Ground Improvement:
Empirical or scientific approach?

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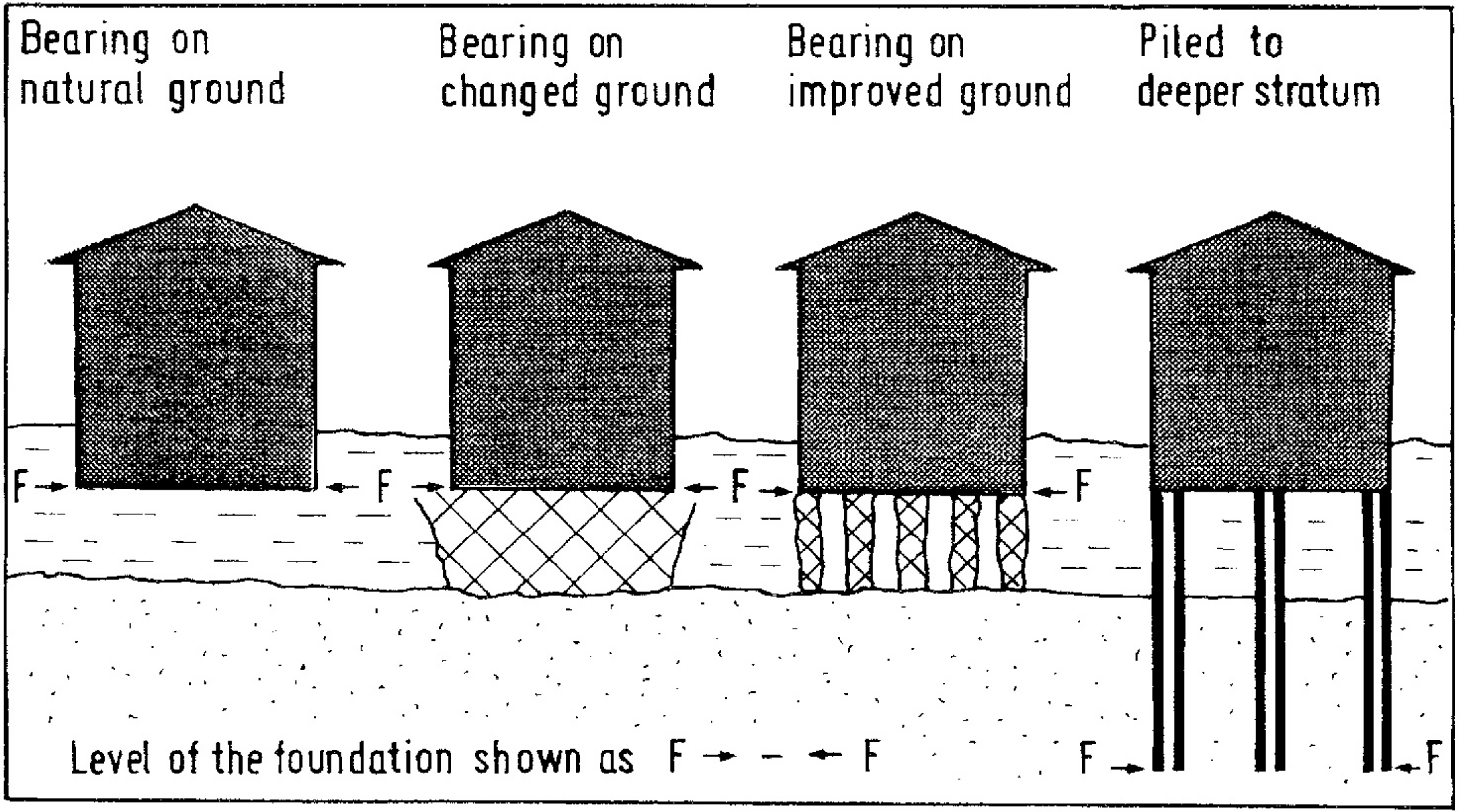
Ground Improvement – General:



Ground Improvement – General:

= old, but fast growing discipline in civil engineering

= major topic in geotechnical engineering

→ Technical Committee of ISSMGE on Ground Improvement

→ State-of-the-art-report on ground improvement by Jian Chu and Serge Varaksin for the 17th ICSMGE in Alexandria, October 2009.

Ground Improvement – State-of-the-art-report:

A good ground improvement method should be based on sound concepts and working principles.

The notion of “concept” is linked to the art of engineer.

It requires:

- the knowledge of the fundamental behaviour of soils
- the knowledge of various ground improvement techniques
- understanding of soil-structure interaction
- the knowledge of performance and limitations of available equipment
- economics

Ground Improvement – Classification:

Classification of ground improvement methods proposed by the TC of ISSMGE:

A. Ground improvement without admixtures in **non-cohesive soils** or fill materials
B. Ground improvement without admixtures in **cohesive** soils
C. Ground improvement with admixtures or inclusions
D. Ground improvement with grouting type admixtures
E. Earth reinforcement

Ground Improvement – Classification:

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 (also see Table 4)	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	D1. Particulate grouting	Grout granular soil or cavities or fissures in soil or rock by injecting cement or other particulate grouts to either increase the strength or reduce the permeability of soil or ground.
	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.

Ground Improvement – General:

= Many techniques are vailable

= Several tecniques can be used in very different soils

$\Rightarrow$ Analytical design methods will never be available for all combinations technique-soil

$\Rightarrow$ Empirism will remain important for the design of ground improvement works

Gerond Improvement – General:

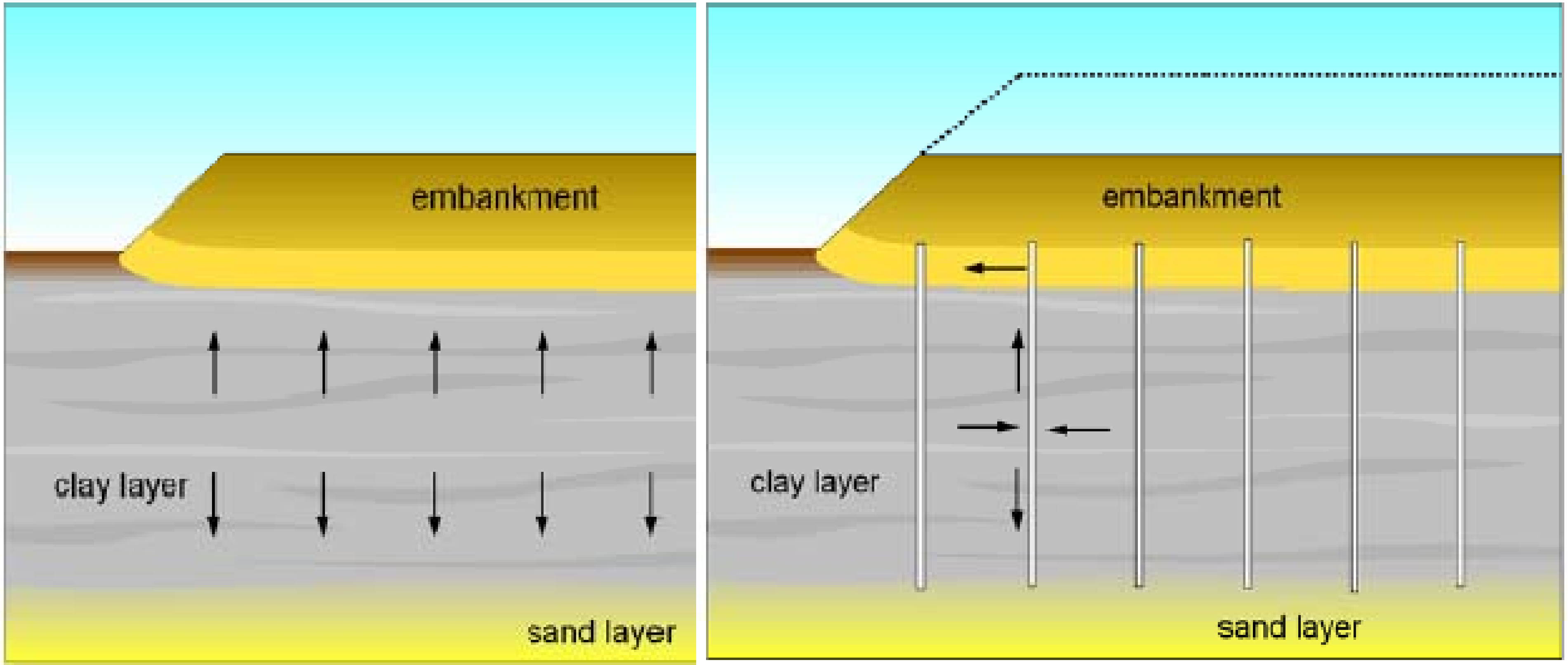
Exampels:

- Vertical drains
- Stone columns
- Deep mixing

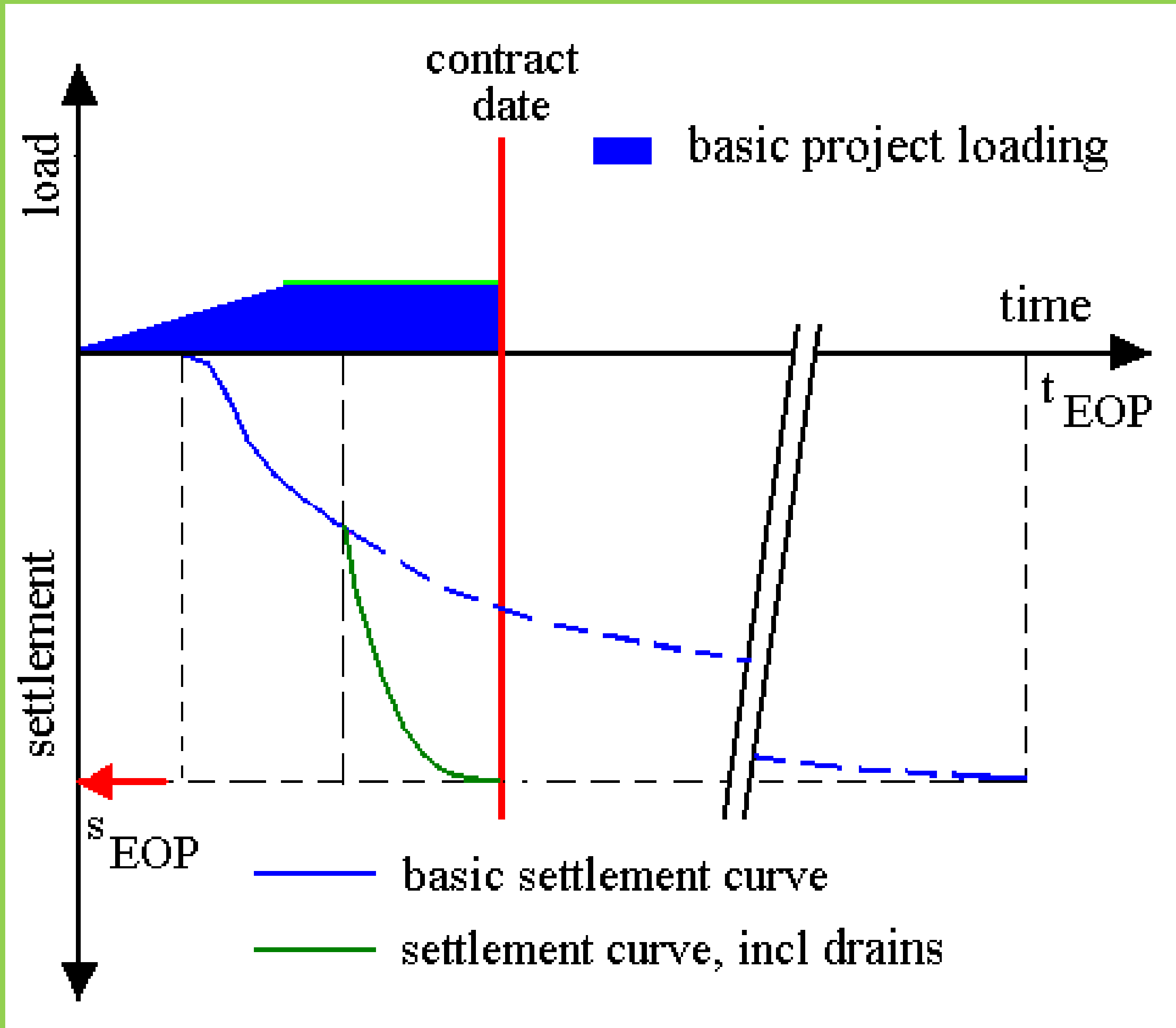
Vertical drains – General:

<u>Aim:</u>

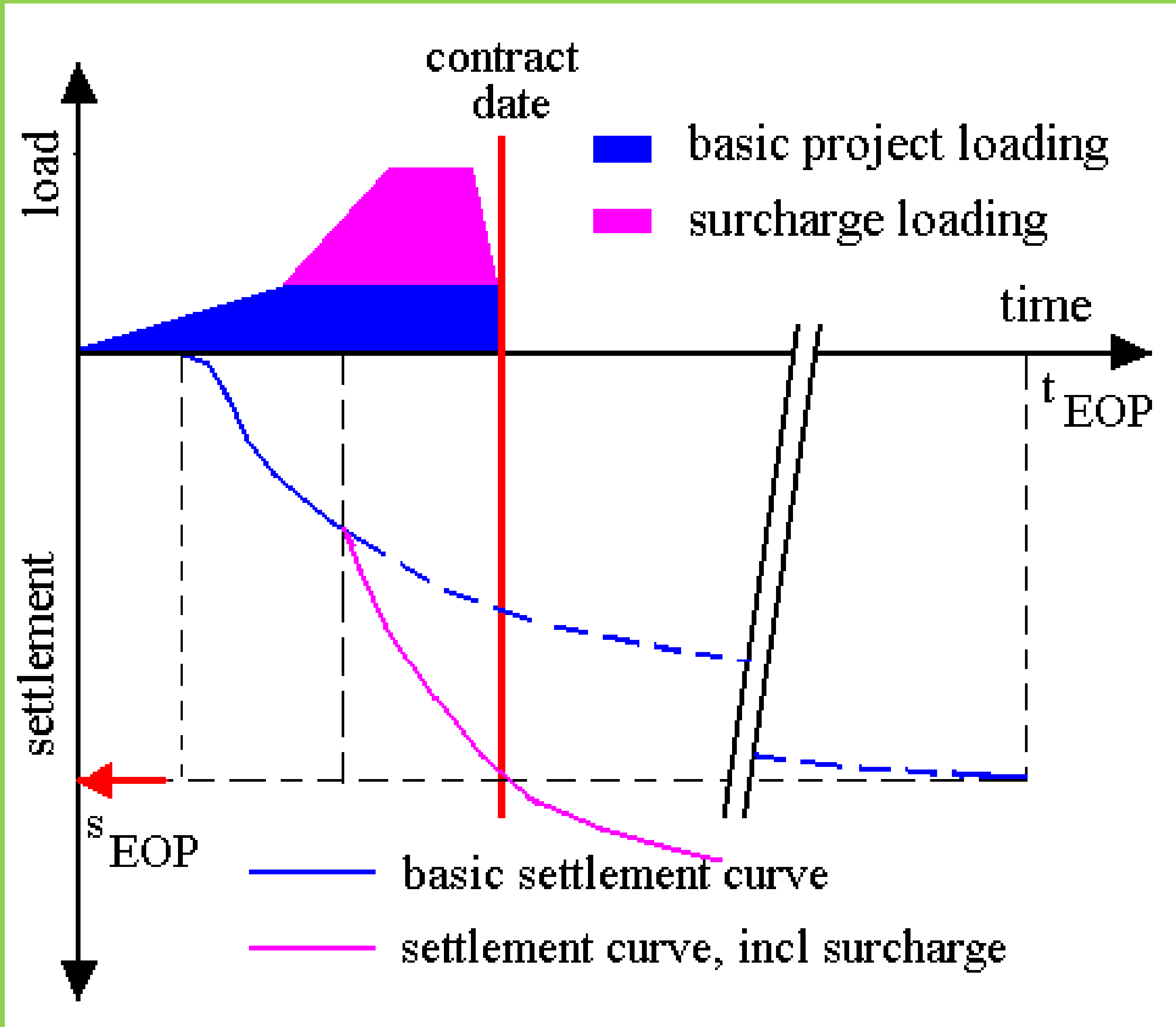
- accelerate settlements
- increase bearing capacity



Vertical drains – settlements:

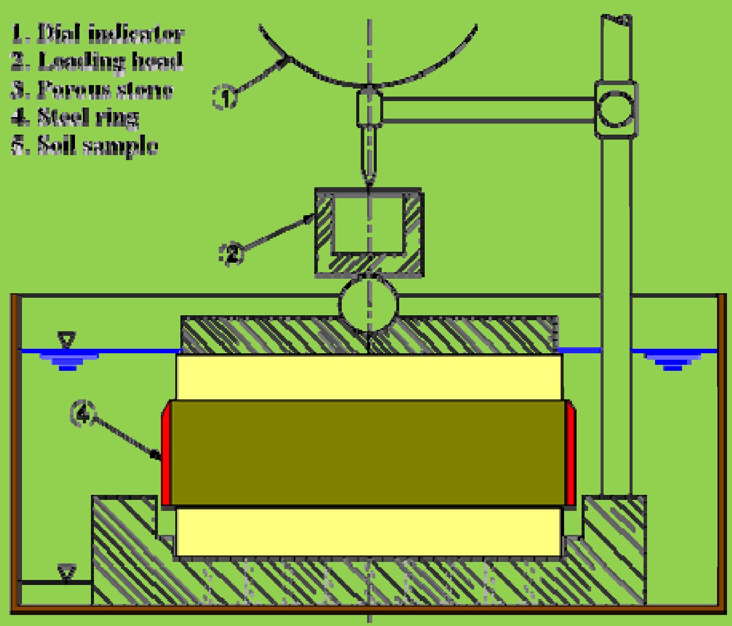


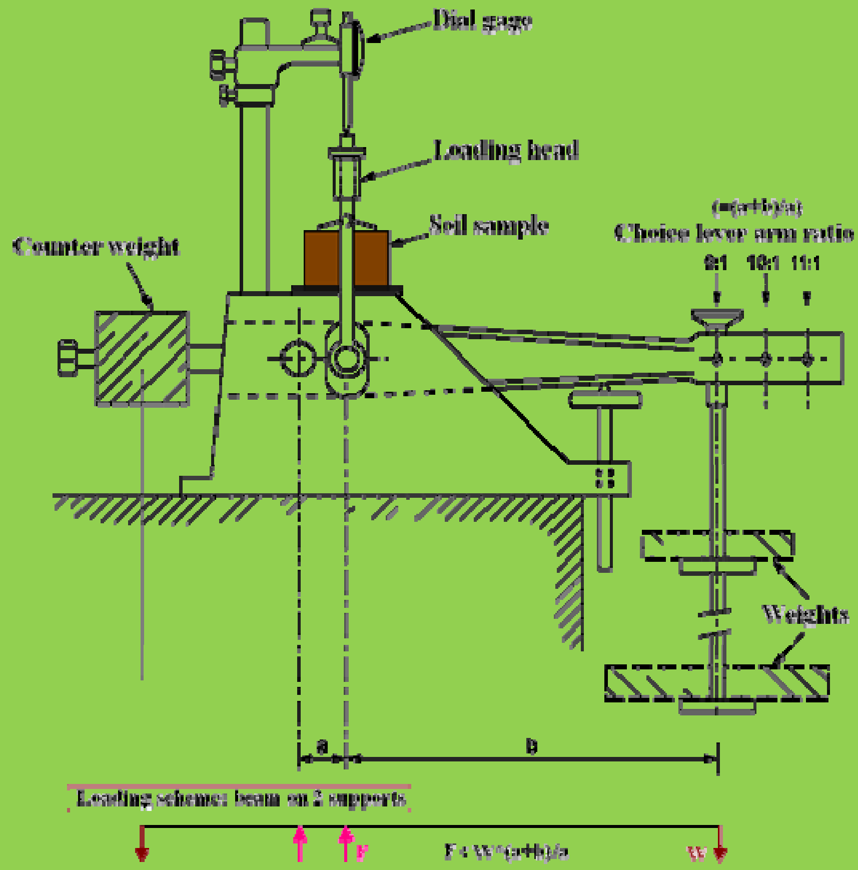
Vertical drains – peloading:



Vertical drains – Design:

The intermediate distance between the vertical drains is determined based on c_v deduced from oedometer tests

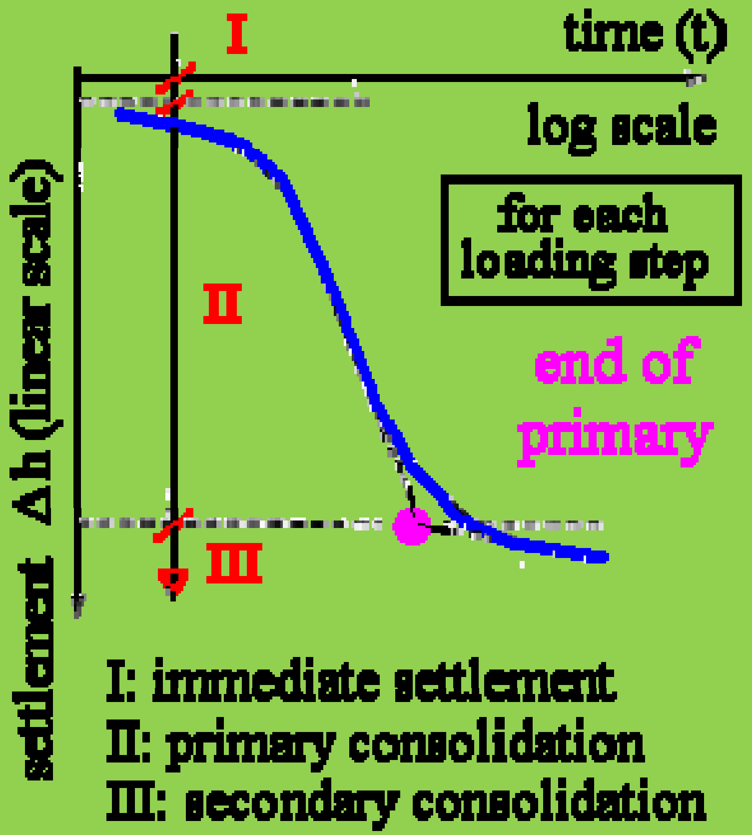




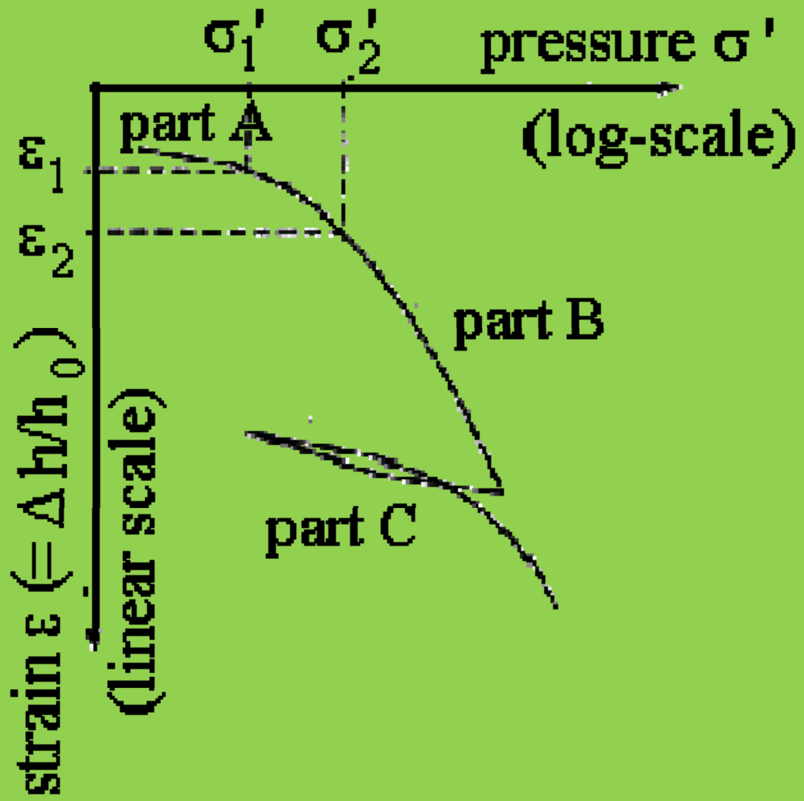
Oedometer:

Vertical drains – Design:

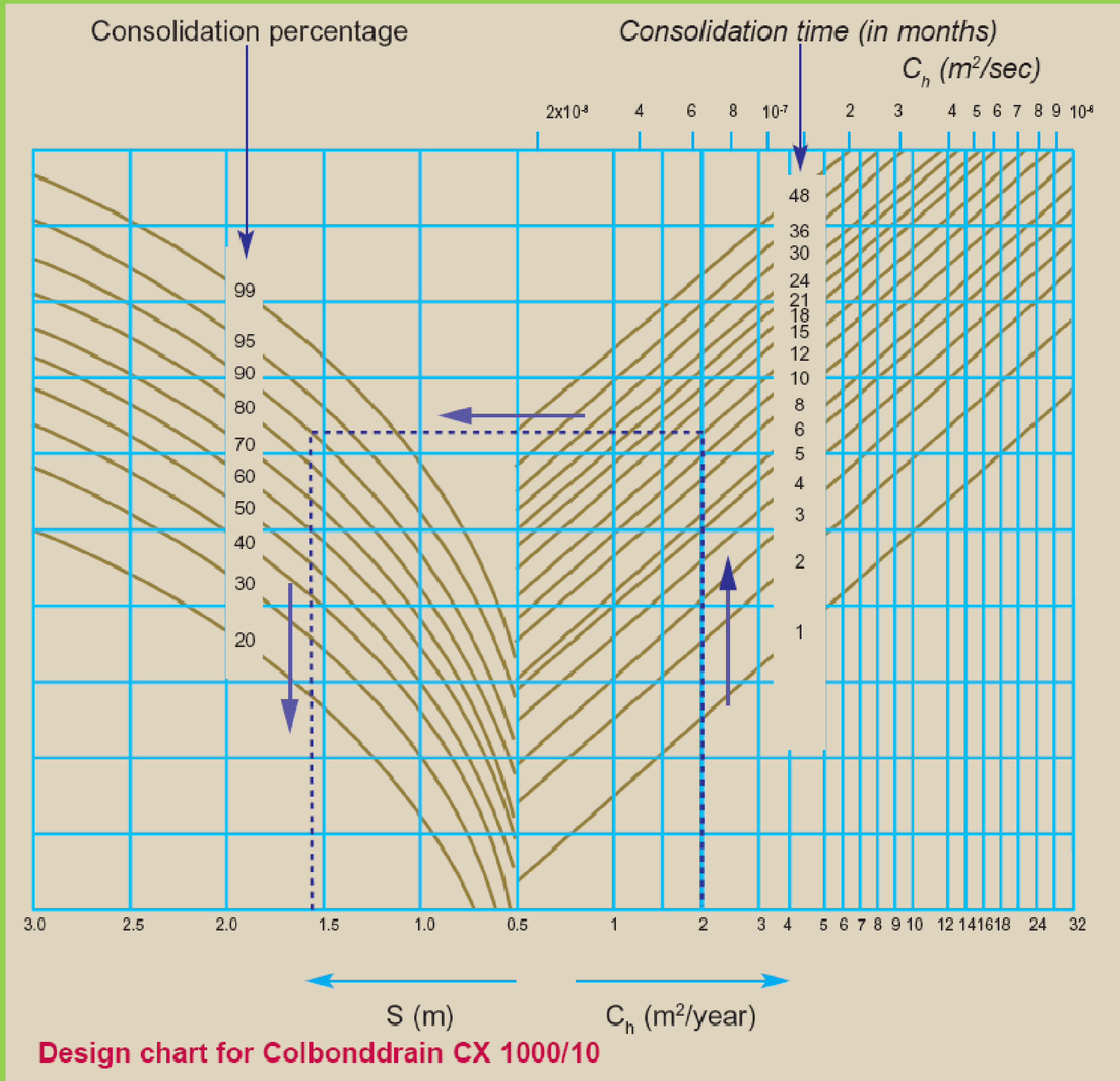
Settlement vs. time for a loading step



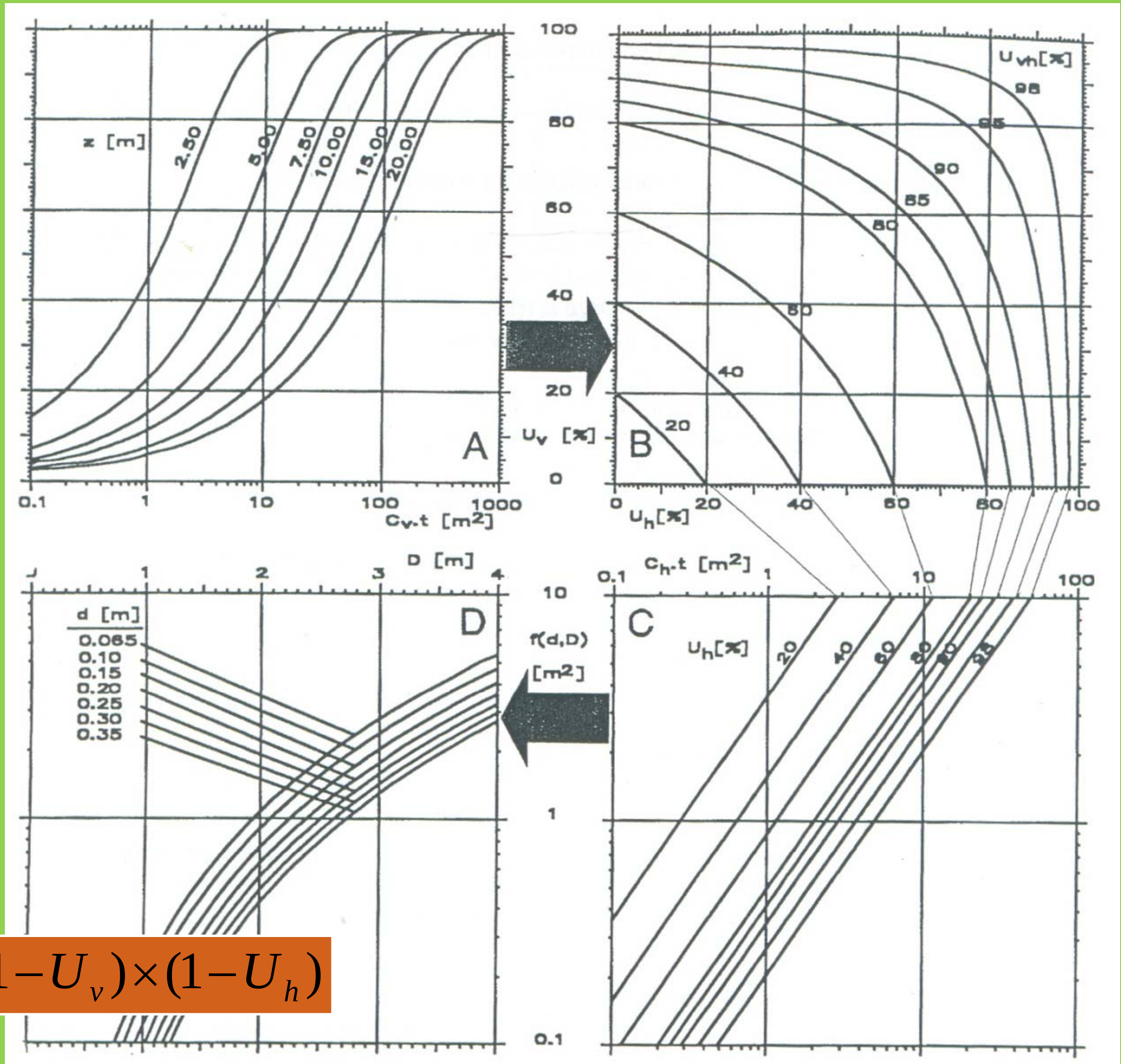
Load-settlement diagram



Vertical drains – Common design graphs:



Vertical drains – Common design graphs:



$$1-U_{vh}=(1-U_{v})\times(1-U_{h})$$

Vertical drains – Design:

Design graphs based on c_h –value:

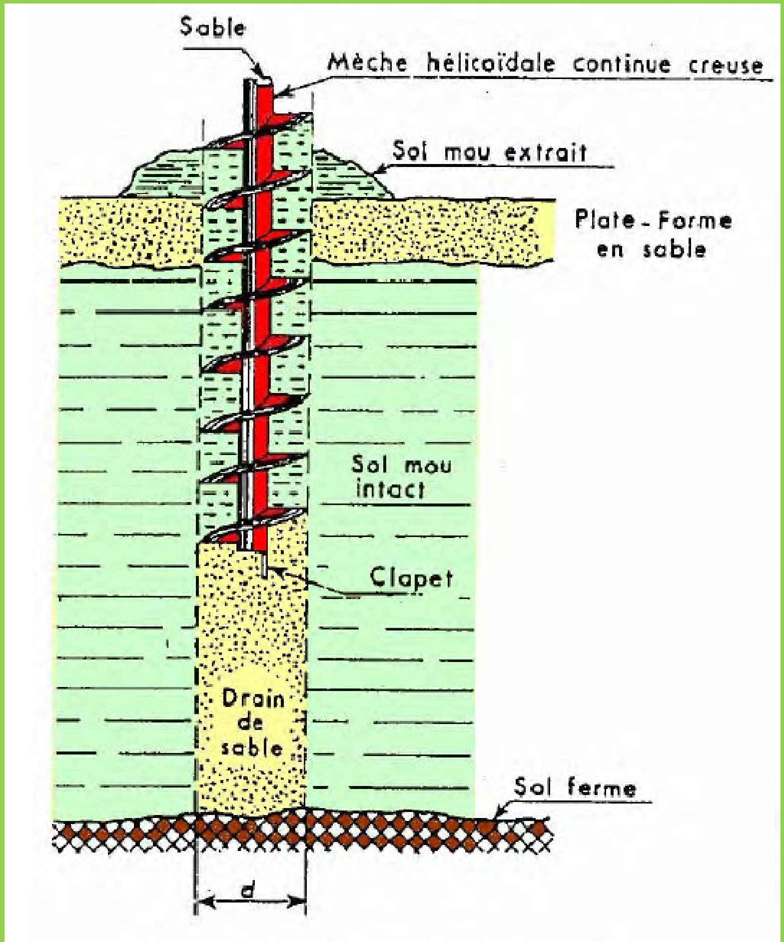
c_h = 1,5 à 10 x c_v

Common procedure:

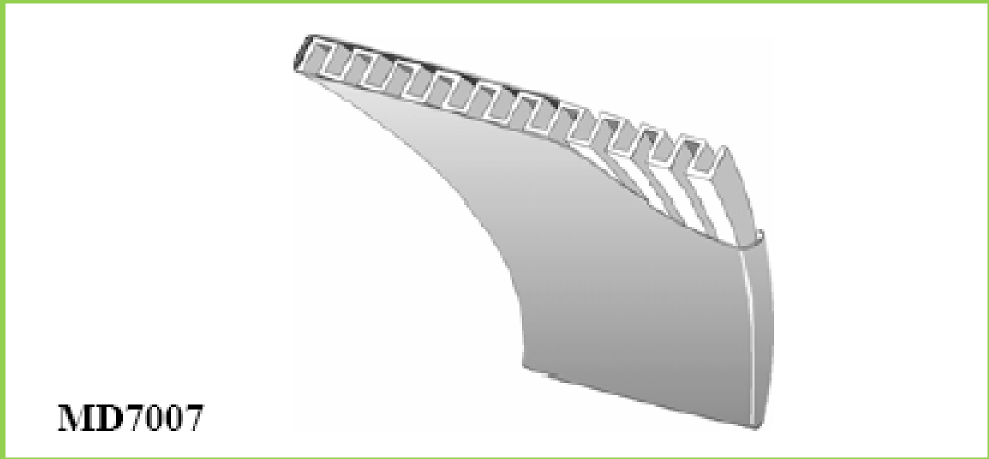
- For small projects:
  - $\rightarrow$ conservative c_h value
- For large projects:
  - $\rightarrow$ test field at the beginning
  - $\rightarrow$ extrapolation of obtained results

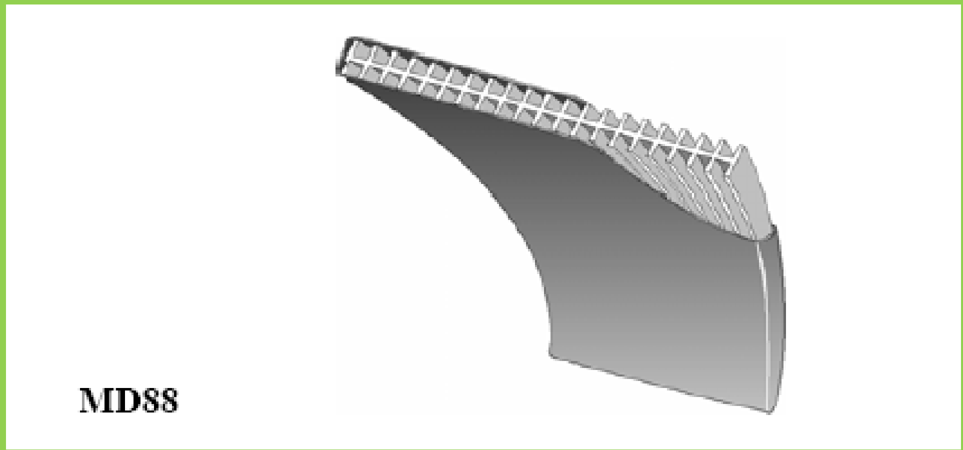
Vertical drains – Execution:

sand piles

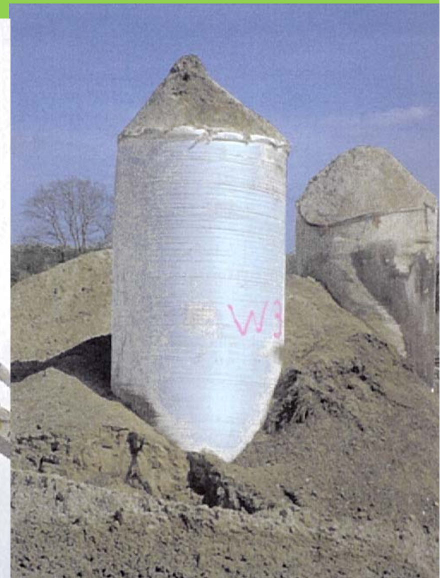


prefabricated vertical drains





Sandpiles sourrounded with geotextiles:



Installation of prefabricated vertical drains:

Installation of prefabricated vertical drains at TCP terminal:

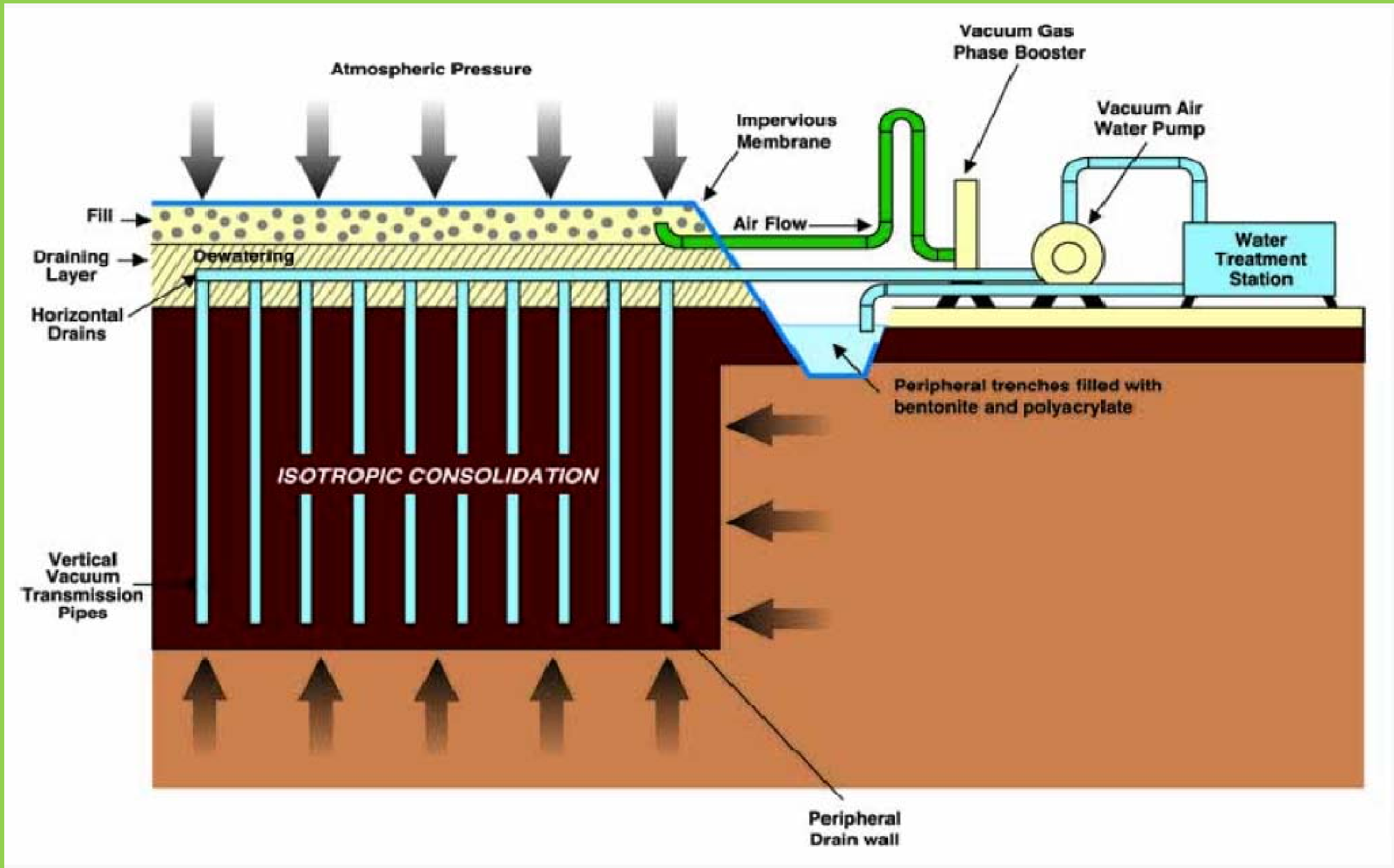
Installation of prefabricated vertical drains at TCP terminal:

Installation of preload at TCP terminal:

Vertical drains – preloading:

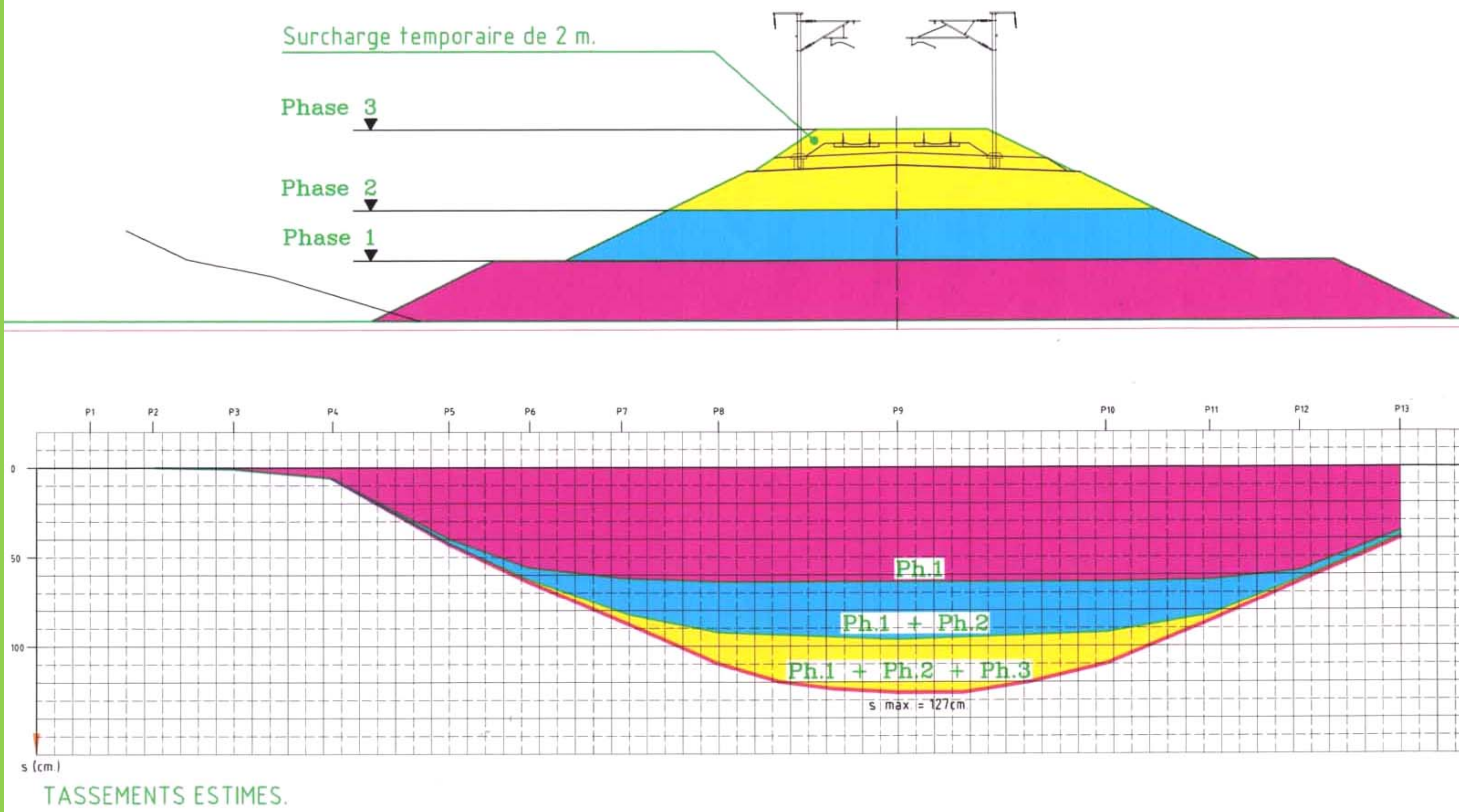
Normally by means of soil

Alternative: vacuum

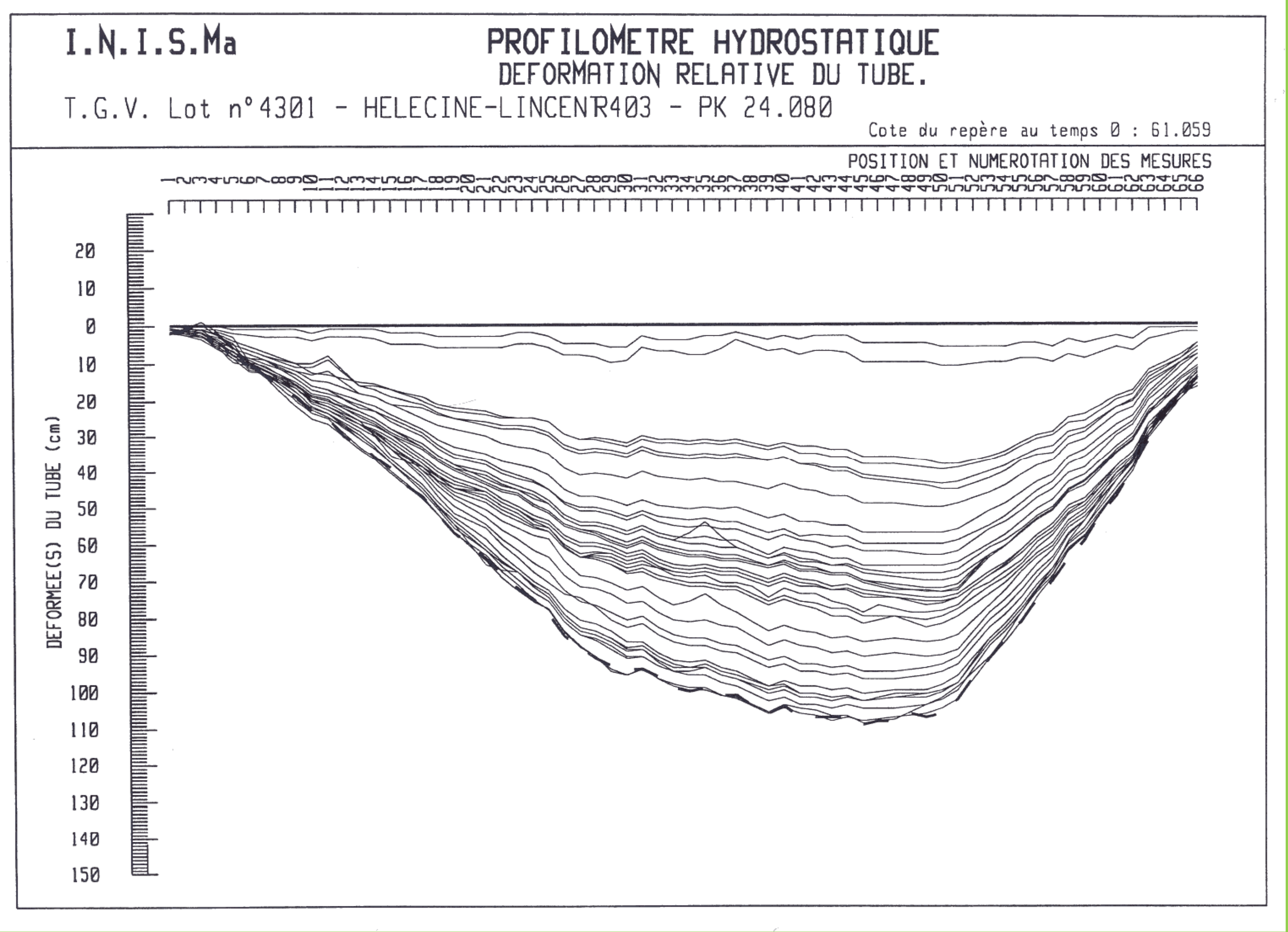


Controll of settlements – prediction:

« GOLLARD » VALLEY
Embankment performed in 3 phases



Controll of settlements - Measurements:



Vertical drains – Conclusion:

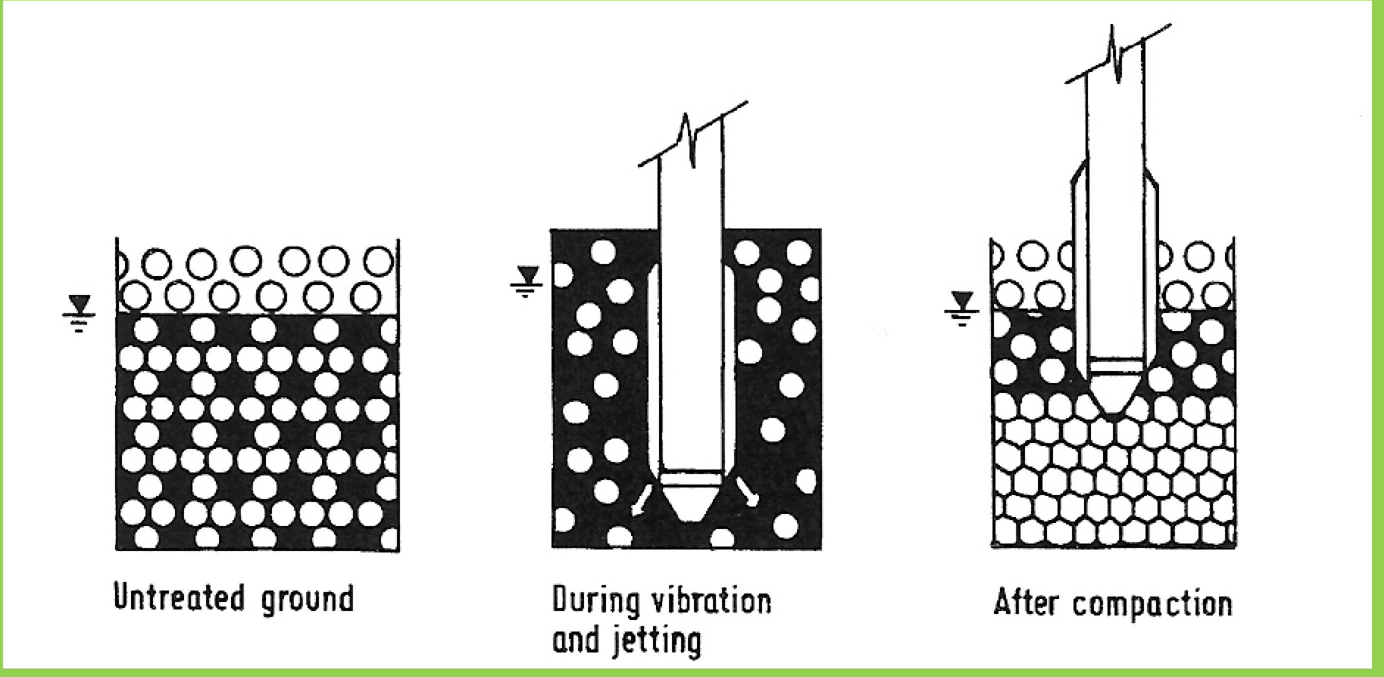
- Analytical approach based on results of oedometer tests
- Information from previuos projects in similar conditions is very important to:
  - check the c_v values from oedometer tests
  - determine the c_h value
  - become aware of possible anomalies
- Controll of settlements is very important to improve the predictions for future projects.

Vibrocompaction:

<u>Aim:</u>

to increase the relative density of <u>*loose sands/gravels*</u> and to improve:

- the bearing capacity, f.i. underneath isolated foundations
- the stiffness, f.i. underneath foundation slabs
- the shear resistance, f.i. underneath slopes
- to avoid liquefaction

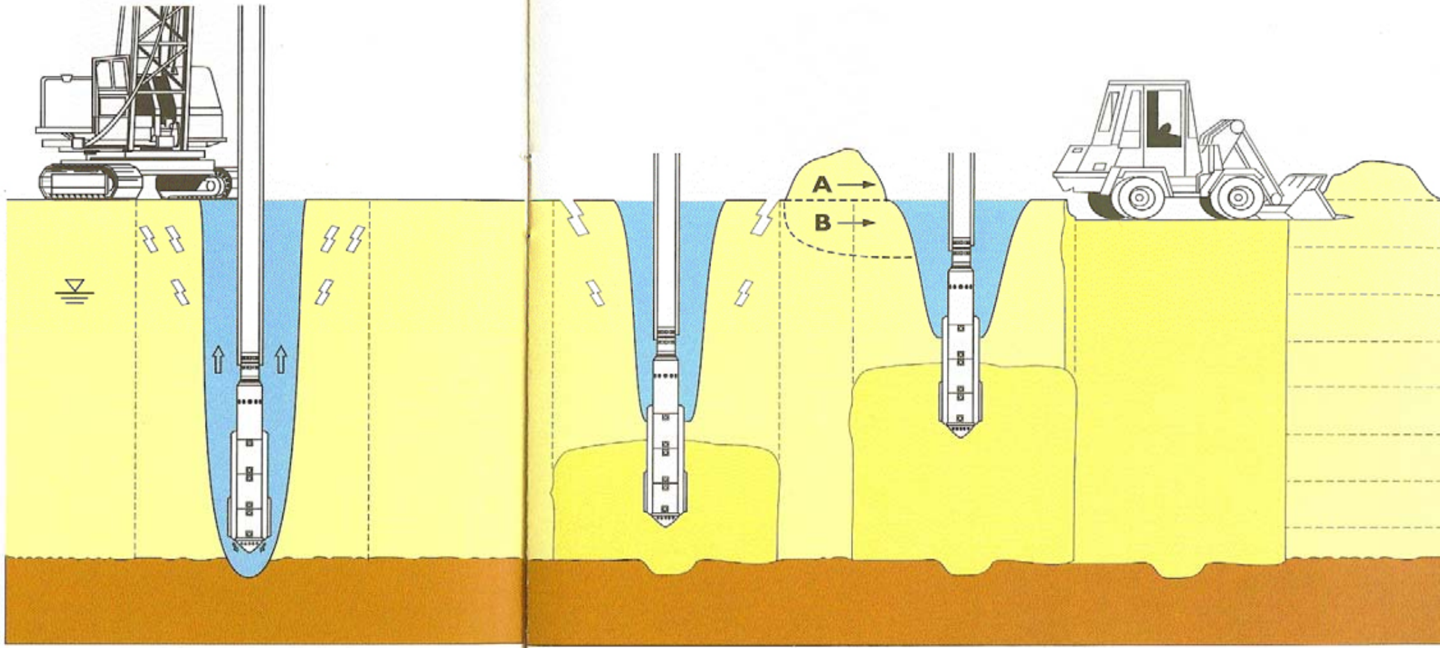


Vibrocompaction:

<u>Execution:</u>

- Horizontal vibrations (= vibroflot nail):
  - wet method
  - dry method
- Vertical vibrations (= vibratory probing)

Vibrocompaction – wet method:



The Process STEPS

1 Penetration

At full water pressure the vibrator penetrates to design depth and is surged up and down as necessary to agitate sand, remove fines and form an annular gap around the vibrator. Once at depth the water flow is stopped or reduced.

2 Compaction

Under the action of induced horizontal forces the soil particles surrounding the base of the vibrator are rearranged to a denser state of compaction. The vibrator is raised in steps after the required compaction is achieved.

3 Refilling

During compaction sand fill is added which is either imported (A) or from the existing soil (B). The surface of the area being compacted may either settle up to 15% of the treated volume or the equivalent volume has to be imported.

4 Finishing

With an economical layout of the compaction probes, an optimum improvement can be achieved. The surface of the compacted area has to be relevelled and, if required recompacted with a surface vibrator.

Vibrocompaction – wet method at TCP terminal:

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Vibrocompaction – wet method:

<u>Design:</u>

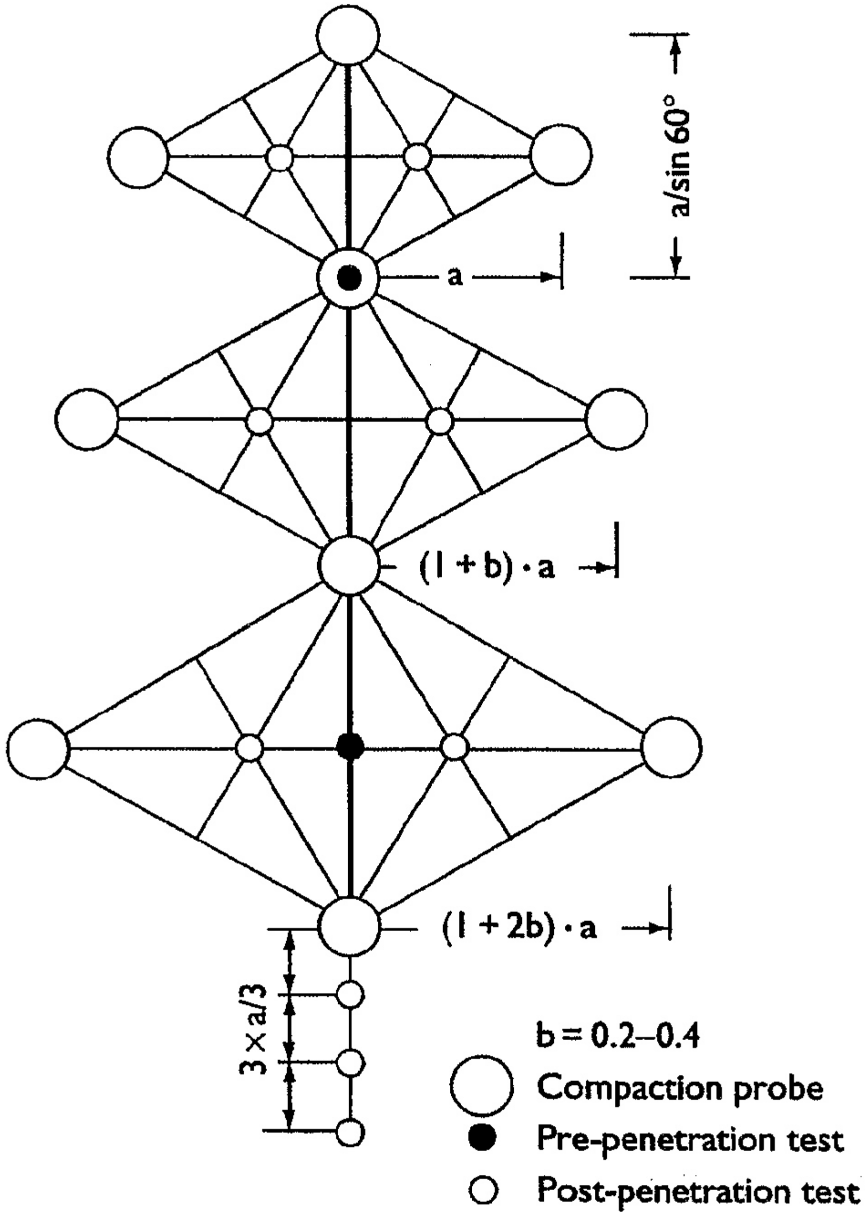
- Vibrocompaction can only be performed in soils having less than 15% fine particles (< 74µm)

- The intermediate distance between the compaction points is determined based on:
  - the bearing capacity and stiffness to be obtained
  - the available equipment

- In most cases preliminary tests are necessary to determine the intermediate distance to be applied

Vibrocompaction – Design:

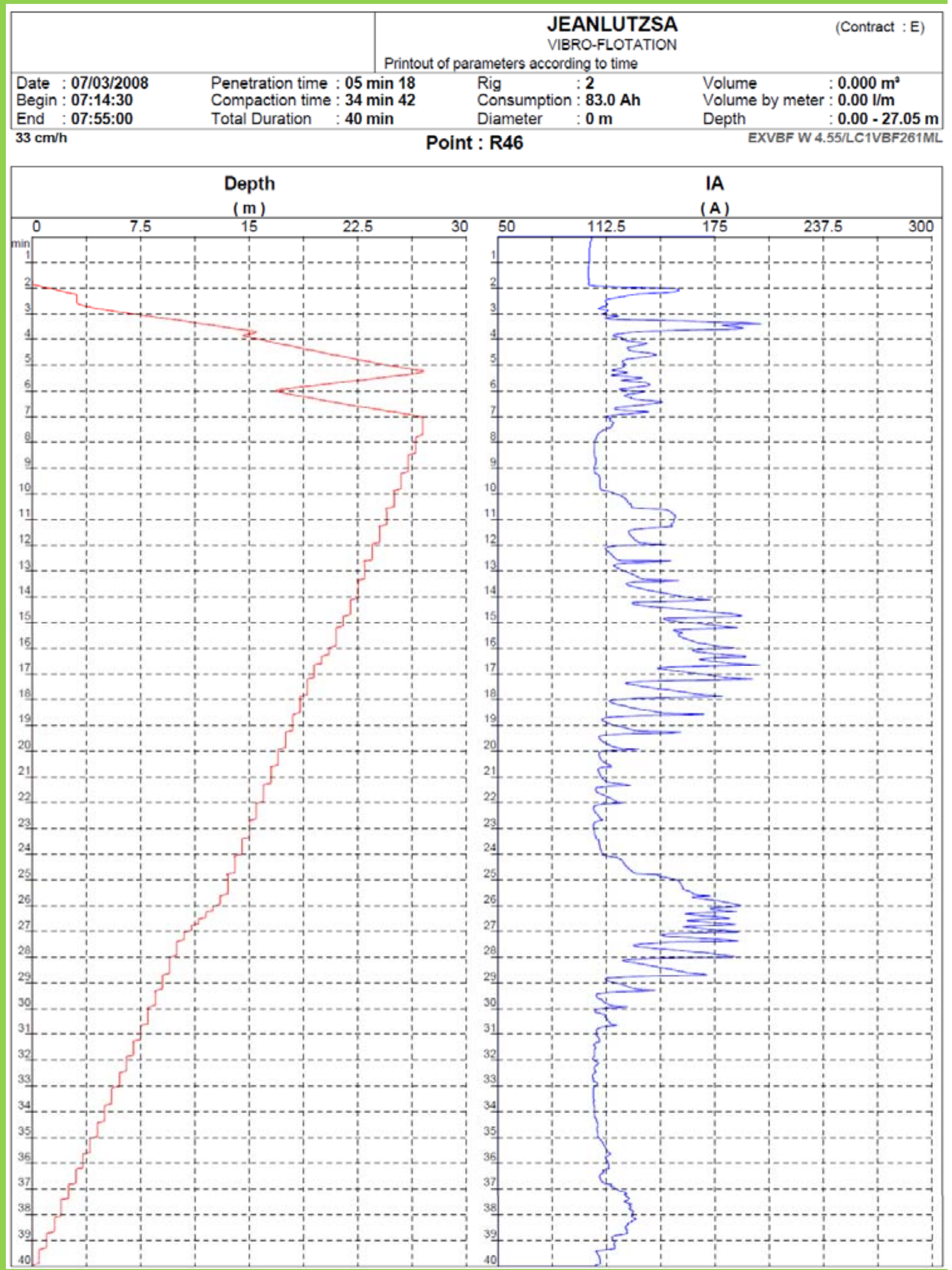
<u>Preliminary tests:</u>
Typical pattern for
- compaction points
- pre-compaction tests
- post-compaction tests



Vibrocompaction:

Control:

- during execution:
  - energy consumption
  - induced settlements
- after execution:
  - SPT or CPT test



Vibrocompaction - conclusion:

- Analytical approach will never be possible
  - ⇒ conservative desgn for small projects
  - ⇒ preliminary tests for large projects

- Good knowledge of the soil to be compacted is absolutely necessary (% < 74 µm)

- Controll methodology is very important

- New methods are developped:

  example = Rapid Impact Compaction
  - additional compaction is more easy
  - controll during compaction is possible = settlement per blow

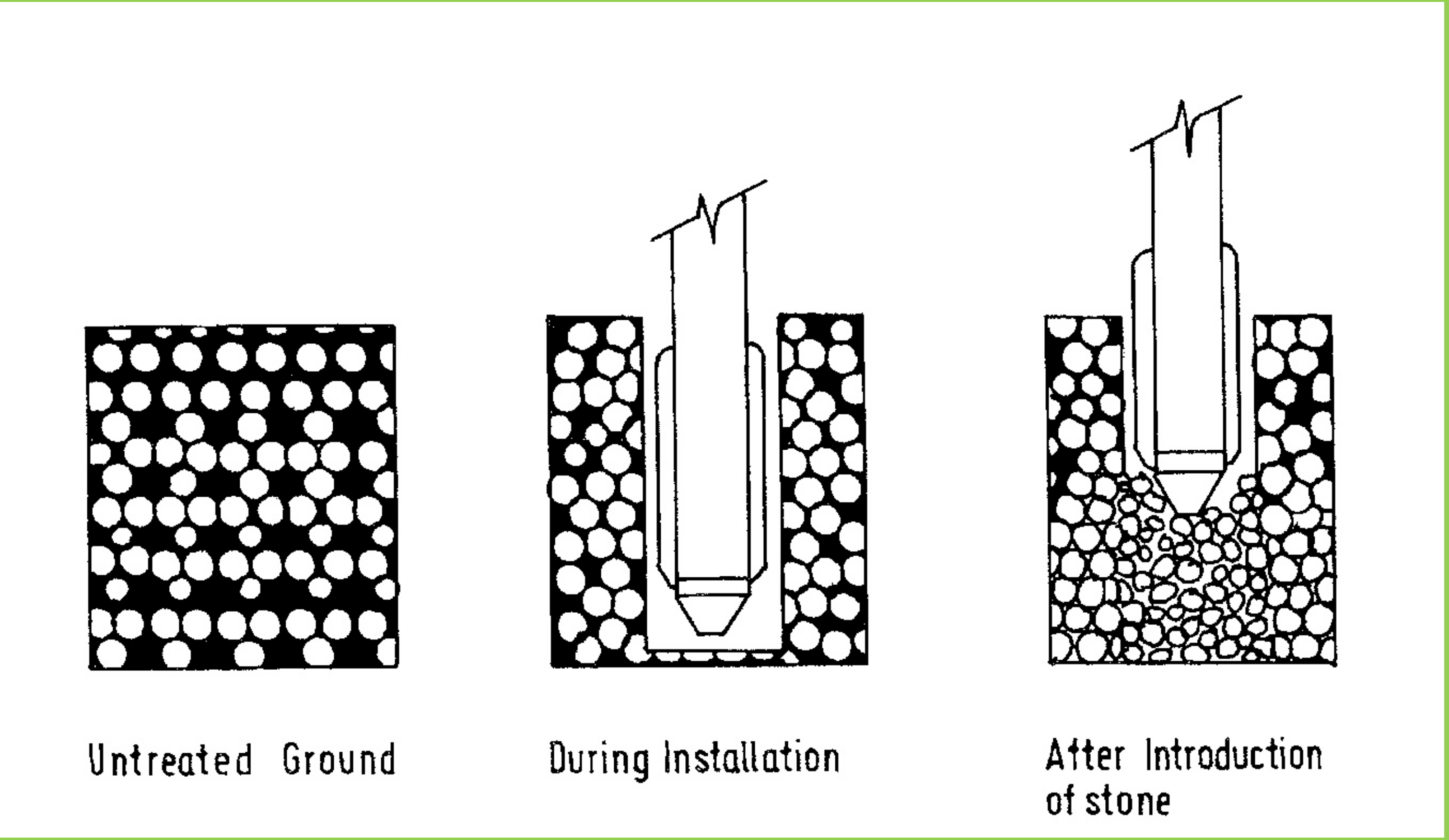
- Rapid Impact Compaction
- Driving on a steel plate 1 m diameter
- Each Impact point 30-40 blows
- Special Pattern with 2 or 3 passes
- Equipment: BSP
- Depth of influence: up to 6 m

Rapid Impact Compaction:

Stone columns:

<u>Aim:</u>

to improve the bearing capacity and / or the stiffness of *<u>soft clays and soft silts.</u>*

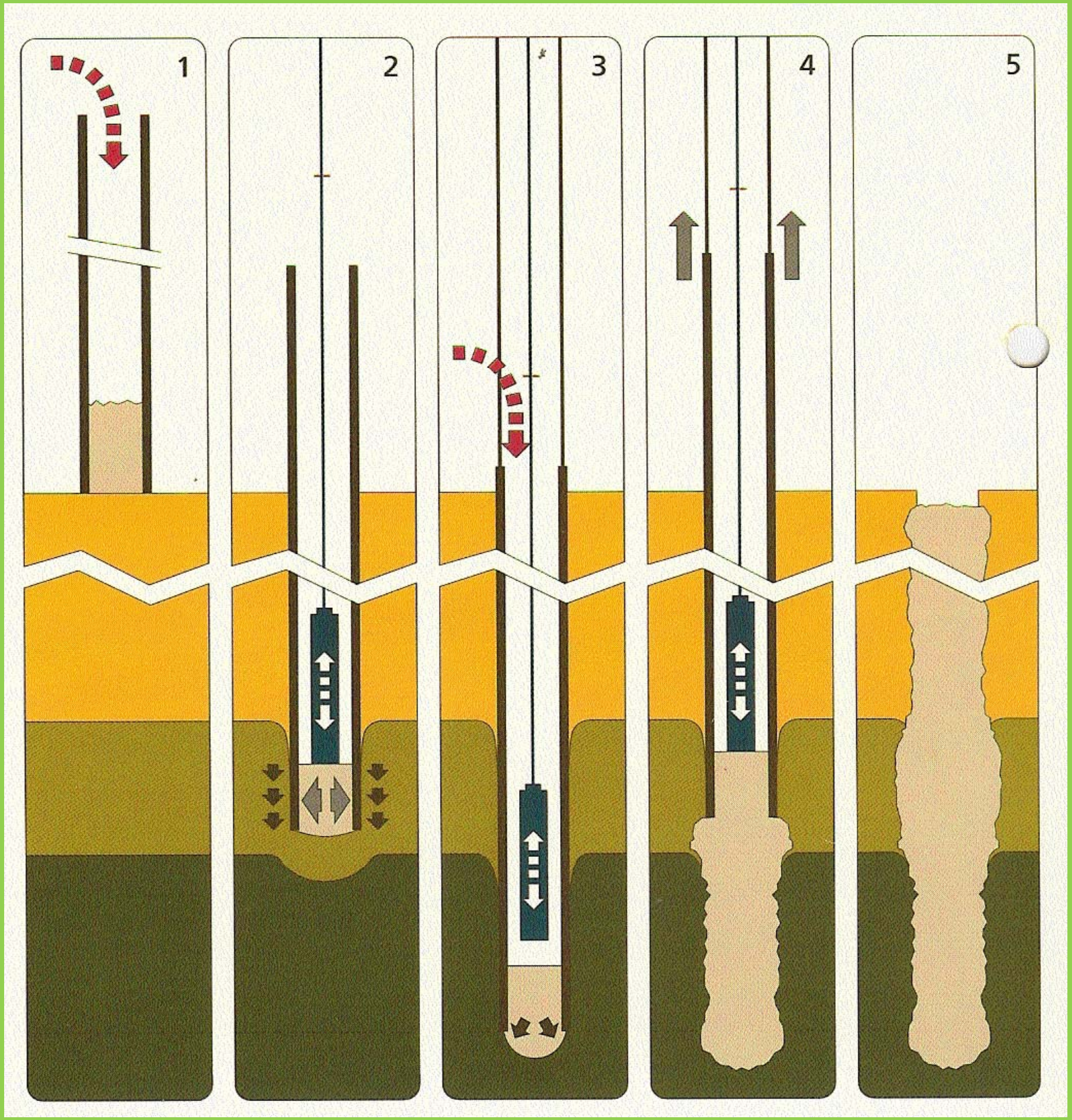


Stone columns:

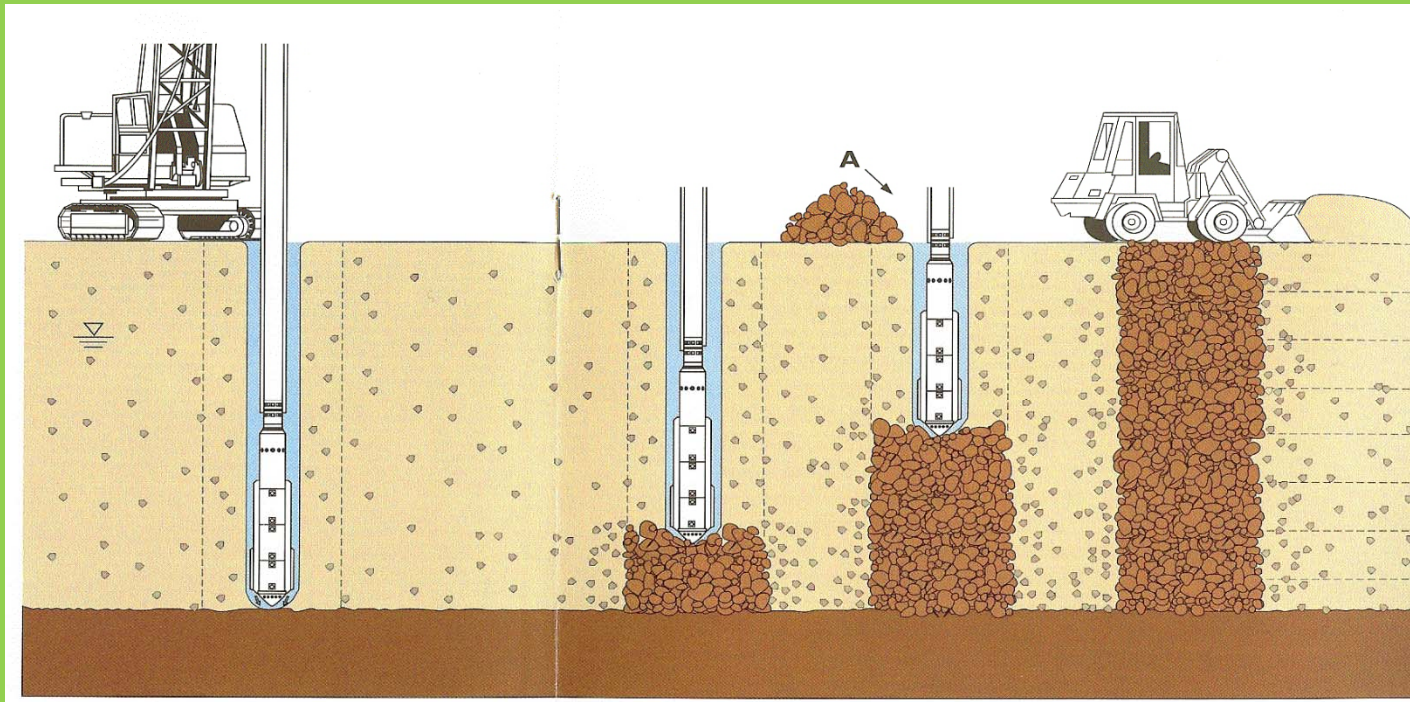
<u>Execution:</u>

- by driving a steel tube into the soil and filling it up with stones or gravel
- with special equipment (= vibroflot nail) wet or dry method

Stone columns by driving a steel tube:



Stone columns with vibroflot nail – **wet** method:



The Process — **STEPS**

1 Penetration

Assisted by jetting water, the oscillating vibrator penetrates to the designed depth under its own weight. Thereafter the water jets are adjusted in such a way that an annular space remains open around the vibrator and its extension tube.

2 Replacement

Once at depth coarse grained backfill material is now filled into the hole down to the toe of the vibrator. By moving the vibrator in small steps up and down and by the horizontal forces of the machine itself, the supplied stones are pressed into the existing soil.

3 Finishing

With stones being added as required this process is repeated up to ground level, leaving on completion a well compacted, tightly interlocked stone column surrounded by soil of enhanced density.




Stone columns with vibroflot nail – **dry** method:

The Production Sequence

1
Vibrator placed on top of the working platform.

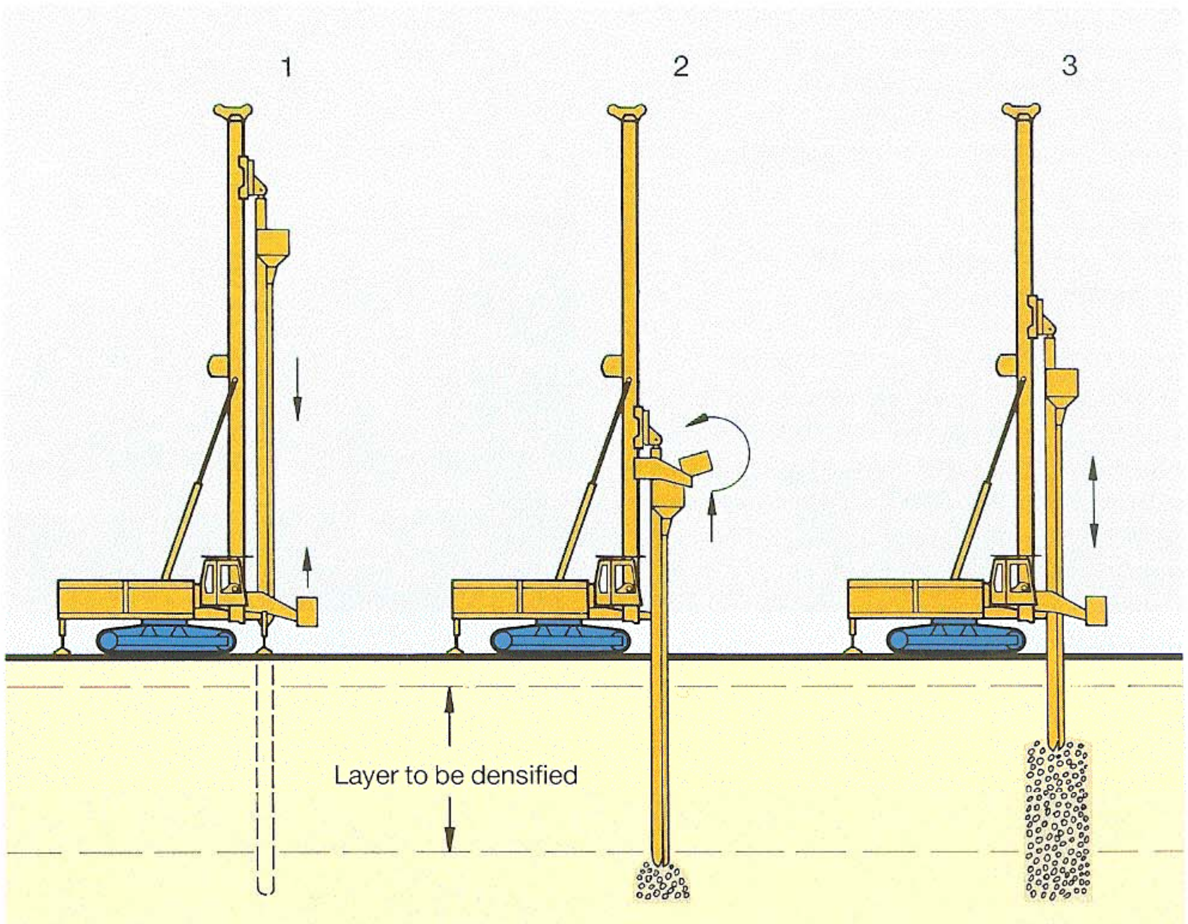
Transfer pipe and storage container filled with import materials.

2
Vibrator lowered to desired depth.

Vibrator retracted in 0,5 m (20 in) intervals; import material exits tip.

3
Vibrator lowered again, thereby densifying the import material.

Sequence repeated until optimal densification achieved.



Stone columns – Design:

The intermediate distance between the columns is determined based on:

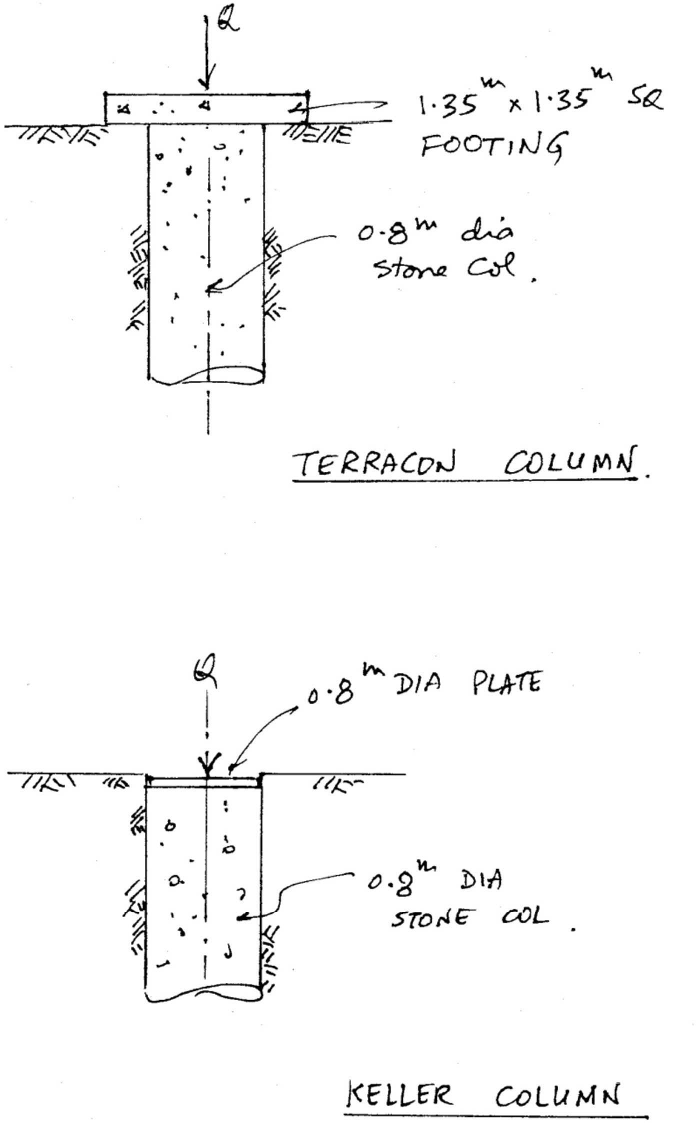
- the load to be transmitted
- the shear strength of the soil
- the allowable settlements
- the diameter of the stone columns

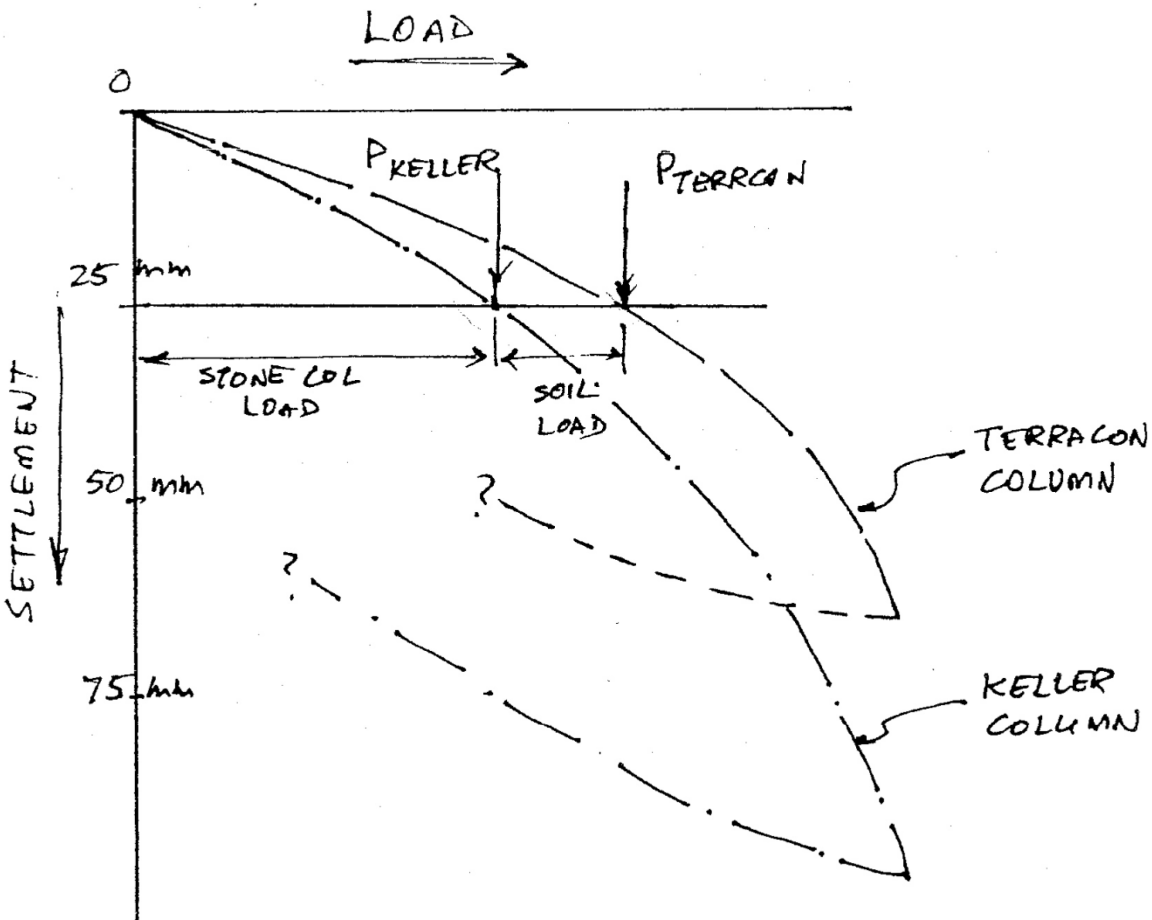
2 aproaches:

→Priebe method = plastic deformation of the stone column is allowed

→ Stone column as bearing element = max. load limited to 250 à 350 kN based on static load tests

Stone columns – Static load tests:





Load settlement curve is influenced by the test set-up

Stone columns – Conclusion:

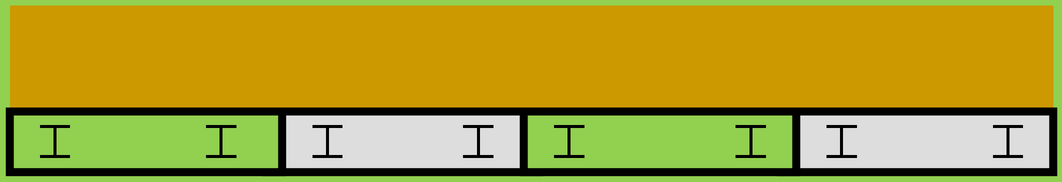
- Stone columns are applicable in almost all soils , except peat
- Analytical approaches are available:
  → Very different behaviour when plastic deformation is allowed or not
- Controll methodology is very important

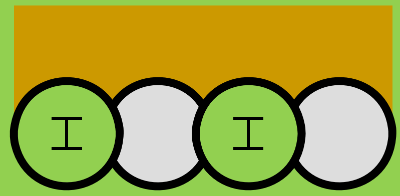
Soil mixing – General:

<u>Aim:</u>

Stabilise the soil by mixing it with a binder (= cement, lime and/or additives)in order to:

- increase the bearing capacity and / or the stiffness
- realise retaining walls





Soil mixing – General:

Soil and water retaining walls

- temporary (or permanent)
- soil mix determines the bending stiffness of the wall
- bending moments : only the reinforcement (steel beams) is taken into account
- soil mix transfer the ground/water pressures to the reinforcement

Execution:

Special mixing tools have been developed for dry and wet mixing

- 1, 2 or more vertical shafts with mixing blades or augers
- special tools for cutter soil mixing and block stabilisation

Deep mixing - execution methods:

Deep mixing

Belgium

wet

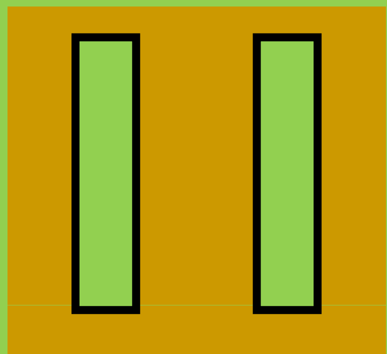
Dry

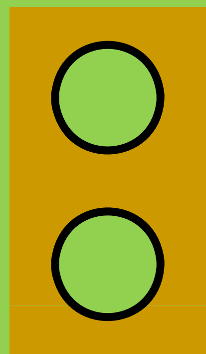
CSM

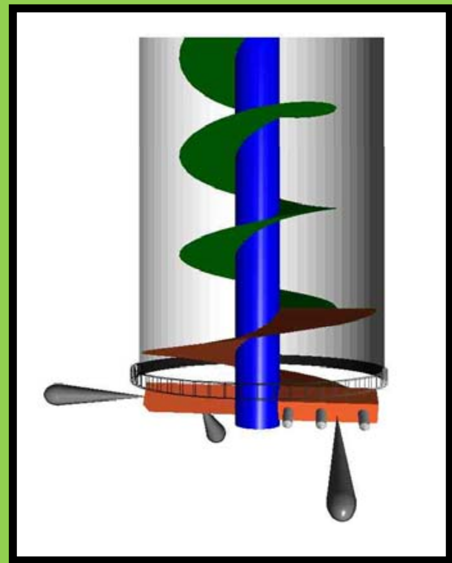
Rotatie

Rotatie + jet

Soetaert





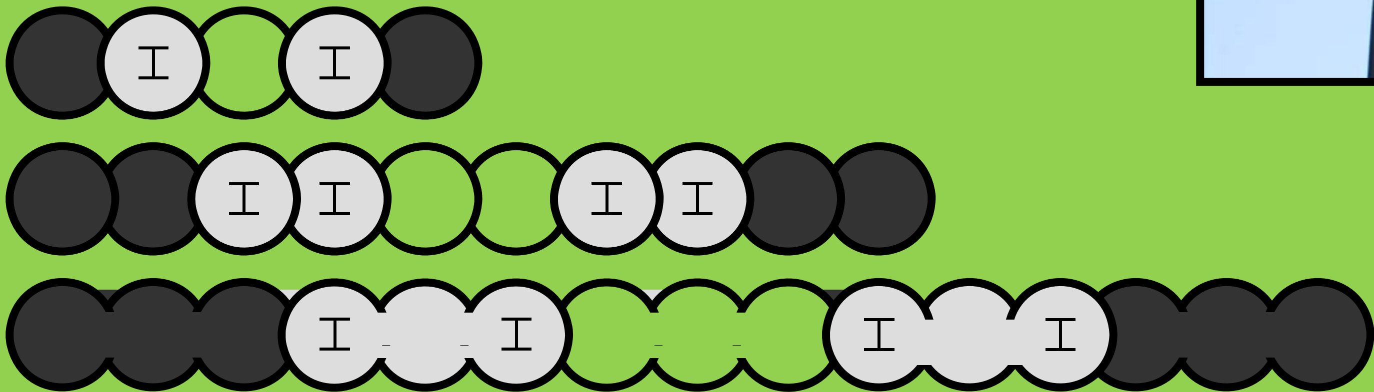


Smet

Soil mix systems on the Belgian Market

C-mix (TWINMIX, TRIPLE C-mix)

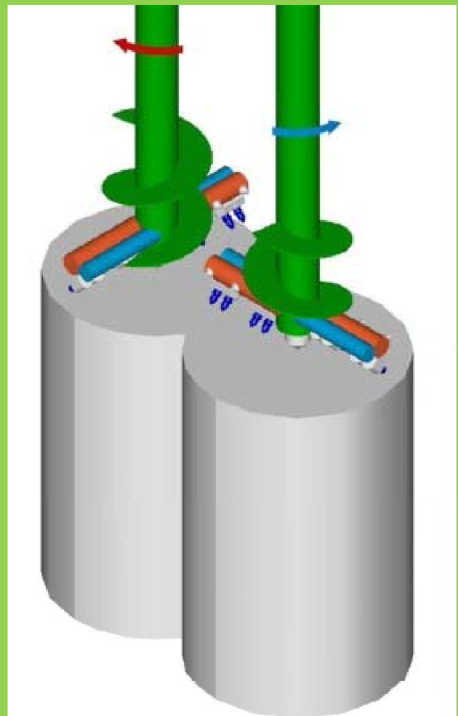
– Mainly mechanically mixed
  - High rotation speed
  - Special mixing tool



Soil mix systems on the Belgian Market

Tubular Soil Mixing (Twin / Triple – soil mix)

- Combination jet-grouting and auger pile techniques
- Mainly hydraulic mixing (up to 500 bar)



Smet

Soil mix systems on the Belgian Market

CSM : Cutter Soil Mixer

- Commercialised system to realize panels

Soetaert

Soil mix systems on the Belgian Market

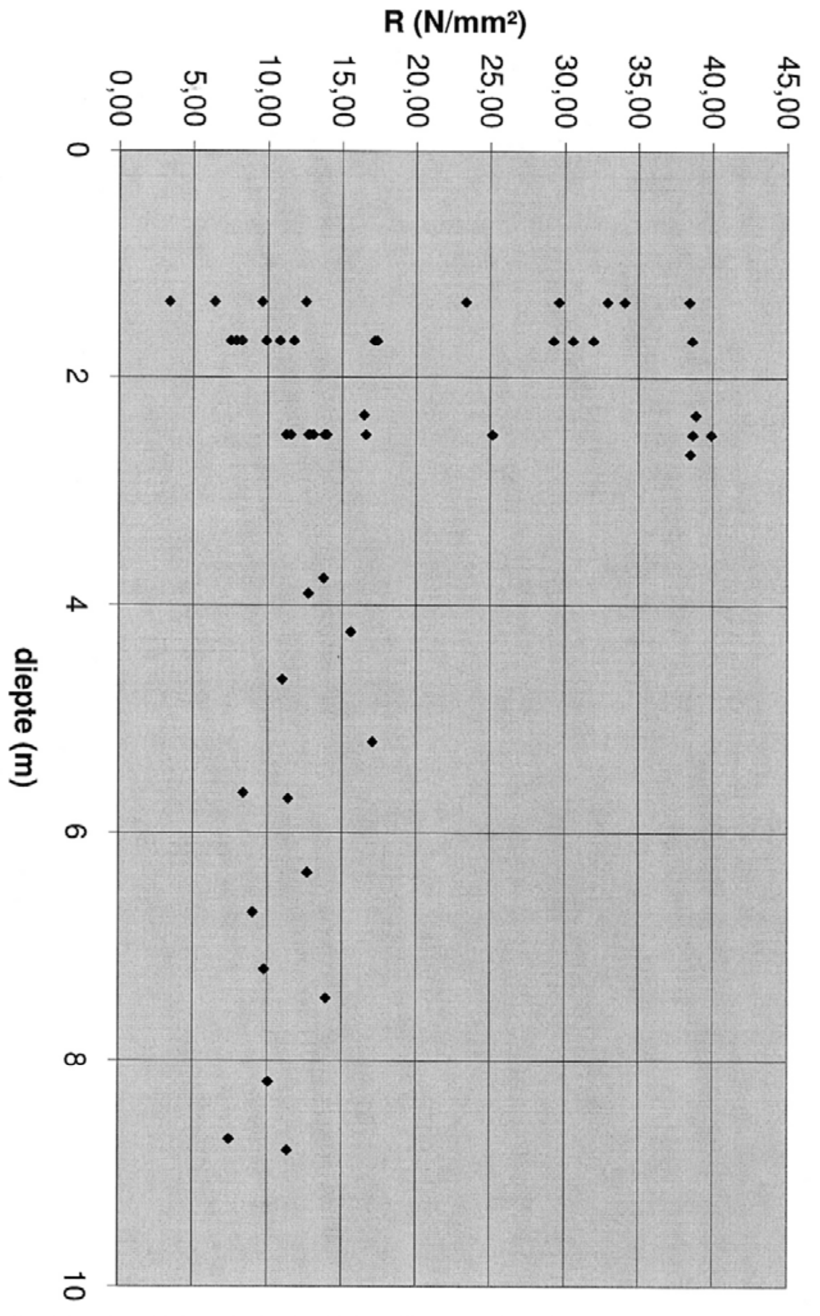
Deep mixing – Belgian research:

- UCS = Unconfined Compressive Strength of a large number of cored samples
  - Determination of the characteristic value
  - Increase of strength with time

- Elastic modulus of soilmix material

- Influence of soil inclusions
  - Characterisation of soil inclusions
  - Prediction of influence on strength and stiffness

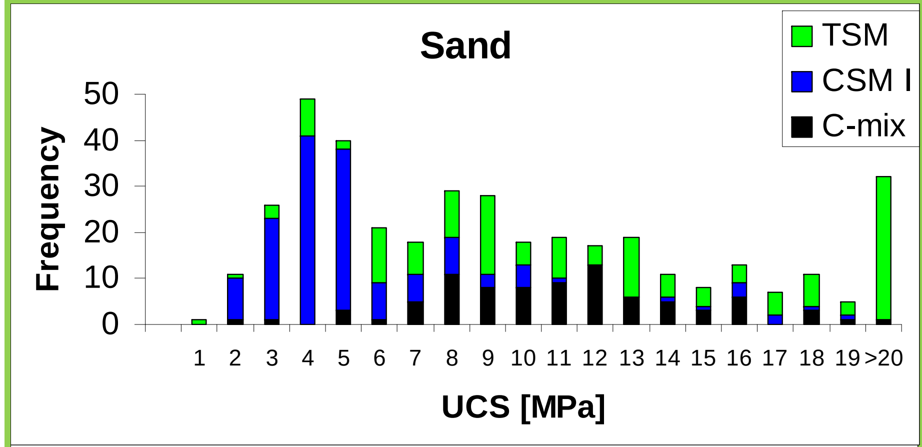
- Monitoring of soilmix structures

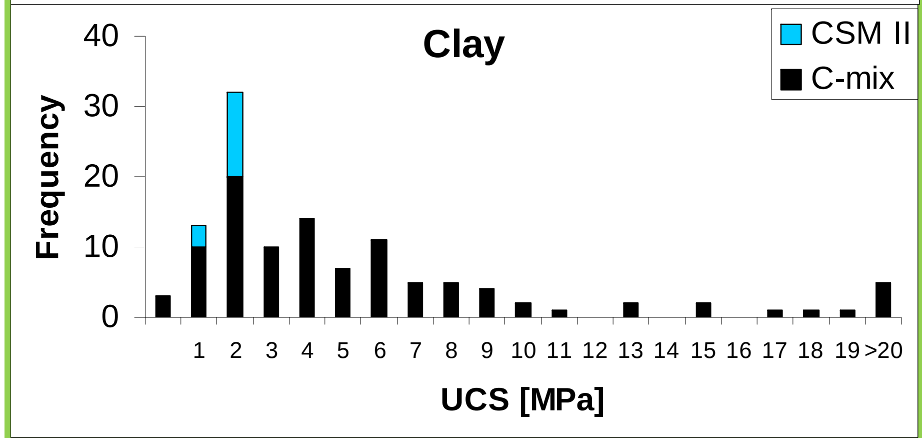


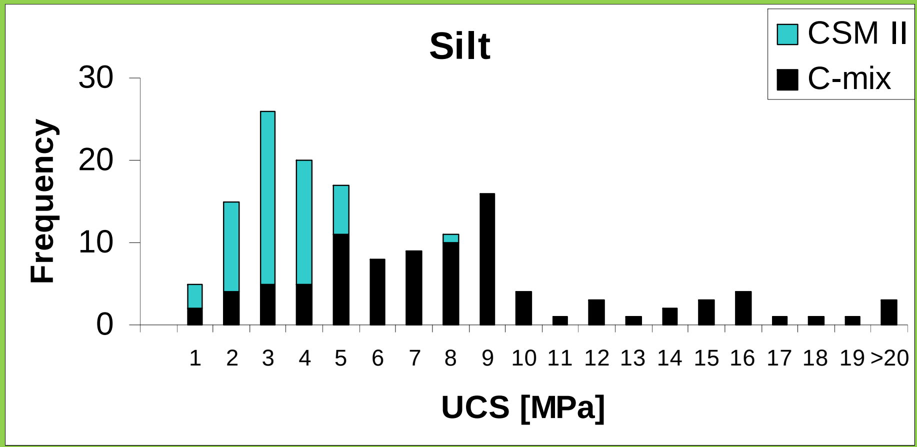
UCS on core samples
Problem:
- large scatter
- determination of the
  characteristic value

Laboratory tests on soil mix cores (23 sites)

- Tested soil mix material
  - 950 UCS and 100 E-modulus tests
- Uniaxial Compressive Strength (EN 206)
  - Cored soil mix samples Ø 10 cm; height 10 cm

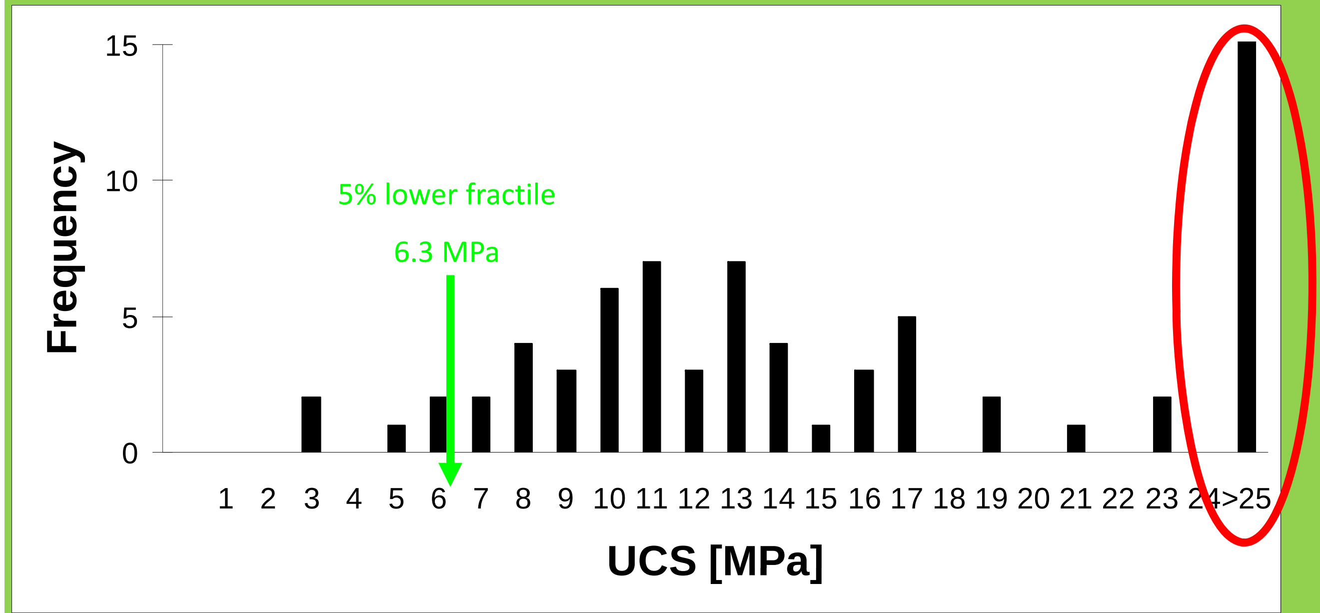






Laboratory tests on soil mix cores (23 sites)

- Interpretation UCS results (EC7)
  - Soil mix cores
    - example: job site Ghent KII in tertiary sand
  - 52 UCS tests
  - Determination of 5% lower fractile UCS
    - Traditionally : Gaussian approach (-0.7 MPa (!))
    - Better (in most cases) : log-normal distribution (5.0 MPa)



Gaussian approach:

Av. UCS

$\mu = 17.2$ MPa

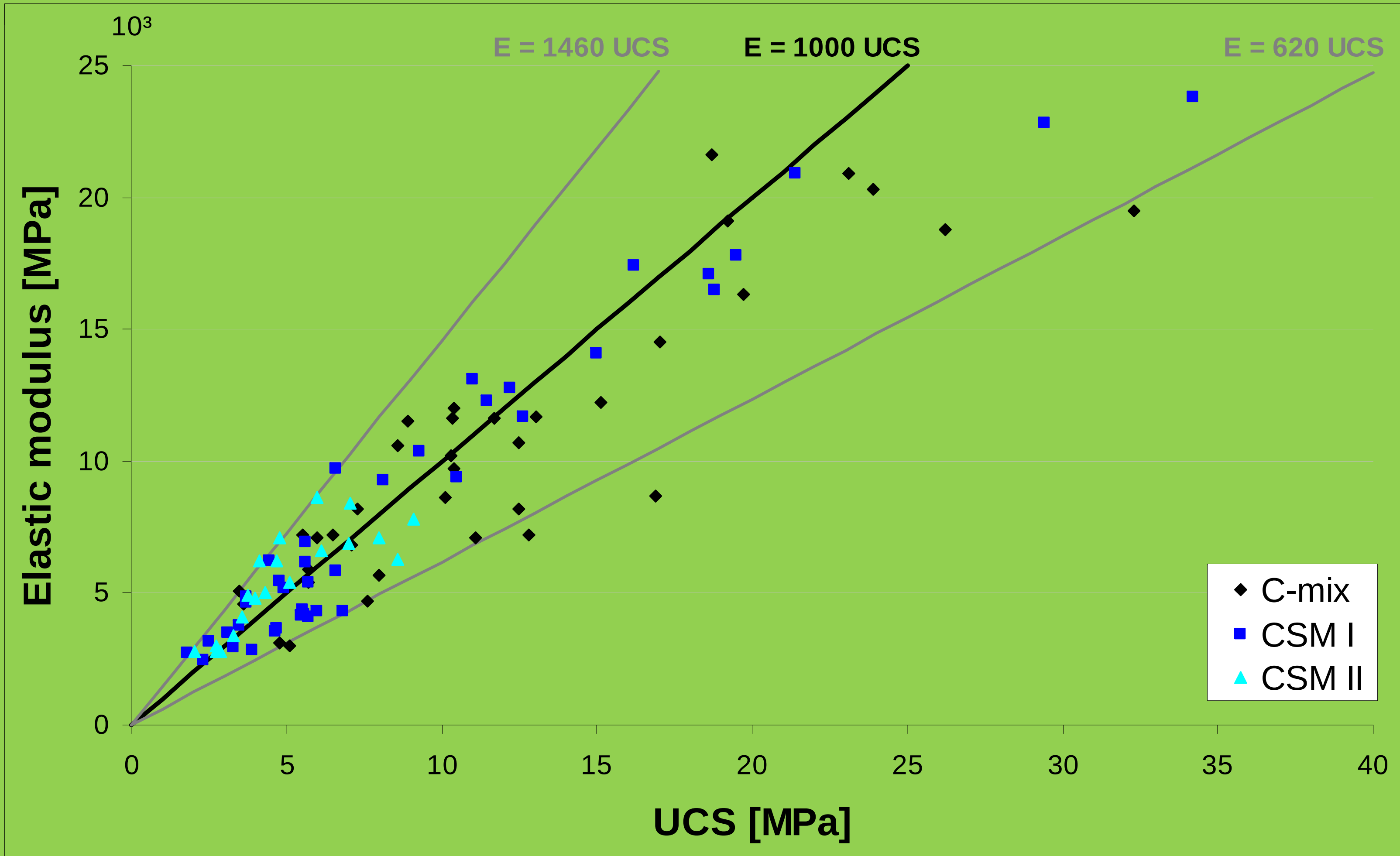
Standard deviation UCS

$\sigma = 10.9$ MPa

Characteristic ucs (5% fractile)

$\mu - 1.64 \cdot \sigma = -0.7$ MPa (!)

- Elastic modulus (NBN B15-203)
  - Test is more difficult (more expensive)
  - Cored soil mix samples Ø 10 cm; height 20 cm



Deep mixing – Belgian research:

- UCS soilmix versus UCS concrete
  - Characteristic UCS < 60% Average UCS
  - UCS column type > UCS of CSM
  - Standard variation UCS of column type > CSM
  - Variation depends on experience of contractor

- Elastic modulus ≅ 1000 x UCS

- Problem: unknown influence of soil inclusions

Deep mixing – Soil inclusions:

- Criteria needed to deal with cored samples presenting soil inclusions
- Proposal BBRI (Belgian Building Research Institute)

  If inclusion > Diameter/6

  then exclusion of test sample

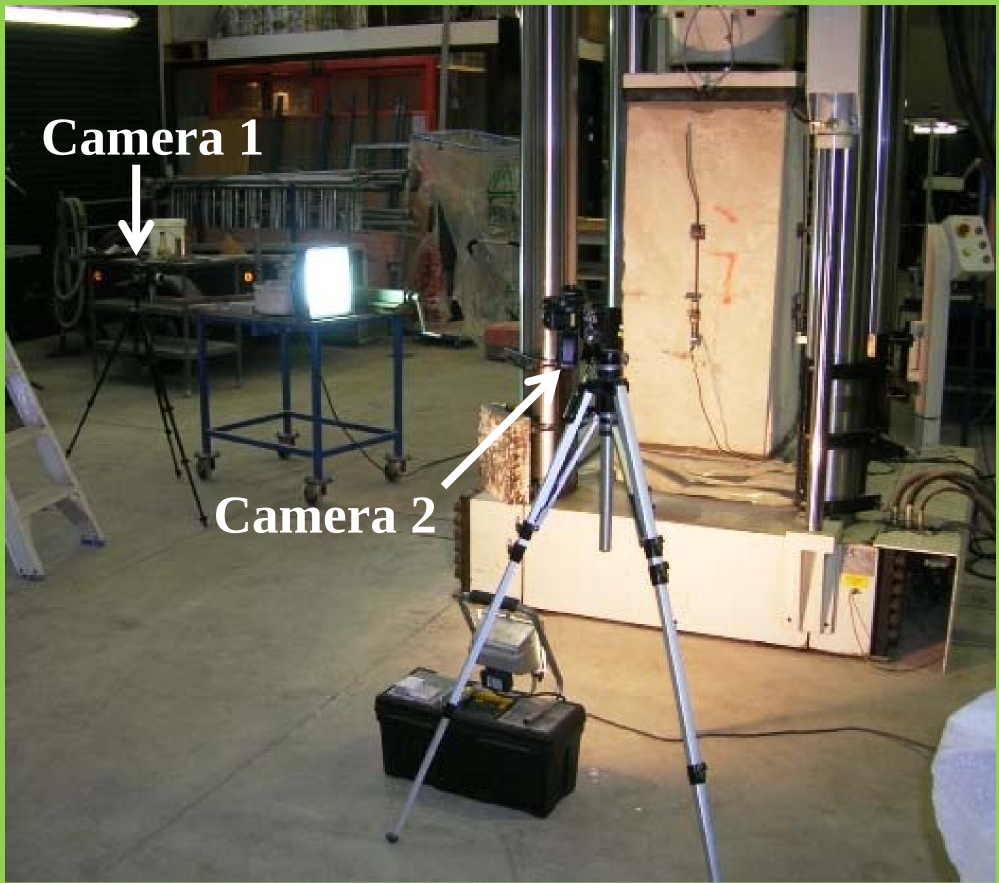
  maximum 15% of test samples may be excluded

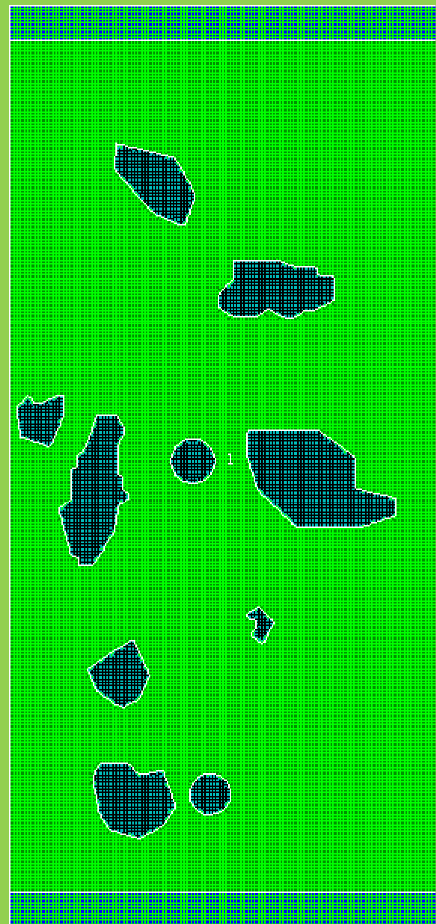
Deep mixing – Soil inclusions:

Further research:

a) testing of large scale samples

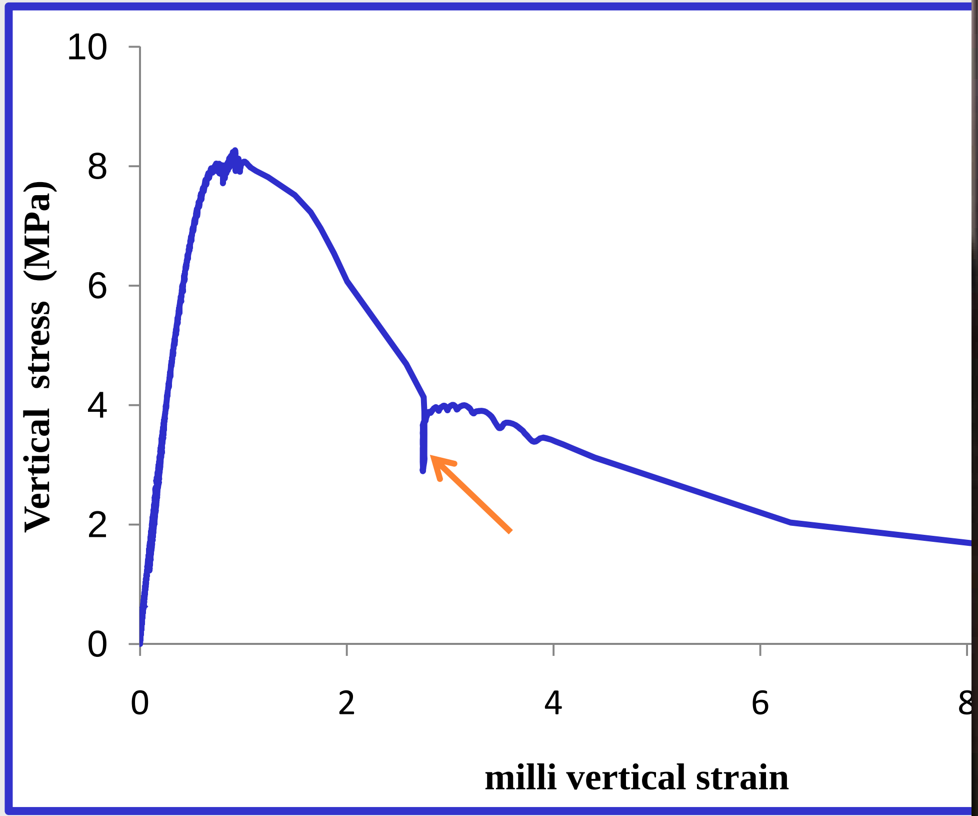
b) numerical modelling



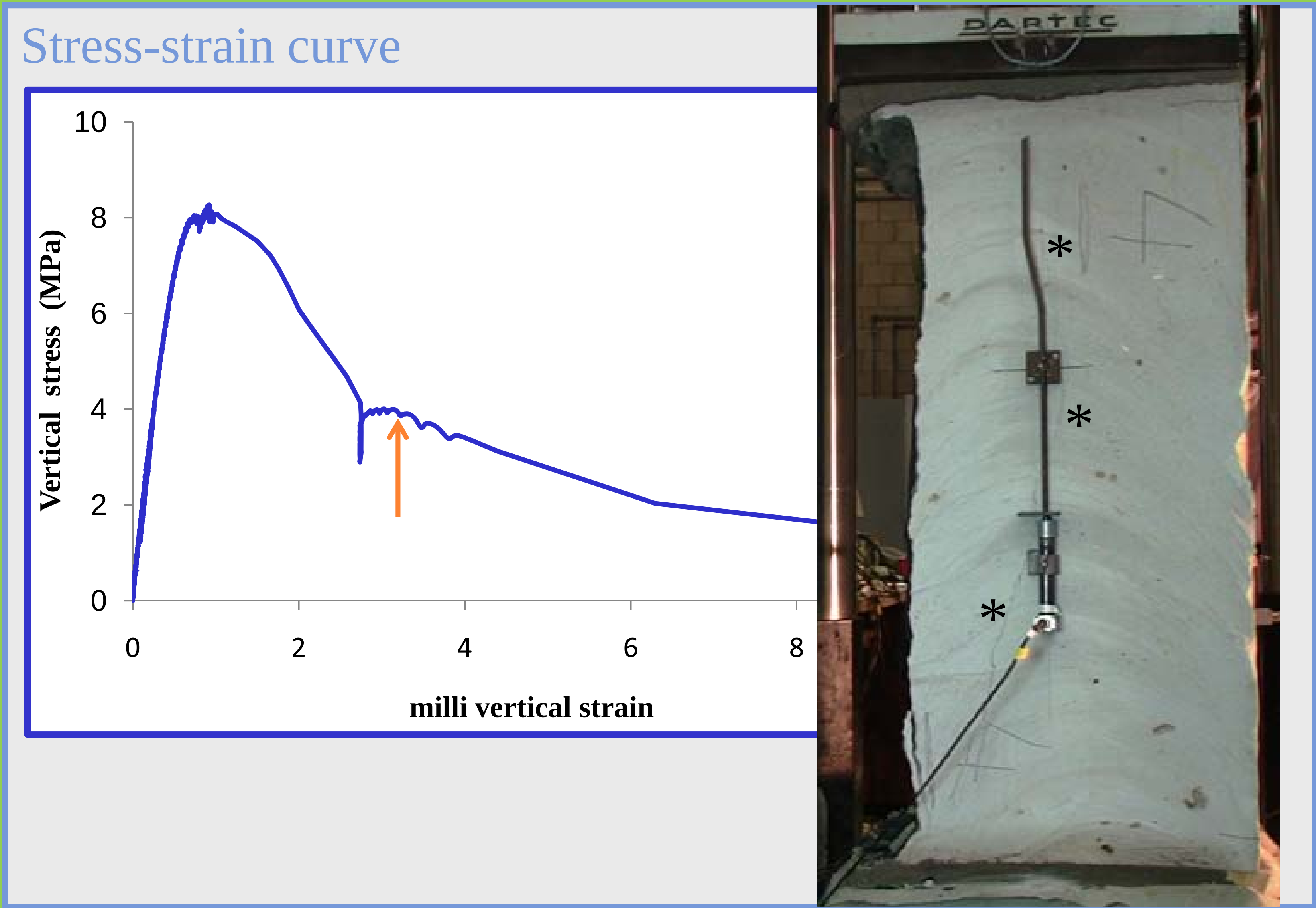


Deep mixing – Large scale testing:

Stress-strain curve

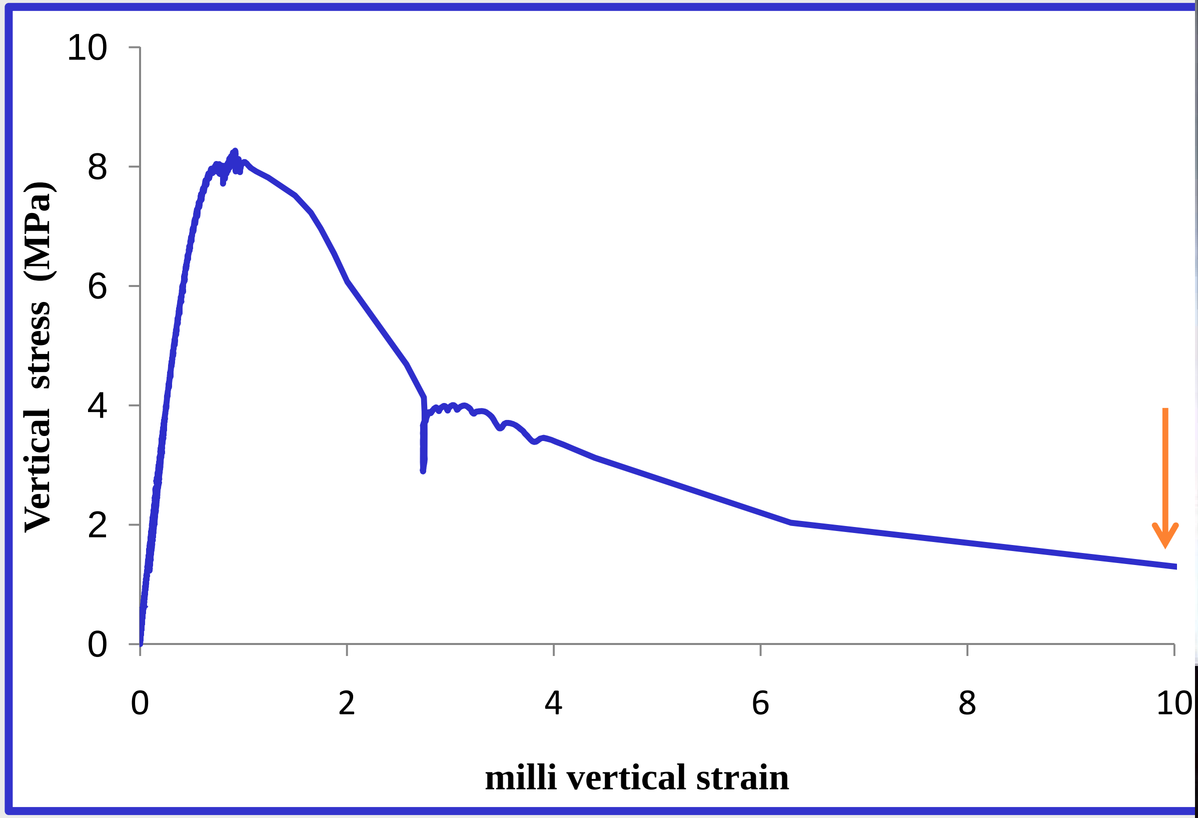


Deep mixing – Large scale testing:



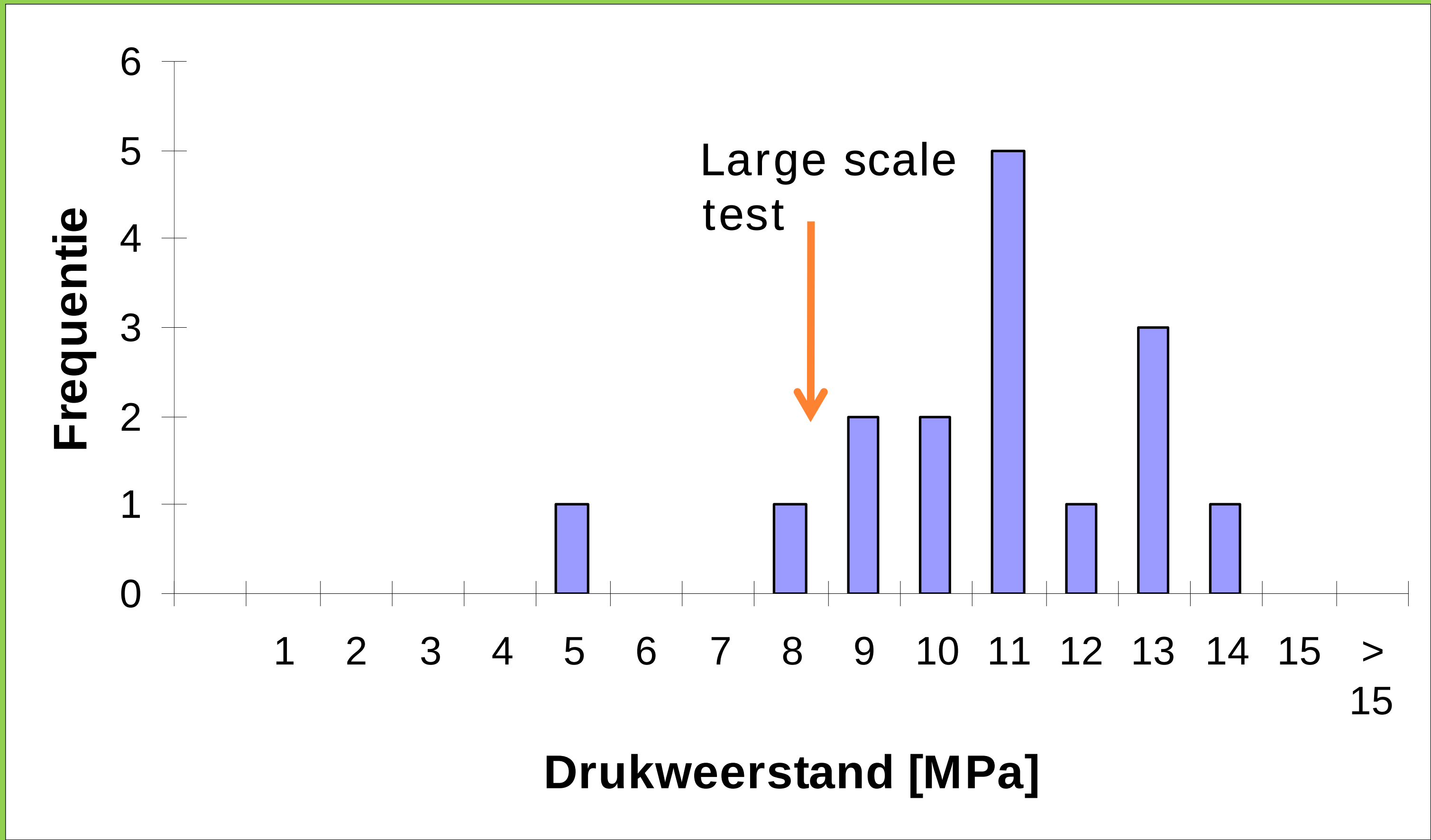
Deep mixing – Large scale testing:

Spanningss-vervormings curve



Deep mixing – Large scale testing:

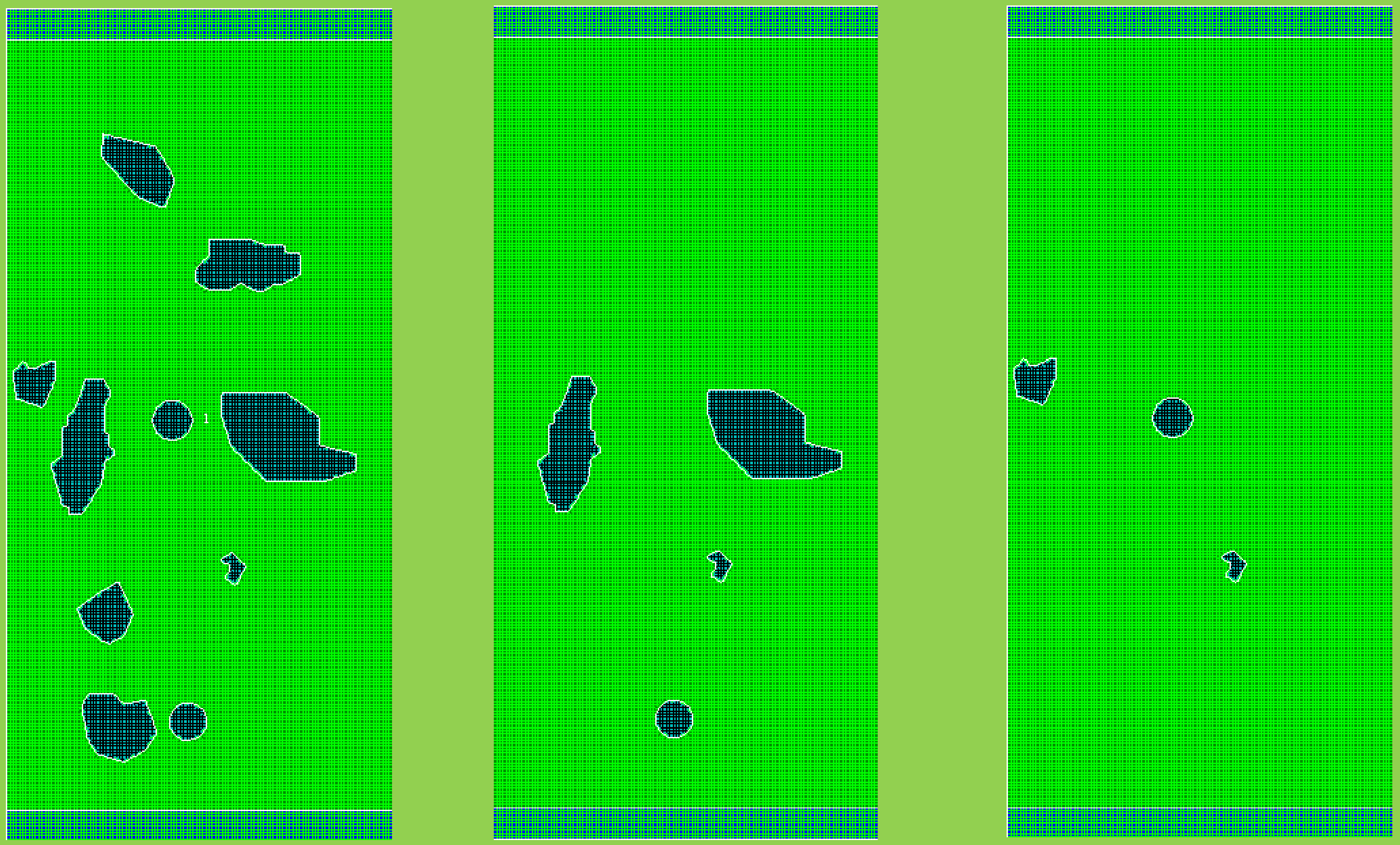
The results of the large scale tests are compared with the UCS values determined on cored samples



Deep mixing – Numerical modelling:

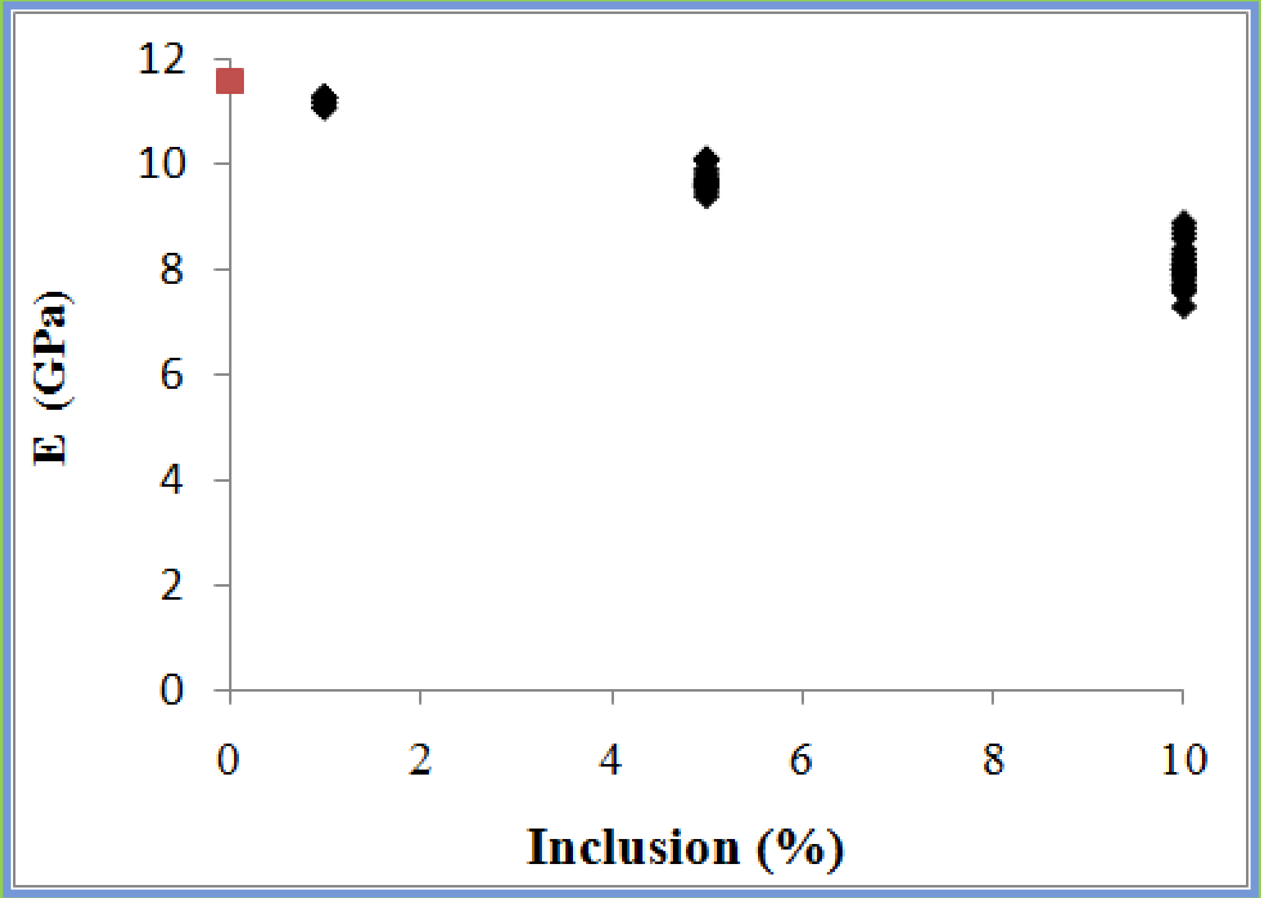
For different quantities shapes of inclusions

Example: quantity of inclusions



Deep mixing – Numerical modelling:

First results : Influence of the number of inclusions on the elastic modulus



Deep mixing – Conclusion:

- Analytical design is not possible for all combinations:
  - execution method
  - soil type
  - amount of binder

- Controll methodology is very important for retaining walls

- Interpretation of Unconfined Compressive Strength difficult:
  - large scatter
  - influence of soil inclusions

Deep mixing – Conclusion:

⇒ Large scale testing

⇒ Numerical modelling

⇒ Research program of the BBRI is a good example of how to deal with new methods/materials:

- Testing by one single organisation
- Uniform interpretation method
- Additional research to improve the interpretation

General conclusion:

- Design of ground improvement works will always remain a combination of analytical design and empirism

  → both approaches are necessary

  → cooperation academics - contractors

- Research projects are helpfull/necessary to:
  - better understand influence of execution details
  - improve empirism
  - improve cooperation academics - contractors

- Research projects will never lead to general analytical design methods

General conclusion:

- Important also are:
  - clear communication
  - clear controll methodology

- Exchange of experiences will remain very important

  → TC Ground Improvement of ISSMGE

  → www.bbri.be/go/tc17


Thank you !