INTRODUCTION TO SOIL IMPROVEMENT, PARAMETERS, CLASSIFICATION, CASE HISTORY OF KAUST

PRESENTED BY
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17TH INTERNATIONAL CONFERENCE ON
SOIL MECHANICS & GEOTECHNICAL ENGINEERING

STATE OF THE ART REPORT

Construction Processes
Procédés de Construction

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Menard, France

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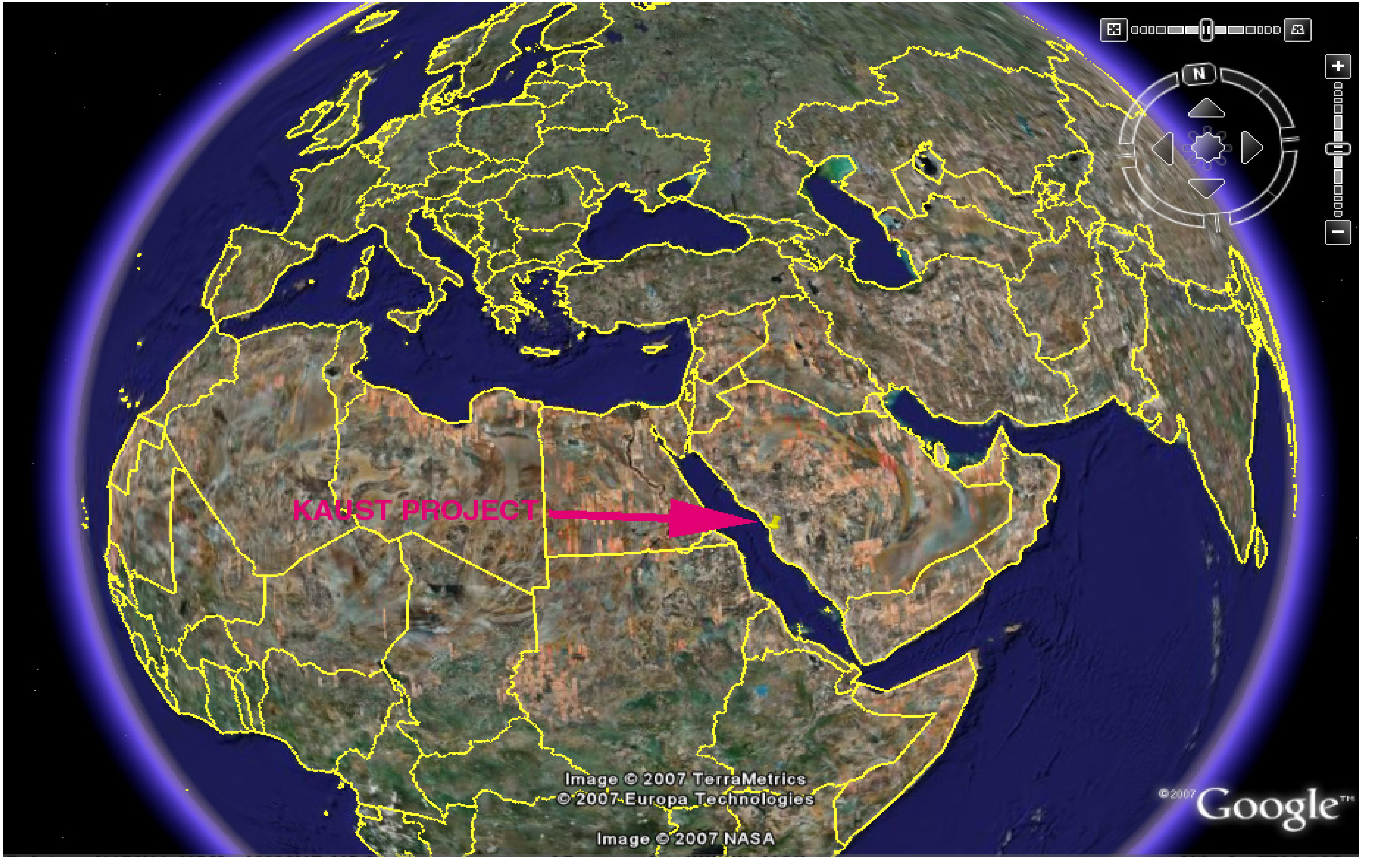
NOTA : TC 17 meeting ground improvement – 07/10/2009
Website : www.bbri.be/go/tc17

Category	Method	Principle
A. Ground improvement without admixtures in non-cohesive soils or fill materials	A1. Dynamic compaction	Densification of granular soil by dropping a heavy weight from air onto ground.
	A2. Vibrocompaction	Densification of granular soil using a vibratory probe inserted into ground.
	A3. Explosive compaction	Shock waves and vibrations are generated by blasting to cause granular soil ground to settle through liquefaction or compaction.
	A4. Electric pulse compaction	Densification of granular soil using the shock waves and energy generated by electric pulse under ultra-high voltage.
	A5. Surface compaction (including rapid impact compaction).	Compaction of fill or ground at the surface or shallow depth using a variety of compaction machines.
B. Ground improvement without admixtures in cohesive soils	B1. Replacement/displacement (including load reduction using light weight materials)	Remove bad soil by excavation or displacement and replace it by good soil or rocks. Some light weight materials may be used as backfill to reduce the load or earth pressure.
	B2. Preloading using fill (including the use of vertical drains)	Fill is applied and removed to pre-consolidate compressible soil so that its compressibility will be much reduced when future loads are applied.
	B3. Preloading using vacuum (including combined fill and vacuum)	Vacuum pressure of up to 90 kPa is used to pre-consolidate compressible soil so that its compressibility will be much reduced when future loads are applied.
	B4. Dynamic consolidation with enhanced drainage (including the use of vacuum)	Similar to dynamic compaction except vertical or horizontal drains (or together with vacuum) are used to dissipate pore pressures generated in soil during compaction.
	B5. Electro-osmosis or electro-kinetic consolidation	DC current causes water in soil or solutions to flow from anodes to cathodes which are installed in soil.
	B6. Thermal stabilisation using heating or freezing	Change the physical or mechanical properties of soil permanently or temporarily by heating or freezing the soil.
	B7. Hydro-blasting compaction	Collapsible soil (loess) is compacted by a combined wetting and deep explosion action along a borehole.

C. Ground improvement with admixtures or inclusions	C1. Vibro replacement or stone columns	Hole jetted into soft, fine-grained soil and back filled with densely compacted gravel or sand to form columns.
	C2. Dynamic replacement	Aggregates are driven into soil by high energy dynamic impact to form columns. The backfill can be either sand, gravel, stones or demolition debris.
	C3. Sand compaction piles	Sand is fed into ground through a casing pipe and compacted by either vibration, dynamic impact, or static excitation to form columns.
	C4. Geotextile confined columns	Sand is fed into a closed bottom geotextile lined cylindrical hole to form a column.
	C5. Rigid inclusions (or composite foundation, also see Table 5)	Use of piles, rigid or semi-rigid bodies or columns which are either premade or formed in-situ to strengthen soft ground.
	C6. Geosynthetic reinforced column or pile supported embankment	Use of piles, rigid or semi-rigid columns/inclusions and geosynthetic girds to enhance the stability and reduce the settlement of embankments.
	C7. Microbial methods	Use of microbial materials to modify soil to increase its strength or reduce its permeability.
	C8 Other methods	Unconventional methods, such as formation of sand piles using blasting and the use of bamboo, timber and other natural products.

Concept and application of ground improvement for a 2,600,000 m²

FUTURE UNIVERSITY CAMPUS


KAUST PROJECT
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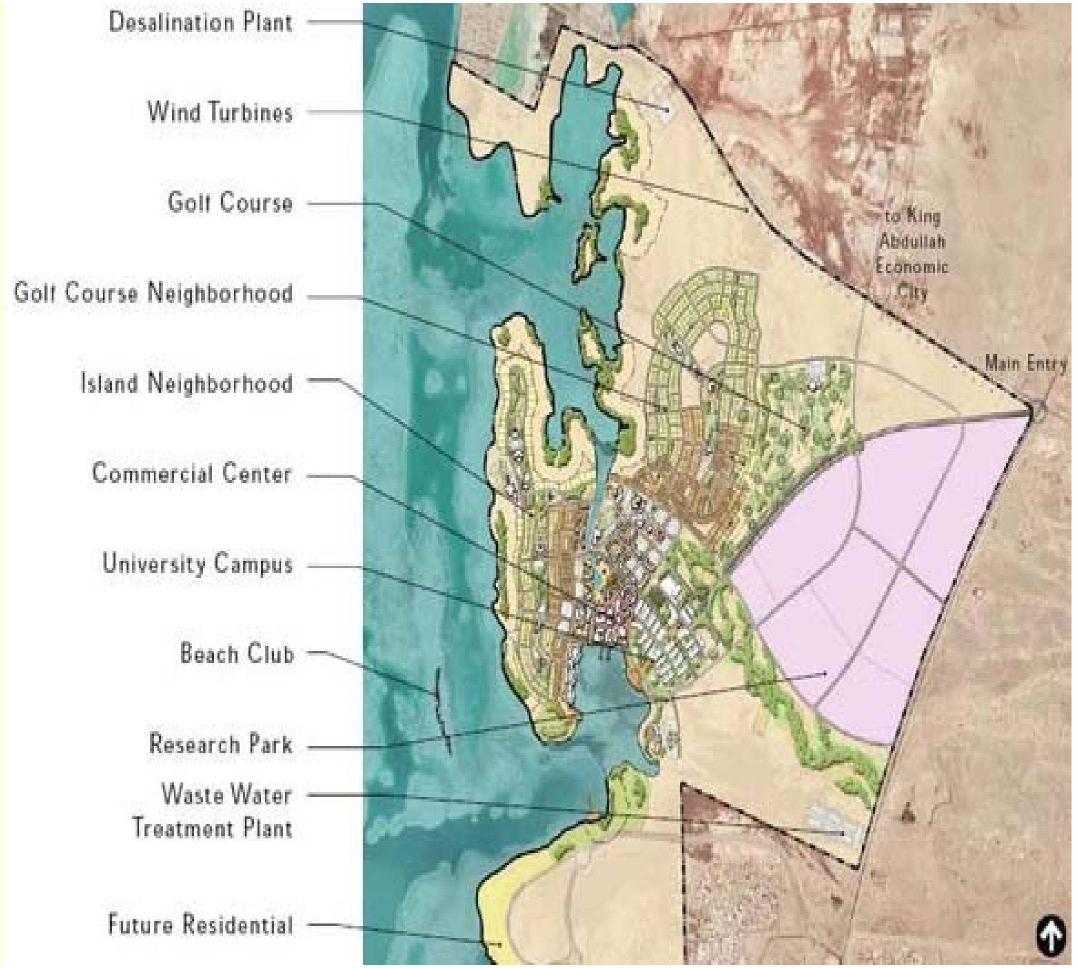
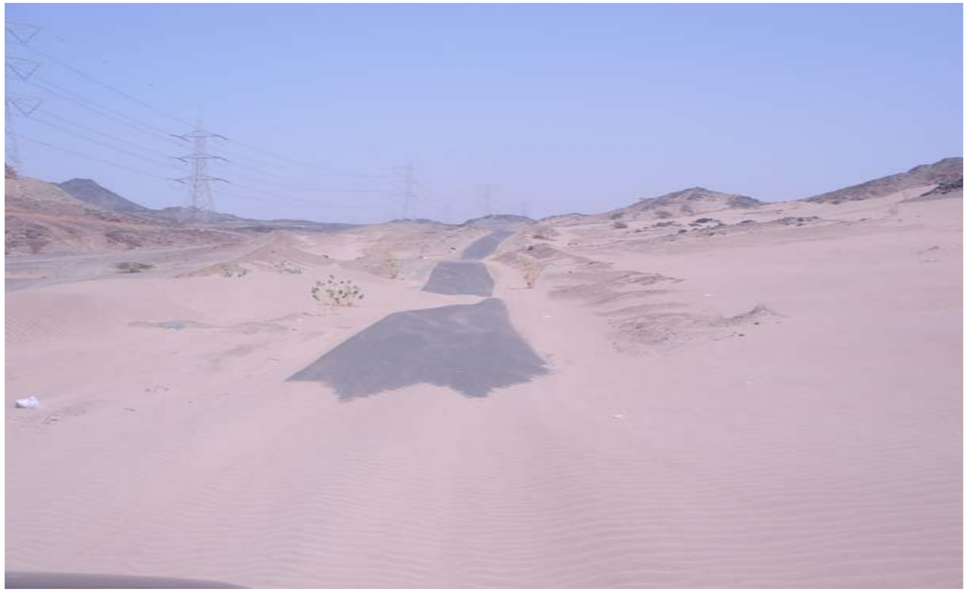
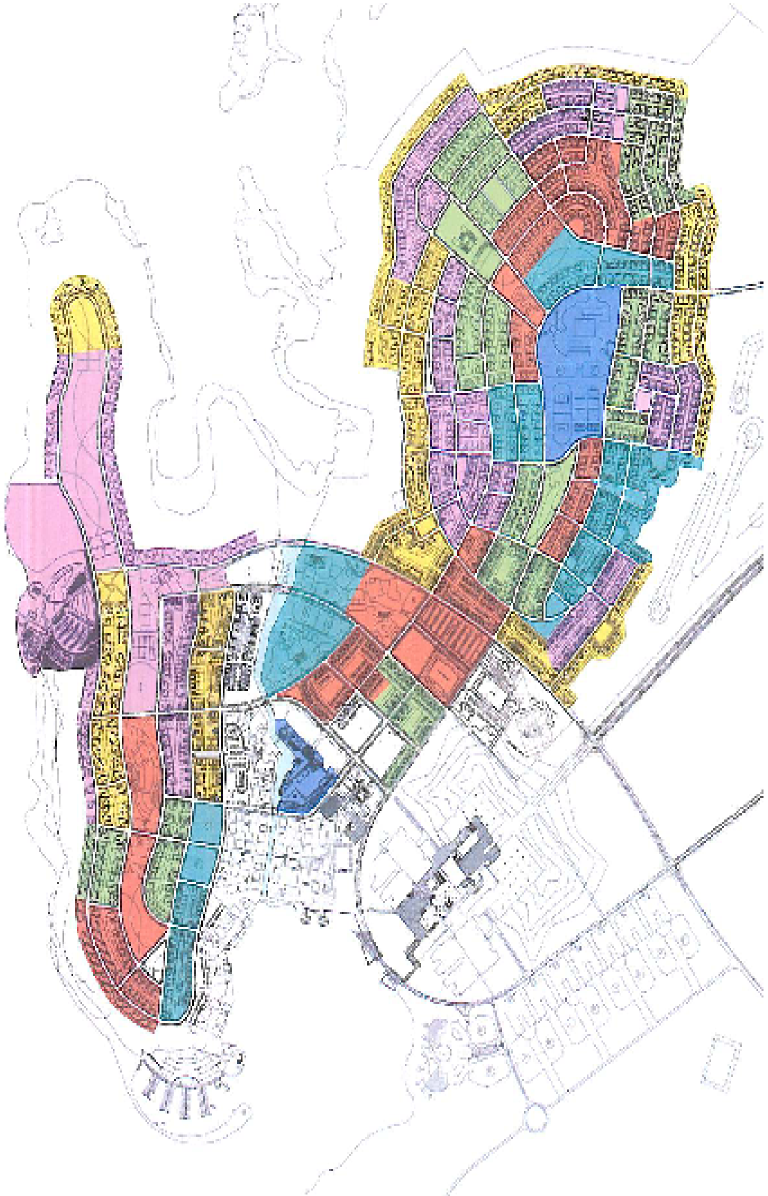
Typical Master Plan



The Future Site




Surat

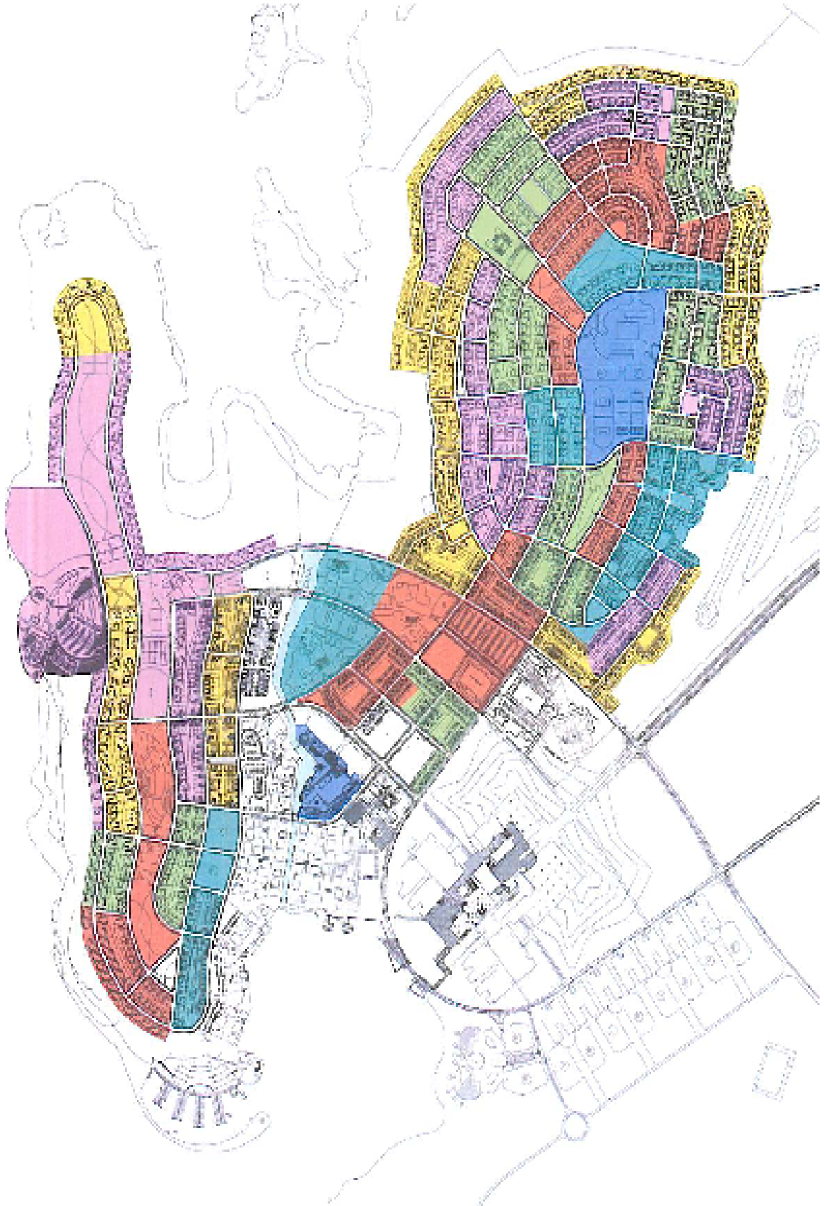


AREAS TO BE TREATED

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

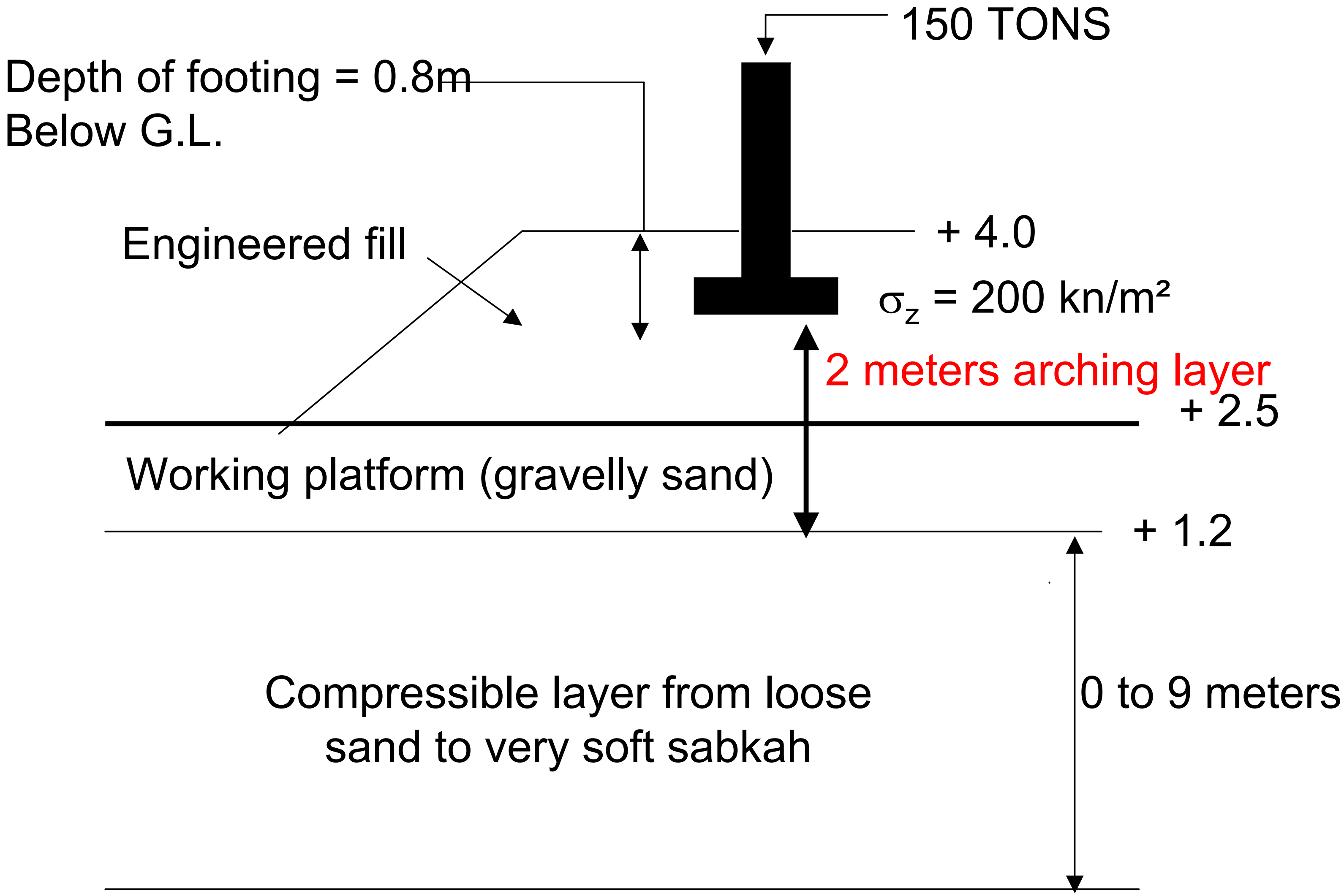
SCHEDULE

- 8 month

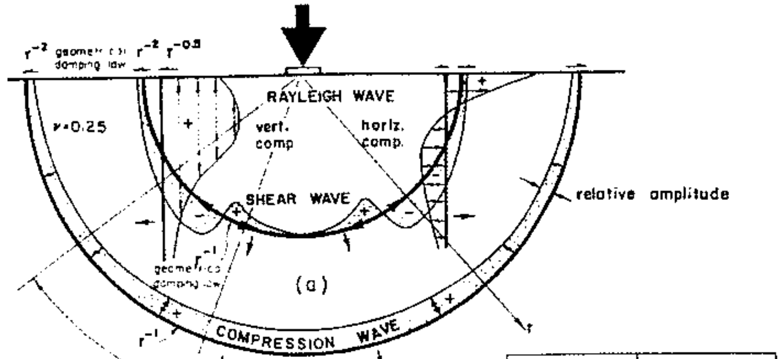


KAUST
Dates for soil improvement

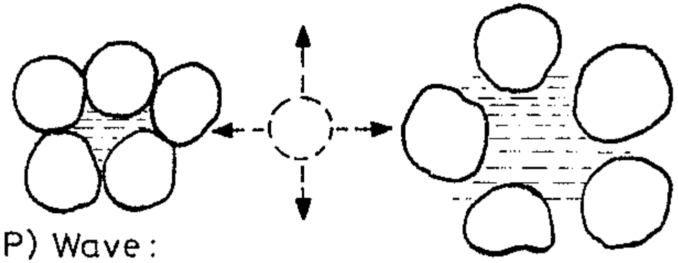
- Isolated footings up to 150 tons
- Bearing capacity 200 kPa
- Maximum footing settlement 25 mm
- Maximum differential settlement 1/500
- Footing location unknown at works stage


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

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

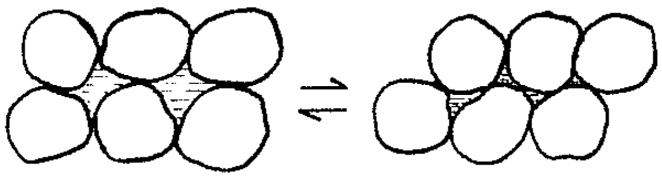


WAVE TYPE	PERCENT OF TOTAL ENERGY
RAYLEIGH	67
SHEAR	26
COMPRESSION	7



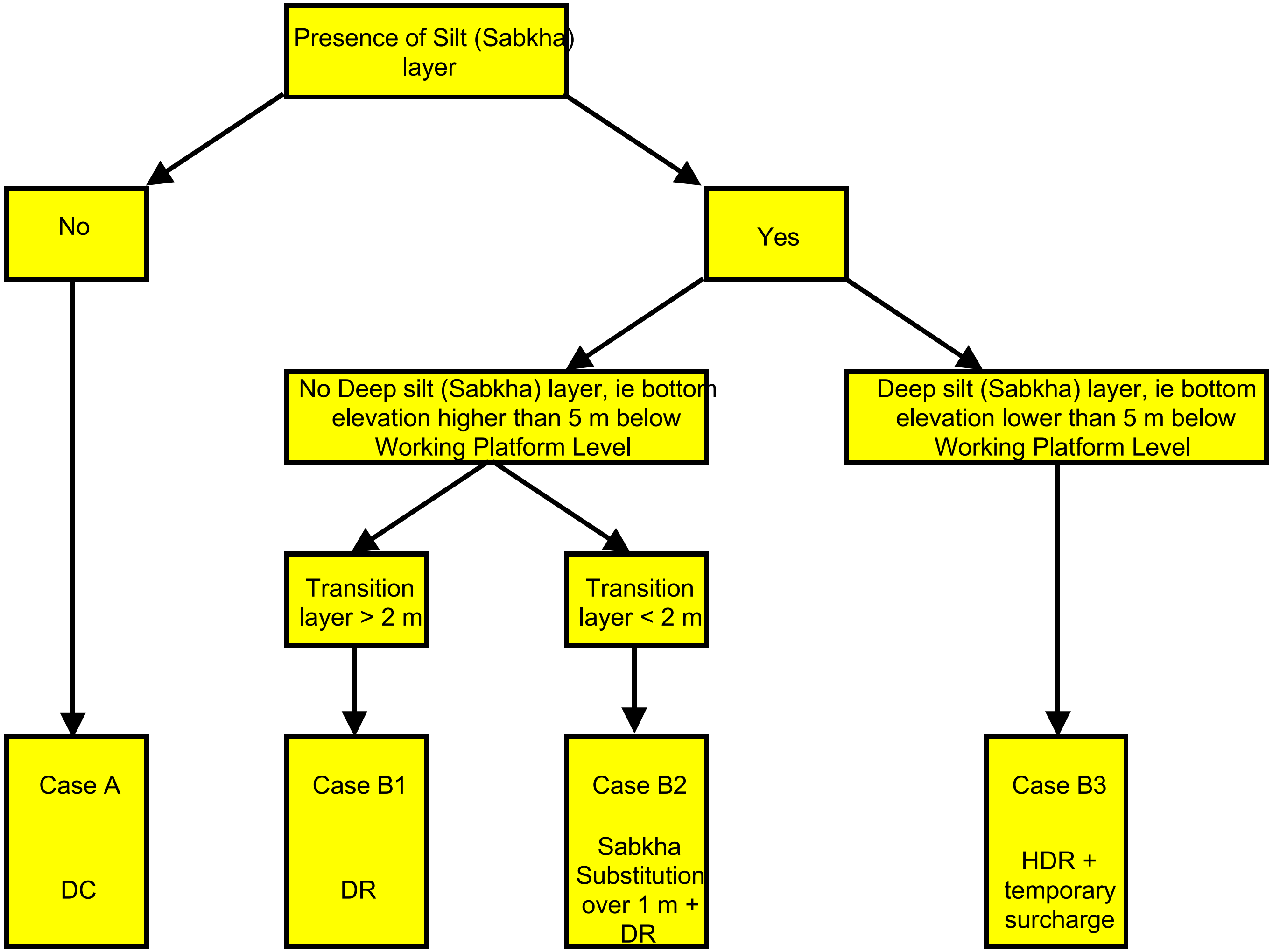
(P) Wave:

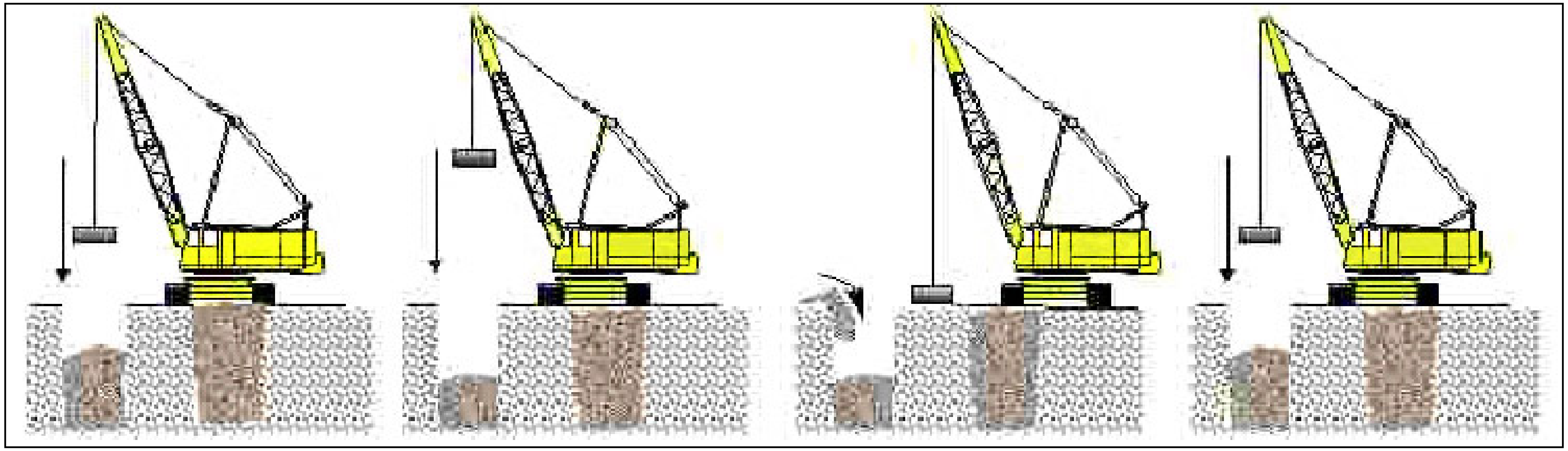
- Increases pore water pressure
- Dislocates soil matrix



(S) And rayleigh waves:

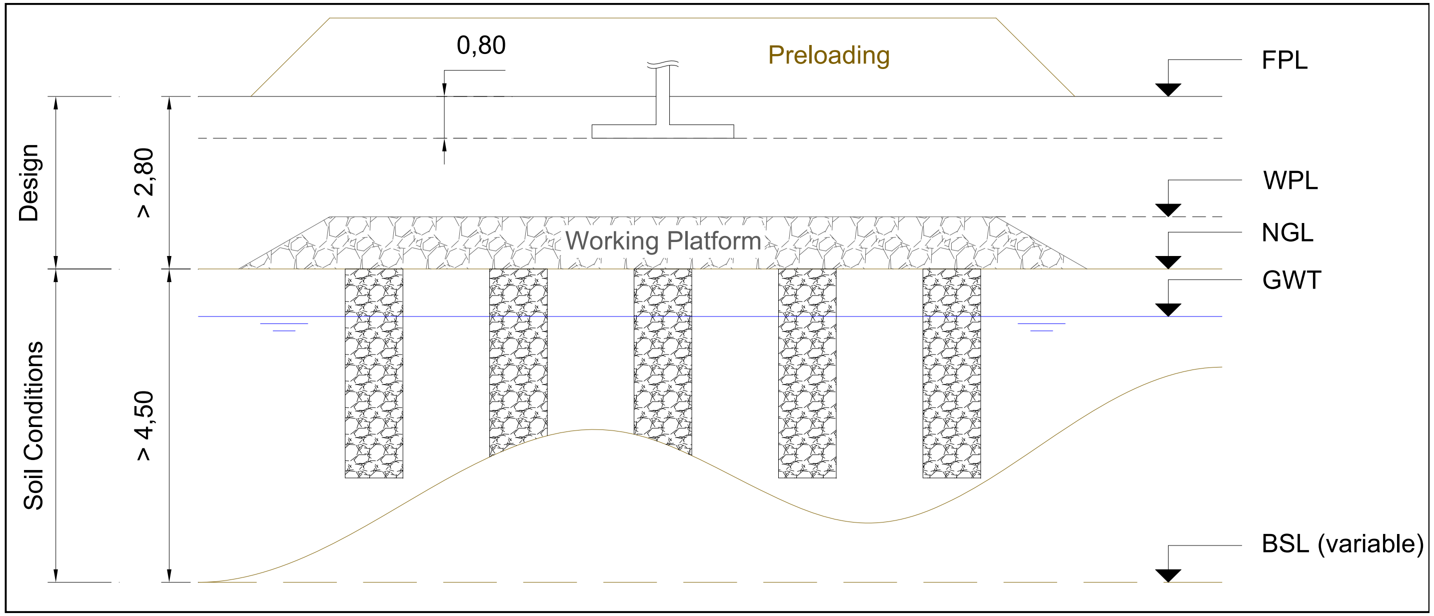
- Shear soil grains
- Rearrange structure towards denser state


Presence of Silt (Sabkha) layer
No
Yes
No Deep silt (Sabkha) layer, ie bottom elevation higher than 5 m below Working Platform Level
Deep silt (Sabkha) layer, ie bottom elevation lower than 5 m below Working Platform Level
Transition layer > 2 m
Transition layer < 2 m
Case A
DC
Case B1
DR
Case B2
Sabkha Substitution over 1 m + DR
Case B3
HDR + temporary surcharge

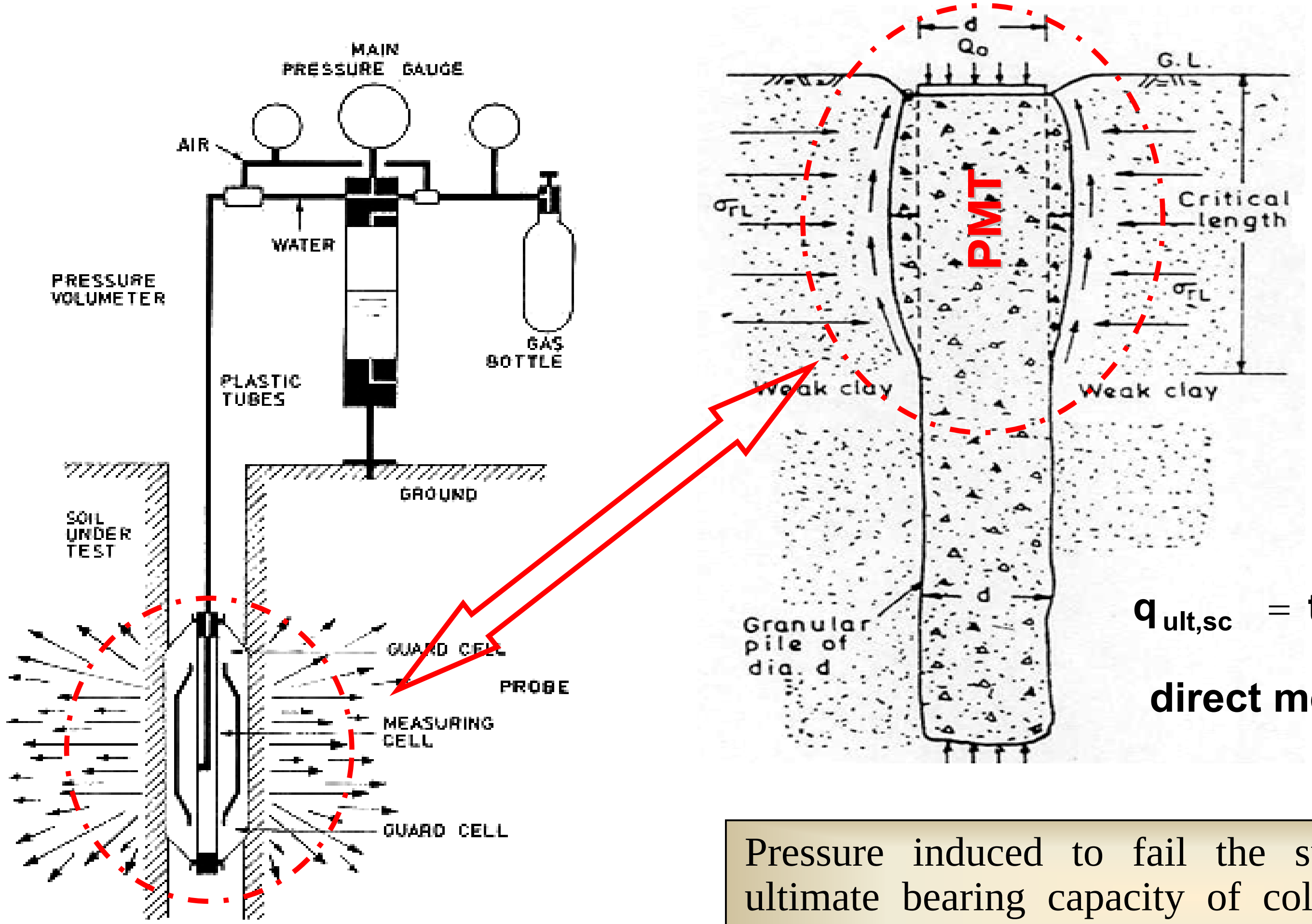


DR (Dynamic Replacement)

HDR (High Energy Dynamic Replacement) + surcharge



PMT loading test applies the ***cavity expansion theory*** which is similar to granular column bulging under applied vertical load.

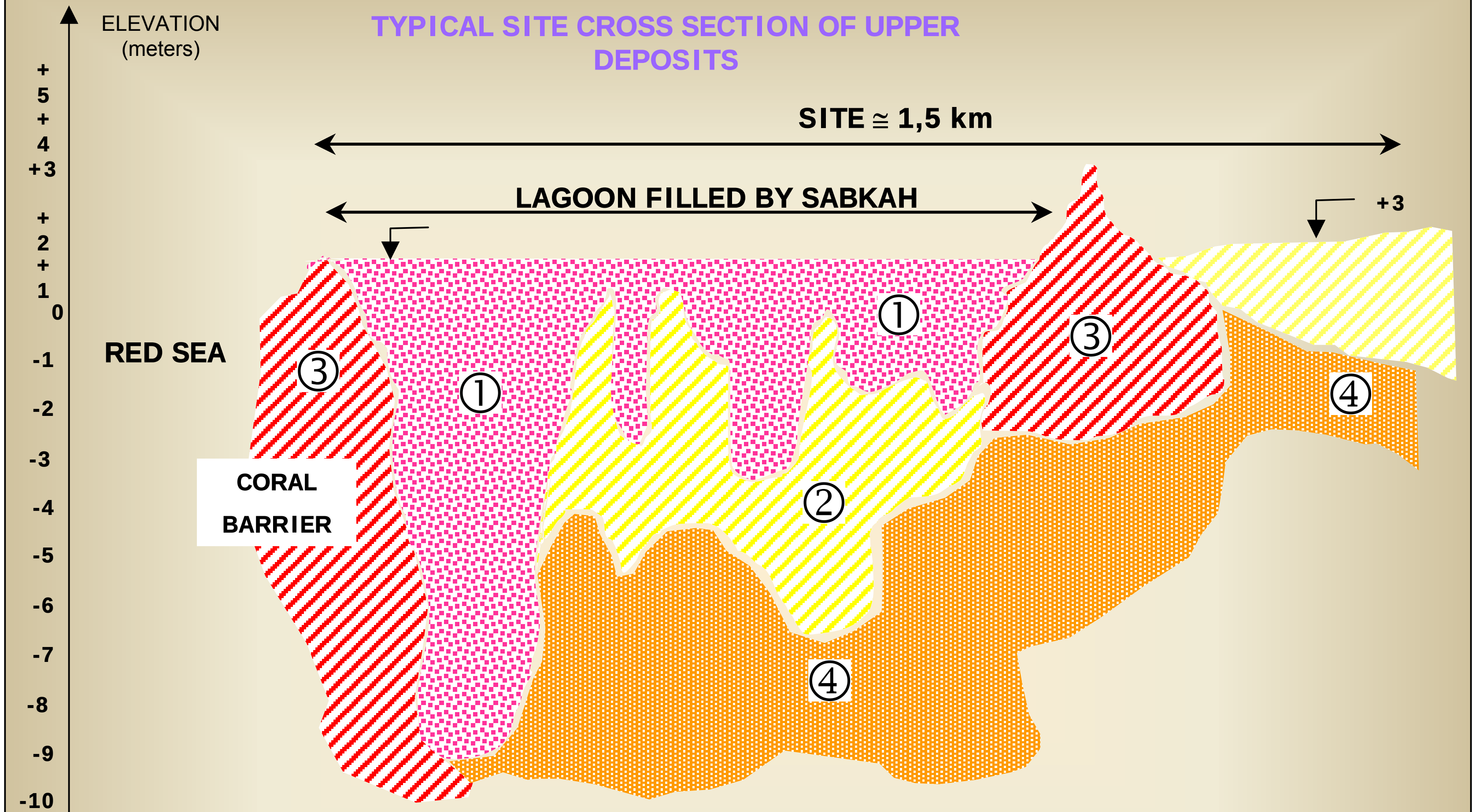


$$q_{ult,sc} = \tan^2\left(\frac{\pi}{4} + \frac{\varphi_{sc}}{2}\right) P_L$$

direct measurement of P_L

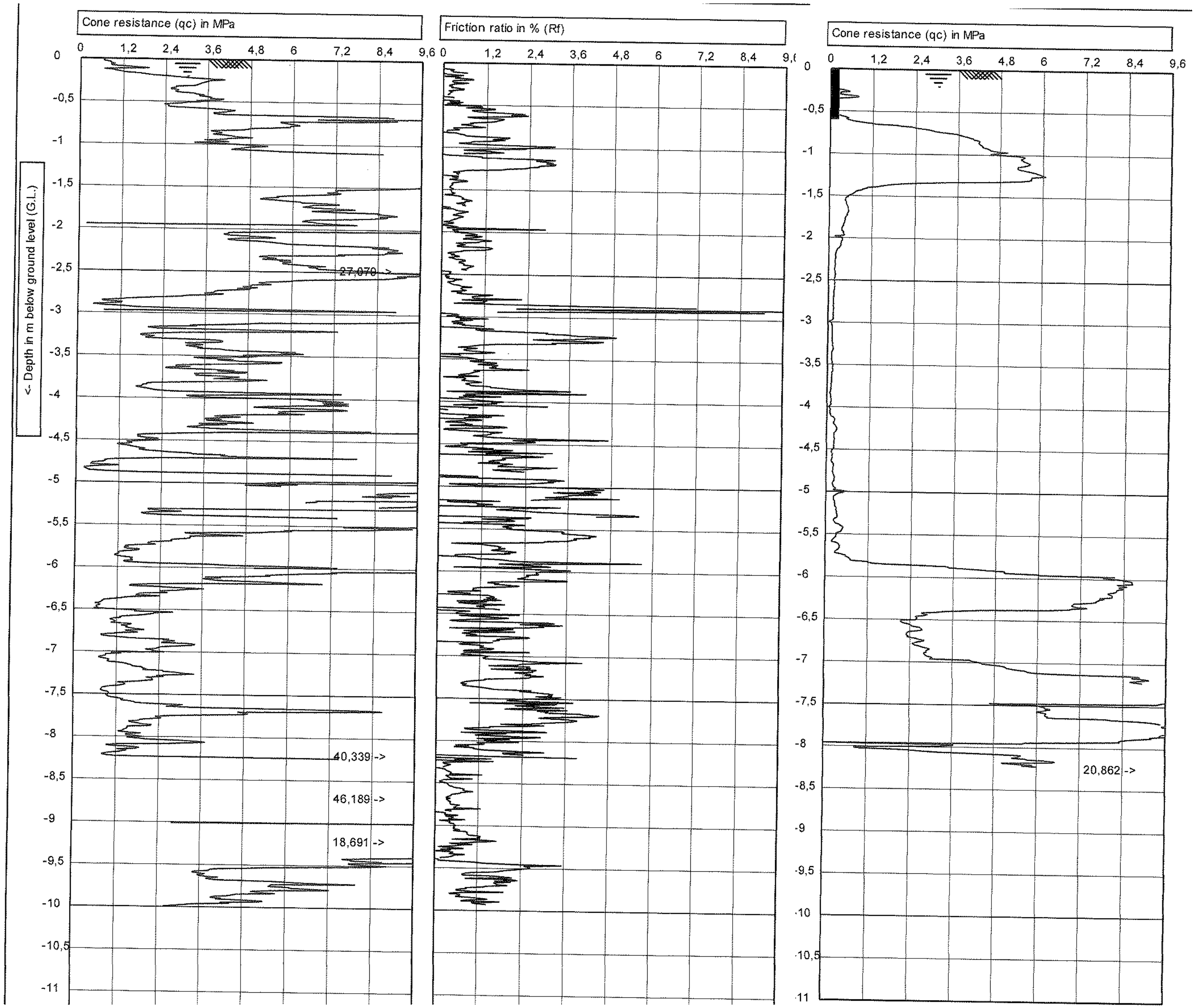
Pressure induced to fail the surrounding soil = ultimate bearing capacity of column supported by lateral pressure of the surrounding soil.

TYPICAL SITE CROSS SECTION OF UPPER DEPOSITS

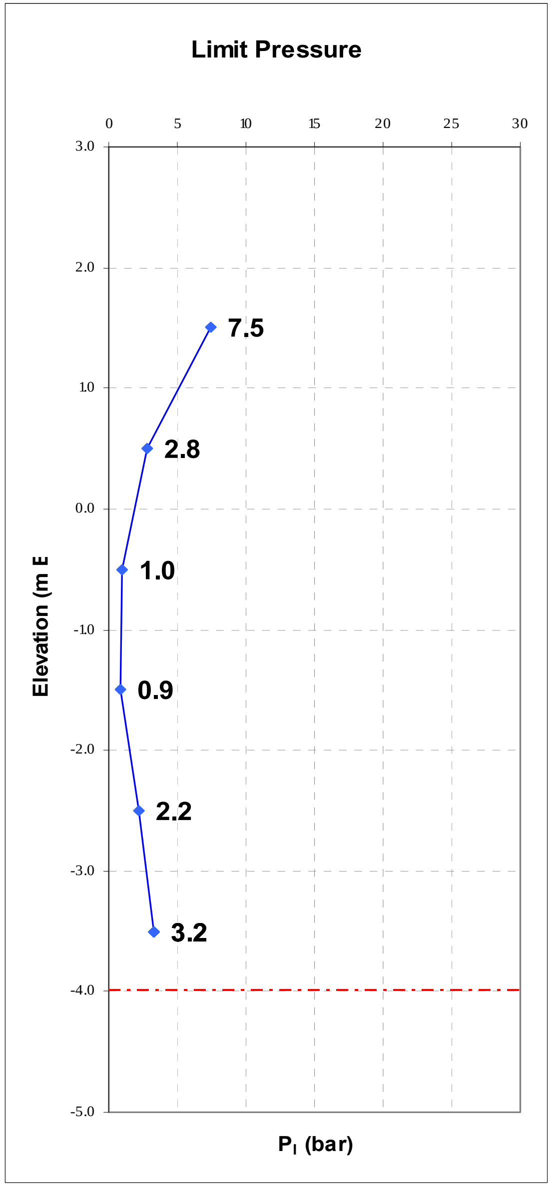


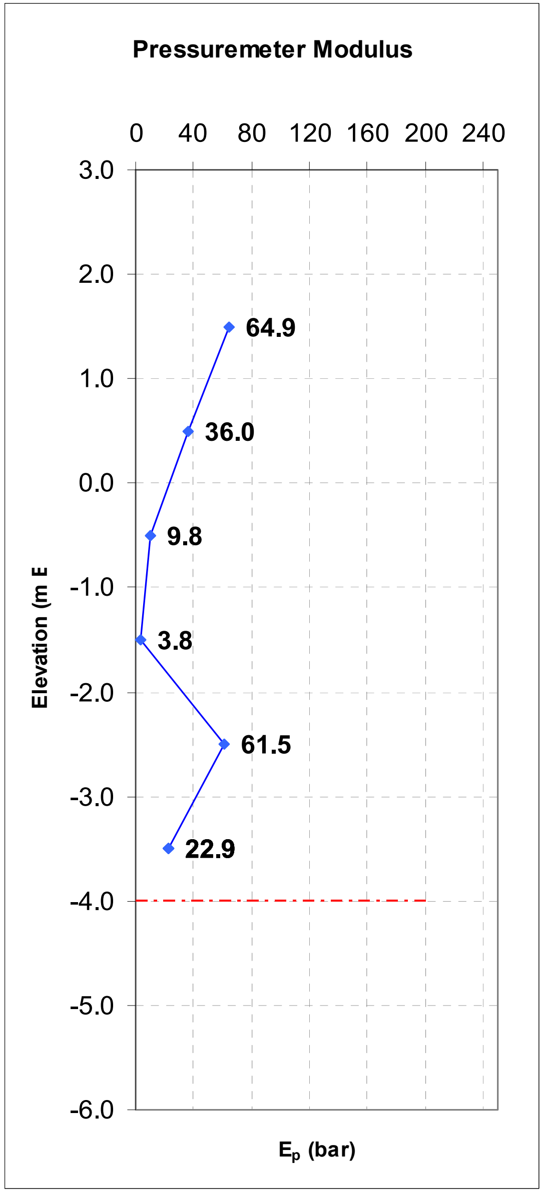
LAYER	USC	w %	% fines	N	Qc BARS	F_R %	P_L BARS	E_P BARS
1 - SABKAH	SM + ML	35-48	28-56	0-2	0-2	1,2-4	0,4-1,9	avr-17
2 - LOOSE SILTY SAND	SM	-	15-28	3-9	12-45	0,5-1,2	2,1-4	18-35
3 - CORAL	-	26-35	-	6-12	-	-	5,1-7,2	35-60
4 - LOOSE TO MED DENSE SAND	SM	-	12-37	3-18	15-80	0,5-1,8	4-12	28-85

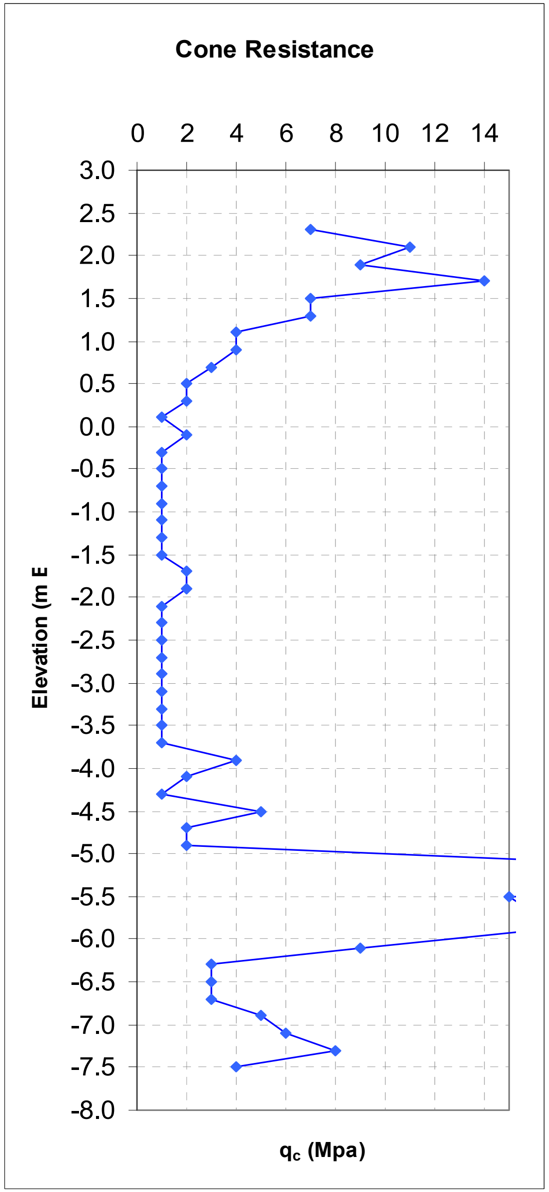
Variation in soil profile over 30 meters



Typical soil profile



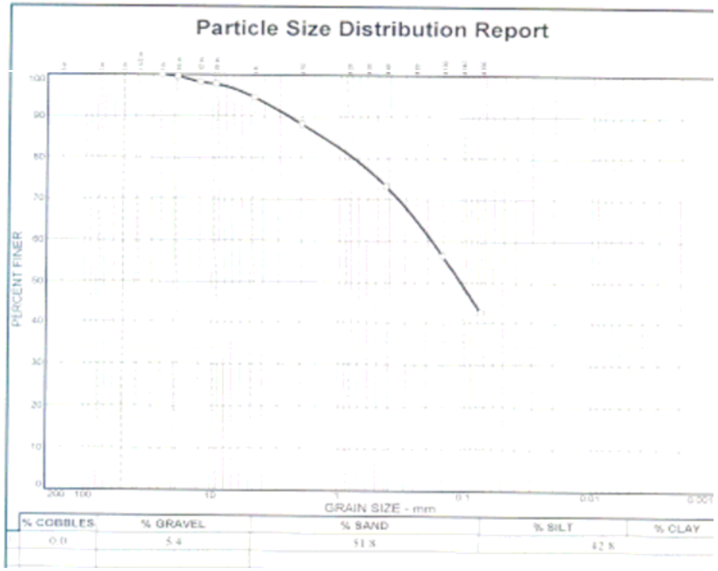




1. Project management (4)
2. Production team (32)
3. Mecanical team (18)
4. Survey team (16)
5. Administrative team (6)
6. Geotechnical team (8)
7. Safety and Quality (2)
8. Logistic team (4)

Typical surface conditions

Typical test pits (120) and grain size



- 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

Equipment Resources

- 13 DC/DR Rigs of 95 to 120 tons
- 15 pounders from 12-23 tons
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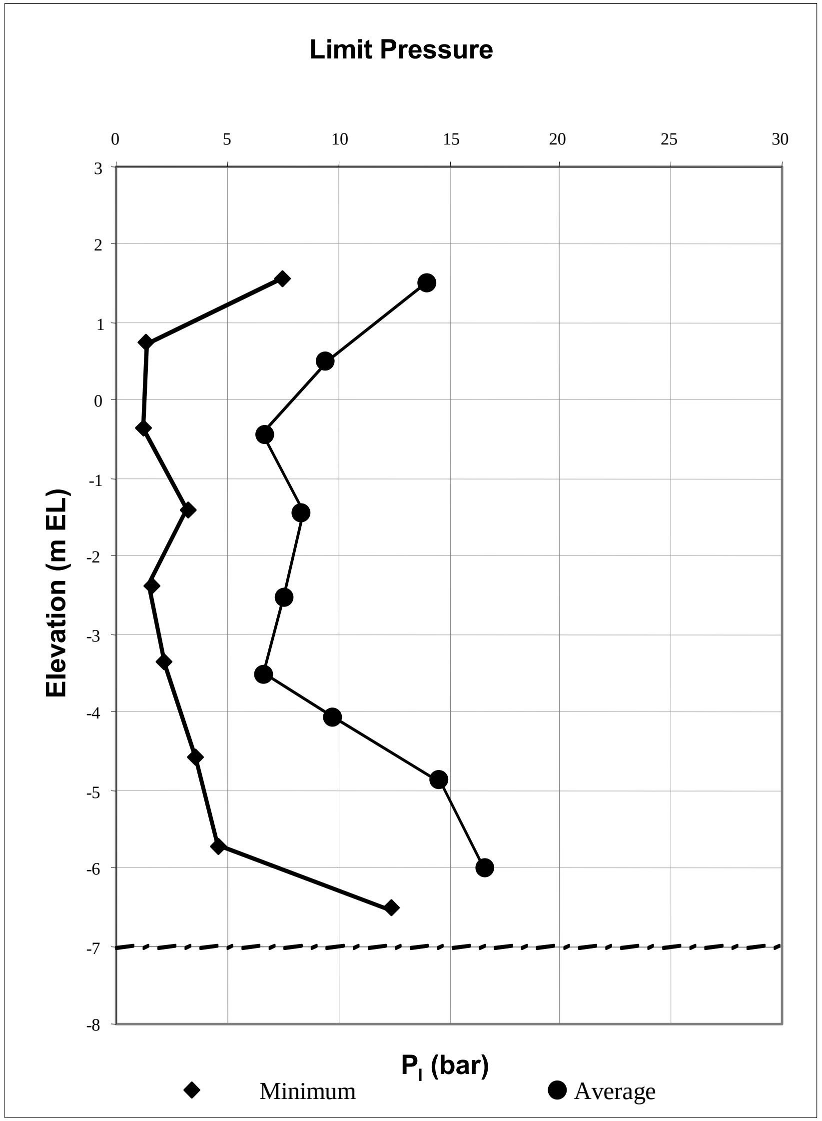
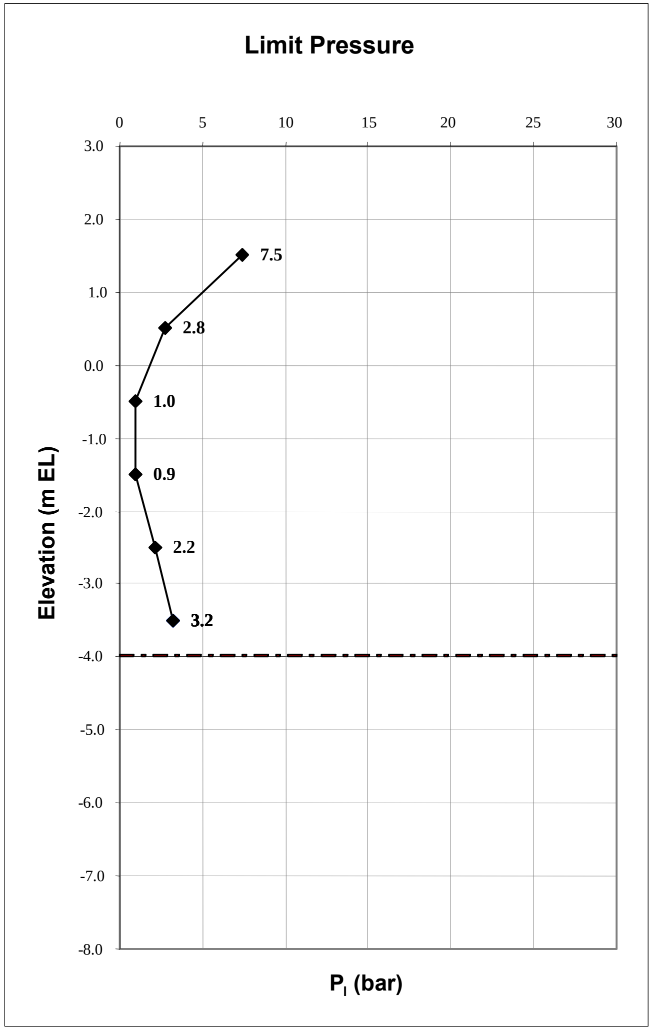
PMT results before DC

Before DC

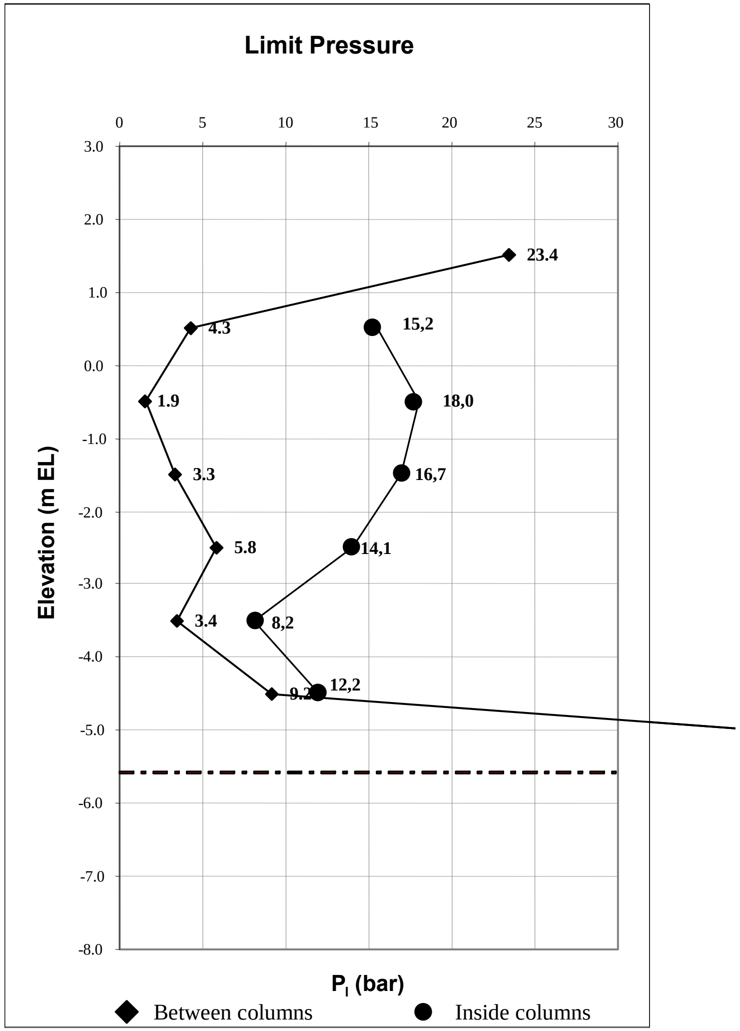


PMT results before and after DR

Before DR

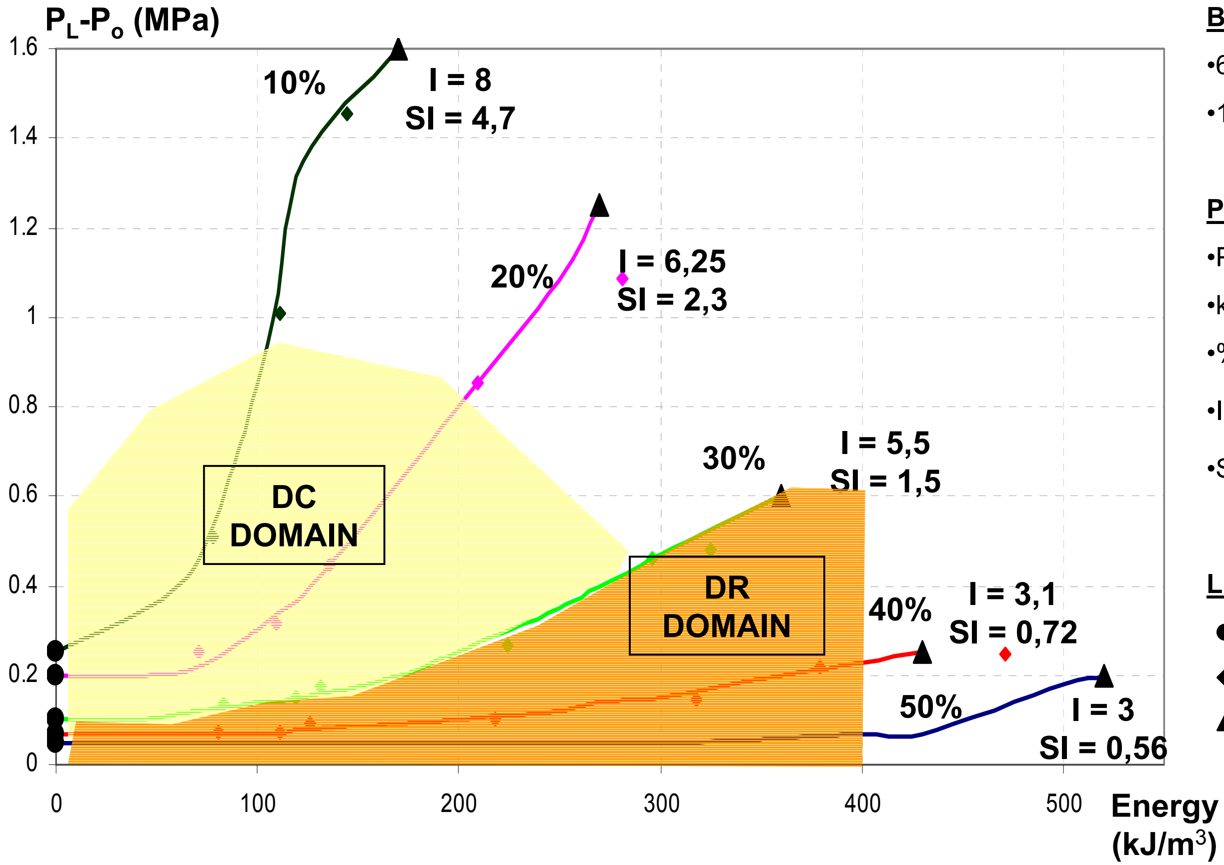


After DR – Between columns



ANALYSIS OF (P_L-P_o) IMPROVEMENT AS FUNCTION OF ENERGY AND FINES

K.A.U.S.T. – Saudi Arabia



BASIS

- 60 grainsize tests
- 180 PMT tests

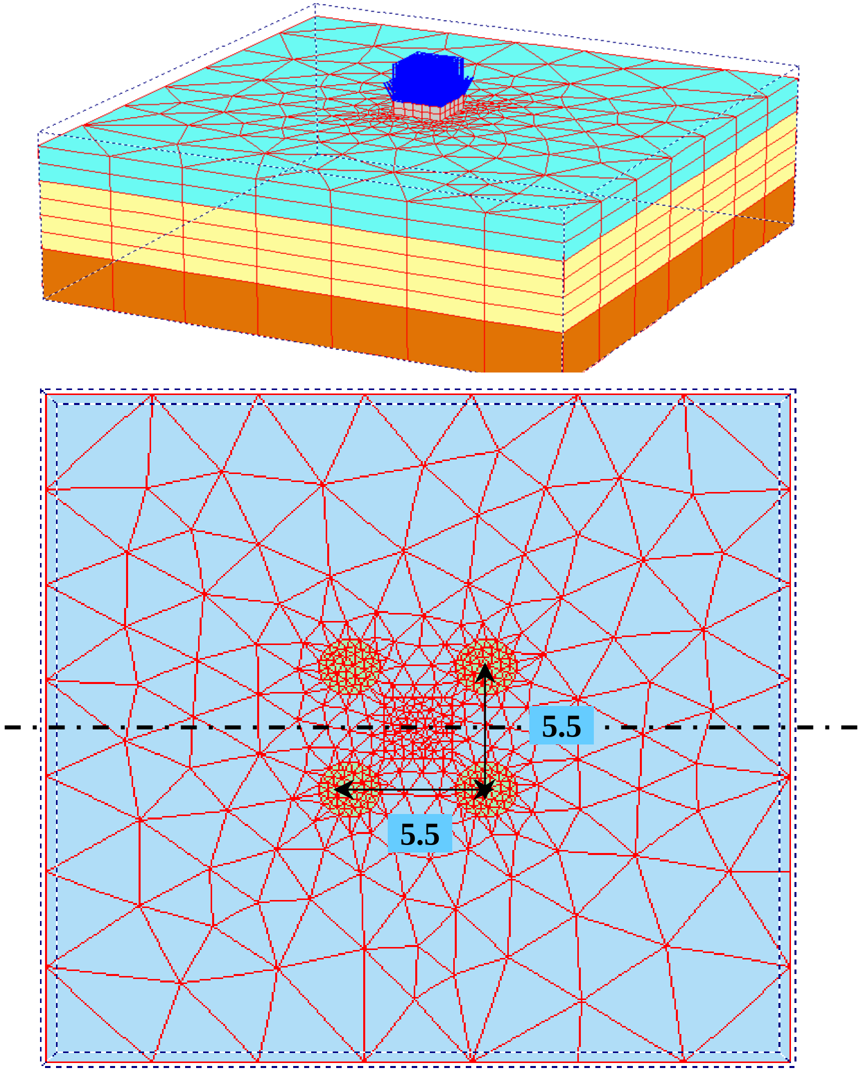
PARAMETERS

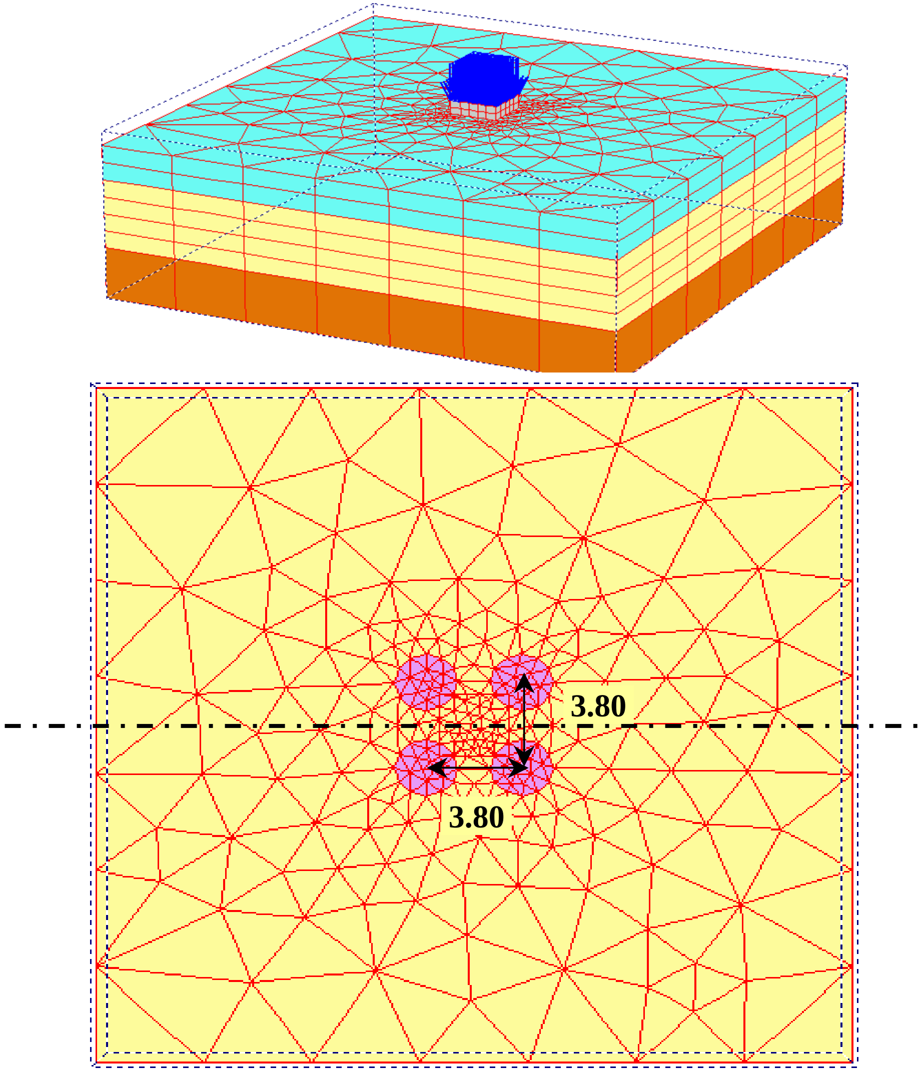
- $P_L - P_o$ = pressuremeter limit pressure
- kJ/m³ = Energy per m³ (E)
- % = % passing n°200 sieve
- I = improvement factor $\frac{P_{LF}}{P_{Li}}$
- S.I : energy specific improvement factor $\frac{I \times 100}{E}$

LEGEND

- ● Average pre-treatment values
- ◆ Average values between phases
- ▲ Average post-treatment values

ANALYSIS OF WORST CASE FOR VARIOUS GRIDS





A – Identify depth trend of SABKAH by CPT Tests

B – Closely eywitness the penetration of pounder to confirm DC or DR treatment

C – Verify by PMT that factor of safety is at least 3 for bearing capacity

D – Verify by stress analysis that limit pressure at any depth exceeds factors of safety of at least 3 in order to safely utilize the settlement analysis (no creep)

E – Vary the grid to obtain at any location the condition D

F – Test the gravelly sand columns and check if specified settlement is achieved

G – Monitor surcharge if HDR is required

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

MENARD SOLTRAITEMENT

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_3 =	1,10
Width of the footing	B	2,74	m		λ_2 =	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	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

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

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**

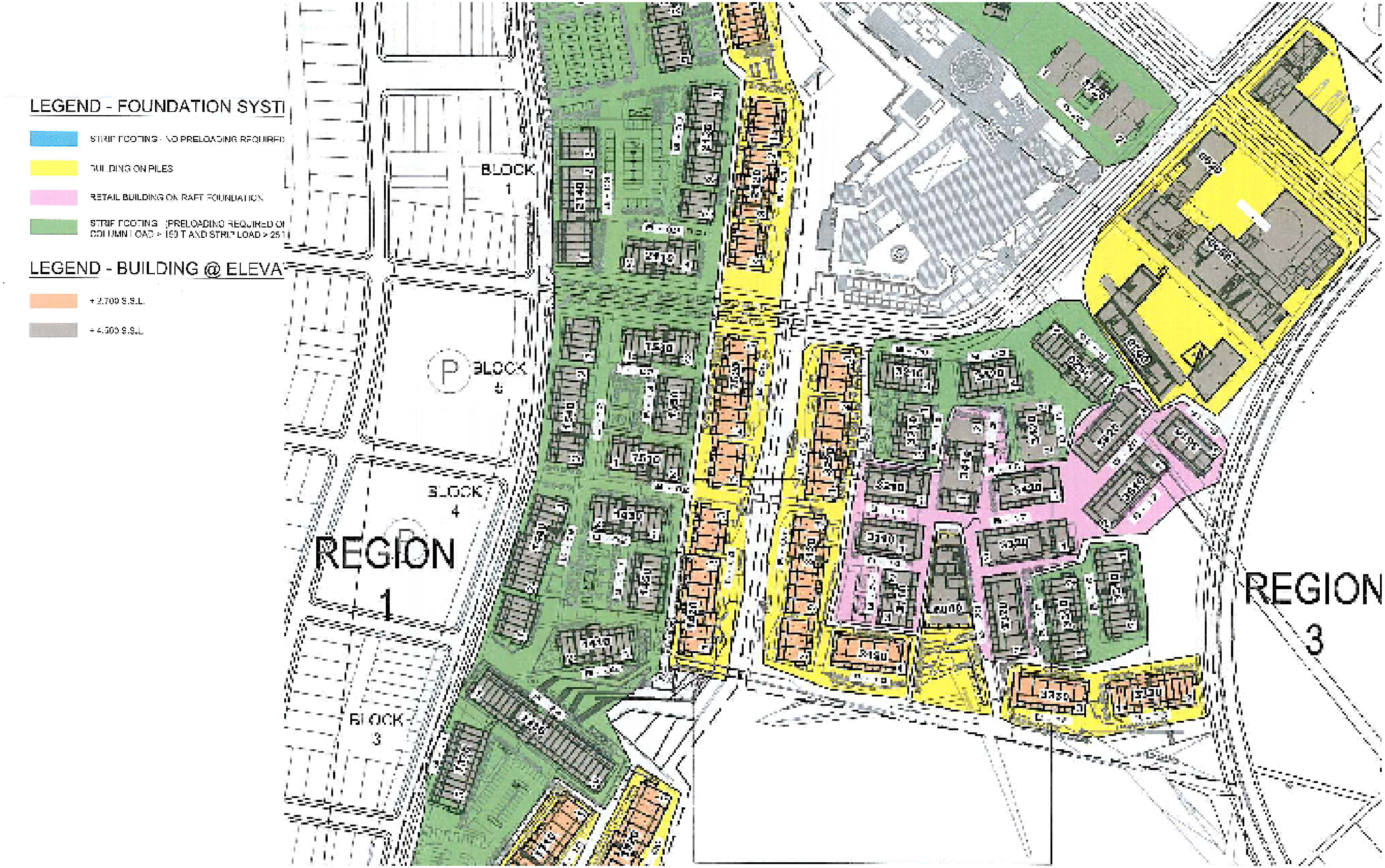
Higher than 200 kPa => Specification reached

Settlement

$$w = \frac{1.33}{3E_B}pR_o\left(\lambda_2\frac{R}{R_o}\right)^{\alpha_{2,16}} + \frac{\alpha_1}{4.5E_A}p\lambda_3 R$$

w **5,83 mm**

Lower than 25 mm => Specification reached


LEGEND - FOUNDATION SYSTI
STRIP FOOTING - NO PRELOADING REQUIRED
BUILDING ON PILES
RETAIL BUILDING ON RAFT FOUNDATION
STRIP FOOTING (PRELOADING REQUIRED OI
COLUMN LOAD > 150 T AND STRIP LOAD > 25 T
LEGEND - BUILDING @ ELEVA
+ 2.700 S.S.L.
+ 4.500 S.S.L.
BLOCK 1
BLOCK 5
BLOCK 4
BLOCK 3
REGION 1
REGION 3

It can be assumed that those impacts du generate a pore pressure at least equal to the pore pressure generated by the embankement load.

This new consolidation process with the final at a time t'_f, where

$$T_V = 0{,}848 = \frac{C'_v (t'_1 - t_1)}{H^2} + \frac{C_v T_1}{H^2}$$

With

$$C'_V = C_V \left[1 + \frac{du}{\Delta\sigma(1 - U_1)} \right]$$

The following equation allows to compare the respective times of consolidation being :

t'_f with impact

t_f without impact

$$t'f = \frac{du}{du + \Delta\sigma(1 - U_1)} t_1 + \frac{\Delta\sigma(1 - U_1)}{du + \Delta\sigma(1 - U_1)} t_f$$

For the considered case,

$$du = U\Delta\sigma$$

and thus $t'_f = U_1 t_1 + (1-U_1)t_f$

The Table allows to compare the gain in consolidation time, at different degrees of consolidation.

U_1	10%	20%	30%	40%	50%	60%	70%	80%	90%
t_1/t_f	0.009	0.037	0.083	0.148	0.231	0.337	0.474	0.669	1.00
t'_1/t_f	0.901	0.807	0.725	0.659	0.615	0.602	0.632	0.735	1.00

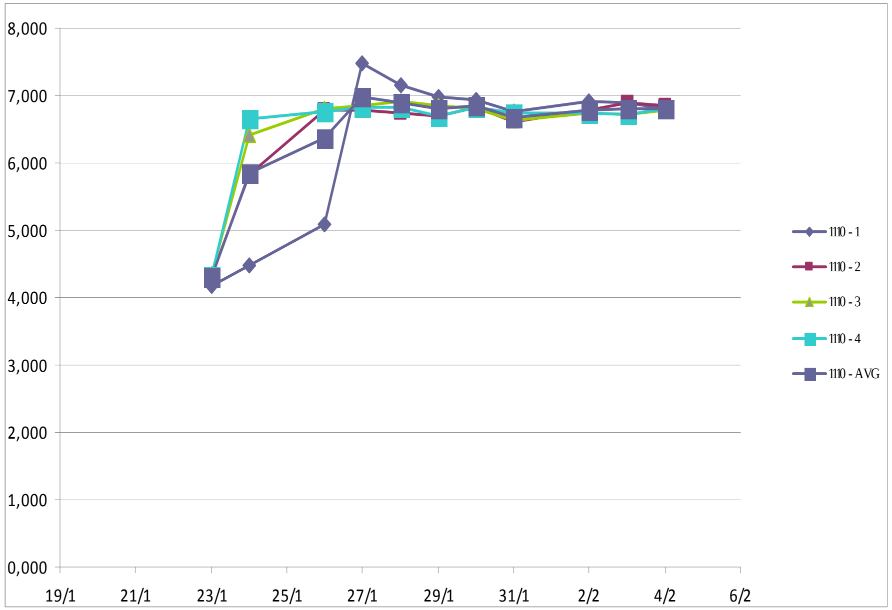
Supposing primary consolidation completed

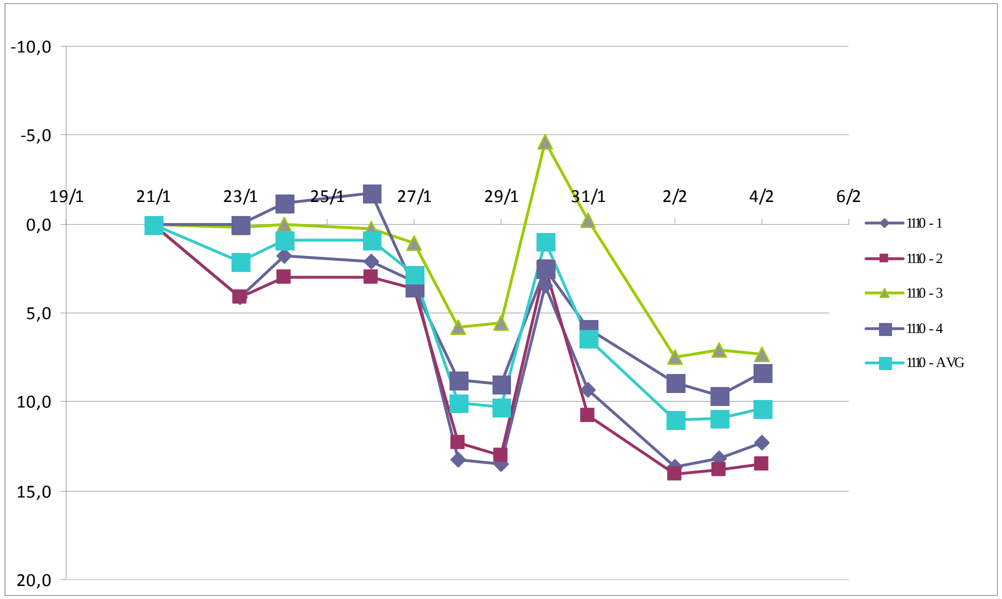
U = 0.9 or T = 0.848 if $du = U_1\Delta\sigma$,
then $t'_f = U_1 t_1 + (1-U_1)t_f$

The optimal effectiveness occurs around U_1 = 60%.

One can thus conclude that, theoretically the consolidation time is reduced by 20% to 50%, what is for practical purpose insufficient.

Dynamic surcharge


8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0,000
19/1
21/1
23/1
25/1
27/1
29/1
31/1
2/2
4/2
6/2
1110 - 1
1110 - 2
1110 - 3
1110 - 4
1110 - AVG


-10,0
-5,0
0,0
5,0
10,0
15,0
20,0
19/1
21/1
23/1
25/1
27/1
29/1
31/1
2/2
4/2
6/2
1110 - 1
1110 - 2
1110 - 3
1110 - 4
1110 - AVG

THANK YOU