GROUND IMPROVEMENT WORKSHOP 11-12 JUNE 2010

PERTH, AUSTRALIA

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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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.

D. Ground improvement with grouting type admixtures	D2. Chemical grouting	Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate to either increase the strength or reduce the permeability of soil or ground.
	D3. Mixing methods (including premixing or deep mixing)	Treat the weak soil by mixing it with cement, lime, or other binders in-situ using a mixing machine or before placement
	D4. Jet grouting	High speed jets at depth erode the soil and inject grout to form columns or panels
	D5. Compaction grouting	Very stiff, mortar-like grout is injected into discrete soil zones and remains in a homogenous mass so as to densify loose soil or lift settled ground.
	D6. Compensation grouting	Medium to high viscosity particulate suspensions is injected into the ground between a subsurface excavation and a structure in order to negate or reduce settlement of the structure due to ongoing excavation.
E. Earth reinforcement	E1. Geosynthetics or mechanically stabilised earth (MSE)	Use of the tensile strength of various steel or geosynthetic materials to enhance the shear strength of soil and stability of roads, foundations, embankments, slopes, or retaining walls.
	E2. Ground anchors or soil nails	Use of the tensile strength of embedded nails or anchors to enhance the stability of slopes or retaining walls.
	E3. Biological methods using vegetation	Use of the roots of vegetation for stability of slopes.

D2487 – 10

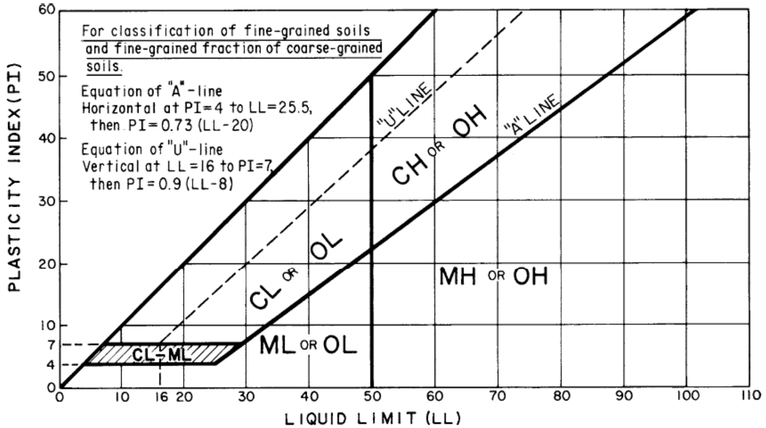
TABLE 1 Soil Classification Chart

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification: Group Symbol	Soil Classification: Group Name[B]
COARSE-GRAINED SOILS More than 50 % retained on No. 200 sieve	Gravels (More than 50 % of coarse fraction retained on No. 4 sieve)	Clean Gravels (Less than 5 % fines[C])	$Cu \geq 4$ and $1 \leq Cc \leq 3$[D]	GW	Well-graded gravel[E]
			$Cu < 4$ and/or $[Cc < 1$ or $Cc > 3]$[D]	GP	Poorly graded gravel[E]
		Gravels with Fines (More than 12 % fines[C])	Fines classify as ML or MH	GM	Silty gravel[E,F,G]
			Fines classify as CL or CH	GC	Clayey gravel[E,F,G]
	Sands (50 % or more of coarse fraction passes No. 4 sieve)	Clean Sands (Less than 5 % fines[H])	$Cu \geq 6$ and $1 \leq Cc \leq 3$[D]	SW	Well-graded sand[I]
			$Cu < 6$ and/or $[Cc < 1$ or $Cc > 3]$[D]	SP	Poorly graded sand[I]
		Sands with Fines (More than 12 % fines[H])	Fines classify as ML or MH	SM	Silty sand[F,G,I]
			Fines classify as CL or CH	SC	Clayey sand[F,G,I]
FINE-GRAINED SOILS 50 % or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	inorganic	PI > 7 and plots on or above "A" line[J]	CL	Lean clay[K,L,M]
			PI < 4 or plots below "A" line[J]	ML	Silt[K,L,M]
		organic	$\frac{\textit{Liquid limit – oven dried}}{\textit{Liquid limit – not dried}} < 0.75$	OL	Organic clay[K,L,M,N] Organic silt[K,L,M,O]
	Silts and Clays Liquid limit 50 or more	inorganic	PI plots on or above "A" line	CH	Fat clay[K,L,M]
			PI plots below "A" line	MH	Elastic silt[K,L,M]
		organic	$\frac{\textit{Liquid limit – oven dried}}{\textit{Liquid limit – not dried}} < 0.75$	OH	Organic clay[K,L,M,P] Organic silt[K,L,M,Q]
HIGHLY ORGANIC SOILS	Primarily organic matter, dark in color, and organic odor			PT	Peat

Unified Soil Classification

OTHER MATERIAL SYMBOLS

Poorly Graded Sand with Clay	Sand
Clayey Sand	Silt
Sandy Silt	Well Graded Gravelly Sand
Low to High Plasticity Clay	Gravelly Silt
Poorly Graded Gravelly Sand	Asphalt
Topsoil	Boulders and Cobble
Well Graded Gravel with Clay	
Well Graded Gravel with Silt	



SAMPLE TYPES

- Split Spoon
- Shelby Tube
- Rock Core
- Grab Sample

ADDITIONAL TESTS

CA	CHEMICAL ANALYSIS (CORROSIVITY)	(200)	(WITH % PASSING NO. 200 SIEVE
CD	CONSOLIDATED DRAINED TRIAXIAL		
CN	CONSOLIDATION	SW	SWELL TEST
CU	CONSOLIDATED UNDRAINED TRIAXIAL	TC	CYCLIC TRIAXIAL
DS	DIRECT SHEAR	TV	TORVANE SHEAR
PP	POCKET PENETROMETER (TSF)	UC	UNCONFINED COMPRESSION
(3.0)	(WITH SHEAR STRENGTH IN KSF)	(1.5)	(WITH SHEAR STRENGTH IN KSF)
RV	R-VALUE		
SA	SIEVE ANALYSIS: % PASSING #200 SIEVE	UU	UNCONSOLIDATED UNDRAINED TRIAXIAL
▽	WATER LEVEL (WITH DATE OF) MEASUREMENT	WA	WASH ANALYSIS
		(200%)	(WITH % PASSING NO. 200 SIEVE)

PENETRATION RESISTANCE
(RECORDED AS BLOWS / 0.5 FT)

SAND & GRAVEL		SILT & CLAY		
RELATIVE DENSITY	BLOWS/FOOT*	CONSISTENCY	BLOWS/FOOT*	COMPRESSIVE STRENGTH (TSF)
VERY LOOSE	0 - 4	VERY SOFT	0 - 2	0 - 0.25
LOOSE	4 - 10	SOFT	2 - 4	0.25 - 0.50
MEDIUM DENSE	10 - 30	FIRM	4 - 8	0.50 - 1.0
DENSE	30 - 50	STIFF	8 - 15	1.0 - 2.0
VERY DENSE	OVER 50	VERY STIFF	15 - 30	2.0 - 4.0
		HARD	OVER 30	OVER 4.0

* NUMBER OF BLOWS OF 140 LB HAMMER FALLING 30 INCHES TO DRIVE A 2 INCH O.D. (1-3/8 INCH I.D.) SPLIT-BARREL SAMPLER THE LAST 12 INCHES OF AN 18-INCH DRIVE (ASTM-1586 STANDARD PENETRATION TEST).

2.1 – UD: 2'' or 3 ' Shelby Tube

Suitable for cohesive soils *UNDISTURBED*

2.2 – Piston sampler Osterberg

Suitable for cohesive and fine granular soils *UNDISTURBED*

2.3 – SPT: suitable for cohesive and granular Soil *REPRESENTATIVE SAMPLE*

2.4 – Core barrel

Suitable for rock type of soils *UNDISTURBED*

2.5 – Block sample *REPRESENTATIVE SAMPLE*

Define terms important for Unified Soil Classification System

Percent Fines

Mechanical Analysis

Liquid Limit

Plastic Limit, Plasticity Index

Water Content

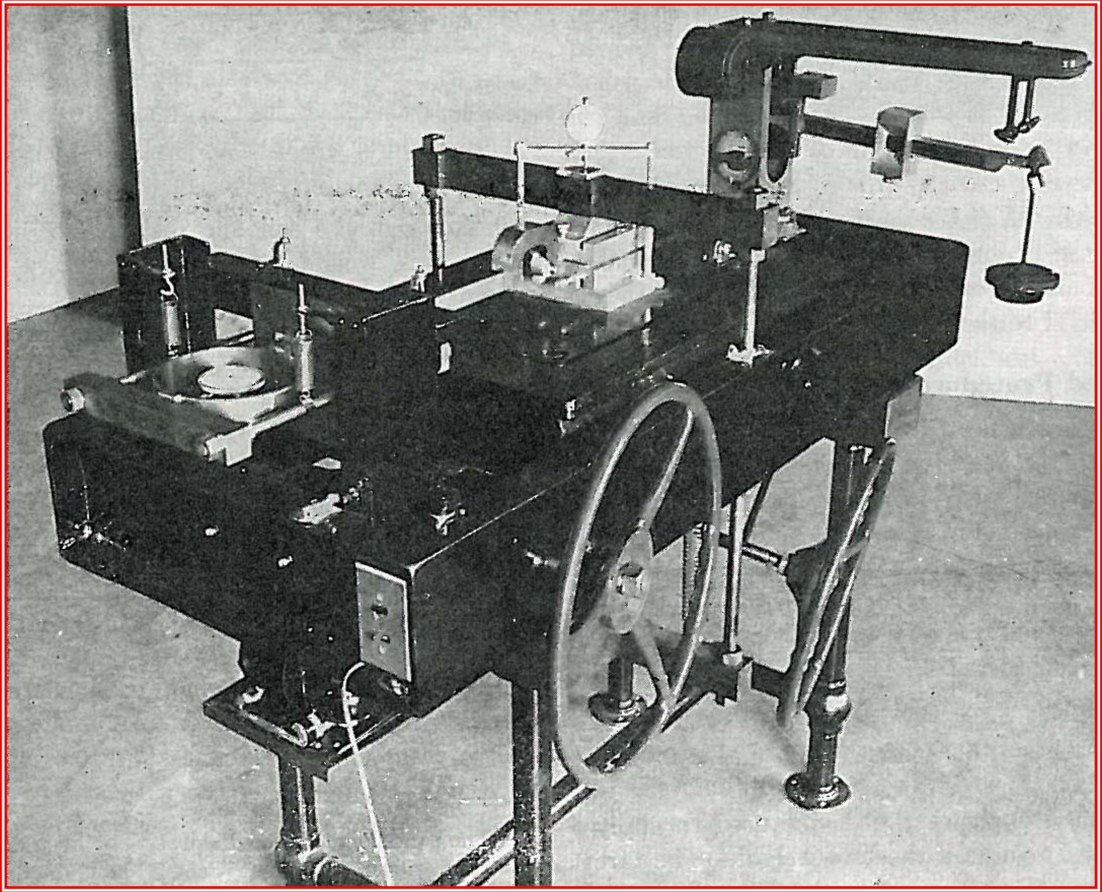
Organic

Laboratory Engineering Properties

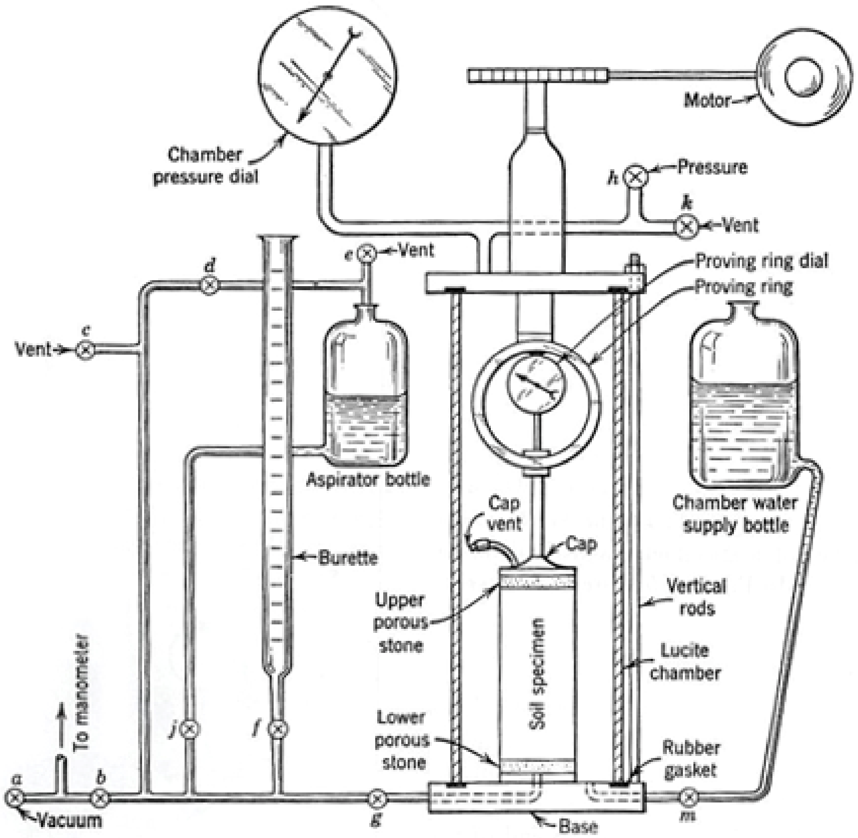
Direct shear test

ϕ (imposed failure plane)

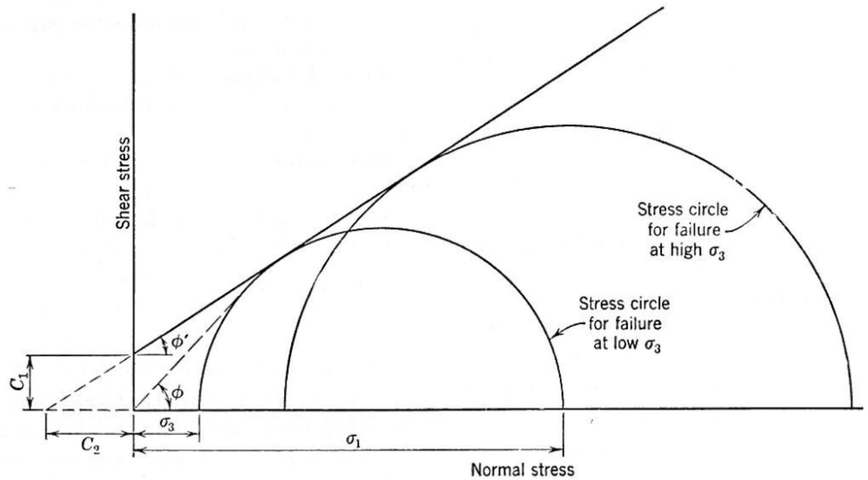
τ, ϕ



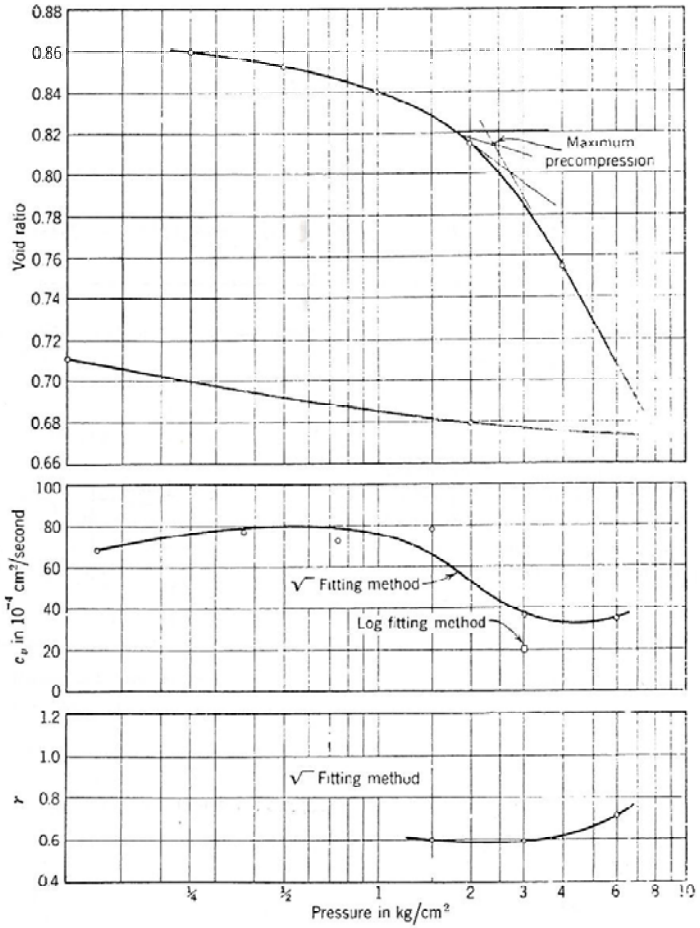
Triaxial on cohesionless soil



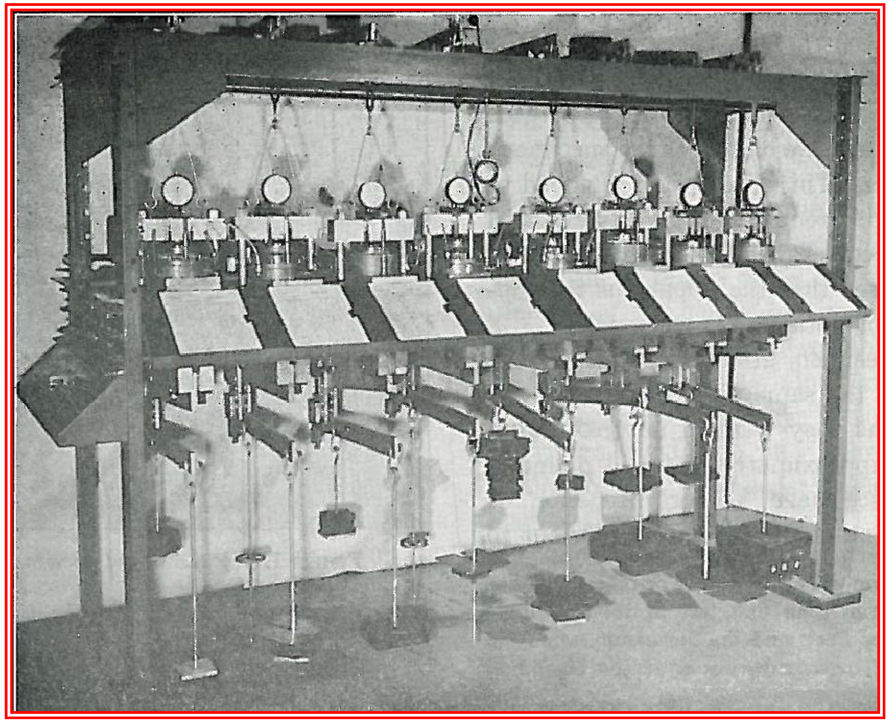
ϕ, Mohr Coulomb curve



W, C_o, C_e, C_v, P_c, k, A_v, C_α



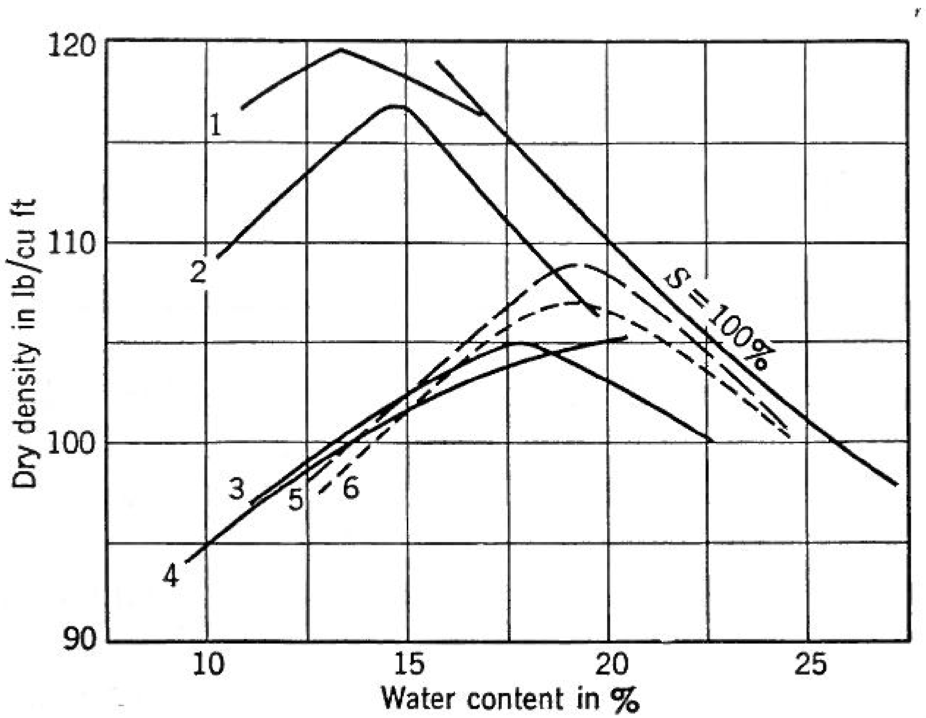
Consolidation test

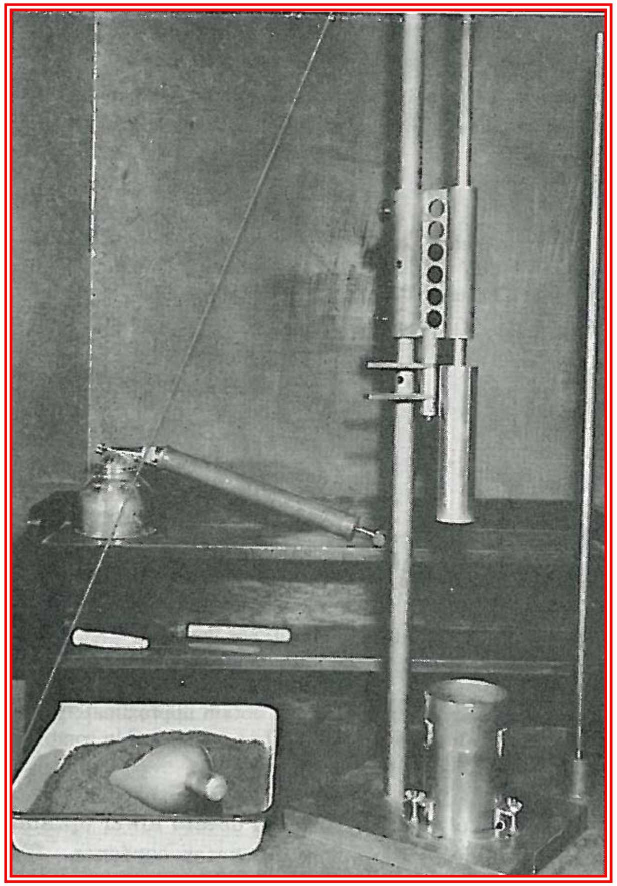


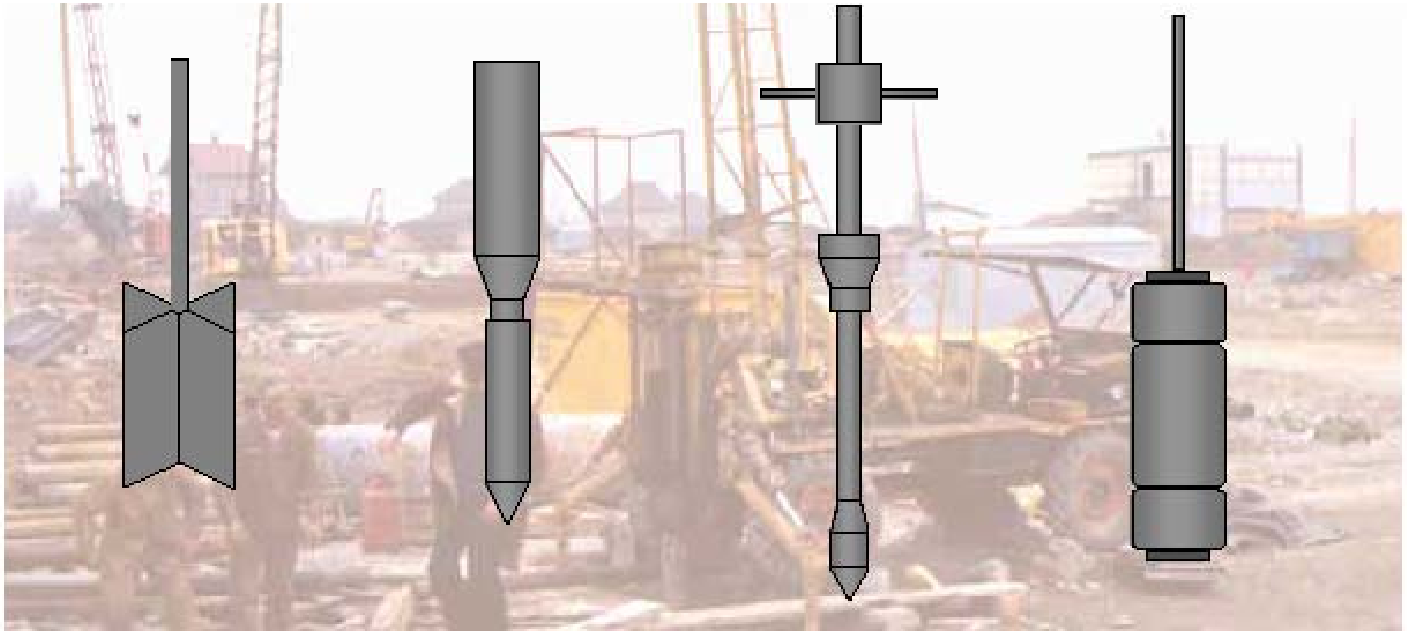
Frame with consolidation units

Proctor Test

w, w_{cpt}, γ_{max}, Proctor curve







Vane test (VT)

Static Cone Penetration Test (CPT)

Standard Penetration Test (SPT)

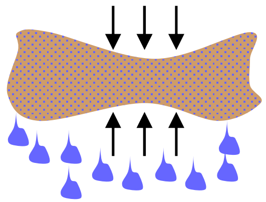
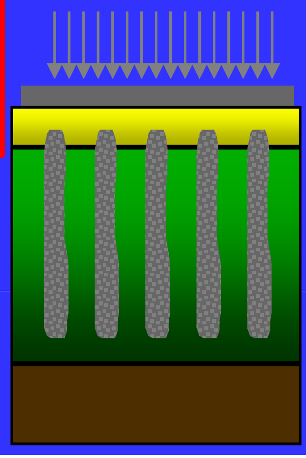
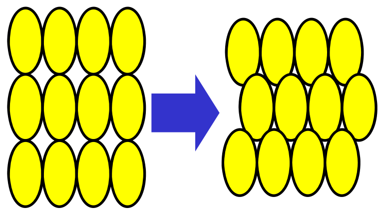
Pressuremeter (PMT)

Why Soil Improvement ?

- To increase bearing capacity and stability (avoid failure)
- To reduce post construction settlements
- To reduce liquefaction risk (seismic areas)

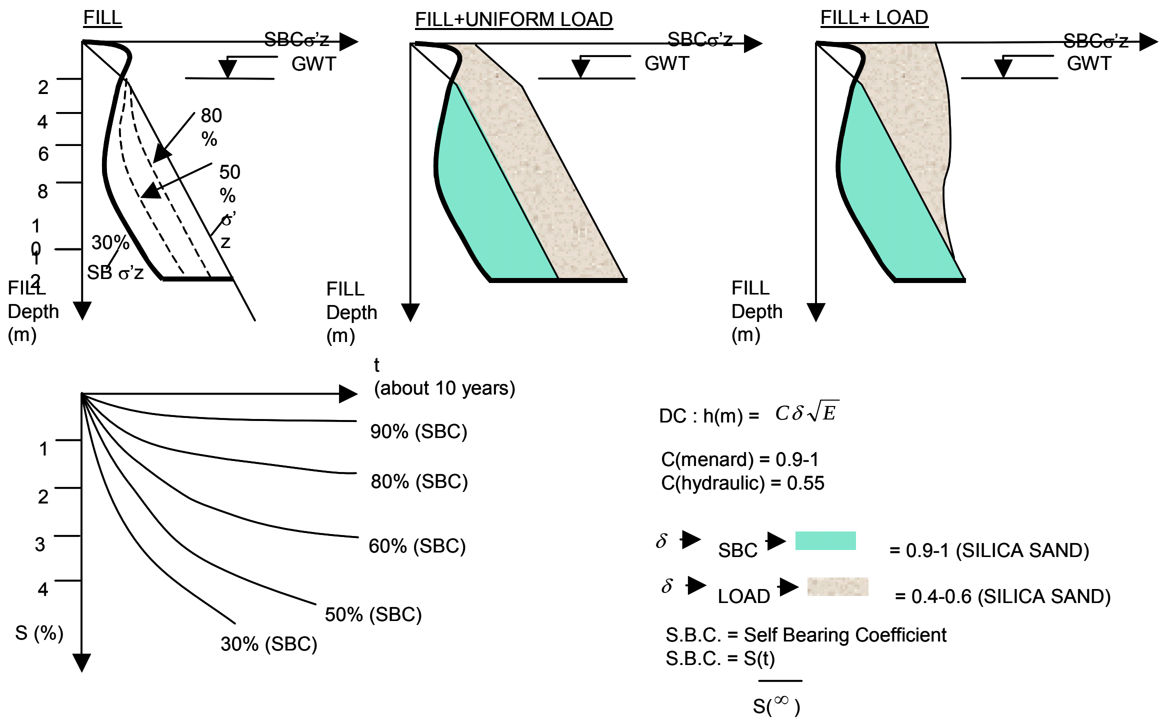
Advantages over classical solutions

- Avoid deep foundation (price reduction also on structure work like slab on pile)
- Avoid soil replacement
- Save time
- Avoid to change site
- Save money !

	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 	

- Soil characteristics
  - -Cohesive or non cohesive
  - - Blocks?
- Water content, water table position
- Organic materials
- Soil thickness
- Structure to support
  - -Isolated or uniform load
  - -Deformability
- Site environment
  - -Close to existing structures
  - -Height constraints
- Available construction time

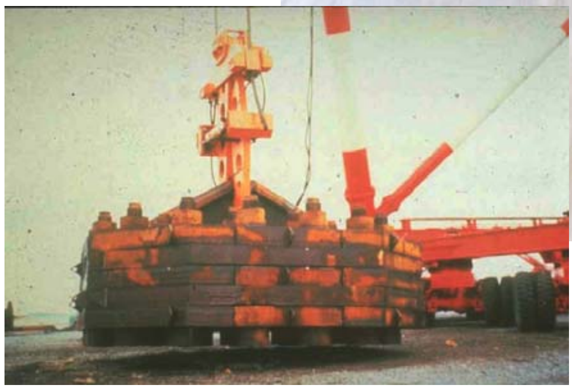
CONCEPT



PARAMETERS

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

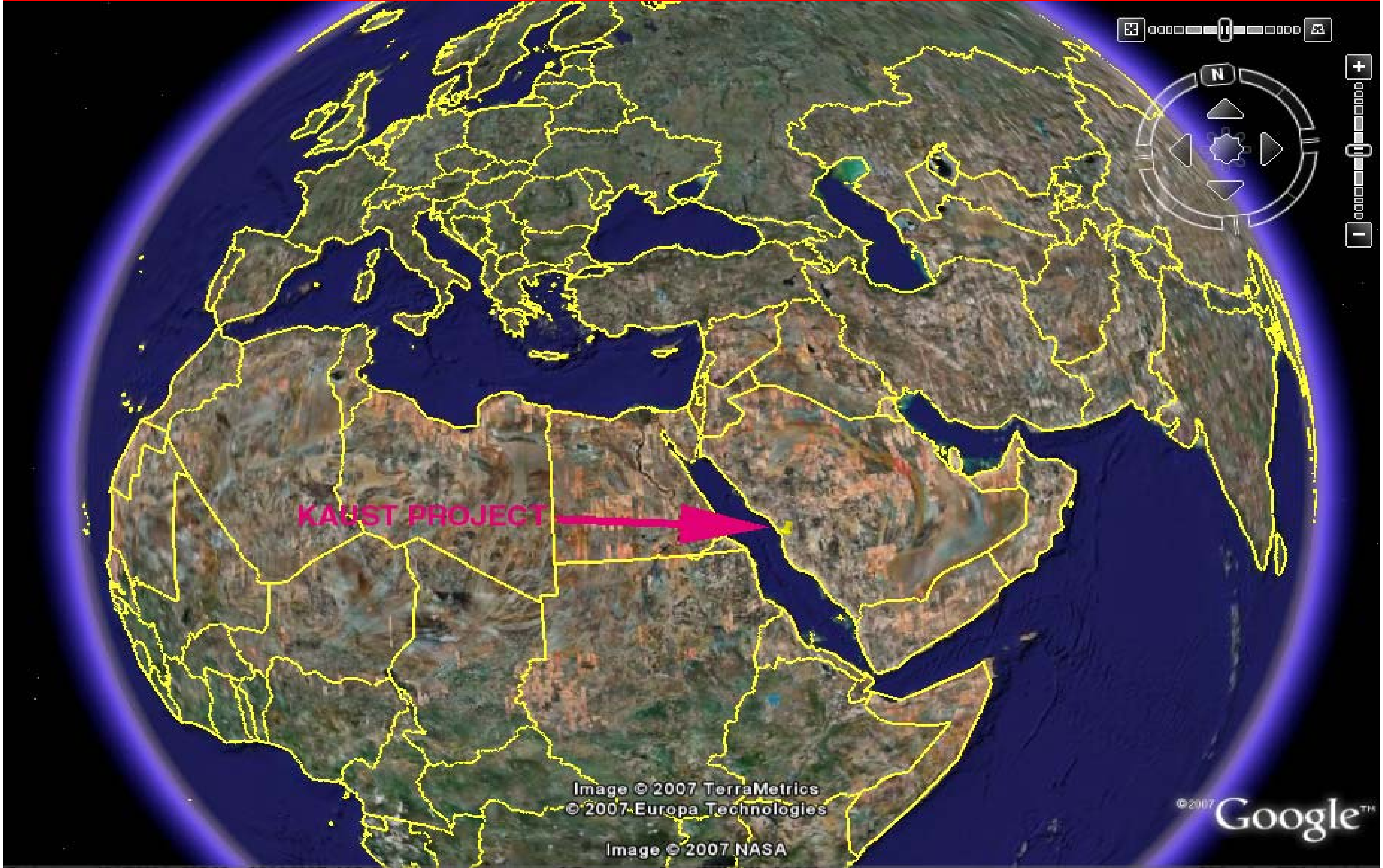
Nice International Airport Runway consolidation
Granular soil



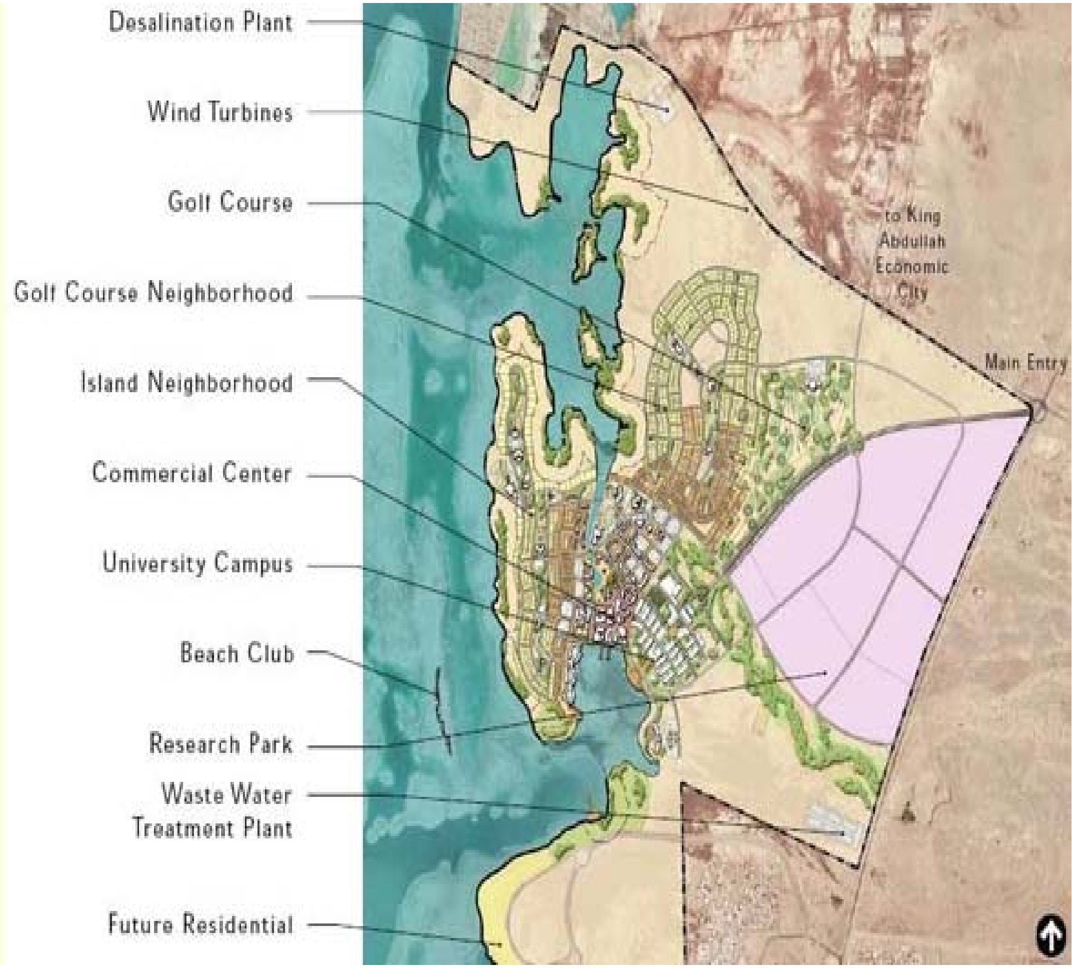
Very high energy (170 t, 23 m)

Concept and Application of 2,600,000 m² of ground improvement for King Abdulla University of Science & Technology (KAUST)

LOCALISATION



Master Plan

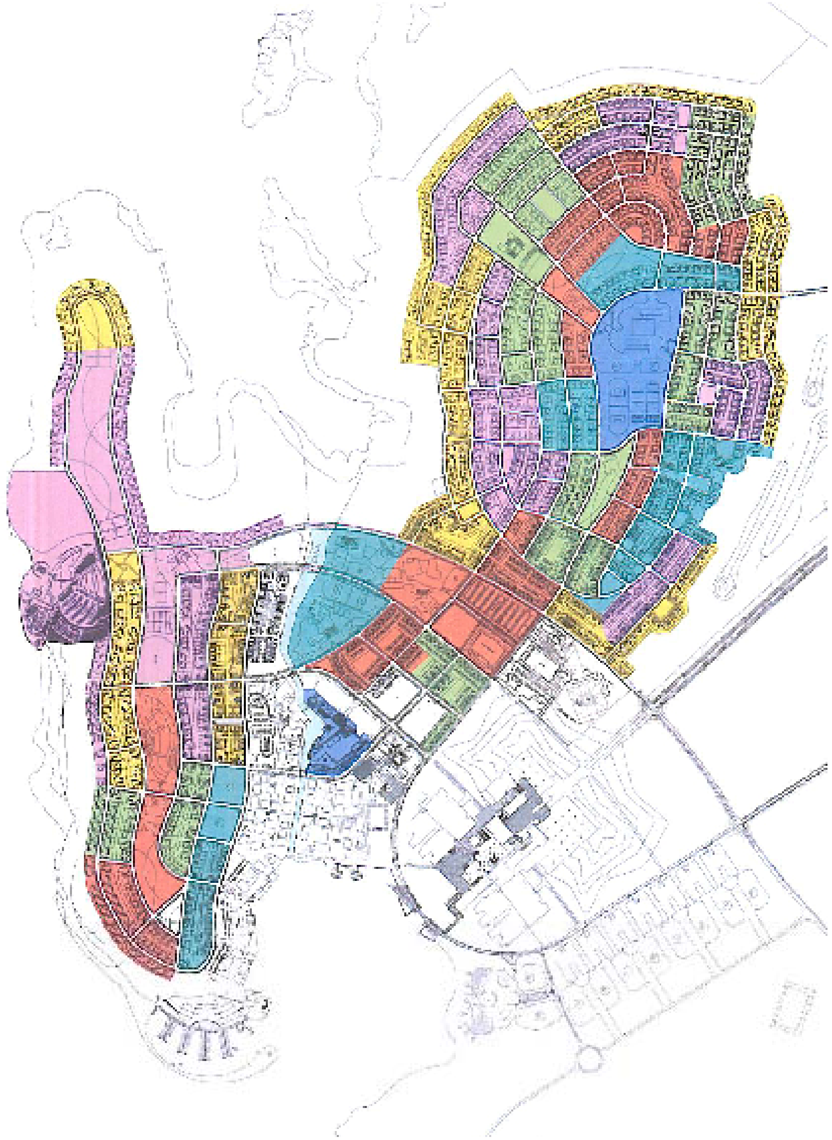


Desalination Plant
Wind Turbines
Golf Course
Golf Course Neighborhood
Island Neighborhood
Commercial Center
University Campus
Beach Club
Research Park
Waste Water
Treatment Plant
Future Residential
to King Abdullah Economic City
Main Entry

Original site Conditions

Jeddah, a modern city

Discovering the Habitants

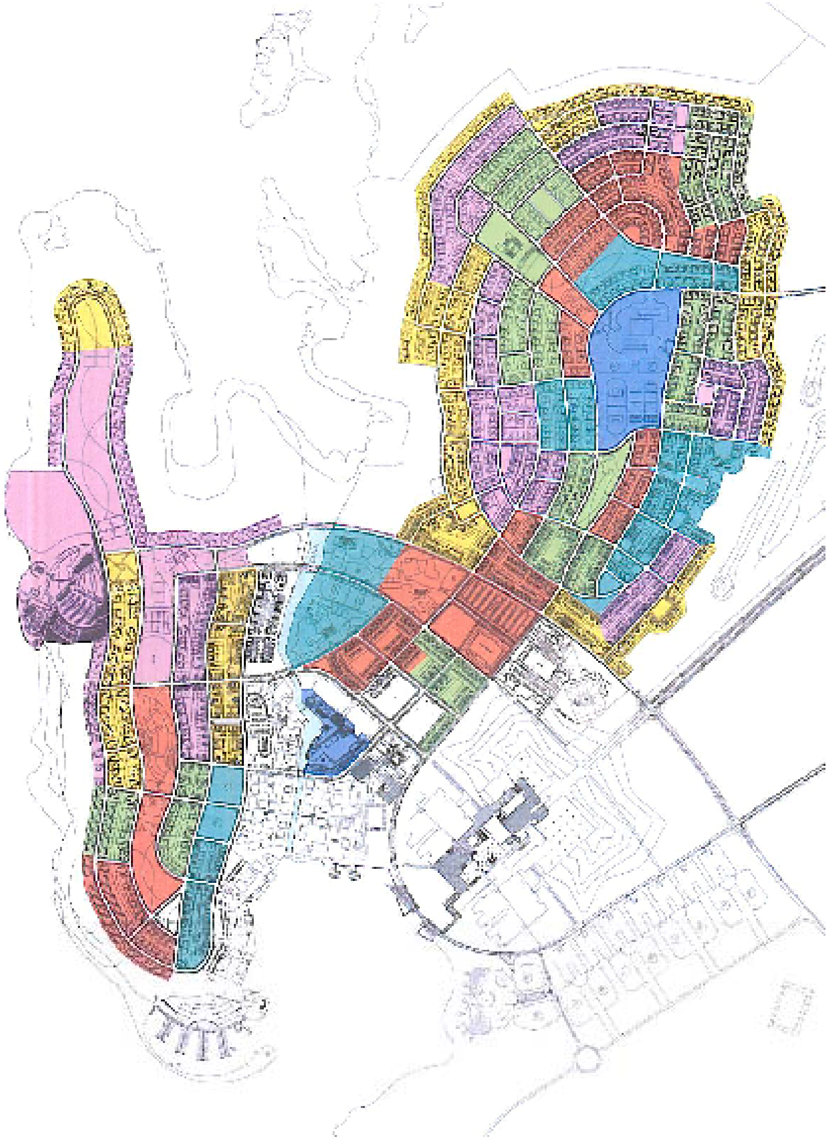


Areas to be treated

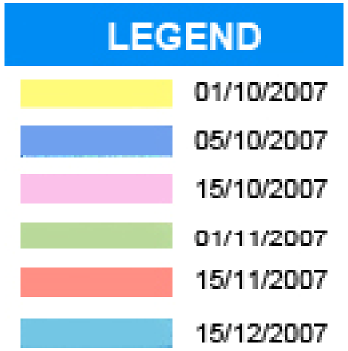
- Al Khodari (1,800,000 m^2
- Saudi Bin Ladin 720,000 m^2

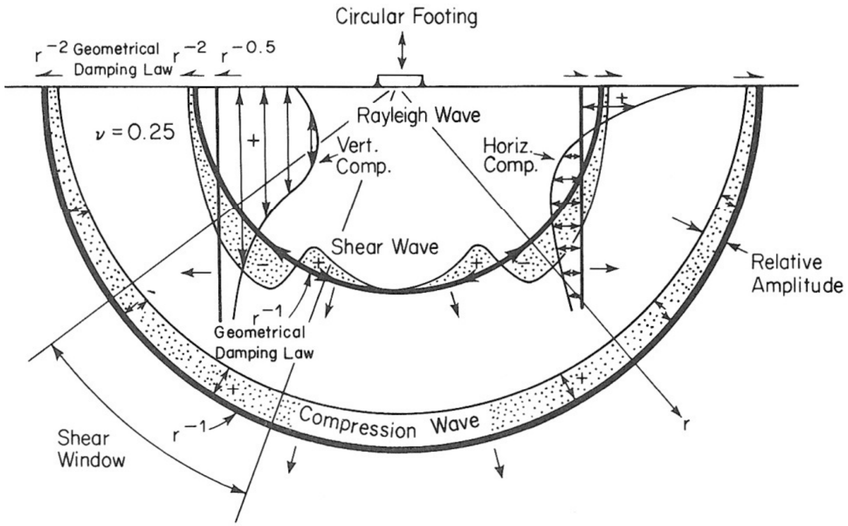
Schedule

- 8 months



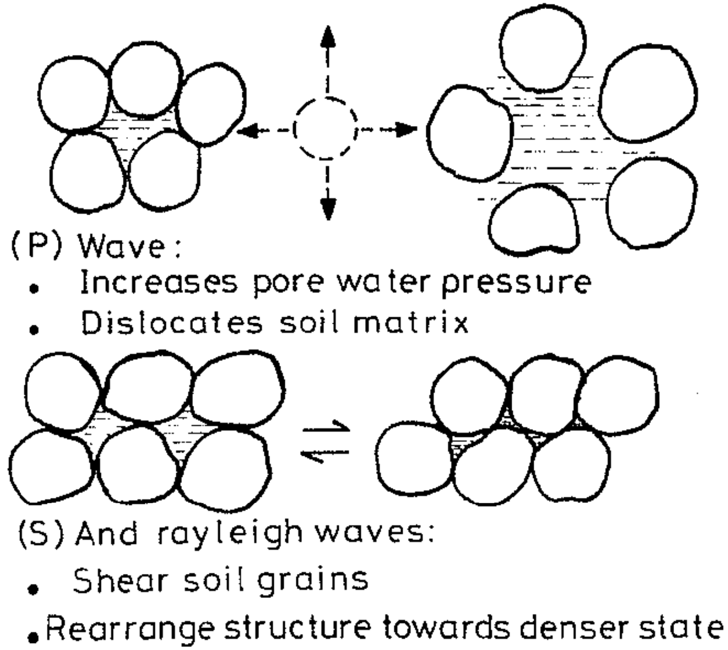
KAUST
Dates for soil improvement



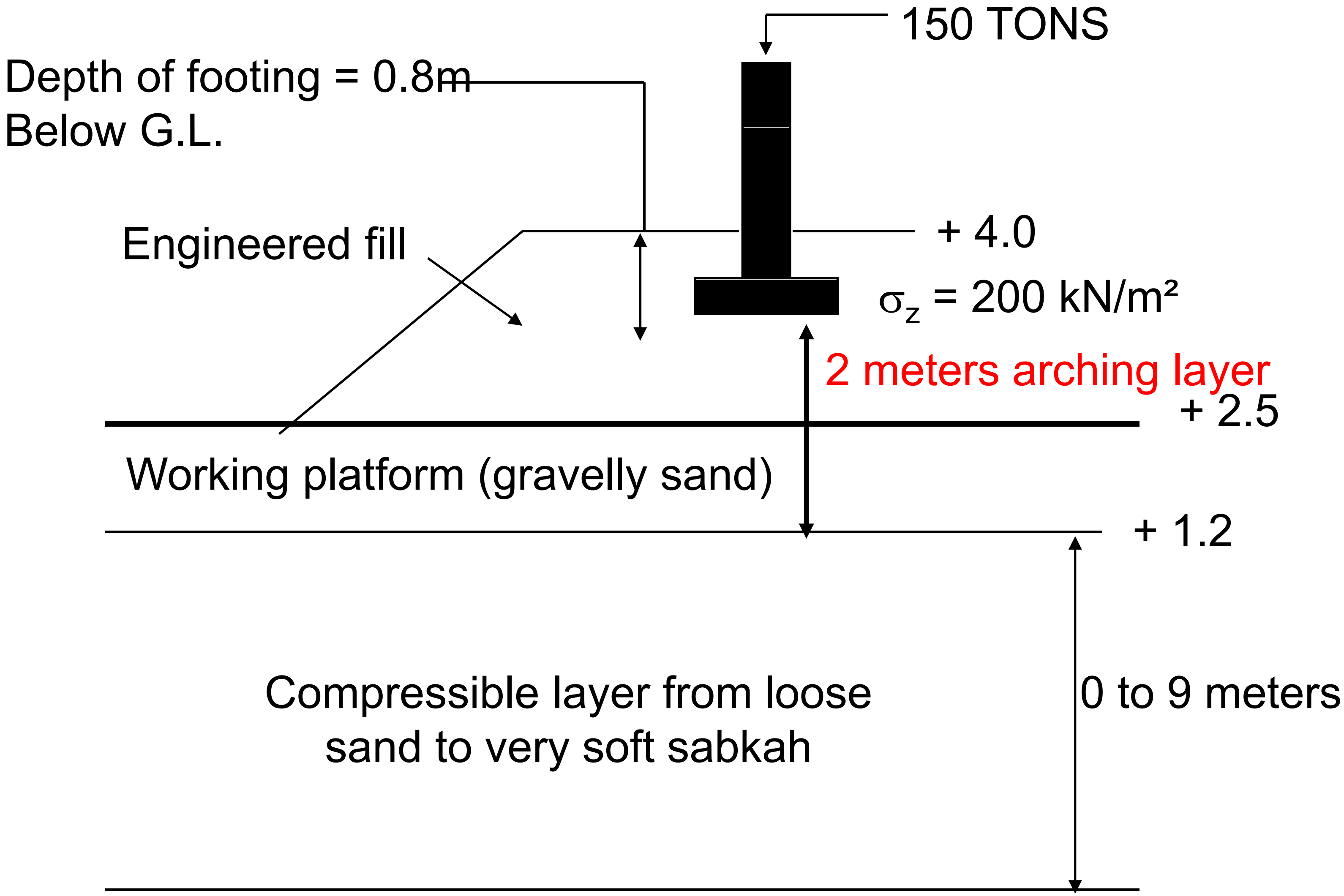


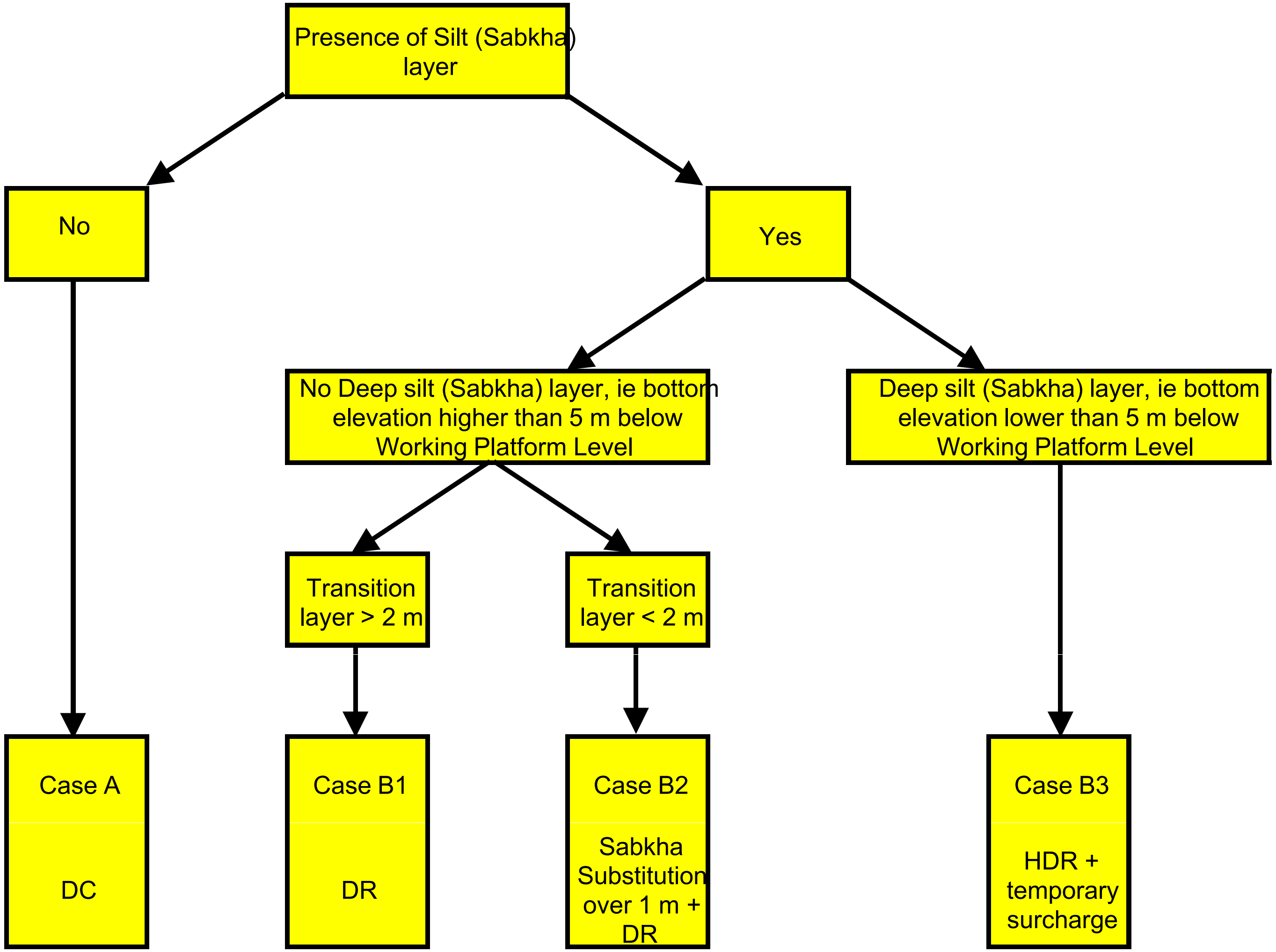
Wave Type	Percent of Total Energy
Rayleigh	67
Shear	26
Compression	7

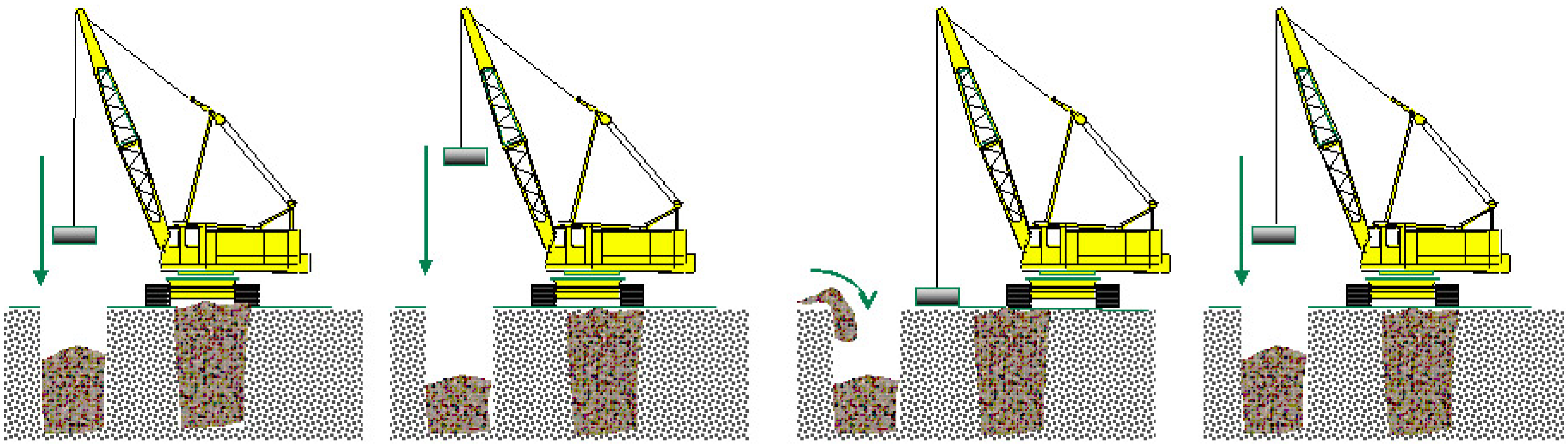
After R.D. Woods (1968)



- 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

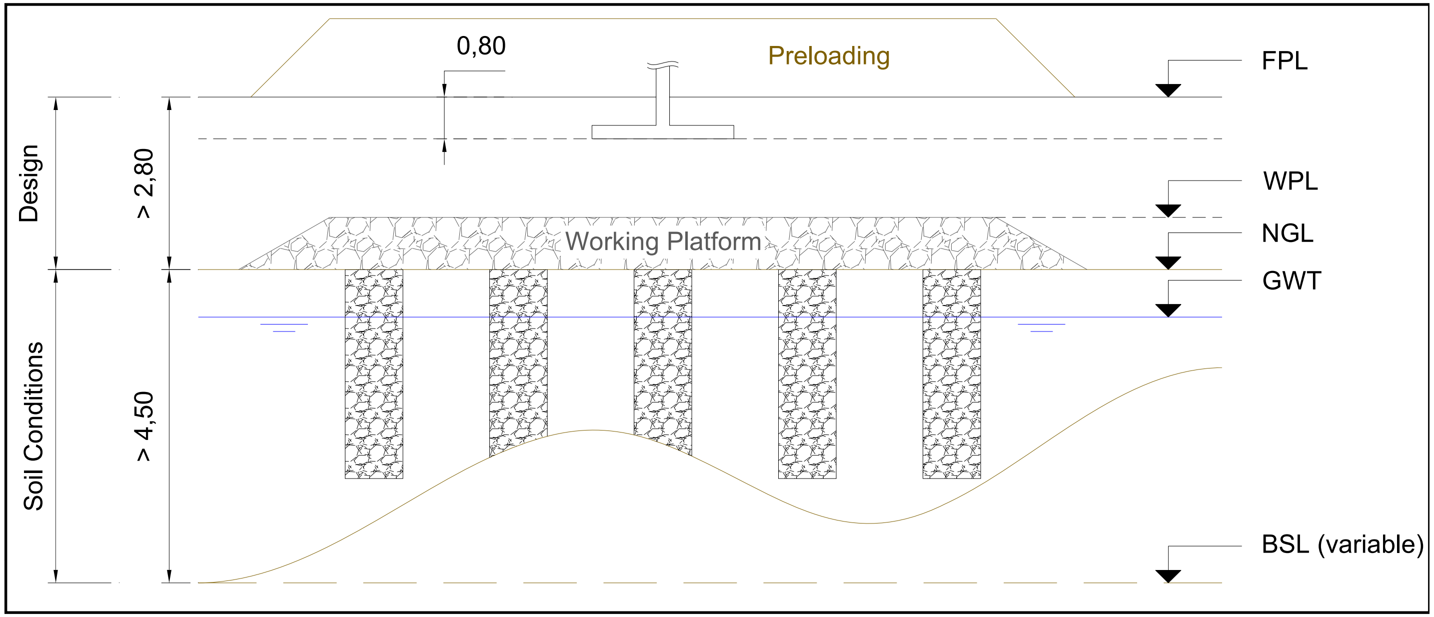

150 TONS
Depth of footing = 0.8m
Below G.L.
Engineered fill
+ 4.0
σz = 200 kN/m²
2 meters arching layer
+ 2.5
Working platform (gravelly sand)
+ 1.2
Compressible layer from loose
sand to very soft sabkah
0 to 9 meters


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

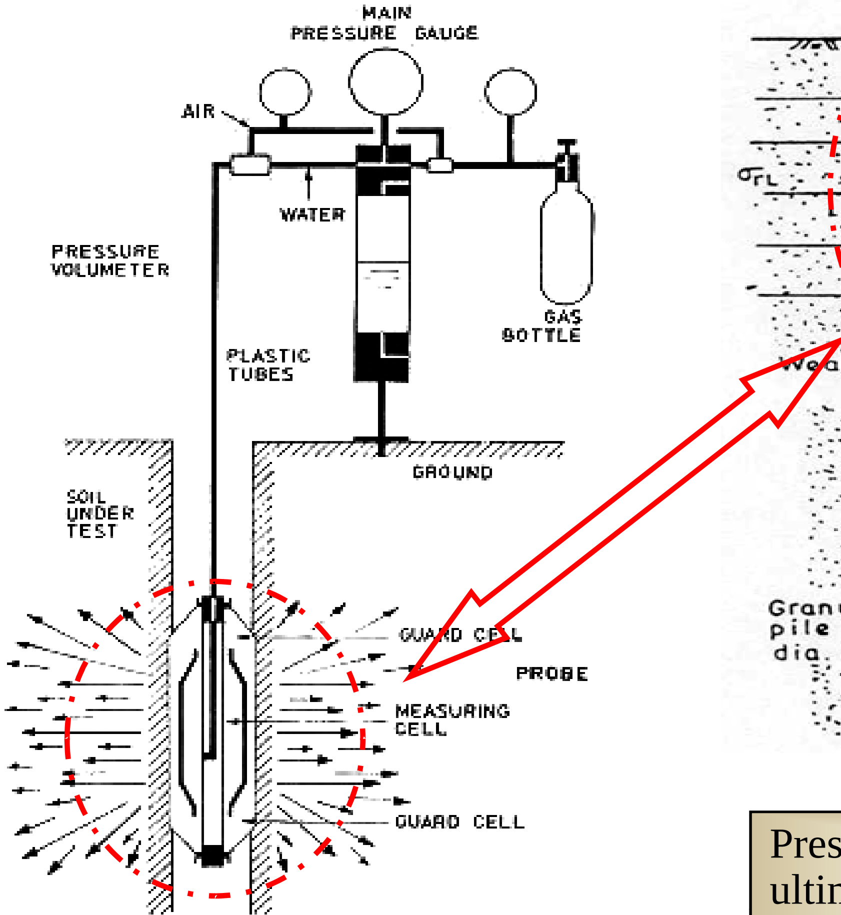


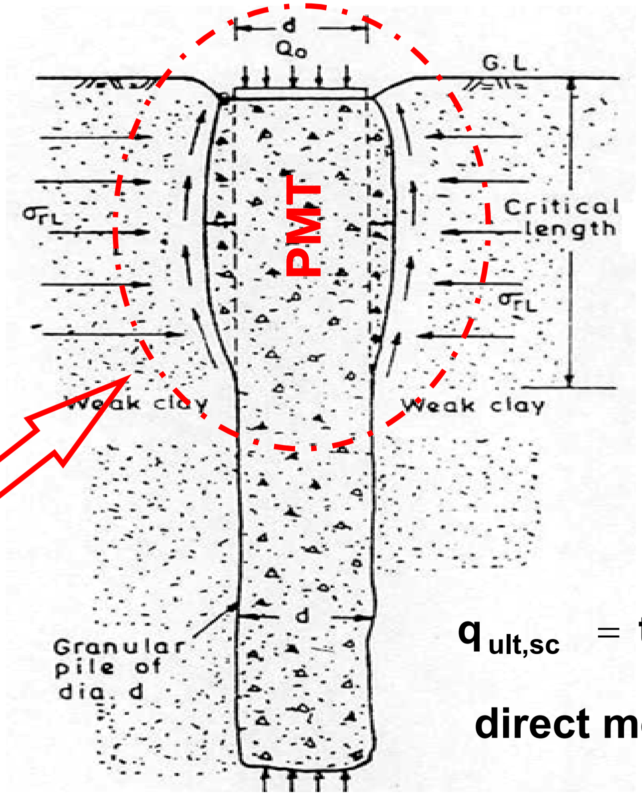
DR (Dynamic Replacement)

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.

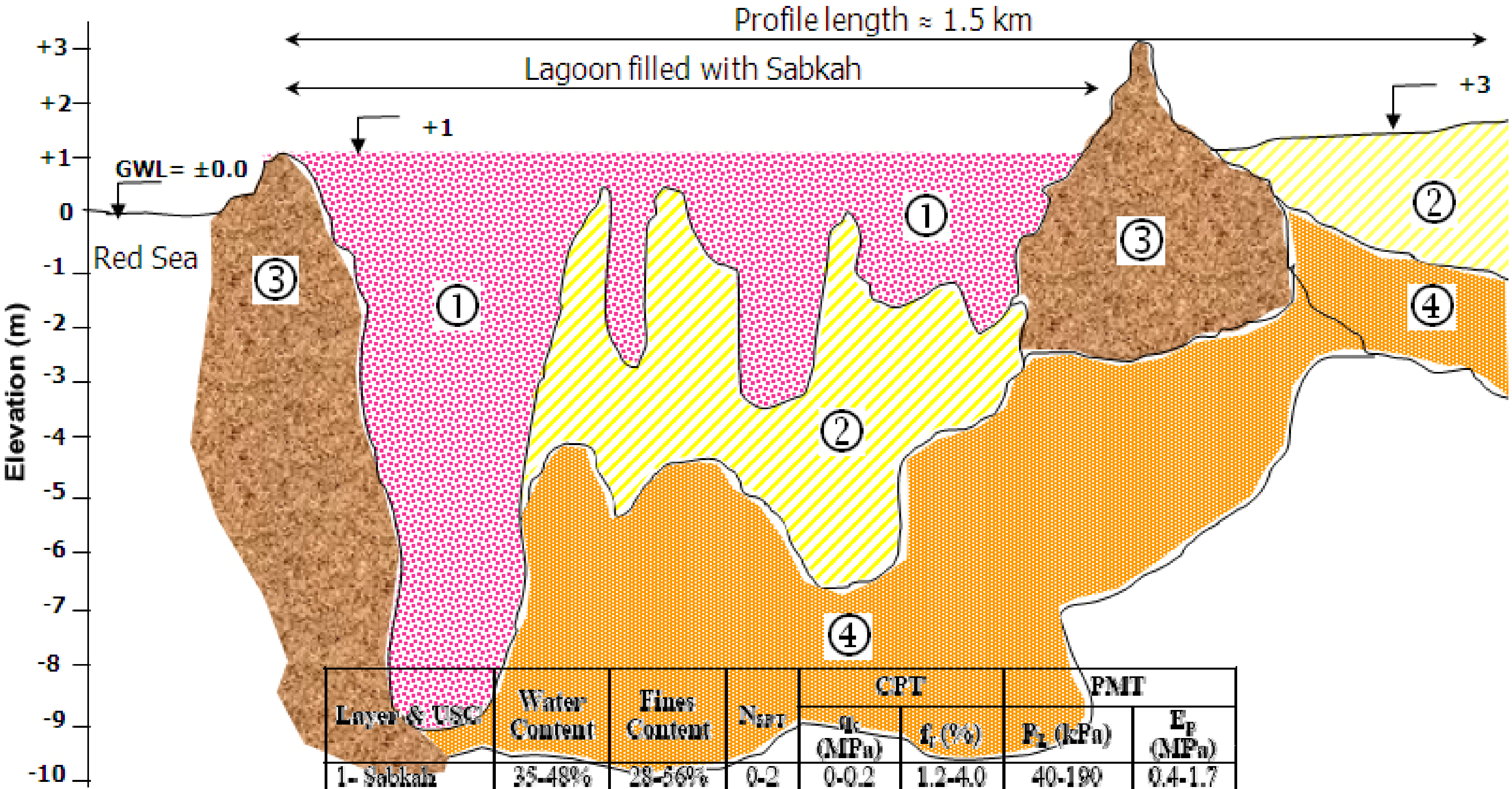




$$q_{ult,sc} = \tan^2\left(\frac{\pi}{4} + \frac{\varphi_{sc}}{2}\right) P_L$$

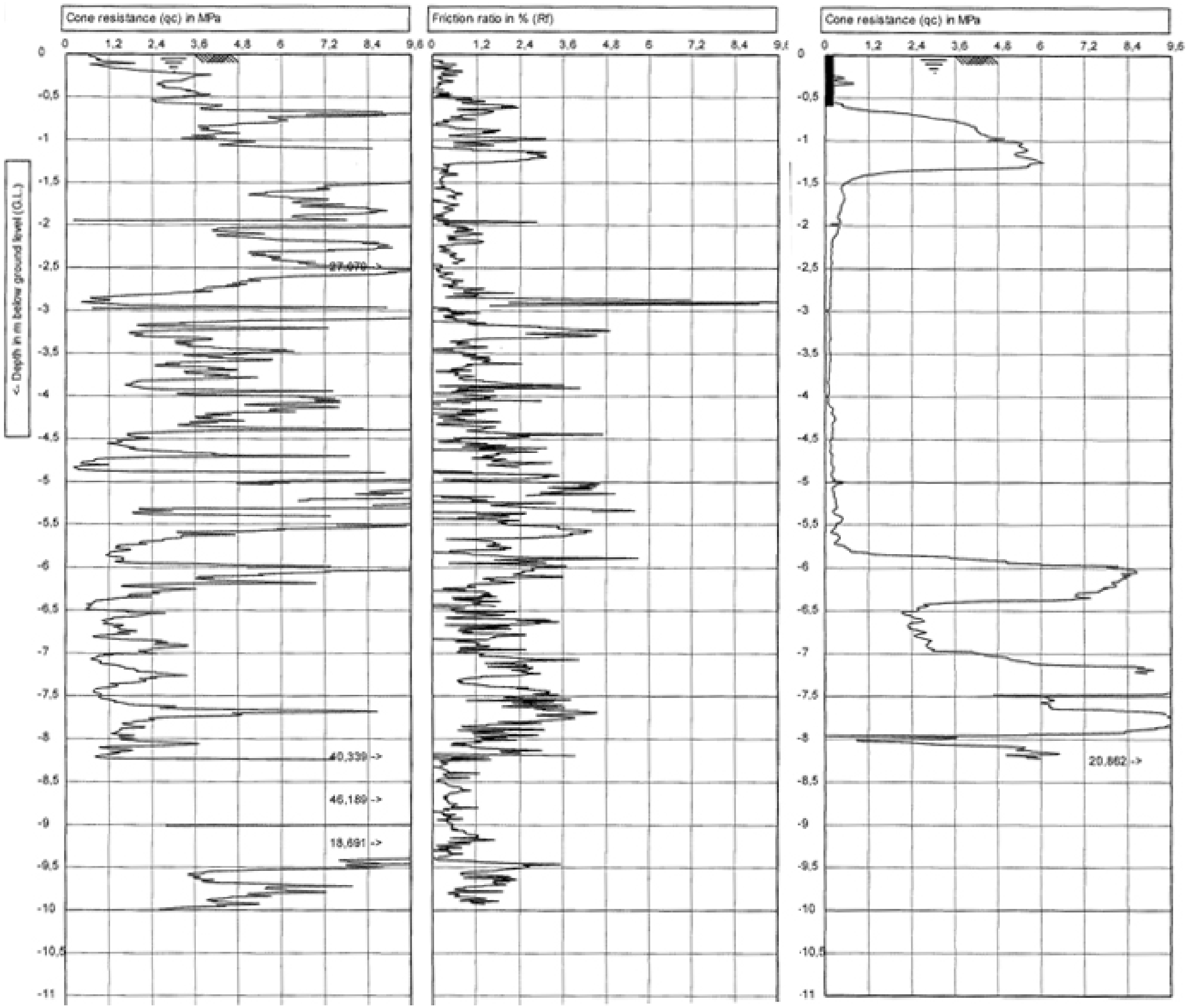
direct measurement of P_L

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

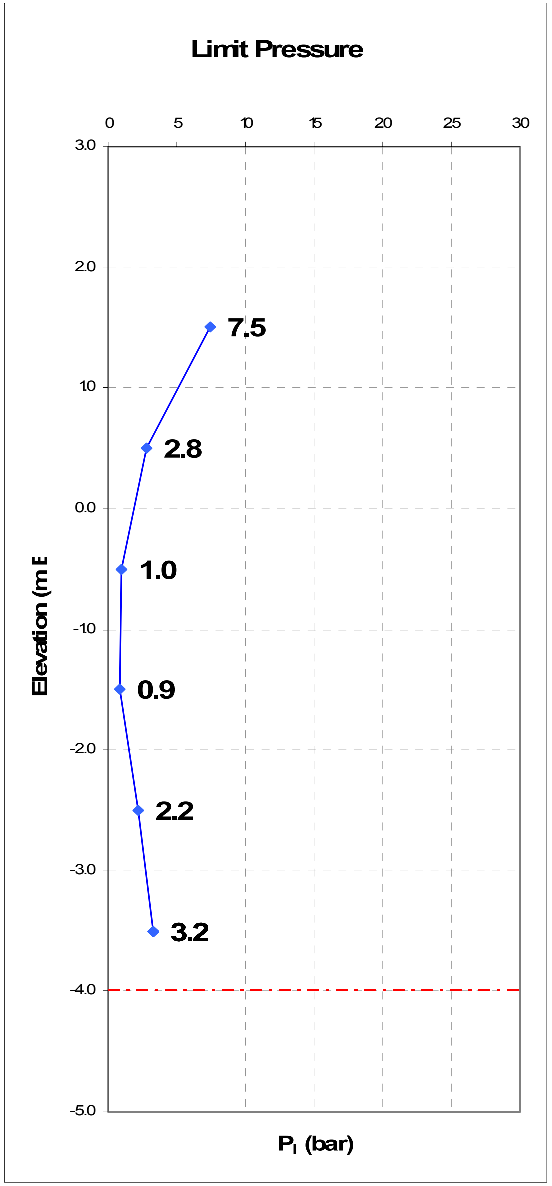


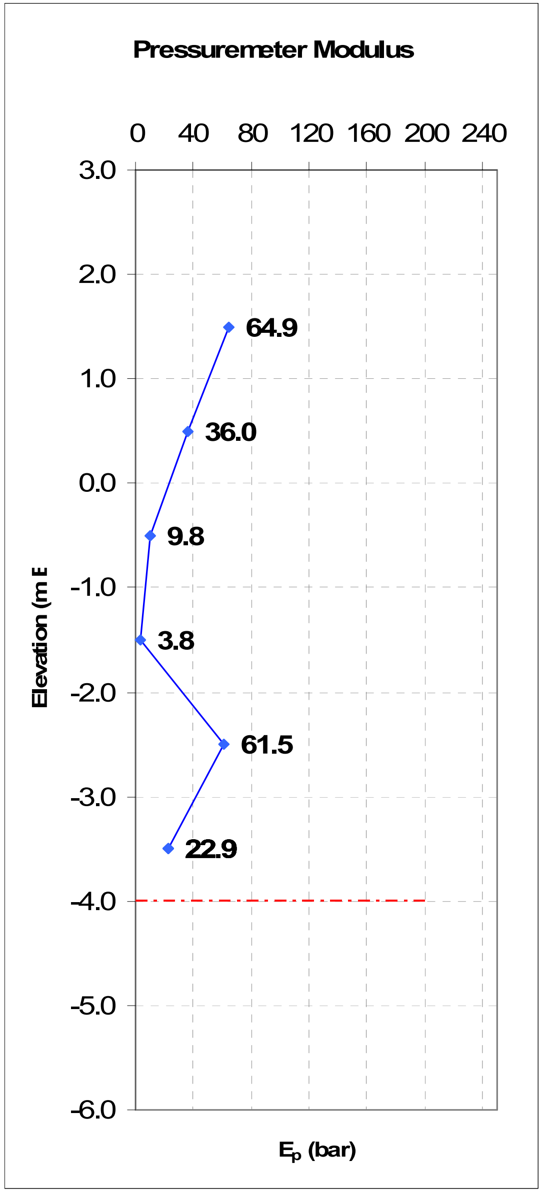
Layer & USC	Water Content	Fines Content	N_{SPT}	CPT		PMT	
				q_c (MPa)	f_r (%)	P_L (kPa)	E_P (MPa)
1- Sabkah (SM+ML)	35-48%	28-56%	0-2	0-0.2	1.2-4.0	40-190	0.4-1.7
2- Silty Sand (SM)	-	15-28%	3-9	1.2-4.5	0.5-1.2	210-400	1.8-3.5
3- Coral	26-35%	-	6-12	-	-	510-720	3.5-6.0
4- Sand (SM)	-	12-37%	3-18	1.5-1.8	0.5-1.8	400-1200	2.8-8.5

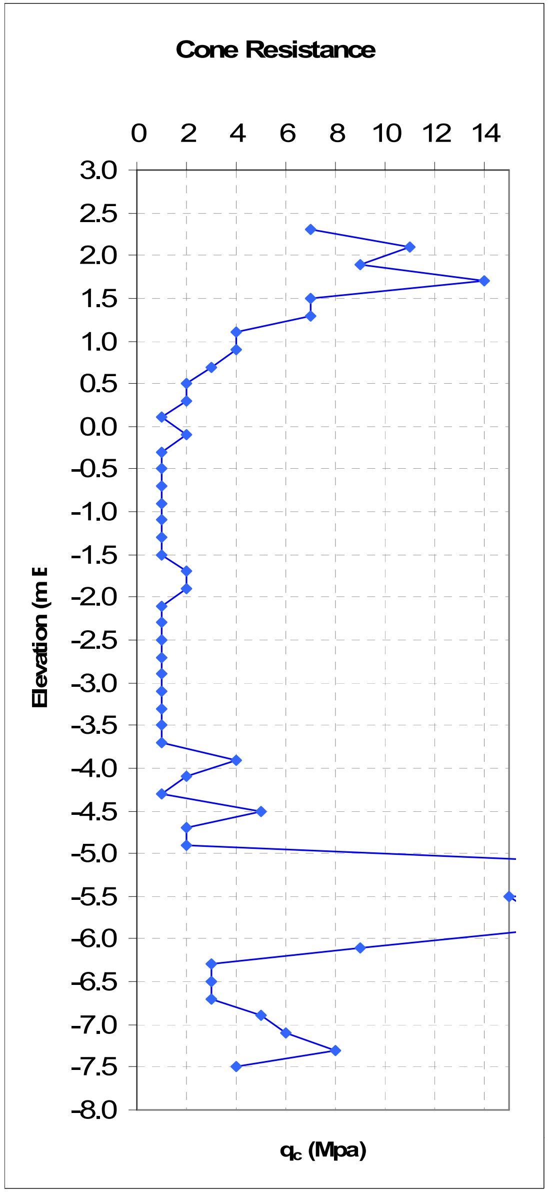
Variation in soil profile over 30 meters



Typical soil profile



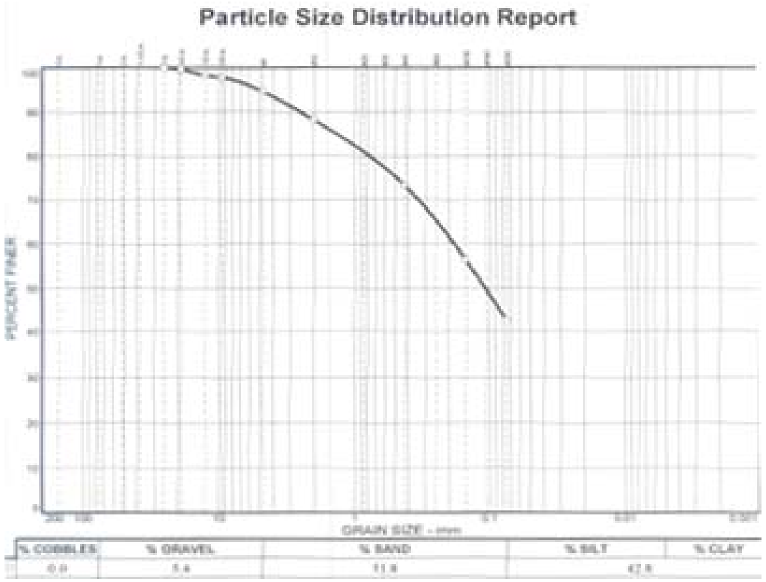




1. Project management (4)
2. Production team (32)
3. Mechanical team (18)
4. Survey team (16)
5. Administrative team (6)
6. Geotechnical team (8)
7. Safety and Quality (2)
8. Logistic team (4)

Typical surface conditions


Typical test pits (120) and grain size



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

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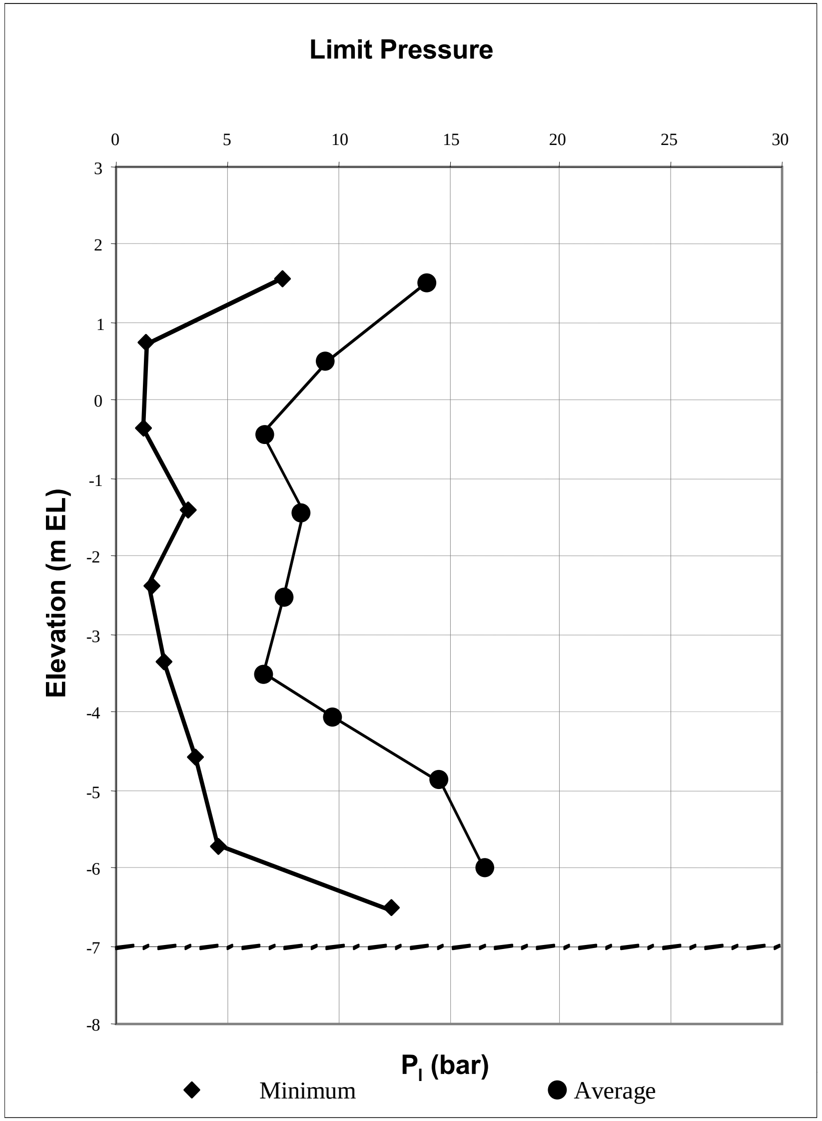
- 1 forklift
- 3 CPT rigs
- 1 drill + pressuremeter
- 15 containers
- 1 set of site offices

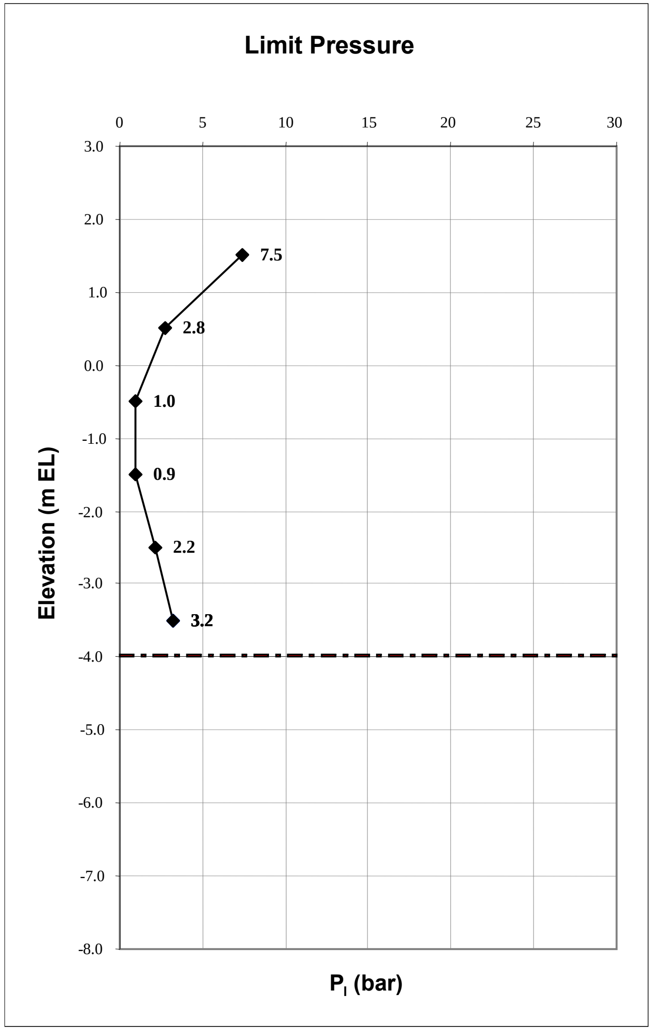
PMT RESULTS BEFORE DC

Before DC

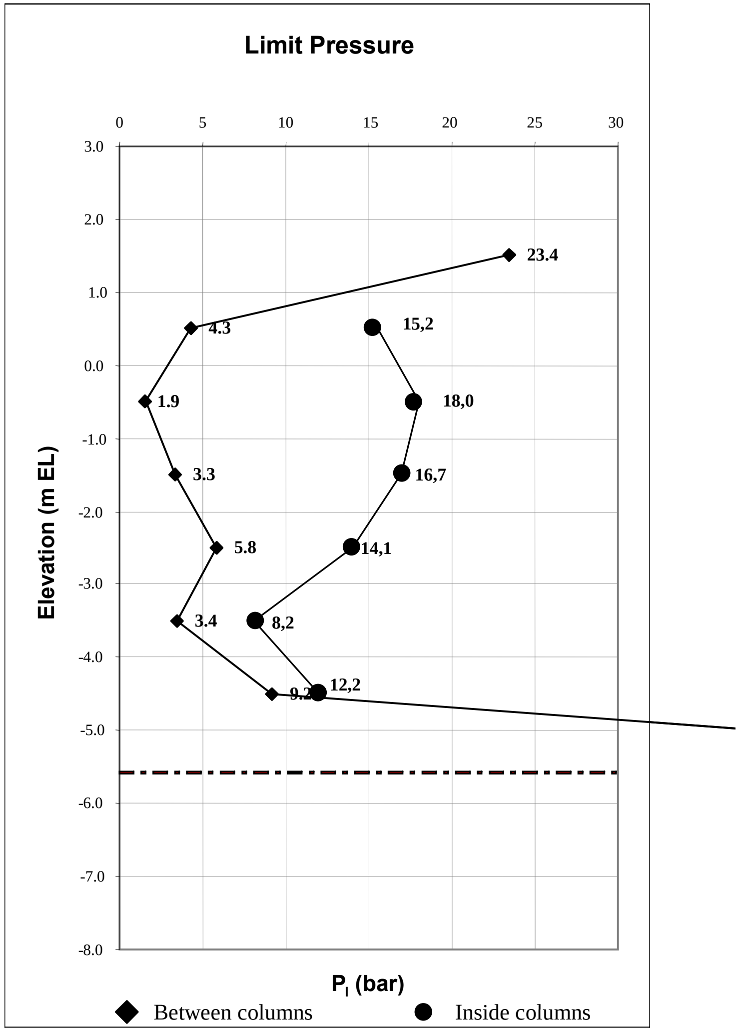


PMT RESULTS BEFORE AND AFTER DR

Before DR

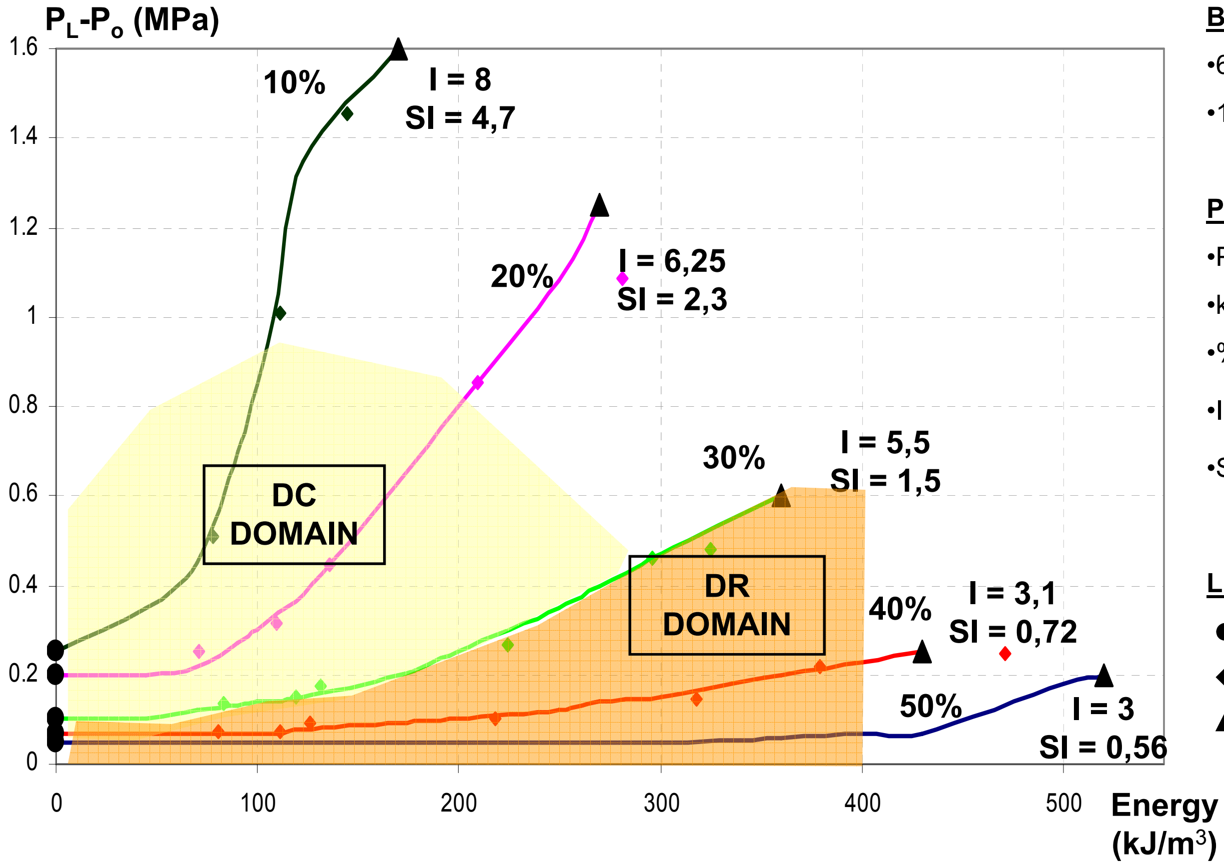


After DR – Between columns



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

KAUST – Saudi Arabia



BASIS

- 60 grainsize tests
- 180 PMT tests

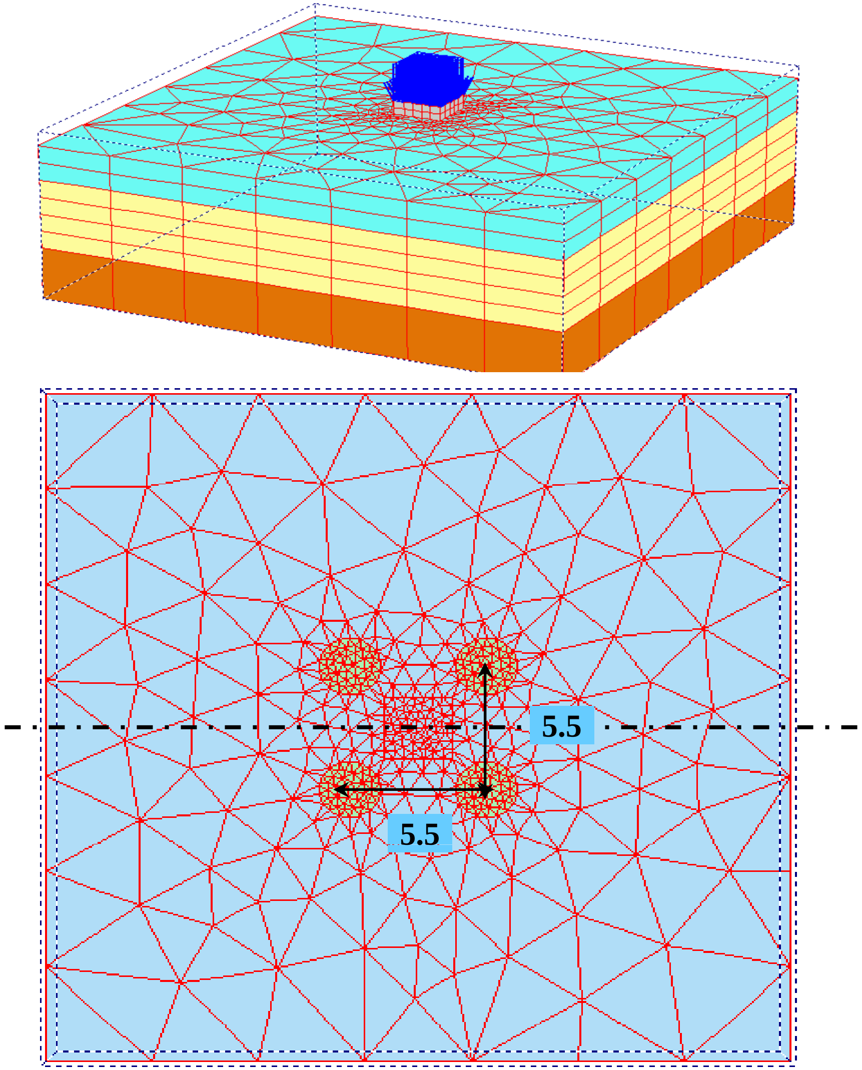
PARAMETERS

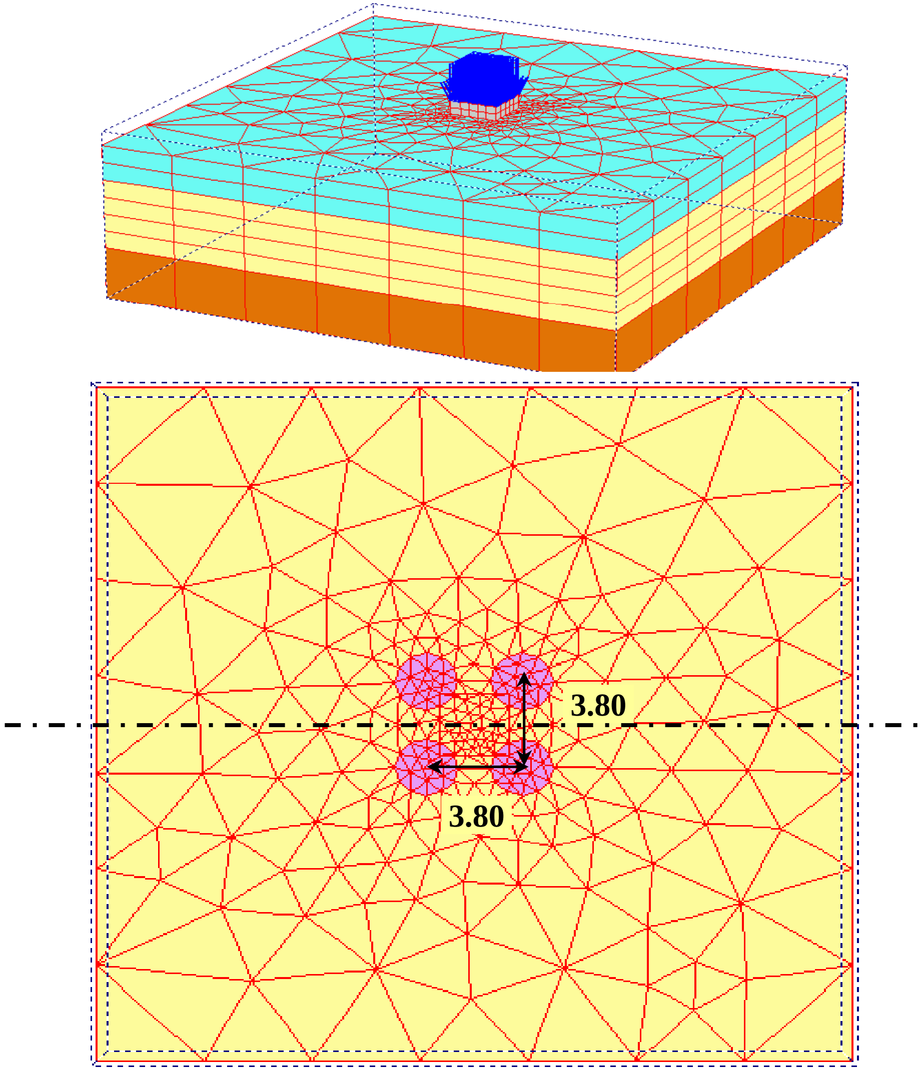
- $P_L - P_o$ = pressuremeter limit pressure
- kJ/m³ = Energy per m³ (E)
- % = % passing n°200 sieve
- I = improvement factor $\frac{P_{LF}}{P_{Li}}$
- S.I : energy specific improvement factor $\frac{I \times 100}{E}$

LEGEND

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

Analysis of Worst Case Scenario for Various Grids





A – Identify depth trend of SABKAH by CPT Tests

B – Closely eye witness 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

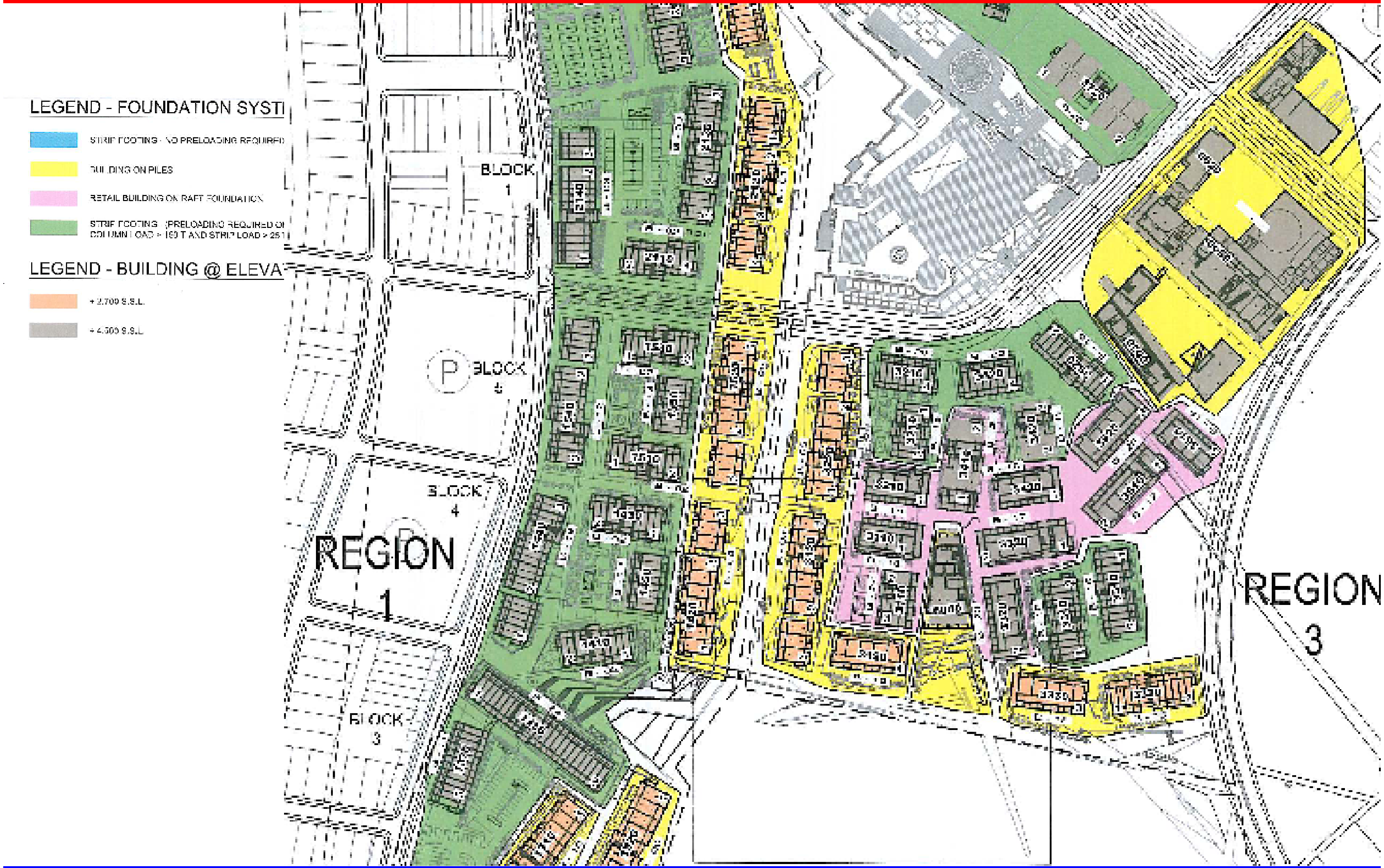
D – Verify by stress analysis that limit pressure at any depth exceeds factors of safety of at least 3 in order to safely utilize the settlement analysis (no creep)

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

PROVISIONNAL MASTER PLAN



It can be assumed that those impacts do generate a pore pressure at least equal to the pore pressure generated by the embankment 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 $du = U_1\Delta\sigma$,

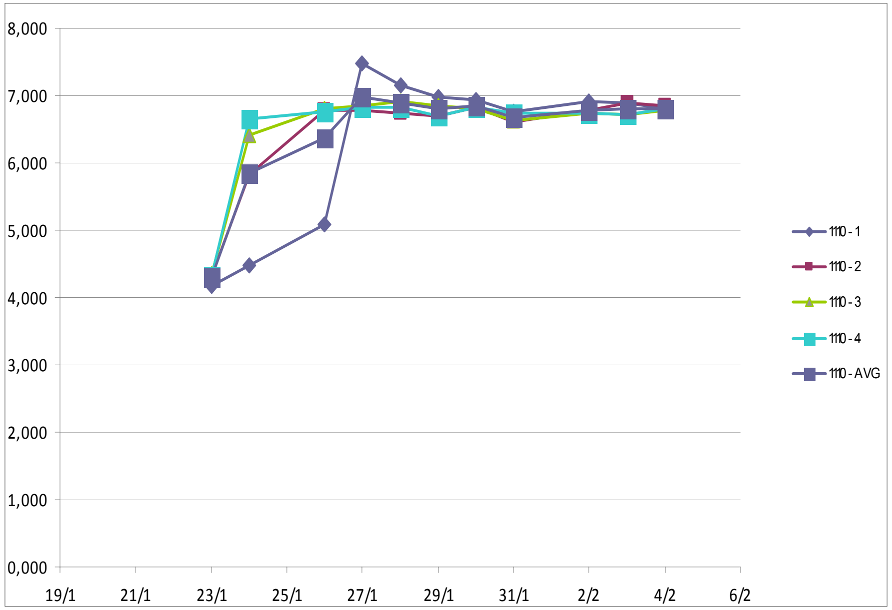
then $t'_f = U_1 t_1 + (1-U_1)t_f$

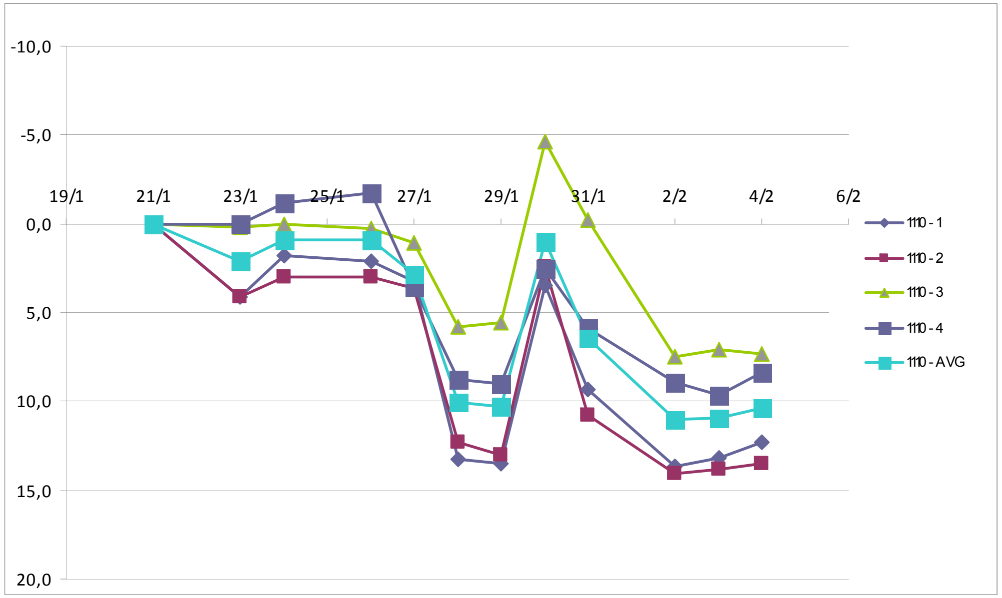
The optimal effectiveness occurs around $U_1 = 60\%$.

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

Dynamic surcharge

Settlement curves from dynamic surcharge





Thank You