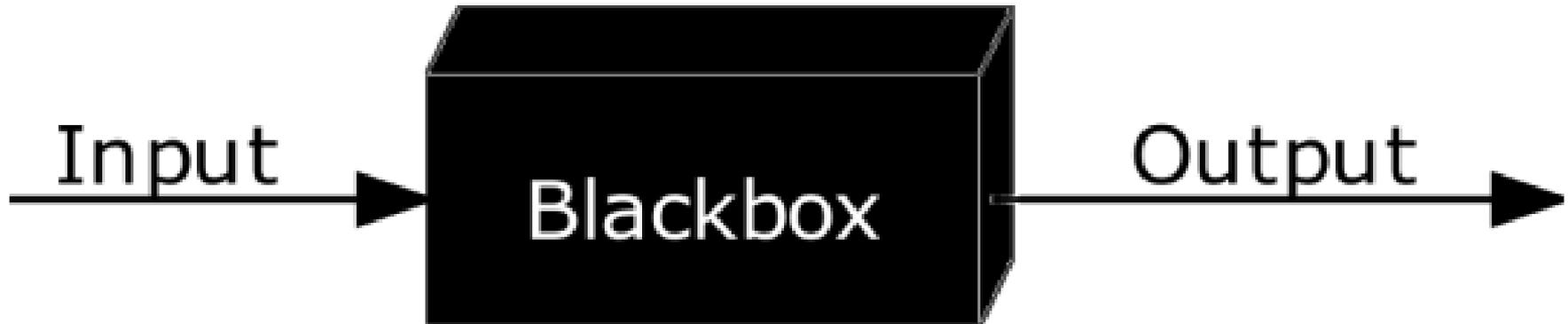
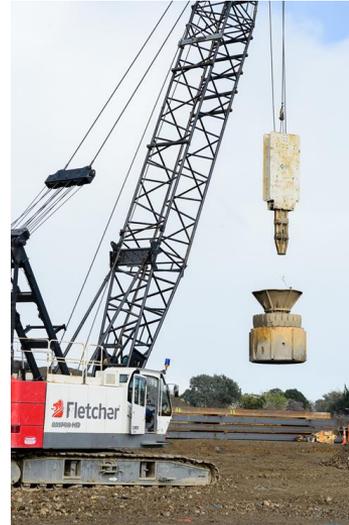


Ground Improvement Techniques: Dynamic Compaction

—
Martin Larisch & Tim Pervan

Ground Improvement - What is it?

Ground Improvement = Black Box?



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Ground Improvement - Introduction

Ground Improvement

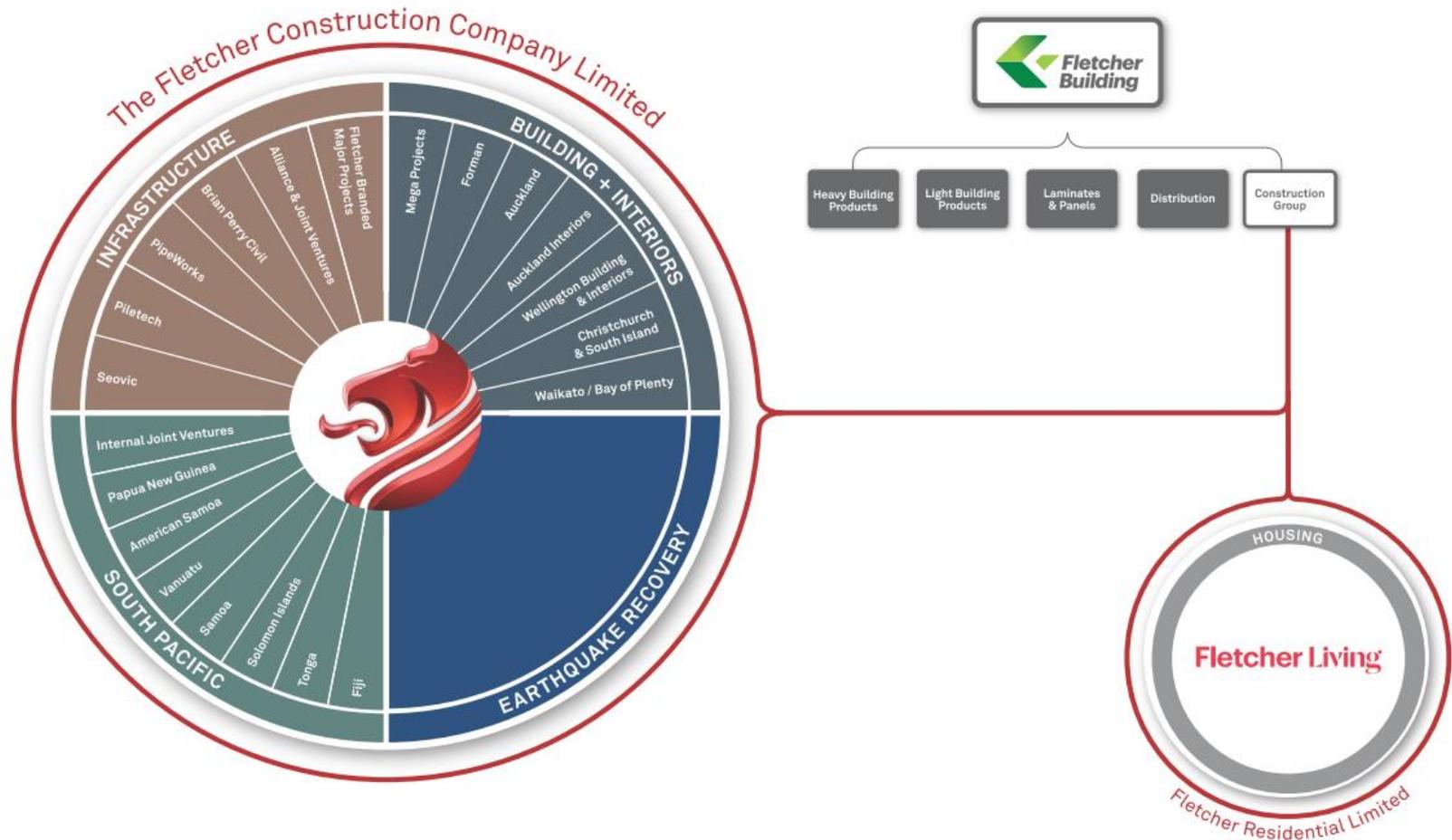
Improve the existing soil formation by changing the soil properties by mechanical or chemical treatment.

Ground improvement doesn't create structural elements (like piles) to 'bridge' unsuitable soil layers but it improves the ground itself to allow for shallow foundations.

Ground improvement is mainly used for:

- Settlement reduction / control
- Liquefaction mitigation

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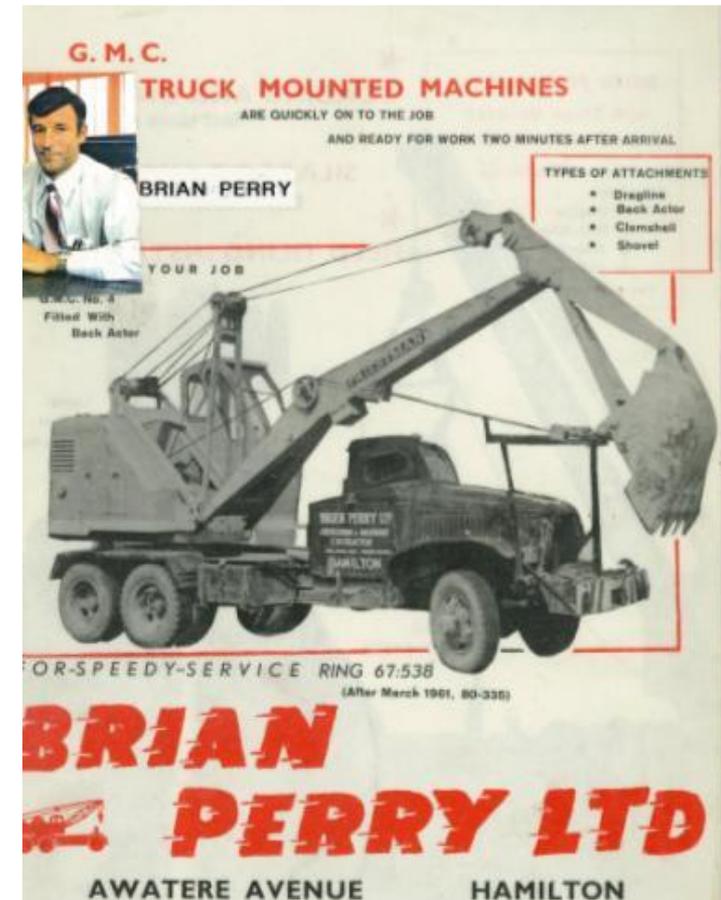
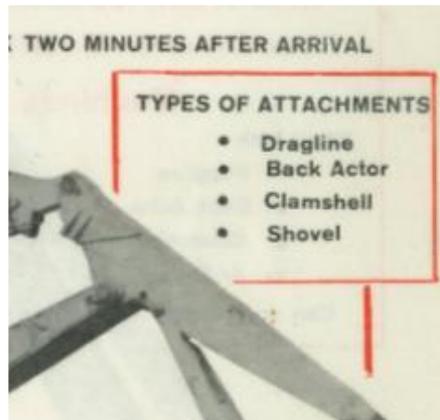
Brian Perry Civil

Established in 1954
in Hamilton

Head office today
in Auckland (Penrose).

Branches in:

- Hamilton
- Auckland
- Christchurch
- Wellington



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Brian Perry Civil

Four branches around New Zealand

- 350 employees (80 engineers)
- Turnover \$230m

Our Focus

- Self performing, high-risk civil engineering contracting
- Projects up to \$50m
- Smart use of technology
- Drive innovation and strong client focus



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BRIAN
PERRY
CIVIL

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Areas of Expertise

Foundations



Infrastructure



Environment



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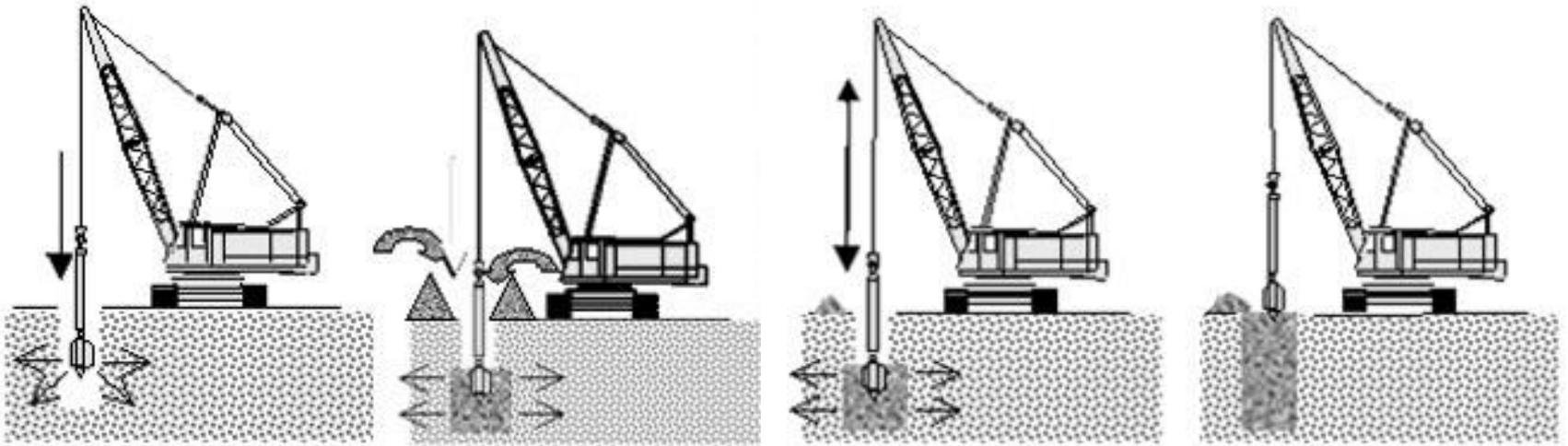
Ground Improvement - Methods

Overview of some ground improvement methods:

- Vibro compaction
- Vibro replacement
- Soil mixing
 - Jet grouting
 - Deep soil mixing (vertical)
 - Deep soil mixing (horizontal / block)
- Rigid Inclusions
- Dynamic replacement
- Dynamic compaction

Vibro Compaction (VC) - Introduction

Vibro compaction (VC) is a cost effective GI method which allows to specifically target deeper treatment areas.



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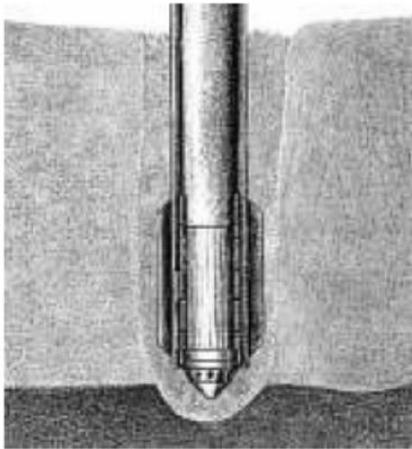
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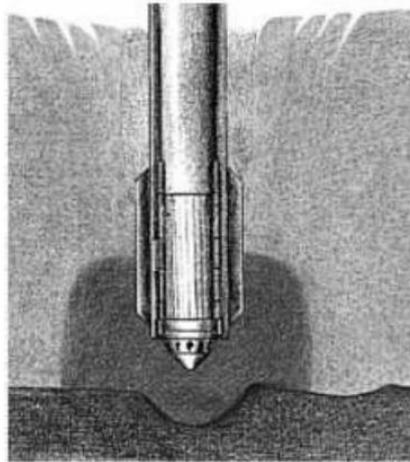
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Vibro compaction (VC) - Introduction

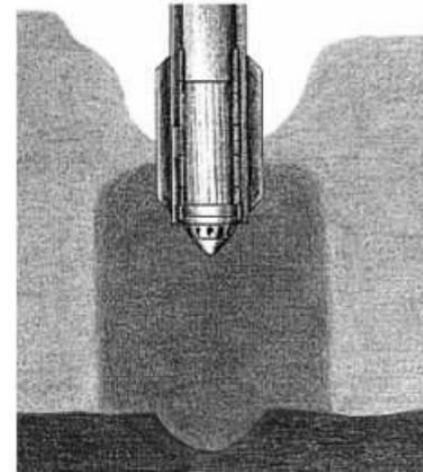
Vibro compaction



Penetrate with full air and /or water down facing nose jets

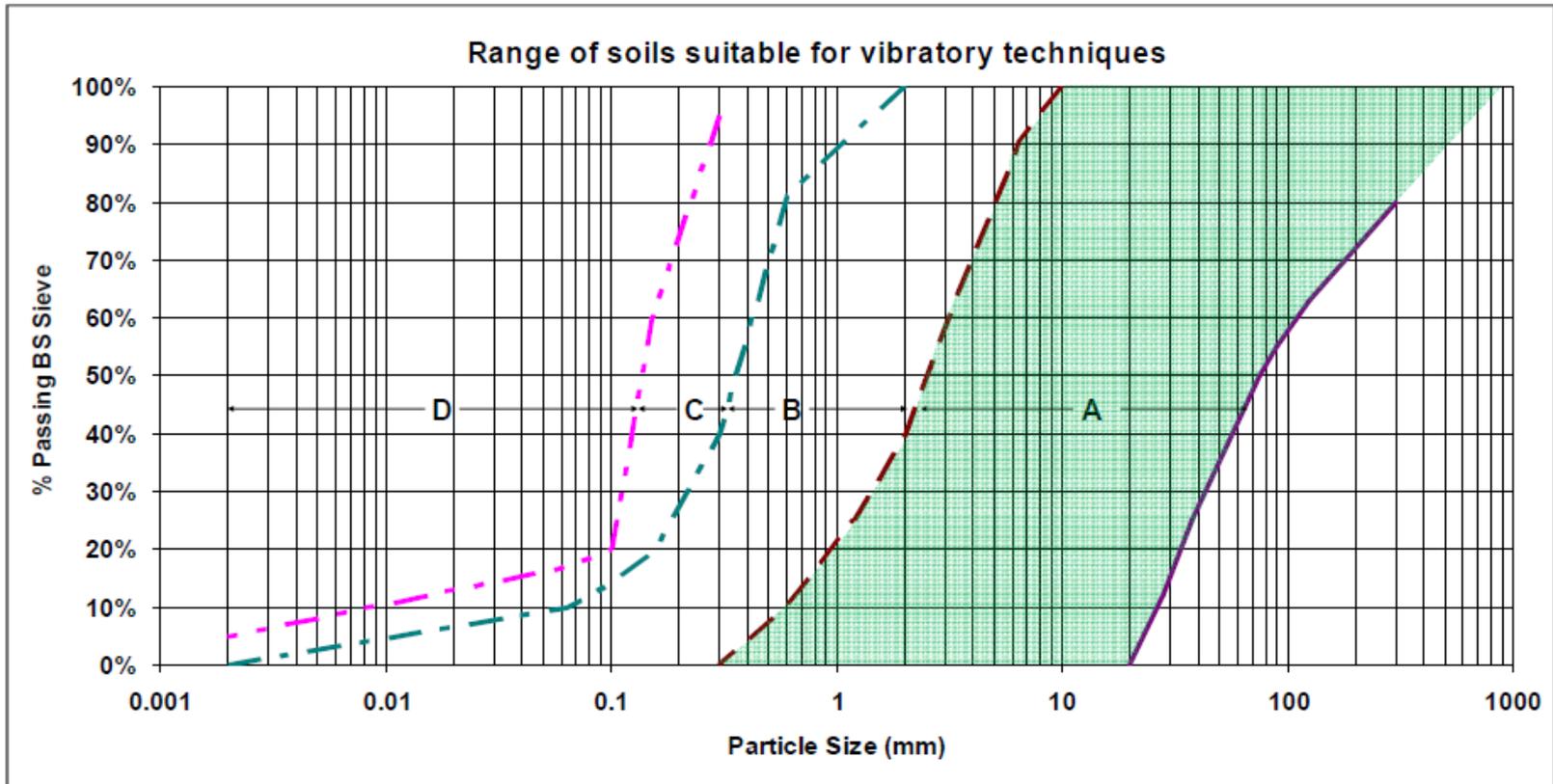


Nose jets are turned off and the side jets turned on to cause the flow of soil towards the probe



The probe is raised in approx. 0.5m steps to ground level using a predetermined criterion.

Vibro Compaction (VC) – Suitable Soils

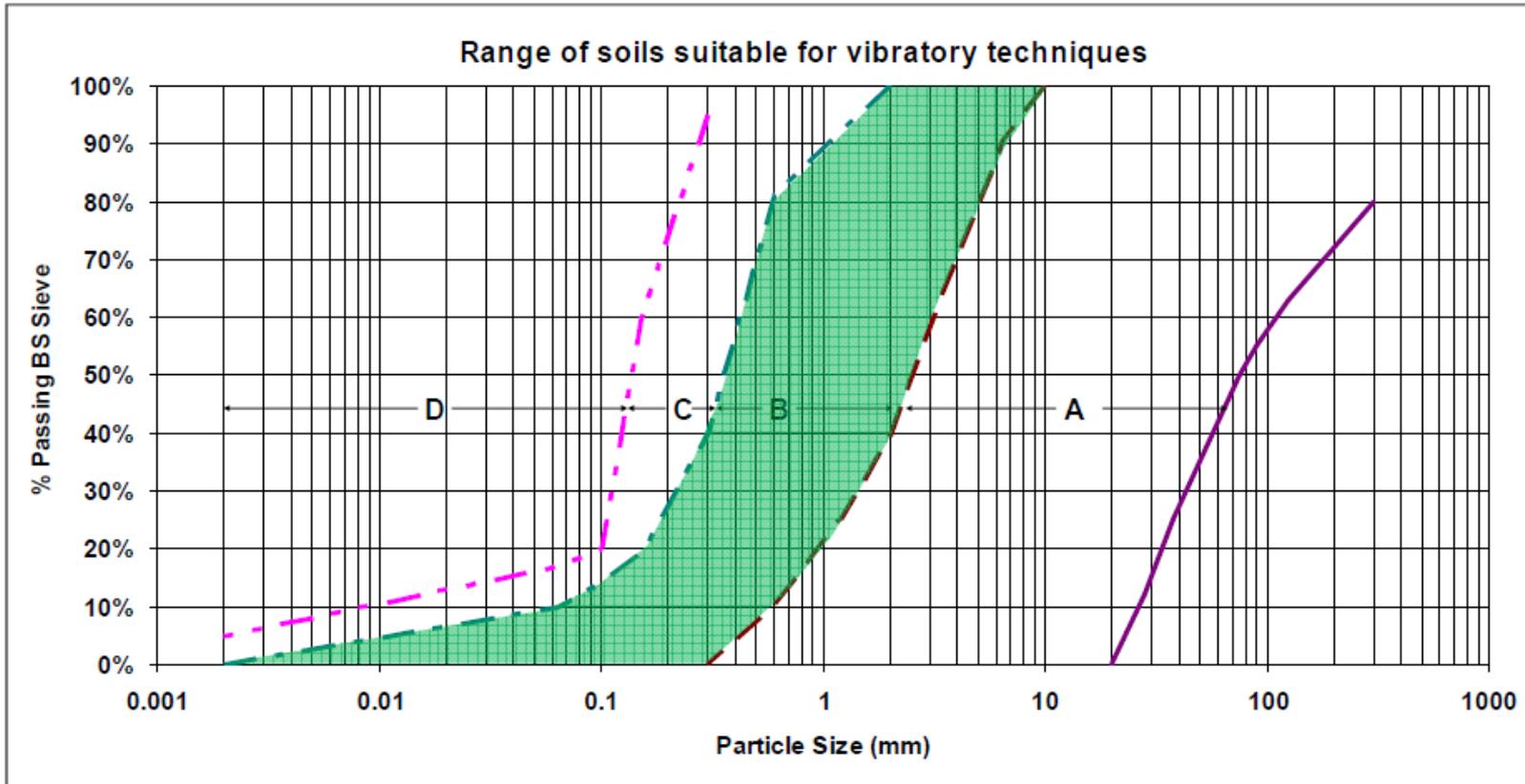


Zone A:

The soils of this zone are very well compactable.

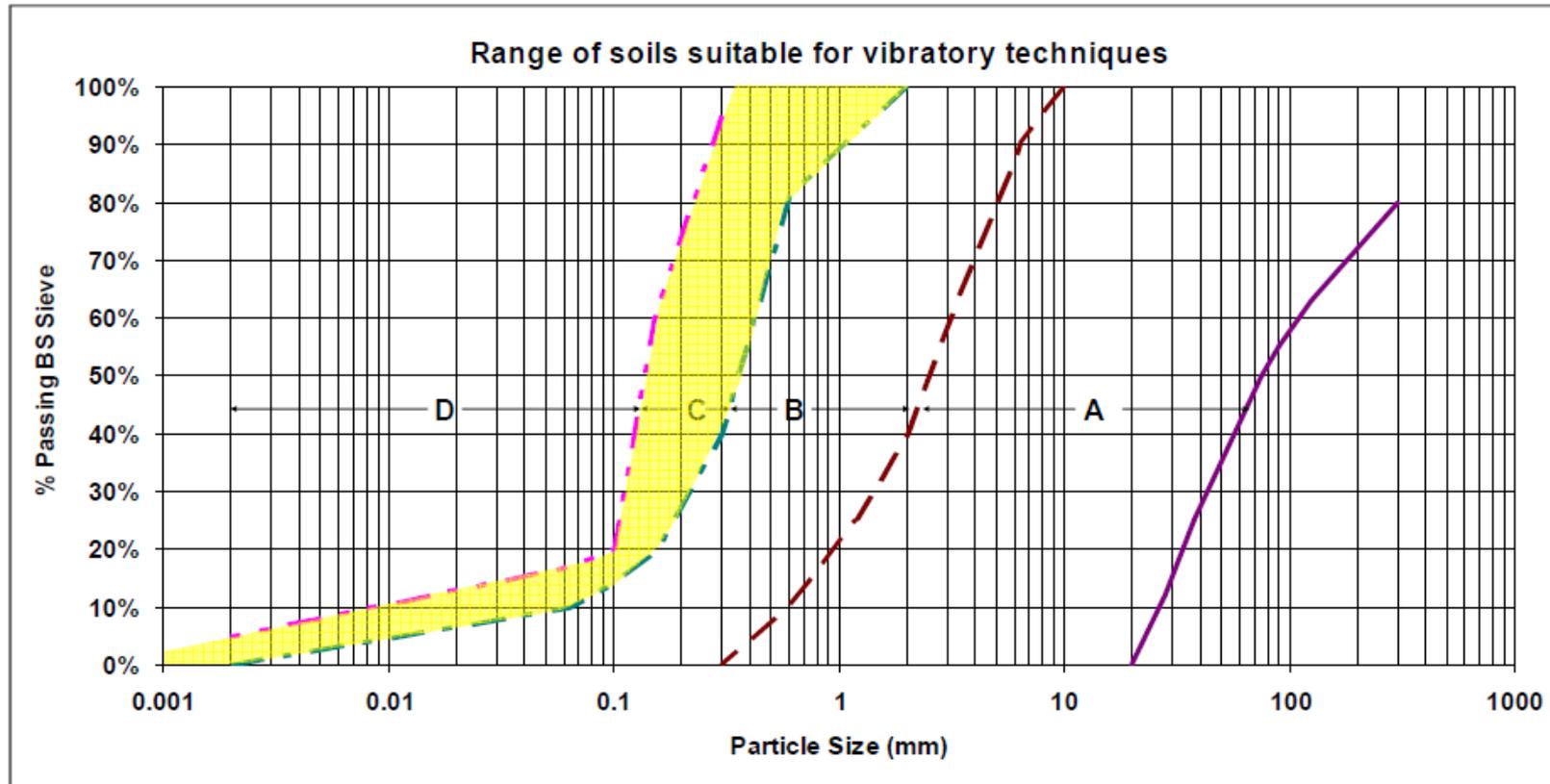
The right borderline indicates an empirically found limit where the amount of cobbles and boulders prevents compaction because the vibro probe cannot reach the compaction depth.

Vibro compaction (VC) – Suitable Soils



Zone B: The soils in this zone are suited for Vibrocompaction.
They have a fines content of less than 10 %.

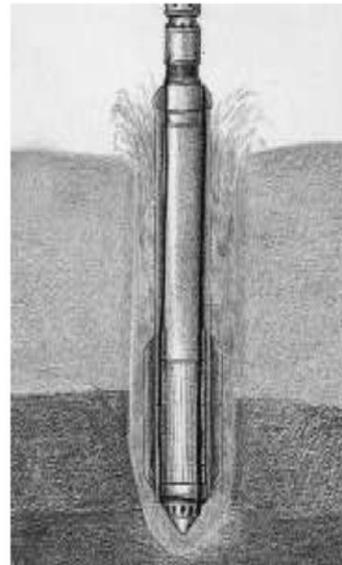
Vibro replacement (VR) vs Vibro compaction (VC)



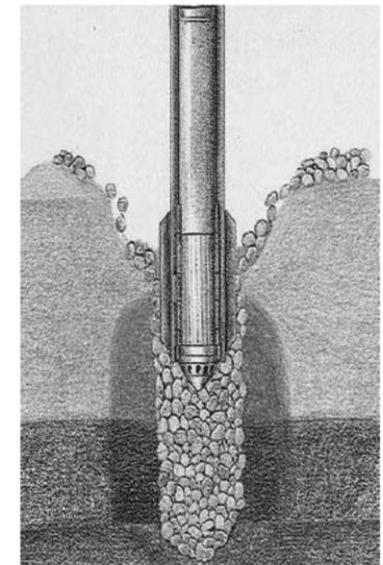
Zone C: Compaction is only possible by adding suitable sand or stone fill from the surface, with the fill being introduced and compacted in stages, each charge of fill being thoroughly compacted by moving the vibro-probe up and down in small steps (vibroreplacement / stone columns).

Vibro replacement (VR) - Introduction

Vibro replacement (wet top feed)



Penetrate with full water pressure on nose jets



Form stone column by introducing aggregate in stages from the surface. Reduced water from nose jets

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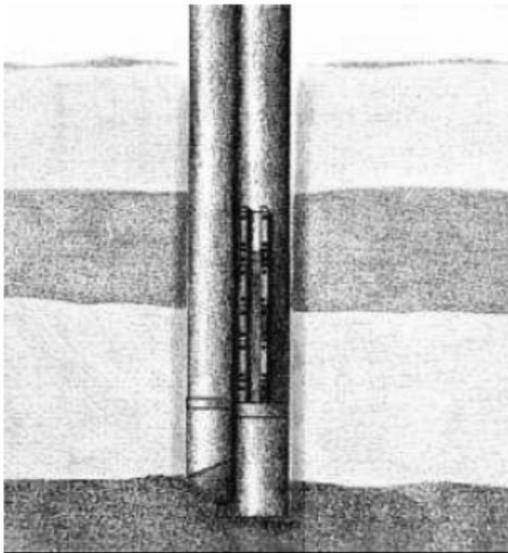


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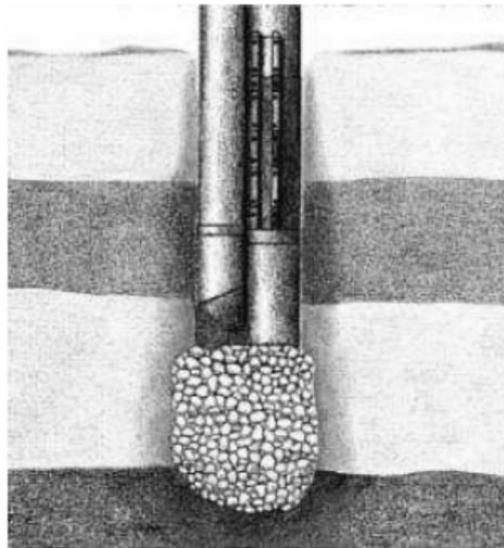
Vibro replacement (VR) - Introduction

Vibro replacement (dry bottom feed)



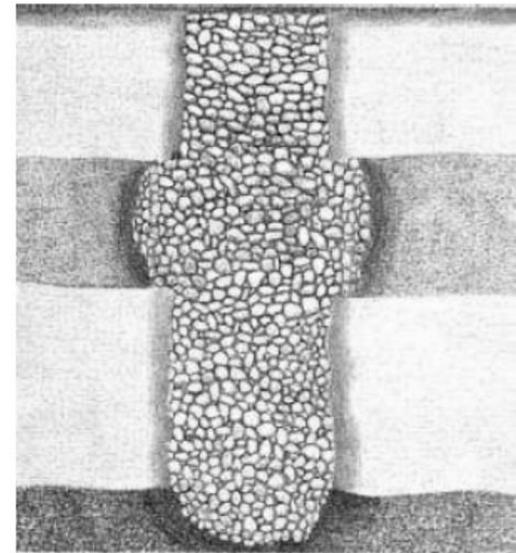
Penetration

The vibroprobe penetrates by vibration and with the aid of compressed air to the required depth



Installation

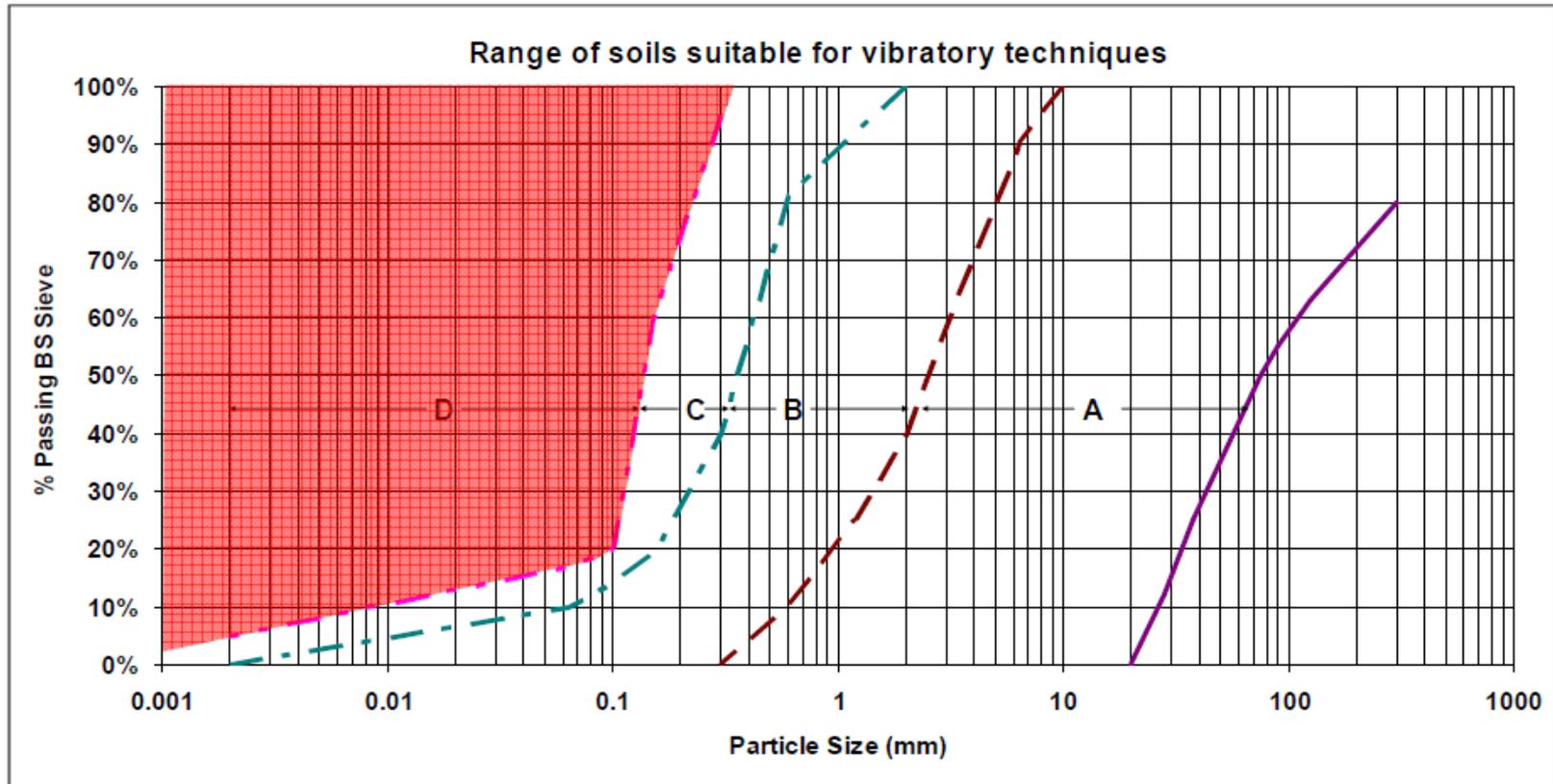
The stone column is installed by adding gravel through the separate gravel pipe alongside the vibroprobe



Completion

The surface is leveled and surface compacted

Vibro replacement (VR) – Suitable Soils



Zone D: Stone columns are a solution for a foundation in these soils. There is a resulting increase in bearing capacity and reduction on total and differential settlements due to the strength and stiffness of the stone column relative to that of the natural ground.

Vibro replacement (VR) Methods - CAUTION

Methodologies:

- Vertical movements (sheet piling probe)
- Lateral movements (VR probe)
- Different performance in similar (granular) ground conditions



Deep Soil Mixing (DSM) - Introduction

Deep Soil Mixing (DSM)



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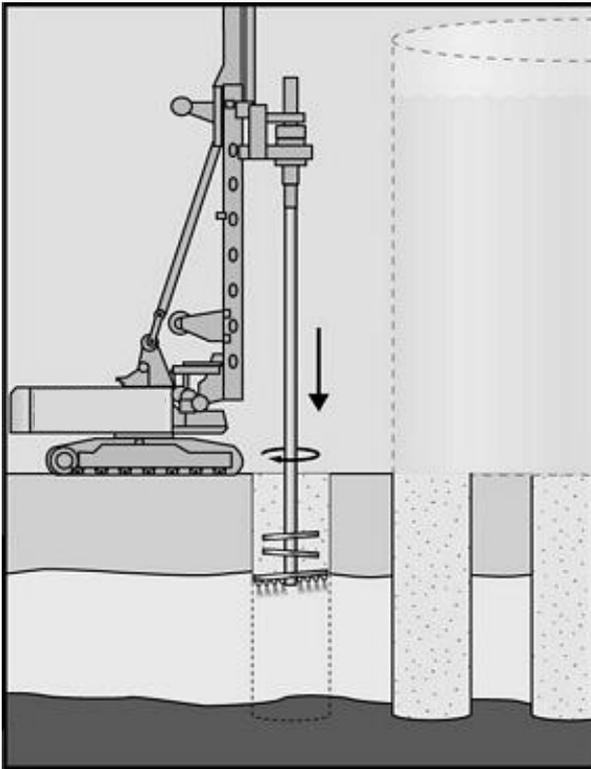


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Deep Soil Mixing (DSM) - Introduction

Deep Soil Mixing (DSM) - vertical columns



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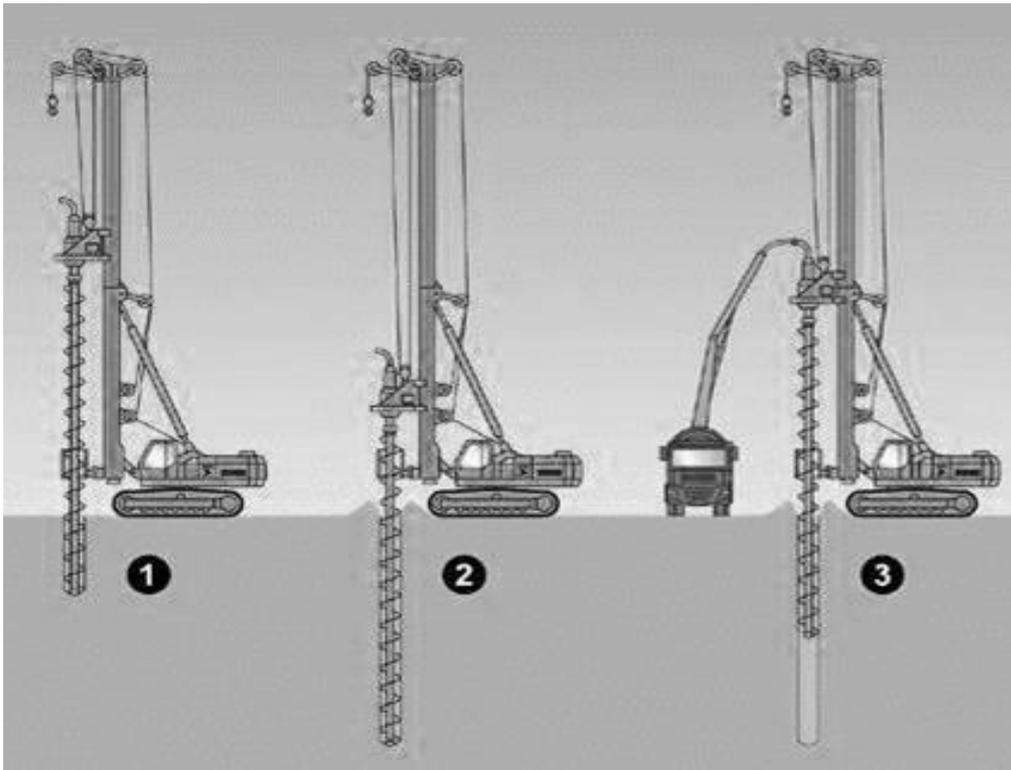
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Deep Soil Mixing (DSM) - Vertical columns

- Good mixing quality also in plastic clay
- Precise diameter and good verticality
- High production rates
- By limiting the jetting pressures, the cement content, the resulting column strength and the column modulus are relatively constant
- Column diameter: 600 to 1000 mm
- Column depth: typically up to 15m, greater depths are possible depending on rig size, soil properties, column diameter and consistency
- Column strengths between 0.5 MPa and 2 MPa are typical, depending on ground conditions, mixing time and cement content

Continuous Flight Auger (CFA) - Introduction

CFA lattice structures - vertical columns



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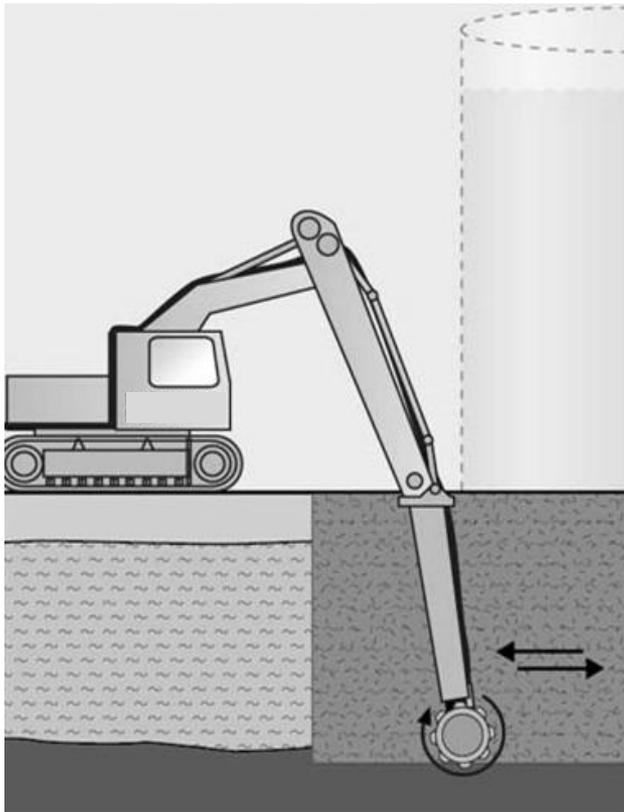


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Deep Soil Mixing (DSM) - Introduction

Deep Soil Mixing (DSM) - mass mixing



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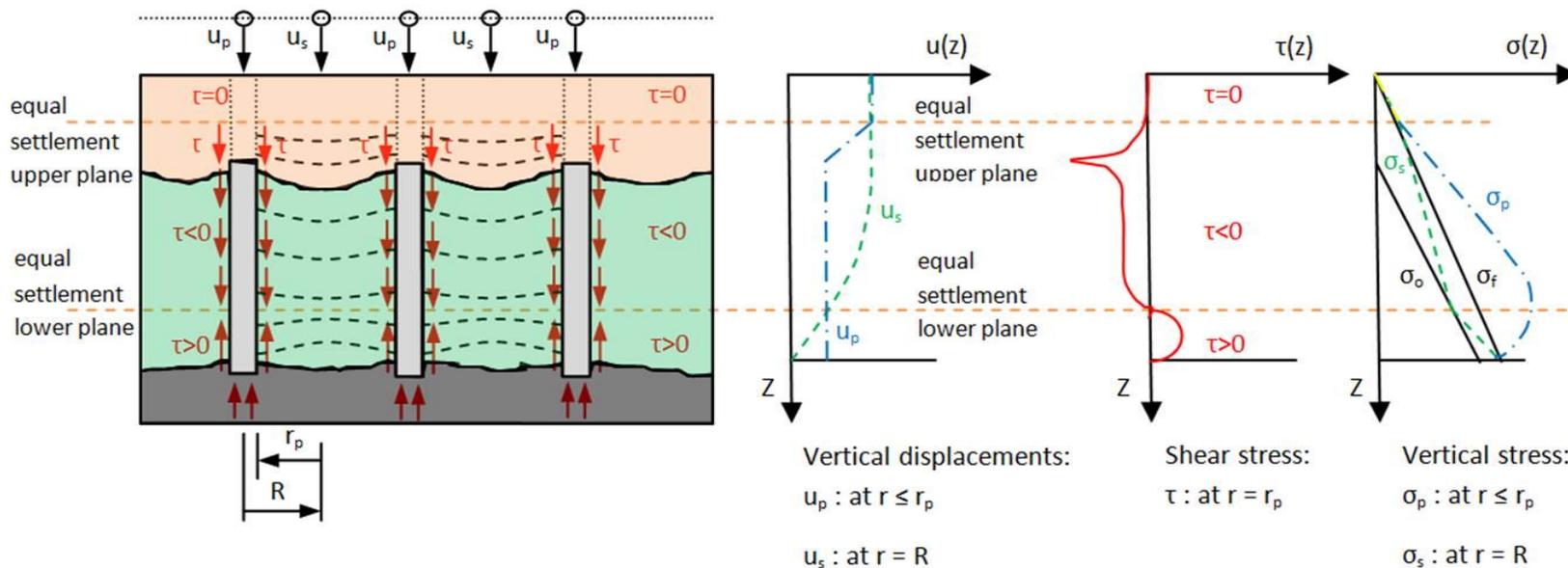
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Deep Soil Mixing (DSM) - Mass mixing

- Good mixing quality in granular soils
- High production rates
- The cement content, the resulting 'soilcrete' strength and the 'soilcrete' modulus are relatively constant
- Panel width: 600 to 1500 mm
- Panel depth: typically up to 5m, greater depths are possible depending on rig size, soil properties
- 'Soilcrete' strengths between 0.5 MPa and 2 MPa are typical, depending on ground conditions, mixing time and cement content

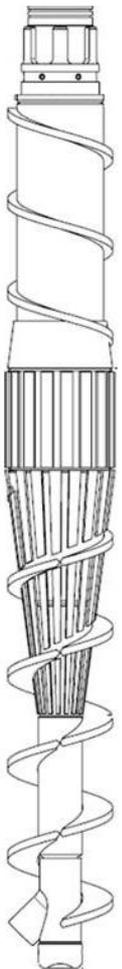
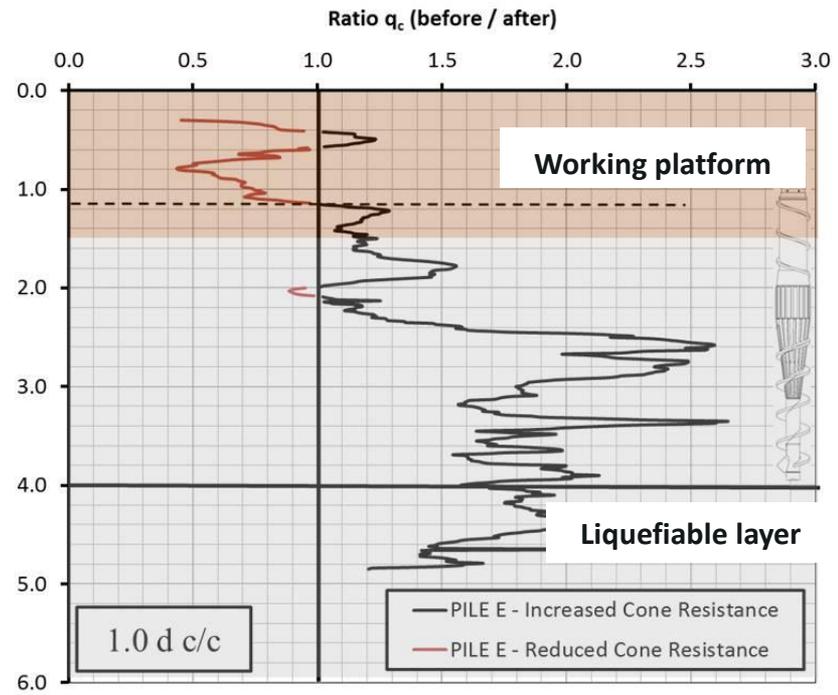
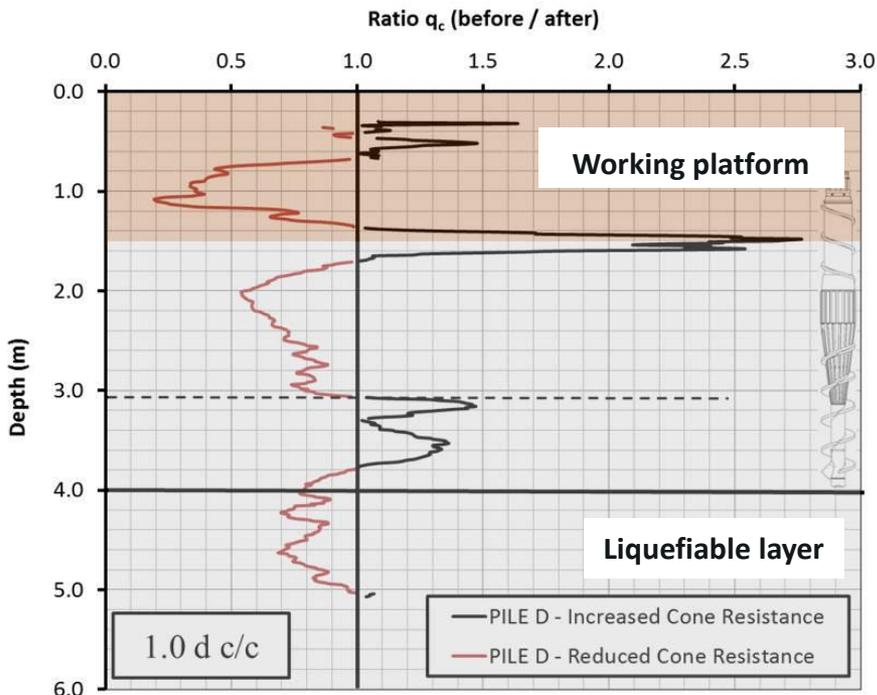
Rigid Inclusions (RI) - Introduction

Rigid Inclusions with Drilled Displacement Piling (DDP) methods
 Innovative methodology with potential for liquefaction mitigation



Rigid Inclusions (RI) - Installation effects

Rigid Inclusions with Drilled Displacement Piling (DDP) methods
Installation effects are critical for soil densification!



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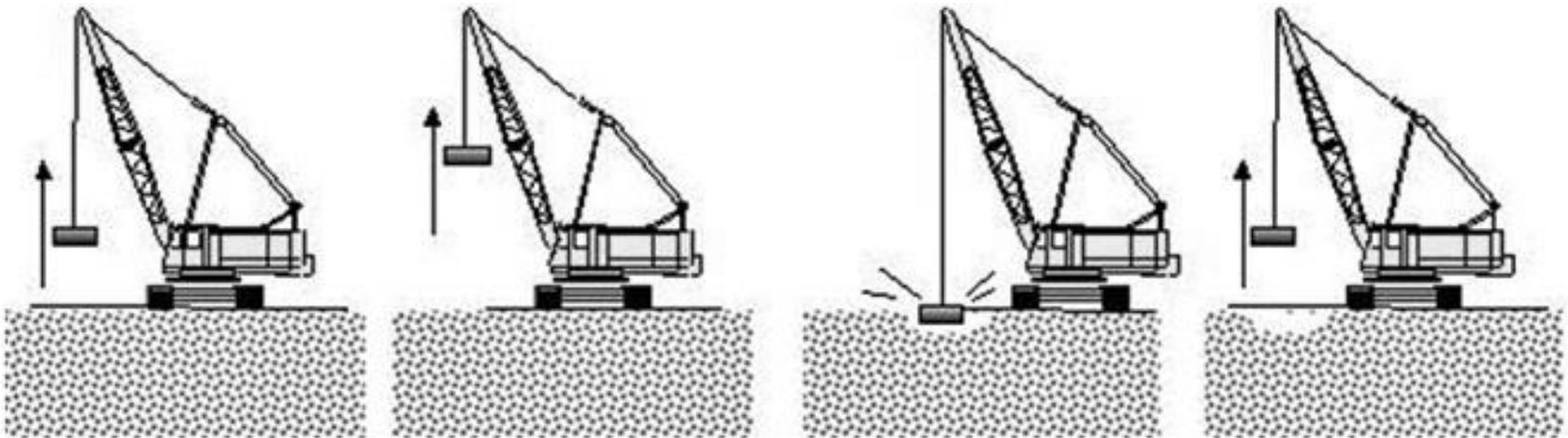
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Rigid Inclusions (CMC, CSC, DDP) - Introduction

- Densification potential in loose granular soils if penetration rate is sufficient and auger geometry is suitable
- Penetration of hard layers possible
- High production rates
- The use of concrete (usually 5 to 15 MPa) keeps the column modulus very constant
- Column diameters:
 - 450mm to 900 mm for non-displacement techniques
 - 360mm to 450mm for drilled displacement techniques
- Column depth: typically up to 25m, greater depths are possible depending on rig size, soil properties

Dynamic Compaction (DC) - Introduction

Dynamic compaction (DC) is a cost effective and efficient method for ground improvement works.



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Dynamic Compaction (DC) - Introduction

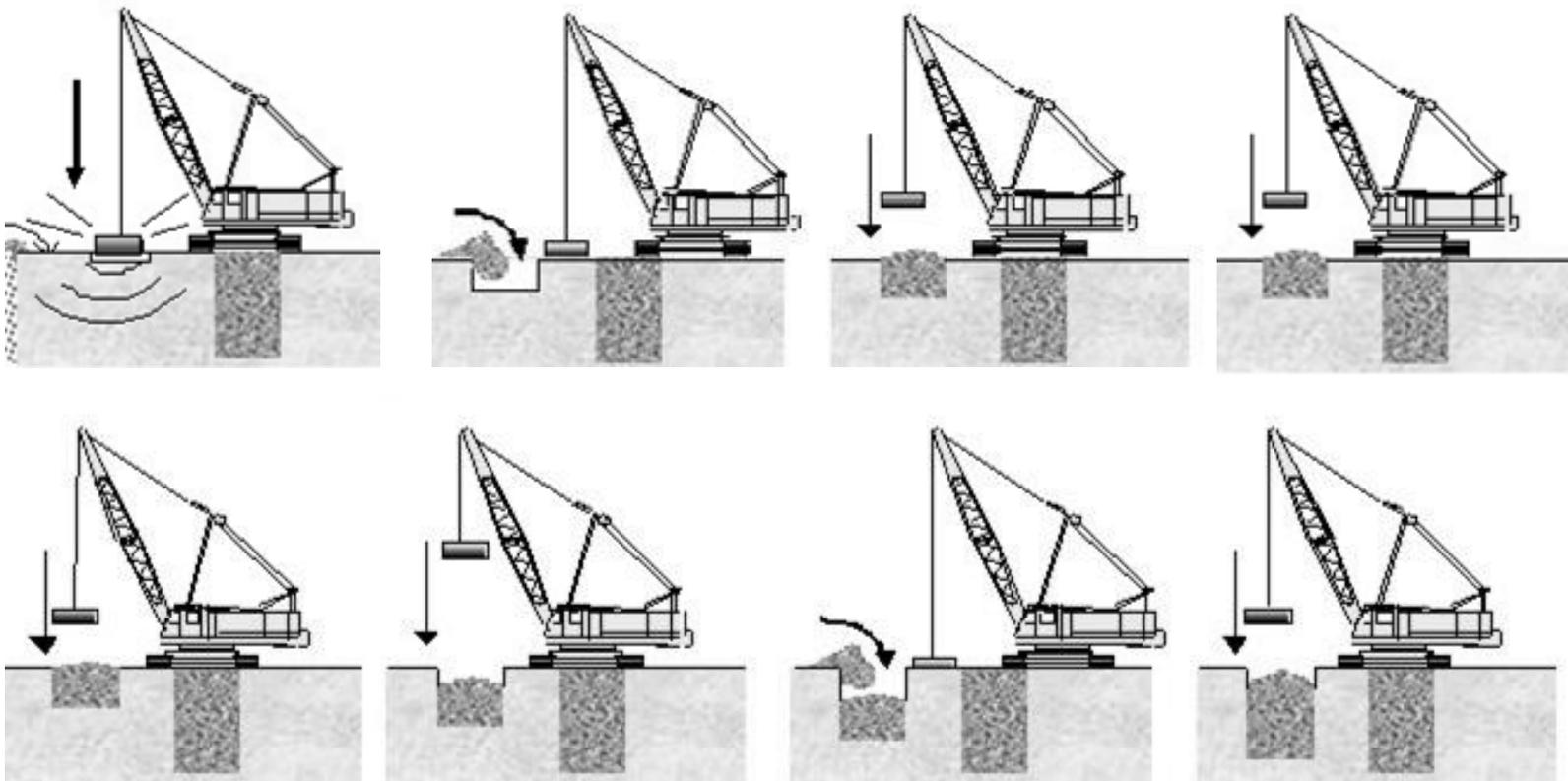
Dynamic compaction (DC) strengthens weak soils by controlled high-energy tamping (dropping a static weight from a defined height).

The reaction of the soil during the treatment varies with soil type and energy input.

Typically drop weights range from 6-20 ton dropped from heights up to 20m. Weights are typically constructed using steel plates, box steel and concrete (also suitably reinforced mass concrete).

Dynamic Replacement (DR) - Overview

Dynamic replacement (DR) is another cost effective GI method.



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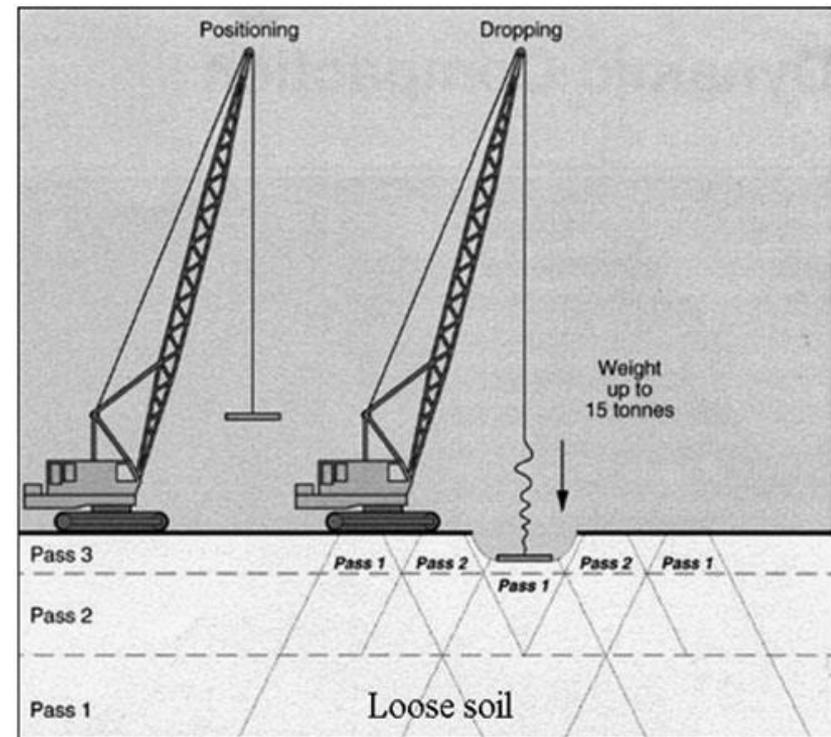


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Dynamic Compaction (DC) - Introduction

Dynamic compaction (DC) is applied in different passes to improve the ground efficiently:

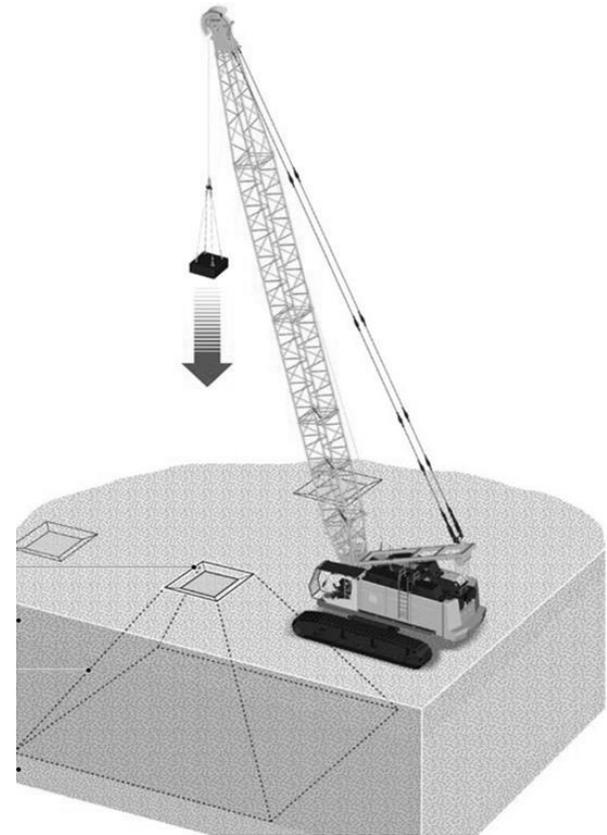
- Pass 1: 'deep' treatment
- Pass 2: 'intermediate treatment'
- Pass 3: 'shallow treatment'



Dynamic Compaction (DC) - Introduction

Dynamic compaction (DC) is applied in different passes to improve the ground efficiently:

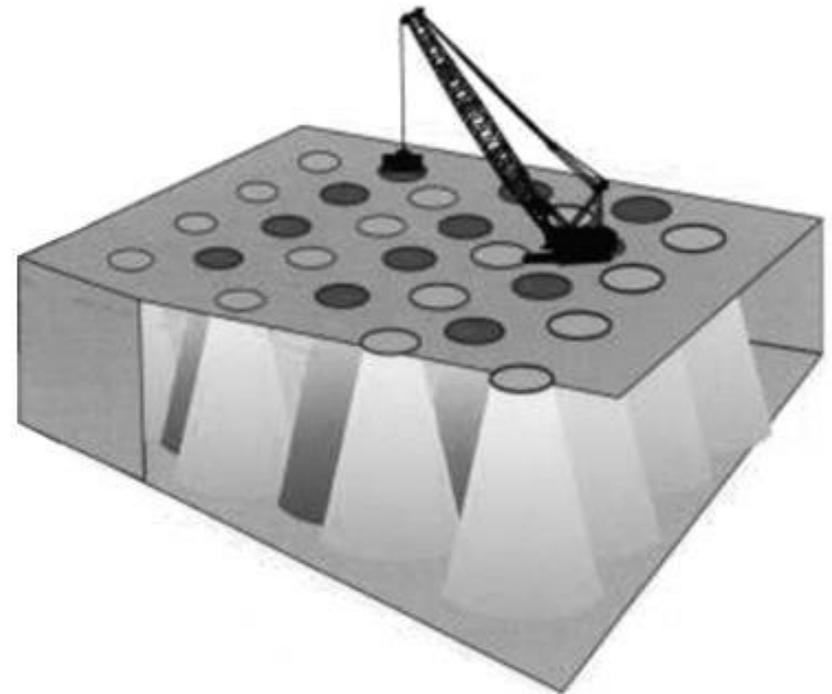
- Pass 1: 'deep' treatment
- Pass 2: 'intermediate treatment'
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Dynamic Compaction (DC) - Introduction

Dynamic compaction (DC) is applied in different passes to improve the ground efficiently:

- Pass 1: 'deep' treatment
- Pass 2: 'intermediate treatment'
- Pass 3: 'shallow treatment'



Dynamic Compaction (DC) - Design requirements

It is important to understand the design requirements of your project in order to determine the best treatment / solution:

- Bearing capacity
- Settlement improvement
- Liquefaction mitigation
- Long term performance
- Other (e.g. backfilling landfill sites or collapsing cavities)

Is a load transfer / distribution layer required?

Dynamic Compaction (DC) - Suitable soil groups

Soil groups (typically) suitable for treatment by Dynamic Compaction

General Soil Type	Degree of Saturation	Suitability for DC
Granular deposits in the grain size range of boulders to sand with 0% passing the 0.074mm sieve	High or Low	Excellent
Granular deposits containing not more than 35% silts	High	Good
	Low	Excellent
Semi-permeable soil deposits, generally silty soils containing some sands but less than 25% clay with $PI < 8$	High	Fair
	Low	Good
Impermeable soil deposits generally clayey soils where $PI > 8$	High	Not Recommended
	Low	Fair-minor improvements water content should be less than plastic limit
Miscellaneous fill including paper, organic deposits, metal and wood	Low	Fair-long term settlement anticipated due to decomposition. Limit use to embankments
Highly organic deposits peat-organic silts	High	Not recommended unless sufficient energy applied to mix granular with organic soils

Working principle - Granular soils

In dry granular materials tampering improves engineering properties of the soil.

Physical displacement of particles and low-frequency excitation will:

- reduce the void ratio and
- increase the relative density

to provide improved load bearing and enhanced settlement criteria.

The existing density and grading of the soil are major factors how efficiently a granular soil deposit can be improved.

Working principle - Granular soils (high energy)

Below the ground water table and after a suitable number of surface impacts, pore pressure rises to a sufficient level to introduce liquefaction.

Low frequency vibrations caused by further stress impulses will then re-organise the particles into a denser state.

Dissipation of pore water pressures in conjunction with the effective surcharge of the liquefied layer by the soils above, results in further increase in relative density over a relatively short time period.
(1-2 days in well graded sands to 1-2 weeks in silty sands)

Working principle - Granular soils (low energy)

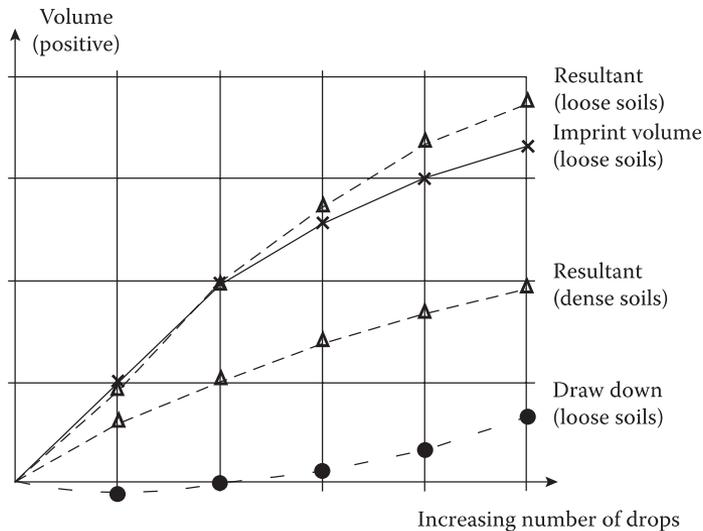
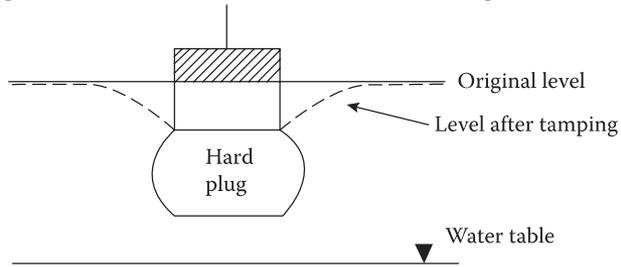
DC can be used without inducing the liquefied state (which is almost impossible in loose sandy deposits with high ground water tables...)

The treatment without liquefaction is aimed to provide compaction by displacement without dilation or high excess pore pressure by using a smaller number of drops from a lower drop height.

This approach, where applicable, requires significantly lower energy input than the liquefaction approach with consequent economies.

Volumetric response of granular soils

Typical volumetric response of granular soil treated by DC



Working principle - Cohesive soils

The mechanism for achieving improvements of:

- cohesive natural soils,
- soft near-saturated clay fill or
- recent hydraulically placed fill

is more complex than that of granular soils. With conventional consolidation theory, a static surcharge loading will collapse voids within clay fills and expel water to induce consolidation and increase strength. The rate at which this occurs is dependent upon the imposed load, coefficient of consolidation, and length of drainage path.

Working principle - Cohesive soils

In contrast, dynamic compaction applies a virtually instant localised surcharge that collapses voids and transfers energy to the pore water. This creates zones of a positive water pressure gradient that forces water to rapidly drain from the soil matrix. This effect is accelerated further by the formation of additional drainage paths through shear and hydraulic failure of the soil as the weight hits the ground. Consolidation therefore occurs more rapidly and literally squeezes the water out of the soil to effectively 'pre-loading' the ground.

Working principle - Cohesive soils

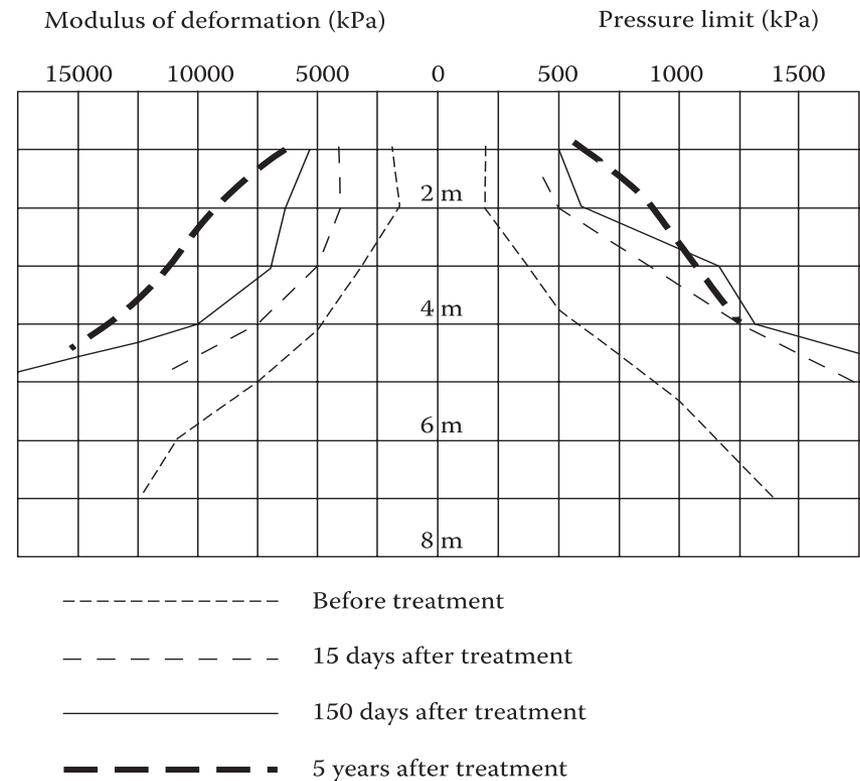
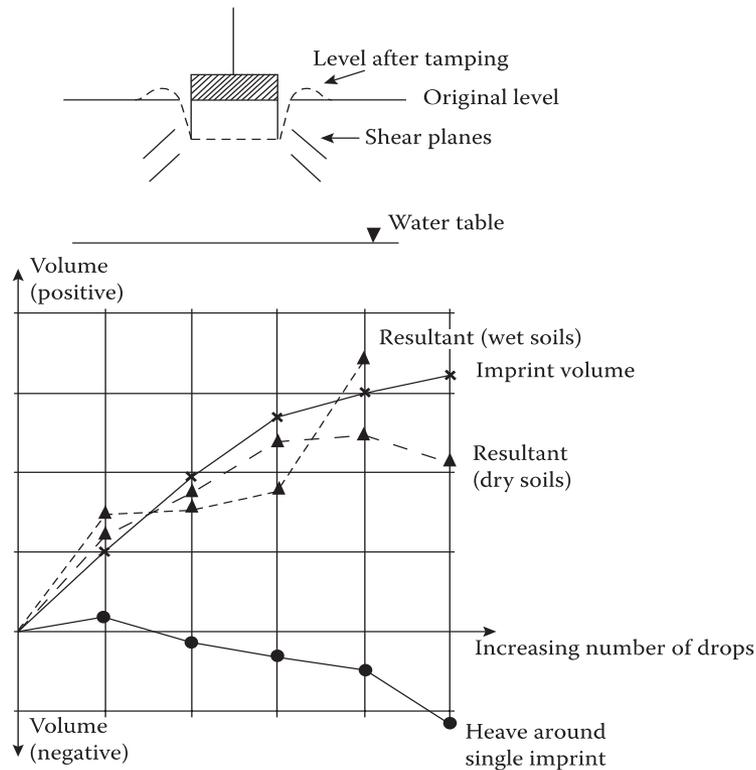
The treatment of cohesive soil above the ground water table can lead to significant improvements in bearing capacity.

Cohesive soils below the ground water table, a larger reduction of the moisture content is required in the presence of a smaller available pore-pressure gradient and a longer drain path.

Only nominal degrees of improvement have been achieved in thick layers of relatively weak saturated clays and silts, even with additional measures like wick drains, stone columns or aggregate filled trenches.

Volumetric response of cohesive soils

Typical volumetric response of cohesive soil treated by DC



Dynamic Compaction (DC) - Depth of treatment

Menard originally proposed that the effective depth of treatment was related to the metric energy input expressed as

$$D = K\sqrt{WH}$$

Where

- W is the weight in tonnes,
- H the drop height in meters, and
- K is the modification factor for soil type

FILL TYPES	K
Stiff Clay	0.35
Old Refuse	0.4
Rock Fill	0.5
Hard Fill	0.5

Dynamic Compaction (DC) - Depth of treatment

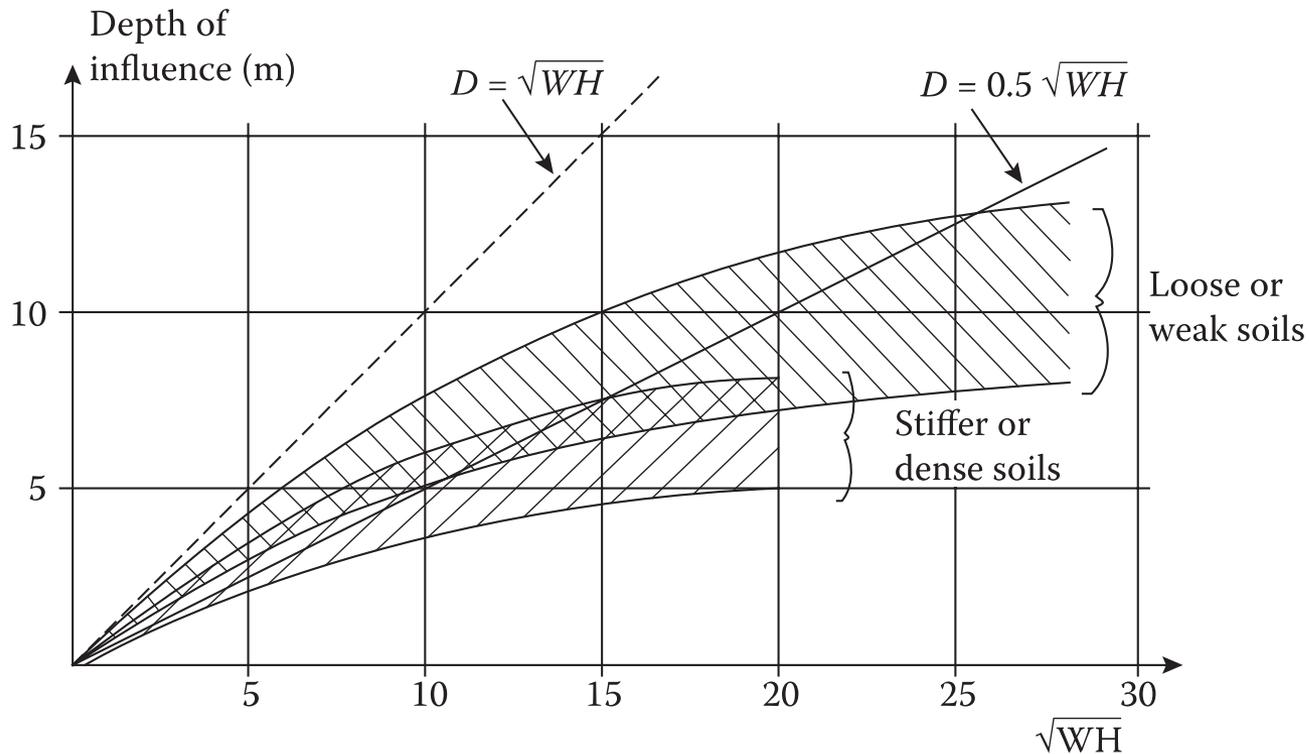
It is important to understand the project requirements as kinetic energy impact at the point of treatment is critical in depth treatment and increasing the drop height will increase the velocity.

The shape of the improvement in the ground tends to be similar to the Boussinesq distribution of stress for a circular foundation.

Modification of energy levels at each tamping pass can be used to custom-design the treatment scheme to a specific soil profile and engineering requirement.

Dynamic Compaction (DC) - Depth of treatment

The figure below suggests that factors as high as 0.9 could apply for shallow depths of loose granular soils (typical values are lower)



Dynamic Compaction (DC) - Quality control

It is normal procedure to test treated ground during the progress of the compaction works for control purposes to assess the effectiveness of the treatment. This provides the designer with assurance that the specified level of compaction will achieve the degree of improvement required. Quality control testing during treatment often involves in-situ penetration tests (e.g. CPT or SPT) which may form part of the final assurance testing. Test methods, frequency of testing and criteria for acceptance should be agreed at tender stage. The frequency of testing will be affected by factors particular to each project, for example, the variability of the ground before treatment, the nature of the structure to be supported and its sensitivity to post-treatment movements.

Ground Improvement - Summary

- It is important to fully understand the design requirements
- It is important to understand the ground improvement methodology and it's specific advantages and limitations
- Dynamic compaction can be very effective in granular soils
 - High energy
 - Low energy
- Dynamic compaction can be used with caution in cohesive soils and soils with organic layers
- Noise and vibration effects of different ground improvement techniques must be considered and how these can be managed
- New technologies offer greater opportunities and unknown risks

Project Example

M2PPP Alliance



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DC Project Example – M2PP

MacKay's to Peka Peka Expressway

- 18km Long 4 lane expressway
- 15 road bridges the longest being 250m across the Waikanae River
- 2 significant pedestrian overpass bridges
- Project Value = \$600M NZD

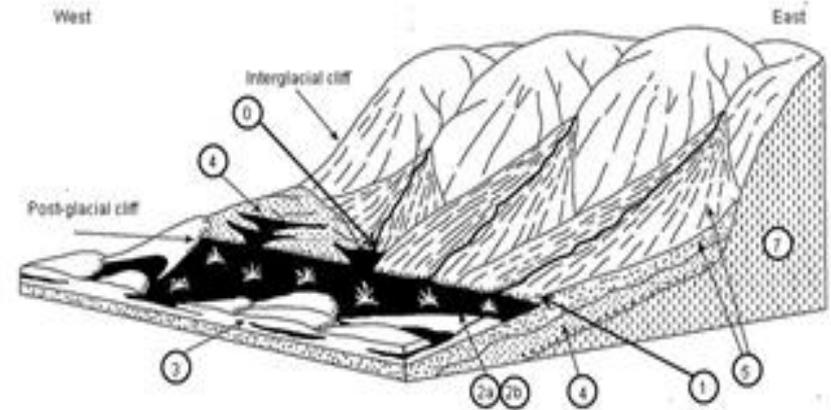


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M2PP – Geology and Seismicity

- Design PGA up to **0.98g** in a 1/2500 year ULS event.
- Extensive sections underlain by potentially liquefiable dune sands and silts



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M2PP – Geology and Seismicity

- Approximately 50% of the earthwork footprint is underlain by peat.
- Ground water levels are near surface



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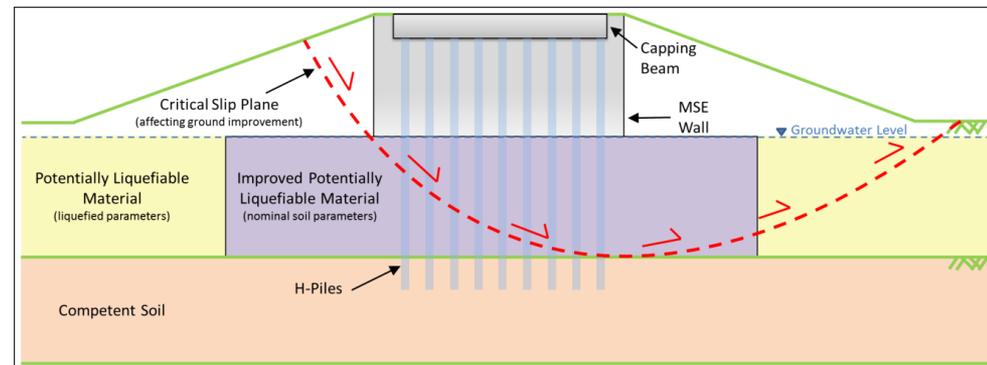
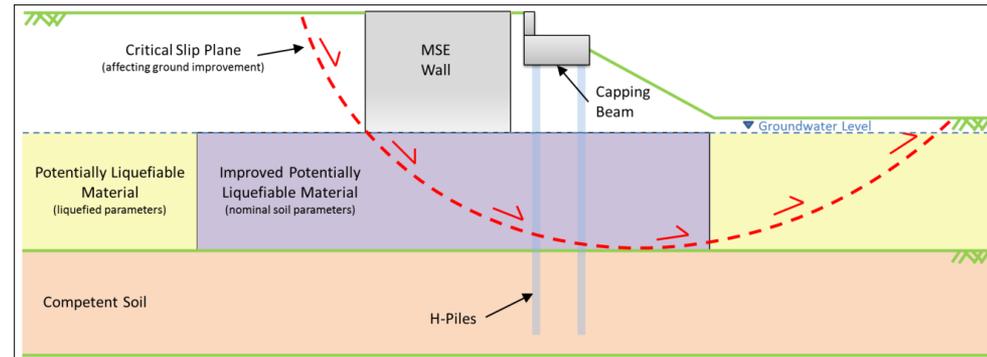


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Design Requirements

- Displacement based design adopted for all bridges
- Ground Improvement used under bridge abutments to control seismically induced displacements of bridge abutment soil.
- Displacements typically between 100mm – 200mm.



Design Requirements

- Ground Improvement Methods – Considered at Design Stage
 - Gravel (stone) Columns
 - Concrete / In situ mix lattice
 - Vibro Compaction – Latter Changed to Dynamic Compaction



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Stone Columns



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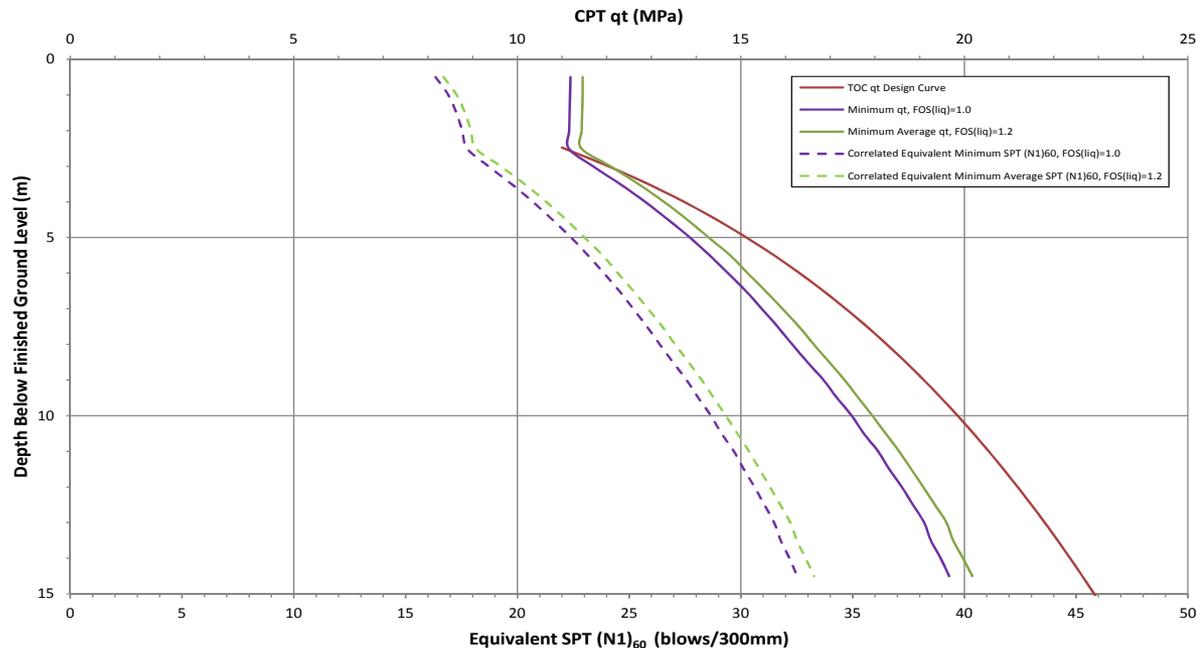
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Design Philosophy

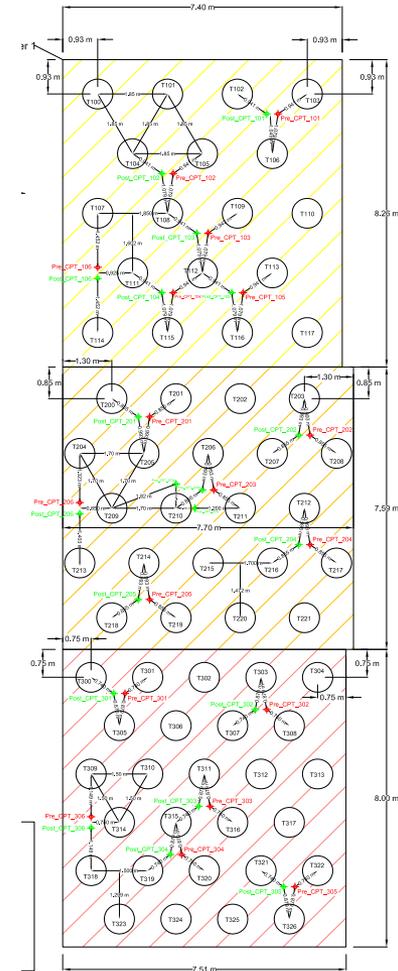
- Stone Columns & Vibro Densification

- Improve sandy or gravelly soils
- Intent was to densify surrounding soils – increasing horizontal effective stress
- Shear stiffening and drainage effects not incorporated
- Verification using CPT qt curves based on FOS_{liq} = 1.0 and 1.2
- Curves based on 2500 year return period



Stone Columns

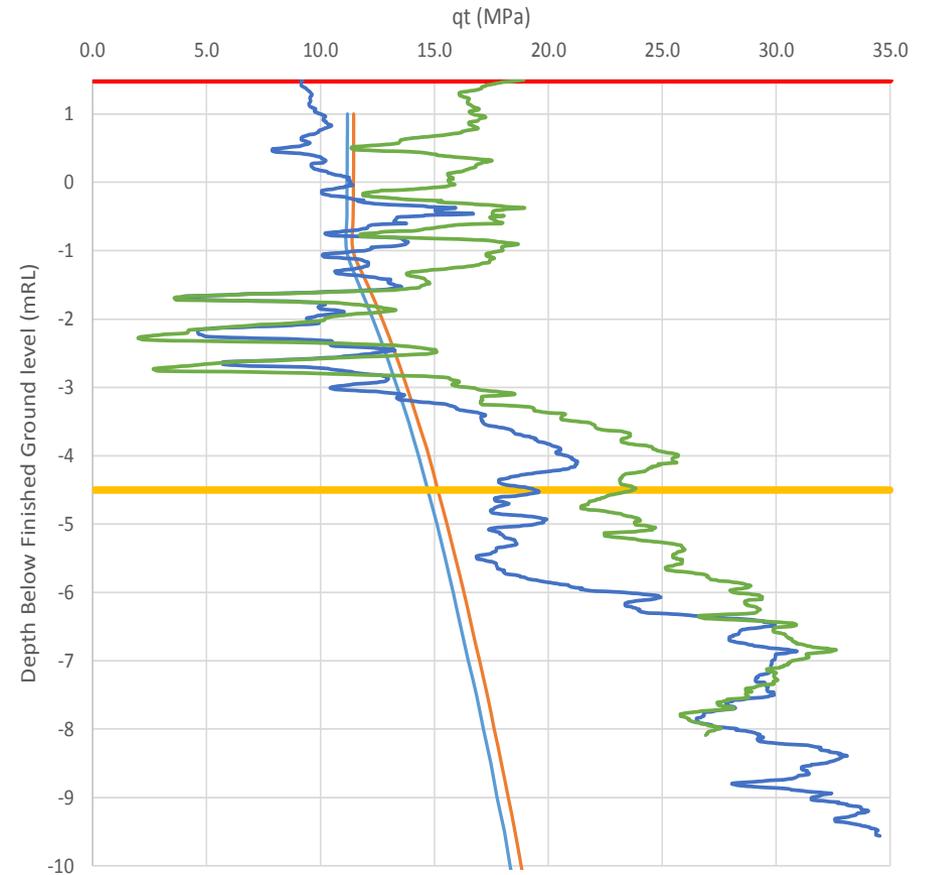
- Construction method
 - Top feed columns using wet flush method
 - 65/40 gap graded ballast
 - 2000m³ U bend pounds
- Column Size and Spacing
 - Design - 600mm diameter columns at a 35% replacement ratio
 - Tried varying spacing's (1.85m, 1.7m, 1.5m)
 - Final - 900mm diameter columns at 32.6% replacement ratio



Stone Columns

- Results

- Good response in sands and gravels
- Poor response in silt layers
- Column Diameter varied between 900mm and 1100mm



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CFA Concrete Lattice



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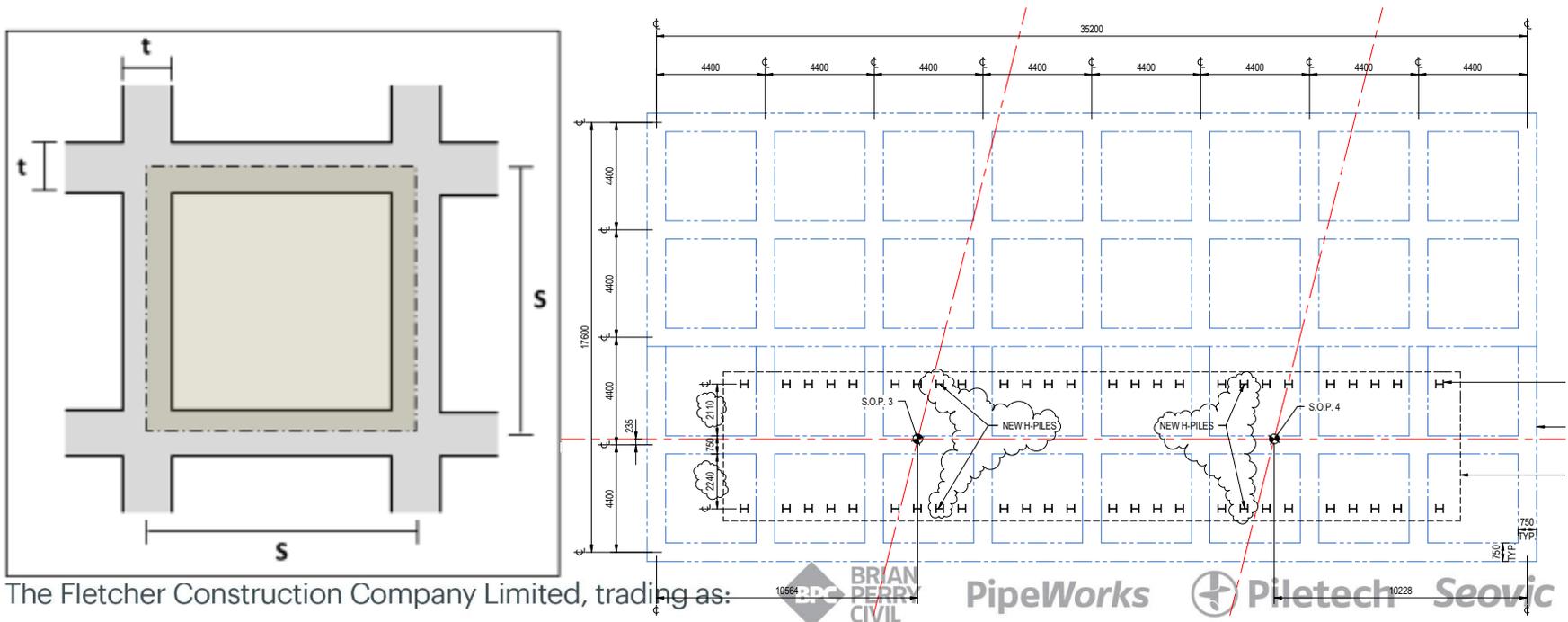
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Design Philosophy

- CFA Concrete Lattice

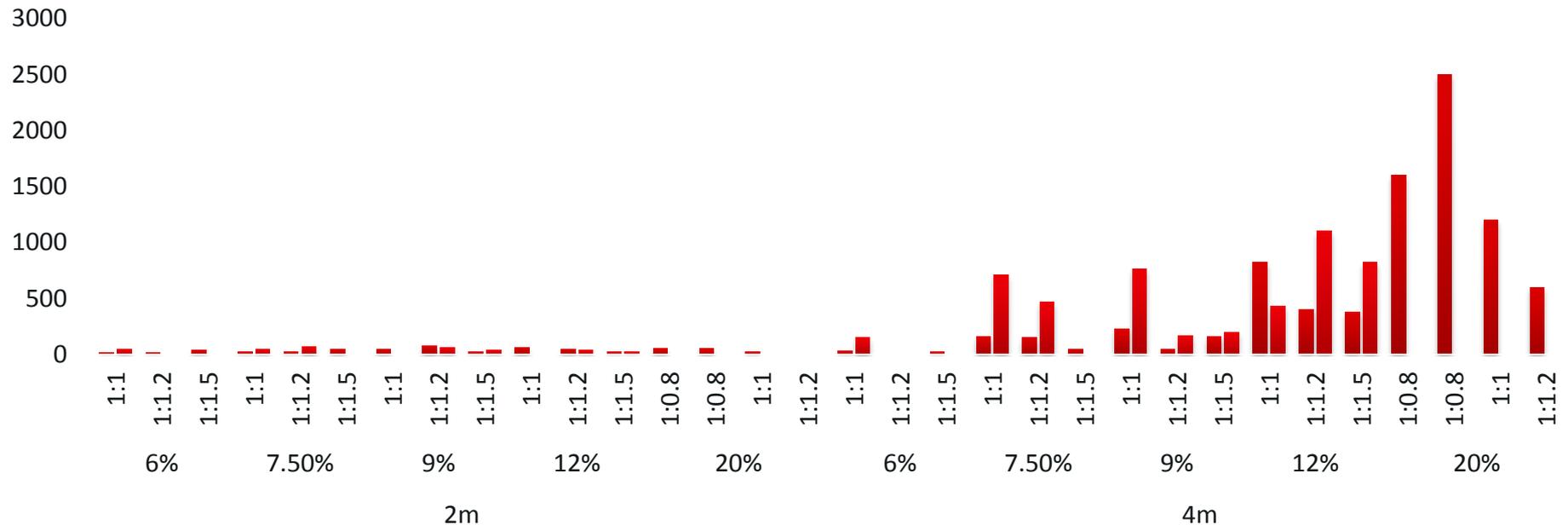
- Sites containing silty soils unsuitable for improvement by stone columns
- Improvement by increasing the cyclic stiffness in composite action.
- Design based on the stress re-distribution method – Baez & Martin (1994)
- OTREC (2013) design approach used applying a reduction factor to account for partial shear and flexural behavior considering all lattice elements.
- Verification of lattice strength by converting $G_{lat} - E_{mod} - UCS$ for on site testing



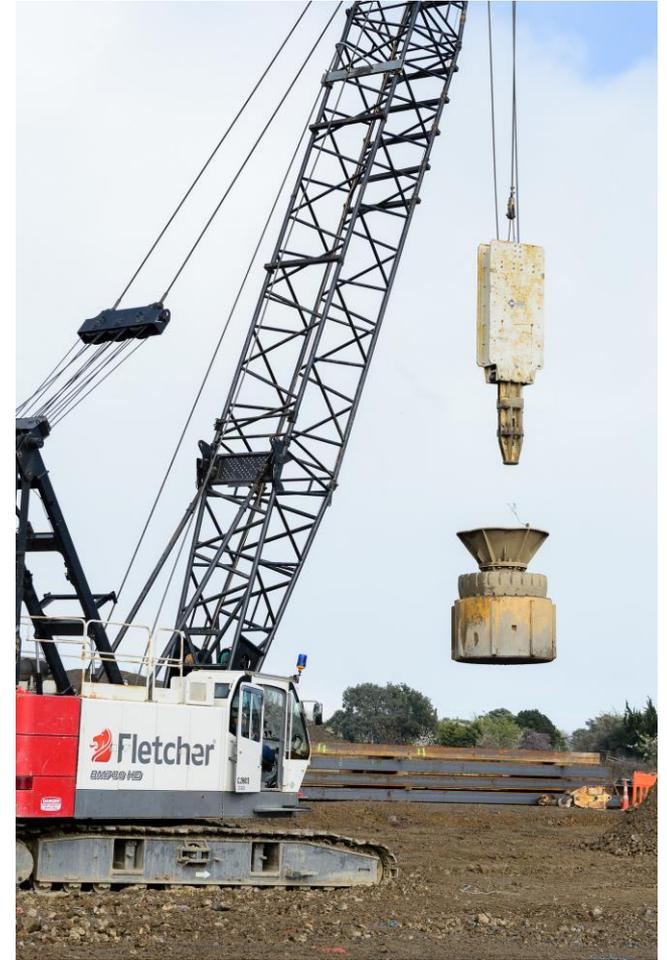
Concrete Lattice

- Initial design requirements
 - Shear stiffness = 400kPa
 - Elastic Modulus = 960kPa
 - UCS = 1200kPa
- Soil Mixing Laboratory Trials
 - Mix ratio's = 6%, 9%, 12%, 20% by weight
 - W/C Ratios = 1, 1.2, 1.5
 - Sand samples taken from 2m & 4m deep.

UCS Results 7 & 28 day



Vibro Compaction & Dynamic Compaction



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Dynamic Compaction in Action



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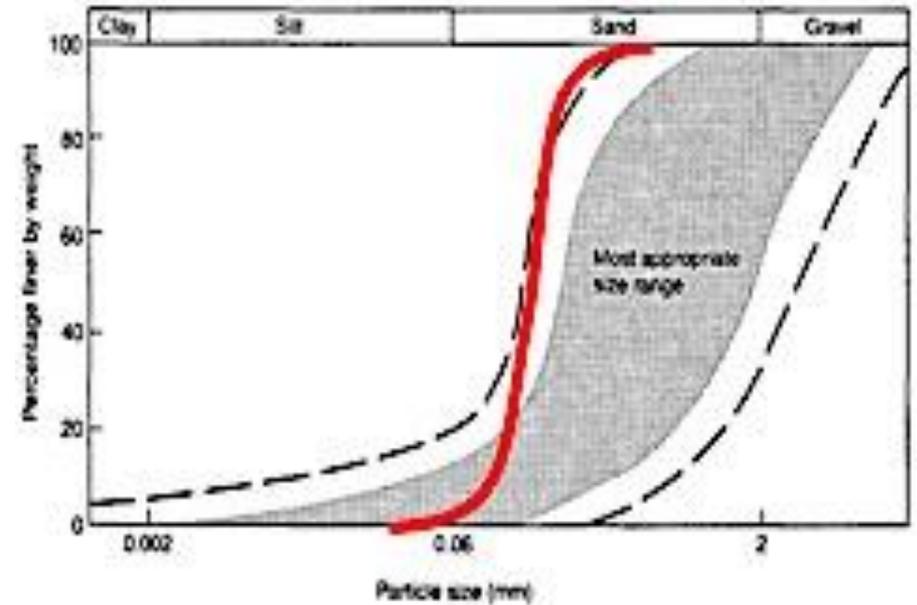
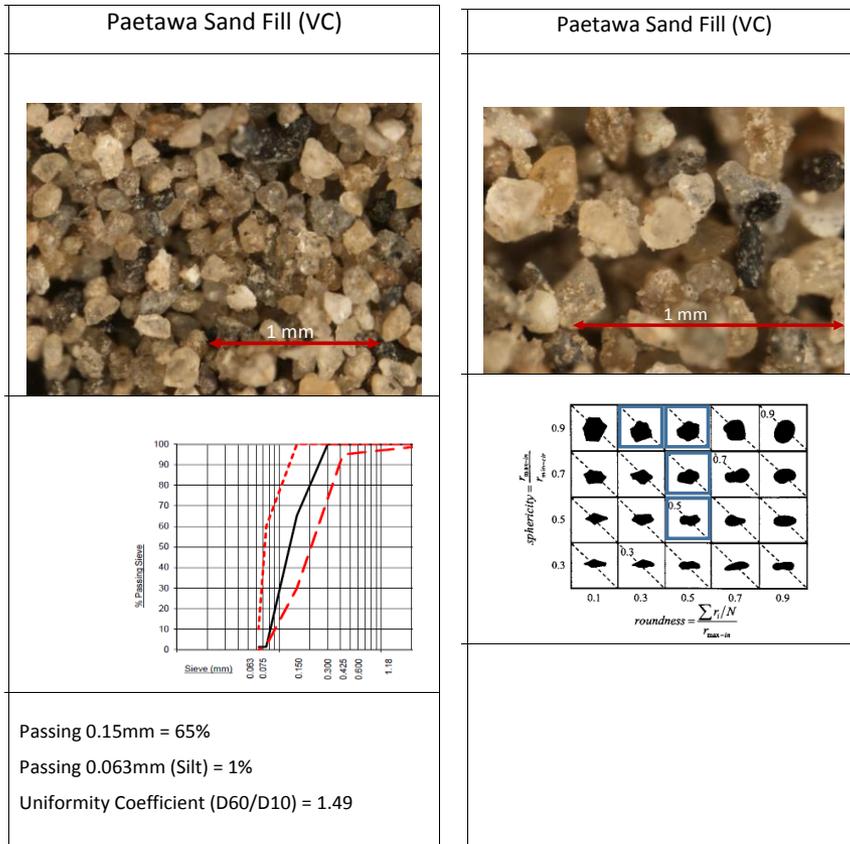
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Vibro Compaction

Vibro Compaction Trials did not work

- Sand failed to migrate down towards the probe tip



Dynamic Compaction

- Treatment depth varied between 5-8m
- Average Energy applied was between 150-200t-m/m²
- Used at 6 different bridge sites



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Design Process

1. Identify design parameters
2. Check SI for suitability of treatment method
3. Establish treatment / pass layout
4. Determine average energy input required
5. Establish weight, drop height, drops per point & passes
6. Calculate any predicted surface settlement (if required)
7. Evaluate environmental effects
8. Complete trial compaction to confirm predictions
9. Undertake DC
10. Test

4. Determine Average Energy Required

Type of Deposit	D50 (mm)	PI	Permeability range (m/s)	Total Energy Input (t-m/m ³)
Pervious Coarse-grained (sand)	>0.1	0	$> 1 \times 10^{-4}$	< 30 t-m/m ³
Semi-pervious, (silts)	0.01 to 0.1	< 8	1×10^{-4} to 10^{-8}	< 40 t-m/m ³
Impervious above the water table (silt or clay)	<0.01	> 8	$< 1 \times 10^{-8}$	< 40 t-m/m ³
Landfill				< 50 t-m/m ³

4. Determine Average Energy Required

Pass	Grid	Weight	No. of Drops	Drop height	Treatment Depth	Total Energy (t-m/m ²)	Total Energy (t-m/m ³)
1	6m x 6m	13t	14	12m	6m	60	10
2	6m x 6m	13t	14	12m	6m	60	10
3	6m x 6m	13t	14	8m	6m	40	7
4	6m x 6m	13t	14	8m	6m	40	7
Total Energy input						200	34

9. Undertake DC



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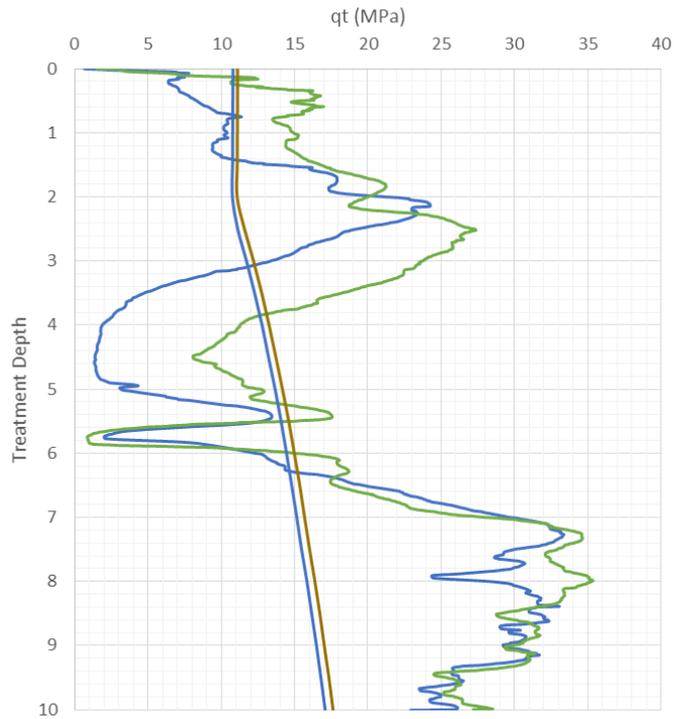


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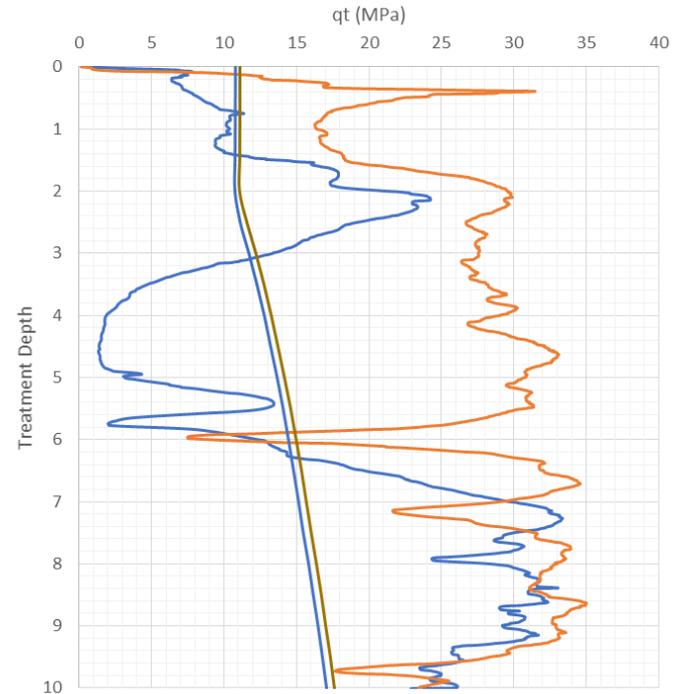
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10. Results

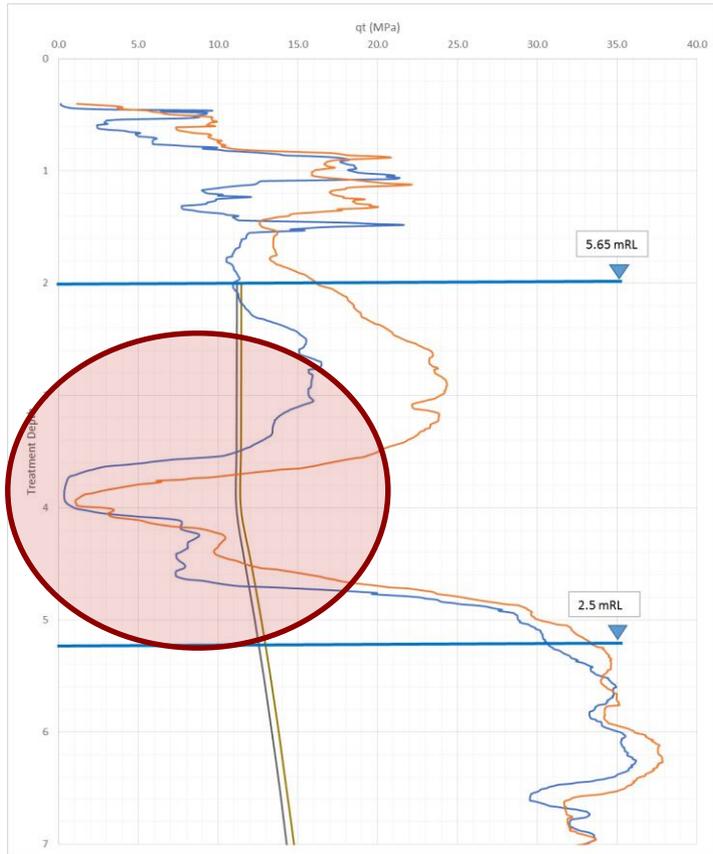
20t-m/m³



34t-m/m³



10. Results - Peat



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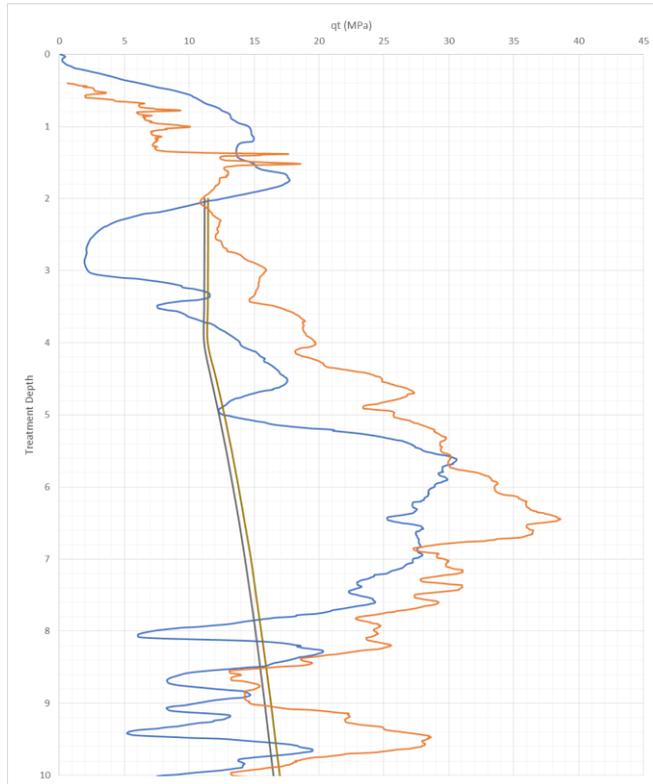
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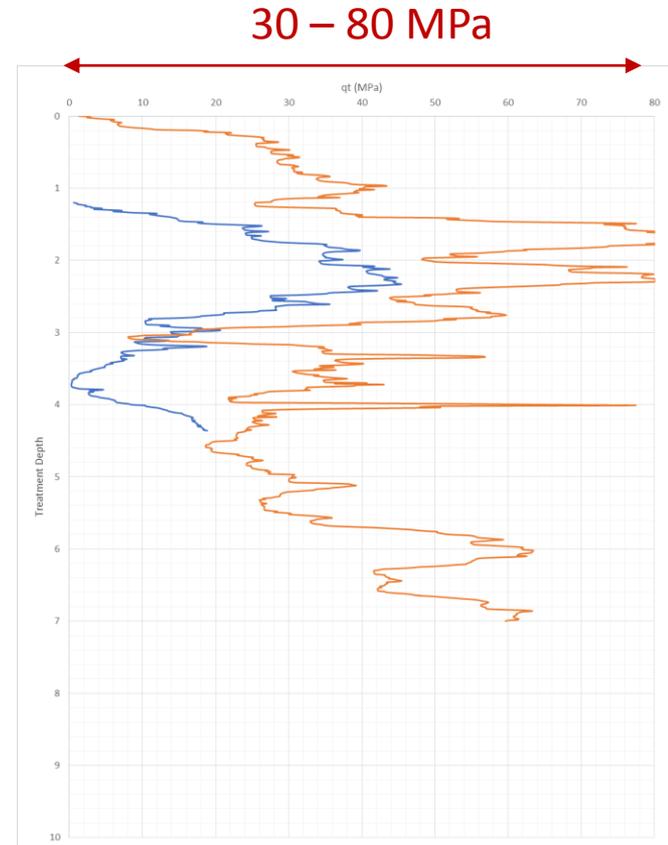
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Results – High Energy vs Low Energy

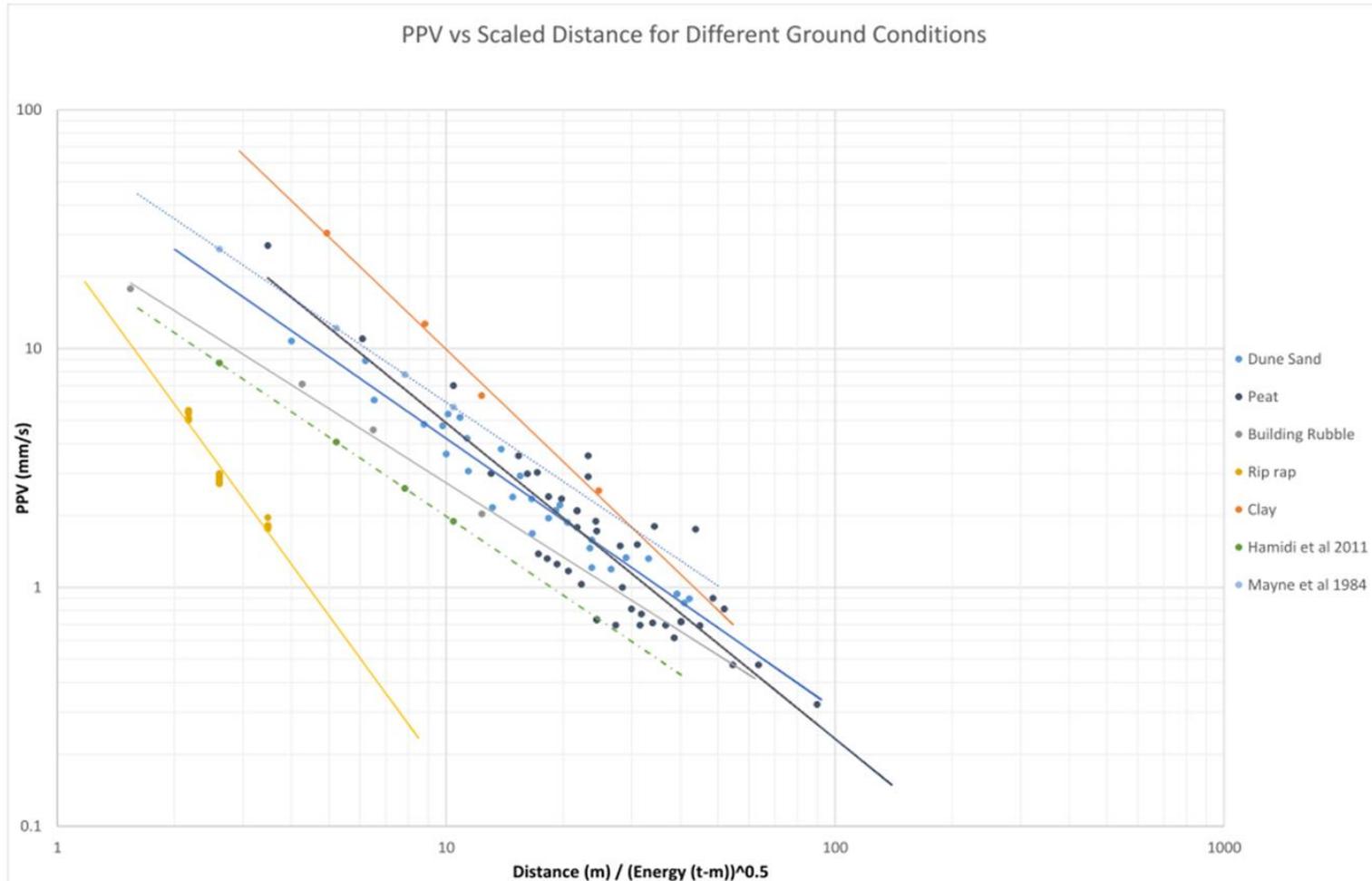
High Energy – 10m depth



Low energy – Stiff upper layer



Environmental Effects



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Environmental Effects

British Standard BS 5228-2:2009 defines the following guidance values for resultant peak particle velocities (PPV) at the foundation level for buildings in good condition:

- Structural damage: 50mm/s
- Minor architectural damage: 15mm/s
- Felt by occupants: 2.5mm/s

Contingency plan:

- Review drop height & drop weight
- Re-locate occupants if necessary
- Review and amend GI method



Innovations and R&D

- Currently working on developments in the following areas:
 - Dynamic Replacement in peat deposits
 - With and without the use of PVD drains
 - Dynamic Replacement Mixing method in peat deposits
 - Driving columns of sand into peat using low energy blows
 - Using high energy blows to then disperse sand column into the surrounding peat
 - Underwater ground improvement for land reclamation
 - DR columns, crane and barge work.
 - Drilled displacement columns in granular soil conditions
 - DDP columns for liquefaction mitigation

Discussion

Thank you for your attention!

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