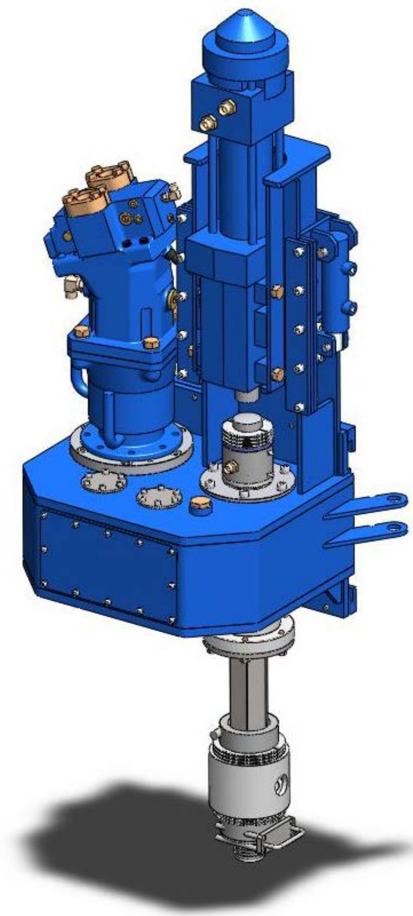


Self bored tube system STAF®



Roto percussion drilling

to reduce casing friction



The pressuremeter curve

- Typical PMT field record (manual recording)

FEUILLE D'ESSAI PRESSIOMETRIQUE :

CHANTIER de CROSNE

Date : 17/5/97 Heure :

Forage n° F4 Profondeur : 3 m

Type de forage : Taillant Ø 64 mm

Sonde Ø et mise en œuvre : 4 TF 56 mm

Feuille n° Pression différentielle :

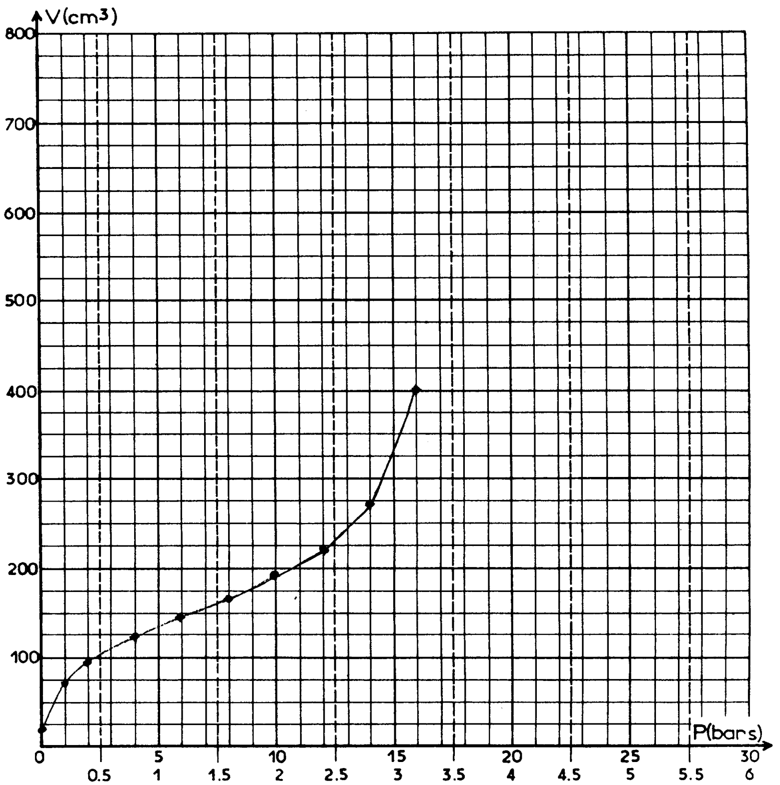
Pression	Volume	Diff.	Pression	Volume	Diff.
0	20		Report		
		52			
1	61	11	—		
	72				
		20			
2	90	2	—		
	92				
		28			
4	117	3	—		
	120				
		24			
6	142	2	—		
	144				
		20			
8	163	1	—		
	164				
		24			
10	186	2	—		
	188				
		31			
12	216	3	—		
	219				
		52			
14	263	8	—		
	271				
		69			
16	350	50			
	400				
18	↓				
—					

E PI

Inertie : F18

Nom de l'opérateur ELISABETH

COURBE PRESSION VOLUME :



Typical PMT test

- Geobox automatic test piloting and recording

European Pressuremeter Surveys Company
11 avenue Francis de Pressensé 93571 SAINT-DENIS LA PLAINE cedex
Tél. 33 (0)1 41 62 80 00 Fax 33 (0)1 49 17 90 00 catherine.pineau@afnor.fr

MENARD PRESSUREMETER TESTA DATA
Borehole expansion test conforming to EN ISO 22476-4 procedure B

SITE	
File	2366
Country	France
Job site identification	PARIS
Location plan ref.	IGC 23-15
Borehole number	FP 401

PROBE

CELL PARAMETERS				TUBING & FLUID PARAMETERS					PRESSURE LOSS PARAMETERS	
Code	44 g.c.t_l			Type	Coaxial X	Liquid	Nature	Eau	Correction sheet reference	ET10120202
Length		Cover			Twin		Unit weight γ_l/γ_w	1,00	Ultimate pressure loss p_{el} (MPa)	0,272
210 mm		Rubber		Total length (m)		Gas	Nature	Azote	VOLUME LOSS PARAMETERS	
370 mm	X	Reinforced mesh		30,00			Compressibility λ_g (m^{-1})	0,00016	Correction sheet reference	CA10120201
Type		Metallic mesh		MEMBRANE PARAMETERS					Calibration cylinder diameter d_i (mm)	65,0
E		Metallic strips		Supplier type and cote			m4		Calibration coefficient a (cm^3/MPa)	2,354
G	X	Slotted tube	X	Pressure loss p_m (MPa)			0,044		Probe volume V_s (cm^3)	1009,2

TEST	
Test number (or depth)	ES11120202
Test date and time	12 nov 02 - 13:19
Control unit number	-G200E-
Data logger number	201
Operator's name	TL
Differential pressure (MPa)	-0,100
Observations (weather, etc.)	sun 18°C

FIELD DATA									DATA CORRECTED from P&V losses			
Step	PRESSURES pr (MPa)				VOLUMES V(t) (cm^3)				PRESSURE	VOLUME	SLOPE m_i	CREEP
	1 s	15 s	30 s	60 s	1 s	15 s	30 s	60 s	p (MPa)	V^{60} (cm^3)	$\Delta V^{60/30}/\Delta p$ (cm^3/MPa)	$\Delta V^{60/30}$ (cm^3)
0								0,0				
1	0,052	0,052	0,047	0,055	30,6	58,2	77,8	88,3	0,028	87,9		10,4
2	0,101	0,097	0,096	0,096	92,6	97,5	99,3	100,5	0,066	99,8	312	1,2
3	0,138	0,153	0,151	0,155	103,6	109,1	111,6	114,0	0,115	112,9	271	2,5
4	0,198	0,200	0,205	0,203	118,9	123,2	125,7	128,7	0,156	127,2	350	3,1
5	0,247	0,250	0,253	0,251	133,6	138,5	141,6	144,7	0,195	142,8	397	3,1
6	0,300	0,303	0,305	0,310	149,6	156,3	160,6	166,7	0,236	164,5	528	6,1
7	0,348	0,347	0,350	0,353	171,6	179,0	183,3	190,6	0,266	188,1	777	7,3
8	0,408	0,405	0,395	0,402	198,6	208,4	214,5	224,4	0,299	221,5	1032	9,8
9	0,455	0,455	0,452	0,455	232,9	245,8	255,6	273,4	0,328	270,2	1687	17,8
10	0,501	0,504	0,505	0,505	283,8	299,8	315,1	339,0	0,350	335,5	2869	23,9
11	0,548	0,552	0,550	0,554	350,0	370,2	388,0	423,0	0,369	419,2	4532	34,9
12	0,603	0,603	0,599	0,601	438,9	463,4	488,6	533,9	0,390	529,9	5343	45,4
13	0,641	0,652	0,649	0,650	550,5	582,3	614,8	673,7	0,413	669,3	6054	58,8
14												
15												
16												
17												
18												
19												
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22												
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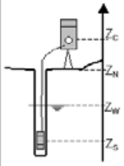
24												

LEVELS



Datum	Levels	Relative levels
Z_C	83,80	+ 0,80
Z_N	83,00	0 (borehole top)
Z_W	86,00	- -3,00
Z_S	81,00	- 2,00

BOREHOLE		
Localization system		X =
		Y =
Drilling rig		BE 2050
Drilling method (table C abbreviations)		THC.63
Drilling tool	type	fishtail
	diameter (mm)	63,5
Casing foot at (m depth)		n.a.
Drilling fluid		none
Drilling length before testing	from level (m)	2,00
	to level (m)	2,70
	time completed	

UNITS		
Elevations	metre	m
Times	second	s
Volumes	cubic centimetre	cm^3
Pressures	Megapascal	MPa

Typical PMT test report and interpretation

European Pressuremeter Surveys Company

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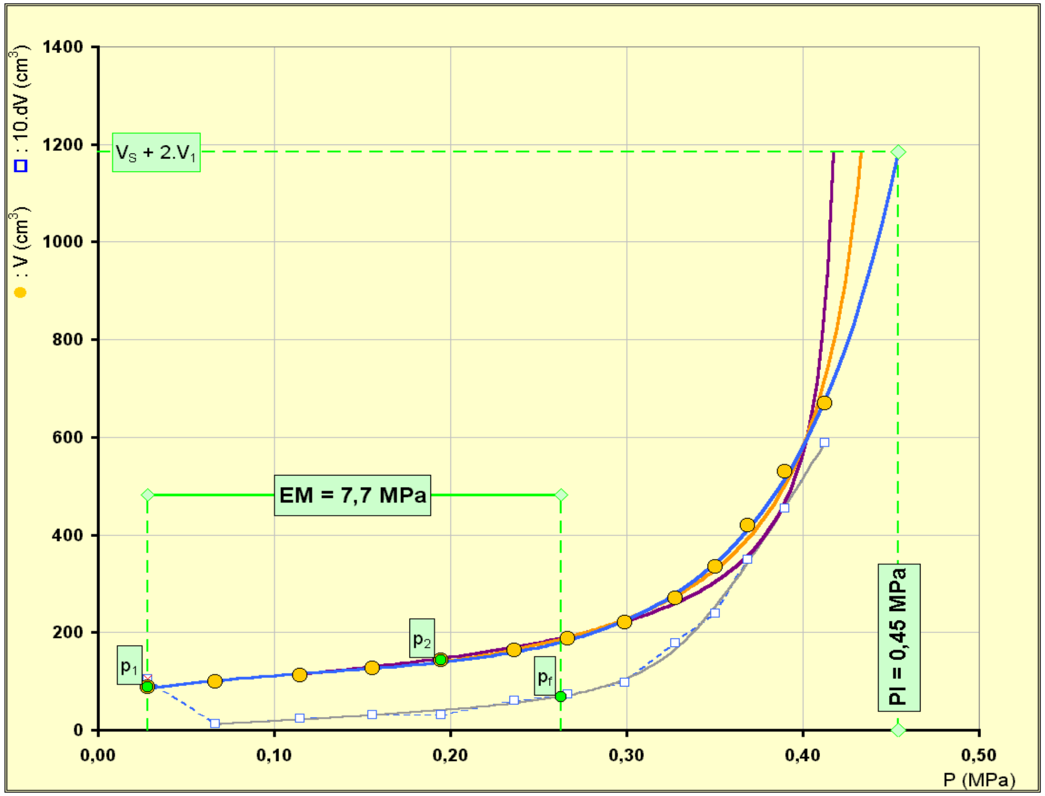
Tél . 33 (0)1 41 62 80 00 Fax 33 (0)1 49 17 90 00 catherine.pineau@afnor.fr

MENARD PRESSUREMETER REPORT AND INTERPRETATION

Borehole expansion test conforming to EN ISO 22476-4 procedure

File	2366
Test reference	ES11120202
Job site identification	EVRY
Borehole	FP.401
Test depth	2,00



CALCULATED NORMATIVE RESULTS	
σ_{hs}	0,018
p_1	0,03
p_2	0,19
p_f	0,26
p_l	0,45
p_l^*	0,44
E_M	7,7
E_M / p_l	16,9
E_M / p_l^*	17,6

EXTRAPOLATION METHODS PARAMETERS		
inverse volumes	A	-2,64E-02
	B	1,23E-02
	Average error (cm³)	1,44E+01
hyperbolic	C	4,22E-01
	D	1,12E+04
	Average error (cm³)	3,49E+01
double hyperbolic	A1	1,42E+06
	A2	-7,12E+04
	A3	2,84E+07
	A4	3,00E+02
	A5	-2,00E+01
	A6	5,74E-01
	Average error (cm³)	5,21E+00

COMMENTS

Geomatech XPressio 2.10

What is a pressuremeter modulus

- Compression modulus $E = \sigma / \varepsilon$
- Shear modulus $G = \tau / \gamma$
- Poisson coefficient (ν) $\nu = -\left(\frac{d\phi}{\phi}\right) \Big/ \left(\frac{d\ell}{\ell}\right)$

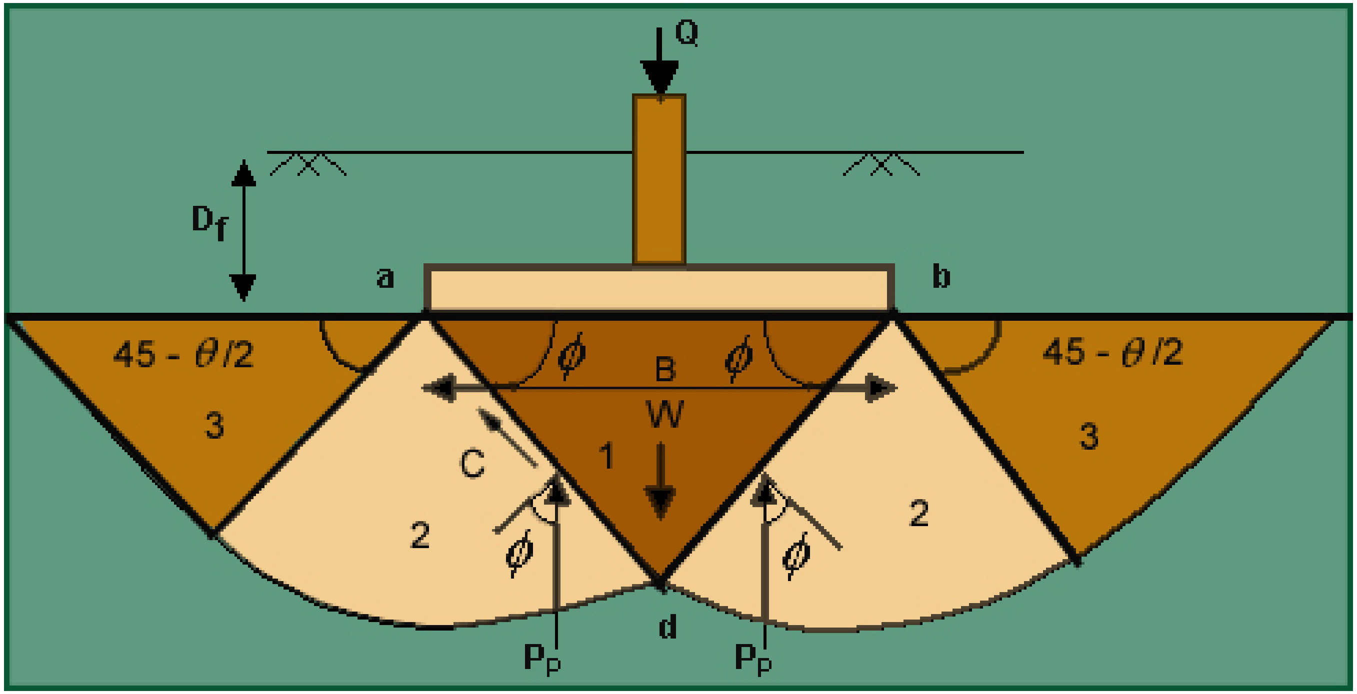
- The relation between moduli is $E = 2(1+\nu) \cdot G$

- Ménard proposes to always adopt $\nu = 1/3$

so $E_M = 2(1+\nu) \cdot V_m \cdot \frac{\Delta P}{\Delta V}$ or $E_M = \frac{8}{3} . (V_S + \frac{V_1 + V_2}{2}) . \frac{\Delta P}{\Delta V}$

Bearing capacity

- Prandtl and Terzaghi theory and limitations



Prandtl's Theory on Bearing Capacity Analysis

Prandtl 1920 developed an equation based on his study of penetration of long hard metal puncher into softer materials for computing the ultimate bearing capacity. He made the following assumptions for the derivation.

- The material is softer, homogeneous and isotropic.
- The material is weightless and possesses only friction and cohesion.
- The problem is two dimensional
- The base of the puncher is smooth.
- The material behaves as a rigid body.
- The volume change will be Zero.
- The resulting deformation will be a plastic deformation.

Bearing capacity after Terzaghi	Bearing capacity after Ménard
Function of (h, γ, D, c, Φ)	Function of $q_L - q_o = k_p (p_{LM} – p_o)$

$$q_L - q_o = k_p (p_{LM} – p_o)$$

here qL is the ultimate bearing stress at the footing or pile tip

- q_o the vertical overburden stress at pile tip depth
- k_p the Ménard Bearing Factor at footing or pile tip and type of soil
- p_{LM} the Ménard limit pressure at footing or pile tip depth
- p_o the insitu horizontal effective stress at footing or pile tip depth

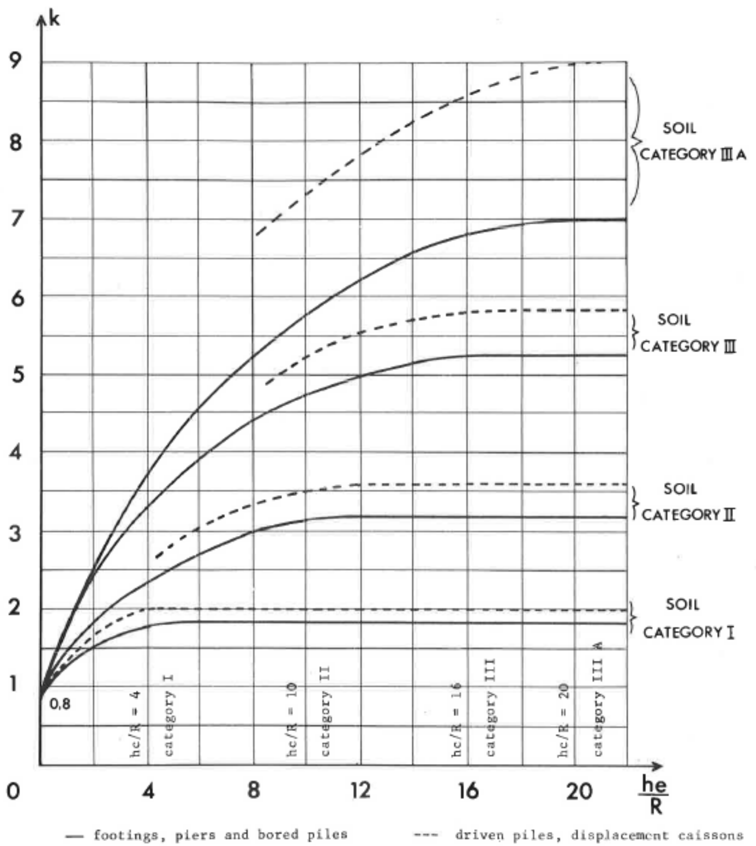
and it appears that, below a “critical depth”, the tip bearing capacity alone is much

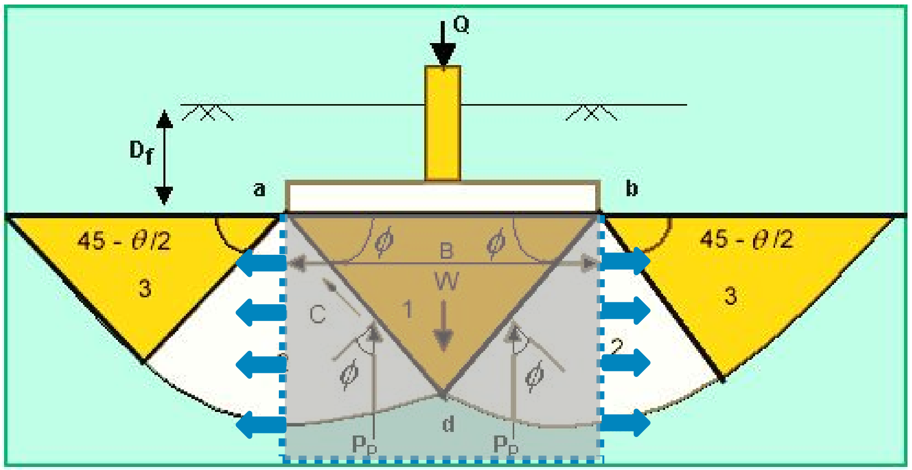
less than predicted by the c’ and Φ’ (Mohr - Coulomb)

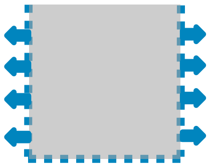
Pressuremeter bearing capacity factor

BEARING FACTOR AGAINST EMBEDMENT

FOR ISOLATED FOOTINGS, PIERS AND PILES





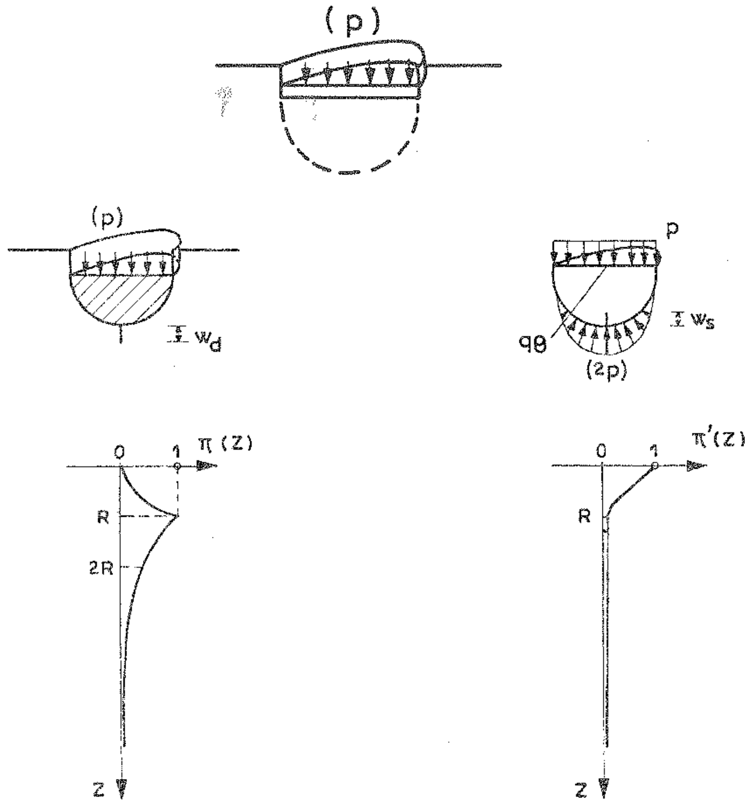


Pressuremeter probe, equal active zone
Surrounding soil passive reaction

Settlement and deformation

D/ Menard deformation approach

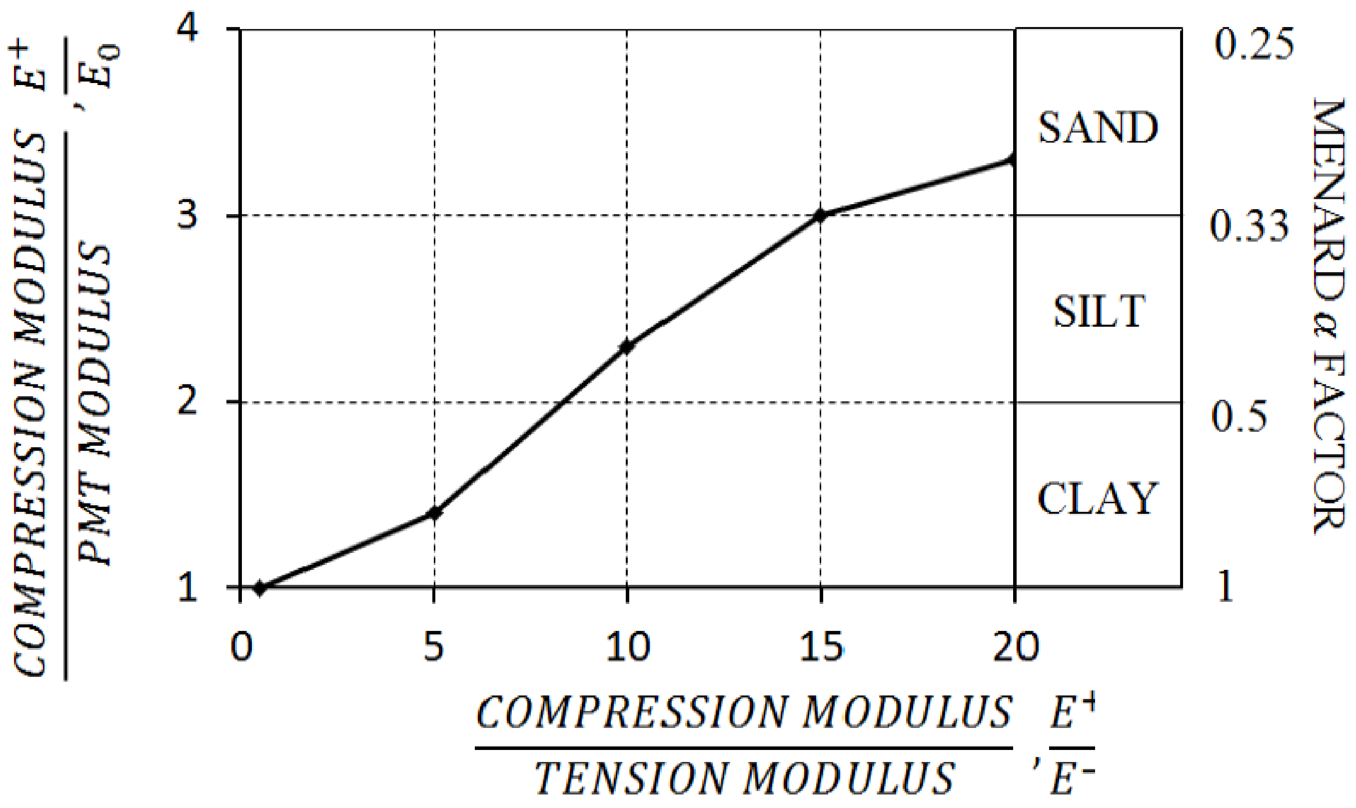
$W_{(10\ years)}=$



Shear domain

Spherical domain or volumetric

NO TENSION IN SOIL IMPACTS THE PMT MODULUS BECAUSE ELASTICITY ASSUMES TENSION



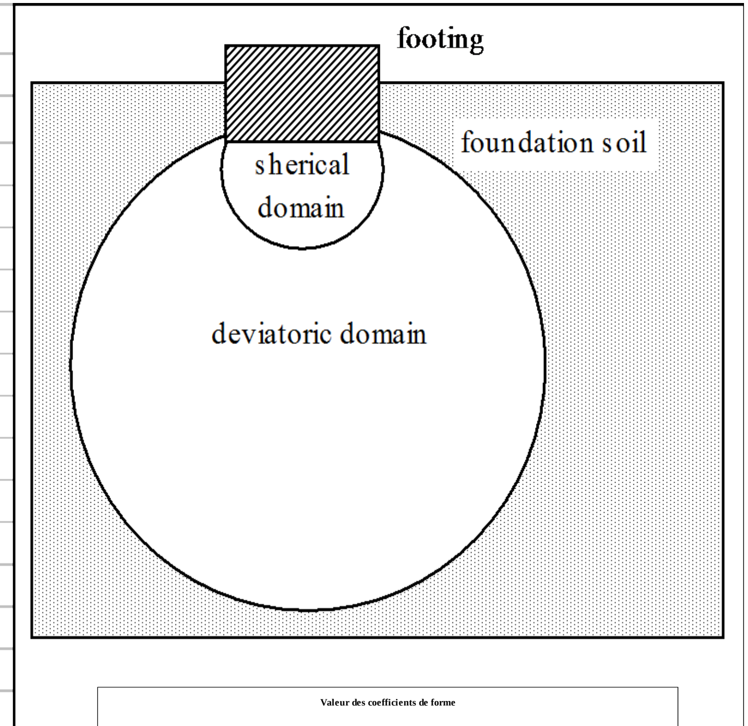
Briaud, Ménard lecture 2013

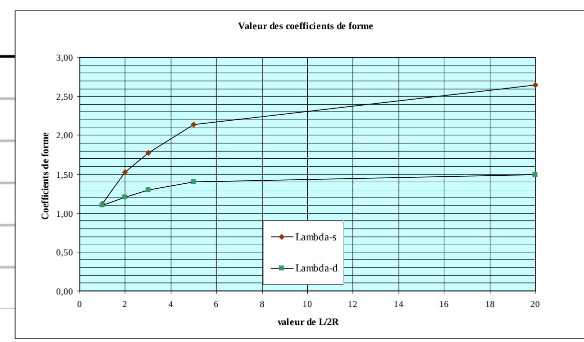
The Menard Pressuremeter : Settlement calculation under a footing

half width reference radius	R	0,30	m
Reference radius	R_0	0,30	m
Footing length	L	0,60	m
Pression sur la fondation	p	9,40	bars
PMT modulus in deviatoric domain	Ed	250	bars
PMT modulus in spherical domain	Es	250	bars
Rheological factor	α	1/4	
Shape factor	λd	1,10	
Shape factor	λs	1,12	

$$W = \frac{1.33}{3E_d} p R_0 \left(\lambda_d \frac{R}{R_0}\right)^{\alpha} + \frac{\alpha}{4.5E_s} p \lambda_s R$$

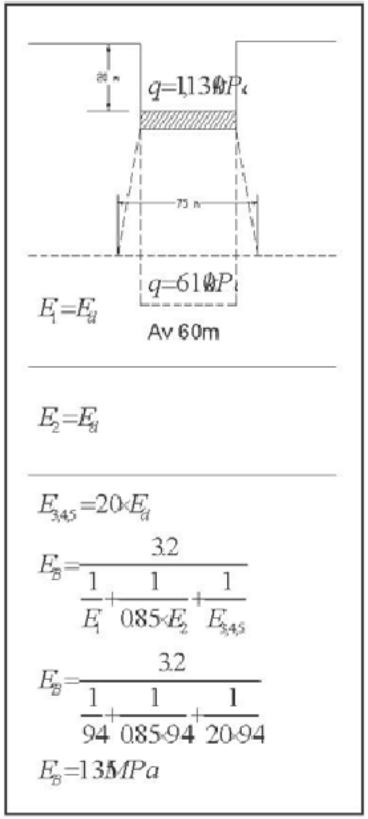
Results			
Spherical strain	Ws	0,07	cm
Deviatoric strain	Wd	0,51	cm
Calculated settlement	**W**	**0,58**	**cm**





SETTLEMENT UNDER HIGH RISE BUILDINGS IN CHICAGO

TERZAGHI LECTURE 2009
Clyde N. BAKER Jr



Pressuremeter Data

$E_{d_{Av}} = 94.3 Mpa$

$E^{+}_{Av} = 267 Mpa$

$\alpha = \frac{E_d}{E^{+}} = 0.35$, Use 0.4

Settlement Calculation – Menard Empirical Method

$$s_{Menard} = \frac{1.33}{3 \times E_B} q R_0 \left(\lambda_2 \frac{R}{R_0} \right)^{\alpha} + \frac{\alpha q \lambda_3 R}{4.5 E_1}$$

$\lambda_2, \lambda_3 = 1$ for a circle

$R_0 = 30 cm$

$$s_{Menard} = 0.55 cm + 2.16 cm = 27.1 mm$$

Settlement Calculation – Elastic Theory

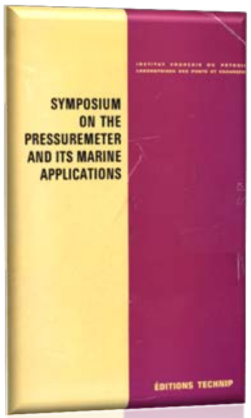
$$s_{Elastic} = \frac{\mu_0 \mu_1 q B}{E}$$

$$s_{Elastic} = \frac{0.35 \times 0.92 \times 6{,}100 \times 75{,}000}{250{,}000} = 59 mm$$

Measured 24 mm

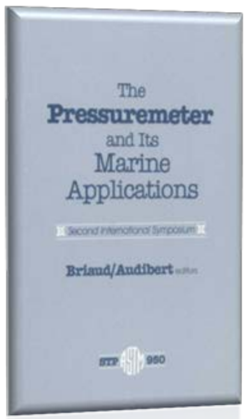
Pressuremeter through international symposiums and norms

1982
Paris, FRANCE



23
papers

1986
Texas, USA

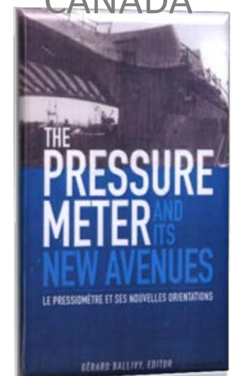


26
papers

1990
Cambridge, UK

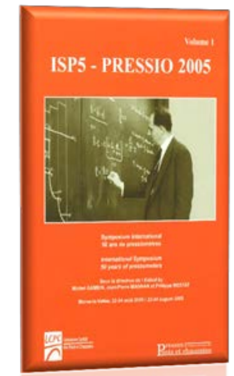
36
papers

1995
Sherbrooke, CANADA



54
papers

2005
Paris, FRANCE

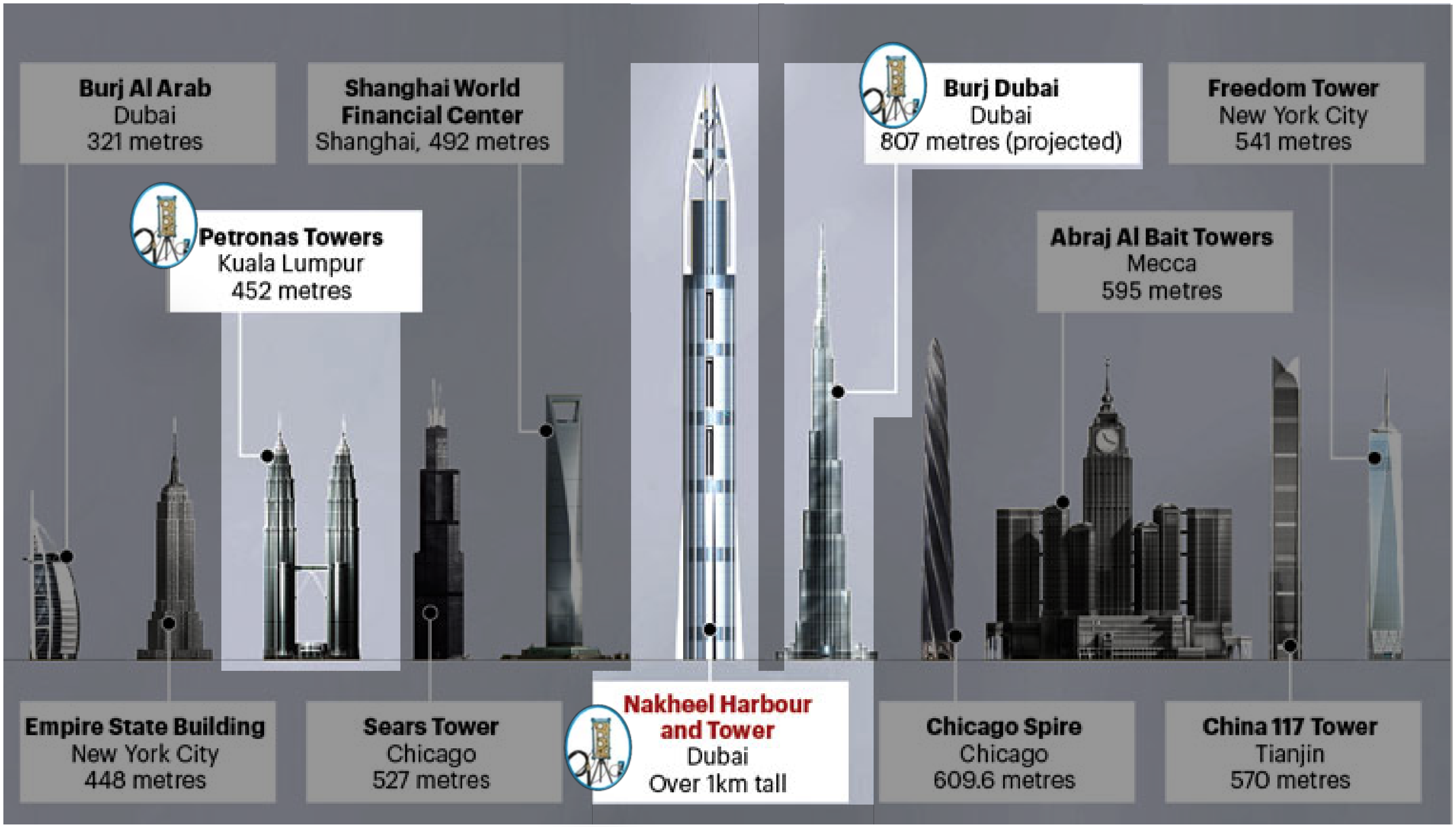


72
papers

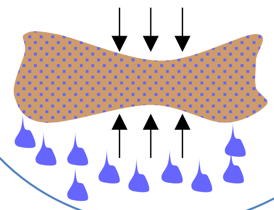
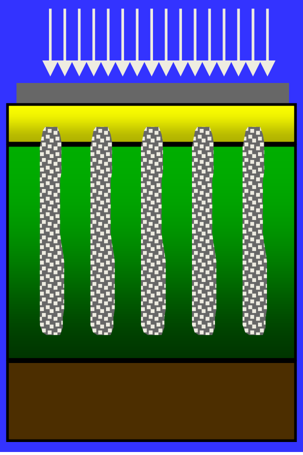
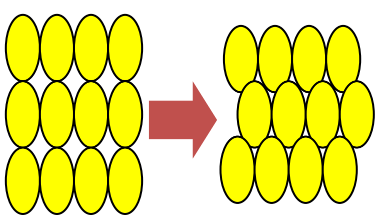
Applicable standards:

USA => ASTM D 4719
Europe => EN ISO 22476-4, DIN EN ISO 22476-4
Russia => GOST 20276-2012

Foundations designed with Ménard pressuremeter



Soil Improvement Techniques

	Without added materials	With added materials
Cohesive soil **Peat , clay …**	1 Drainage 2 VAcuum 	4 Dynamic replacement 5 Stone columns 6 CMC 7 Jet Grouting 8 Cement Mixing 
Soil with friction **Sand , fill**	3 Dynamic consolidation 4 Vibroflottation 	

Vertical drains

CONCEPT

-Stable subsoil for surcharge

-Soil can be penetrated

-Time available is short

-Some residual settlement is allowed

PARAMETERS

1 – Depth

2 – Drainage path

3 – Cohesion

4 – Consolidation parameters

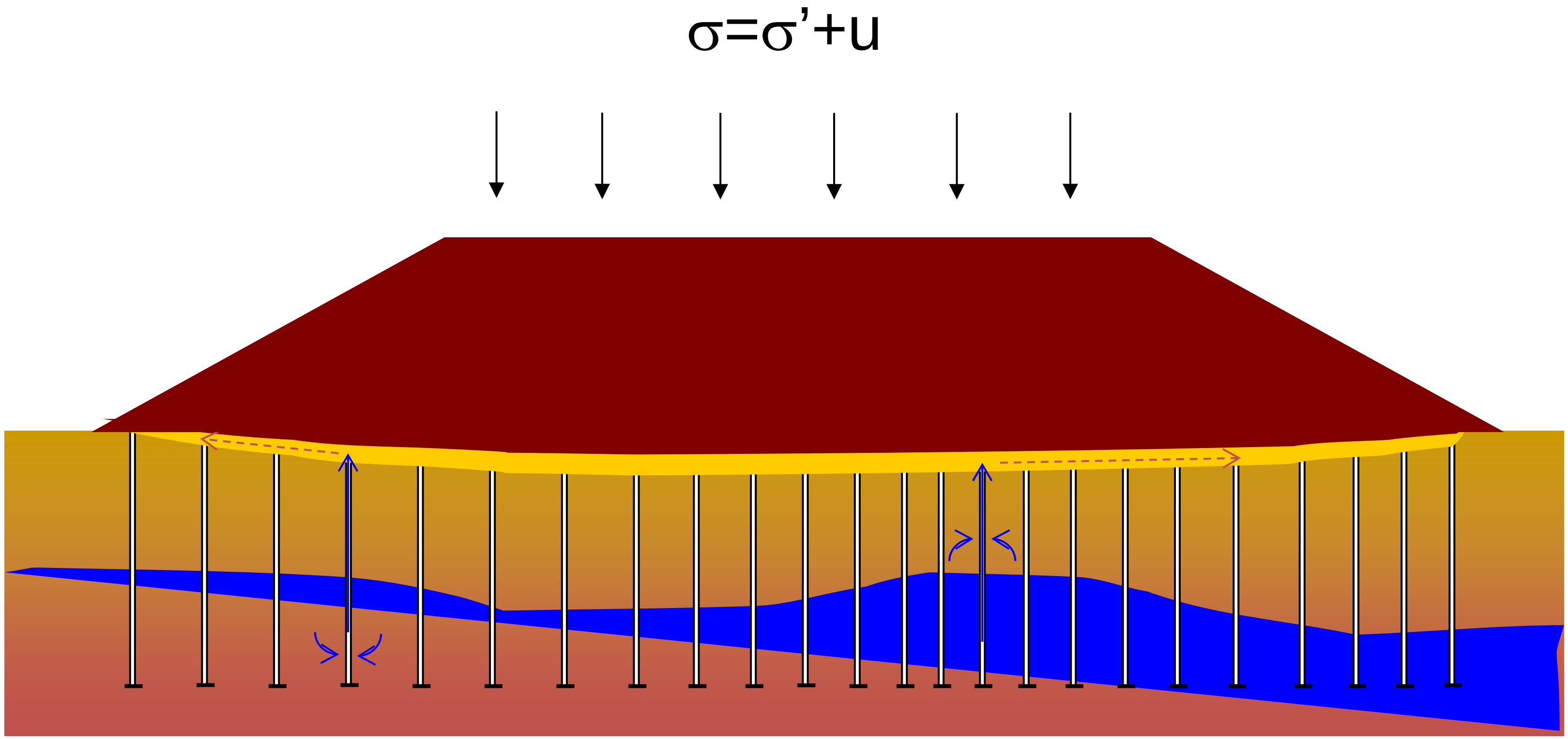
(oedometer, CPT)

e_O, C_C, C_V, C_R, C_α, t,

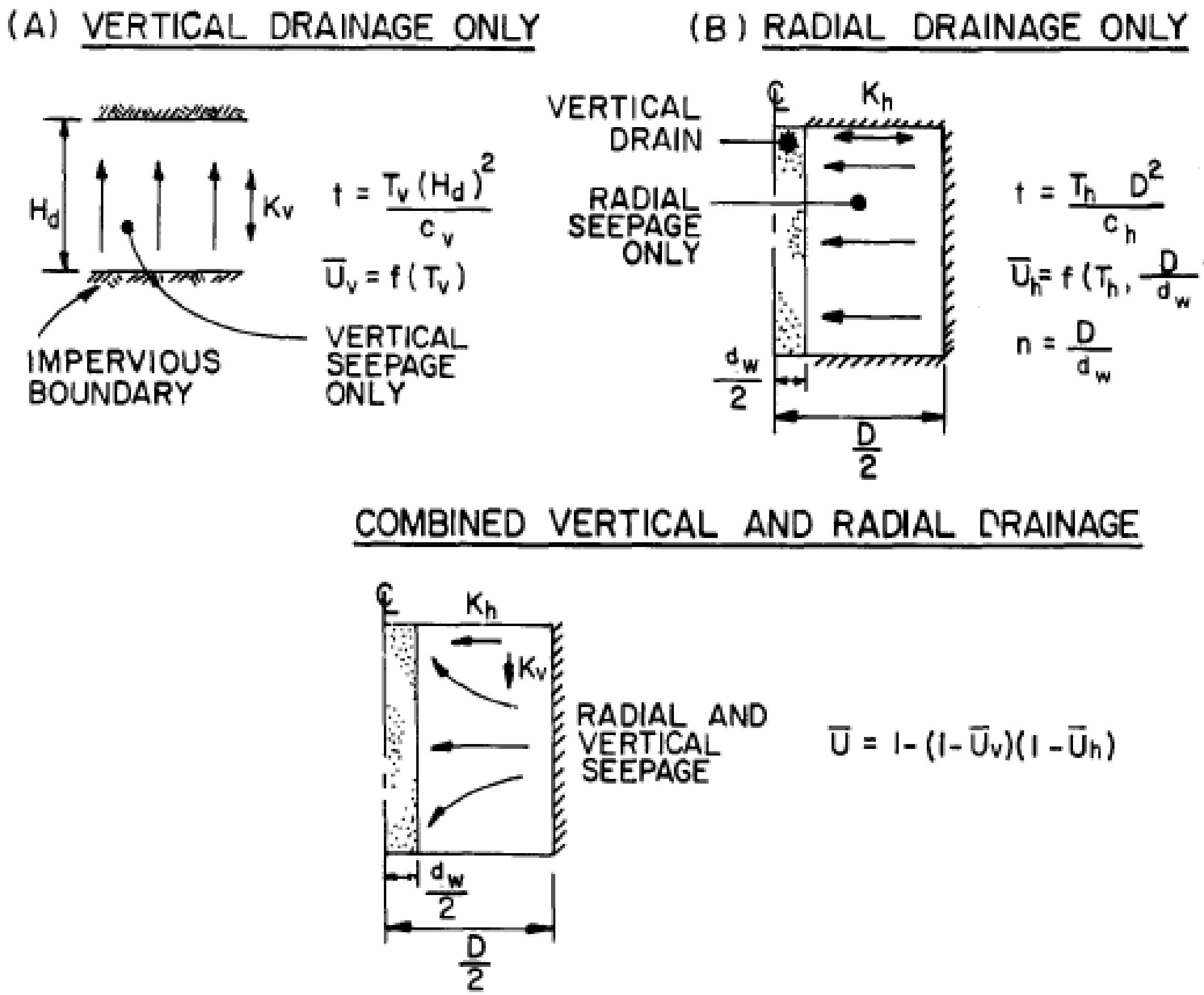
CPT dissipation test

Preloading with vertical drains

high fines contents soils



Radial and Vertical consolidation



Vertical drains: material

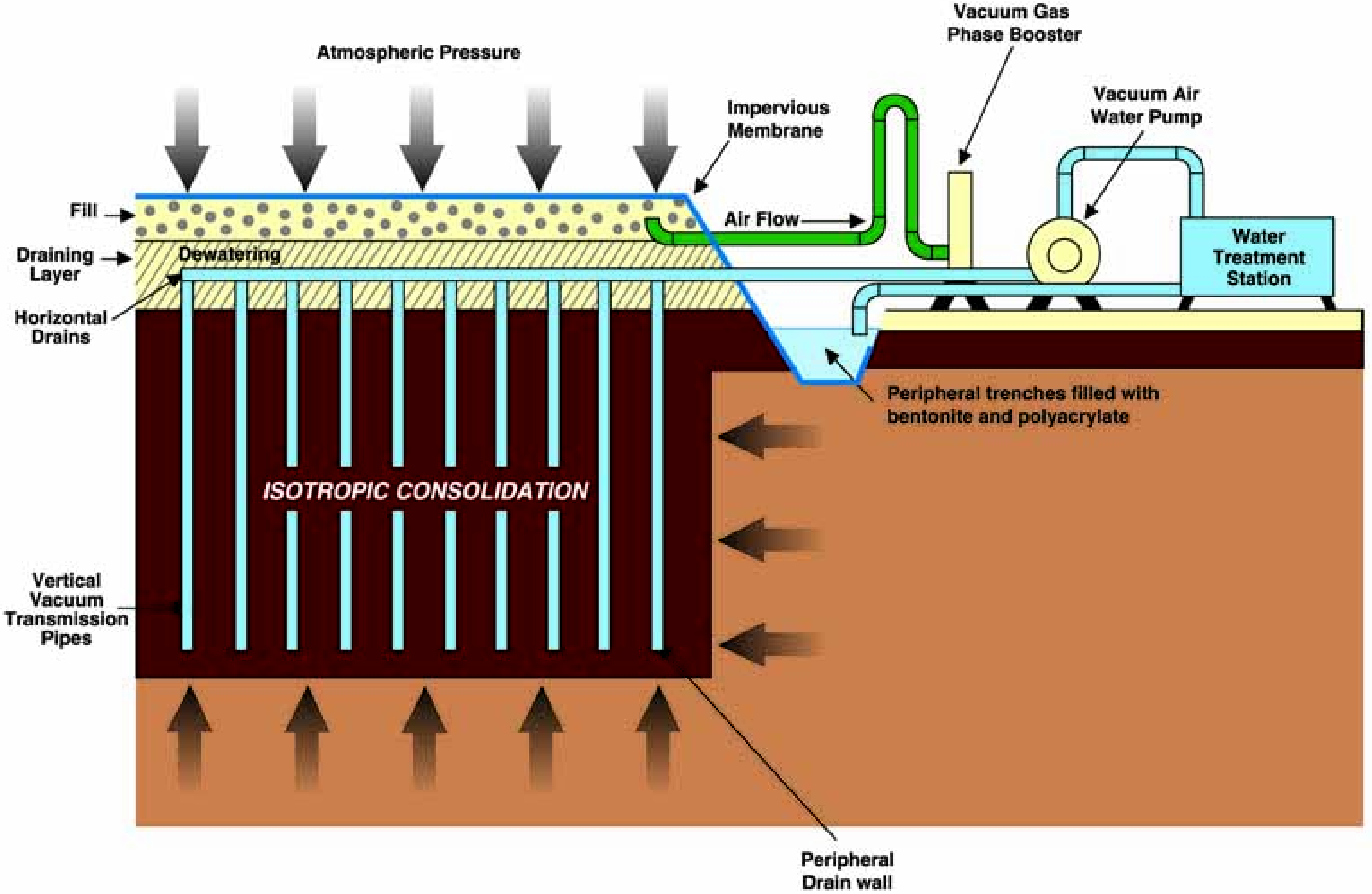
High fines contents soils

5 cm , PVC

Flat drain circular drain *vertical drain + geotextile*

Vertical Drains

Vacuum Consolidation (high fines contents soils)



VACUUM (J.M. COGNON PATENT)

Vacuum Consolidation

CONCEPT

-Soil is too soft for surcharge

-Time does not allow for step loading

-Surcharge soil not available

-Available area does not allow for berns

PARAMETERS

1 – Depth
2 – Drainage path
3 – Condition of impervious soil
4 – Watertable near surface
5 - Absence of pervious continuous layer
6 – Cohesion
7 - Consolidation parameters (oedometer, CPT)
e_O, C_C, C_V, C_R, C_α, t,
CPT dissipation test
8 – Theoretical depression value
9 – Field coefficient vacuum
10 – Reach consolidation to effective pressure in every layer
11 – Target approach

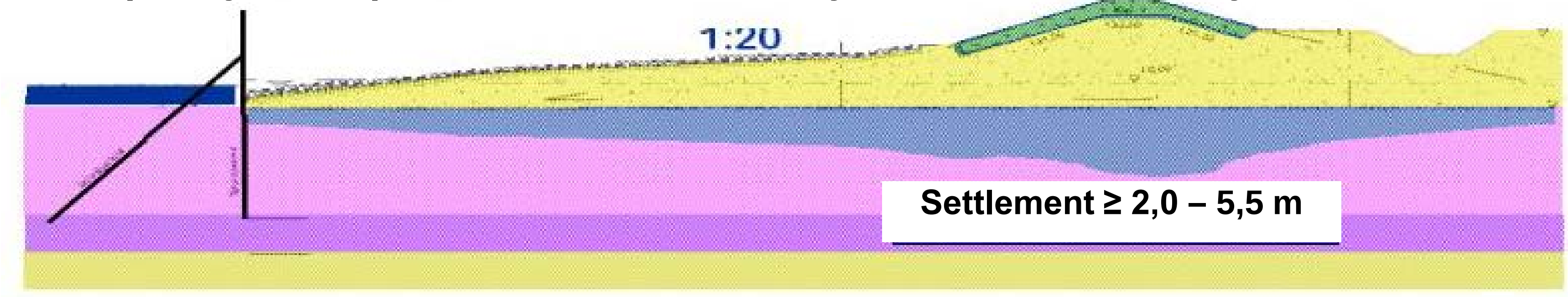

A380
A380

Case history – EADS Airbus Plant, Hamburg

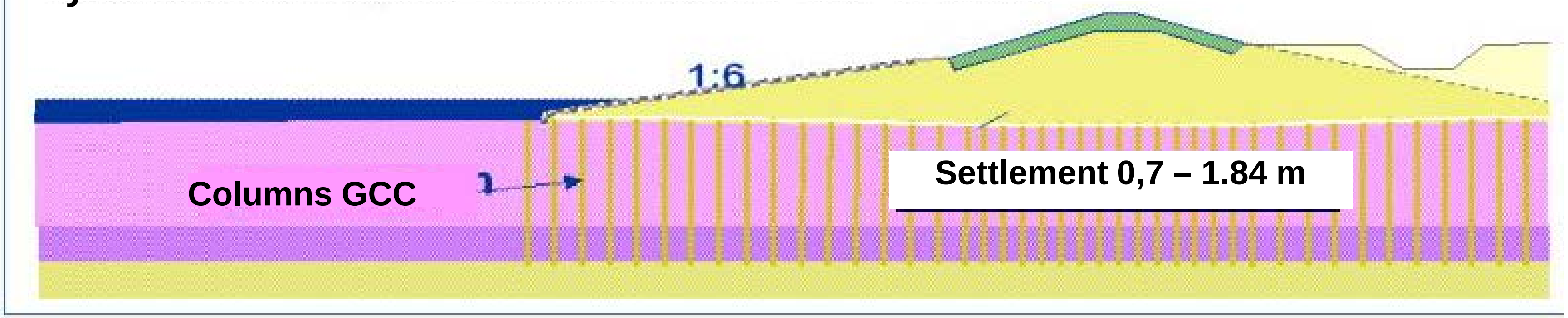
General overview of Airbus site

Basic design and alternate concept of Moebius–Menard

Temporary sheet pile wall – in 5 month – dyke construction in 3 years



Dyke construction to +6.5 in 8.5 month and to + 9.00 in 16 month



Subsoil characteristics

Soil type	Water content	Density	Shear strength		Deformation Modulus (under σ_z = 100 kN/m²)	Coefficient of consolidation	Coefficient of secondary consolidation
	W (%)	γ/γ' – kN/m³	$\delta'(°)/c'$ (kN/m²)	C_u (kN/m²)	E_s (MN/m²)	C_v (m²/year)	C_α (-)
Mud	142	13/3	20/0	0.5-5	0.8	0.35	0.03
Young clay	119	14/4	20/0	2-10	0.9	0.35	0.03
Clay	70	15/5	17.5/10	5-20	1.5	0.5	0.02
Peaty clay	139	14/4	20/5	5-20	0.9	0.4	0.03
Peat	240	11/1	20/0	5-15	0.5	≥ 0.4	0.04


How to move on the mud !

Case history – EADS Airbus Plant, Hamburg

Case history – EADS Airbus Plant, Hamburg

PORT OF BRISBANE – PADDOCK S3B

PROJECT OVERVIEW

- **Located at the mouth of the Brisbane river;**
- **New reclamation area:** 234 ha **enclosed in the Port Expansion Seawall;**
- **Part of the new reclaimed area to be ready in 5years;**
- **Seawall construction completed in 2005;**

PORT OF BRISBANE – PADDOCK S3B

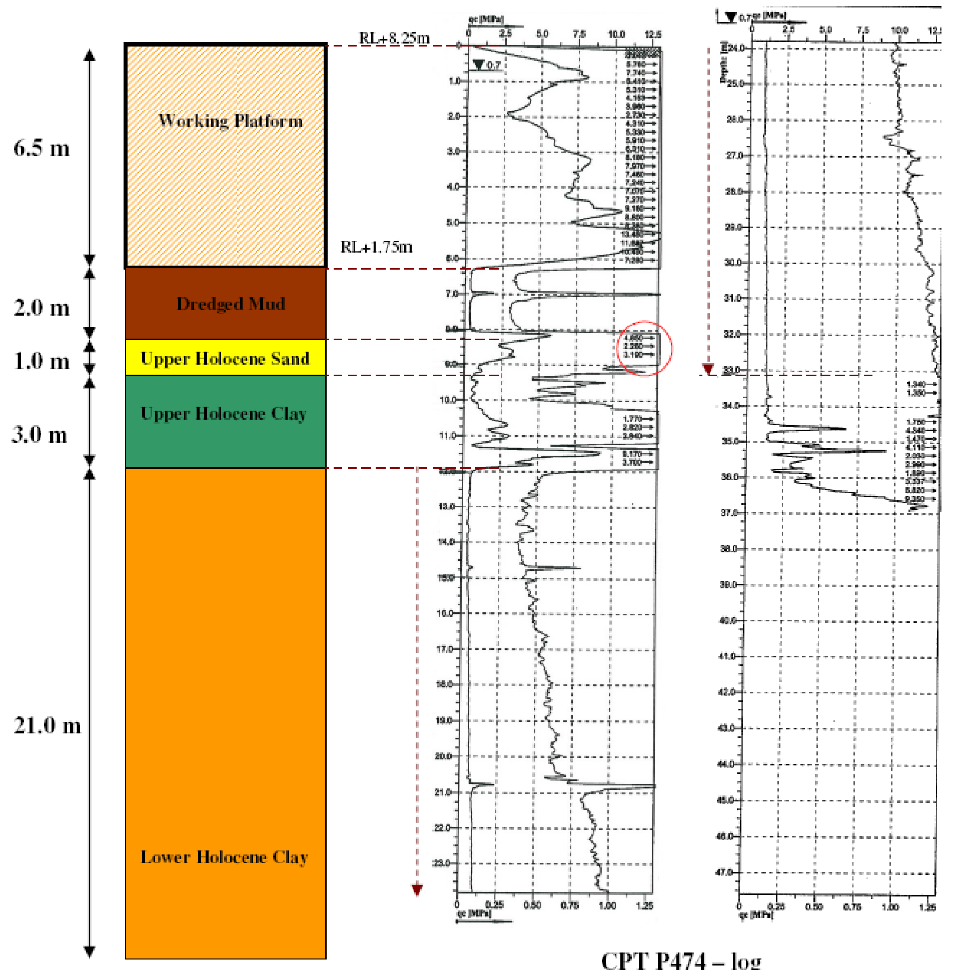
GEOLOGICAL SOIL PROFILE

AREA 2a

P474 location

- Water level during construction: RL+7.1m and RL+8.3m at vacuum start

- Working platform at RL+8.6m (thickness=6.8m) as of 22/12/08

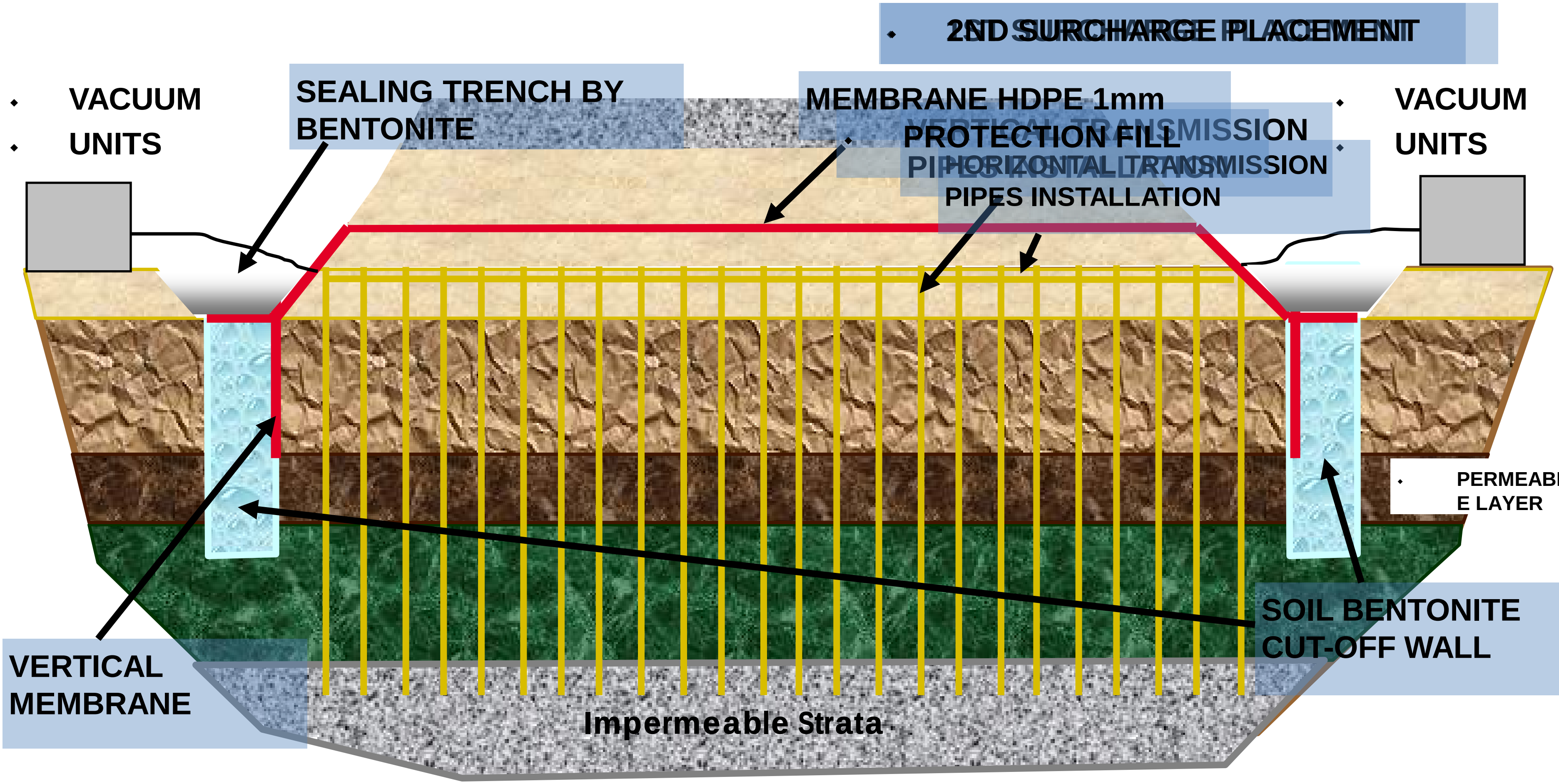


Simplified Soil Profile for Consolidation Calculation

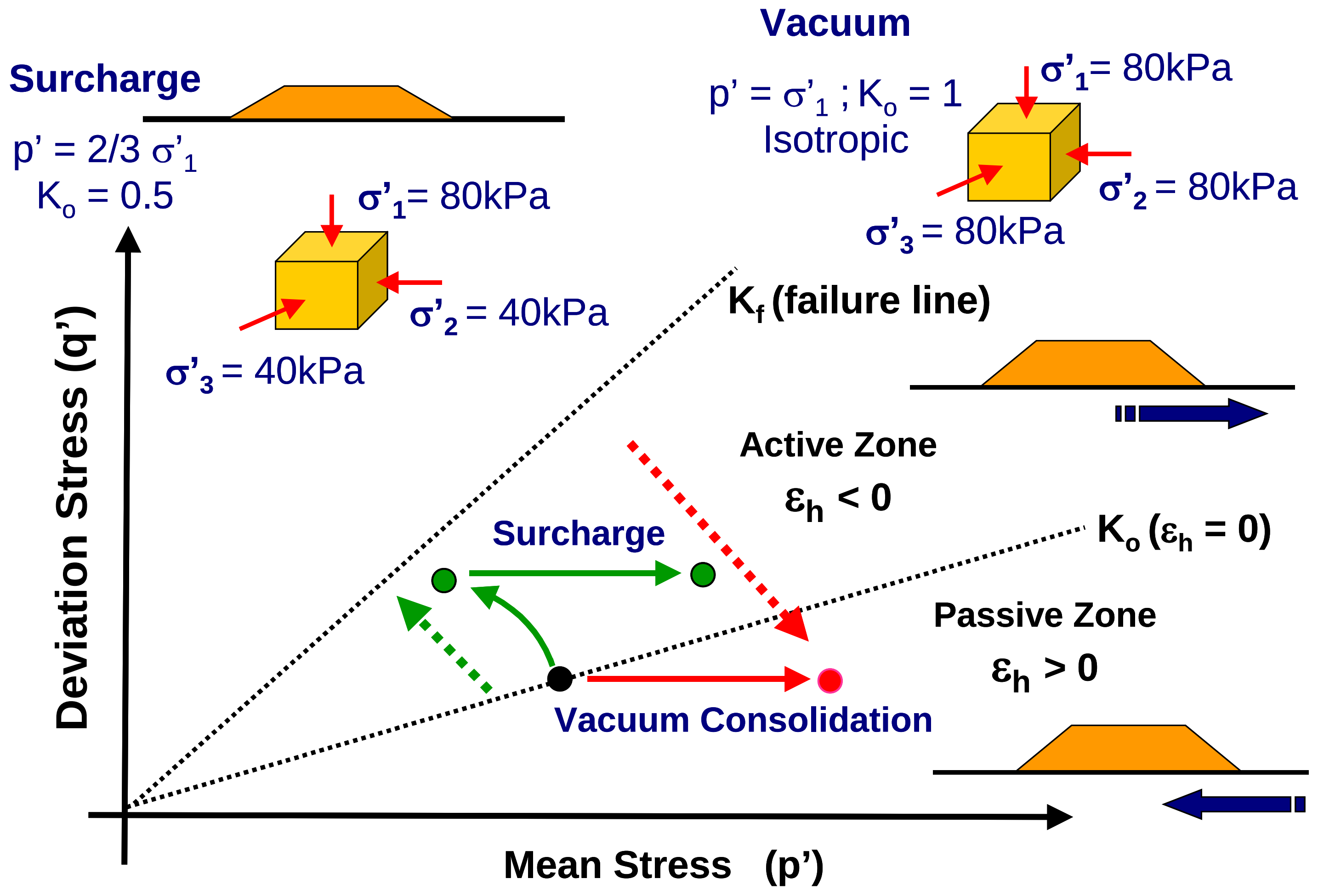
CPT P474 – log
As of 06/09/06

PORT OF BRISBANE – PADDOCK S3B

CONSTRUCTION SEQUENCE

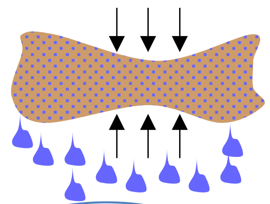
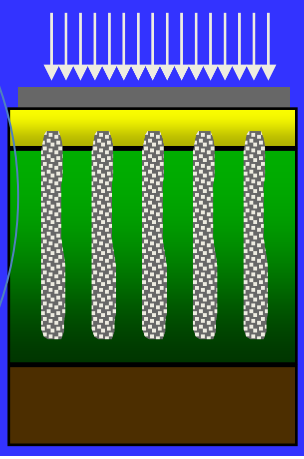
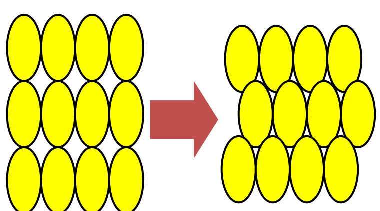


Stress path for Vacuum Process



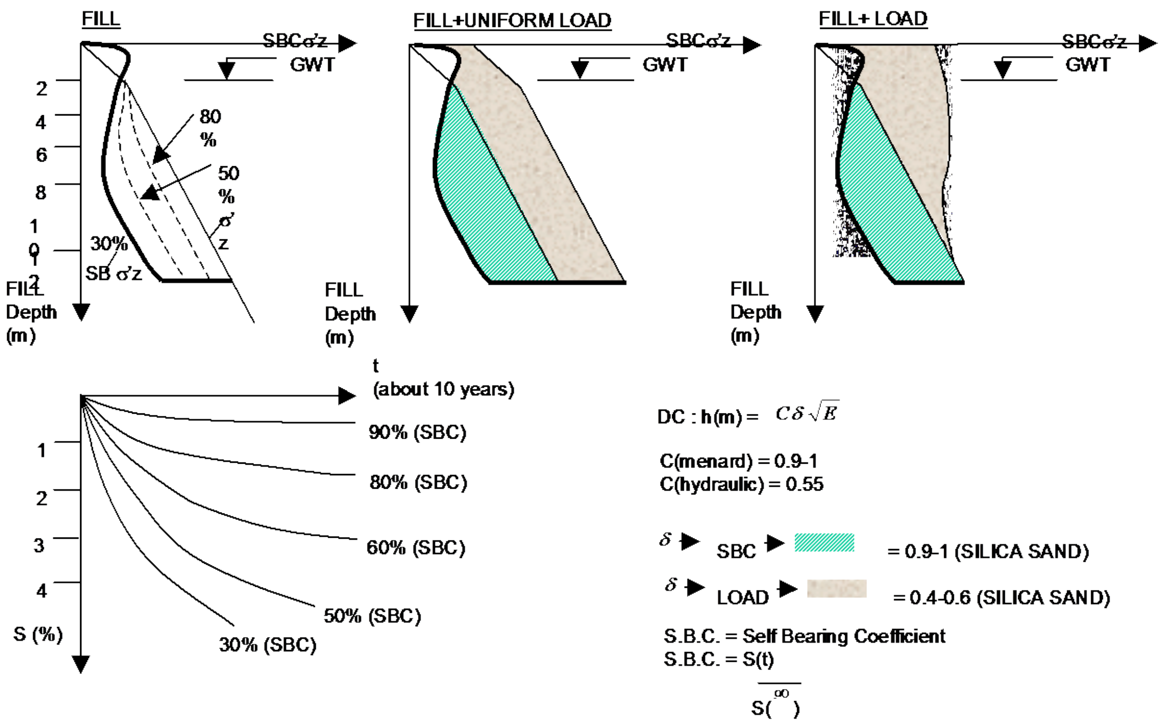
Case history : Kimhae (Korea) - 1998

Ground Improvement with compaction

	Without added materials	**With added materials**
Cohesive soil **Peat , clay …**	1 Drainage 2 VAcuum 	4 Dynamic replacement 5 Stone columns 6 CMC 7 Jet Grouting 8 Cement Mixing 
Soil with friction **Sand , fill**	3 Dynamic consolidation 4 Vibroflottation 	

Parameters for Concept

CONCEPT



PARAMETERS

- Age if fill saturated or not
- P_L
- Selfbearing level
- ∅
- E_P or E_M
- Q_C, F_R,
- N
- R.D. (???)
- Shear wave velocity
- Seismic parameters
- Grain size

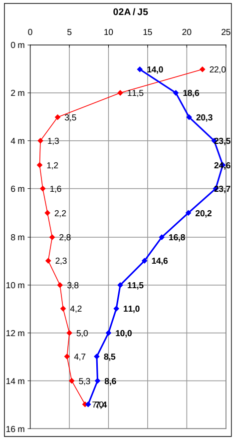
Case History

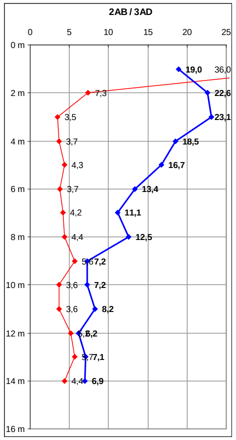
Nice airport runway consolidation
Granular soil

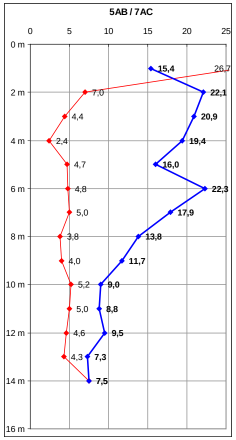
Very high energy (200 t , 24 m)

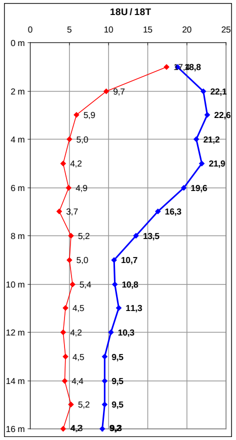
AL AIN AL QUO'A in ABU DHABI

- **1.1 Millions m² treated**
- **Maximum depth=16m**







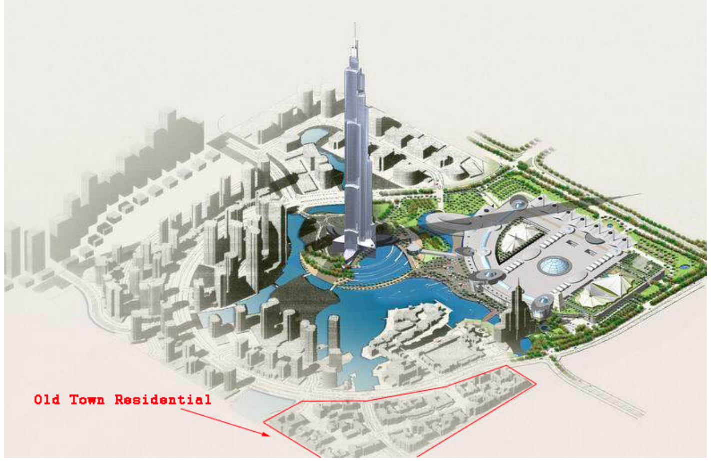


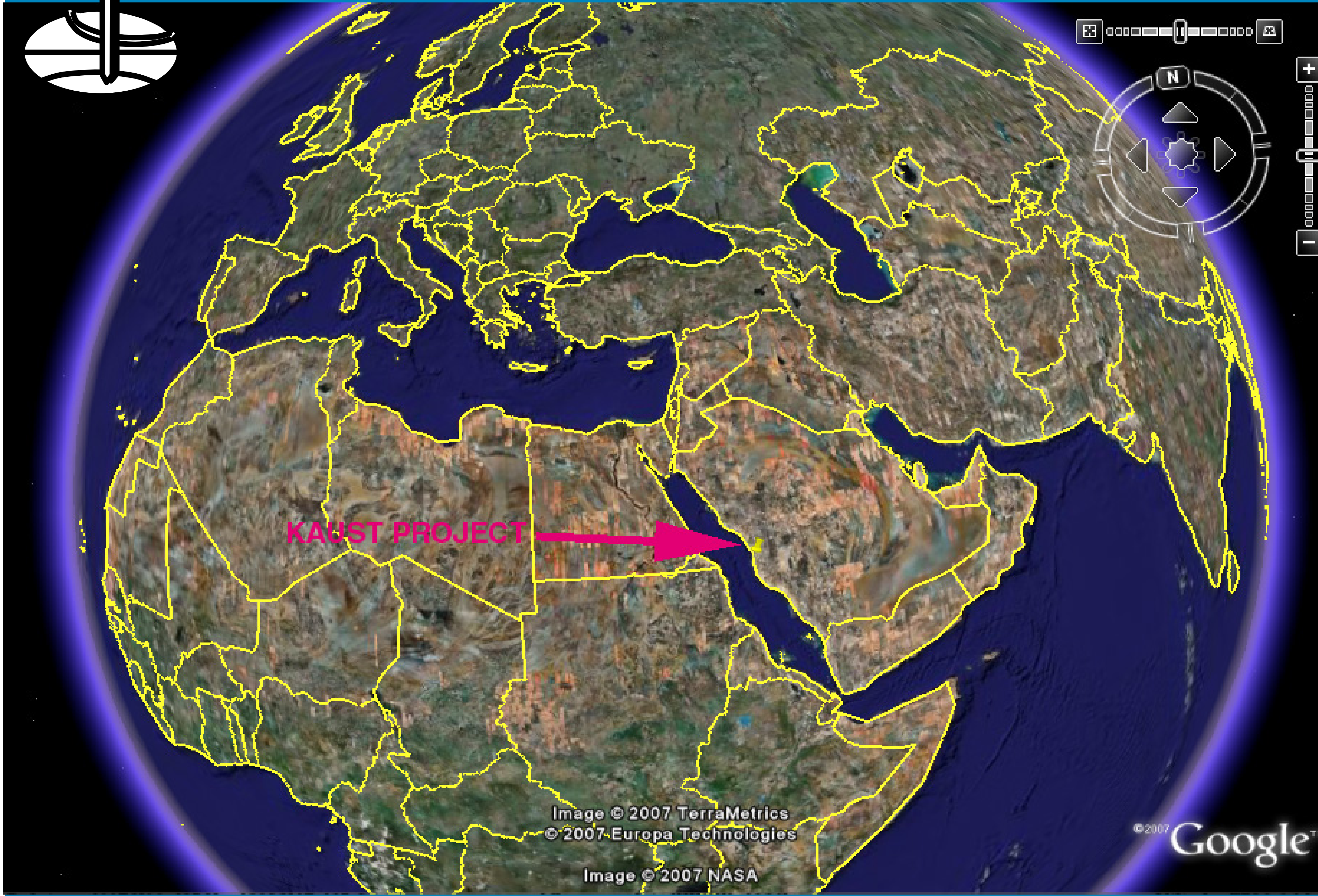
DC: Dredged fill of New Corniche Road, Abu Dhabi, UAE 2003



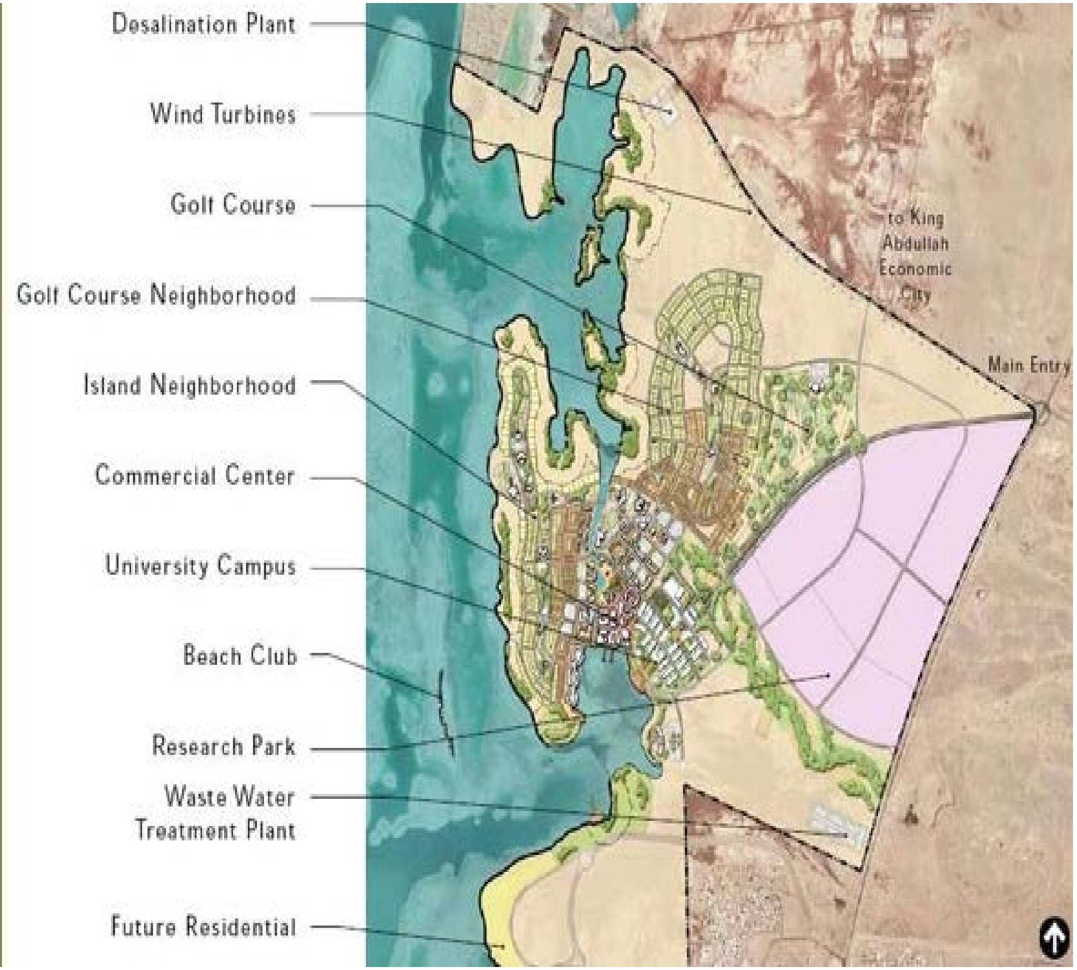


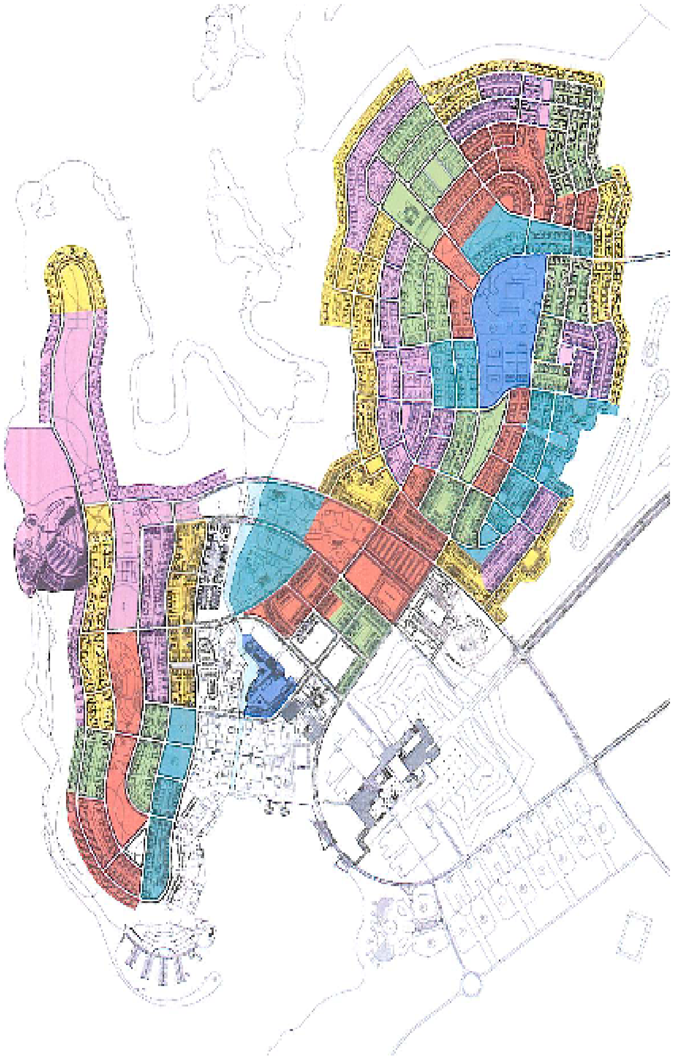
DC: Burj Dubai Old Town Residential, UAE 2004




KAUST PROJECT
Image © 2007 TerraMetrics
© 2007 Europa Technologies
Image © 2007 NASA
©2007 Google™

Typical master plan





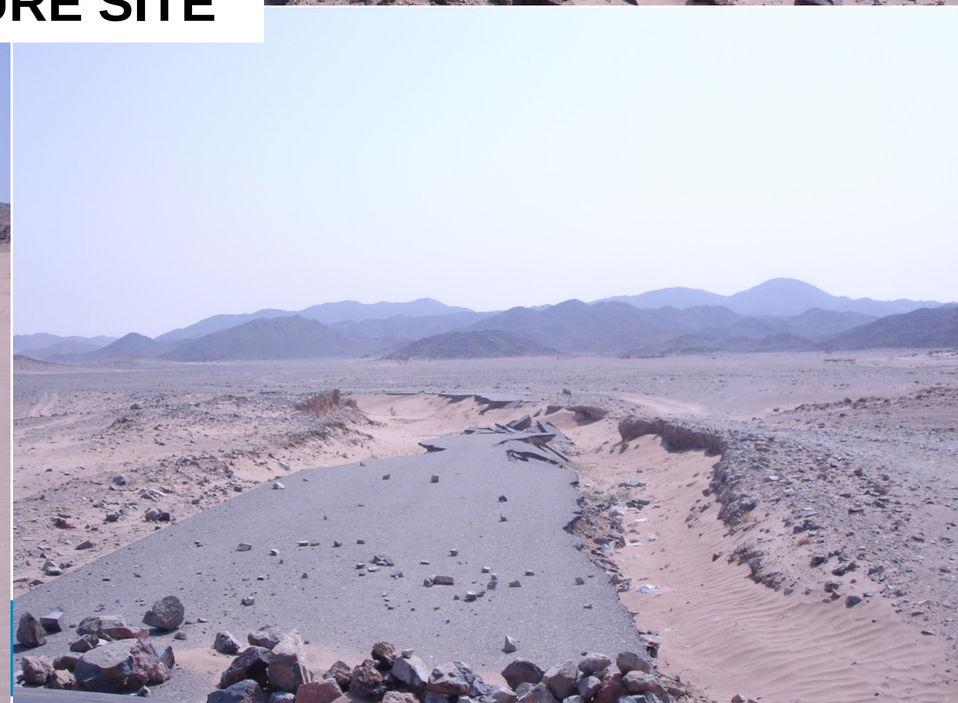
AREAS TO BE TREATED

- **AL KHODARI (1.800.000 m2)**
- **BIN LADIN (720.000 m2)**

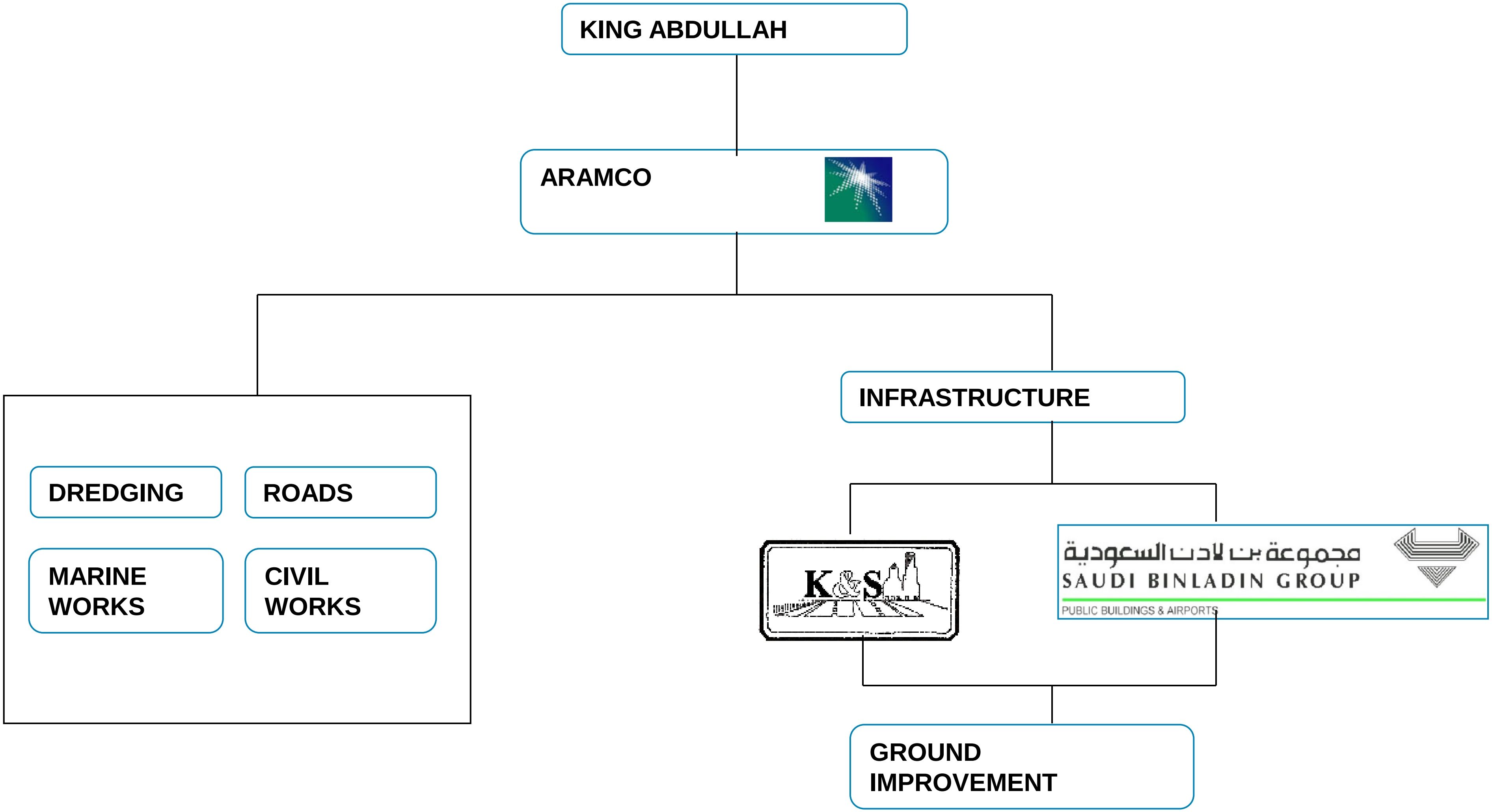
SCHEDULE

- **8 months**

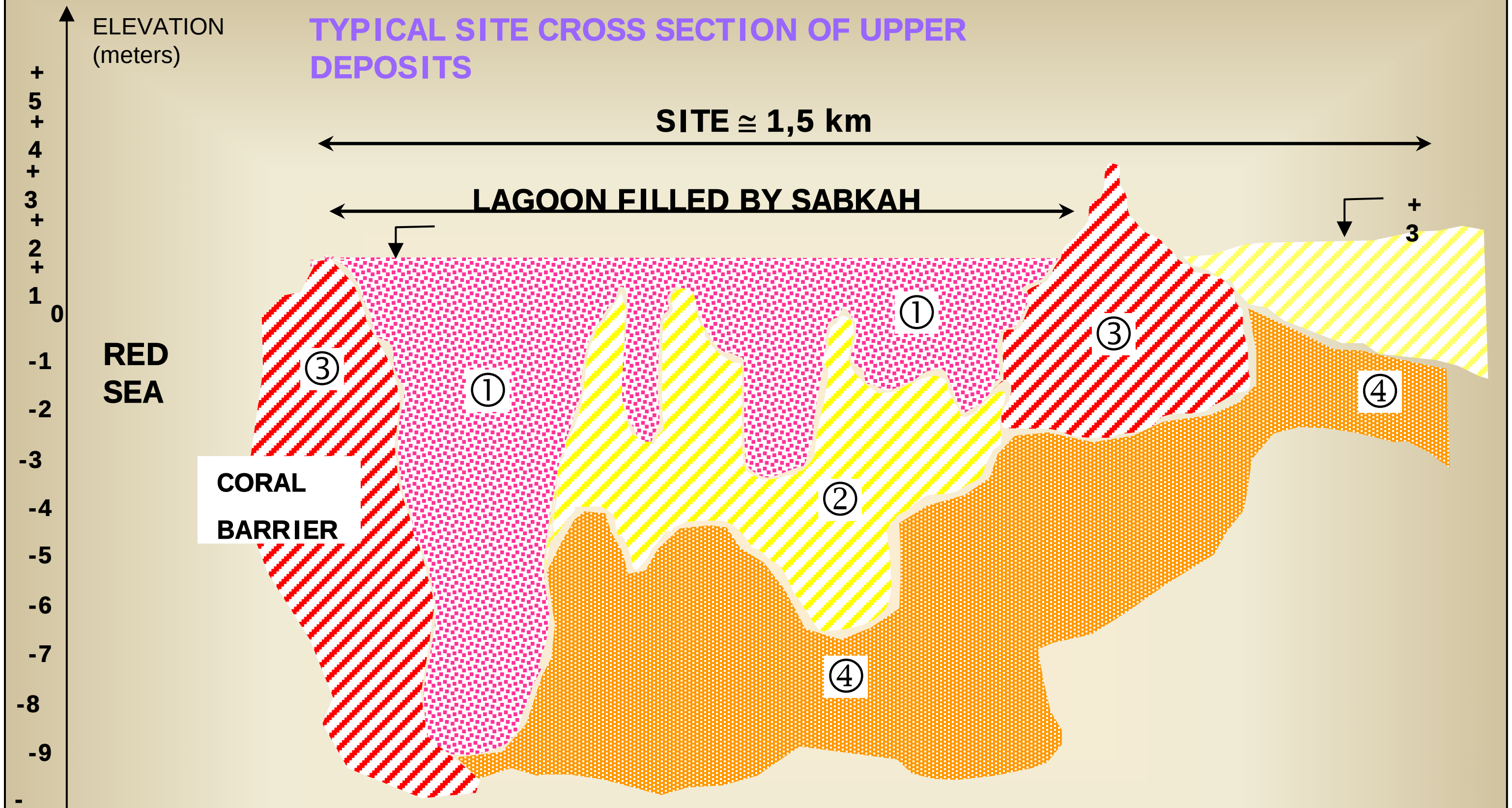
THE FUTURE SITE



Project structure

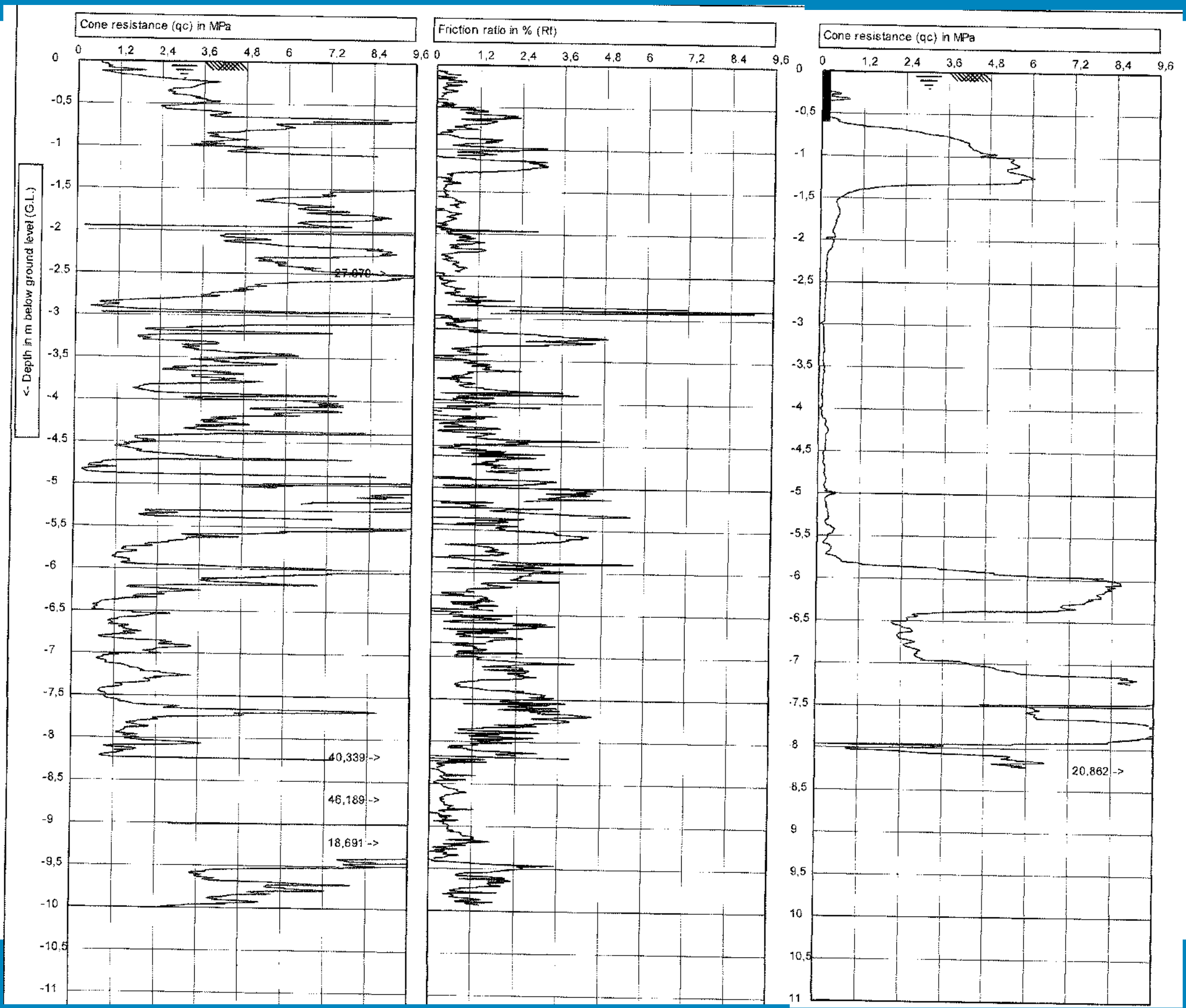


TYPICAL SITE CROSS SECTION OF UPPER DEPOSITS

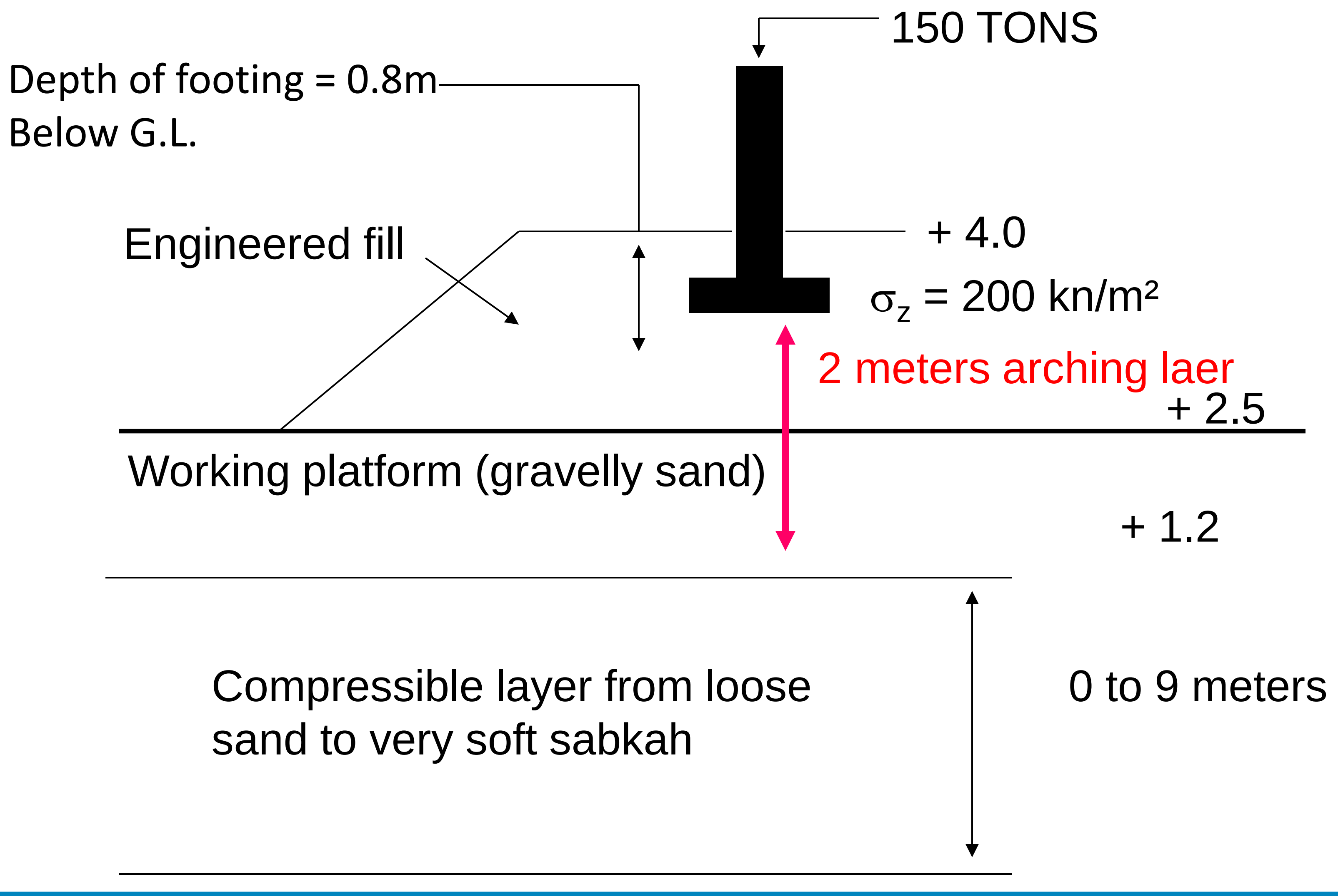


LAYER	USC	w %	% fines	N	Qc BARS	F_R %	P_L BARS	E_P BARS
1 - SABKAH	SM + ML	35-48	28-56	0-2	0-2	1,2-4	0,4-1,9	avr-17
2 - LOOSE SILTY SAND	SM	-	15-28	3-9	12-45	0,5-1,2	2,1-4	18-35
3 - CORAL	-	26-35	-	6-12	-	-	5,1-7,2	35-60
4 - LOOSE TO MED DENSE SAND	SM	-	12-37	3-18	15-80	0,5-1,8	4-12	28-85

VARIATION IN SOIL PROFILE OVER 30 METERS

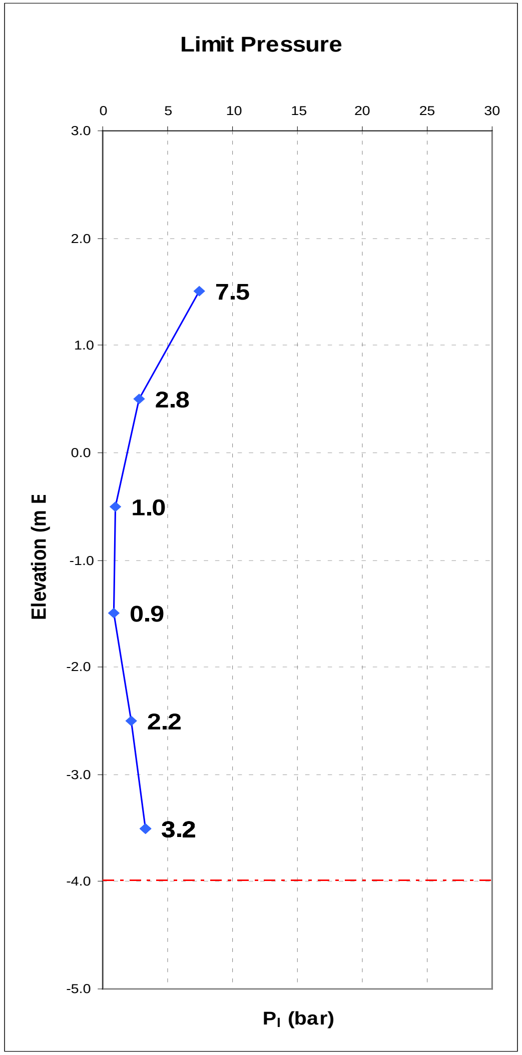


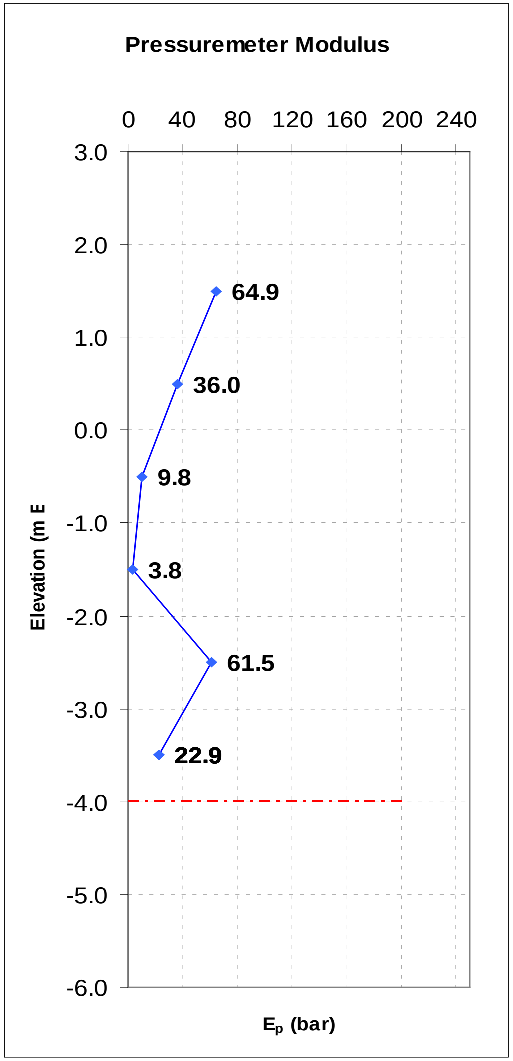
Concept

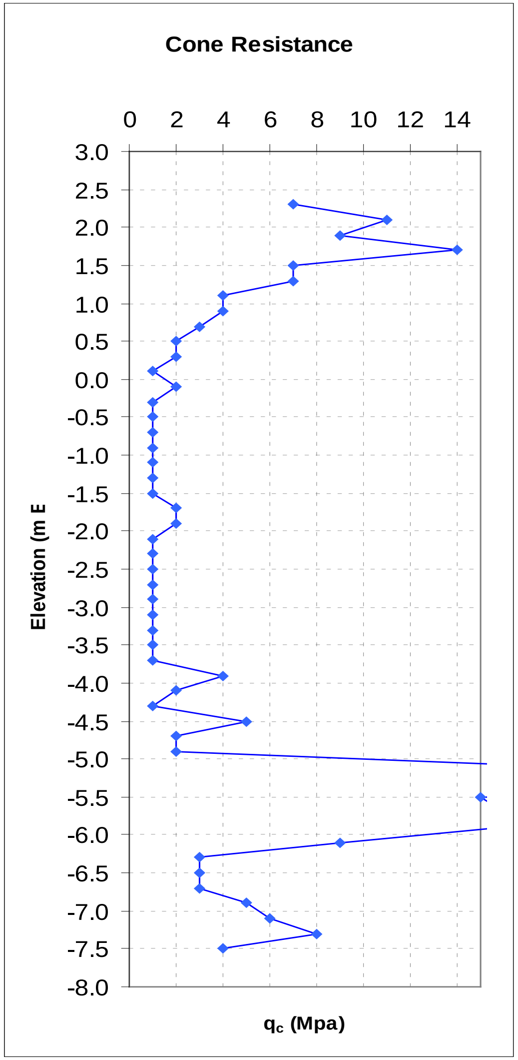


150 TONS
Depth of footing = 0.8m
Below G.L.
Engineered fill
+ 4.0
σz = 200 kn/m²
2 meters arching laer
+ 2.5
Working platform (gravelly sand)
+ 1.2
Compressible layer from loose
sand to very soft sabkah
0 to 9 meters

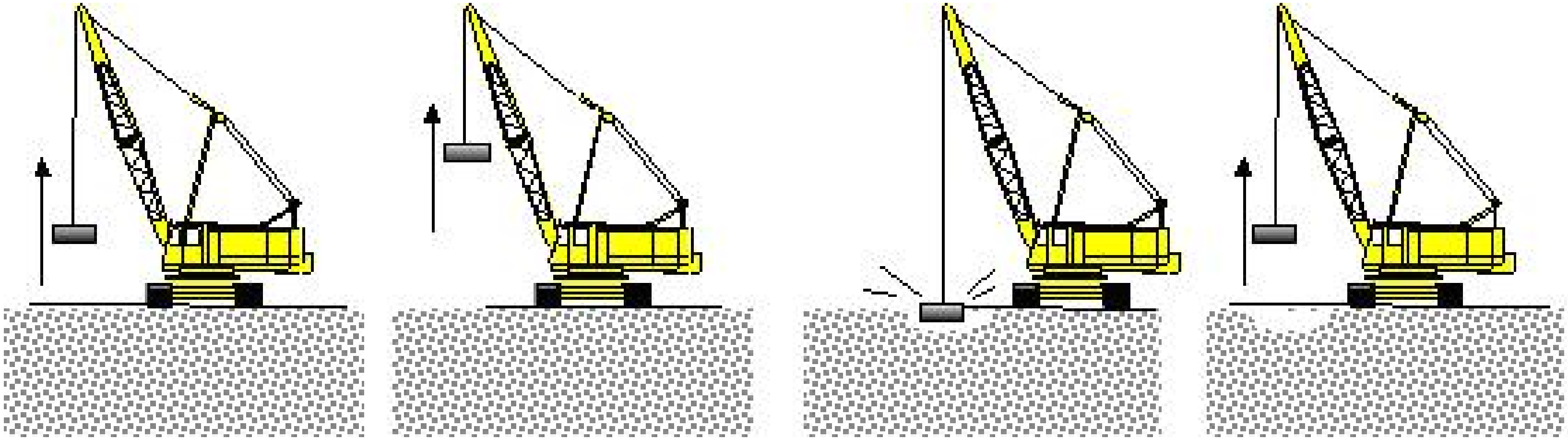
TYPICAL SOIL PROFILE

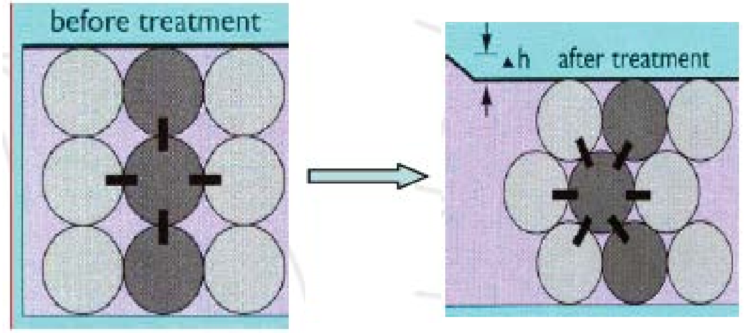






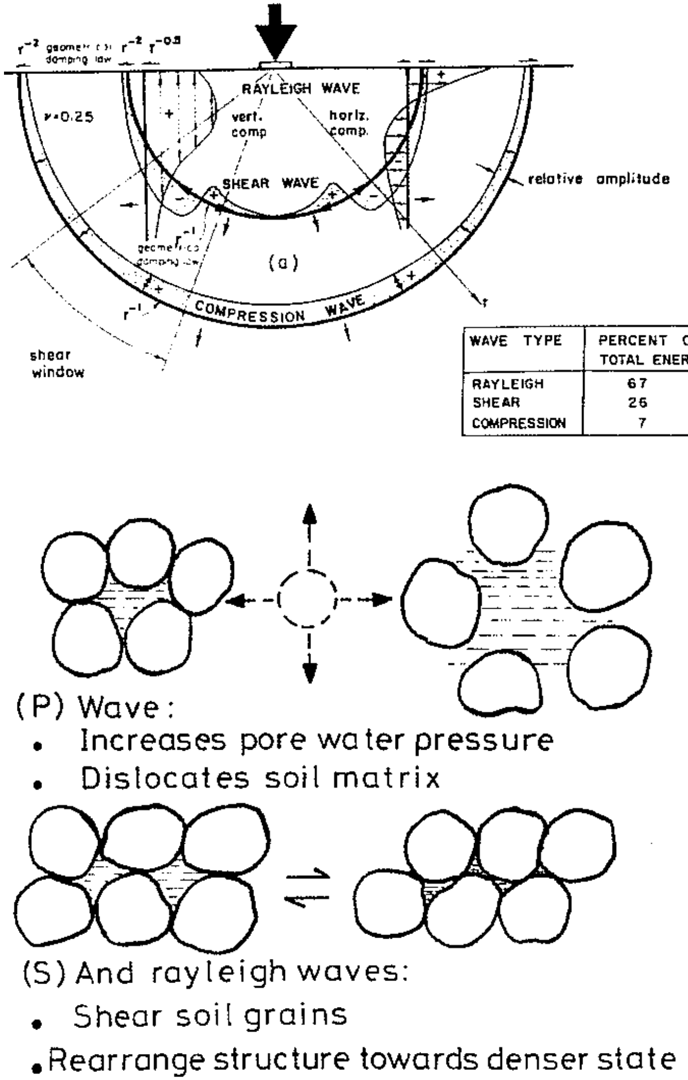
SELECTION OF TECHNIQUE

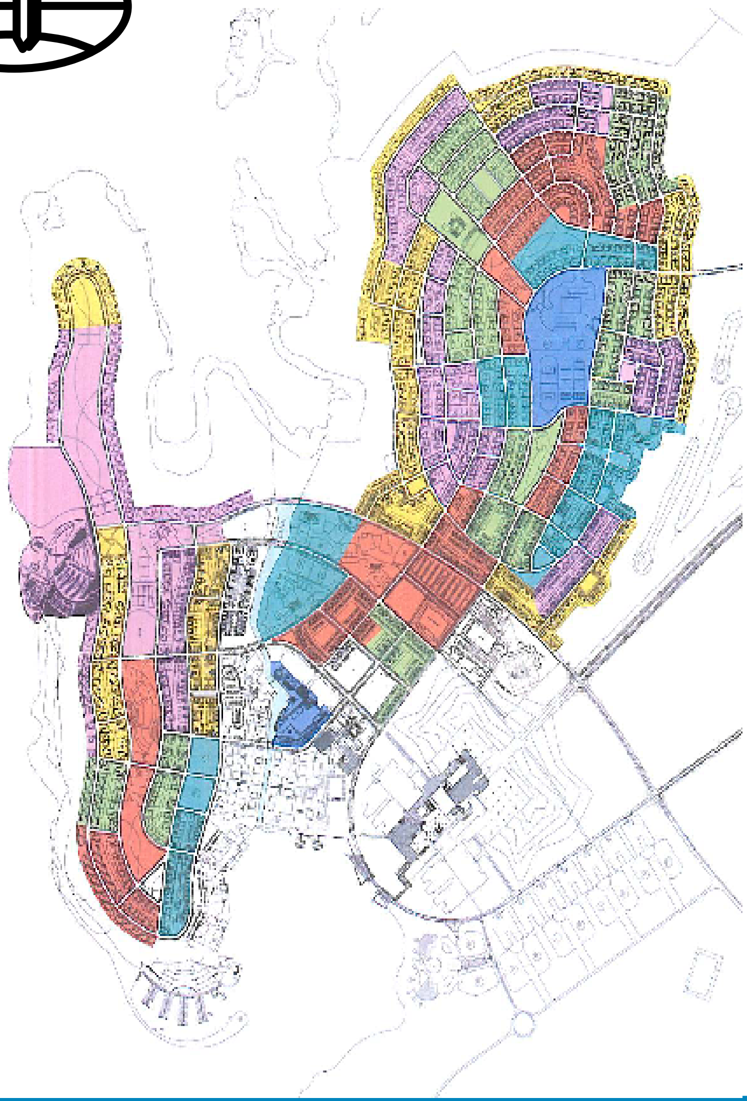




DC (Dynamic Compaction)

Shock waves during dynamic consolidation – upper part of figure after R.D. Woods (1968).





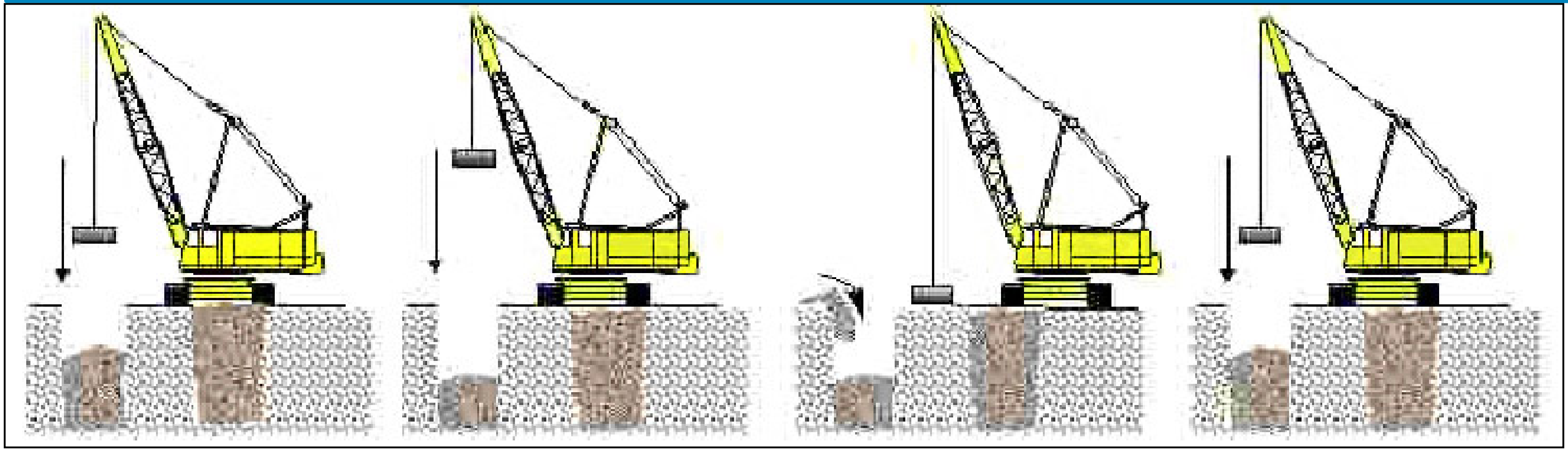
KAUST

Dates for soil improvement

LEGEND

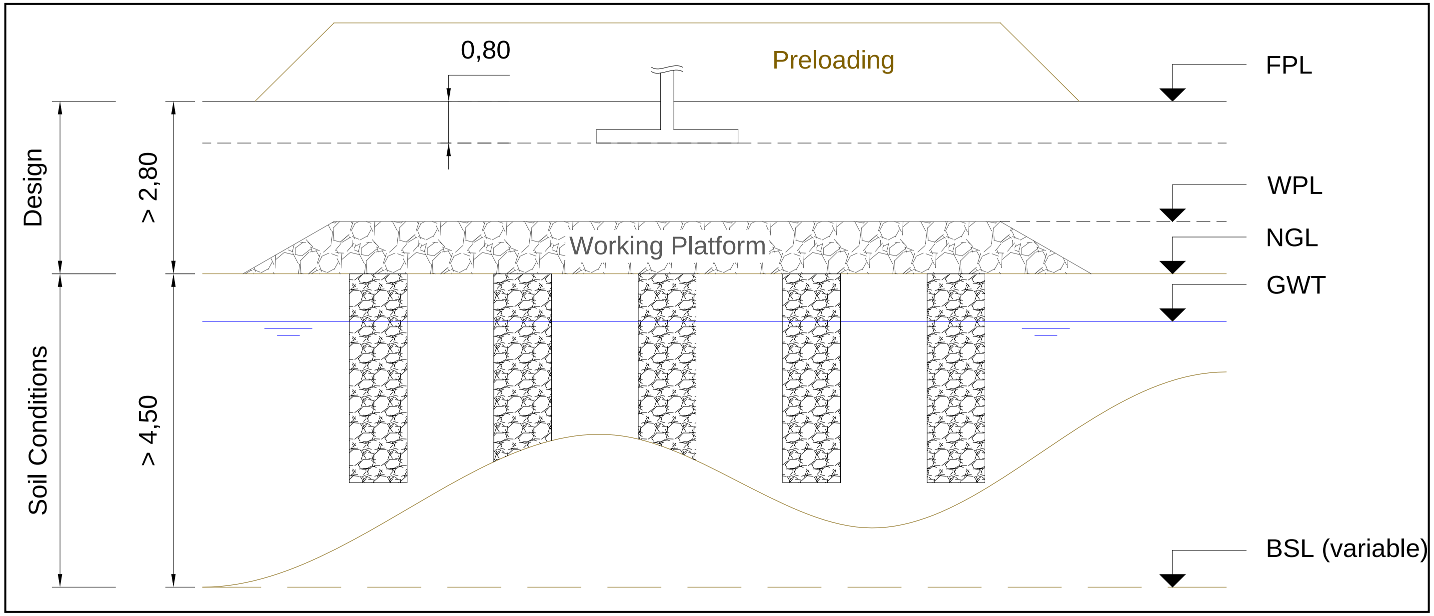
- 01/10/2007
- 05/10/2007
- 15/10/2007
- 01/11/2007
- 15/11/2007
- 15/12/2007

SELECTION OF TECHNIQUE



DR (Dynamic Replacement)

HDR (High Energy Dynamic Replacement) + surcharge

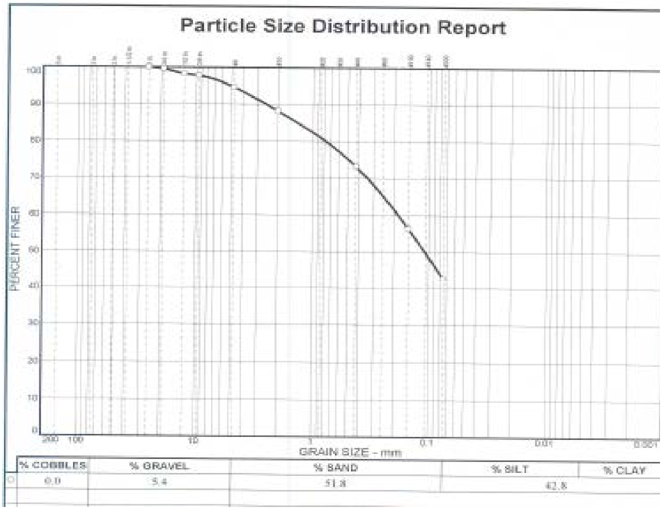


EQUIPMENT RESOURCES

- 13 DC/DR Rigs of 95 to 120 tons
- 15 pounders from 12-23 tons
- 30 vehicles (bus, 4x4, pick-up, berlines)
- 1 truck with crane
- 1 forklift
- 3 CPT rigs
- 1 drill + pressuremeter
- 15 containers
- 1 set of site offices

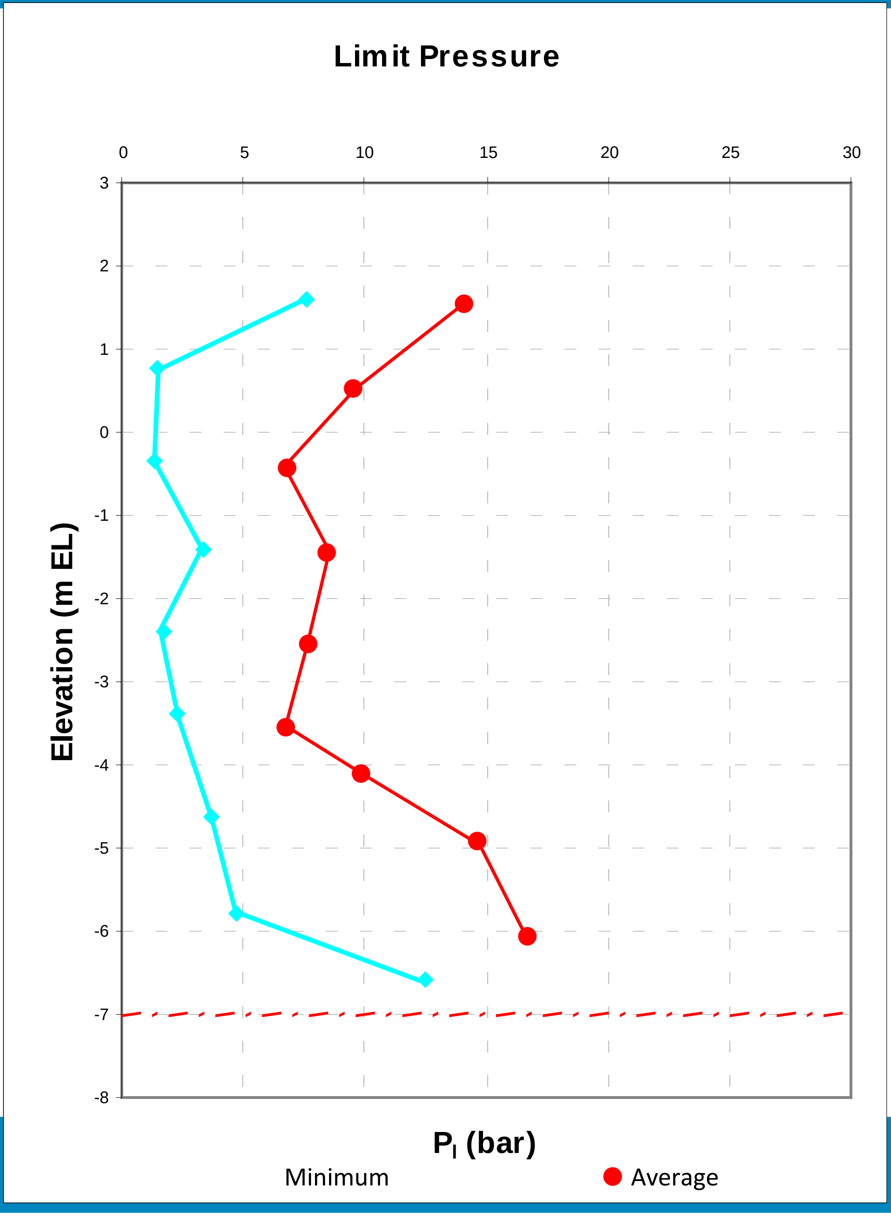
TYPICAL SURFACE CONDITIONS

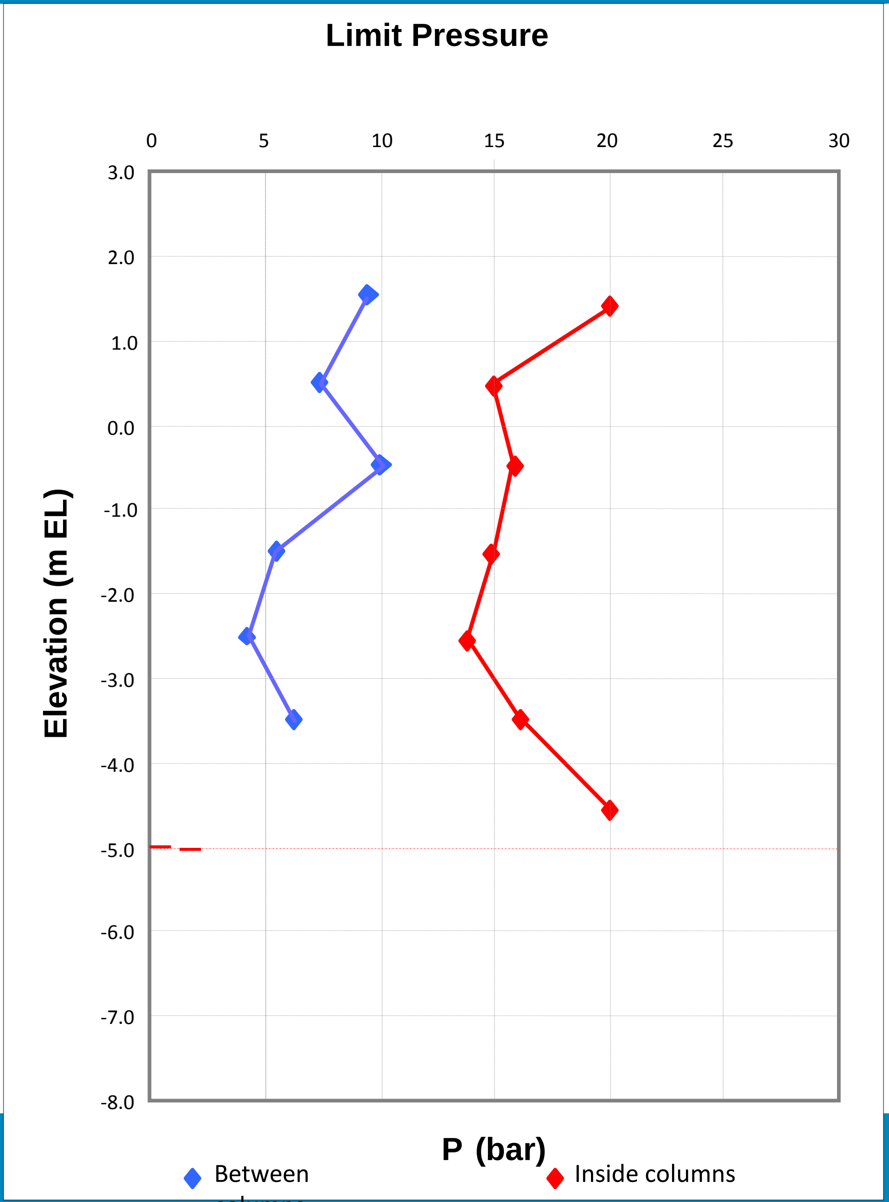
TYPICAL TEST PITS (120) AND GRAIN SIZE



Before DC

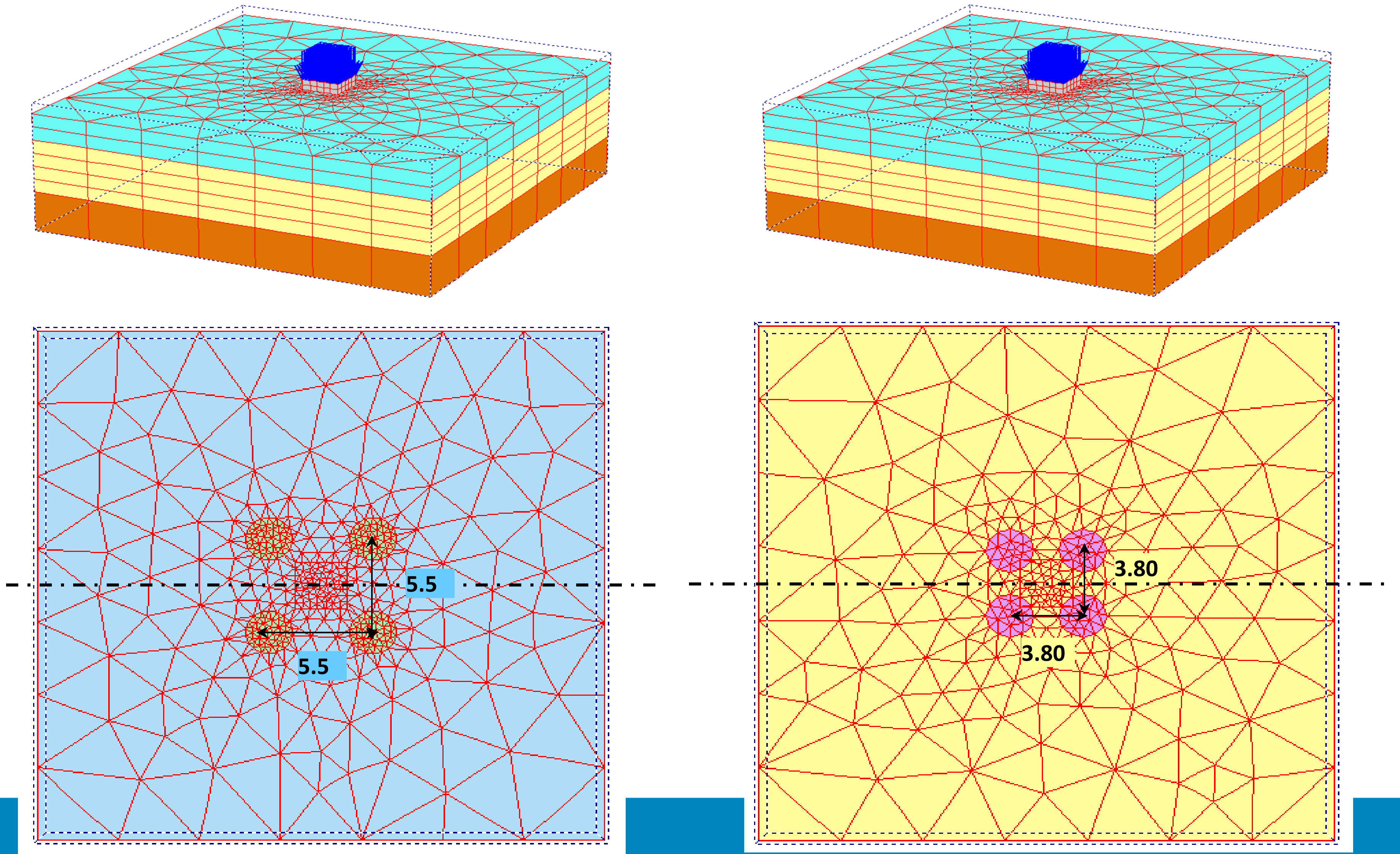
After DC – Between columns





STRESS DISTRIBUTION

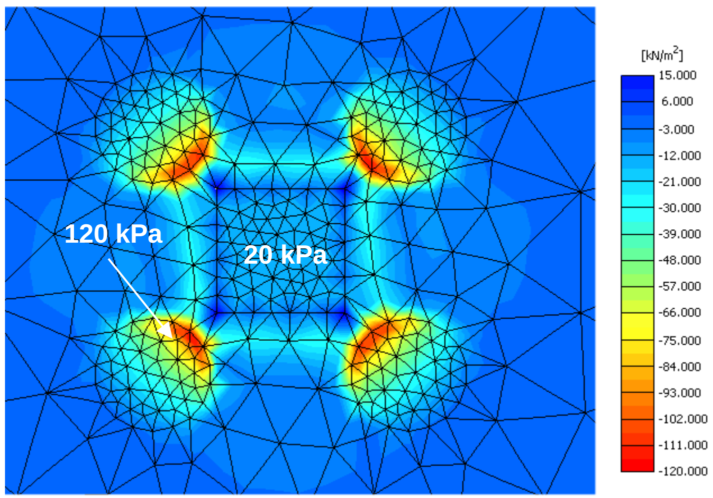
ANALYSIS OF WORST CASE FOR VARIOUS GRIDS



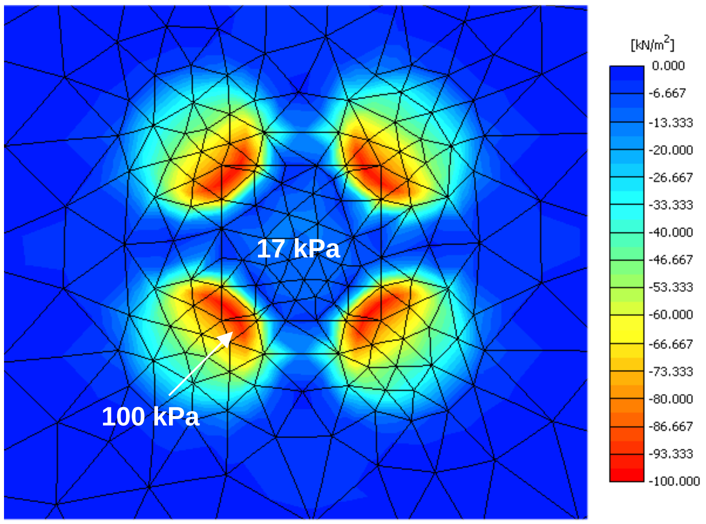
STRESS DISTRIBUTION

Grid 5,50 x 5,50

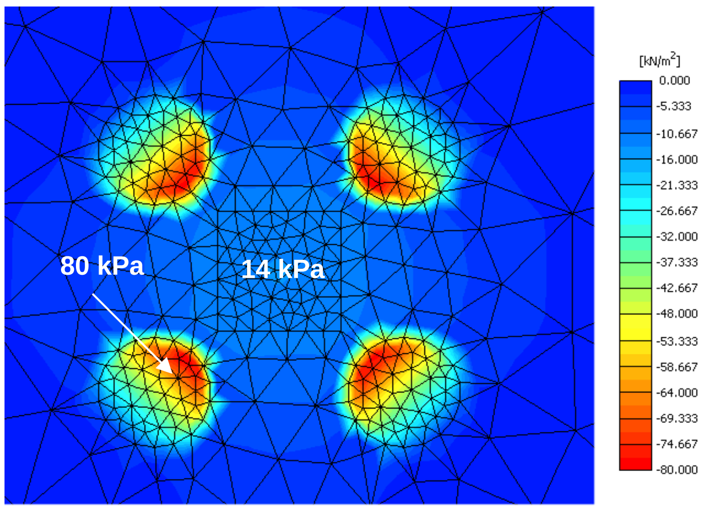
Grid 3,80 x 3,80



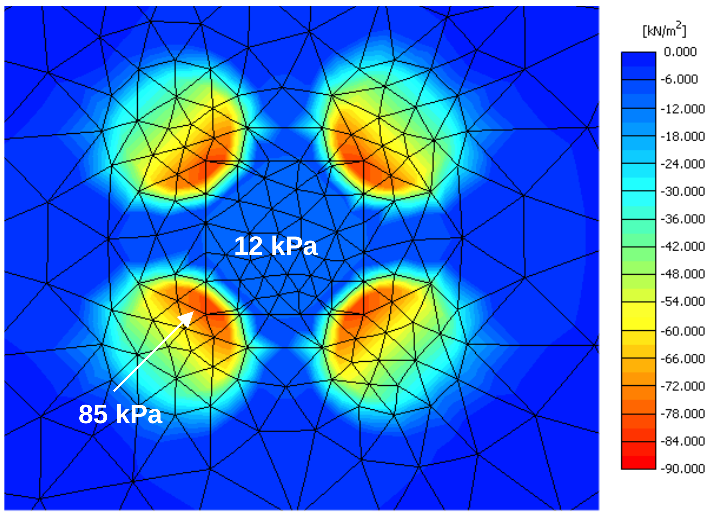
Vertical effective stresses (sig'-yy)



Vertical effective stresses (sig'-yy)



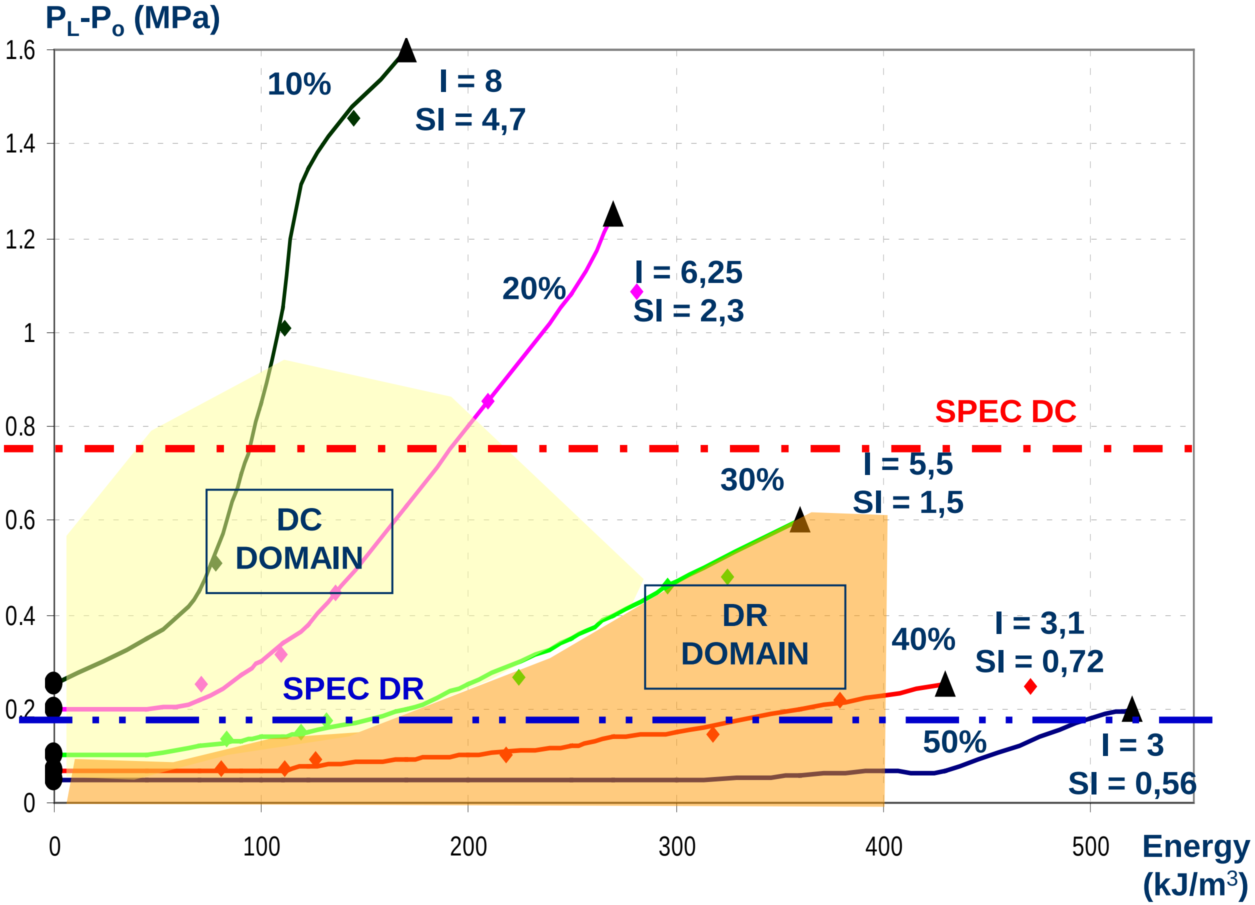
Vertical effective stresses (sig'-yy)



Vertical effective stresses (sig'-yy)

ANALYSIS OF (PL-Po) IMPROVEMENT AS FUNCTION OF ENERGY AND FINES

K.A.U.S.T. – Saudi Arabia



BASIS

- 60 grainsize tests
- 180 PMT tests

PARAMETERS

- $P_L - P_o$ = pressuremeter limit pressure
- kJ/m³ = Energy per m³ (E)
- % = % passing n°200 sieve
- I = improvement factor $\frac{P_{LF}}{P_{Li}}$
- S.I : energy specific improvement factor $\frac{I \times 100}{E}$

LEGEND

- ● Average pre-treatment values
- ◆ Average values between phases
- ▲ Average post-treatment values
- SPEC DC : $P_L - P_o \geq 0.75$ MPa
- SPEC DR : PL – Po ≥ 0.18 MPa

SPREAD SHEET OF CALCULATION OF SETTLEMENT AND BEARING CAPACITY

Calculation of the Settlement and Bearing Capacity of a foundation
According to D60

MENARD

Project Name:		**According to PMT #:**				**Dated:**				
Zone Ref #		**X**		**Y**		**Z**				

DESCRIPTION OF SOIL, TREATMENT AND FOOTING TYPE

Footing Characteristics

Load		150	tons			
Mean contact stress	p	0,20	MPa	Hence:	L/B =	1,0
Length of the footing	L	2,74	m	And:	λ_c =	1,10
Width of the footing	B	2,74	m		λ_d =	1,12
Embedment	D	0,80	m			

DR Description

Mesh	5,50	m
Diameter	2,20	m
Hence, a =	12,6%	
Pressuremeter characteristics		
According to calibration #		
$E_{m\text{-}DR}$	10,0	Mpa
$P_{l\text{-}DR}$	1,5	Mpa
α_{DR}	1/3	

Soil Description

Layer #	Description	Soil category	DR	Thickness (m)	Depth from FPL (m)	γ (kN/m3)	Pressuremeter characteristics – Inter Prints (after Soil Improvement, as per above mentionned PMT): E_m (MPa)	Pl (MPa)	α	Pressuremeter characteristics – Homogeneized soil: E_m (MPa)	Pl (MPa)	α
1	Engineering fill	III		1,5	1,5	20	20,0	2,5	1/3	20,0	2,50	1/3
2	Working platform	III		1,0	2,5	20	17,0	2,4	1/3	17,0	2,40	1/3
3	Soft Material	II		1,0	3,5	20	11,1	1,3	1/3	11,1	1,30	1/2
4	Soft Material	II		1,0	4,5	20	6,3	1,0	1/3	6,3	1,00	1/3
5	Soft Material	II		1,0	5,5	20	16,3	2,5	1/3	16,3	2,50	1/3
6	Soft Material	II		1,0	6,5	20	12,2	2,1	1/3	12,2	2,10	1/3
4	Soft Material	II		1,0	7,5	20	3,7	0,6	1/3	3,7	0,60	1/3
5	Sandy material	III		20	27,5	20	35,0	5,0	1/3	35,0	5,00	1/3

Remark: The depth described is sufficient

$$P_{l\text{-}eq} = aP_{l\text{-}DR} + (1-a)P_{l\text{-}soil} \qquad \alpha_{eq} = a\alpha_{DR} + (1-a)\alpha_{soil} \qquad E_{m\text{-}eq} = aE_{m\text{-}DR}\frac{\alpha_{eq}}{\alpha_{DR}} + (1-a)E_{m\text{-}soil}\frac{\alpha_{eq}}{\alpha_{soil}}$$

D60 MODELISATION

Modulus

E1	18,41	MPa
E2	11,84	MPa
E3,5	7,20	MPa
E6,8	35,00	MPa
E9,16	35,00	MPa

$$E_A = E_1$$

$$E_B = \frac{4}{\frac{1}{E_1} + \frac{1}{0.85E_2} + \frac{1}{E_{3,5}} + \frac{1}{2.5E_{6,8}} + \frac{1}{2.5E_{9,16}}}$$

E_A	18,41 MPa	(spherical modulus)
E_B	12,68 MPa	(deviatoric modulus)
α_1	0,33	Spherical component
$\alpha_{2,16}$	0,34	Deviatoric component

Limit Pressure

pl'2	2,46 MPa	Hence	pl'e	1,81 MPa	Thus	he/R	0,83
pl'3	1,33 MPa	And	he	1,13 m	And	k	1,07

CALCULATION RESULTS

Bearing Capacity

$$q_a = \frac{k}{3}p'_{le}$$

qa **643 kPa**

Higher than 200 kPa => Specification reached

Settlement

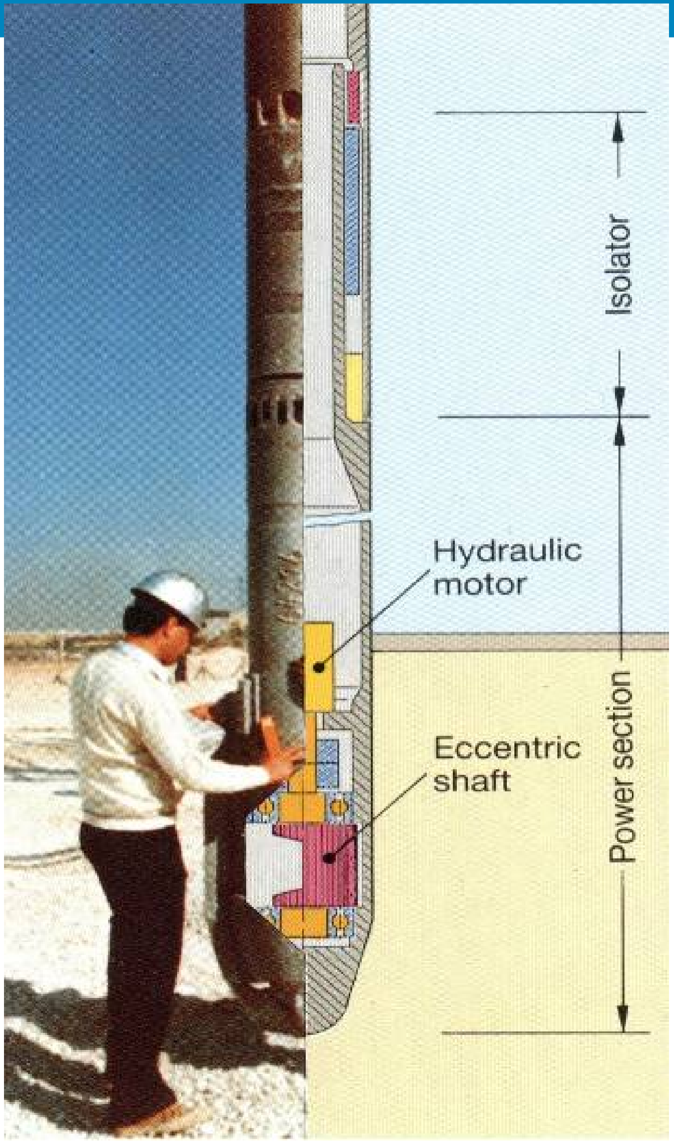
$$w = \frac{1.33}{3E_B}pR_o\left(\lambda_d\frac{R}{R_o}\right)^{\alpha_{2,16}} + \frac{\alpha_1}{4.5E_A}p\lambda_c R$$

w **5,83 mm**

Lower than 25 mm => Specification reached

Dynamic surcharge

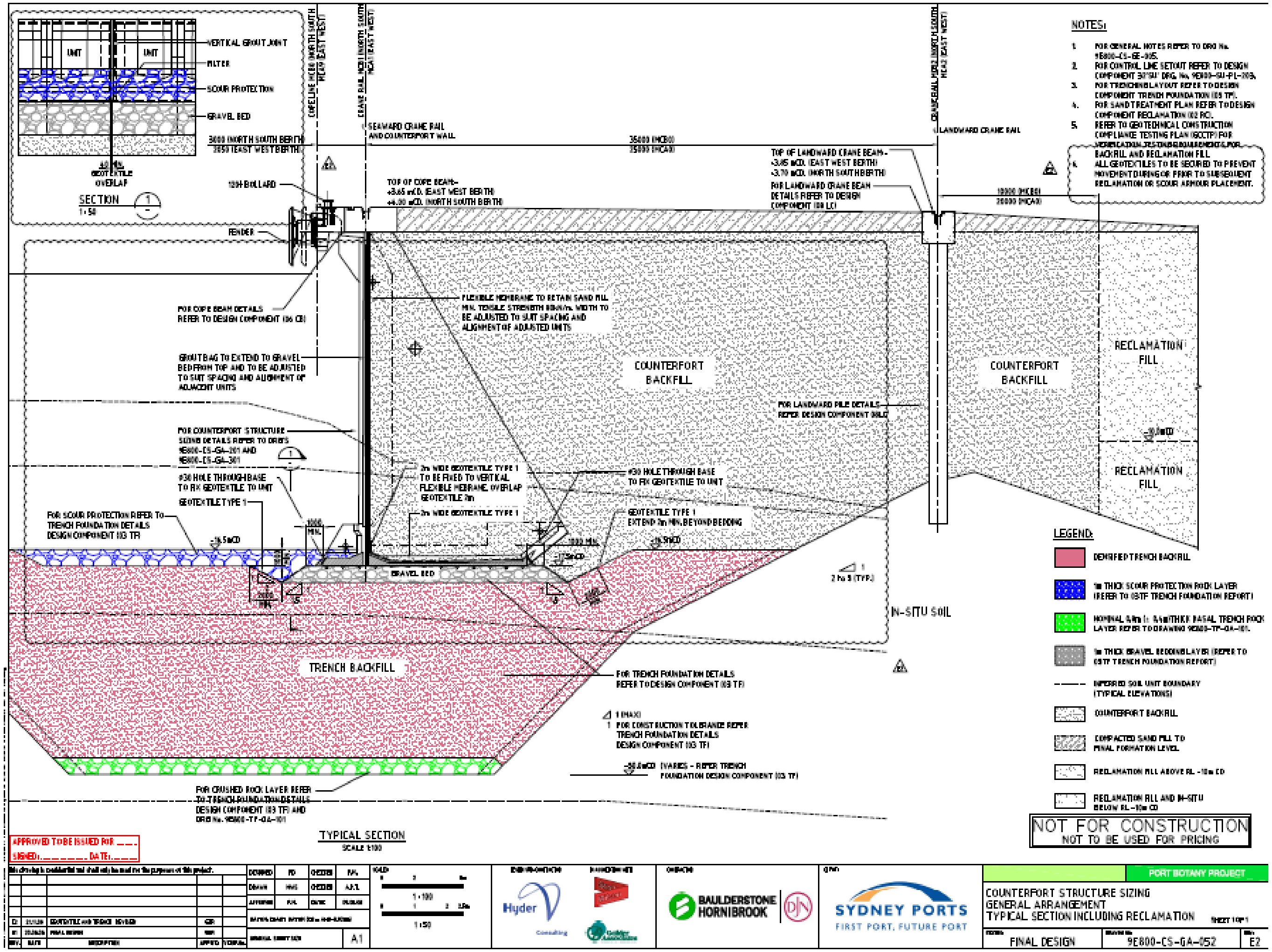
VIBROFLOTS


Isolator
Hydraulic motor
Eccentric shaft
Power section

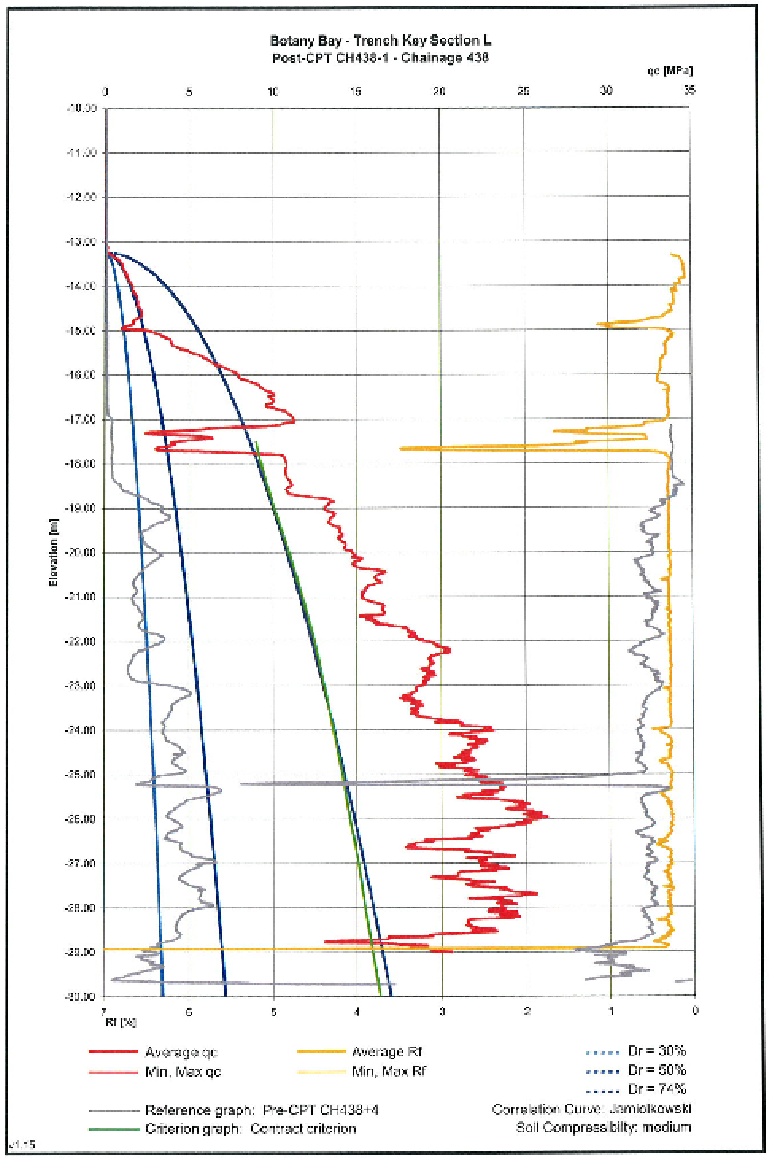

Amplitude
28 – 48mm

PORT BOTANY EXPANSION PROJECT

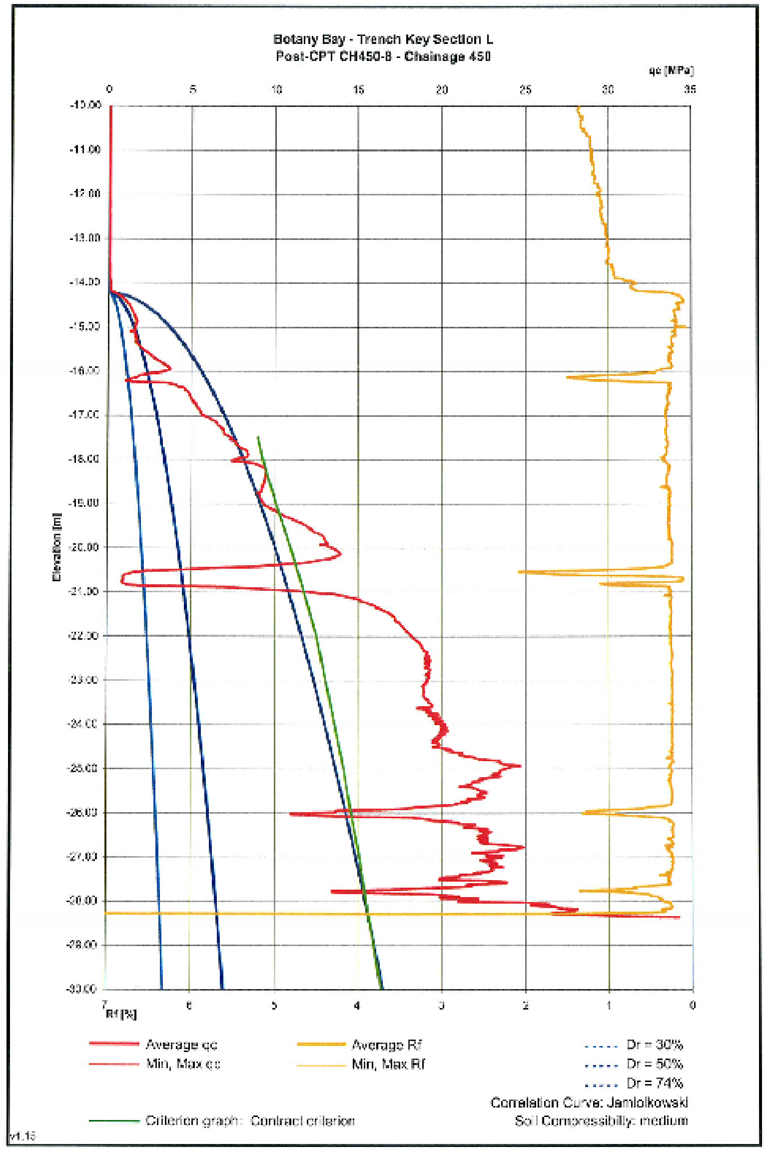
GENERAL ARRAGEMENT COUNTERFORTS INCLUDING RECLAMATION



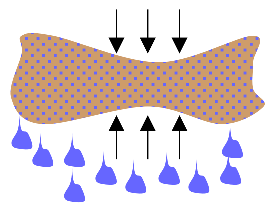
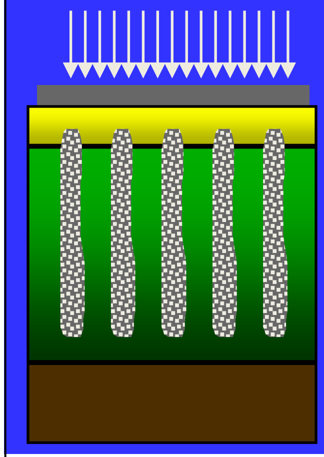
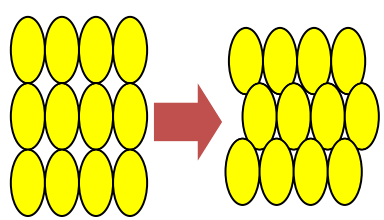
PORT BOTANY EXPANSION PROJECT



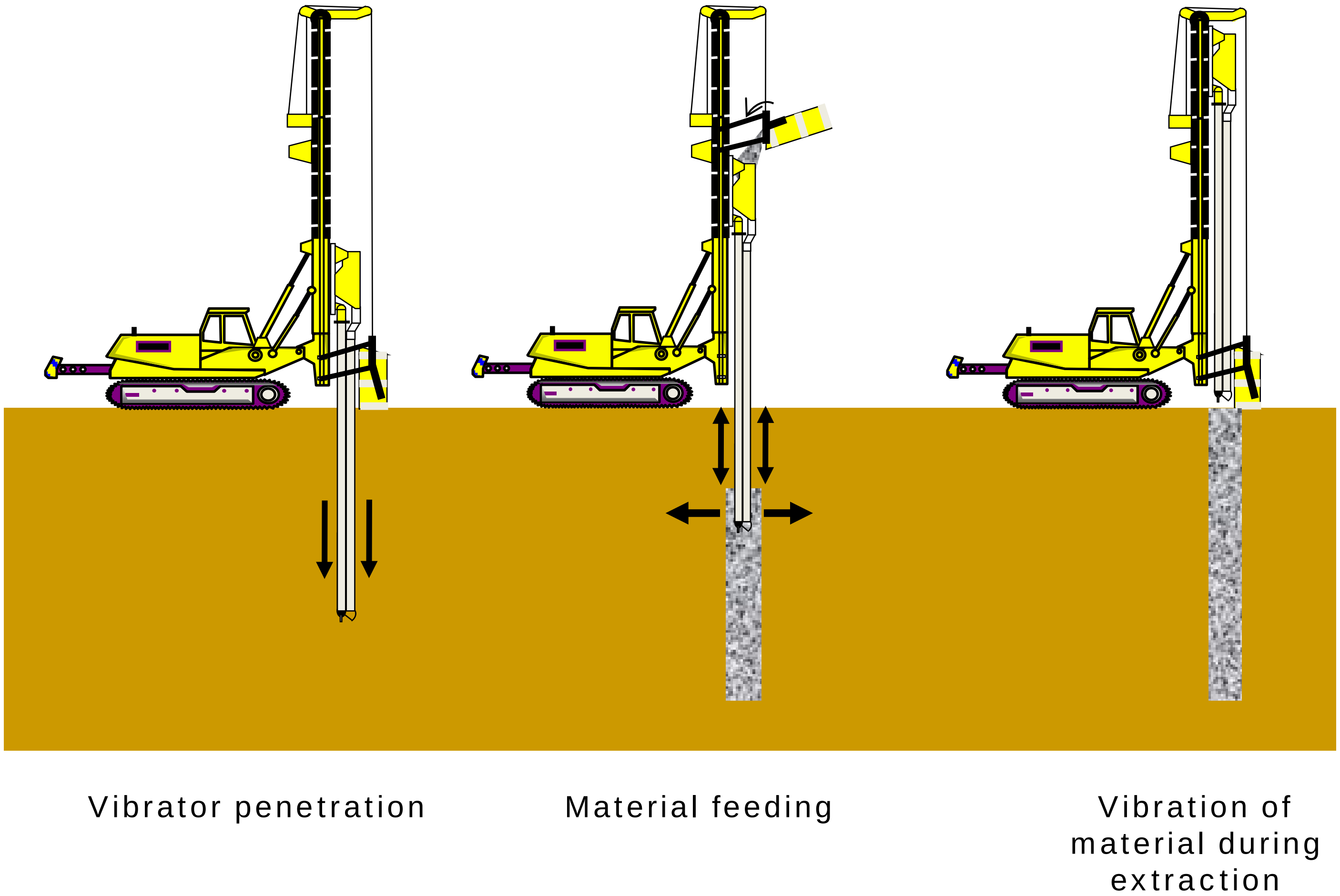
PORT BOTANY EXPANSION PROJECT



Ground Improvement with inclusions: stone columns

	Without added materials	**With added materials**
Cohesive soil **Peat , clay …**	1 Drainage 2 VAcuum 	4 Dynamic replacement 5 Stone columns 6 CMC 7 Jet Grouting 8 Cement Mixing 
Granular soil **Sand , fill**	3 Dynamic consolidation 4 Vibroflottation 	

Stone Columns – Bottom Feed

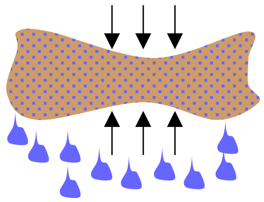
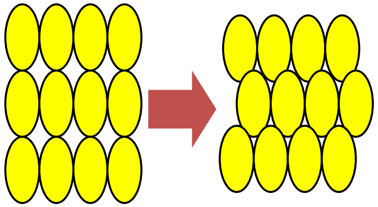
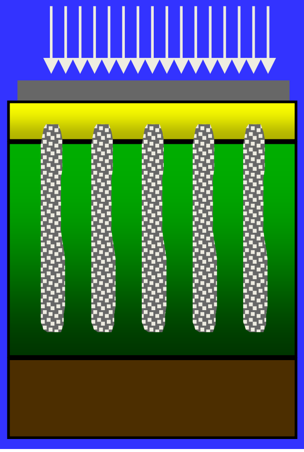


Principle of the technology - bottom feed with air tank

Stone Columns – Bottom Feed

Stone Columns bottom feed to 22 m depth

Ground Improvement with inclusions: Deep Mixing

	Without added materials	With added materials
Cohesive soil **Peat , clay …**	1 Drainage 2 VAcuum 	4 Dynamic replacement 5 Stone columns 6 CMC 7 Jet Grouting 8 Cement Mixing
Granular soil **Sand , fill**	3 Dynamic consolidation 4 Vibroflottation 	

Construction principles and equipment

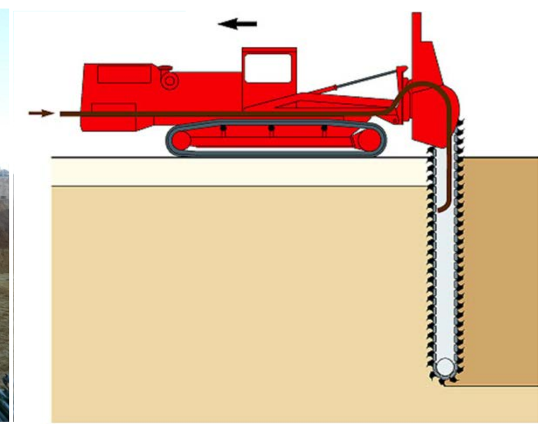
Execution process and ground improvement patterns

- Two types of installation method: wet and dry mixing

- Ground improvement patterns:

  - Soil-cement columns
  - Rectangular soil mix panels
  - Continuous barriers
  - Global mass stabilization

Quasthoff. State of the art in "Dry Soil Mixing" – Basics and case study . IS-GI 2012



Construction principles and equipment

Wet soil-cement column systems

CVR C-mix® system

Denies et al. **Soil Mix walls as retaining structures – Belgian practice. IS-GI 2012**

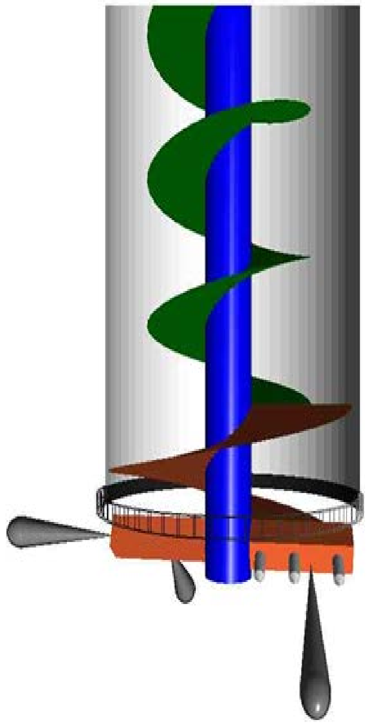
Typical characteristics:

Water/Cement weight ratio (W/C): 0.6 to 0.8 (-)
Amount of cement: 350 to 450 kg/m3
Spoil return: up to 30%

Construction principles and equipment

Wet soil-cement column systems

SMET Tubular Soil Mix (TSM®) system



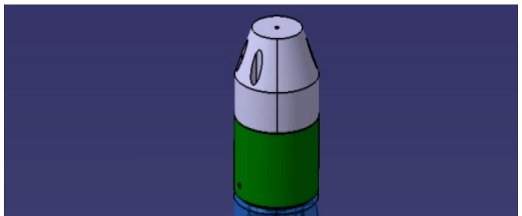
Denies et al. Soil Mix walls as retaining structures – Belgian practice. IS-GI 2012

Typical characteristics:
Water/Cement weight ratio (W/C): 0.6 to 1.2 (-)
Amount of cement: 200 to 450 kg/m3
Spoil return: up to 30%

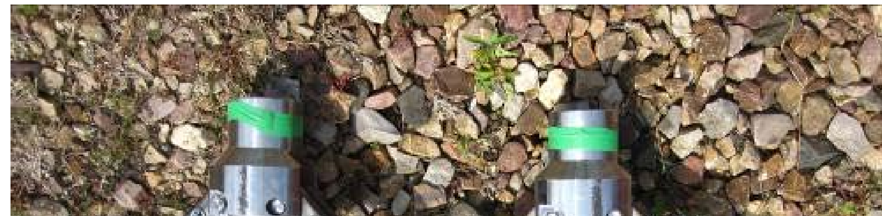
Construction principles and equipment

Wet soil-cement column systems

Keller Foundations FLAPWINGS® system



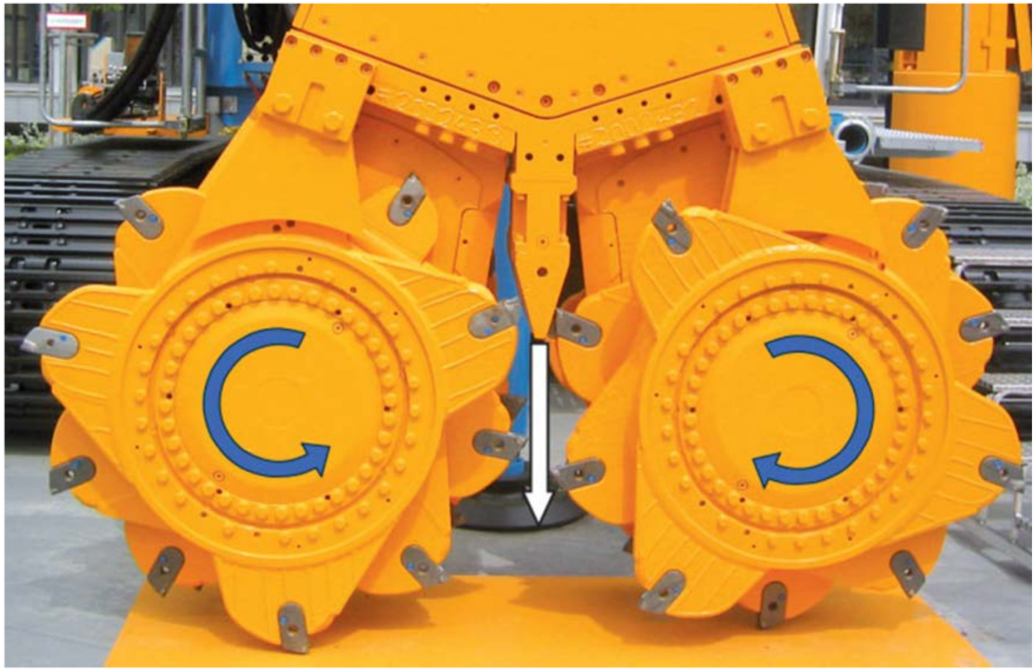
Soletanche Bachy SPRINGSOL® system



The drilling can be protected by steel tubes to avoid grout pollution of the top layers like ballast of railways

Construction principles and equipment

Cutter Soil Mixing (CSM®) system for soil mix panels



Gerressen and Vohs. **CSM-Cutter Soil Mixing – Worldwide experiences of a young soil mixing method in challenging soil conditions. IS-GI 2012**

Several case histories in the proceedings of the IS-GI 2012

Typical characteristics in Belgium:

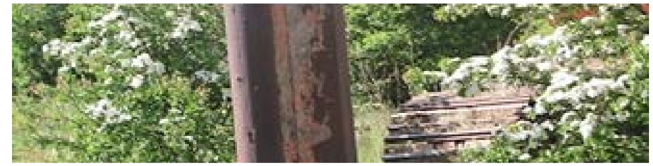
Water/Cement weight ratio (W/C): 0.6 to 1.2 (-)

Amount of cement: 200 to 400 kg/m3

Spoil return: up to 30%

Construction principles and equipment

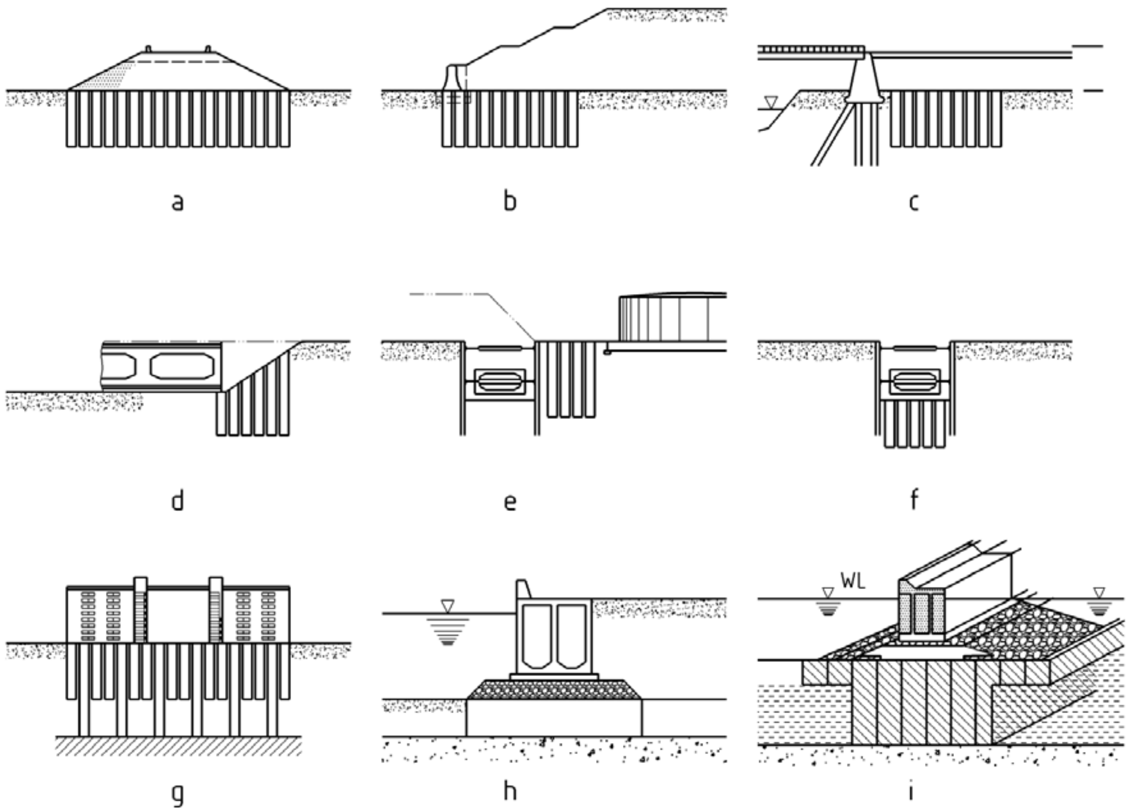
ALLU® mass stabilization system



Al-Tabbaa et al. Soil Mix Technology for Integrated Remediation and Ground Improvement: Field Trials. IS-GI 2012

Wet and dry methods are available

Deep mixing – EN 14679 (CEN TC 288) : field of application



- a Road embankment stability/settlement
- b High embankment stability
- c Bridge abutment uneven settlement
- d Stability of cut slope
- e Reducing the influence from nearby construction
- f Braced excavation earth pressure/heave
- g Pile foundation lateral resistance
- h Sea wall bearing capacity
- i Break-water bearing capacity

Field of applications and case histories

Earth/water retaining structures

Peixoto et al. Permanent Excavation Support in Urban Area using Cutter Soil Mixing technology at Cannes. IS-GI 2012

Since 2000 in Belgium: applications for DSM

- *earth/water retaining structures and foundations*
- *permanent function*
- *always deeper and larger project*

Field of applications and case histories

Earth/water retaining structures

Construction of shafts with CSM technology

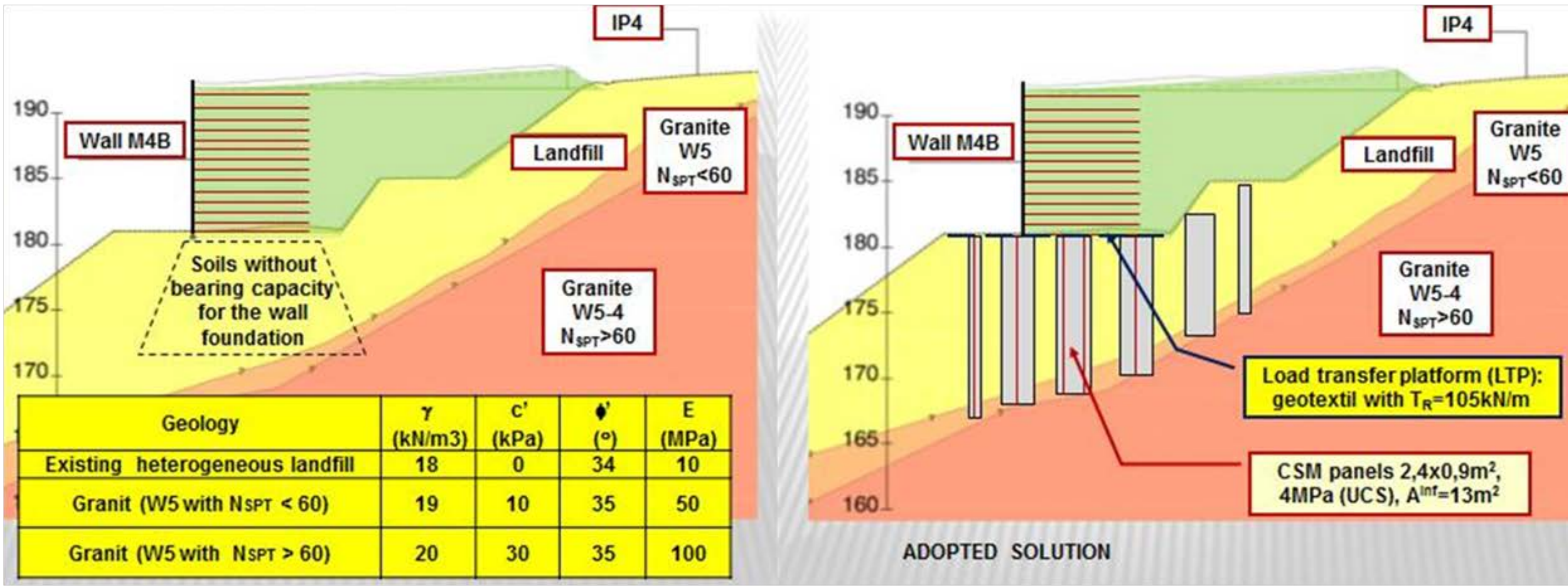
<u>Pinto et al.</u> Ground Improvement Solutions using CSM Technology. IS-GI 2012

Field of applications and case histories

Slope stabilization

Widening of an existing road platform:

Slope stabilization and foundation of the retaining wall



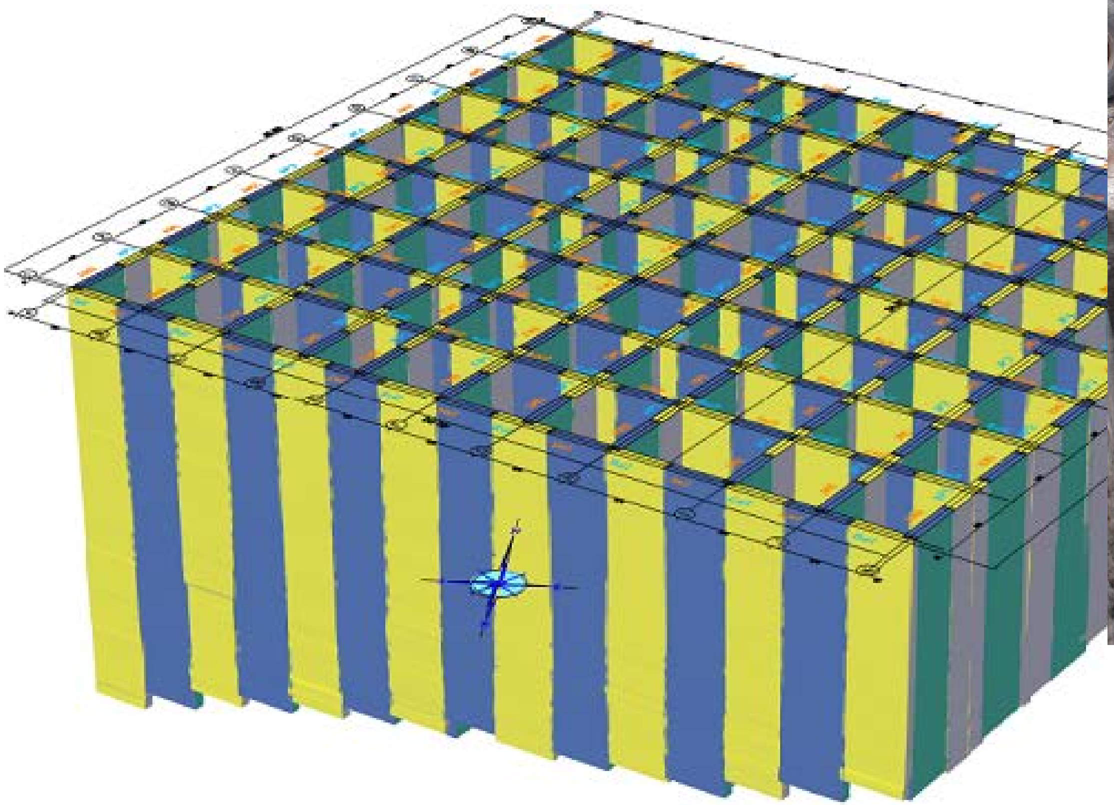
Geology	γ (kN/m3)	c' (kPa)	φ' (º)	E (MPa)
Existing heterogeneous landfill	18	0	34	10
Granit (W5 with NSPT < 60)	19	10	35	50
Granit (W5 with NSPT > 60)	20	30	35	100

Pinto et al. Ground Improvement Solutions using CSM Technology. IS-GI 2012

Field of applications and case histories

Barrier against liquefaction and post-liquefaction damages

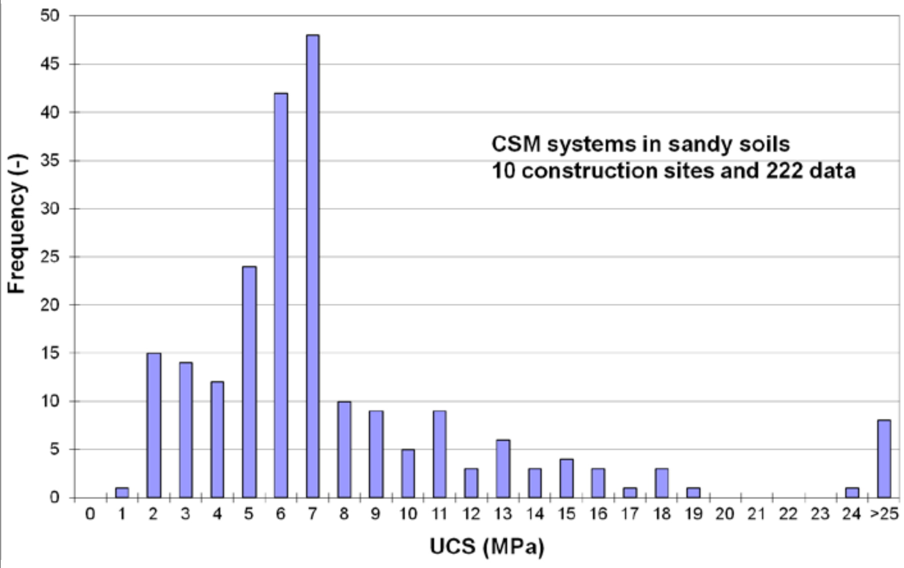
3D arrangement of Geomix® caissons



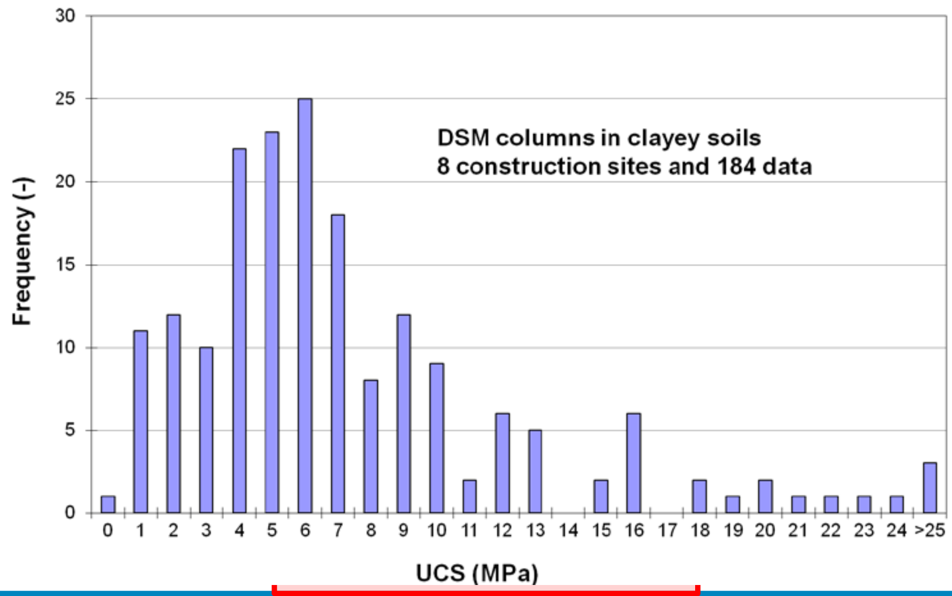
<u>Benhamou and Mathieu.</u> Geomix Caissons against liquefaction. IS-GI 2012

Hydro-mechanical characterization of DSM material: some results form the research project in B

Typical UCS values



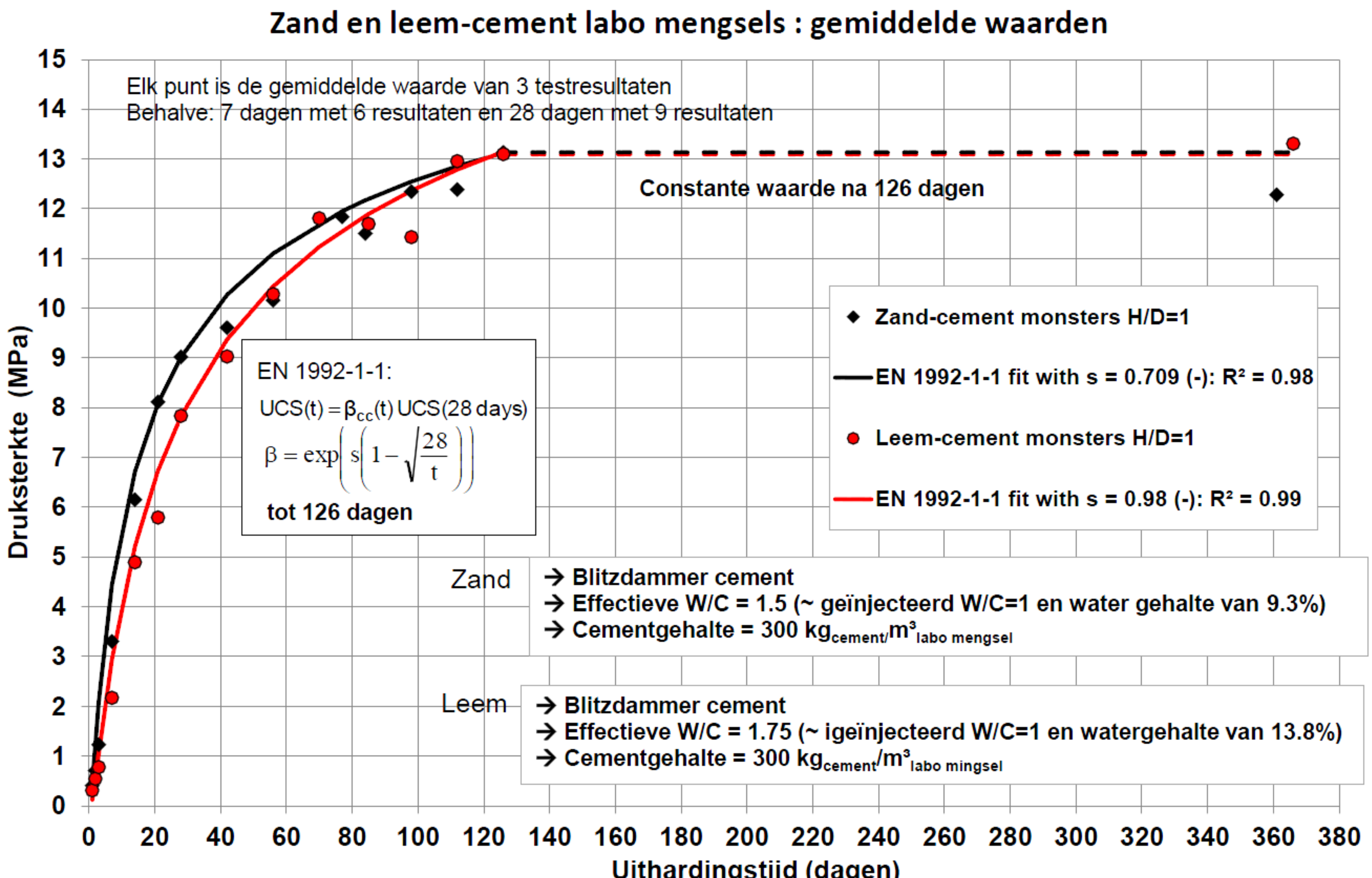
DSM core samples



Denies et al. SOIL MIX WALLS as retaining structures – mechanical characterizatio
Brussels 2012

Hydro-mechanical characterization of DSM material: some results form the research project in B

UCS and curing time effect (NEW RESULTS)



UCS

Time (days)

Hydro-mechanical characterization of DSM material: some results form the research project in B

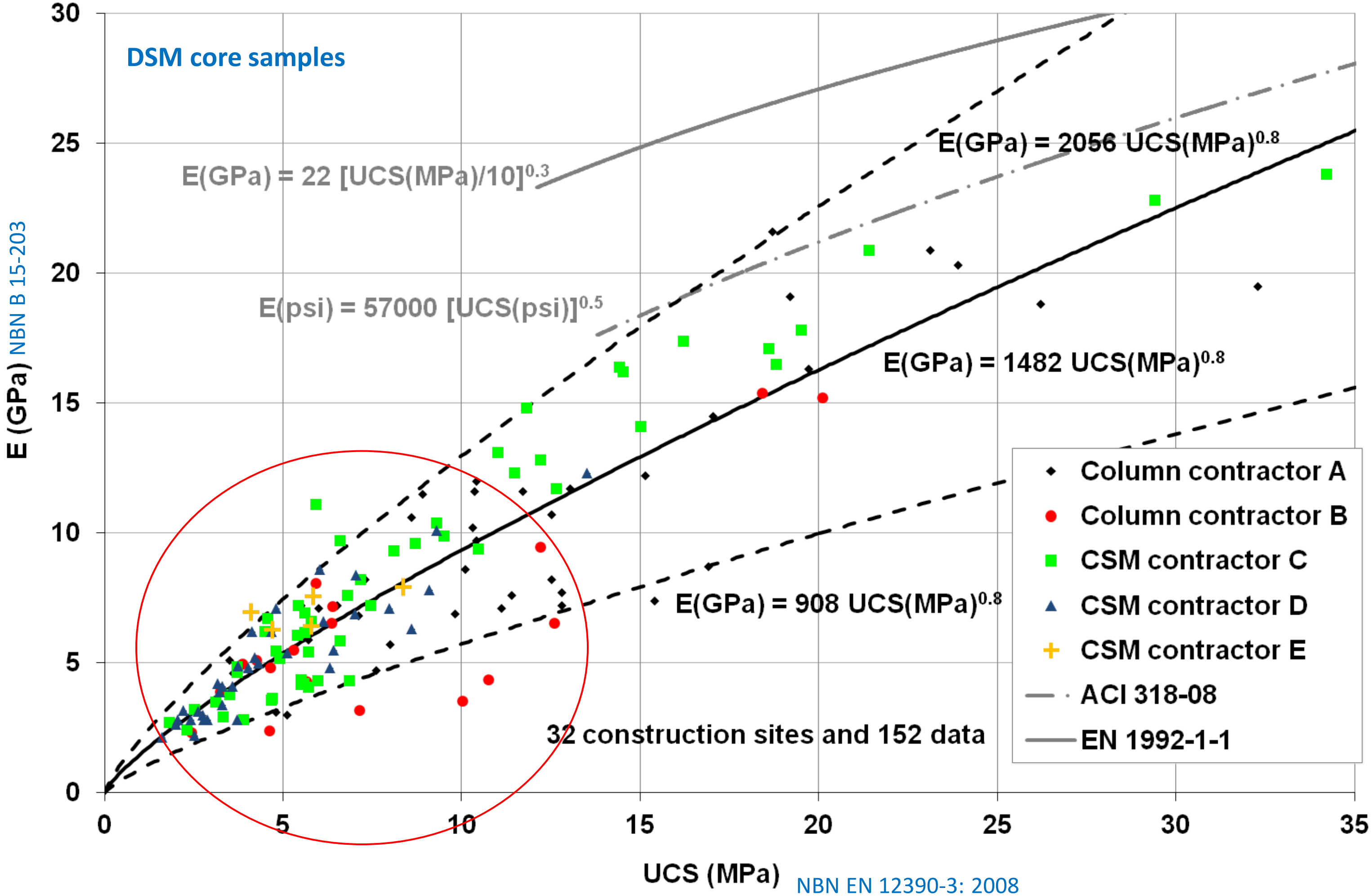
UCS and curing time effect (NEW RESULTS)

	$UCS\ (time) = \beta .\ UCS\ (28\ days)$	
	Sand-Cement samples	Loam-Cement samples
7 days	$\beta = 0.37$	$\beta = 0.28$
28 days	$\beta = 1$	$\beta = 1$
56 days	$\beta = 1.13$	$\beta = 1.31$
126 days	$\beta = 1.46$	$\beta = 1.67$

After 126 days : no increase of UCS

Hydro-mechanical characterization of DSM material: some results form the research project in B

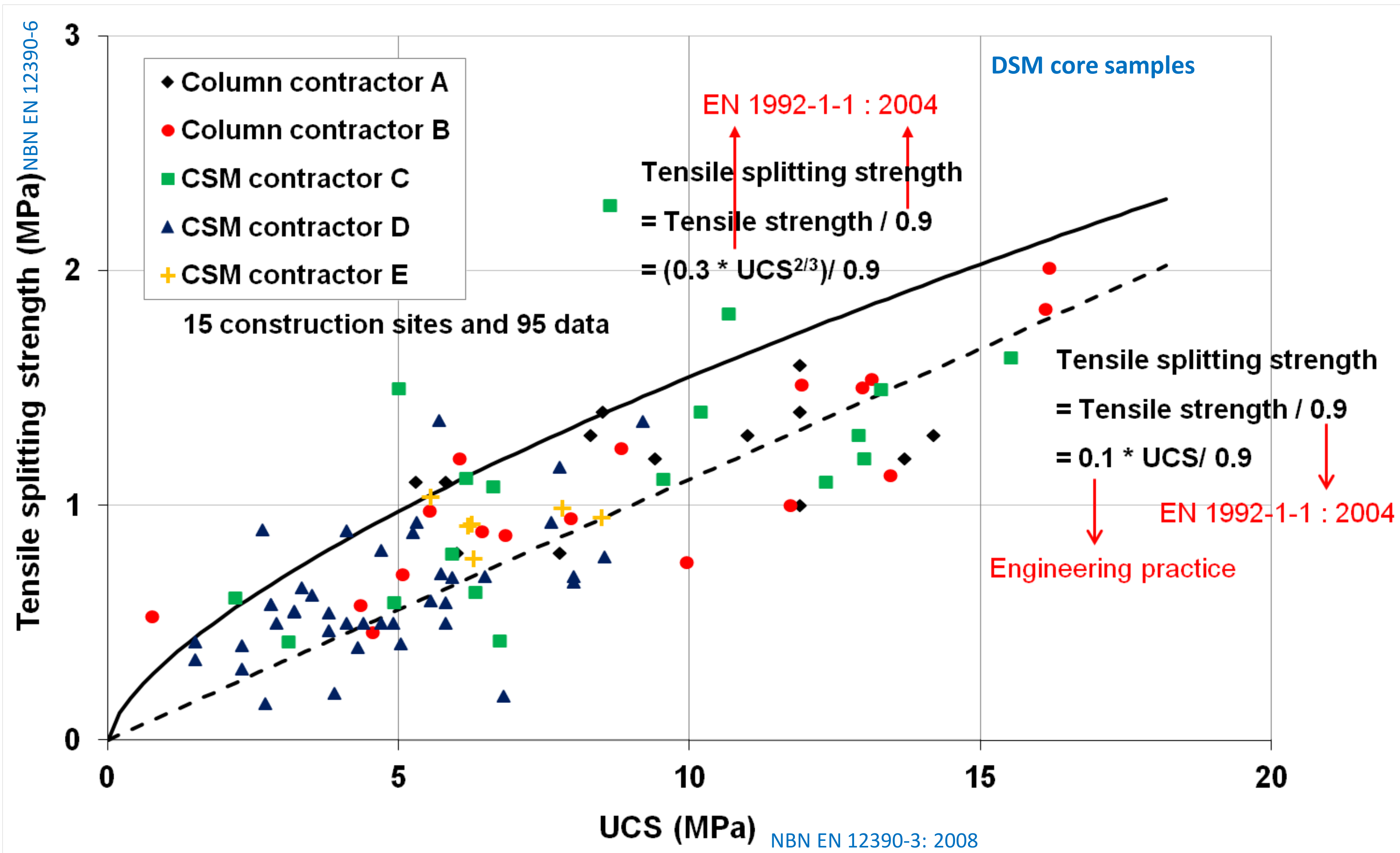
UCS and Modulus of Elasticity (E)



Denies et al. SOIL MIX WALLS as retaining structures – mechanical characterization. IS-GI, Brussels 2012

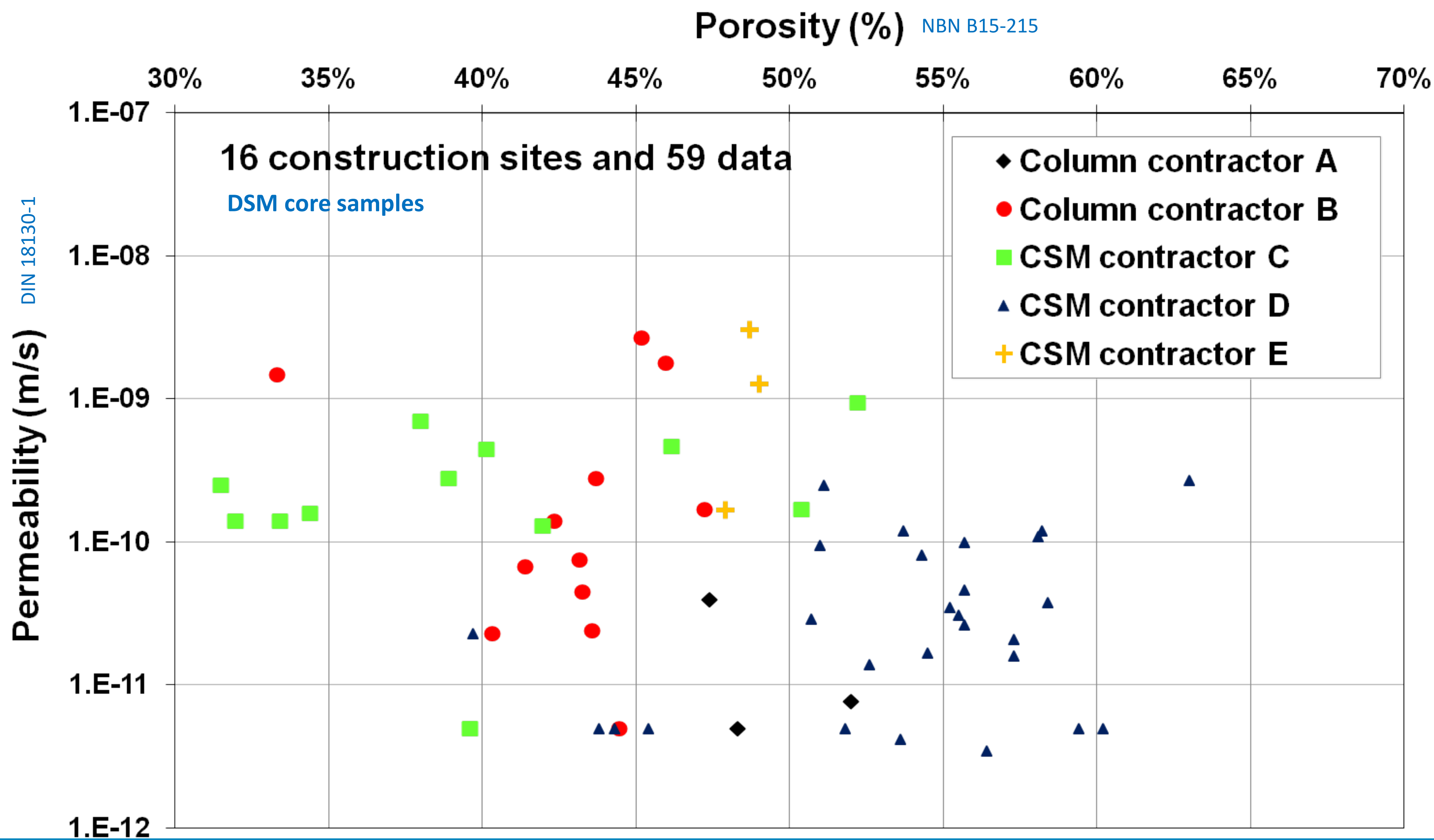
Hydro-mechanical characterization of DSM material: some results form the research project in B

UCS and Tensile splitting strength (T)



Hydro-mechanical characterization of DSM material: some results form the research project in B

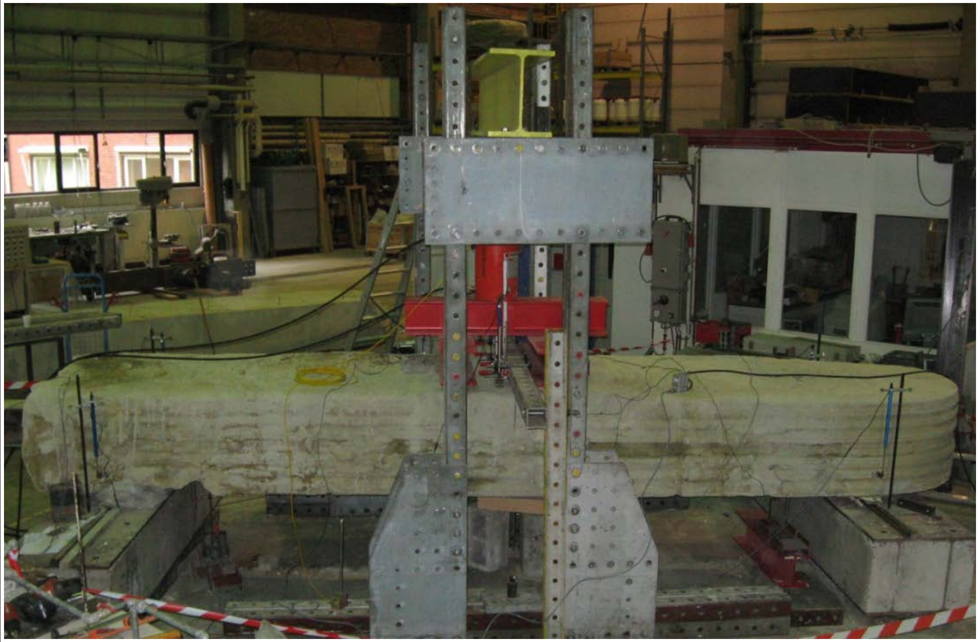
Porosity and permeability

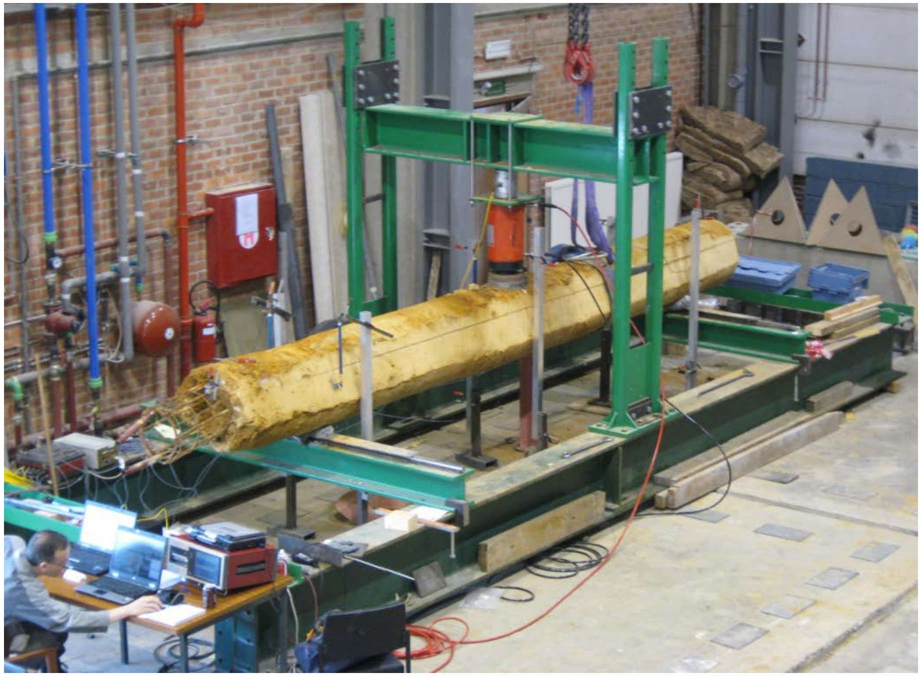


Denies et al. SOIL MIX WALLS as retaining structures – mechanical characterization. IS-GI, Brussels 2012

Hydro-mechanical characterization of DSM material: some results form the research project in B

Large-scale bending tests @ BBRI *(17 tests – 7 sites)*

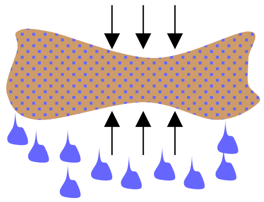
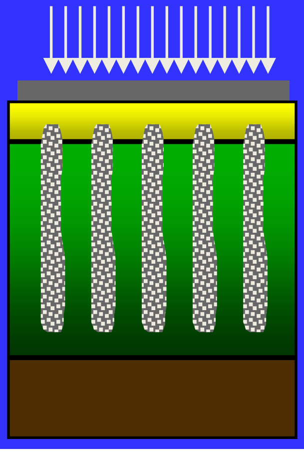
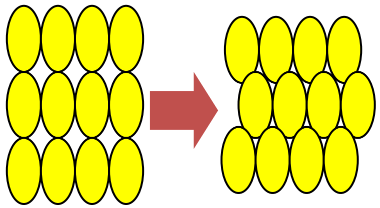




→ In situ EI characteristics

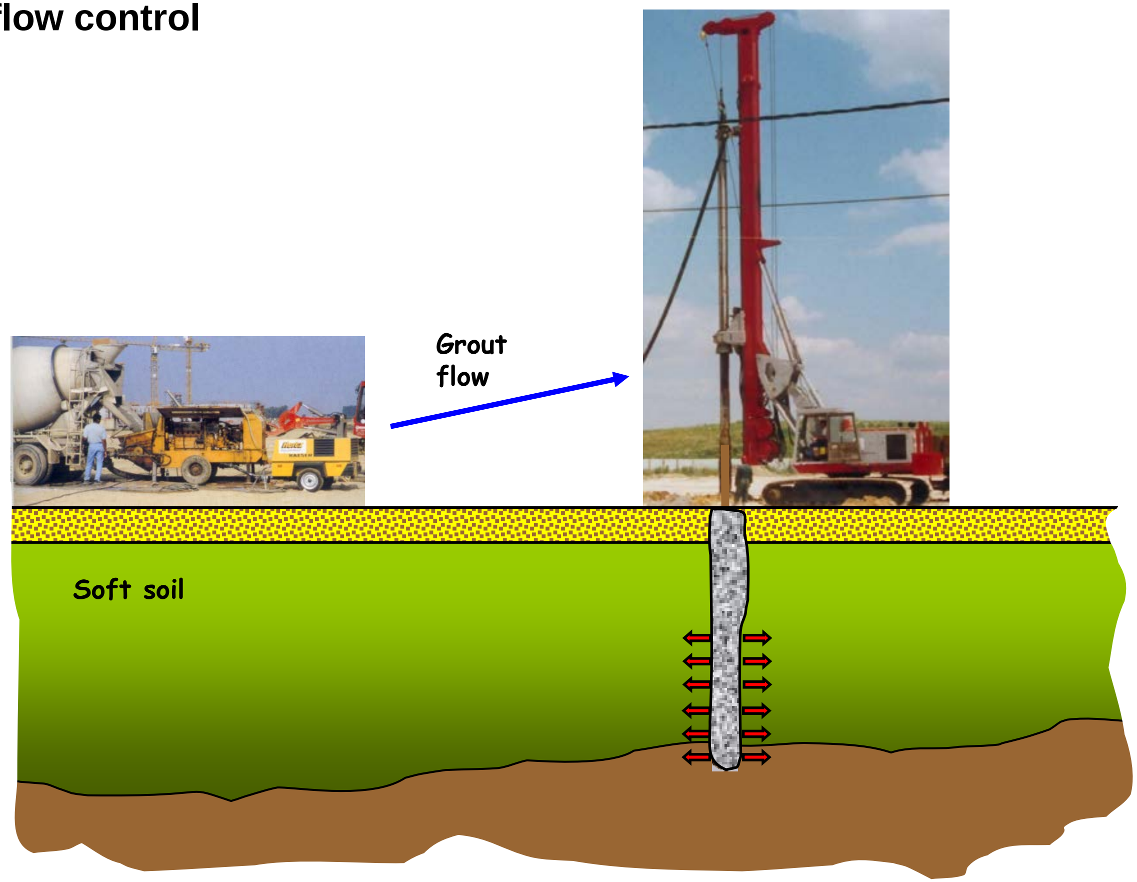
→ Effect on strains in steel reinforcement

Ground Improvement with inclusions: CMC

	Without added materials	With added materials
Cohesive soil **Peat , clay …**	1 Drainage 2 VAcuum 	4 Dynamic replacement 5 Stone columns 6 CMC 7 Jet Grouting 8 Cement Mixing 
Granular soil **Sand , fill**	3 Dynamic consolidation 4 Vibroflottation 	

CMC – Execution

- Fleet of specilized equipment
  - Displacement auger => quasi no spoil
  - High torque and pull down
- Fully integrated grout flow control

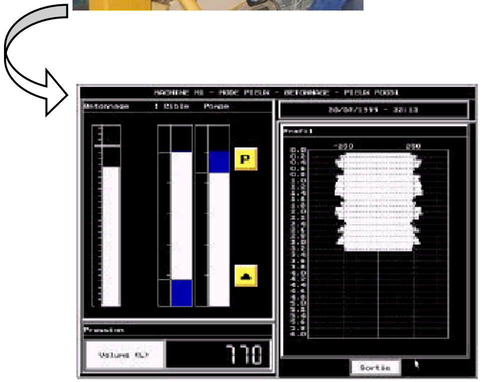


CMC – Typical Testing

- **Load testing on isolated CMC**
  - **Checking of individual capacity,**
  - **Checking of adequate soil parameters taken into account.**

- **Compression tests on material**
  - **Checking of good grout resistance**

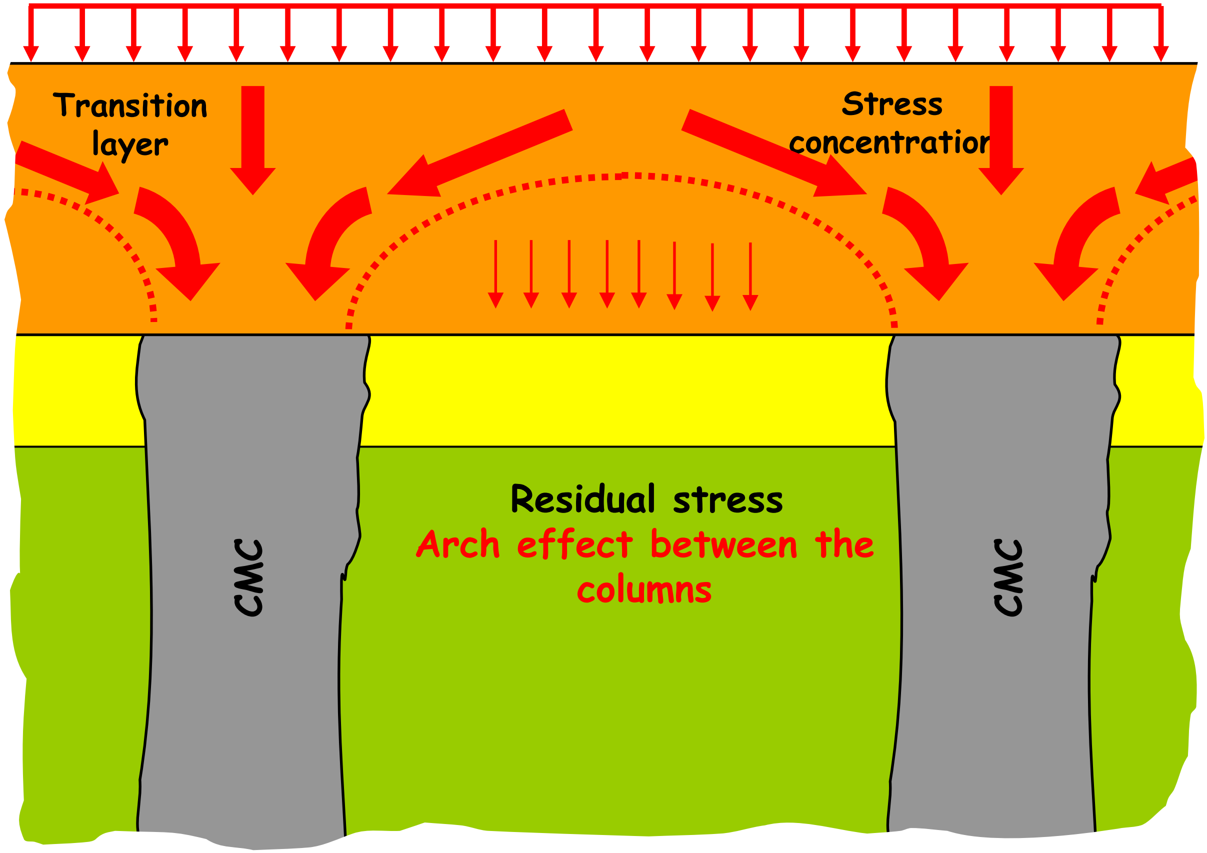
- **Data recording system during execution**
  - **Recording of drilling parameters => Checking of anchorage,**
  - **Recording of grouting parameters => No necking**



CMC – Execution

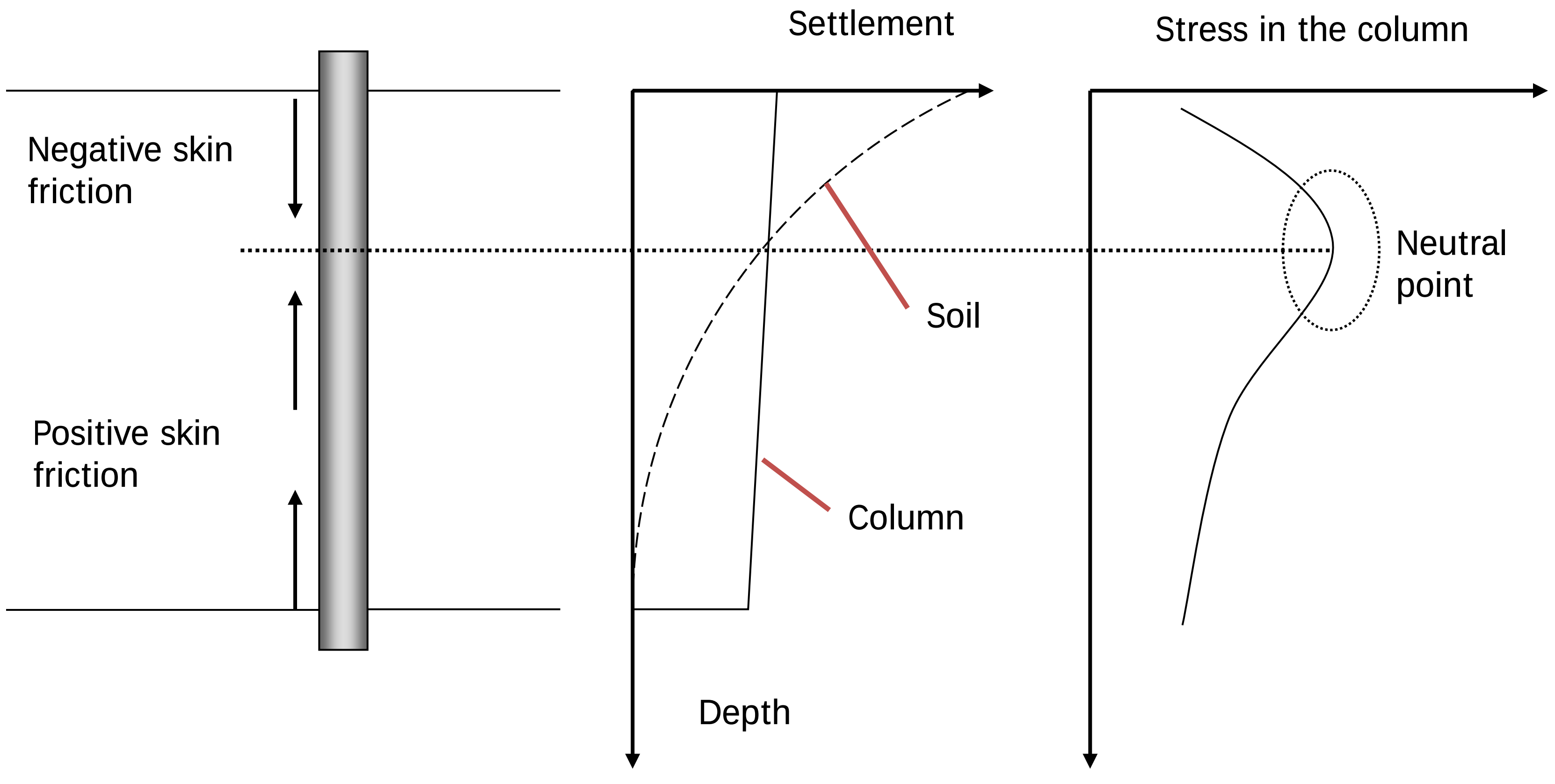
CMC Principle

- **Create a <u>composite material</u> Soil + Rigid Inclusion (CMC) with:**
  - **Increased bearing capacity**
  - **Increased elastic modulus**
- **Transfer the load from structure to CMC network with a <u>transition layer</u>**



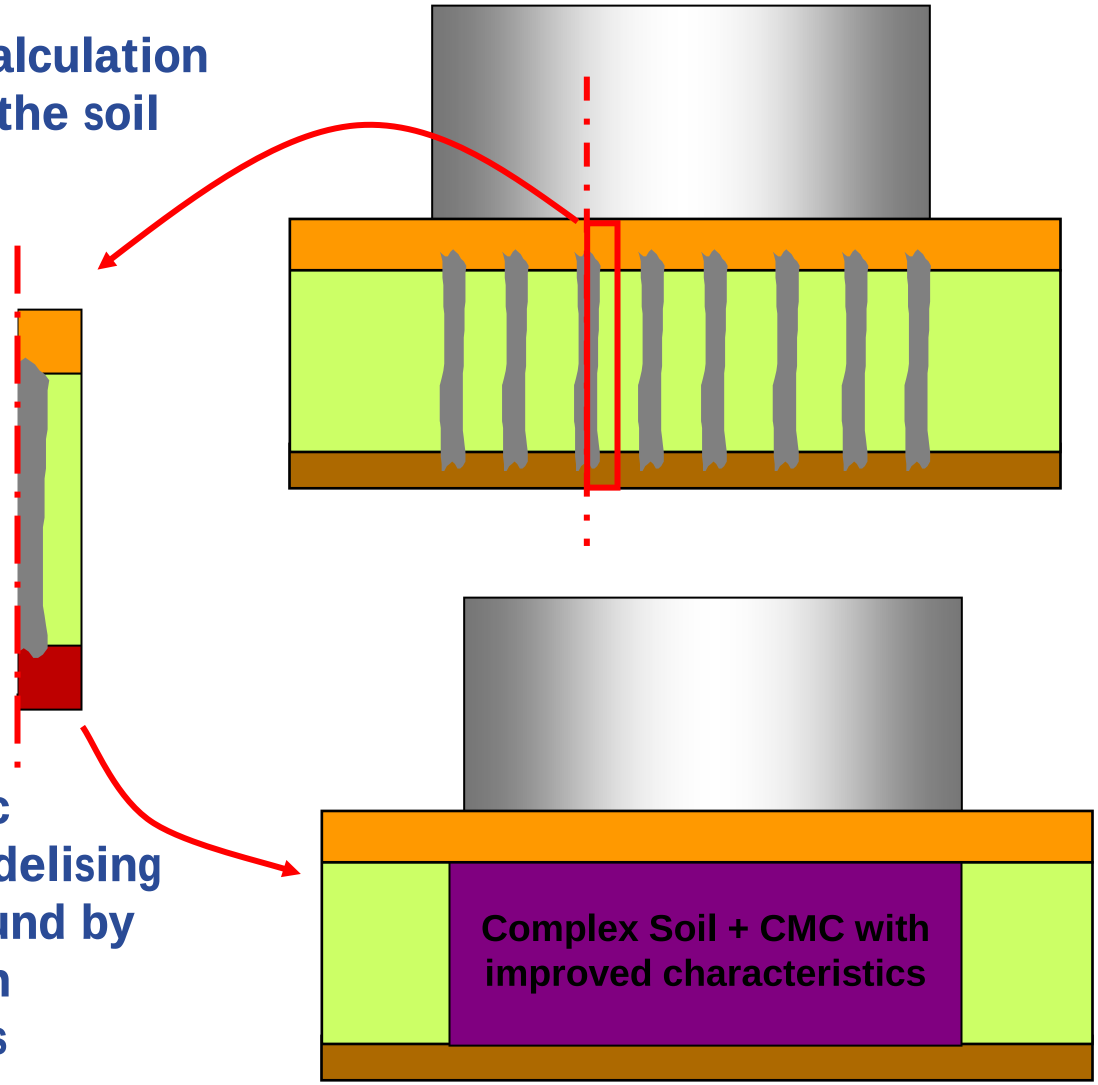
CMC - Basic behavior under uniform load

- **Negative skin friction allows to develop a good arching effect**



CMC Design - Principle

Axisymetric FEM calculation with one CMC and the soil => eq. Stiffness



Global axisymetric calculation by modelising the improved ground by material having an improved stiffness

CMC Design – Specific case of non vertical loading

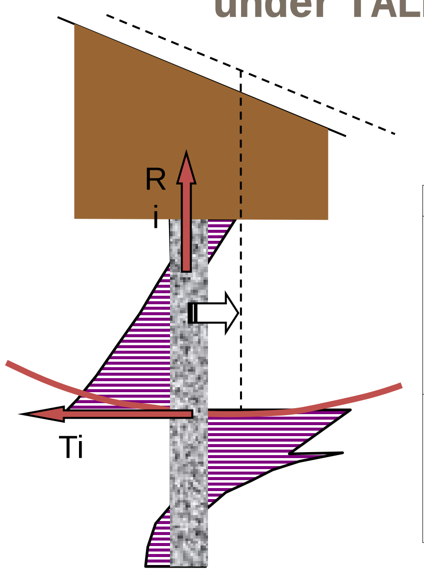
- **Calculation principle**

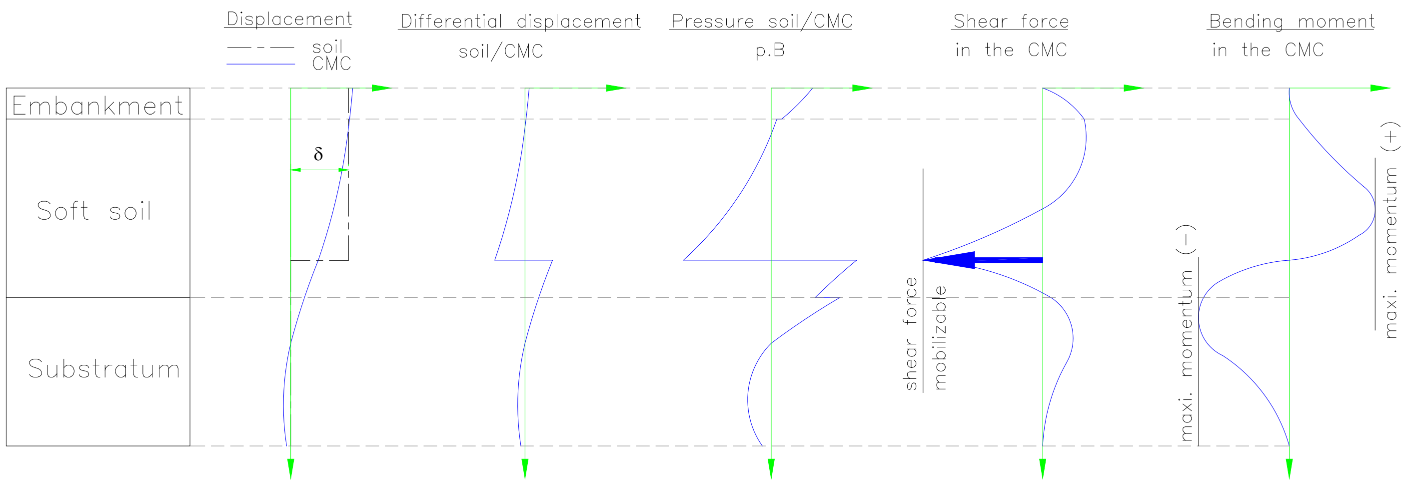
1/ Estimation of the vertical stress in the column (% of the embankment load),

2/ Thus maximum momentum so that M / N ≤ D / 8 (no traction in the mortar),

3/ Thus maximum shear force taken by the includion (similar to a pile to which a displacement is applied),

4/ Modeling of the CMC as nails working in compression + imposed shear force under TALREN software (or equivalent).

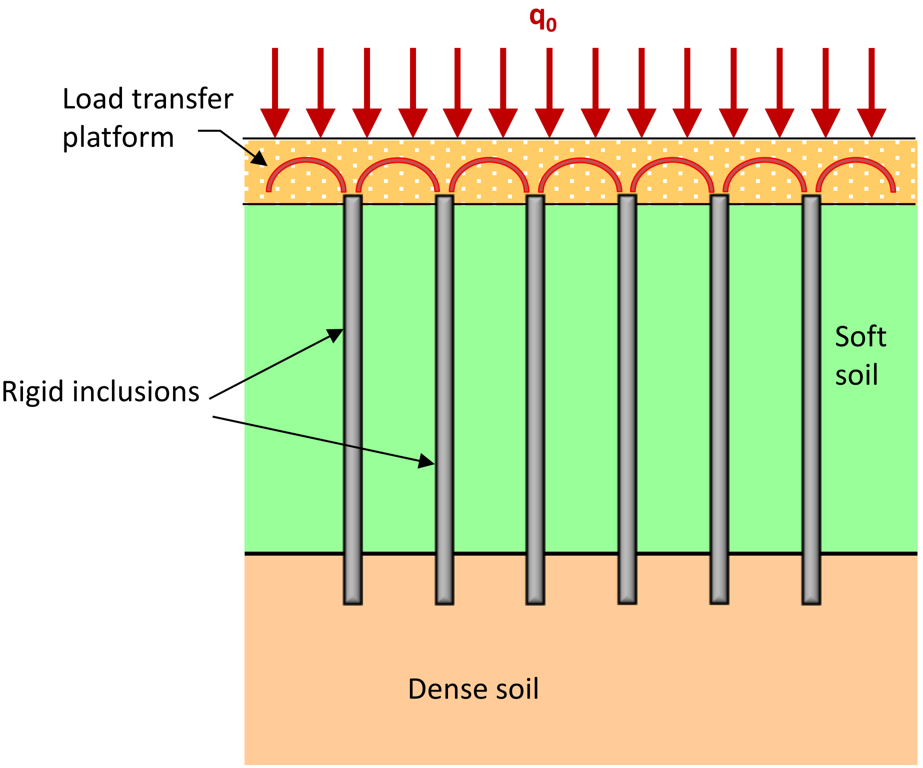


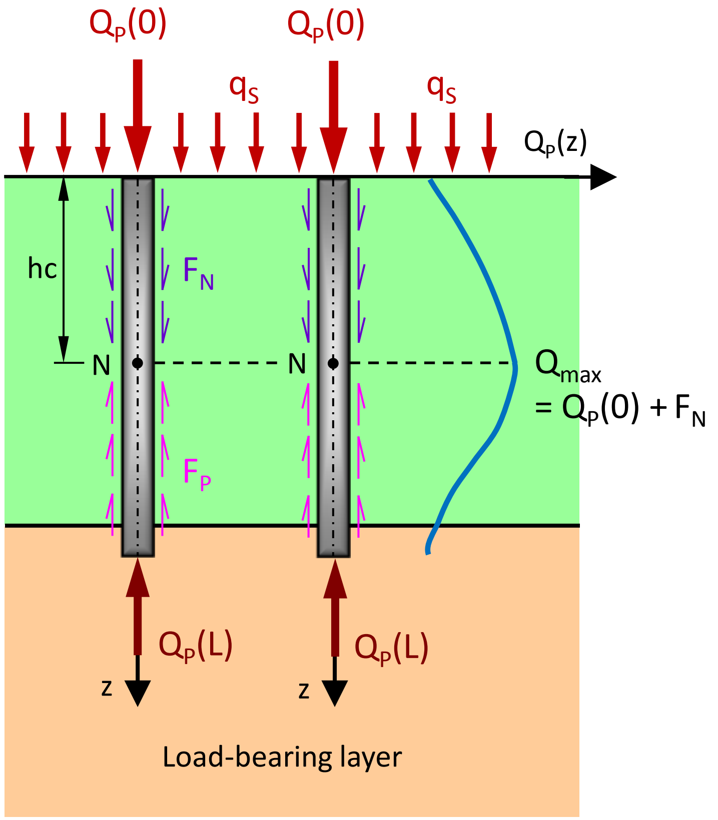


CMC Design – Benefits for the structure

- **Structure shall be designed as if soil was of good quality**
  - Specialist contractor provides structural designer with bearing capacity, k, etc…
- **No connection between foundation and structure**
  - Structure is less complex to be designed,
  - No stiff connection, thus no increase under seismic analysis,
  - Structure very simple to be built: footings and slab on grade, no pile cap, thus benefit in terms of cost and speed of execution

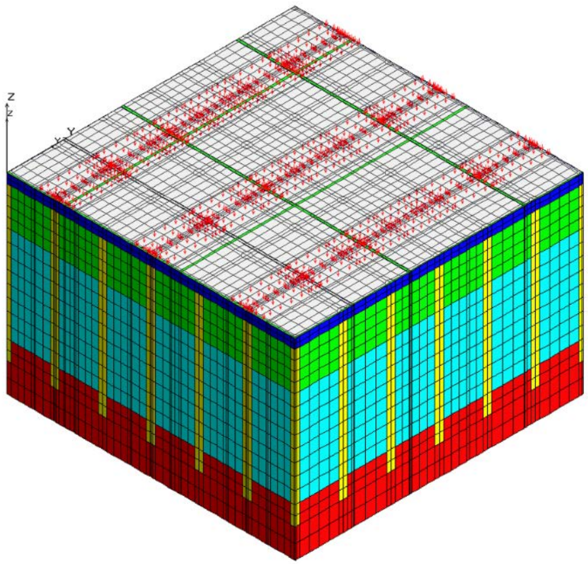
General behaviour of rigid inclusions

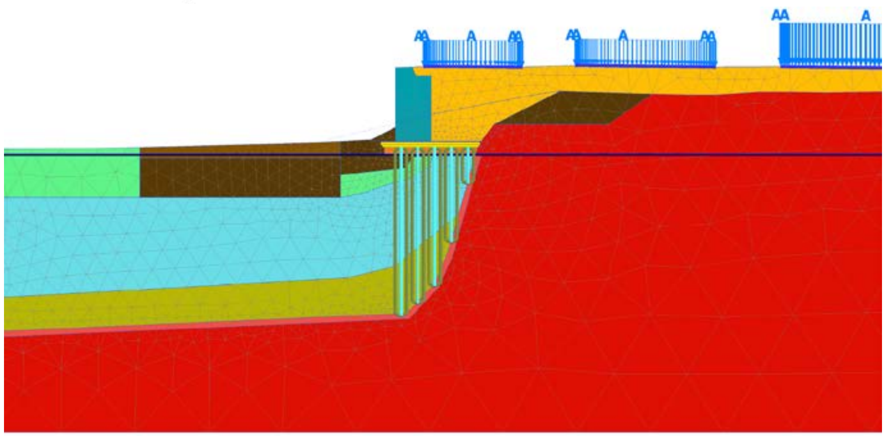


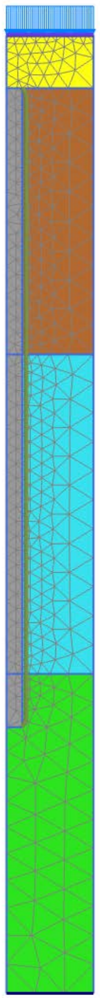


$$Q_P(0) + F_N = Q_{max} = F_P + Q_P(L)$$

Rigid inclusions design based on Finite Element Models





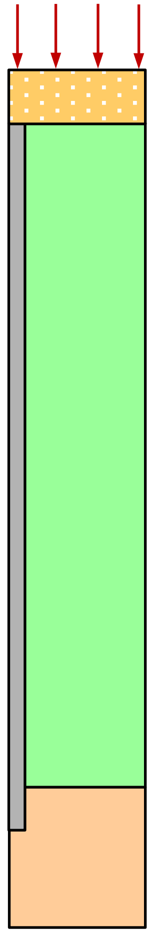


Rigid inclusions design based on Finite Element Models

- Use of linear elastic perfectly plastic law with Mohr-Coulomb's failure criterion

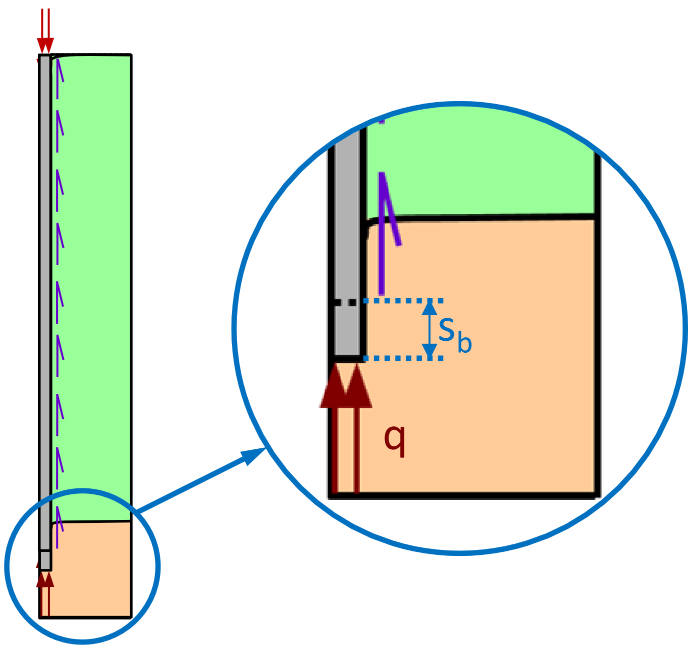
- Main basic parameters
  - Young's modulus E_Y
  - Poisson's ratio ν
  - Unit weight γ
  - Effective cohesion c'
  - Effective friction angle φ'

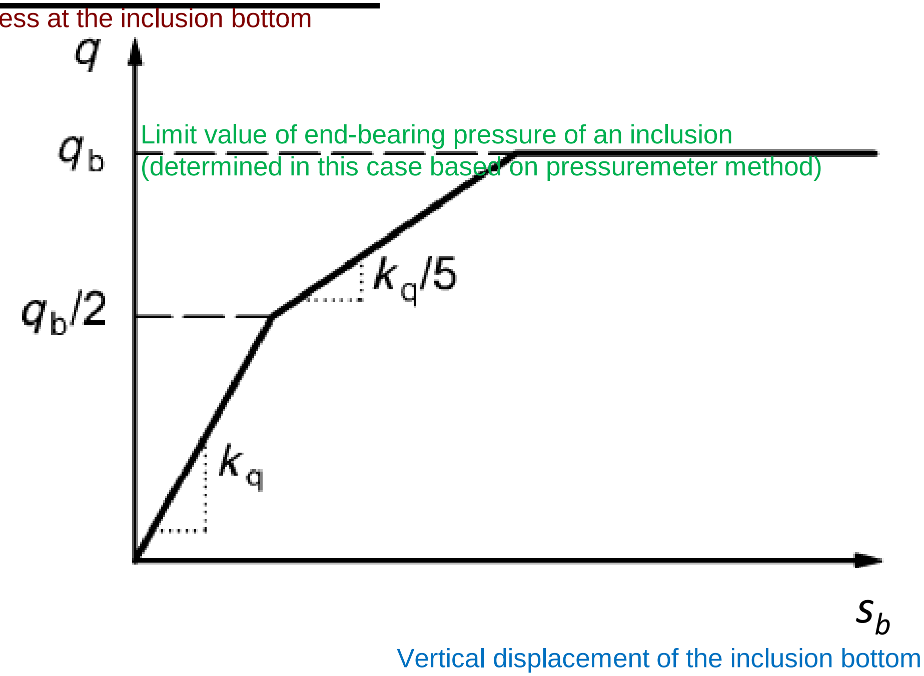
- Which values should be input ?
  - $\mathbf{E_Y = \frac{E_m}{\alpha}}$?
  - c' and φ' determined from lab tests ?



Semi-empirical mobilization laws of Frank and Zhao

- <u>Behaviour at the inclusion bottom</u>

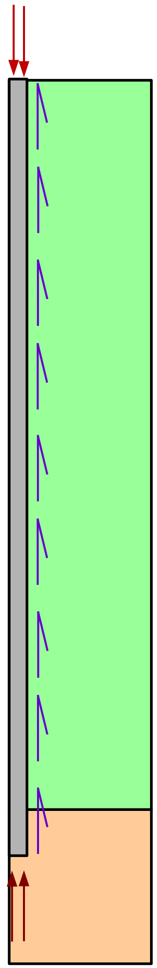




$$k_q = \frac{11E_M}{B}$$ for fine-grained soils, $$k_q = \frac{4.8E_M}{B}$$ for granular soils

B : inclusion diameter

Calibration of FEM input parameters on Frank & Zhao's laws



$E_Y = E_m/\alpha$

$c' = q_s$ (q_s determined based on pressuremeter method)

$\varphi' \approx 0°$

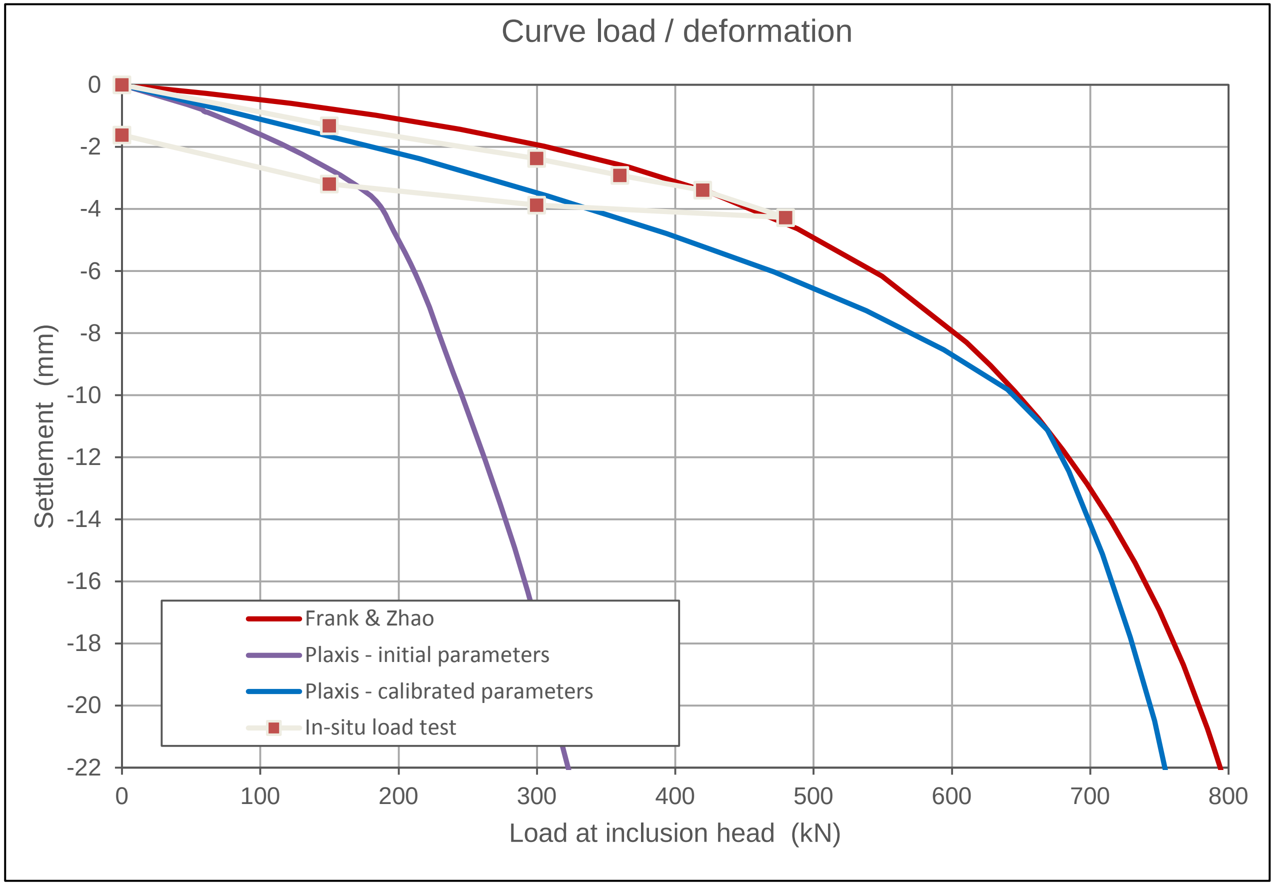
$E_Y = 1.5$ to $6 \times E_m/\alpha$

$c' = q_b/9$ (q_b determined based on pressuremeter method), API (1991)

$\phi' \approx 0°$

Example: Plate Load Tests in Venette, France

- Load test curve with calibrated parameters – Comparison with in-situ load test

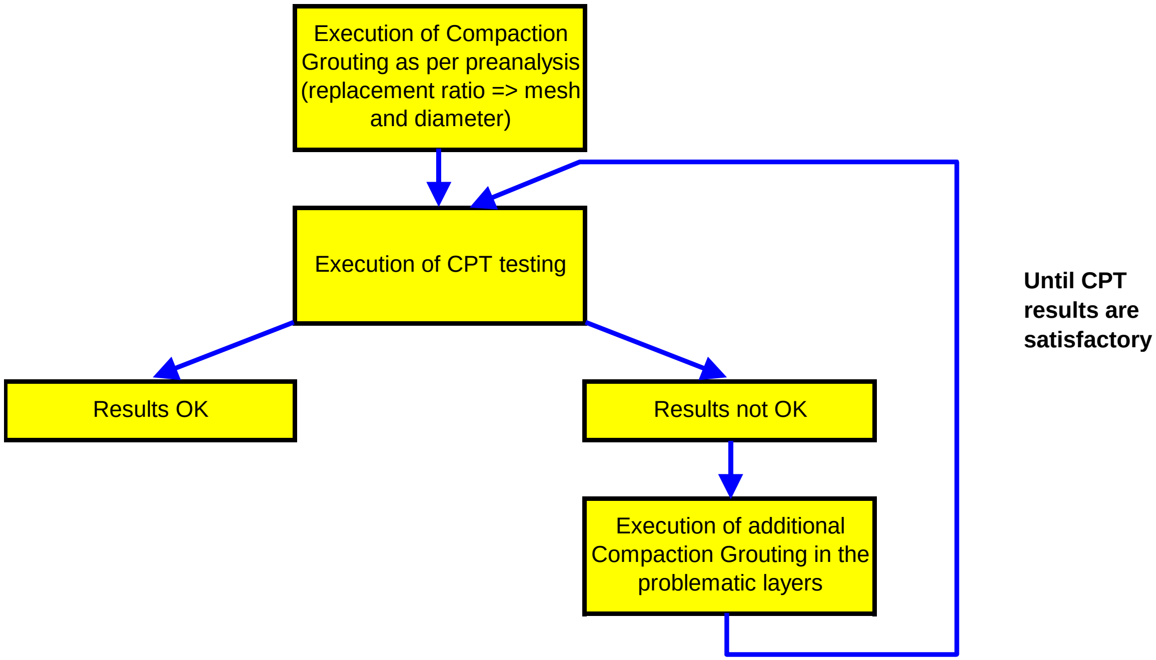


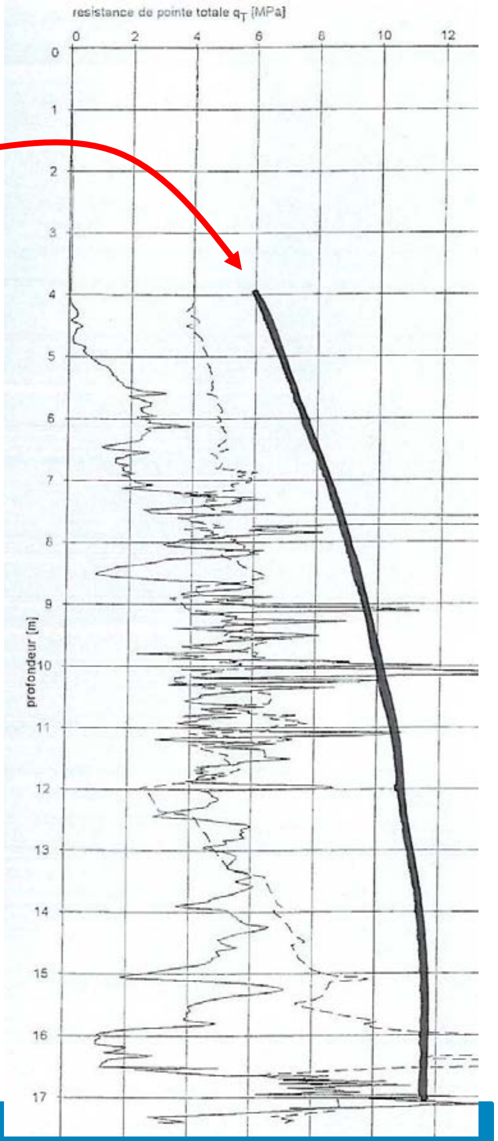
Conclusion

- Classical determination of the FE input parameters is often very conservative
- The calibration of the input parameters on the empirical curves from Frank & Zhao allows to better simulate the rigid inclusion behaviour
- The Frank & Zhao curves require the use of the pressuremeter test parameters E_m et p_l
- Three modelling parameters need to be calibrated:
  - Effective cohesion
  - Effective friction angle
  - Young's modulus

New Developement – CMC as Compaction Grouting - Design

- **Principle: Execution and testing procedure**
  - **Seismic parameters (seism PGA, Magnitude) => qc soil profile to be achieved (Seed and Idriss methodology)**
  - **Estimation of Replacement ratio to achieve required qc**
  - **Execution of Works and testing by CPT**
  - **Additional grouting if necessary**



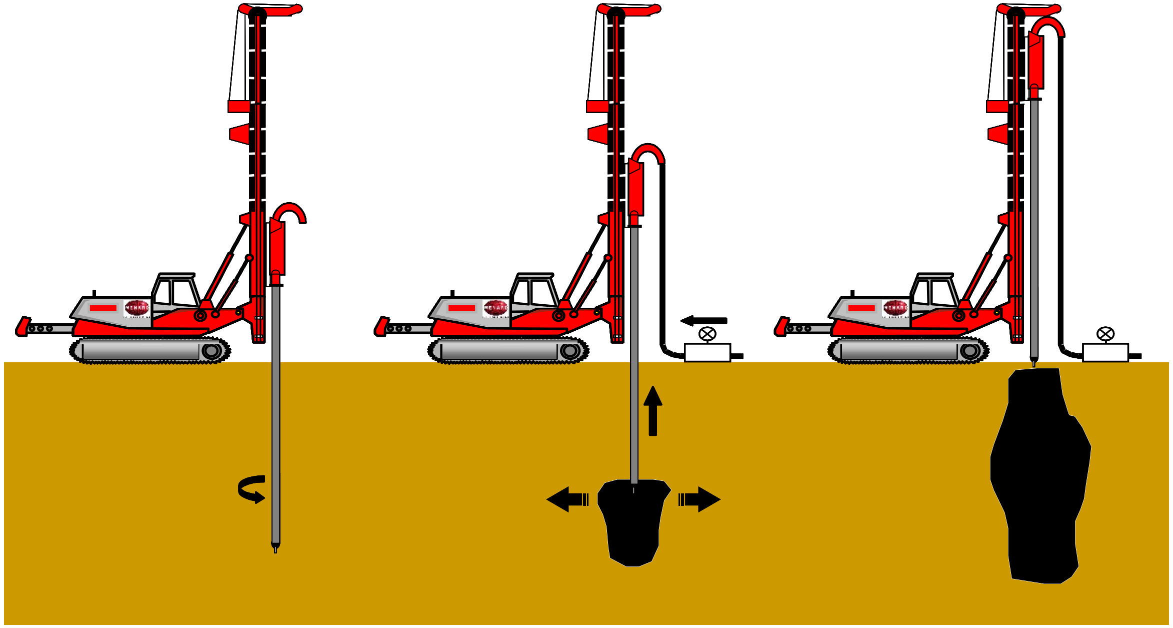


New Developement - CMC as Compaction Grouting - Execution

- **Same type of equipment as for CMC**
  - **Soil displacement rig and Pump,**

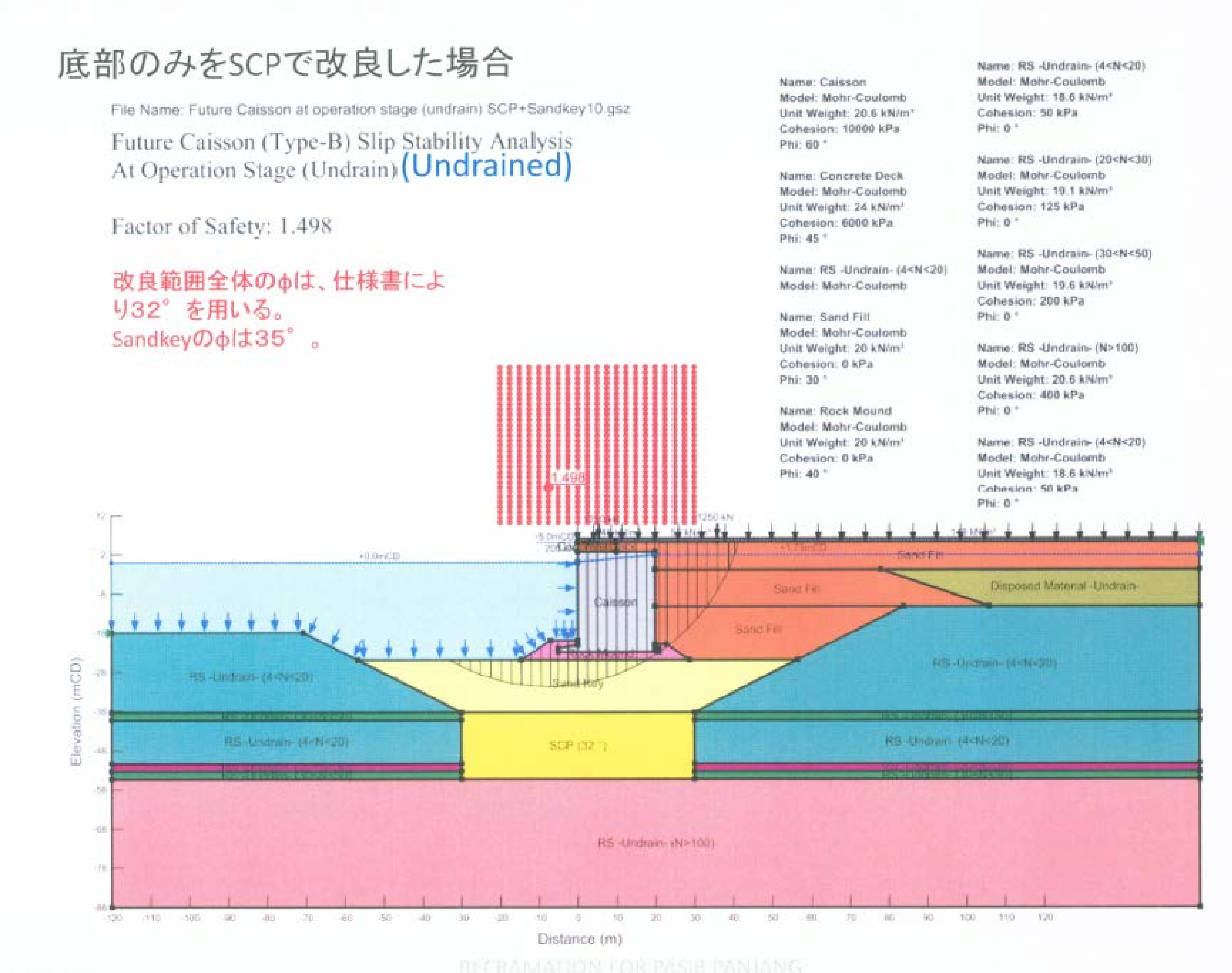
- **Key points**
  - **Quality of grout (grain size distribution, workability, consistancy)**
  - **Injection speed and successive phases**

- **Final Testing = CPT**

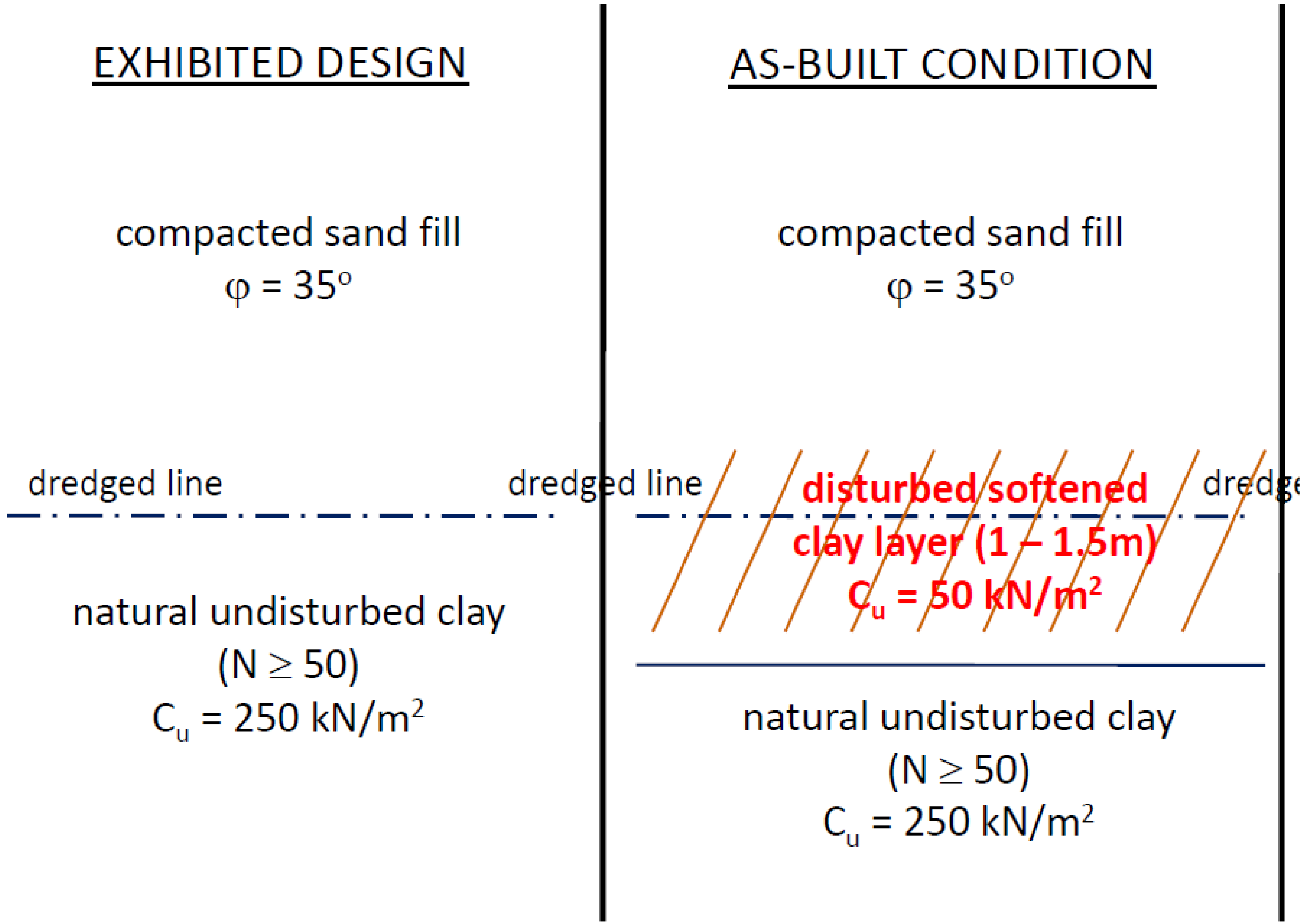


New Developement - CMC as Compaction Grouting – Fos LNG Terminal

Future Caisson Stability Analysis



As built conditions

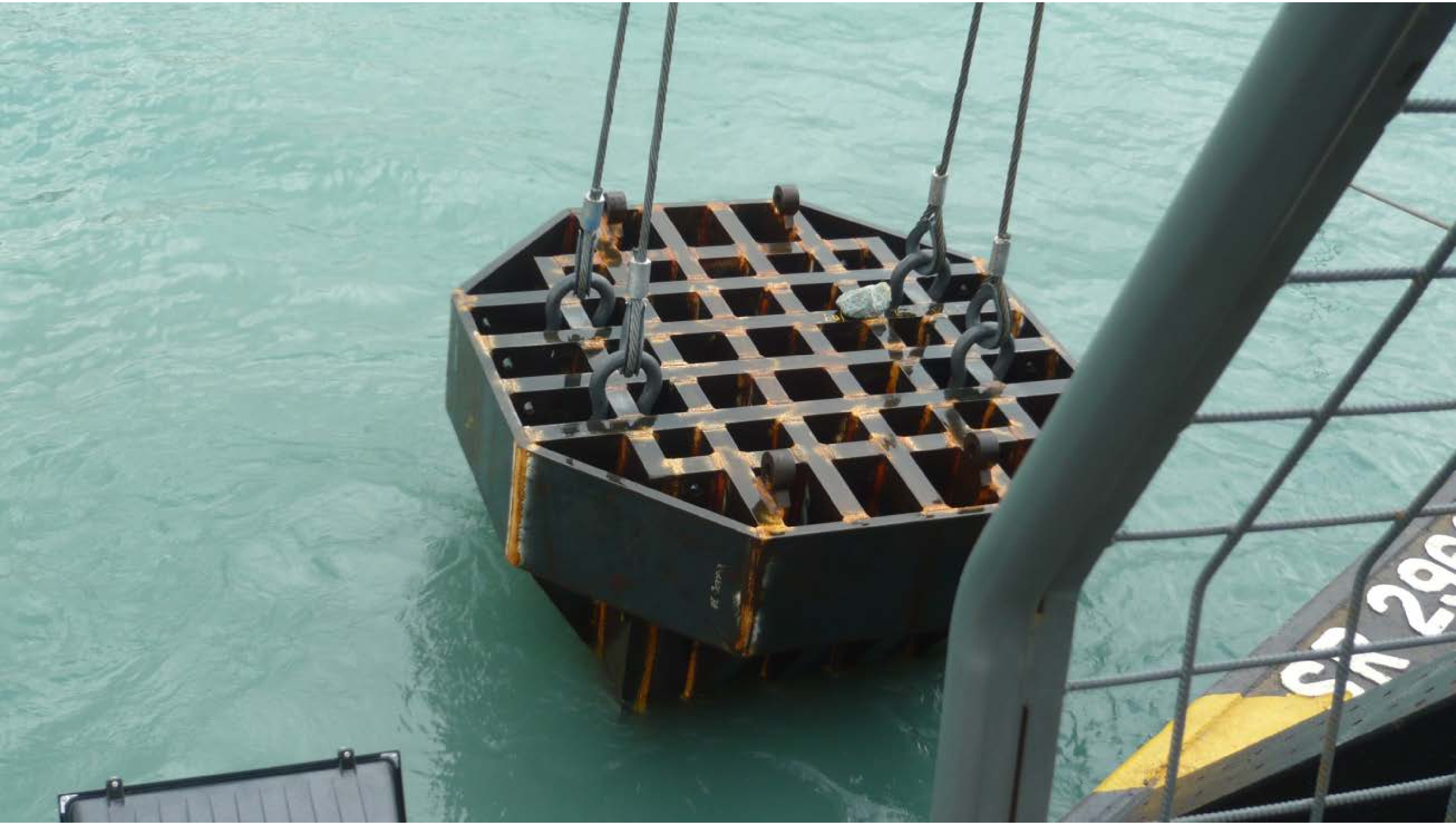


Proposed solution

	EXHIBITED DESIGN	PROPOSED SOLUTION	
	compacted sand fill $\varphi = 35^o$	compacted sand fill $\varphi = 35^o$	
1.3m	compacted sand fill $\varphi = 35^o$ $C = 0$	**compacted rock mat** **($\varphi = 45^o$ $C = 0$)**	1.3m
	dredged line		
1.5m	undisturbed clay $\varphi = 0^o$ $C_u = 250$ kN/m^2	**15% rock ($\varphi = 45^o$) + 85% clay ($C_u = 80$ kPa)**	1.5m
	natural undisturbed clay ($N \geq 50$) $\varphi = 0^o$ $C_u = 250$ kN/m^2	natural undisturbed clay ($N \geq 50$) $\varphi = 0^o$ $C_u = 250$ kN/m^2	

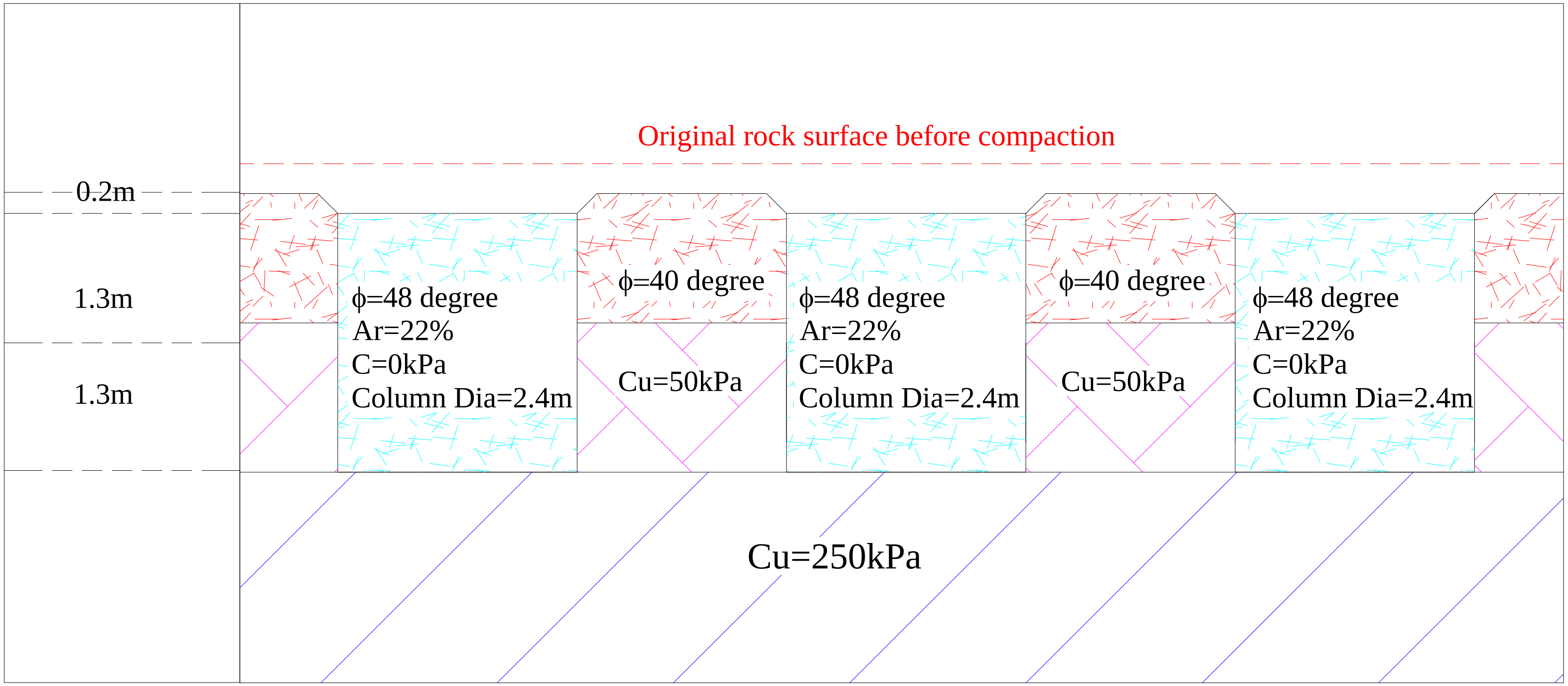
View of pounder construction

View of pounder ready to work



General SFT up

After compaction actual results

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