AGSSEA

ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

DEEP COMPACTION

for Land Reclamation Projects

Ir. Kenny YEE

AGSSEA - ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

Part 1 of 6
THE NEED FOR COMPACTION

COMMON GROUND IMPROVEMENT METHODS

soft CLAY → loose SAND

CONSOLIDATION

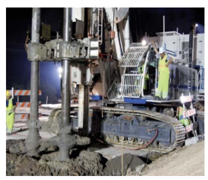
Vertical Drains

Vacuum Consolidation

REINFORCEMENT

Rigid Inclusions (cement grout etc.)

Displacement Cement Columns



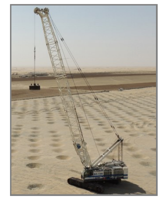
Deep Soil Mixing / Jet Grout Columns

Non-Rigid Inclusions (sand, stone, etc.)

Dynamic Replacement Columns

Vibro Replacement Columns

COMPACTION



Dynamic Compaction

Vibro Compaction

BASIC ENGINEERING CHARACTERISTICS OF SAND

- Particle size: **0.06mm** (fine) – **2mm** (coarse) ⇒ **coarse-grained soil.**
- Good **load-bearing** capacity (medium dense state ~ 100 – 300 kN/m^2).
- Good **drainage** quality (k ~ 10^{-3} to 10^{-5} m/s).
- **Strength** and **volume change** characteristics are not significantly affected by change in moisture conditions.
- Practically **incompressible** when dense.

video

Soil **Liquefaction** - ground failure or loss of strength that causes otherwise stable sandy soil to behave temporarily as a **viscous liquid**. It occurs in saturated loose sandy soil.

EARTHQUAKE (RICHTER SCALE 7.0) IN HAITI

Earthquake shock is the best known cause of liquefaction. Certain construction practices including **dynamic compaction** and **vibro compaction** produce this phenomenon **intentionally** but on a much smaller scale (**localised**).

POTENTIAL PROBLEMS OF LOOSE SATURATED SAND

- **Soil Liquefaction ▶ sudden instability** can occur when they are **loose** and **saturated** even without additional of load.
- **Self-bearing ▶** the state of the soil that it must have so as not to **settle** under its **own weight**.
  - Natural **unconsolidated** soil or a **new fill** – even very lightly loaded structures will undergo large **settlements**. Potential self-weight settlement for uncompacted sand is about **3.5%** of **fill thickness** (CIRIA SP78).
  - **Self-bearing condition** at a depth of less than 10m:

Loose saturated hydraulic sand fill in reclamation projects

Soil Type	PMT - P_L
Sand	600 kN/m^2
Sand & Gravel	800 kN/m^2

AGSSEA - ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

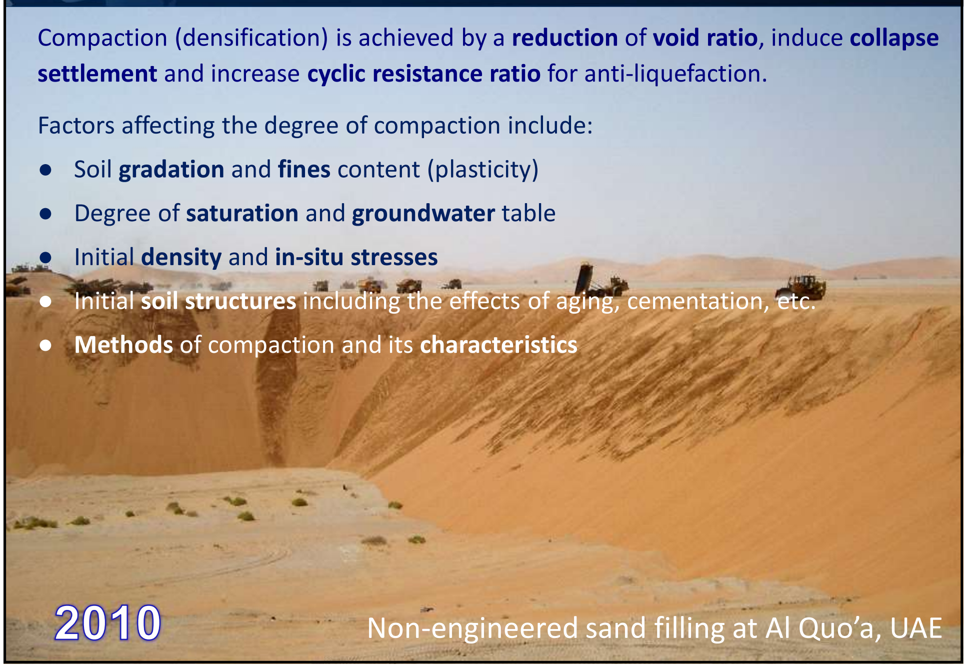
Part 2 of 6
COMPACTION TECHNIQUES

COMPACTION TECHNIQUES

Compaction (densification) is achieved by a **reduction** of **void ratio**, induce **collapse settlement** and increase **cyclic resistance ratio** for anti-liquefaction.

Factors affecting the degree of compaction include:

- Soil **gradation** and **fines** content (plasticity)
- Degree of **saturation** and **groundwater** table
- Initial **density** and **in-situ stresses**
- Initial **soil structures** including the effects of aging, cementation, etc.
- **Methods** of compaction and its **characteristics**



METHODS OF COMPACTION

Impact Roller Compaction (IRC) – moving at **8 to 12 km/h**

- Non-cylindrical multi-sided geometrical drum (3 to 5 sides)
- Compaction energy is derived by turning on their corners and falling to the flat sides – non-**motorised** form of energy unlike in a vibrating roller.

METHODS OF COMPACTION

Rapid Impact Compaction (RIC)

- hydraulic pile-driving hammer
- typical treatment depth ~ 3 – 5m

- Compaction energy is imparted by a falling tamper (**7** to **16 tons**) dropping from a controlled height (up to **1.2m**) onto a circular impact foot up to **1.6m** diameter.

- The frequency of impact is at a rate of **40 – 60** blows per min.
- Generally, **20 – 40** blows per compaction point.

METHODS OF COMPACTION

Dynamic Compaction (DC)

- typical treatment depth ~ 6 – 10m (30m)

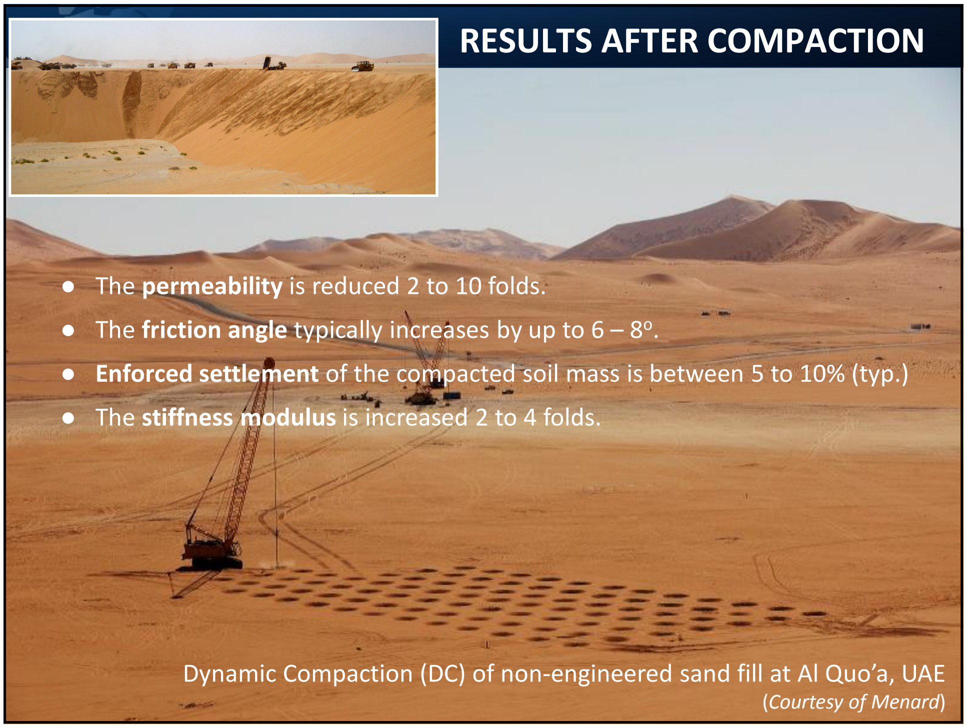
(Courtesy of Trevi)

METHODS OF COMPACTION

(*Courtesy of Keller*)

Vibro Compaction (VC)
typical treatment depth ~ 8 – 15m (50m)

RESULTS AFTER COMPACTION

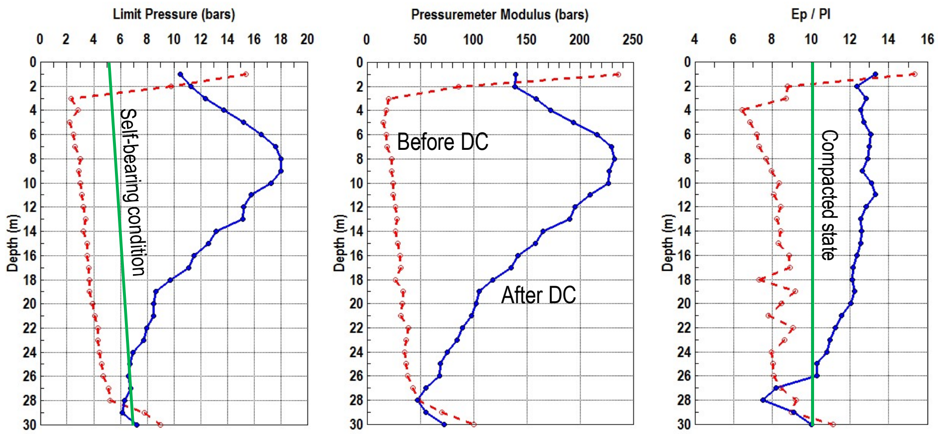


- The **permeability** is reduced 2 to 10 folds.
- The **friction angle** typically increases by up to 6 – 8°.
- **Enforced settlement** of the compacted soil mass is between 5 to 10% (typ.)
- The **stiffness modulus** is increased 2 to 4 folds.

Dynamic Compaction (DC) of non-engineered sand fill at Al Quo'a, UAE
(*Courtesy of Menard*)

PRESSUREMETER RESULTS AT AL QUO'A

Initial condition after 1 year of fill deposition (end-tipping) before any compaction



Before compaction:
$\delta_{SB\ creep}$ (t = 50 years) ~ 63 cm
(approx. 2.4% of thickness)

E_P = stiffness parameter (for settlement)

P_L = strength parameter (for bearing capacity)

AGSSEA - ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

Part 3 of 6

TYPICAL PERFORMANCE CRITERIA

RELATIVE DENSITY

Relative density (D_R): Traditionally, to show how well the **coarse-grained soil** (sand) is **compacted.**

Relative Density (D_R)	Description
0 – 15	Very loose
15 – 35	Loose
35 – 65	Medium dense
65 – 85	Dense
85 – 100	Very dense

An expression of the **void ratio** (e) relative to e_{max} and e_{min}:

$$D_R = \frac{e_{max} - e}{e_{max} - e_{min}} * 100\%$$

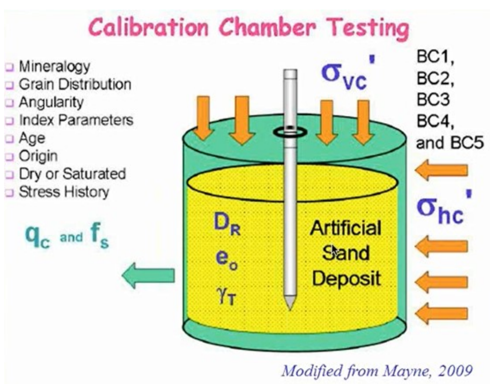
Where

- e_{max} and e_{min} = max. and min. void ratio (determined from laboratory tests; ASTM D4254) ⇒ **well-known problems** with the determination of e_{max} and e_{min}.
- e = in-situ void ratio (computed from the unit weight of the soil but accurate measurements of the unit weight of clean sand are **difficult** or **impossible**).

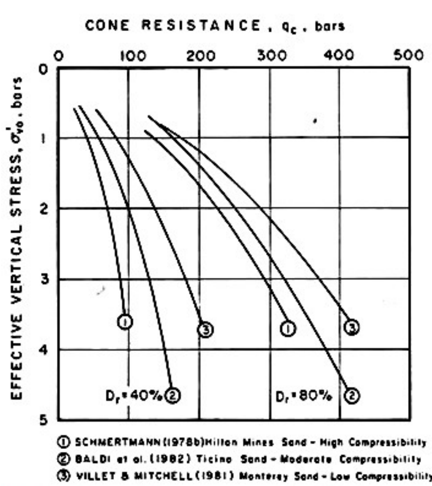
► Mostly, D_R from **correlationships** based on in-situ tests e.g. **CPT**

CALIBRATION CHAMBER TESTING

Most relationships between D_R and CPT are based on large **calibration chamber (CC) testing** – a controlled test environment to study link between CPT q_c and D_R.

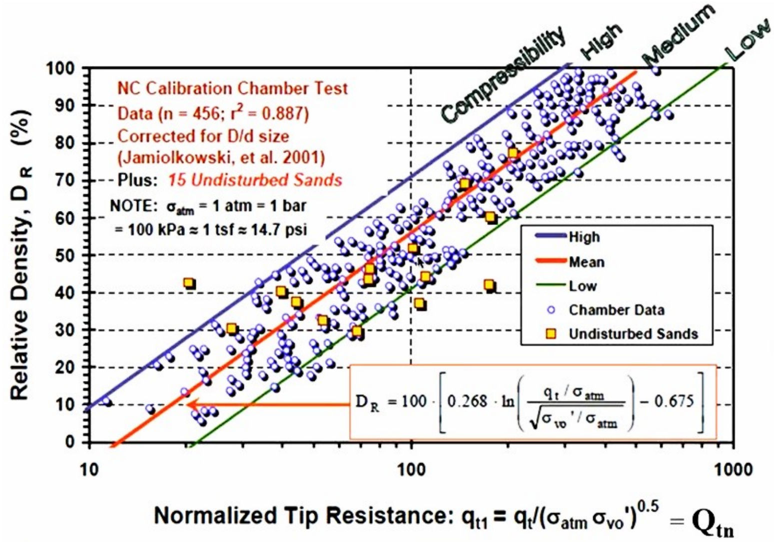


- Limited to **clean** and predominantly quartz sand (for uniform deposition)
- Samples are very **young** (days) – missing out the effect of aging.



RELATIVE DENSITY FROM CPT BASED ON CC TESTS

D_R against the log scale of normalised q_c is almost a linear relationship but still exhibit quite a wide spread of data.



$$D_R = 100 \cdot \left[0.268 \cdot \ln\left(\frac{q_t/\sigma_{atm}}{\sqrt{\sigma_{vo}'/\sigma_{atm}}} \right) - 0.675 \right]$$

Mayne (2009)

PERFORMANCE CRITERIA

Traditional practice:

- **D_R < 50%** – **Liquefaction** occurs principally in **saturated clean sands** and **silty sands**
- **$D_R \geq$ 70%** – The **lower limit** of relative density beyond which liquefaction will not occur ⇒ **dense sands**: with their tendency to **dilate** during cyclic shearing will generate **negative pore water pressure** and increase their resistance to shear stress.

Performance criteria for anti-liquefaction (FHWA, 1992 / 1997):

Description	Relative Density (D_R %)
Floor slabs, flat bottom tanks, embankments	Min. 60 – 65%
Column footings, bridge footings	Min. 70 – 75%
Machinery and mat foundations	Min. 75 – 80%

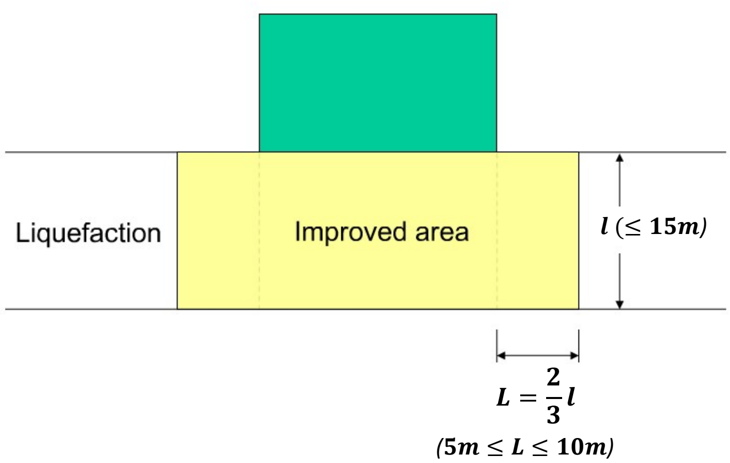
PROPOSED PERFORMANCE / ACCEPTANCE CRITERIA

Is relative density a suitable acceptance criteria for deep compaction (especially below water)? Perhaps, **not**.

- **Difficulties** in measuring density below water; and **uncertainties** associated with the determination of e_{min} and e_{max}.
- Correlations developed from CPT (based on CC testing) ⇒ **large spread** of data.
- **Strength** and **stiffness** not always well represented by D_R.
- Relative density is an **intermediate** parameter – CPT q_c is directly responding to the strength and stiffness ⇒ better to **estimate the friction angle, stiffness and liquefaction directly from CPT** results and not go through the intermediate step of relative density to estimate these parameters.
- Adopt performance or acceptance criteria based on "**Functional (Performance) Requirements**" – true requirements of allowable settlement (cm), required bearing capacity (kN/m^2), etc.; rather than on technical parameters specification (% D_R).

PROPOSED PERFORMANCE / ACCEPTANCE CRITERIA

Extent of Improvement



JGS (1998)

AGSSEA - ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

Part 4 of 6
DYNAMIC COMPACTION

DYNAMIC COMPACTION

An ancient art-of-practice; oldest form of ground improvement is the dropping of heavy weights on to the ground surface to compact soils at depth by **impacts.**

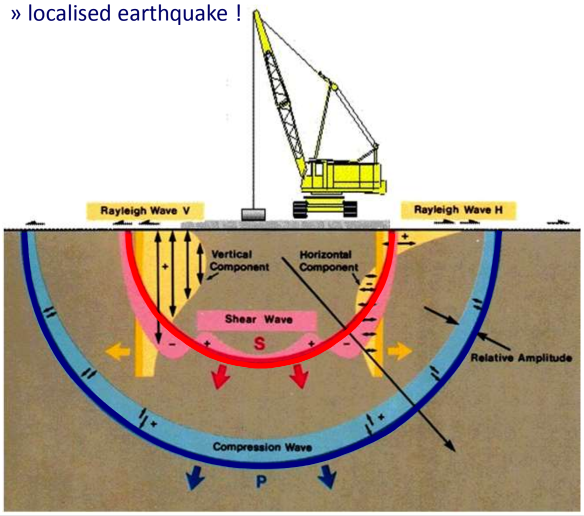
video

Dynamic compaction
Dynamic consolidation
Heavy Tamping

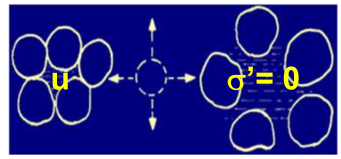
video

MECHANISM OF DYNAMIC COMPACTION

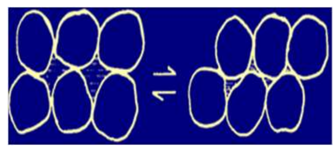
At a radius of 15m from point of impact using 15 ton weight drops from 20m:
PGA vertical **0.25 – 0.3g**
PGA horizontal **0.15g**
» localised earthquake !



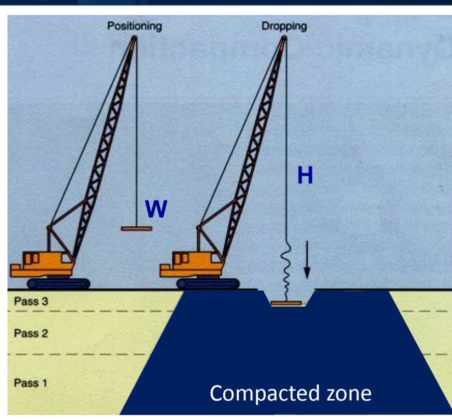
Compression **P-Wave**:
- Increase **pore pressure**
- **Dislocate** soil matrix

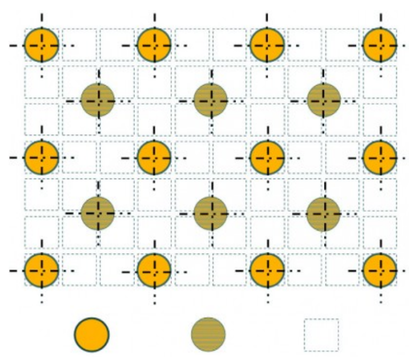


Shear **S-Wave** and
Surface Rayleigh **R-Wave**:
- **Shear** soil particles
- **Re-arrangement** of soil matrix (denser configuration)



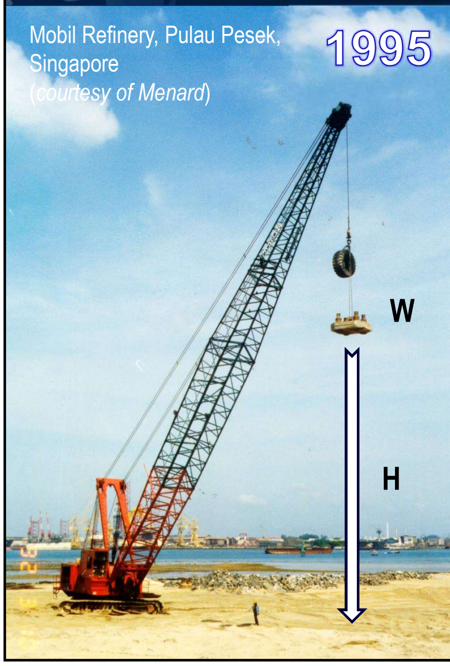
COMPACTION PROCEDURE





Typical DC Process:
- Weights (W) of 10 – 30 tons
- Drop heights (H) of 10 – 25 m
- Spacing ~ 4 – 8m
- 5 – 15 drops per compaction point
- Starts with highest compaction energy and finishes with lowest energy

COMPACTION ENERGY



Compaction energy (E_{comp}) determines:

- the **depth of compaction**
- the **degree of compaction**

Depth of Compaction (D):

$$D = n.\beta.\sqrt{W.H}$$

where

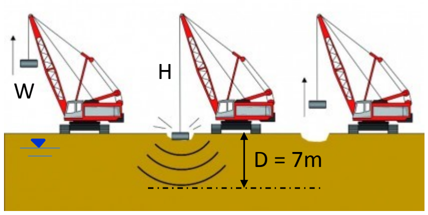
n = function of grain size, degree of saturation, GWT, etc. (= 0.4 to 1.0)

β = efficiency of DC rig (double-hydraulic winch = 0.5; single hydraulic winch = 0.64; mechanical winch = 0.75; rig-drop = 0.89 and free-fall = 1)

W = weight of pounder (tons)

H = height of drop (m)

COMPACTION ENERGY - EXAMPLE



Objective: To compact 7m of clean sand (k > 10^{-5} m/s) to achieve CPT q_c = 12 MPa (initial q_c = 3.5 MPa) with GWT at 2m below surface.

1) Determine the **depth of compaction**

$$D = n.\beta.\sqrt{W.H}$$

where

n = 0.7 for medium clean sand

β = 0.75 for mechanical winch

W = 15 tons

H = 20m

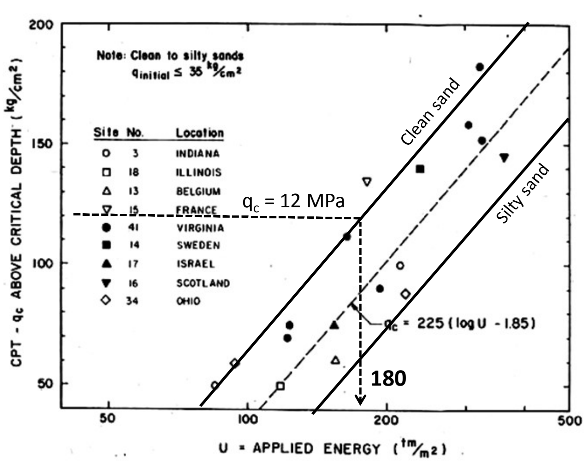
$$D = (0.7).(0.75).\sqrt{(300)} \sim 9m$$

COMPACTION ENERGY - EXAMPLE

2) Determine the required applied energy for **pervious clean sand** (k > 10^{-5} m/s):
   - ⇒ From table: typical applied energy for sand ~ 20 – 25 ton.m/m³ (▶ select 25 ton.m/m³)
   - ⇒ Applied energy per m²
     = 25 ton.m/m³ * 7m (comp. depth)
     = 175 ton.m/m²

Type of Soil	Applied Energy (typical/normal)	Improvement Expected
Pervious coarse grained soil (k > 10^{-5} m/s)	20 – 25 ton.m/m³	Excellent
Semi-pervious fine grained soil	25 – 35 ton.m/m³	Moderate to good
Impervious fine-grained soil (k < 10^{-8} m/s)	Not applicable	Not applicable
Landfills	60 – 110 ton.m/m³	Excellent

COMPACTION ENERGY



3) From graph above, required applied energy to **achieve q_c = 12 MPa** from 3.5 MPa
   - ⇒ For clean sand: typical applied energy ~ 180 ton.m/m² (175 ton.m/m² from previous calculation based on clean sand)
   - ▶ select 180 ton.m/m²

COMPACTION ENERGY

4) Determine the required **compaction pattern**

⇒ Select 2 main phases + 1 ironing phase

⇒ Ironing phase using H = 10m; W = 15 tons; and 2 blows per point at a grid of 2m x 2m
= 10m x 15 tons x 2 blows / 4m^2
= 75 ton.m/m^2

⇒ Main phases using H = 20m; W = 15 tons at a grid of 7m x 7m (= D)

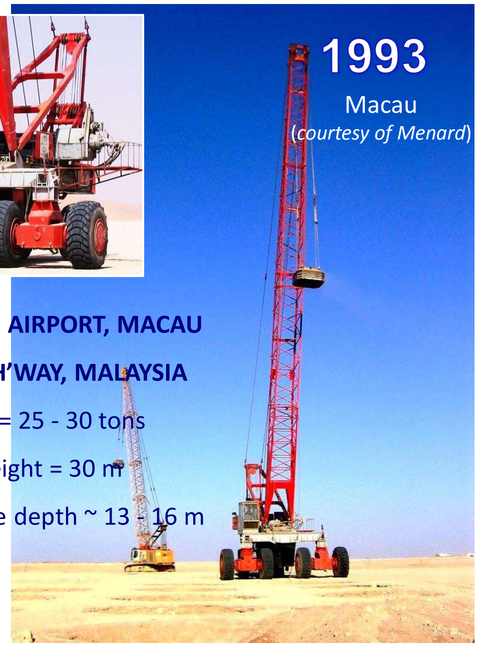
- Applied energy = 180 – 75 ton.m/m^2 (less ironing phase) = 105 ton.m/m^2
- Total energy = 105 ton.m/m^2 * (7 x 7) m^2 = 5,145 ton.m
- Nos. of blows = 5,145/(15ton x 20m) ~ 17 blows for main phases.

	Using 15 tons pounder
Phase 1	10 blows of 20m at 7m grid
Phase 2	7 blows of 20m at 7m grid
Ironing phase	2 blows of 10m at 2m grid

► Validate by field trial

STANDARD DC RIG : 300 – 500 ton.m

HECTO DC RIG : 750 – 900 ton.m



MACAU AIRPORT, MACAU

KESAS H'WAY, MALAYSIA

Weight = 25 - 30 tons

Drop height = 30 m

Effective depth ~ 13 - 16 m

TRIPOD DC MACHINE : 1,600 ton.m

CHANGI AIRPORT, SINGAPORE

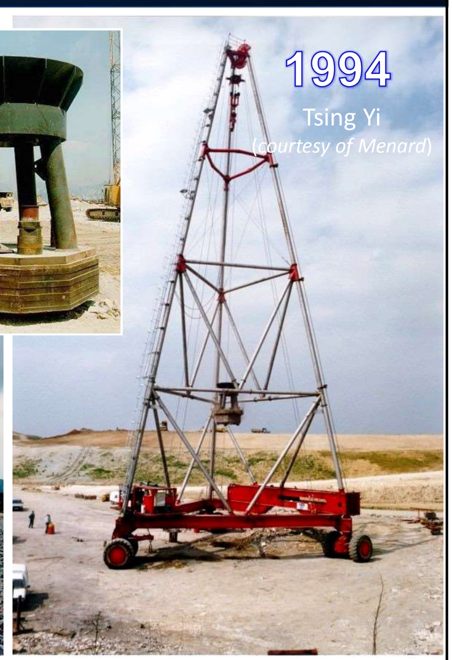
KANSAI AIRPORT, JAPAN

TSING YI OIL TERMINAL, HK

Weight = 40 tons

Drop height = 40 m

Effective depth ~ 20 - 25 m



GIGA DC MACHINE : 4,800 ton.m

NICE AIRPORT, FRANCE (1976)

Weight = 200 tons

Drop height = 24 m

Effective depth ~ 25 - 30 m

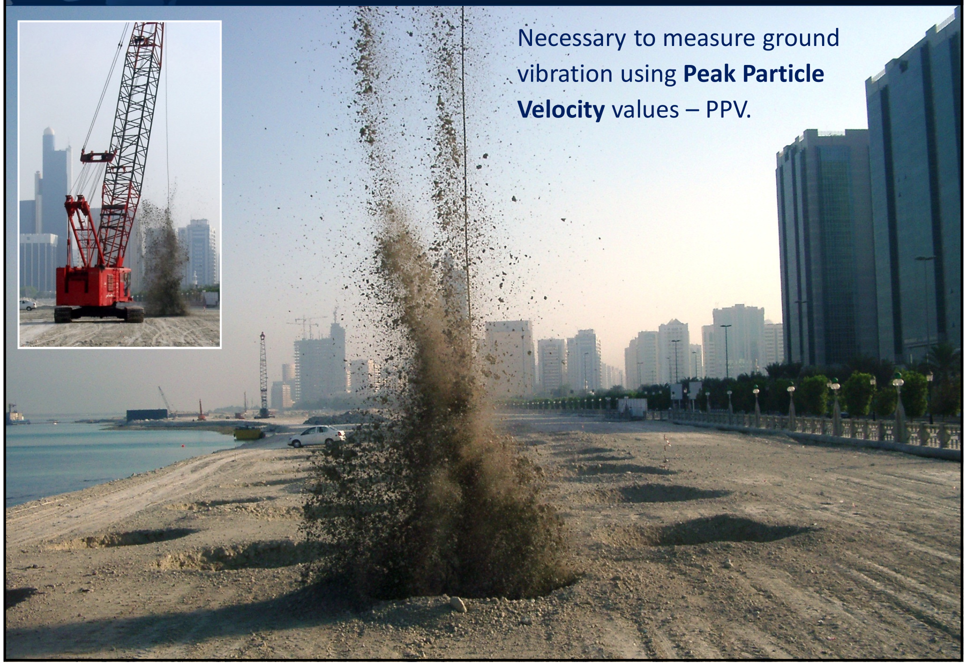
NICE AIRPORT, FRANCE (1976)

video

NICE AIRPORT
200 tons pounder over 24m drop height (capacity 4,800 ton.m) to compact 30m.

SURFACE VIBRATION DUE TO IMPACTS

Necessary to measure ground vibration using **Peak Particle Velocity** values – PPV.



PPV MEASUREMENTS

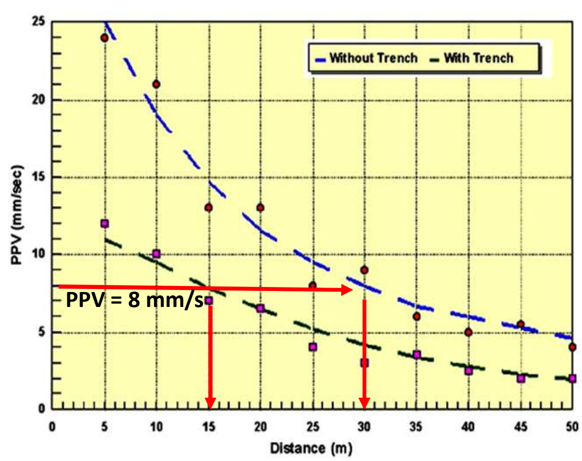
TYPICAL SAFE PPV & DISTANCE

PPV	Structural Effects
PPV ≤ 4 mm/s	No damage
4 mm/s < PPV ≤ 8 mm/s	Damage can occur to sensitive or previously fissured structures
PPV > 8 mm/s	Damage to ordinary structures
PPV > 30 mm/s	Damage to highly rigid structures

Description	Approximate Safe Distance
Rigid structures	20 m
Normal buildings in good condition	30 m
Sensitive structures	50 m

SURFACE TRENCHING

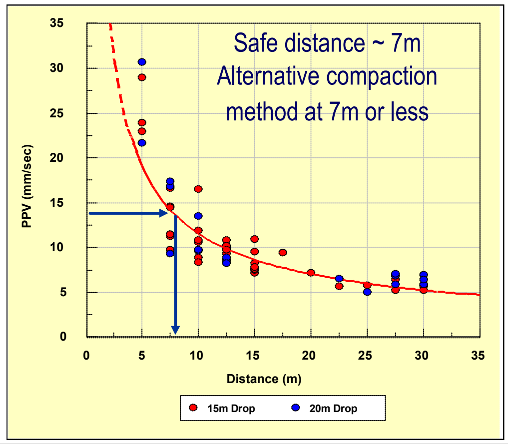
- DC impacts cause surface vibration due to **R-wave**.
- Need to intercept or cut-off surface R-wave by surface **open trenches.**
- Measure **PPV** before & after trenching.



PPV MEASUREMENTS ON SITE

Ipoh-Rawang Double Tracking (Malaysia):

- Due to cost and speed, DC was required to treat as close to the service line as possible.
- Surface vibration $PPV_{DC} < PPV_{TRAIN}$ (= 14 mm/s)



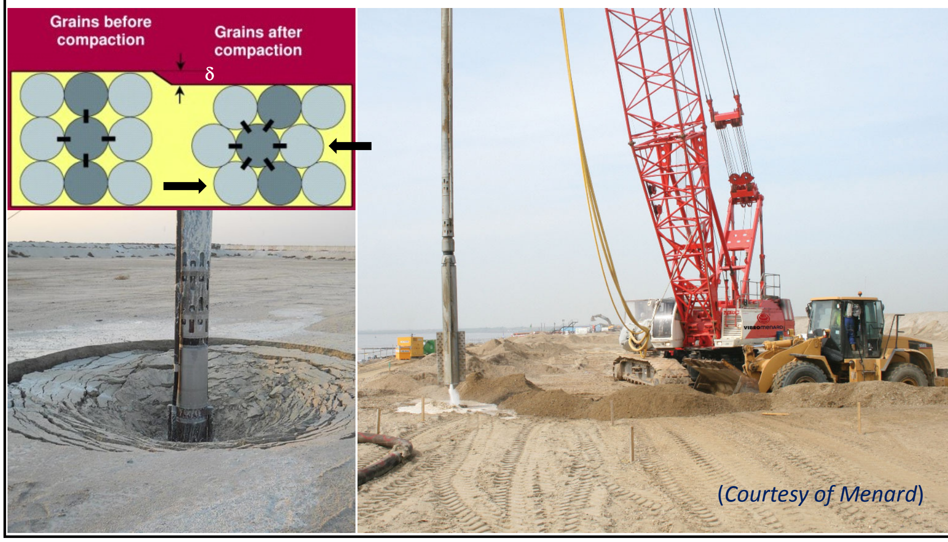
AGSSEA - ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

Part 5 of 6
VIBRO COMPACTION

VIBRO COMPACTION

A process of re-arrangement of soil particles by **shearing** into a denser configuration by **horizontal vibration** using a **vibroflot.**

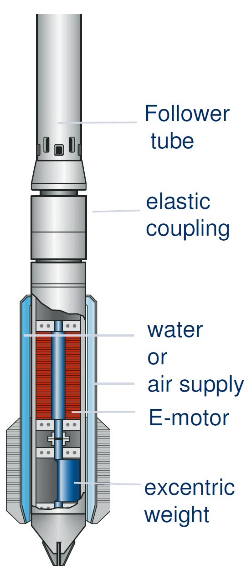
Vibro Compaction
Vibroflotation



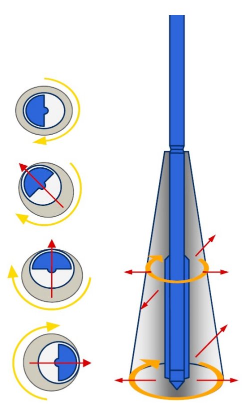
(*Courtesy of Menard*)

THE VIBROFLOT

- Electrical or hydraulic vibroflots

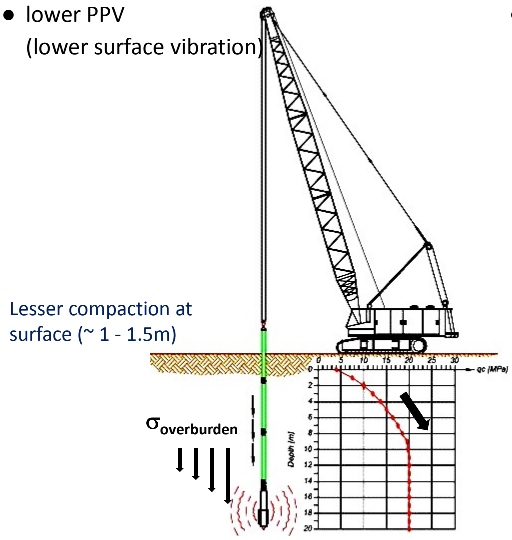


- Frequency ~ 30 - 60 Hz (vibro-compaction: low frequency (30 Hz) with high amplitude / vibro-replacement: high frequency (50 – 60 Hz) with low amplitude)
- Amplitude ~ 8 - 48mm
- Eccentric force: 20 - 47 tons

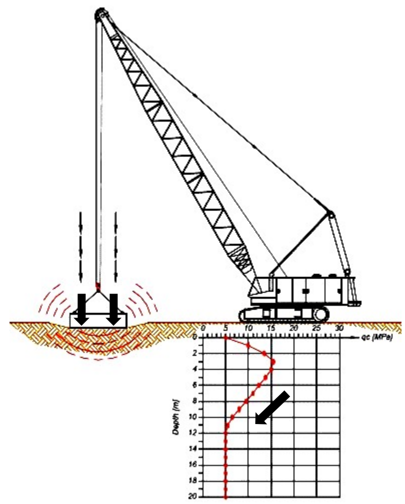


VIBRO COMPACTION / DYNAMIC COMPACTION

- compaction by **lateral vibration force** at depth (higher efficiency at deeper layer – **overburden pressure**)
- lower PPV (lower surface vibration)



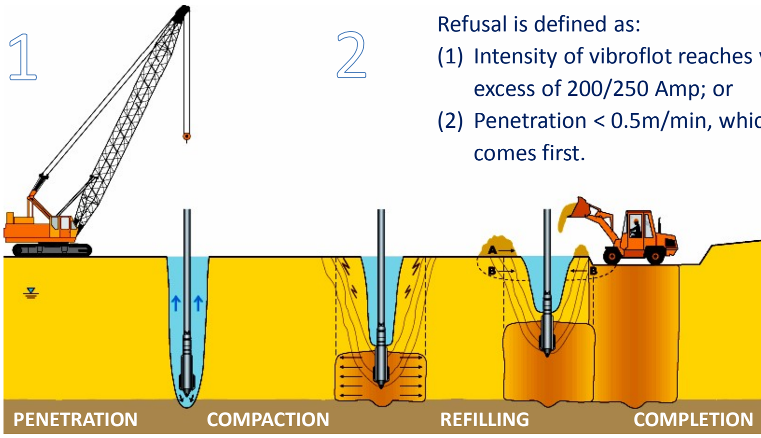
- compaction by **surface impact force** (higher efficiency at shallower layer – **dissipation of energy** with depth)
- higher PPV (higher surface vibration)



COMPACTION PROCESS

video

COMPACTION PROCEDURE



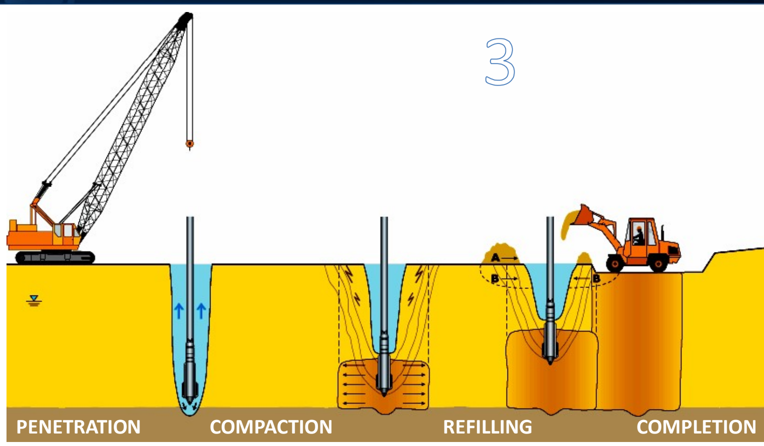
Refusal is defined as:

(1) Intensity of vibroflot reaches values in excess of 200/250 Amp; or
(2) Penetration < 0.5m/min, whichever comes first.

Step 1: At full water/air pressure, the vibroflot penetrates to design depth and is surged up and down as necessary to agitate sand, remove fines and form an annular gap around the vibroflot. The water flow is then reduced at the nose jet.

Step 2: Under the action of induced horizontal forces, the soil particles surrounding the base of the vibroflot are re-arranged to a denser state of compaction. The vibroflot is raised incrementally at 0.5m steps with side jets turned on as compaction is achieved.

COMPACTION PROCEDURE



Step 3: During compaction either imported (A) or in-situ (B) material is introduced. If insitu material is used, the surface of the area being compacted may be lowered by 5 to 10% (typ.) of the treated depth.

Step 4: The surface of the improvement area is then relevelled and densified with a surface roller compactor.

COMPACTION PROCEDURE

Horizontal vibration provides the necessary **shearing** of particles into a denser configuration. **Water** (and **compressed air**) is used to reduce **frictional forces** between soil particles. Source of water is required.

COMPACTION EFFICIENCY

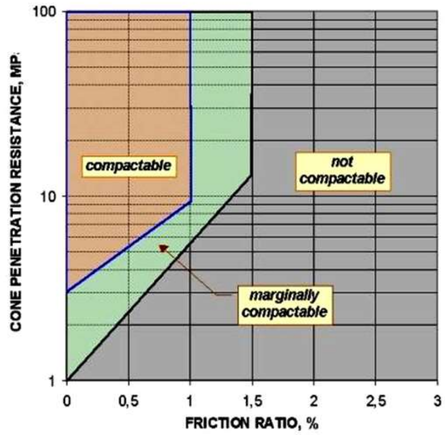
Factors influencing the compaction effort and the attained results:

- Vibroflot amplitude, frequency, power and dynamic (centrifugal) force.
- Compaction spacing, pattern and vibroflot withdrawal technique.
- Backfill material
- In-situ soil (gradation; plasticity)

Central Reclamation Phase 3 (*Courtesy of Bachy Soletanche*)

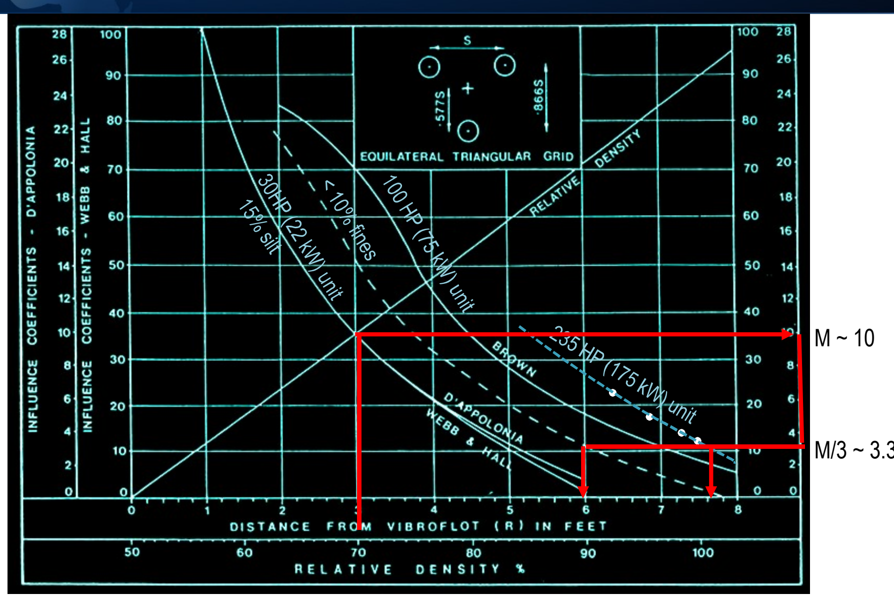
SUITABLE SOILS FOR VIBRO COMPACTION

Soil Type	Effectiveness	Remarks
Sand with < 5% fines	Excellent	Seek expert advice when grain size curve is very steep; high carbonate and/or mica content.
Sand with < 10% fines	Good	Success depends on clay content (< 2 – 3%), grain shape, grain size curve, water table, etc.
Sand with > 10% fines	Poor to marginal	



Based on CPT results
(**Massarsch, 1991**)

CHART FOR COMPACTION SPACING



D_R = 70%; fine < 10% $\Rightarrow$ 0.577S = 7.6ft / S = 13.2ft (4m ▲ grid using 175 kW unit)
or 0.577S = 6ft / S = 10.4ft (3.2m ▲ grid using 75 kW unit)

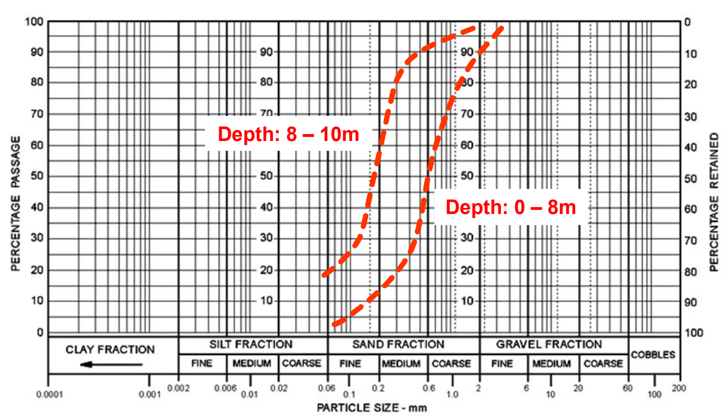
AGSSEA - ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

Part 6 of 6
A CASE HISTORY

COMPACTION OF HYDRAULIC SAND FILL

To compact approx. 8 – 9m thick hydraulic sand fill

- 0 – 8m: fine to coarse sand with **3 – 7% fines** (occasionally up to 14% fines).
- 8 – 9/10m: marginal dirty coarse sand with **17 – 20% fines**
- > 9/10m: silt and clay



COMPACTION CRITERIA

Performance criteria for compaction:

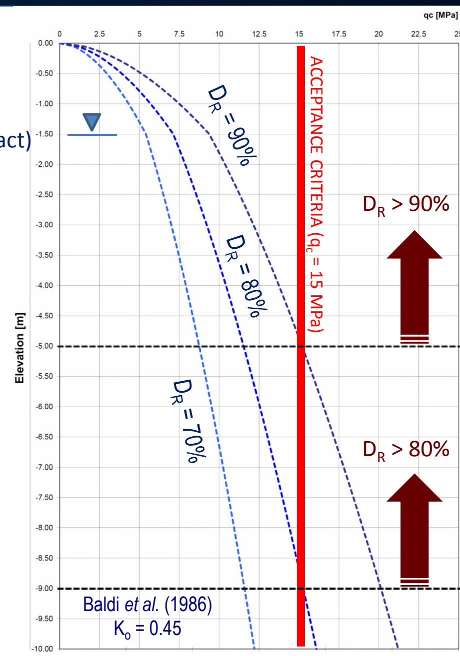
CPT: q_c = 15 MPa (straight-line)

(1st time appearing in a deep compaction contract)

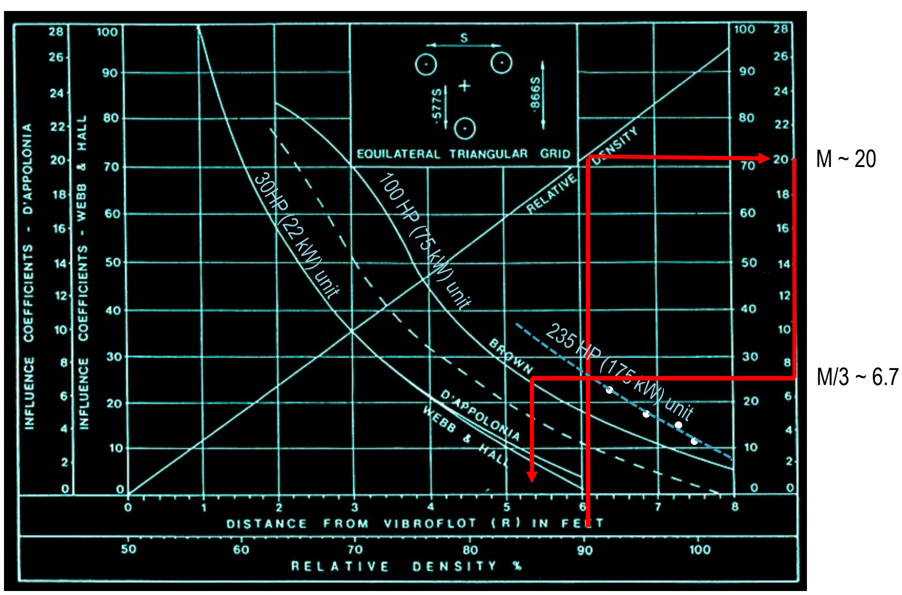
Superimposed Baldi (1986) D_R curves:

0 – 5m depth : D_R > 90 %

5 – 9m depth : D_R ~ 80 – 90 %

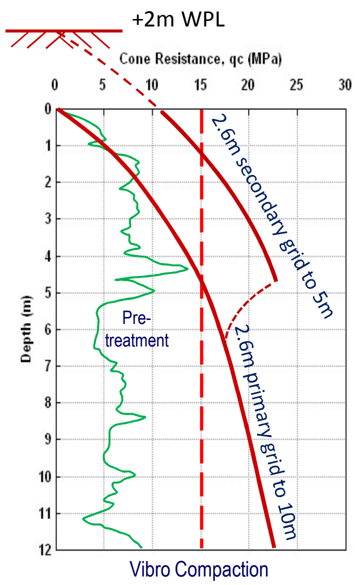


FIELD TRIAL 1 : VIBRO COMPACTION



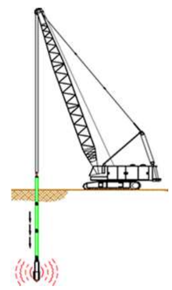
D_R = 90%: 0.577S = 5.4 ft / S = 9.3 ft (2.8m ▲ or 2.6m ■ grid ⇒ 6.8m² per point)

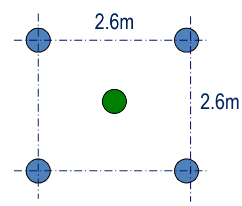
FIELD TRIAL 1 : VIBRO COMPACTION



Using a hydraulic vibroflot of 130 kW:

- Compaction grid of 2.6 m ■ down to 10m (primary grid for D_R = 80 - 90% from 5 - 10m)
- Mid point down to 5m depth (secondary grid for D_R > 90% from 0 – 5m).

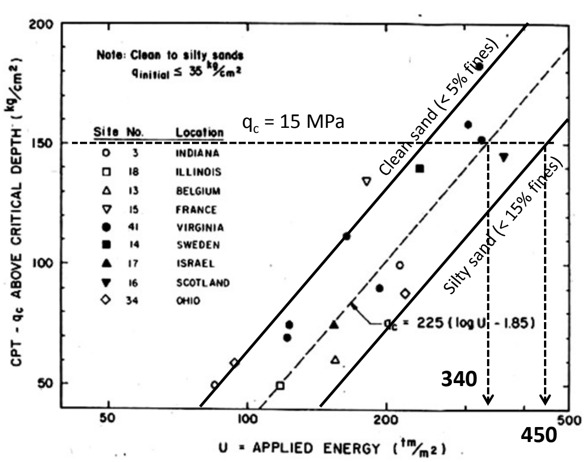




- Dual grid with 2m overburden fill.
- Production: 3,500 m²/mth per rig on single shift.

FIELD TRIAL 2 : DYNAMIC COMPACTION

Note: 0 – 8m: fine to coarse sand with **3 – 7% fines** and occasionally up to **14% fines**



1) $D = n.\beta.\sqrt{W.H}$

where

n = 0.7

β = 0.75 for mechanical winch

W = 18 tons

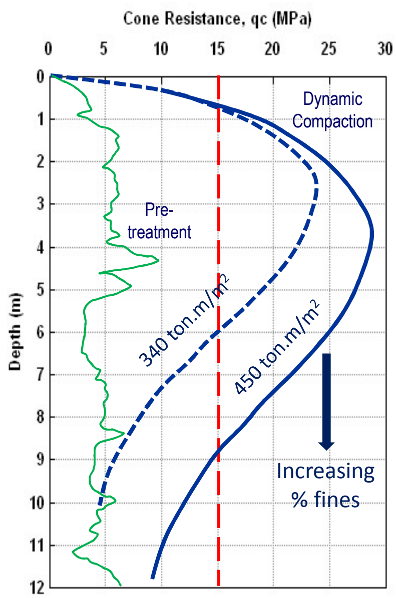
H = 22m

▶ D = 10.5m

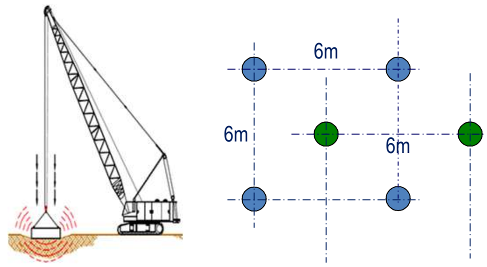
2) For q_c = 15 MPa:

$\Rightarrow$ **U ~ 340 ton.m/m²** (< 10% fines; 0 – 5m) to **450 ton.m/m²** (> 10% fines; 5 – 10m).

FIELD TRIAL 2 : DYNAMIC COMPACTION

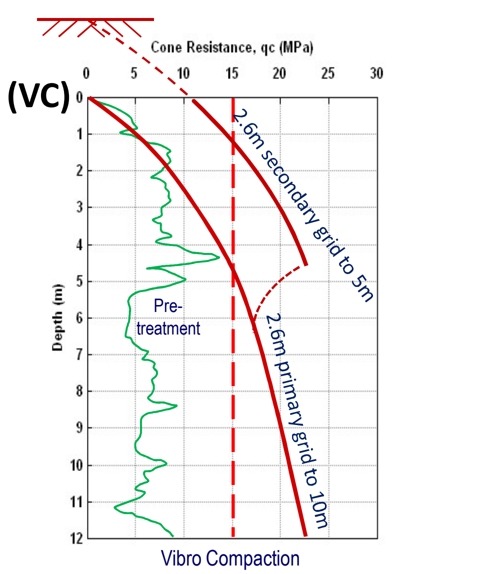


- High compaction energy using 18 tons x 22 m drop height x 16 blows over 2 main phases with total DC energy of about 450 ton.m/m² incl. ironing phase.

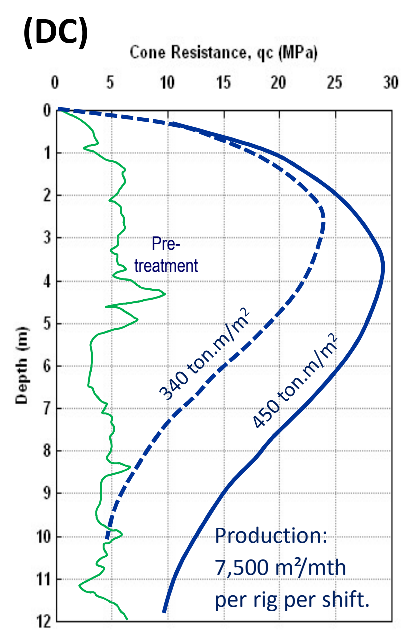


- Production: 7,500 m²/mth per rig per shift.

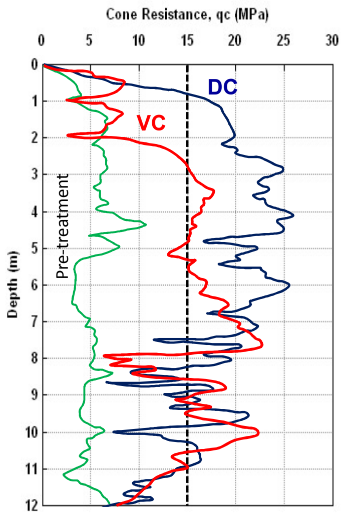
WHICH METHOD TO USE – VC OR DC ?



Production: 3,500 m²/mth per rig on single shift.



POST TREATMENT RESULTS



Enforced settlement:
After VC – 47cm (av. q_c = 18 MPa)
After DC – additional 27cm (av. q_c = 25 MPa)
Total – 74cm (9.2% volumetric strain)

Vibration monitoring (PPV):
Phase 1: 4.4 mm/s at 40m distance
1.4 mm/s at 60m distance
Phase 2: 6.1 mm/s at 40m distance
1.7 mm/s at 60m distance

From 8 – 9m : effectiveness of compaction reduced due to high percentage of silt/clay (17 - 20%).

Completed 90,000m^2 in 4 months after 4 months of in-situ CPT, field trials and "arguments".

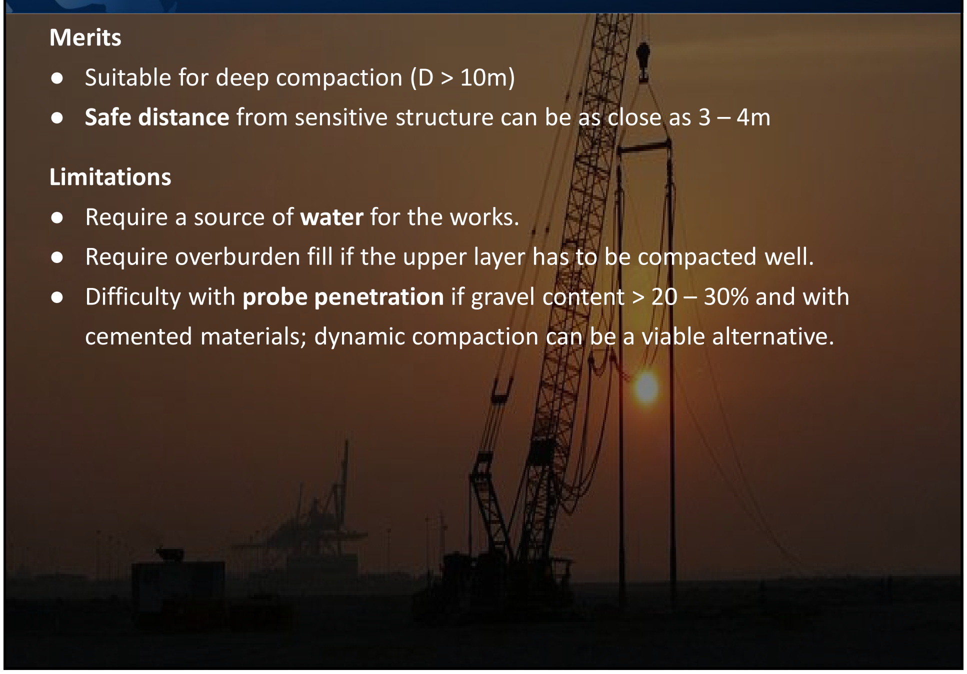
AGSSEA - ASSOCIATION OF GEOTECHNICAL SOCIETIES IN SOUTHEAST ASIA

CONCLUSIONS

CONCLUSION ON COMPACTION METHODS

- Compaction is **quick** and **cost effective** provided the **soil permeability** is sufficiently high (fine content < 10%; clay < 2 – 3%) to allow rapid **dissipation of excess pore water pressure** generated during compaction process.
- Compaction **field trials** are necessary to validate operation parameters and performance (acceptance) criteria before commencement of full production works. **QA/QC**, **compaction records** and **pre and post compaction in-situ tests** (e.g. PMT, CPT, etc.) are important part of the works.
- **Friction angle** of the soil must be initially high enough to permit the passage of the compaction shear waves. This requirement is usually satisfied if the soil is well-graded (uniformly graded soil is difficult to compact).
  $\Rightarrow$ some specify min. 30^{o} at void ratio corresponding to a D_R of min. 35%.
- "Dirty" granular soil is not effectively **compactable**. Consider other methods of ground improvement using **REINFORCEMENT** (dynamic replacement instead of DC; vibro replacement instead of VC or others).
- DC and VC have their own **merits**, **limitations** and **economy**.

MERITS AND LIMITATIONS OF VIBRO COMPACTION



Merits

- Suitable for deep compaction (D > 10m)
- **Safe distance** from sensitive structure can be as close as 3 – 4m

Limitations

- Require a source of **water** for the works.
- Require overburden fill if the upper layer has to be compacted well.
- Difficulty with **probe penetration** if gravel content > 20 – 30% and with cemented materials; dynamic compaction can be a viable alternative.

MERITS AND LIMITATIONS OF DYNAMIC COMPACTION

Merits

- **Cost effective** for larger treatment area (> 50,000m^2) – **simple** process and high **production** rate (10,000m^2/mth per rig).
- Economic treatment depth ($D \leq 5 – 7$m).
- **Non-saturated collapsible soil** / **non-engineered** fill: Dynamic compaction is suited to collapse the soil matrix where fines content and soil permeability is not an issue. Only **collapse of voids** and **expulsion of gas** upon repeated impacts.

Limitations

- Excessive **surface vibration** due to heavy impacts; **safe distance** (> 30m).
- Deep compaction (> 10m) may not be economical; vibro compaction can be a viable alternative.