People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

Mohamed Khider University - Biskra

Faculty of Science and Technology

Department of Civil Engineering and Hydraulics

Course - Soil Improvement and Reinforcement

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Objectives of the Course on Soil Improvement and Reinforcement

In many civil engineering projects, natural soils do not always possess the mechanical and hydraulic characteristics required to directly support structural loads. Indeed, some soils exhibit low bearing capacity, high compressibility, insufficient shear strength, or high sensitivity to variations in water content, which may lead to excessive settlements, instability, or even structural failure.

To overcome these limitations, geotechnical engineers use a range of techniques aimed at modifying or improving the in-situ properties of soils in order to ensure the stability, safety, and durability of civil engineering structures. These techniques, commonly referred to as soil improvement and reinforcement methods, involve increasing soil density, reducing compressibility, enhancing mechanical strength, or controlling permeability.

The objective of this course is to introduce students to the fundamental principles of soil improvement and the various techniques used in geotechnical engineering to treat problematic ground conditions. The course first presents the basic concepts required to understand soil behavior, as well as the importance of geotechnical investigations in the characterization of ground conditions.

It then examines the main soil improvement methods, including:

- Densification techniques for granular soils,
- Consolidation methods for compressible soils,
- Reinforcement techniques using inclusions or geosynthetic materials,
- As well as grouting and soil stabilization techniques used to improve the mechanical and hydraulic properties of soils.

By the end of this course, students will be able to understand geotechnical problems related to natural soils, identify appropriate soil improvement techniques according to ground conditions, and evaluate their applicability in civil engineering projects.

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Chapter I — Fundamental Soil Concepts for Ground Improvement and Reinforcement Projects

I.1. Objective of Geotechnical Investigation

Before applying any soil improvement or reinforcement technique, it is essential to have a thorough understanding of the ground conditions.

Geotechnical investigation makes it possible to:

- Identify the nature and stratigraphy of soils,
- Determine their mechanical and hydraulic properties,
- Establish a geotechnical model of the site,
- Predict the behavior of the soil under applied loads.

The process consists of interpreting the results of laboratory and in-situ tests in order to determine characteristic values, which are subsequently converted into design values used for the structural design of engineering works.

I.2. Soil Description and Fundamental Parameters

Soil is a three-phase medium composed of: Solids (soil particles), Water, Air.

This model allows the definition of the fundamental parameters used in geotechnical engineering:

- Water content (w)
- Void ratio (e)
- Porosity (n)
- Degree of saturation (s_r)

These parameters directly control:

- Soil compressibility,
- Shear strength,
- Permeability.

In many soil improvement techniques, the primary objective is to reduce the void ratio and increase soil density.

I.3. Soil Types and Geotechnical Behavior

Soils can generally be classified into two major categories

I.3.1. Granular Soils (Sands and Gravels)

The behavior of granular soils mainly depends on:

- Grain size distribution,

- Relative density.

These soils are generally permeable and can be improved through densification techniques, such as:

- Dynamic compaction,
- Vibrocompaction,
- Explosive compaction.

I.3.2. Fine-Grained Soils (Silts and Clays)

The behavior of fine-grained soils mainly depends on:

- Water content,
- Plasticity.

Their properties are described by the Atterberg limits:

- Liquid limit (W_L)
- Plastic limit (W_P)

Plasticity index:

$$I_P = W_L + W_P$$

These soils often exhibit:

- Low permeability,
- High compressibility.

They are commonly improved using techniques such as:

- Preloading,
- Vertical drains,
- Soil inclusions,
- Grouting.

I.4. Geotechnical Investigations

Geotechnical investigations make it possible to characterize in-situ soil conditions and obtain the parameters required for engineering design.

They include the following components

I.4.1. Geological and Hydrogeological Study

This study allows the identification of:

- The origin of geological formations,
- The structure of the ground,

- The presence and level of the groundwater table.

These elements strongly influence soil stability and mechanical behavior.

I.4.2. Geotechnical Boreholes

Boreholes make it possible to:

- Observe the soil stratigraphy,
- Collect soil samples,
- Perform in-situ tests.

The results are generally represented through geotechnical cross-sections, describing the different soil layers.

I.4.3. Geophysical Methods

Geophysical methods allow the investigation of the subsurface without drilling.

The most commonly used techniques are:

- Seismic methods (wave propagation in soils),
- Electrical methods (measurement of soil resistivity).

These methods complement borehole investigations and help detect subsurface heterogeneities.

I.5. Geotechnical Monitoring

Geotechnical monitoring consists of observing the behavior of soils and structures during and after construction.

It makes it possible to:

- Verify design assumptions,
- Control the effectiveness of ground improvement techniques,
- Detect potential instabilities.

I.5.1. Settlement Measurements

Soil settlements can be measured using:

- Settlement gauges,
- Extensometers,
- Profilometers.

These instruments allow monitoring of soil deformation over time.

I.5.2. Measurement of Horizontal Displacements

Lateral soil movements are measured using inclinometers installed in boreholes.

These measurements help detect ground movements and potential instability risks.

I.5.3. Measurement of Pore Water Pressure

Pore water pressure is measured using piezometers.

These measurements allow monitoring of:

- Dissipation of pore water pressures,
- Progress of soil consolidation.

I.6. Conclusion

Geotechnical investigation constitutes a fundamental step in any ground improvement project.

It allows engineers to:

- Identify the nature and condition of soils,
- Select the most appropriate improvement technique,
- Design engineering structures,
- Monitor the effectiveness of improvement works.

The essential parameters that must be known include:

- Soil grain size distribution,
- Water content and plasticity,
- Relative density or void ratio,
- Soil stratigraphy,
- Measured settlements and ground displacements.

These elements form the foundation for the study of soil improvement and reinforcement techniques.

Chapter II — Treatment without Additives for Granular Soils and Fills

II.1 Dynamic Compaction

II.1.1 Introduction

Dynamic compaction is a soil improvement technique developed by Louis Ménard and widely used for the treatment of granular soils, heterogeneous fills and reclaimed land.

This method consists of repeatedly dropping a heavy mass (tamper) from a given height in order to transmit a significant impact energy to the soil, causing densification of the soil mass at depth.

Dynamic compaction belongs to the soil improvement techniques by mass densification.

The principle is based on the transformation of the potential energy of the mass into kinetic energy during impact, which propagates in the soil in the form of mechanical waves.

II.1.2 Mechanism of Dynamic Compaction

During the impact of the tamper, the energy propagates in the soil in the form of mechanical waves:

- Compression waves (P waves)
- Shear waves (S waves)
- Surface waves (Rayleigh waves)

Figure II.1 illustrates the propagation of these waves in the soil after impact.

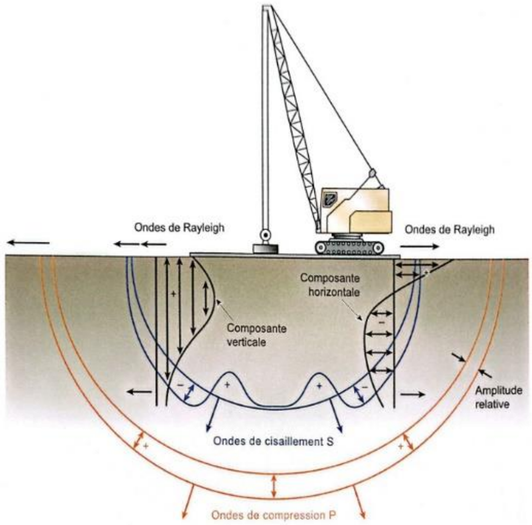


Figure II.1. Waves generated by an impact

In an unsaturated granular soil, the impact causes a rearrangement of the grains leading to:

- A reduction of the void ratio,
- An increase of the relative density,

- An improvement of the mechanical characteristics of the soil.

In a saturated soil, the impact generates a rapid increase in pore water pressure, followed by a progressive dissipation.

Figure II.2 shows the simultaneous evolution of the applied energy, deformations, pore pressure and bearing capacity.

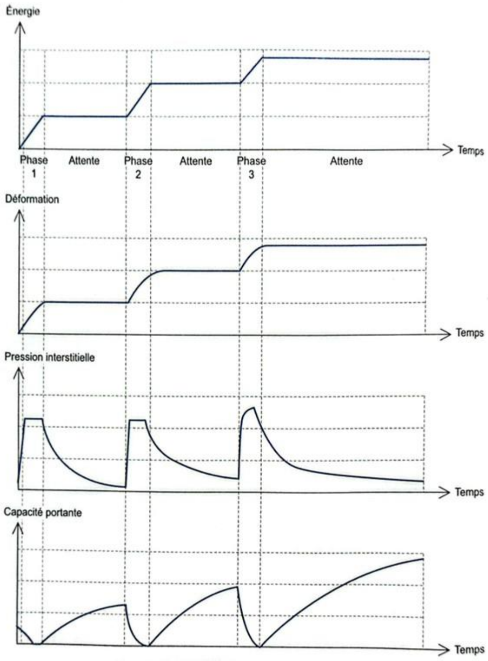


Figure II.2. Effect of tamping on a saturated soil

The effective improvement of the soil occurs after dissipation of excess pore pressures.

II.1.3 Principle of Dynamic Compaction

Dynamic compaction consists of dropping a heavy mass from a significant height (10 to 25 m) in order to transmit a high energy to the soil.

Figure II.3 illustrates the general principle of the technique.

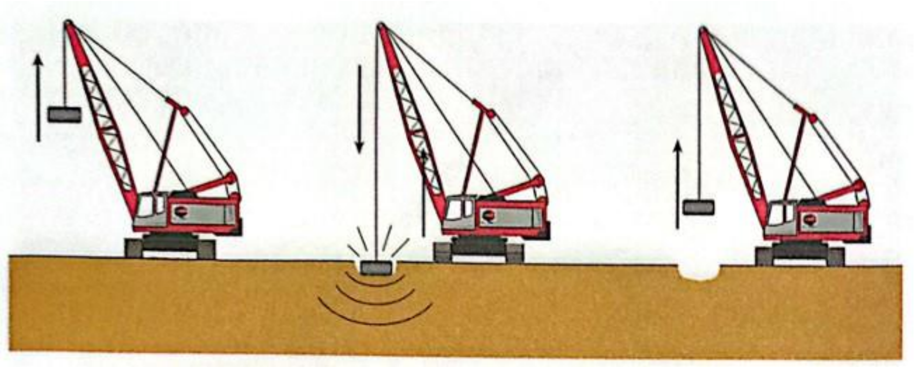


Figure II.3. Principle of dynamic compaction (Ménard)

The masses used may reach several tens of tonnes, which makes it possible to transmit a significant energy to the soil and obtain densification at depth.

II.1.4 Treatable Soil Types

The efficiency of dynamic compaction strongly depends on the grain size distribution of the soil and the fines content.

Figure II.4 presents the efficiency criteria of the technique.

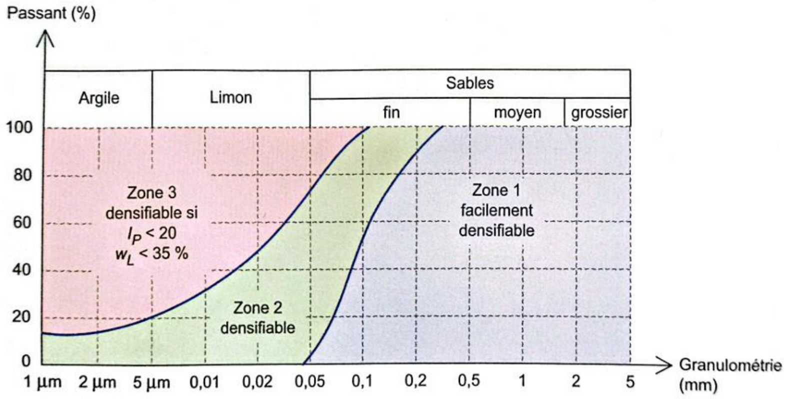


Figure II.4. Efficiency criteria of soils for dynamic compaction (Van Impe, 1995)

Dynamic compaction is particularly effective for:

- Sands
- Gravels
- Heterogeneous granular fills

In practice:

- Fines content < 20 % : very favorable
- Fines content < 30 % : acceptable efficiency
- Clay content < 12 % recommended

Highly cohesive or plastic soils are generally not well suited for this technique.

II.1.5 Depth of Influence

The unit energy of an impact is given by:

$$E = W \times H$$

Where:

- W is the mass of the tamper
- H is the drop height

The depth of improvement depends on this energy and can be estimated by the empirical relation proposed by Ménard:

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

Mitchell (1981) introduced a correction coefficient:

$$D = \alpha\sqrt{W.H}$$

where α depends on the nature of the soil and the execution conditions.

Figure II.5 presents the correlation between the applied energy and the treatment depth.

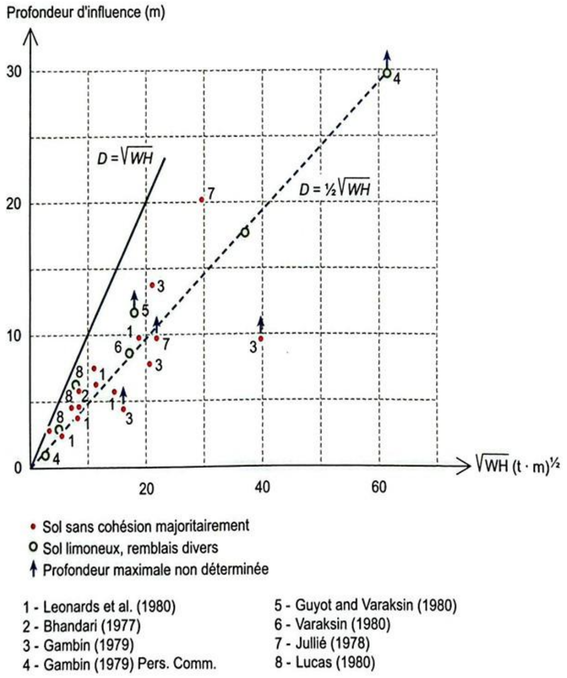


Figure II.5. Correlation between unit energy and treated depth (Mitchell, 1981).

II.1.6 Execution Method

Dynamic compaction is carried out by successive impacts distributed according to a grid defined on the ground surface.

The treatment is generally carried out in several phases:

- Large grid for deep treatment
- Intermediate grid
- Dense grid for surface homogenization

Figure II.6 shows an example of a treatment grid.

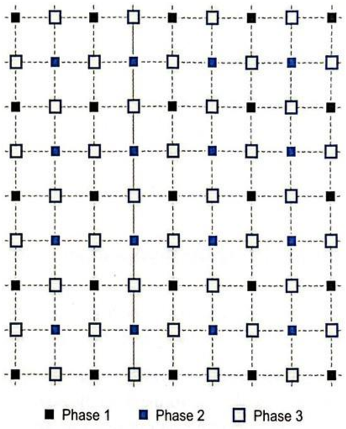


Figure II.6. Example of treatment grid

After each phase, the craters formed by the impacts must be backfilled before the next phase.

II.1.7 Dynamic Replacement

When the soil is too compressible to be simply densified, dynamic replacement is applied.

The principle consists of:

- Creating a crater by impact of the tamper,
- Introducing a granular material,
- Recompacting this material by successive impacts.

This results in the formation of rammed ballast columns, which improve the bearing capacity and reduce settlements.

This technique makes it possible to extend the use of dynamic compaction to more compressible soils.

II.1.8 Conclusion

Dynamic compaction is a deep ground improvement method based on the application of high impact energy, allowing effective densification of granular soils and fills.

Its efficiency mainly depends on:

- The grain size nature of the soil
- The applied energy (W × H)
- The treatment phasing
- The control of settlements and pore pressures

Dynamic replacement makes it possible to extend the field of application of this technique by creating densified granular inclusions in highly compressible soils.

II.1.9 Example of Calculation for Dynamic Compaction

II.1.9.1 Objective of the Example

This example illustrates a simple calculation used to estimate:

- The impact energy transmitted to the soil,
- The approximate depth of improvement obtained by dynamic compaction.

Dynamic compaction consists of dropping a heavy mass (tamper) from a significant height in order to densify granular soils and increase their bearing capacity.

II.1.9.2 Data of the Problem

A dynamic compaction treatment is carried out with the following parameters:

Mass of the tamper: $W = 20\ tons$, Drop height: $H = 15\ m$, Coefficient depending on soil conditions: $\alpha = 0.7$

The objective is to determine:

- The impact energy,
- The depth of influence of the treatment.

II.1.9.3 Calculation of the Impact Energy

The unit energy transmitted during one impact is given by: $E = W.H$

Substituting the values: $E = 20 \times 15 = 300t/cdotpm$

This value represents the energy transmitted to the soil by a single impact of the tamper.

The depth of improvement can be estimated using the empirical relation proposed by Ménard: $D = \sqrt{W.H}$

Substituting the values: $D = \sqrt{20 \times 15}$

$$D \approx 17.3$$

This value represents the theoretical depth of soil improvement obtained with dynamic compaction.

II.1.9.5 Corrected Depth Using the Mitchell Coefficient

Mitchell (1981) introduced a correction coefficient to consider soil conditions: $D = \alpha\sqrt{W.H}$

Substituting the values: $D = 0.7\sqrt{20 \times 15}$

$$D \approx 12.1$$

This corrected value provides a more realistic estimation of the treatment depth depending on soil characteristics.

II.1.9.6 Interpretation of the Results

From this calculation, it can be observed that:

- increasing the mass of the tamper increases the transmitted energy,
- increasing the drop height also increases the energy,
- the depth of soil improvement is directly related to the impact energy.

Dynamic compaction is particularly effective for:

- sands,
- gravels,
- heterogeneous granular fills,

While highly cohesive soils are generally less suitable for this technique.

II.2 Vibrocompaction

II.2.1 Introduction and General Principle

Vibrocompaction is a deep densification technique for granular soils obtained by introducing a vibrating probe into the soil which transmits high-intensity vibrations to the soil mass.

Under the effect of vibrations, the soil undergoes a temporary mobilization of the granular skeleton, allowing the grains to rearrange into a denser configuration. This results in a reduction of the void ratio and an increase in the relative density of the soil.

This technique is used to:

- Improve the bearing capacity of the soil,
- Reduce settlements,
- Decrease the risk of liquefaction of saturated sands.

The general principle of the process is illustrated by Figure II.7.

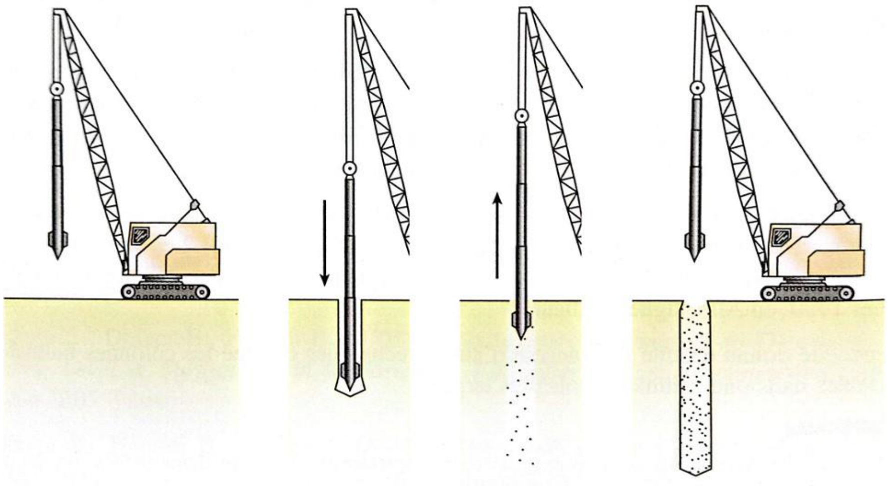


Figure II.7. Schematic principle of vibrocompaction (Ménard)

II.2.2 Equipment and Mechanism of Action

The main element of the process is the vibrator, consisting of a vibrating probe suspended from a crane. Vibrations are produced by rotating eccentric masses which transmit significant vibratory energy to the soil.

Under the effect of these vibrations:

- The soil becomes temporarily disturbed,
- The grains rearrange under the effect of gravity,
- The soil reaches a denser and more stable state.

The structure of a vibrator is illustrated by Figure II.8.

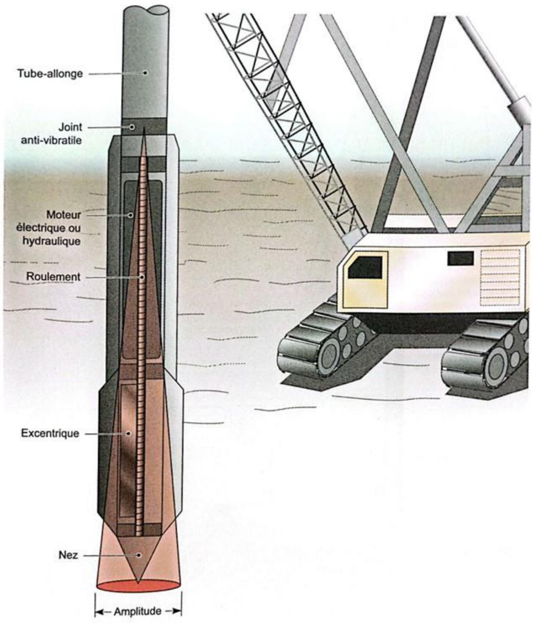


Figure II.8. Typical diagram of a vibrator used for vibrocompaction

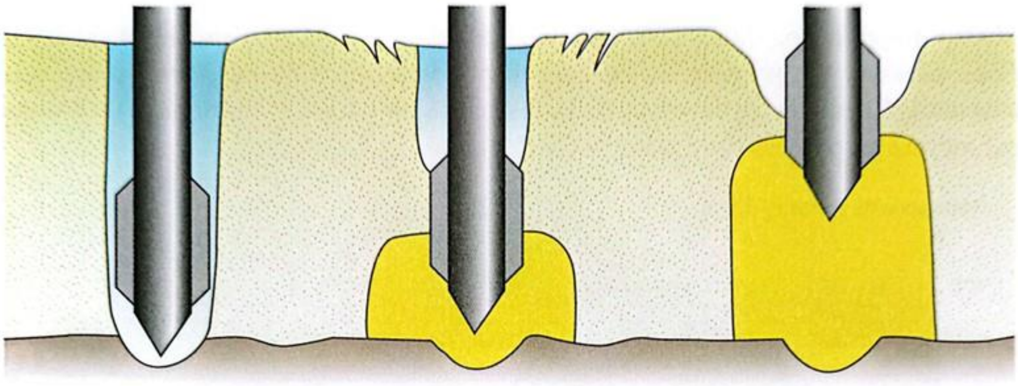
II.2.3 Execution Procedure

The treatment is carried out point by point according to a regular grid pattern. Each point affects a soil zone whose extent depends on the nature of the soil and the vibration energy.

The vibrocompaction procedure generally includes three stages:

- Penetration of the vibrator to the treatment depth,
- Compaction by vibration during the gradual withdrawal of the vibrator,
- Backfilling of surface settlements by adding granular material.

This sequence is illustrated by Figure II.9.



Pénétration
L'aiguille pénètre dans le sol jusqu'à la profondeur requise sous l'action des vibrations et du lançage à l'eau et/ou à l'air par les orifices de lançage disposés à la pointe de l'aiguille. Ce lançage est arrêté lorsque la profondeur requise est atteinte.

Compactage
L'aiguille est remontée par passes successives de 0,5 à 1 m (selon vibreur). Le matériau en place se déplace vers la pointe de l'aiguille pour y être compacté sous l'effet du seul lançage latéral au-dessus du vibreur. Un ajout de matériau (sable ou sable et gravier propre) peut alors être fait depuis la surface.

Remblaiement
Les « cratères » et l'affaissement général causés par le compactage font l'objet d'un simple nivellement ou d'un apport de matériau (sable ou sable et gravier propre) selon les besoins du site (niveau général à maintenir ou non).

Figure II.9. Vibrocompaction procedure

The mechanism of soil densification is represented in Figure II.10.

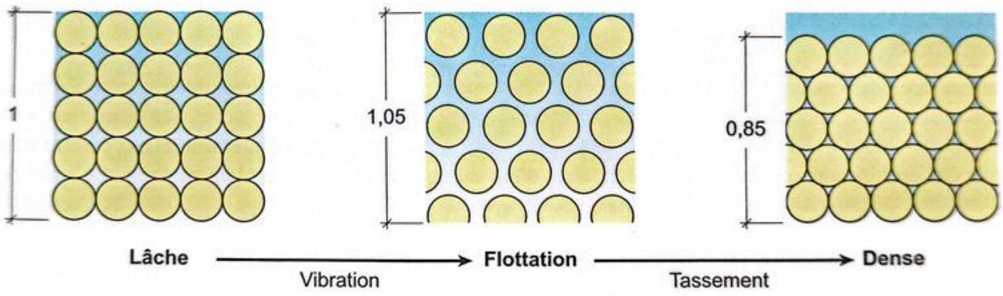


Figure II.10. Principle of vibrocompaction

II.2.4 Field of Application

Vibrocompaction is particularly effective in sands and gravelly sands with low fines content.

The field of application can be evaluated using the CPT test (Cone Penetration Test) as illustrated in Figure II.11.

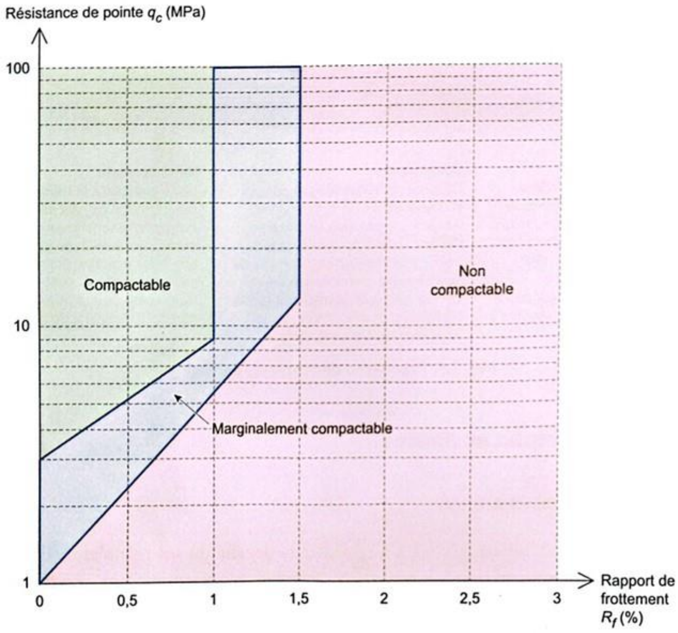


Figure II.11. Vibration compaction of soils based on the CPT test (Massarsch and Heppel, 1991)

The grain size distribution of the soil is also an important criterion for determining the efficiency of the process (See Figure II.12).

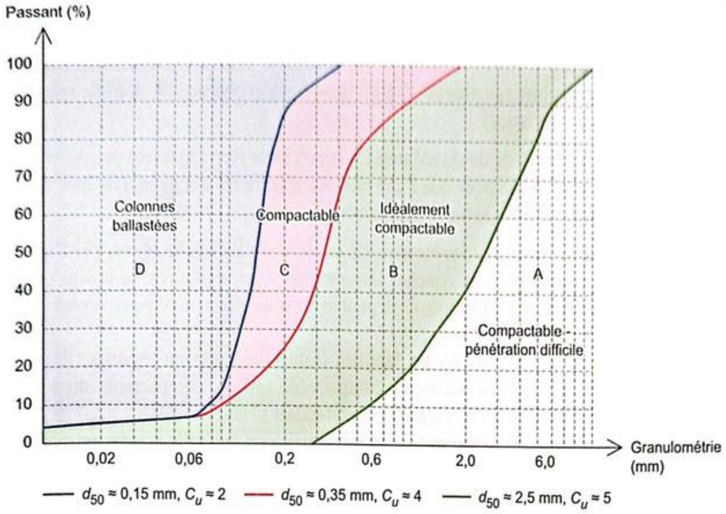


Figure II.12. Field of application of vibrocompaction (grain size distribution)

In practice, the efficiency of vibrocompaction is maximum when:

- The fines content is low (≈ 10–12 % maximum),
- The clay fraction is very limited,
- The soil is sandy or sandy-gravelly.

II.2.5 Design Parameters and Control

The design of vibrocompaction mainly depends on:

- The treatment depth,
- The spacing between compaction points,
- The duration of vibration,
- The energy transmitted to the soil.

A trial section is generally carried out in order to adjust these parameters before the final treatment.

The control of soil improvement is carried out using in situ tests, particularly the CPT, making it possible to compare the characteristics of the soil before and after treatment.

II.2.6 Advantages, Limitations and Selection Criteria

Advantages

Vibrocompaction has several advantages:

- Significant improvement of the density of granular soils,
- Reduction of settlements,
- Reduction of liquefaction risk,
- Possibility of treatment at great depths.

Limitations

The efficiency of the process may be limited by:

- A high content of fines or clays,
- The presence of silty or clayey lenses,
- Soil heterogeneity.

Selection Criteria

Vibrocompaction is particularly suitable when:

- The soils are granular and weakly cohesive,
- Deep densification is required,
- The projects concern fills, platforms or saturated sandy soils.

II.3 Explosive Compaction

II.3.1 Introduction and General Principle

Explosive compaction is a soil improvement technique used mainly for the densification of loose saturated sands. The detonation of buried explosive charges produces an intense vibration of the soil accompanied by excess pore pressure, causing a temporary liquefaction of the soil mass.

After the dissipation of pore pressures, the grains rearrange into a denser structure, which improves the mechanical characteristics of the soil.

An example of implementation on site is presented in Figure II.13.

Figure II.13. View of an explosive compaction site at the moment of detonation, Gdansk – Poland (Ménard Polska)

II.3.2 Field of Application

Explosive compaction is particularly suitable for loose saturated sands containing few fines.

The favorable grain-size range is illustrated in Figure II.14.

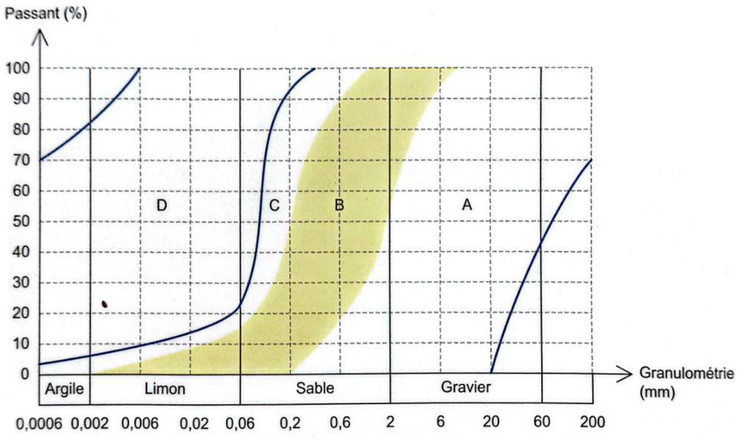


Figure II.14. Grain-size envelope of sands densifiable by explosives

In some cases, the technique may also be used to improve cohesive soils by creating sand drain columns (See Figure II.15).

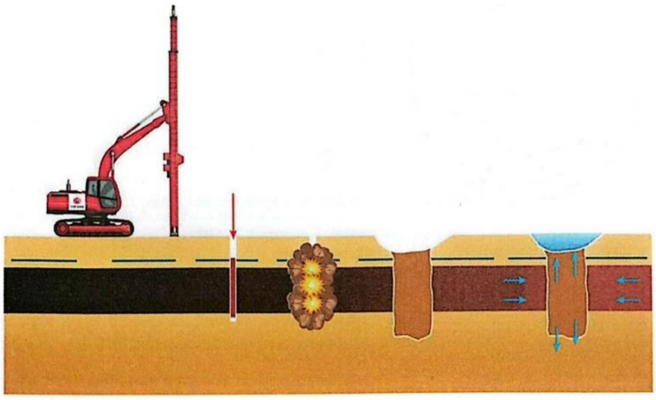


Figure II.15. Construction of sand columns in a clay layer using explosives (Ménard Polska)

II.3.3 Implementation Principle

The method consists of placing explosive charges in boreholes drilled in the soil at different depths.

The installation of charges is illustrated in Figure II.16.

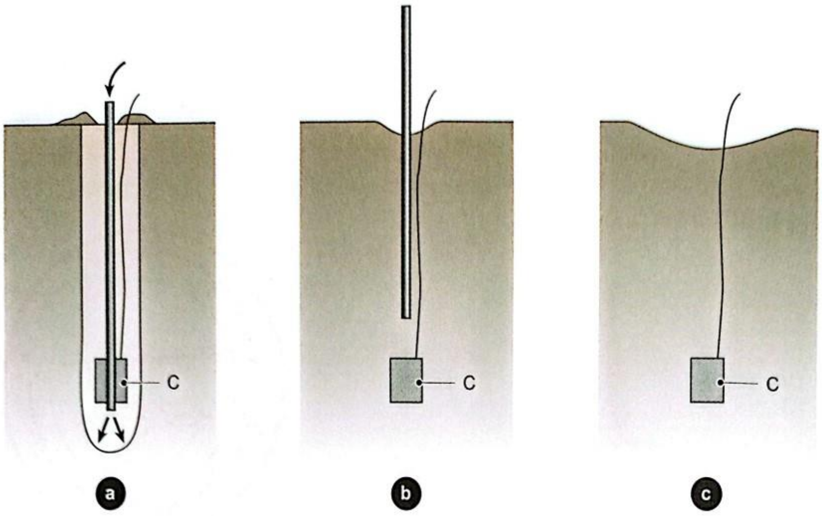


Figure II.16. Installation of explosives (Lyman patent, 1942). a) Launching of charge C using a tube, b) Withdrawal of the tube, c) Sand collapsing onto charge C

The detonations are carried out according to a regular grid pattern, allowing a homogeneous densification of the soil (as presented in Figure II.17).

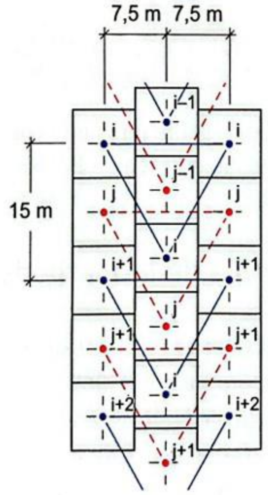


Figure II.17. Typical treatment grid (Carpenter et al., 1985)

The explosions cause a temporary liquefaction of the soil followed by a rearrangement of the grains and settlement of the ground.

II.3.4 Design and Control

The design of the treatment mainly depends on:

- The quantity of explosive,
- The depth of the charges,
- The spacing between the blasting points.

The works are generally carried out in several phases in order to allow the dissipation of pore pressures.

The control of soil improvement is carried out using geotechnical tests (CPT, pressuremeter) before and after treatment.

An example of improvement of the mechanical characteristics of the soil is presented in Figure II.18.

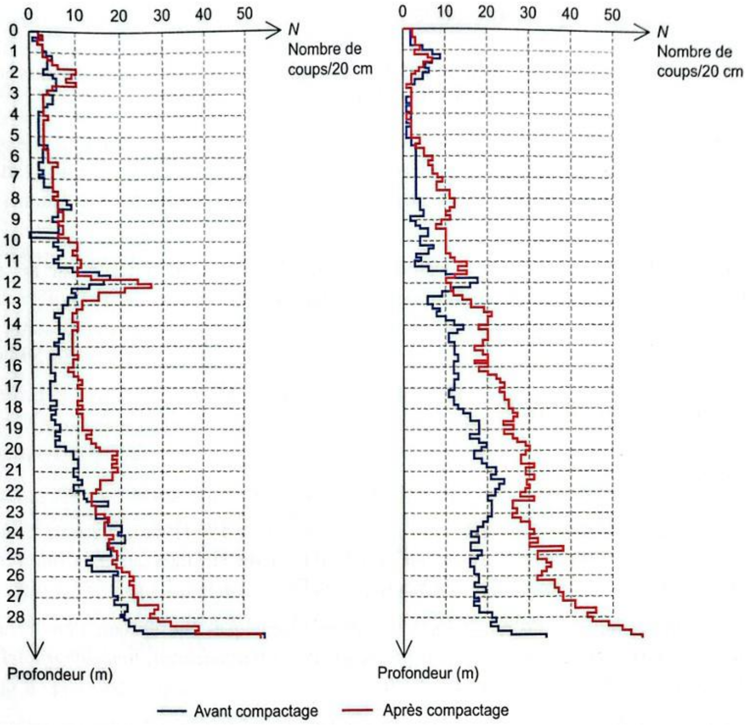


Figure II.18. Improvement of the mechanical characteristics of the treated soil

II.3.5 Advantages, Limitations and Selection Criteria

Advantages

Explosive compaction allows:

- Efficient densification of saturated sands,
- Treatment at great depths,
- Rapid improvement over large areas.

Limitations

However, the technique presents certain constraints:

- Use of explosives,
- Significant vibrations that may affect the environment,
- Efficiency limited to saturated granular soils.

Selection Criteria

Explosive compaction is particularly suitable when:

- The soil is sandy and saturated,
- The area to be treated is large,
- The safety conditions allow the use of explosives.

II.4 Comparison of Ground Improvement Techniques

Table II.1 summarizes the comparison between the three ground improvement techniques presented in this chapter. These methods belong to the category of ground improvement techniques without additives, mainly used for granular soils and embankments.

The comparison highlights their main principles, fields of application, advantages, and limitations, helping to identify the most suitable technique depending on the geotechnical conditions of the project.

Table II.1. Comparison of Ground Improvement Techniques Without Additives for Granular Soils and Fills

Technique	Principle	Suitable Soils	Main Objective	Advantages	Limitations	Selection Criteria
Dynamic Compaction	Repeated dropping of a heavy weight to densify the soil mass	Sands, gravels, heterogeneous fills	Increase density and bearing capacity	Simple technique, large depth of treatment	Significant vibrations, ineffective in cohesive soils	Granular soils with low fines content, large treatment areas, absence of vibration-sensitive structures
Vibrocompaction	Vibratory probe induces rearrangement of soil grains	Sands and gravelly sands	Increase relative density and reduce liquefaction risk	Homogeneous treatment, significant depth of improvement	Sensitive to fines content	Saturated granular soils with low fines content (<10–15%)
Explosive Compaction	Controlled explosions induce soil densification	Saturated sands and underwater deposits	Rapid densification over large areas	Effective at large depths	Difficult to control, strong vibrations	Large isolated sites, saturated granular soils, offshore or marine works

Chapter III — Treatment without Additives for Cohesive Soils

III.1 Replacement, Lightweighting and Compensation

III.1.1 Introduction

A simple method of soil improvement consists of replacing a layer of poor-quality soil with a material having better mechanical characteristics. This technique is called replacement. It makes it possible to increase the bearing capacity and reduce the settlements of structures.

In very compressible soils, another approach consists of reducing the loads applied to the soil by using lightweight materials. This technique is called lightweighting or compensation.

The principle of replacement of a compressible soil is illustrated by Figure III.1.

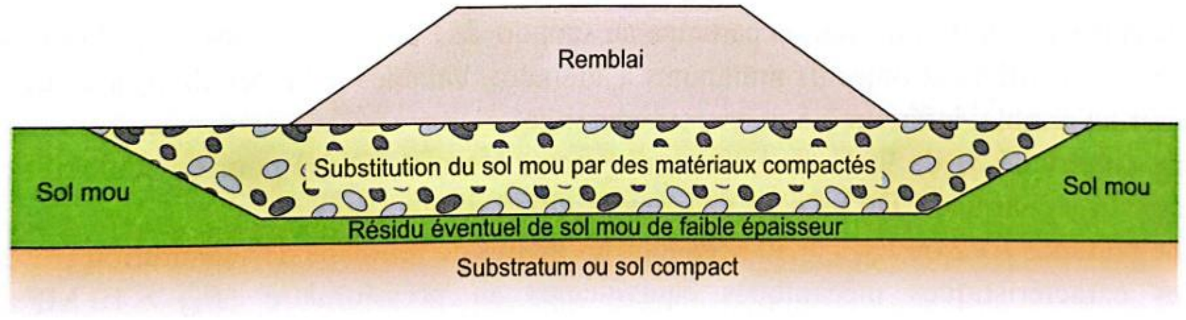


Figure III.1. Substitution of poor soil

III.1.2 Soil Replacement

Replacement consists of excavating all or part of the soft soil and substituting it with compacted granular fill.

This solution makes it possible to:

- Improve the bearing capacity of the ground,
- Reduce settlements,
- Ensure better stability of the structure.

The technical fill is generally composed of compacted granular materials, possibly treated with hydraulic binders. The implementation is carried out in successive compacted layers.

Quality control of the fill mainly relies on:

- Compaction,
- Bearing capacity,
- Deformability of the treated soil.

III.1.3 Lightweighting and Compensation

When soils are very compressible, it may be preferable to reduce the loads applied to the soil rather than increase soil strength.

Two principles are used:

- Replace a conventional fill with a lightweight material,
- Compensate the weight of the fill with a lightweight material.

These two approaches are illustrated by Figures III.2 and III.3.

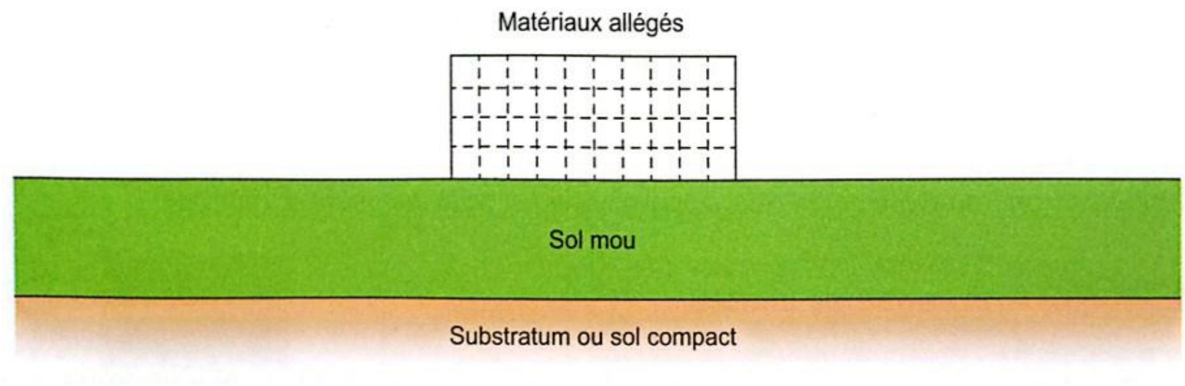


Figure III.2. Replacement of earth fill with a lightweight material

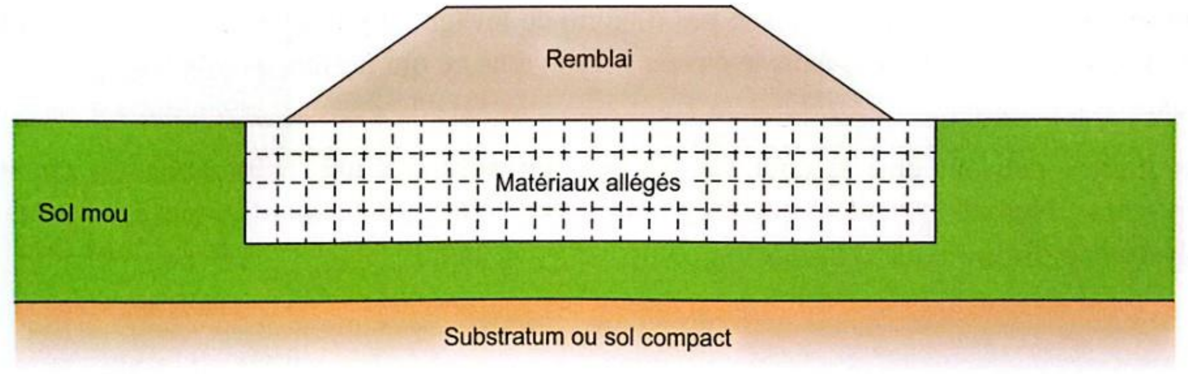


Figure III.3. Compensation of the surcharge of earth fill by a lightweight material

III.1.4 Lightweight Materials

Materials used for lightweighting must have a low unit weight while maintaining sufficient mechanical strength.

The main materials used are:

- Expanded polystyrene (EPS),
- Cellular glass,
- Ultra-light cellular structures,
- Expanded clay beads.

Expanded polystyrene is one of the most widely used materials in civil engineering due to its light weight and good mechanical performance.

Its mechanical behavior is illustrated by Figure III.4.

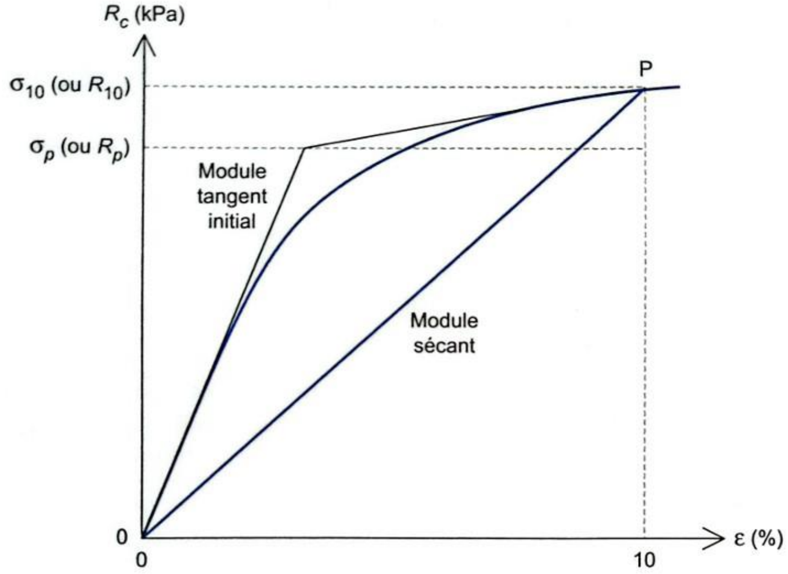


Figure III.4. Stress–strain curve from a unconfined compression test on an expanded polystyrene sample (Setra technical guide, 2006)

III.1.5 Design and Experience Feedback

The design of a replacement or lightweighting project must take into account:

- The geotechnical conditions of the site,
- The loads applied by the structure,
- The expected settlements,
- The stability of the embankment.

These techniques are particularly used for the construction of embankments on highly compressible soils (peat, soft clays).

An example of construction is presented in Figure III.5.

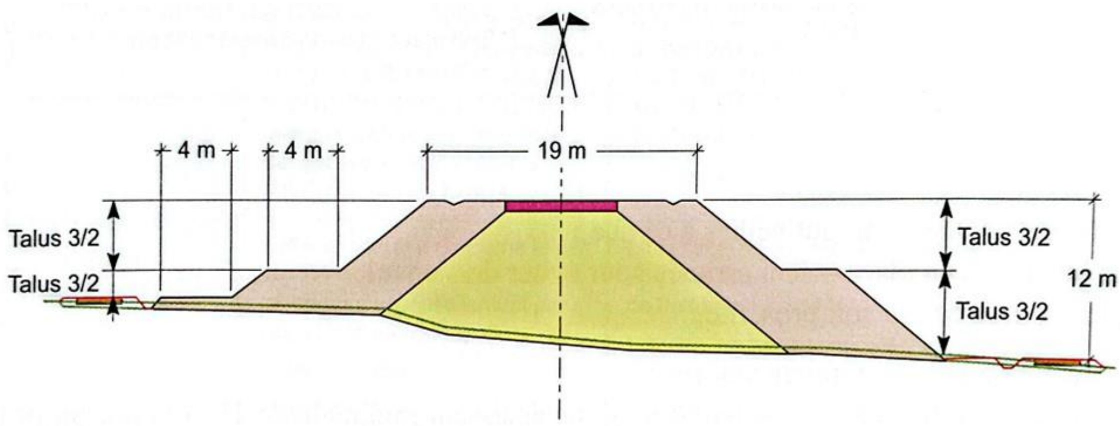


Figure III.5. Cross-section of the access embankment (Colas)

The results show that the use of lightweight materials significantly reduces settlements. The evolution of settlements with and without lightweighting is illustrated by Figure III.6.

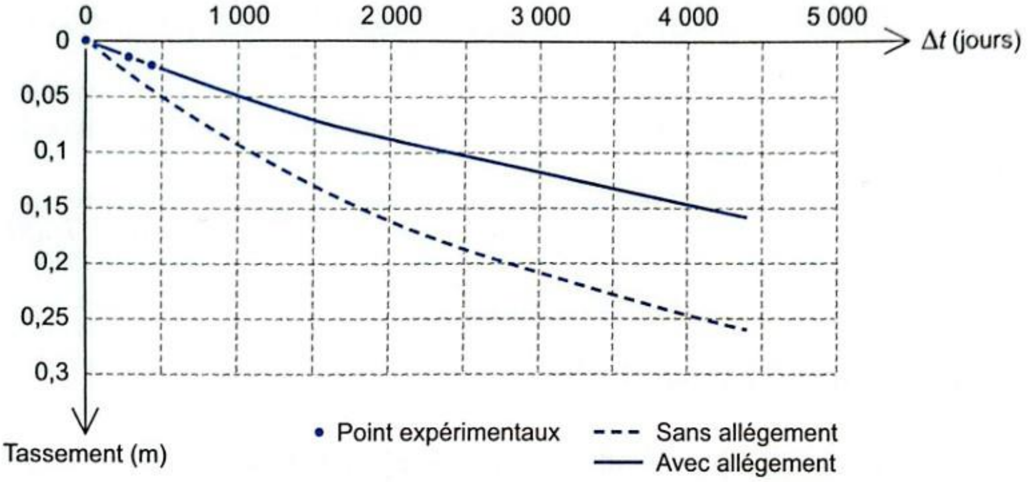


Figure III.6. Settlement curves without and with lightweighting (Guerpillon and Virolet, 2015)

III.1.6 Advantages, Limitations and Selection Criteria

Advantages

- Rapid improvement of soil bearing capacity,
- Reduction of settlements,
- Efficient solution for highly compressible soils.

Limitations

- High cost of some lightweight materials,
- Need for proper site preparation,
- Precautions regarding chemical or mechanical aggressions.

Selection Criteria

These techniques are particularly suitable when:

- The soils are highly compressible,
- Settlements must be limited,

The use of lightweight or replacement materials is technically and economically feasible.

III.2 Preloading by Embankment, with or without Drains

III.2.1 General Principle of Preloading

The preloading technique consists of applying a temporary load (embankment) on a compressible soil before construction of the final structure in order to induce in advance the settlements that would occur under future loads.

This surcharge causes soil consolidation and progressive dissipation of pore pressures, which increases soil strength and reduces future settlements.

The principle of preloading is illustrated by Figure III.7.

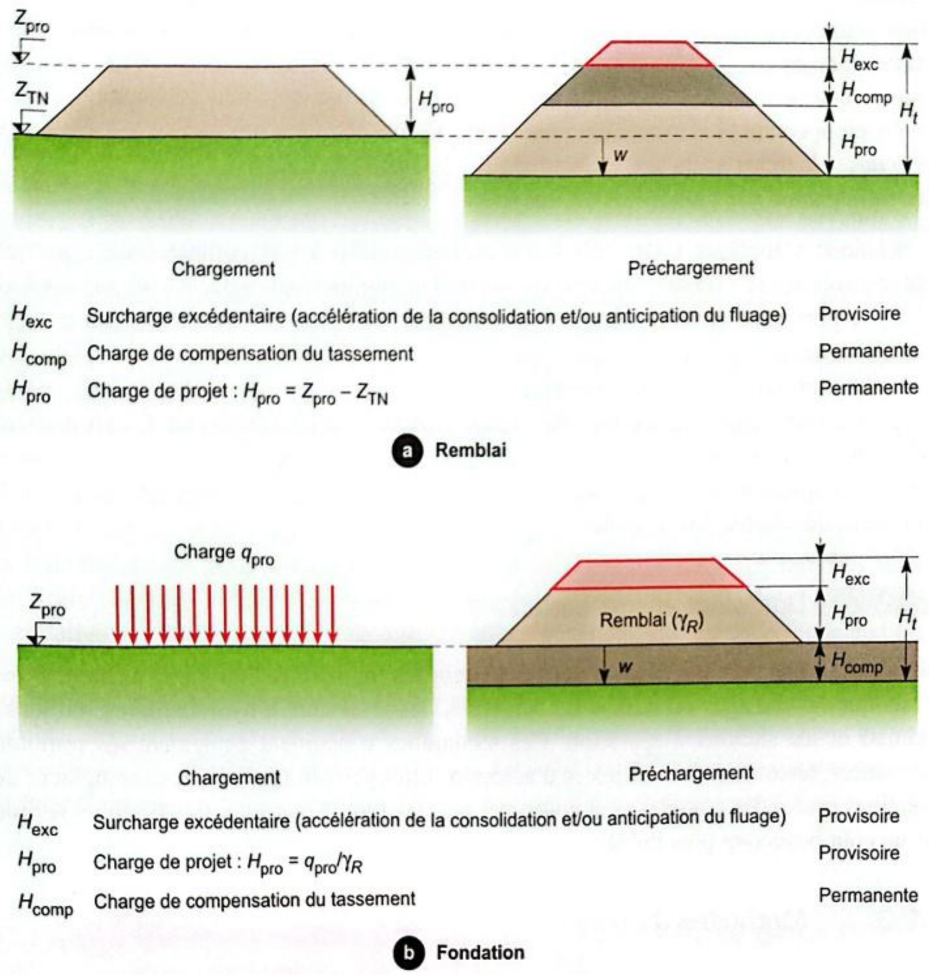


Figure III.7. Definition of surcharge heights in the case of preloading by embankment (a) or foundation (b)

III.2.2 Field of Application

Preloading is mainly used in compressible fine soils, particularly:

- Soft clays,
- Organic clays,
- Muds,
- Peats.

These soils generally exhibit:

- Low permeability,
- High compressibility,
- Significant settlements under loading.

The technique is often used for the construction of:

- Roads and highways,
- Railway embankments,

- Reservoirs,
- Industrial platforms.

III.2.3 Operating Principle

During installation of the preloading embankment, the loads applied to the soil cause:

- An increase in pore water pressures,
- A progressive expulsion of water contained in the soil,
- An increase in effective stresses,
- A reduction in soil volume.

The soil thus undergoes progressive consolidation accompanied by settlements.

The deformation of the soil mass under the effect of the embankment is illustrated by Figure III.8.

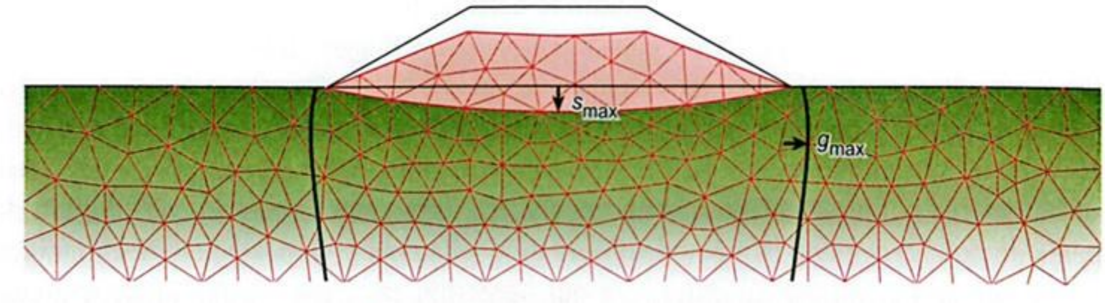


Figure III.8. Two-dimensional deformation of the entire soft clay mass: settlement at the clay surface and lateral displacements at the toe of the slope

III.2.4 Acceleration of Consolidation by Vertical Drains

In low-permeability soils, natural consolidation may be very slow. To accelerate this process, vertical drains are often installed.

These drains allow:

- Reduction of the drainage distance,
- Increase of the rate of pore pressure dissipation,
- Acceleration of soil consolidation.

The influence of drains on the rate of consolidation is illustrated by Figures III.9 and III.10.

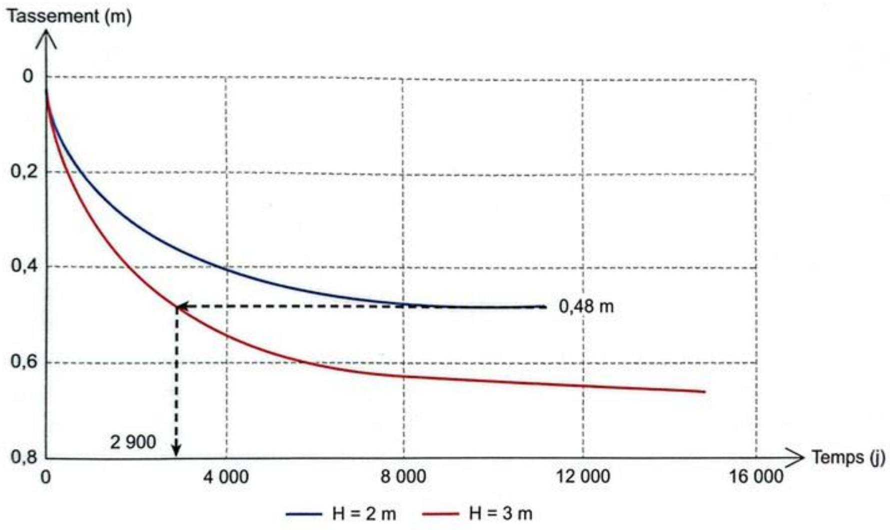


Figure III.9. Consolidation settlement as a function of time for embankments 2 m and 3 m high without drains

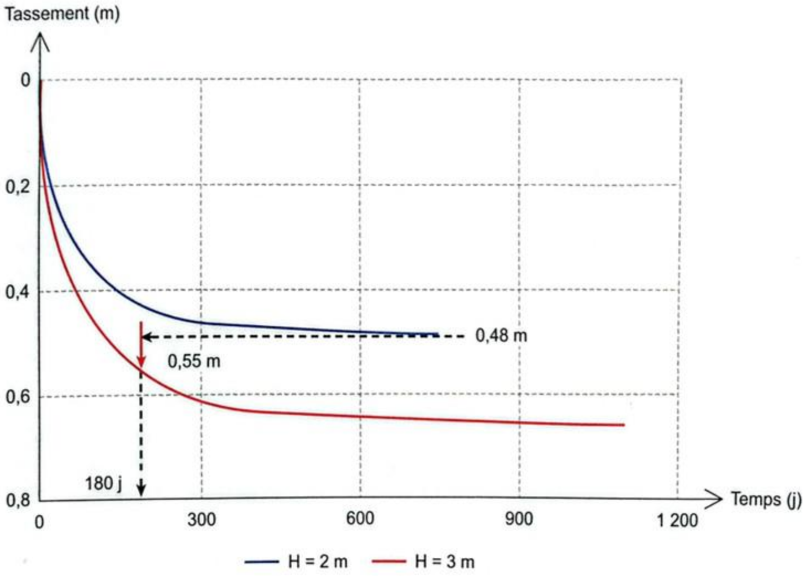


Figure III.10. Consolidation settlement as a function of time for embankments 2 m and 3 m high with drains

These figures show that the use of vertical drains considerably reduces the duration of consolidation.

III.2.4.1 Example — Design of Vertical Drains

III.2.4.1.1 Geotechnical conditions obtained from site investigation

A geotechnical investigation was carried out on a site in order to determine the soil conditions responsible for the observed settlements.

The investigation included boreholes, soil sampling, and laboratory tests such as oedometer tests. These investigations made it possible to identify the soil stratigraphy and the main geotechnical parameters of the encountered layers.

For the purpose of this example, one borehole is considered as the reference case, since it represents the most unfavorable soil conditions.

The following data summarize the geotechnical characteristics of the site.

Table III.1 summarizes the geotechnical investigation data obtained from the test site.

Table III.1. Geotechnical parameters obtained from the reference borehole.

Soil layer	Thickness (m)	γ (kN/m³)	e_0	C_c	C_s
Embankment fill	4.5	21.5	0.784	0.12	0.02
Soft clay	> 6	19.0	0.82	0.20	0.02

Estimated consolidation settlements

The consolidation settlement of the compressible clay layer can be estimated from the oedometer test results using the classical consolidation equation:

$$\Delta h = \left(\frac{H.C_c}{1+e_0}\right)\log\left(\frac{\sigma_f}{\sigma_i}\right)$$

- H = thickness of the compressible clay layer
- C_c= compression index
- e_0 = initial void ratio
- σ_i = initial vertical effective stress
- σ_f = final vertical effective stress.

The magnitude of the settlement depends strongly on the thickness of the compressible clay layer.

Since the boreholes were stopped at a depth of 10 m, the exact thickness of the clay layer remains uncertain. Therefore, settlement estimations were calculated for several possible clay thicknesses.

Based on the compressibility parameters obtained from the site investigation, the estimated settlements for different clay thicknesses are summarized in Table III.2.

Table III.2. Estimated consolidation settlement of the clay layer.

Clay thickness H (m)	Estimated settlement (cm)
6	41
8	46.6
10	51
12	54.6

For the design of vertical drains, the adopted thickness of the compressible clay layer is: $H = 10\ m$

The corresponding estimated settlement is therefore: $\Delta H = 51\ cm$

III.2.4.1.2 Design assumptions

The following assumptions are adopted for the vertical drain design.

- Preloading duration: $t = 2\ months$
- Height of the preloading embankment: $1\ m$
- Target degree of consolidation: $U = 85\ \%$
- Number of drainage faces: 1
- Drain diameter: $d = 5\ cm = 0.05\ m$
- Coefficient of vertical consolidation: $C_v = 5 \times 10^{-8}\ m^2/s$
- Coefficient of horizontal consolidation: $C_h = 5C_v \implies C_h = 2.5 \times 10^{-7}\ m^2/s$

III.2.4.1.3 Geometry of the drain spacing

The vertical drains are installed according to a square grid pattern.

The spacing between drains is: $L = 1.3\ m$

The equivalent diameter of the influence zone is defined by: $D = \frac{2}{\sqrt{\pi}}.L$

III.2.4.1.4 Governing equations

Horizontal consolidation (Barron)

$$U_r = 1 - exp\left(\frac{-8C_h.t}{D^2.\mu}\right)$$

With

$$\mu = F(n) = \frac{n^2}{n^2-1}\ln(n) - \frac{3n^2-1}{4n^2}$$

$$n = D/d$$

Vertical consolidation (Terzaghi)

$$U_v = \left(\frac{1}{1+\frac{1}{2T_v^3}}\right)^{1/6}$$

With

$$T_v = \frac{C_v.t}{H^2}$$

Global consolidation (Carillo)

$$(1-U) = (1-U_v)(1-U_r)$$

III.2.4.1.5 Calculation of horizontal consolidation

Equivalent diameter

$$D = \frac{2}{\sqrt{\pi}}.L = \frac{2}{\sqrt{\pi}} \times 1.3 = 1.467\ m$$

Parameter n

$$n = D/d = 1.467/0.05 = 29.34$$

Parameter μ

$$\mu = \frac{n^2}{n^2-1}\ln(n) - \frac{3n^2-1}{4n^2} = \frac{29.34^2}{29.34^2+1}\ln(29.34) - \frac{3\times 29.34^2-1}{4\times 29.34^2} = 2.633$$

Time conversion

$$2\ months = 60\ days = 5184000\ s$$

Radial consolidation

$$U_r = 1 - exp\left(\frac{-8C_h.t}{D^2.\mu}\right)$$

$$U_r \approx 84\ \%$$

III.2.4.1.6 Vertical consolidation

Time factor

$$T_v = \frac{C_v.t}{H^2} = \frac{5 \times 10^{-8} \times 5184000}{(10)^2} = 0.002592$$

Degree of vertical consolidation

$$U_v = \left(\frac{1}{1+\frac{1}{2T_v^3}}\right)^{1/6} = \left(\frac{1}{1+\frac{1}{2 \times (0.002592)^3}}\right)^{1/6}$$

$$U_v \approx 5.7\ \%$$

III.2.4.1.7 Global consolidation

$$(1-U) = (1-U_v)(1-U_r)$$

$$U \approx 85\ \%$$

III.2.4.1.8 Interpretation

The results show that the installation of vertical drains with a square spacing of: $1.3\ m \times 1.3\ m$

combined with a 1 m preloading embankment applied for two months makes it possible to reach the required degree of consolidation of approximately 85%.

III.2.5 Behavior of Soft Soils under Loading

The behavior of soft soils under a preloading embankment depends on:

- The shear strength of the soil,
- The rate of load application,
- The dissipation of pore pressures.

During embankment construction, it is necessary to check the stability of the soil mass, because excessive surcharge may cause failure.

An example of failure of an embankment under construction is presented in Figure III.11.

Figure III.11. Example of failure of an embankment during construction

III.2.6 Evolution of Settlements

The settlements observed during preloading include:

- Primary consolidation settlements,
- Secondary settlements (creep).

The evolution of settlements over time can be analyzed using consolidation models.

An example of settlement evolution under an embankment is illustrated by Figure III.12.

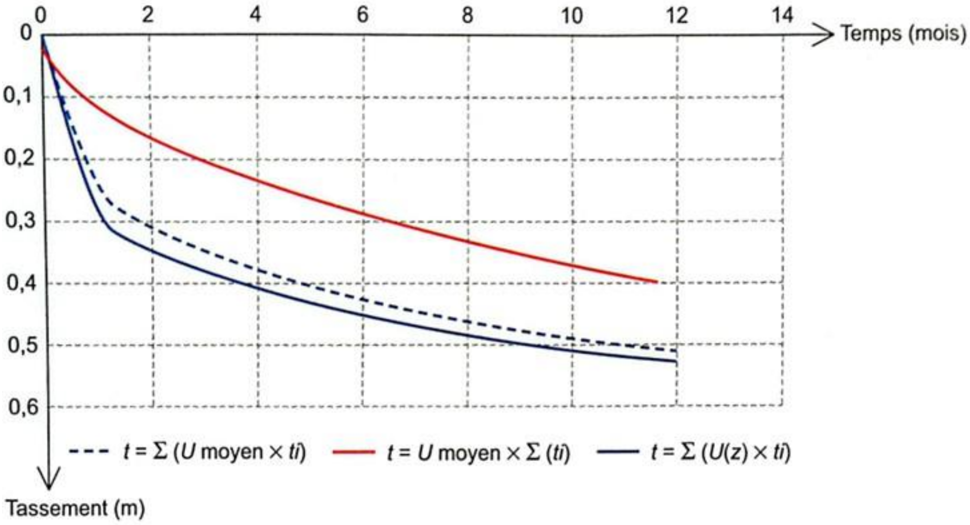


Figure III.12. Settlement evolution along the embankment axis obtained according to different approaches for considering the consolidation process

III.2.7 Advantages, Limitations and Selection Criteria

Advantages

Preloading presents several advantages:

- Simple and economical technique,
- Durable improvement of soil mechanical characteristics,
- Significant reduction of future settlements.

Limitations

Certain constraints must be taken into account:

- Treatment duration sometimes long,
- Need to control embankment stability,
- Large volume of fill materials required.

Selection Criteria

Preloading is particularly suitable when:

- The soils are compressible and poorly permeable,
- The projects concern large-area structures,
- The schedule allows a prior consolidation phase.

The use of vertical drains is often necessary to accelerate consolidation and reduce the duration of treatment.

III.3 Atmospheric Consolidation

III.3.1 General Principle

Atmospheric consolidation (or vacuum consolidation) is a soil improvement technique for soft soils which consists of applying a negative pressure (vacuum) in the soil in order to increase effective stresses and accelerate consolidation.

Unlike preloading by embankment, the total stress applied to the soil remains practically constant. Consolidation is obtained by decreasing pore pressure, which leads to an increase in effective stress and therefore compression of the soil.

The technique generally involves:

- Installation of vertical drains,
- Installation of an impermeable membrane,
- Application of vacuum pumping.

The general principle of the process is illustrated by Figure III.13.

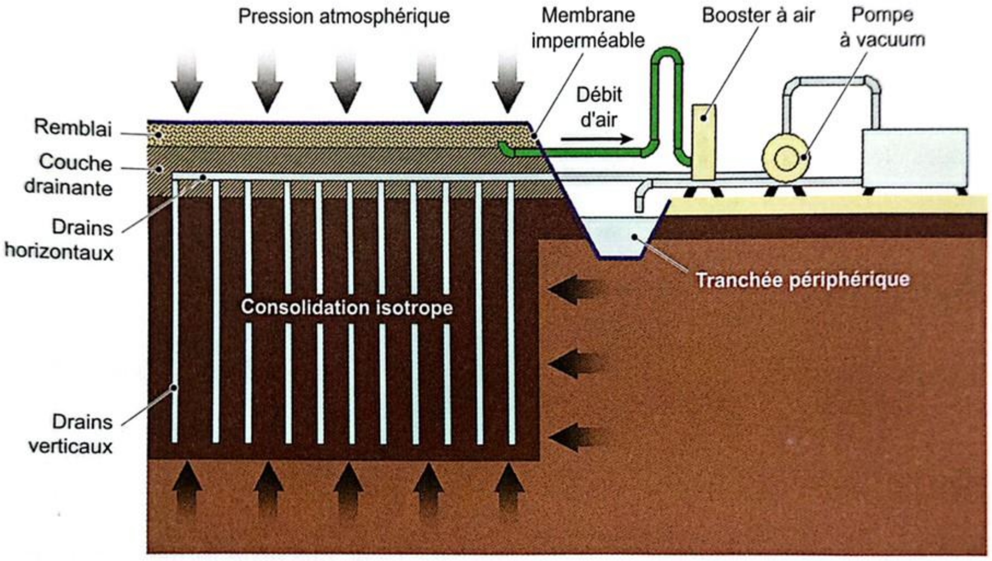


Figure III.13. Principle of implementation of atmospheric consolidation.

This technique is particularly suitable for very compressible saturated clay soils.

III.3.2 Implementation

The implementation of atmospheric consolidation includes several steps.

A drainage platform is first constructed at the ground surface in order to facilitate water evacuation. Prefabricated vertical drains are then installed in the soil to reduce drainage distances and accelerate consolidation.

The area to be treated is then covered with an impermeable membrane, allowing the creation of a vacuum. The drain system is connected to a pumping station that applies the vacuum in the soil.

The entire system makes it possible to reduce pore pressure and accelerate soil consolidation.

III.3.3 Mechanical Principle

The consolidation mechanism is based on the relationship between total stresses, pore pressures and effective stresses:

$$\sigma' = \sigma - u$$

During vacuum application, pore pressure decreases, which causes an increase in effective stress and therefore compression of the soil.

The evolution of stresses in the soil is illustrated by Figure III.14.

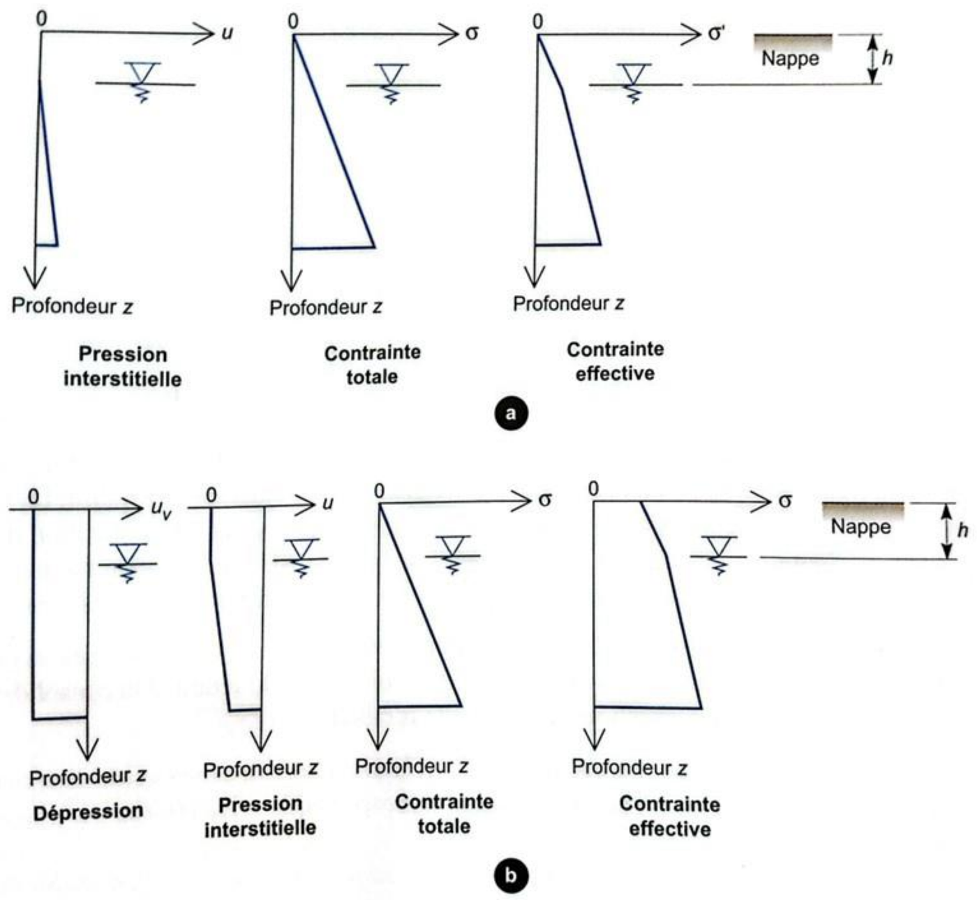


Figure III.14. Stress state in the soil: (a) initial and (b) during atmospheric consolidation

III.3.4 Design and Control

The design of atmospheric consolidation mainly depends on:

- The applied vacuum, generally between 65 and 80 kPa,
- The soil permeability,
- The spacing of vertical drains,
- The duration of pumping.

Monitoring of the treatment is carried out by measurements of:

- Settlements,
- Pore pressures,
- Horizontal displacements.

An example of displacement monitoring is illustrated by Figure III.15.

Figure III.15. A837 highway: inclinometer monitoring at the edge of the vacuum-treated area

III.3.5 Advantages, Limitations and Selection Criteria

Advantages

Atmospheric consolidation presents several advantages:

- Significant acceleration of consolidation of soft soils,
- Reduced risk of failure compared with conventional preloading,
- Possibility of treating large areas,
- Reduction of the required embankment height.

Limitations

Certain limitations must be taken into account:

- Need for a perfectly impermeable membrane,
- Risk of air leakage reducing vacuum efficiency,
- Relatively complex implementation.

Selection Criteria

Atmospheric consolidation is particularly suitable when:

- The soils are highly compressible clays,
- Embankment surcharges are difficult to construct,
- Acceleration of consolidation is required.

III.4 Comparison of Ground Improvement Techniques

Table III.3 summarizes the comparison between the different ground improvement techniques presented in this chapter. These methods belong to the category of ground improvement techniques without additives, mainly applied to cohesive soils.

The comparison highlights their main principles, fields of application, advantages, limitations, and selection criteria, helping to identify the most appropriate technique depending on the geotechnical conditions of the project.

Table III.3. Comparison of Ground Improvement Techniques Without Additives for Cohesive Soils

Technique	Principle	Suitable Soils	Main Objective	Advantages	Limitations	Selection Criteria
Replacement, Lightweight Fill and Compensation	Excavation of compressible soil and replacement or reduction of applied load	Soft clays, peat, organic soils	Improve bearing capacity and reduce settlements	Simple and rapid solution	High cost for deep layers	Shallow compressible layers accessible to excavation
Preloading with Embankments (with or without drains)	Temporary surcharge applied to accelerate soil consolidation	Soft saturated clays	Reduce post-construction settlements	Economical and reliable technique	Long consolidation time	Large projects where sufficient time is available for consolidation
Atmospheric (Vacuum) Consolidation	Application of vacuum pressure beneath an airtight membrane to increase effective stress	Very soft clays and silts	Accelerate consolidation	Reduces risk of embankment instability	More complex installation	Very compressible soils where high surcharge loads would be unstable

Chapter IV — Treatments with Additives or Inclusions for Granular Soils and Embankments

IV.1 Stone Columns

IV.1.1 Introduction and General Principle

Stone columns are a soil improvement technique consisting of constructing columns of compacted granular material (gravel or ballast) in the ground using a vibrator. These columns reinforce compressible soils while improving their drainage.

The principle consists of introducing a vibrator into the soil to create a cavity, which is then filled with granular material compacted by vibration. The columns thus formed constitute a network of draining and resistant inclusions distributed beneath the structure.

The construction of a stone column is illustrated in Figure IV.1.

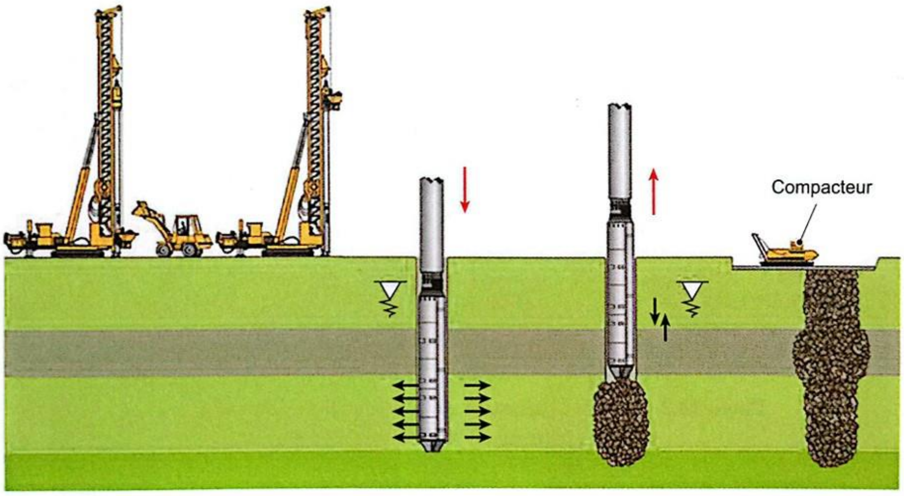


Figure IV.1. Principle of installation of stone columns (Keller)

Stone columns are used to:

- Increase the bearing capacity of compressible soils,
- Reduce settlements under foundations or embankments,
- Accelerate consolidation of cohesive soils,
- Improve the stability of embankments and platforms.

IV.1.2 Operating Principle

The operation of stone columns is based on two main mechanisms.

The first mechanism is a reinforcement effect. Under the loads applied by the structure, a large part of the stresses is taken up by the stone columns, which are much stiffer than the surrounding soil. Stress concentration therefore occurs in the columns, reducing soil deformation.

The second mechanism is a drainage effect. Stone columns consist of highly permeable granular material that acts as a vertical drain. They accelerate the dissipation of excess pore pressures and therefore the consolidation of the soil.

Thanks to these two mechanisms, the soil–stone column system provides a significant reduction in settlements and improves the overall behavior of the soil under load.

IV.1.3 Construction Methods

Stone columns are generally constructed using a vibroflot suspended from a crane.

Two main methods are used.

The first method is the wet method (vibro-replacement). In this method, the vibrator penetrates the soil through the injection of pressurized water. The cavity created is then filled with granular material, which is compacted by vibration during withdrawal of the vibrator.

The second method is the dry method (vibro-displacement). In this case, the granular material is introduced through a feeding tube connected to the vibrator. The gravel is progressively compacted by vibration to form the column.

These techniques allow the construction of columns with diameters generally between 0.6 and 1.2 m, with depths that may reach 20 to 30 m depending on soil conditions.

IV.1.4 Treatment Geometry and Grid Layout

Stone columns are arranged beneath structures according to a regular grid, generally square or triangular.

The grid design depends on:

- Column diameter,
- Spacing between columns,
- Mechanical characteristics of the soil,
- Loads applied by the structure.

The behavior of the treated soil is often studied using an equivalent elementary cell representing the portion of ground influenced by a column.

The determination of the equivalent diameter of this cell according to the grid geometry is illustrated in Figure IV.2.

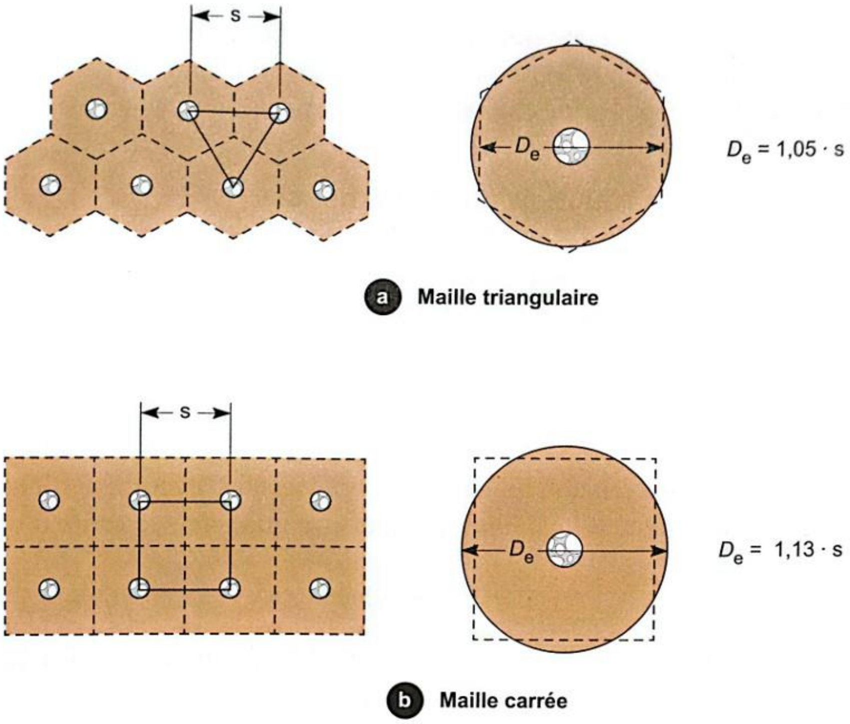


Figure IV.2. Equivalent diameter of the elementary cell according to grid geometry (Balaam and Poulos, 1983)

IV.1.5 Design of Stone Columns

The design of stone columns mainly relies on evaluating the settlement reduction obtained through the treatment.

A commonly used method is the Priebe method, which estimates the soil improvement factor as a function of the replacement ratio (ratio between the area of the columns and the total area of the grid).

The relationship between the improvement factor and the area ratio is illustrated in Figure IV.3.

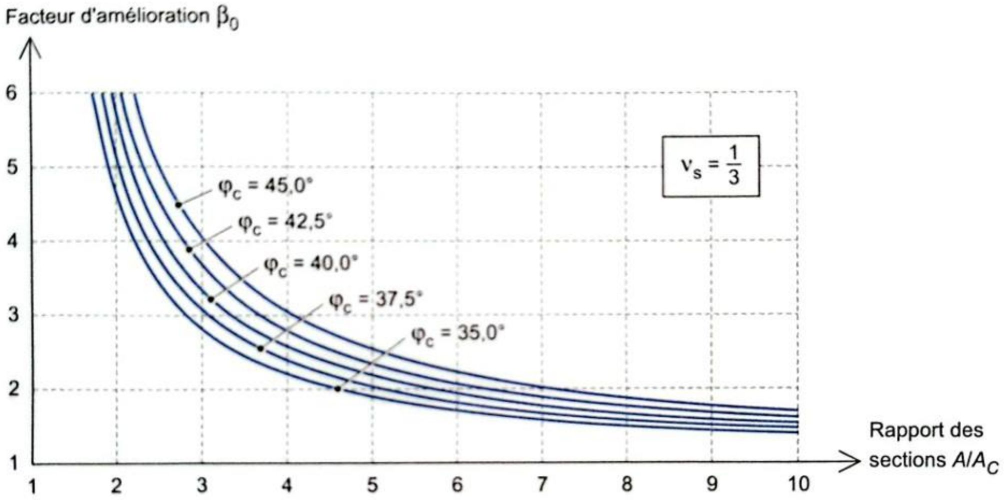


Figure IV.3. Improvement factor as a function of the area ratio (Priebe, 1995)

This approach makes it possible to estimate the reduction in settlements due to the presence of stone columns.

IV.1.6 Possible Failure Modes

The behavior of stone columns under load may lead to different failure modes.

The most frequent mode is lateral bulging of the column when the surrounding soil is weak. In this case, the column deforms laterally under vertical stresses.

Other failure modes may occur, such as punching of the column into the underlying soil or global shear failure of the treated soil mass.

These different failure modes are illustrated in Figure IV.4.

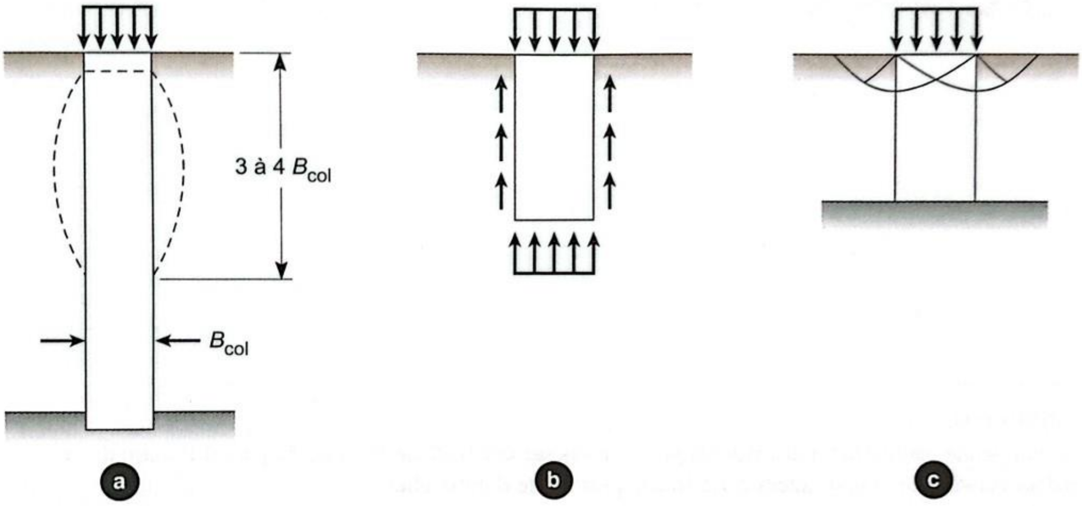


Figure IV.4. Different failure modes of an isolated stone column (Soyez, 1985)

Understanding these mechanisms is essential for the design and safety of structures.

IV.1.7 Advantages of the Technique

Stone columns offer several important advantages:

- Significant improvement of the bearing capacity of compressible soils,
- Reduction of settlements beneath structures,
- Acceleration of consolidation due to the drainage effect,
- Relatively rapid installation,
- Possibility of treating large areas.

IV.1.8 Limitations of the Technique

Despite their advantages, stone columns present certain limitations:

- Limited efficiency in very soft or organic soils,
- Need for sufficient lateral confinement of the soil,

- Difficulty of use in very cohesive or very dense soils,
- Quality control of the columns can sometimes be difficult.

IV.1.9 Selection Criteria for the Technique

Stone columns are generally selected when:

- The soil is compressible but provides some confinement,
- Settlement reduction is required under embankments or platforms,
- The technique must be rapid and economically competitive,
- Soil conditions allow vibroflotation installation.

They constitute an intermediate solution between soil densification techniques and reinforcement techniques using rigid inclusions.

IV.1.10 Example of Design of Stone Columns

IV.1.10.1 Principle

The design of stone columns is often based on the area replacement ratio, which represents the proportion of soil replaced by compacted granular material within the treatment grid.

A higher replacement ratio generally leads to a greater reduction in settlement.

IV.1.10.2 Data of the Example

Consider stone columns arranged in a square grid with:

Column diameter: $d = 0.80\ m$

Column spacing: $s = 2.50\ m$

The objective is to calculate the area replacement ratio.

IV.1.10.3 Calculation of the Column Area

The cross-sectional area of one stone column is:

$$A_c = \frac{\pi . d^2}{4} = \frac{\pi (0.80)^2}{4}$$

$$A_c \approx 0.503\ m^2$$

IV.1.10.4 Calculation of the Tributary Area

For a square grid, the tributary area associated with one column is:

$$A_s = s^2 = (2.50)^2 = 6.25\ m^2$$

IV.1.10.5 Area Replacement Ratio

The area replacement ratio is:

$$a_r = \frac{A_c}{A_s} = \frac{0.503}{6.25}$$

$$a_r \approx 0.08 \approx 8\,\%$$

IV.1.10.6 Interpretation

This means that about 8% of the soil surface is replaced by compacted granular material.

This replacement improves the bearing capacity of the ground and reduces settlement. In practice, a higher replacement ratio generally gives a stronger improvement effect, but it also increases the treatment cost.

For a stone column of diameter 0.80 m installed on a 2.50 m square grid, the calculated area replacement ratio is:

$$a_r \approx 0.08 \approx 8\,\%$$

This parameter is one of the main design values used to estimate the settlement reduction obtained by stone column treatment.

IV.2 Reinforcement by Vertical Rigid Inclusions

IV.2.1 Introduction

Reinforcement by vertical rigid inclusions is a soil improvement technique consisting of installing rigid vertical elements (generally made of concrete or mortar) in the ground to transfer loads from a structure to stronger soil layers.

Unlike conventional piles, these inclusions are generally not directly connected to the structure. Loads are first distributed through a granular load-transfer platform above the inclusions and then transferred to them.

The general principle of a foundation on rigid inclusions is illustrated in Figure IV.5.

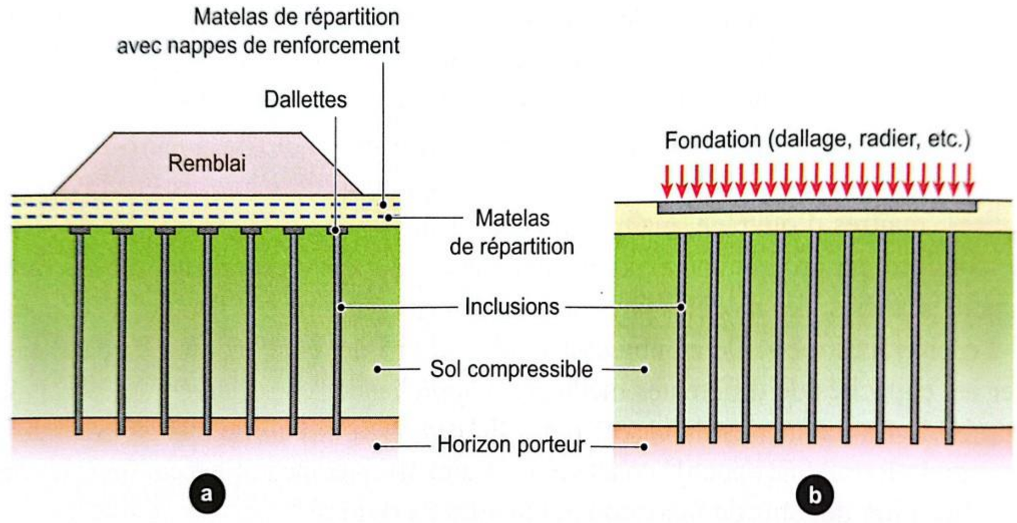


Figure IV.5. Components of a foundation on rigid inclusions

The system generally includes:

- Rigid inclusions anchored in a stronger soil layer,
- A granular load-transfer platform,
- Possibly horizontal reinforcement elements (geosynthetics).

IV.2.2 Description of Rigid Inclusions

A rigid inclusion is a vertical foundation element usually made of concrete, mortar or treated soil, whose stiffness is significantly greater than that of the surrounding soil.

Inclusions are generally constructed by soil displacement or drilling and then filled with concrete or mortar.

Their diameter typically ranges between 25 and 50 cm, and the compressive strength of the concrete may reach 10 to 20 MPa.

Rigid inclusions mainly work in vertical compression, unlike stone columns which mobilize lateral soil resistance.

IV.2.3 Operating Mechanism

The functioning of rigid inclusions is based on load transfer between the soil and the inclusions.

When a structure is built on compressible soil, the applied load is distributed by the load-transfer platform, which progressively causes stress concentration toward the rigid inclusions.

The difference in stiffness between the inclusions and the soil leads to redistribution of loads toward the rigid elements, thereby reducing stresses applied to the compressible soil.

The diffusion of loads in a treated soil mass is illustrated in Figure IV.6.

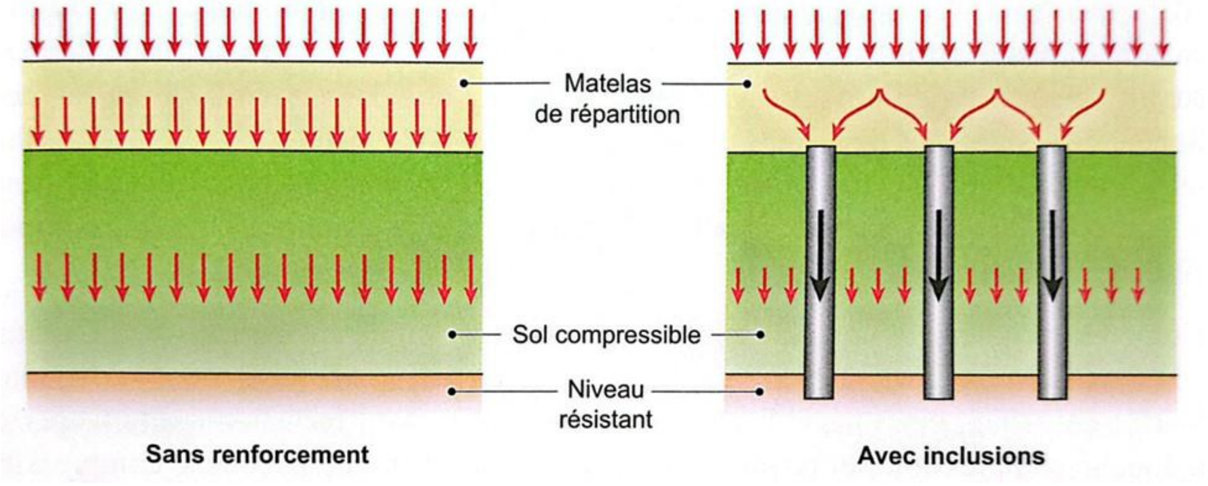


Figure IV.6. Comparison of load diffusion under a large loaded surface, without inclusions or with inclusions

This mechanism allows:

- Reduction of global settlements,
- Improvement of soil bearing capacity,
- Reduction of stresses in the compressible soil.

IV.2.4 Soil–Inclusion Interaction

Load transfer between soil and inclusions occurs mainly through shear in the load-transfer platform and friction along the inclusions.

The interaction mechanisms between inclusions and soil are illustrated in Figure IV.7.

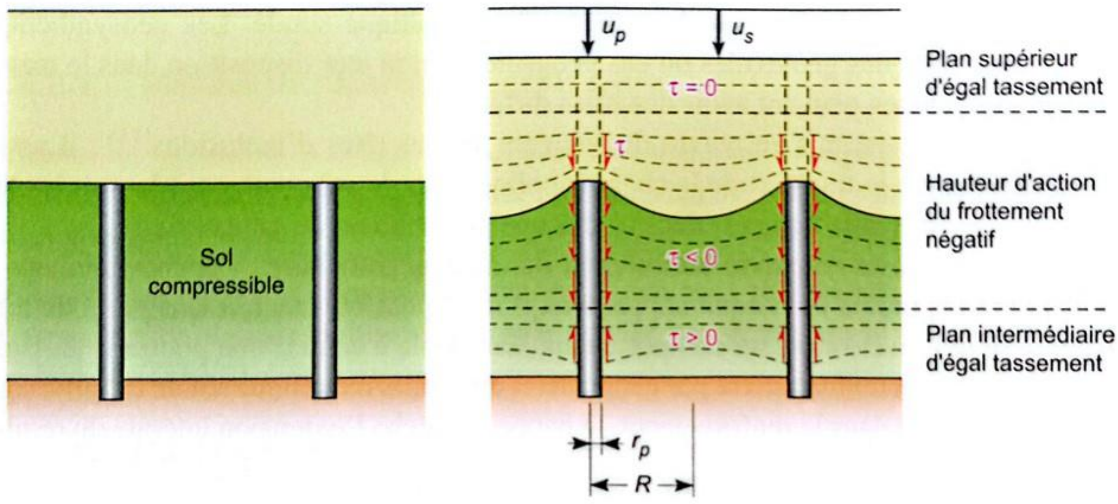


Figure IV.7. Schematic interaction mechanisms in an embankment on inclusions

The overall behavior depends on:

- Relative stiffness between soil and inclusions,

- Thickness and quality of the load-transfer platform,
- Inclusion spacing,
- Load applied by the structure.

IV.2.5 Field of Application

Rigid inclusion reinforcement is particularly suitable for compressible soils when the loads to be transmitted are high.

The technique is commonly used for:

- Road and railway embankments,
- Bridges and engineering structures,
- Industrial buildings,
- Heavily loaded slabs,
- Foundations of reservoirs or industrial structures.

An example of application beneath an embankment is illustrated in Figure IV.8.

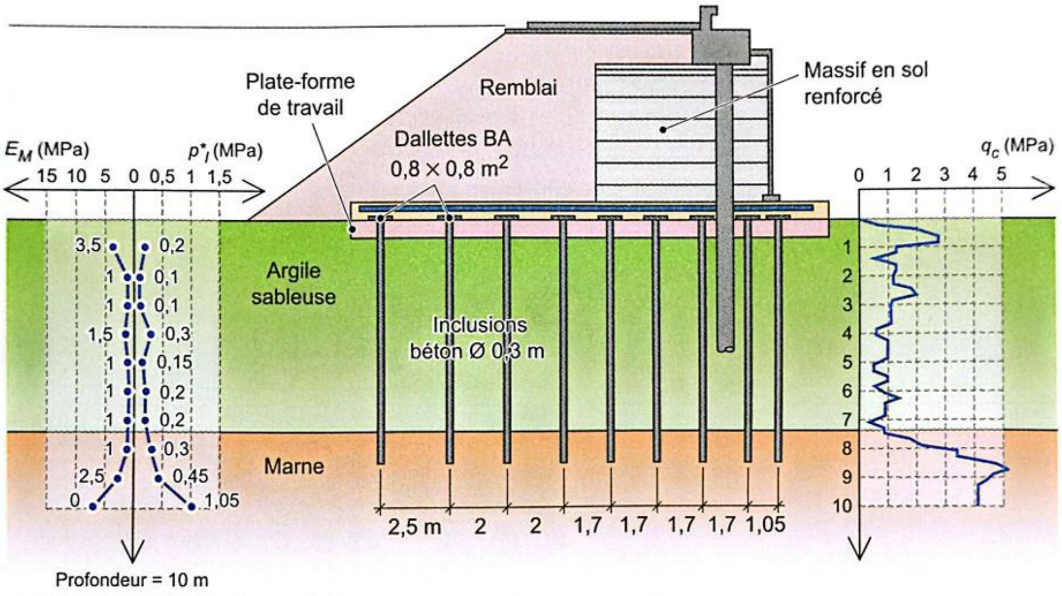


Figure IV.8. Access embankment to a bridge abutment constructed as a reinforced embankment mass

The technique is also used beneath heavily loaded industrial slabs, as illustrated in Figure IV.9.

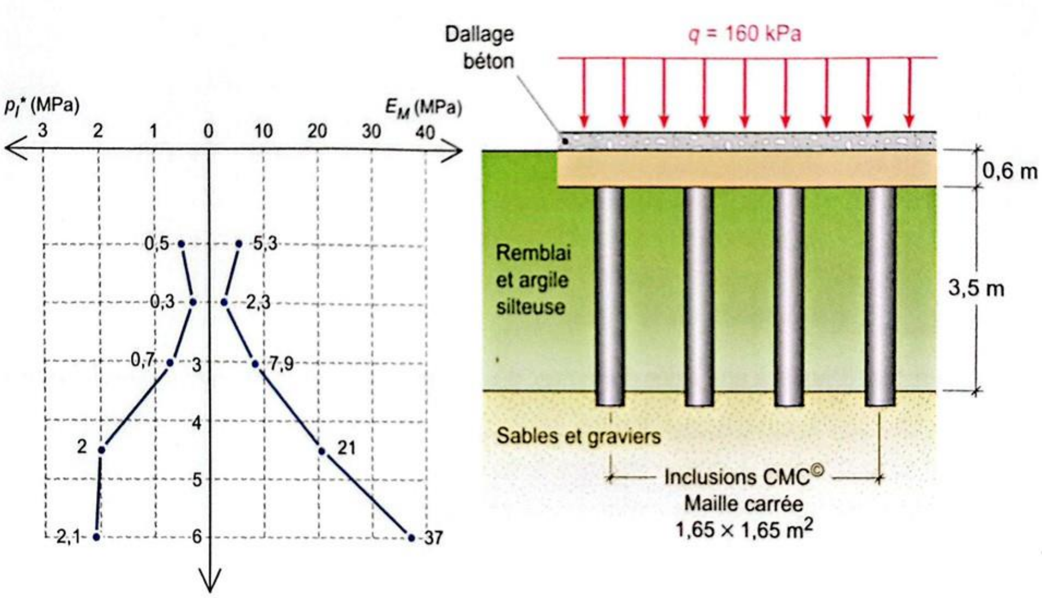


Figure IV.9. Heavily loaded industrial slab

IV.2.6 Design Parameters

The design of rigid inclusions depends on several geometric and mechanical parameters.

The main parameters are:

- Inclusion diameter,
- Inclusion spacing,
- Stiffness of the load-transfer platform,
- Strength of the compressible soil,
- Anchorage depth in the bearing layer.

The efficiency of the treatment can be evaluated using the Settlement Reduction Factor (SRF), which represents the ratio between settlement of untreated soil and reinforced soil.

IV.2.7 Advantages of the Technique

Rigid inclusions offer several advantages:

- Significant settlement reduction,
- Improved bearing capacity of compressible soils,
- Suitable for high loads,
- Relatively rapid installation,
- Possibility of treating large areas.

IV.2.8 Limitations of the Technique

Despite its performance, the technique has certain limitations:

- Need for a properly designed load-transfer platform,
- Higher cost than some soil improvement techniques,
- Need for precise geotechnical design,
- Sensitivity to construction conditions.

IV.2.9 Selection Criteria for the Technique

Rigid inclusions are generally selected when:

- The soil has low bearing capacity,
- Applied loads are high,
- Settlement reduction is a critical requirement,
- Conventional soil improvement techniques are insufficient.

IV.3. Geosynthetics

IV.3.1. Basic Concepts

Geosynthetics are polymeric materials used in civil engineering to improve the mechanical and hydraulic behavior of soils. They are generally placed in the soil or between different layers of materials in order to provide various geotechnical functions.

The main families of geosynthetics are:

- Geotextiles (permeable materials),
- Geotextile-related products (geogrids, geocells, geonets, geomats),
- Geomembranes (impermeable barriers),
- Geocomposites (association of several geosynthetics).

Geotextiles may be woven, knitted or nonwoven and are manufactured from polymers such as polypropylene, polyester or polyethylene.

The different types of geotextiles are illustrated in Figure IV.10.

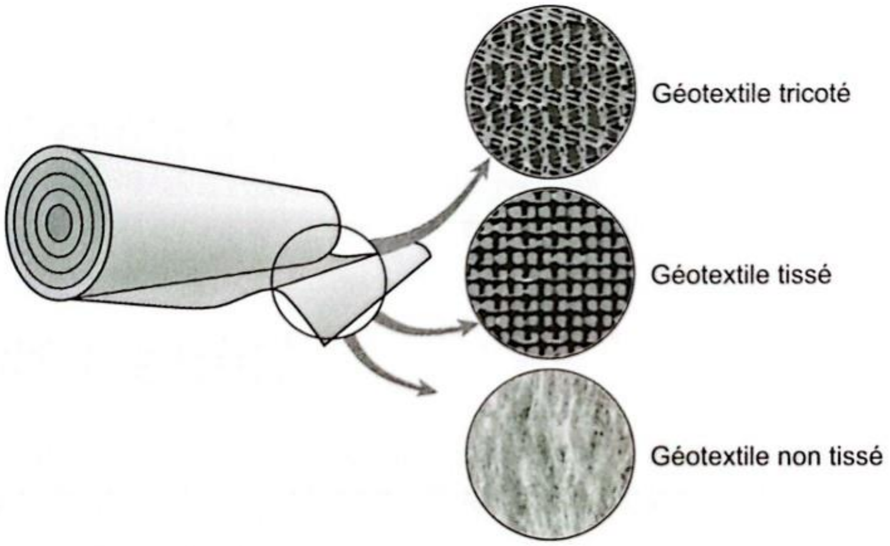


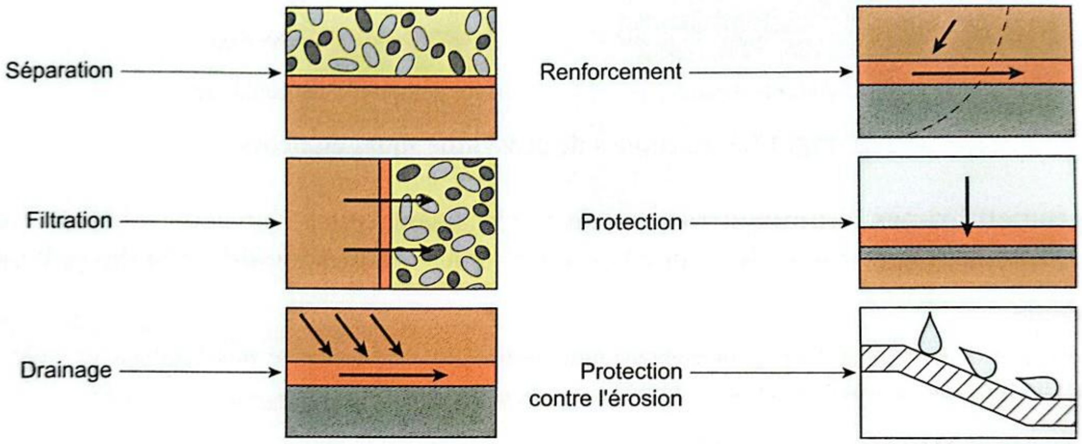
Figure IV.10. Diagram of the different types of geotextile

IV.3.2. Main Functions of Geosynthetics

Geosynthetics can perform several functions in geotechnical works:

- Separation,
- Filtration,
- Drainage,
- Reinforcement,
- Protection,
- Sealing.

These functions are represented in Figure IV.11.



Norme NF EN ISO 10318
Cahier du moniteur

Figure IV.11. Pictograms of the main functions of geotextiles and related products according to NF EN ISO 10318

The separation function consists of preventing the mixing of two soil layers with different characteristics, for example between the subgrade and the base layer of a pavement.

Filtration allows water to pass through while retaining the fine particles of the soil.

Drainage makes it possible to collect and evacuate water in order to reduce pore pressures in soils.

Protection is used in particular to protect geomembranes against mechanical damage.

The sealing function is provided by geomembranes or bentonite geosynthetics in order to prevent the migration of fluids.

IV.3.3. Fields of Application

Geosynthetics are used in many geotechnical structures, in particular:

- Road and railway earthworks,
- Drainage works,
- Dams and canals,
- Retaining structures,
- Tunnels,
- Waste storage facilities.

The choice of the type of geosynthetic depends mainly on the required function (separation, drainage, reinforcement or sealing).

IV.3.4. Reinforcement Geosynthetics

In geotechnical structures, geosynthetics can be used to reinforce soils by mobilizing their tensile strength.

The materials most commonly used for this function are:

- Woven geotextiles,
- Geogrids,
- Reinforcement geocomposites.

The essential mechanical properties for design are:

- Tensile strength,
- Elongation,
- Stiffness,
- Durability.

The typical tensile behavior of a reinforcement geosynthetic is represented in Figure IV.12.

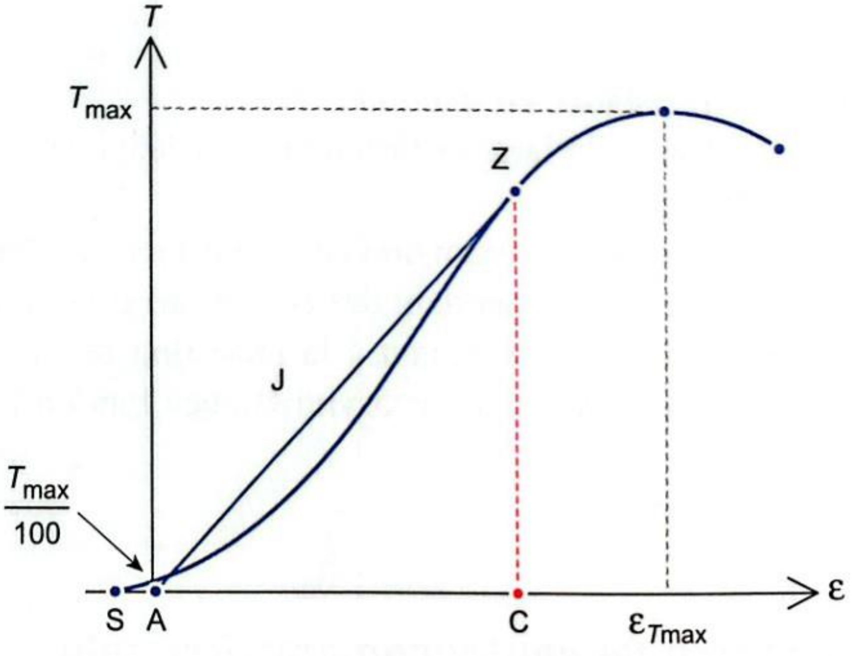


Figure IV.12. Typical tensile strength curve of a reinforcement geosynthetic (NF EN ISO 10319)

IV.3.5. Soil Reinforcement Mechanisms

Soil reinforcement by geosynthetics is mainly based on four mechanisms:

- Tension in the geosynthetic,
- Friction at the soil–geosynthetic interface,
- Anchorage of the geosynthetic,
- Membrane effect.

The transfer of forces between the soil and the geosynthetic takes place mainly by friction at the interface, characterized in the laboratory using shear tests. The principle of this test is illustrated by Figure IV.13.

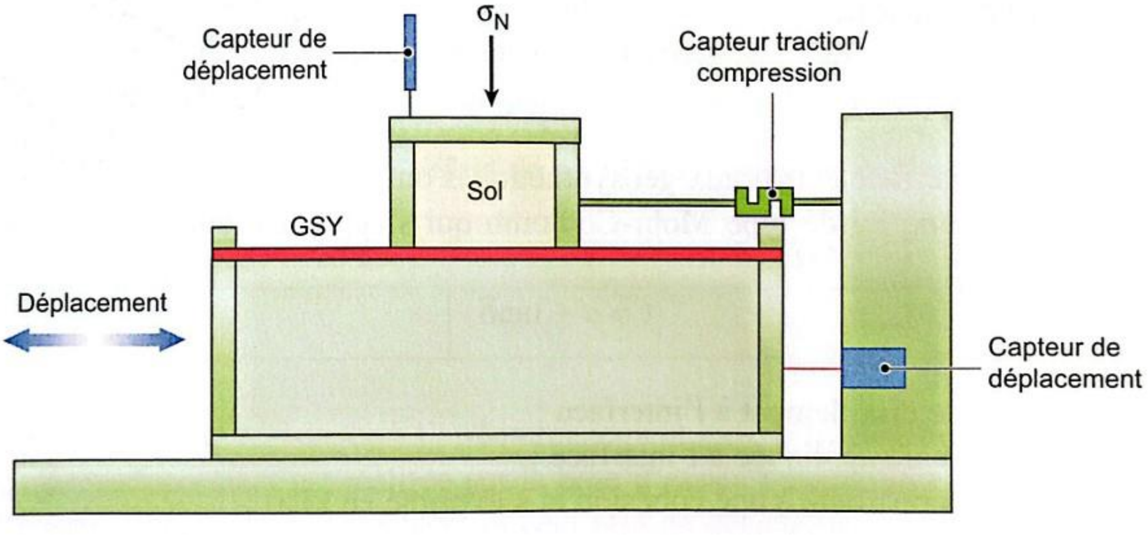


Figure IV.13. Principle diagram of a shear box

Anchorage of the geosynthetic in the soil makes it possible to mobilize its tensile strength effectively and to ensure the stability of reinforced structures.

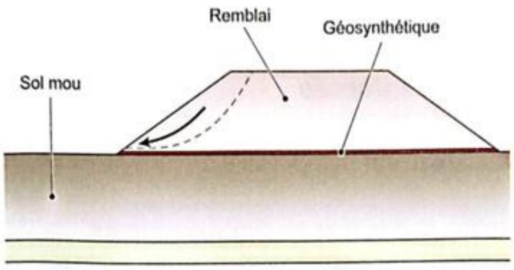
IV.3.6. Applications to Embankments on Compressible Soils

Geosynthetics are widely used to stabilize embankments constructed on compressible soils.

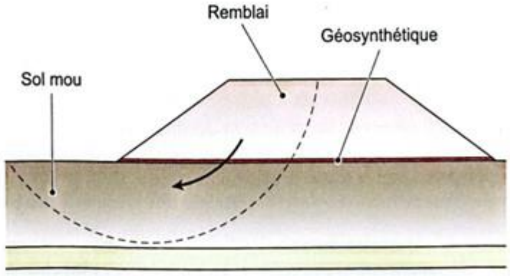
During the design of these structures, several failure modes must be analyzed:

- Local failure of the embankment,
- Global rotational failure,
- Punching failure.

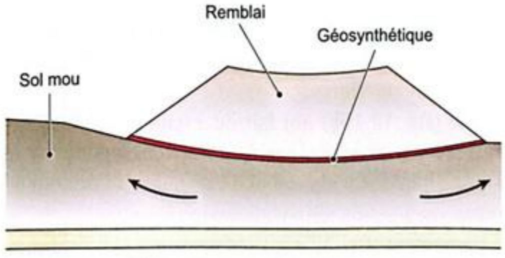
These mechanisms are illustrated in Figure IV.14.



a **Rupture locale du remblai**
(généralement au contact
du géosynthétique)



b **Rupture rotationnelle**
(stabilité mixte)



c **Rupture par poinçonnement**
Défaut de capacité de portance
(stabilité globale)

Figure IV.14. Main types of failure to be considered in the design of reinforced embankments on soft soil

Geosynthetics can also be used in load transfer platforms above rigid inclusions in order to improve the distribution of loads in the soil. This principle is illustrated by Figure IV.15.

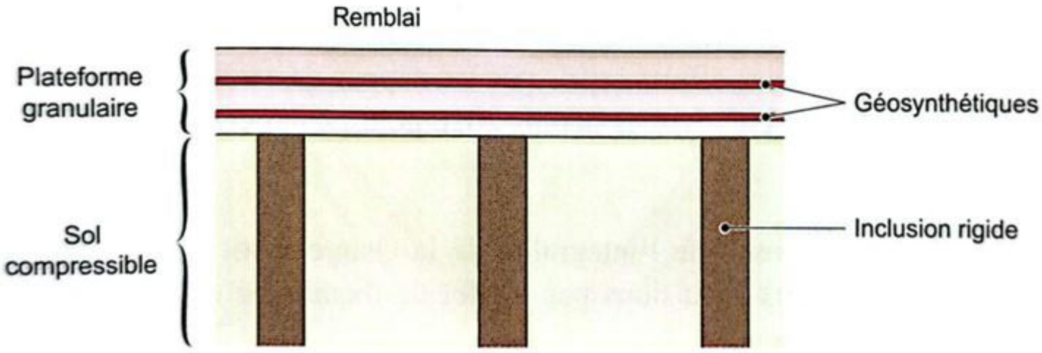


Figure IV.15. Reinforcement by geosynthetics of granular platforms on rigid inclusions

IV.3.7. Conclusion

Geosynthetics now play a major role in the improvement and reinforcement of soils. They make it possible to ensure several essential functions such as separation, filtration, drainage, protection, sealing and reinforcement.

Their effectiveness mainly depends on:

- The mechanical properties of the geosynthetic,
- The soil–geosynthetic interaction,
- The implementation conditions,
- And the design adapted to tension and friction mechanisms.

IV.4 Comparison of Ground Improvement Techniques

Table IV.1 summarizes the comparison between the different ground improvement techniques presented in this chapter. These methods correspond to ground improvement techniques using additives or inclusions, commonly applied to improve the mechanical behavior of soils.

The comparison highlights their main principles, fields of application, advantages, limitations, and selection criteria, helping to identify the most appropriate technique depending on the geotechnical conditions and the requirements of the project.

Table IV.1. Comparison of Ground Improvement Techniques Using Additives or Inclusions

Technique	Principle	Suitable Soils	Main Objective	Advantages	Limitations	Selection Criteria
Stone Columns	Installation of compacted gravel columns in the soil	Soft clays and compressible soils	Increase bearing capacity and reduce settlements	Widely used and efficient technique	Less effective in very soft soils	Compressible soils with sufficient shear strength to allow column installation
Rigid Vertical Inclusions	Rigid elements transfer loads to deeper competent layers	Very compressible soils	Significant settlement reduction	High load-bearing capacity	Higher cost	High structural loads and thick compressible layers
Geosynthetics	Use of geotextiles or geogrids to reinforce soil	Compressible soils and embankments	Soil reinforcement and stabilization	Rapid installation	Durability depends on material properties	Reinforcement of embankments, shallow foundations and slopes

Chapter V — Injection Treatments

V.1. Biological Methods

V.1.1. Introduction and General Principle

Biological methods are soil improvement techniques based on the use of microbiological processes in order to modify the mechanical and hydraulic properties of the soil. These methods rely on the activity of micro-organisms capable of causing biochemical reactions in the soil.

The objective is generally to:

- Increase the mechanical strength of the soil,
- Reduce erodibility,
- Limit the risk of liquefaction,
- Stabilize granular soils.

These techniques constitute an alternative to conventional chemical or cement-based treatment methods, particularly in contexts where the environmental impact is to be limited.

V.1.2. Types of Biological Processes

Several biological processes can be used to improve soils.

Biocalcification

Biocalcification is the most developed process. It consists of causing the precipitation of calcium carbonate ($CaCO_3$) in the soil pores through bacterial activity. The calcite formed acts as a cement between the grains and increases the strength of the soil.

The principle of this mechanism is illustrated in Figure V.1.

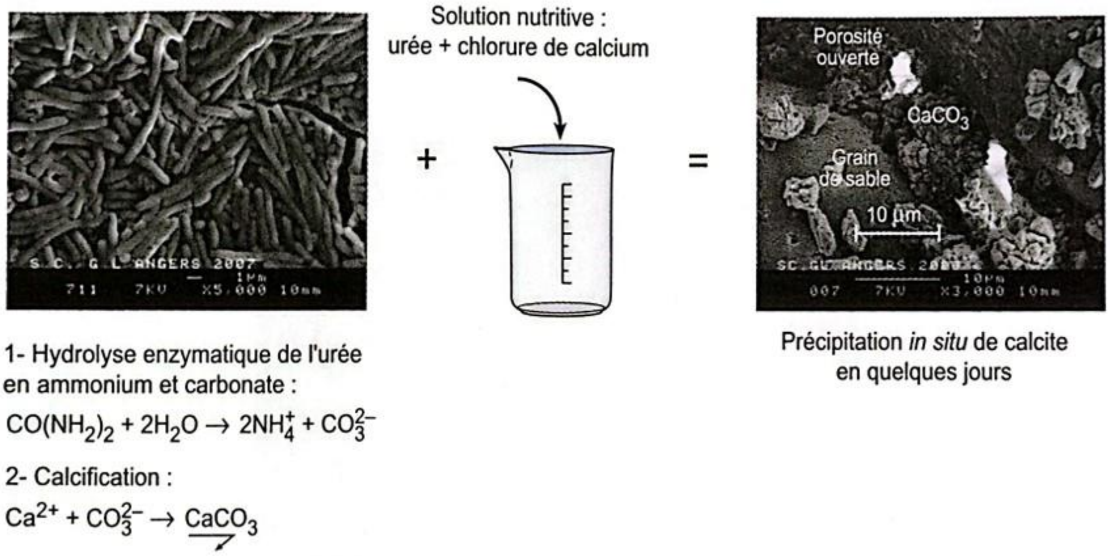


Figure V.1. Principle of biocalcification by the ureolytic pathway (Soletanche Bachy)

The mechanism is based on the hydrolysis of urea by bacteria producing an enzyme called urease. This reaction leads to the formation of carbonate ions, which react with calcium ions to form calcium carbonate ($CaCO_3$).

Biofilm and Biopolymers

Certain bacteria produce extracellular polymeric substances (EPS) that form a biofilm around the soil grains. This biofilm can modify the mechanical properties of the soil and reduce its erodibility.

Production of Biological Gases

Certain microbiological reactions produce gases that modify the degree of saturation of the soil. This modification can help reduce the liquefaction potential in certain granular soils.

V.1.3. Effect on the Mechanical Properties of Soil

The precipitation of calcite in the soil leads to an increase in cohesion and mechanical strength.

The evolution of the strength parameters as a function of the amount of calcite formed is illustrated in Figure V.2.

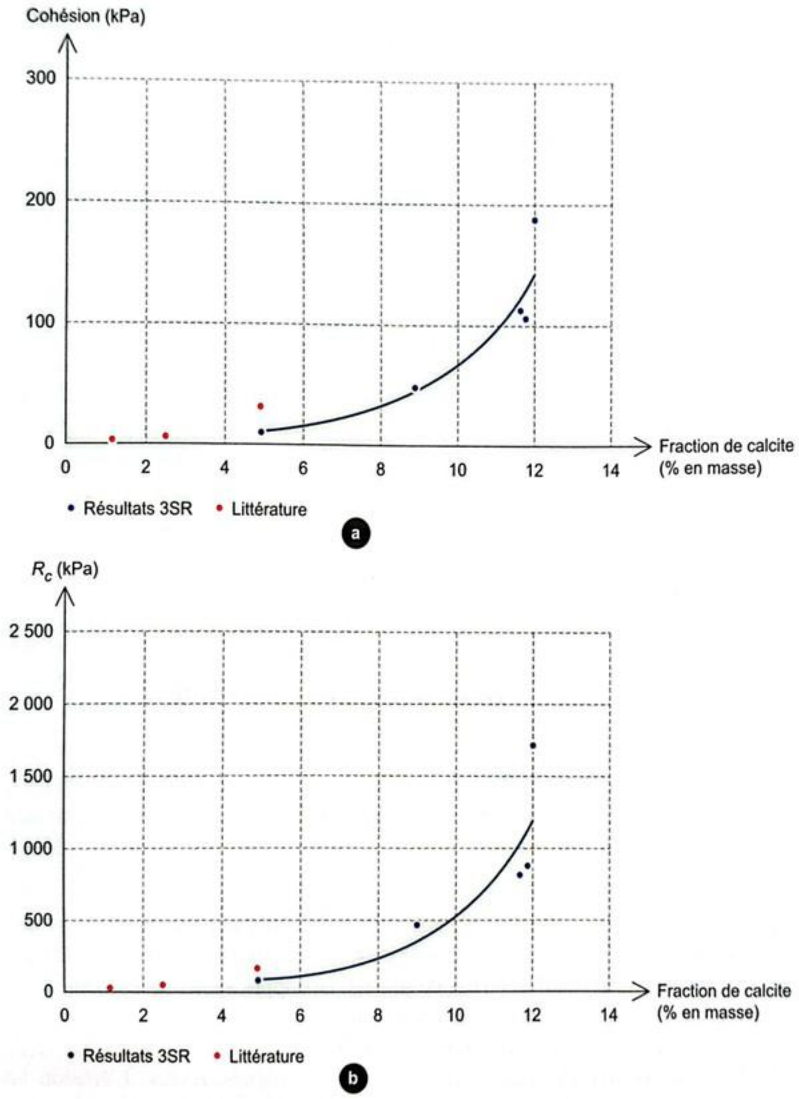


Figure V.2. Evolution of strength parameters (Dadda, 2017)

The increase in the calcite fraction generally leads to:

- An increase in cohesion,
- An increase in compressive strength,
- An improvement in soil stiffness.

The treated soil may then exhibit behavior close to that of a weakly cemented sandstone.

V.1.4. Field of Application

Biological methods are mainly suited to granular soils, in particular:

- Sands,
- Gravelly sands.

The grain-size conditions favorable to the process are illustrated in Figure V.3.

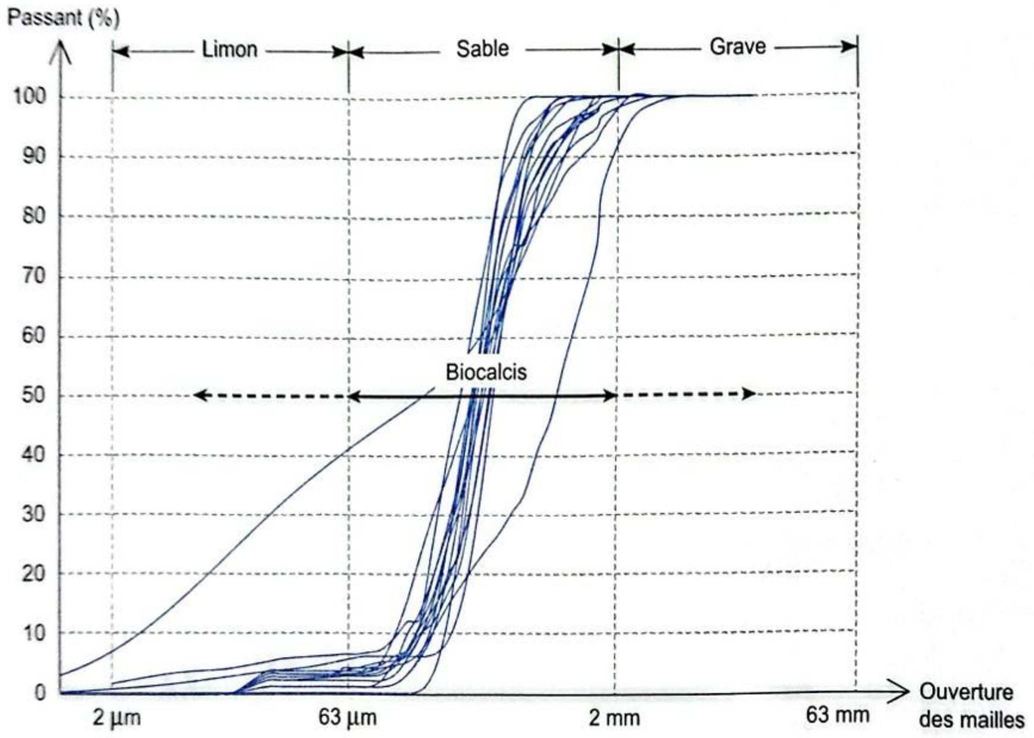


Figure V.3. Grain-size curves of biocalcifiable soils and field of application of Biocalcis

The main applications are:

- Reduction of liquefaction risk,
- Increase in shear strength,
- Stabilization of granular soils,
- Reduction of internal erosion.

V.1.5. Implementation

Implementation of the process generally relies on the injection of solutions containing the bacteria and the nutrients necessary for the biochemical reactions.

The main steps are:

- Injection of the bacterial solution into the soil,
- Injection of the nutrient solution containing urea and calcium,
- Progressive precipitation of calcium carbonate in the soil pores,
- Formation of a natural cement between the grains.

An example of the layout of boreholes for injection is illustrated in Figure V.4.

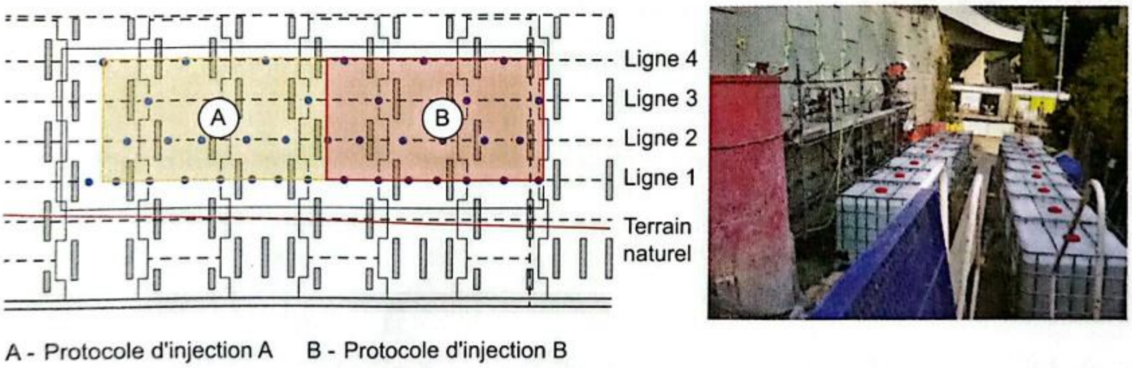


Figure V.4. Layout of boreholes for treatment by biocalcification (Soletanche Bachy)

V.1.6. Control of the Treatment

Control of the treatment is based on:

- Measurement of bacterial activity,
- Monitoring of chemical reactions,
- Evaluation of the quantity of calcium carbonate formed,
- Performance of mechanical tests on the treated soil.

These controls make it possible to verify the effectiveness of the treatment and the homogeneity of the cementation in the soil mass.

V.1.7. Advantages and Limitations

Advantages

Biological methods present several advantages:

- Mechanical improvement of the soil without the use of cement,
- Possibility of in situ treatment,
- Interesting environmental potential,
- Adaptation to granular soils.

Limitations

Certain limitations must be taken into account:

- Complex control of the biological process,
- Sensitivity to environmental conditions,
- Difficult diffusion of the solutions in certain soils,
- Possible presence of chemical by-products to be managed.

V.1.8. Conclusion

Biological methods constitute an innovative approach to soil improvement. Biocalcification is the most developed technique and is based on the precipitation of calcium carbonate produced by bacterial activity.

This natural cementation makes it possible to increase the cohesion and strength of granular soils, which makes these techniques particularly suitable for the stabilization of sands and the reduction of liquefaction risk.

V.2. Cement Grouting and Chemical Grouting

V.2.1. Introduction and General Principle

Soil grouting is an improvement technique consisting of introducing a liquid grout under pressure into the soil in order to modify its mechanical or hydraulic properties. After injection, the grout hardens in the soil voids and forms a more coherent structure making it possible to consolidate the ground or improve its watertightness.

The propagation of the grout mainly depends on:

- Soil permeability,
- Grout viscosity,
- Injection pressure.

The principle of the treatment is illustrated in Figure V.5.

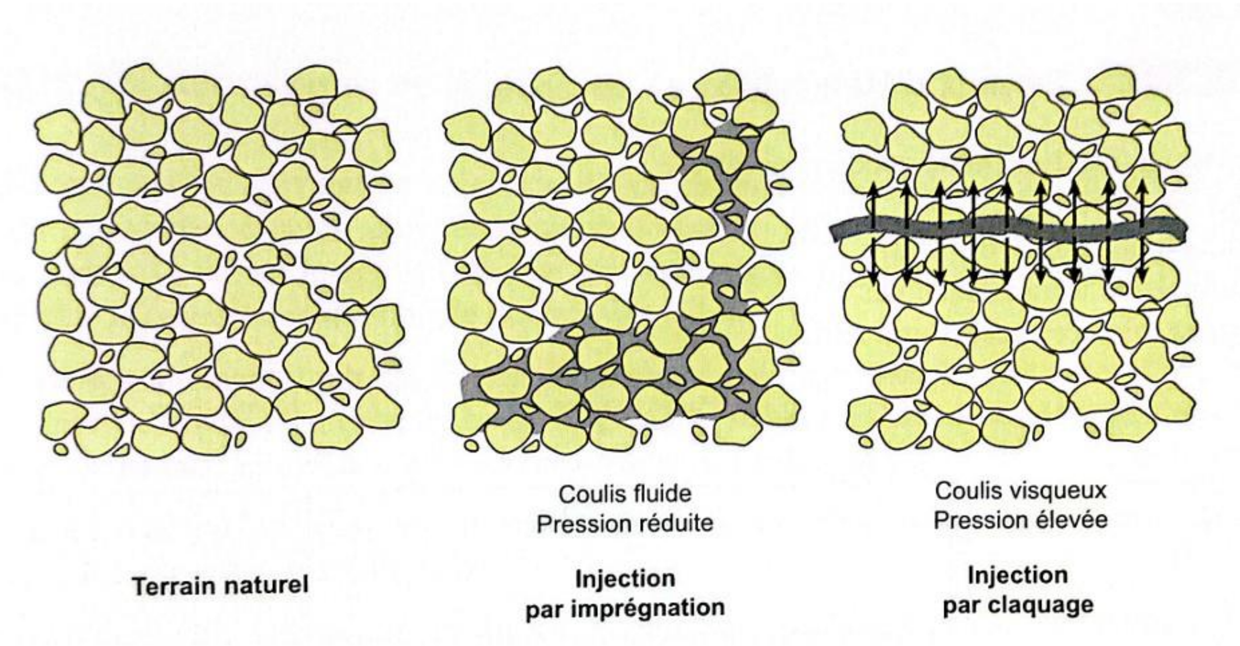


Figure V.5. State of the ground before and after injection

This figure shows the penetration of the grout into the soil voids and the formation of a consolidated mass after hardening.

V.2.2. Injection Mechanisms

The penetration of the grout into the soil can occur according to two main mechanisms:

- **Impregnation Grouting**

Impregnation grouting consists of filling the soil pores with a fluid grout without modifying the structure of the ground. The diffusion of the grout depends directly on soil permeability and the applied pressure.

This technique is particularly suited to permeable granular soils.

- **Hydraulic Fracturing Grouting**

When the injection pressure exceeds the strength of the soil, cracks may appear in the ground, allowing the grout to propagate by hydraulic fracturing. This method is used in less permeable soils or in certain consolidation works.

V.2.3. Fields of Application

Grouting is mainly used for two objectives:

- **Ground Watertightness**

Grouting makes it possible to reduce soil permeability and limit water circulation. It is used in particular for:

- Dam curtains,
- Grouted rafts,
- Tunnels in loose ground,
- Cut-off walls.

An example of application is illustrated in Figure V.6.

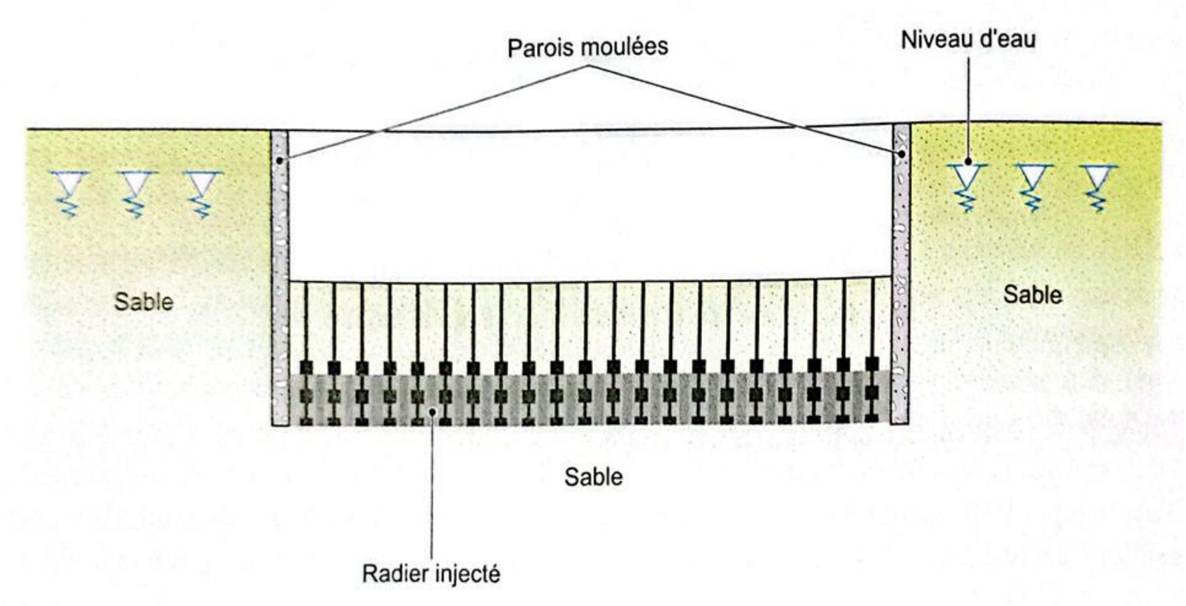


Figure V.6. Example of a grouted raft

This figure shows the creation of a grout curtain beneath a raft in order to limit water infiltration.

- **Soil Consolidation**

Grouting can also improve the mechanical characteristics of the soil, particularly for:

- Strengthening of existing foundations,
- Rehabilitation of structures,
- Stabilization of cavities,
- Treatment of soils before excavation.

V.2.4. Types of Injection Grouts

The injected materials, called grouts, are divided into two major categories:

- **Hydraulic Binder-Based Grouts**

These grouts are generally composed of:

- Cement,
- Bentonite,
- Water and admixtures.

They are used for the consolidation of granular soils and the filling of voids. The possibility of injection depends strongly on ground permeability, as illustrated in Figure V.7.

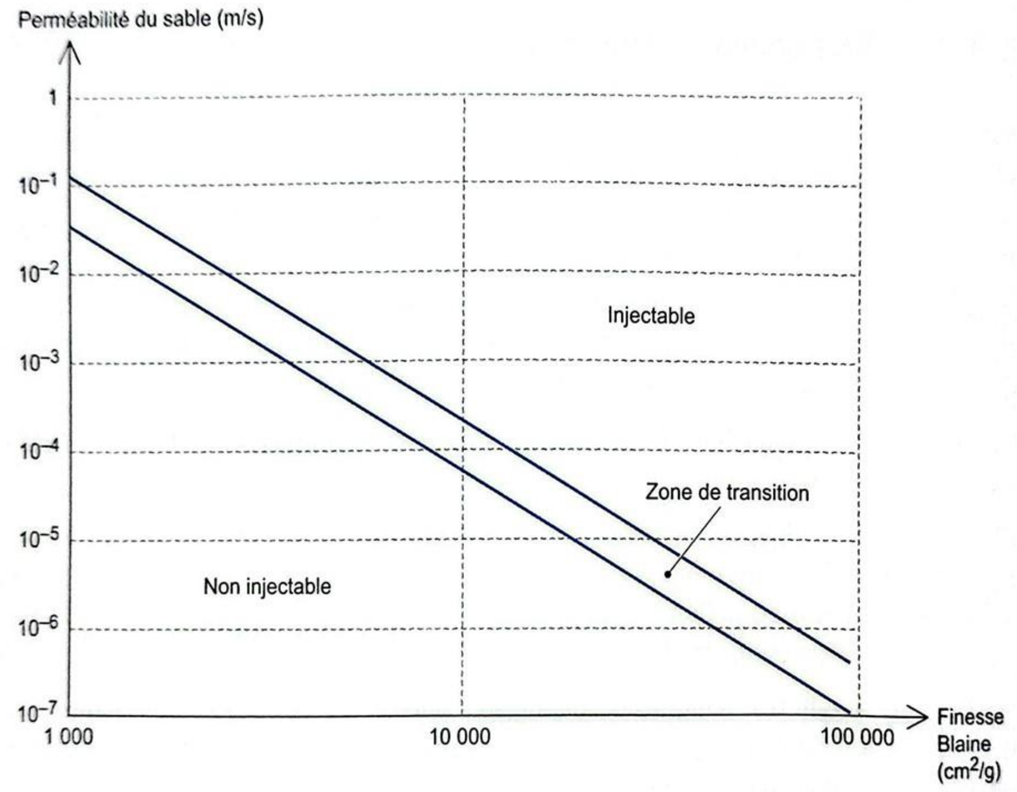


Figure V.7. Injectability ranges of hydraulic grouts

This figure shows that injection becomes difficult when the soil grain size is very fine and permeability decreases.

- **Chemical Grouts**

Chemical grouts are very fluid solutions capable of penetrating finer soils. The products used may be:

- Silica gels,
- Chemical resins,

- Polymer solutions.

They make it possible to obtain finer impregnation of the soil and a significant reduction in permeability.

V.2.5. Grouting Implementation

The execution of a grouting treatment generally includes:

- Drilling of injection points,
- Preparation of the grout,
- Injection under pressure,
- Control of injection parameters.

The grid of boreholes depends on the nature of the soil, its permeability, and the objective of the treatment. The possible arrangements of boreholes are illustrated in Figure V.8.

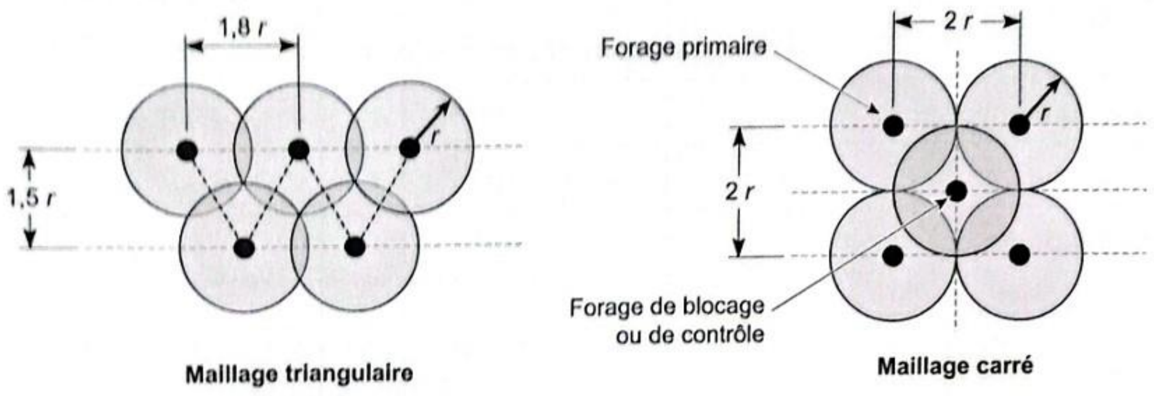


Figure V.8. Definition of grid layouts

This figure shows the two main configurations used on site: triangular grid and square grid, which make it possible to ensure homogeneous coverage of the treated ground.

V.2.6. Advantages and Limitations of the Technique

Advantages

Grouting presents several advantages:

- Improvement of the mechanical strength of the soil,
- Reduction of permeability,
- Possibility of localized treatment,
- Technique suited to the rehabilitation of existing structures.

Limitations

Certain limitations must be taken into account:

- Difficulty of injection in very fine soils,

- Delicate control of grout propagation in the soil,
- Sometimes high cost of chemical products,
- Influence of hydrogeological conditions.

V.2.7. Selection Criteria for the Technique

The choice of the type of grouting mainly depends on:

- Soil grain size distribution,
- Ground permeability,
- Objective of the treatment (watertightness or consolidation).

In practice:

- Cement grouts are used in granular or fissured soils,
- Chemical grouts are used in finer soils requiring very penetrating impregnation.

V.2.8. Conclusion

Cement grouting and chemical grouting constitute an important soil improvement and reinforcement technique. They make it possible to consolidate the ground and reduce its permeability by filling the soil voids with a grout injected under pressure.

The effectiveness of the treatment mainly depends on soil permeability, grout properties, and the grid of boreholes, which must be adapted to the geotechnical conditions of the site.

V.3. Deep Mixing Method (DMM)

V.3.1. Introduction and General Principle

The Deep Mixing Method (DMM) is a soil improvement technique consisting of mixing the soil in place with a binder in order to form a stabilized material called soilmix. Mixing is carried out directly in the ground using rotating tools that simultaneously ensure soil mixing and incorporation of the binder.

The binders used are mainly:

- Cement,
- Lime,
- Slag,
- Fly ash.

This technique makes it possible to improve the mechanical properties of the soil by increasing its strength and reducing its compressibility. It is particularly suited to soft cohesive soils, organic soils and compressible clays.

V.3.2. Principle of Execution

The treatment consists of introducing a rotating tool into the soil that mixes the ground with a binder to form a stabilized soil.

Two main methods are used depending on the way the binder is introduced:

- **Dry Method**

In this method, the binder is injected in powder form during the withdrawal of the mixing tool. The water naturally present in the soil allows hydration of the binder.

The operating principle is illustrated in Figure V.9.

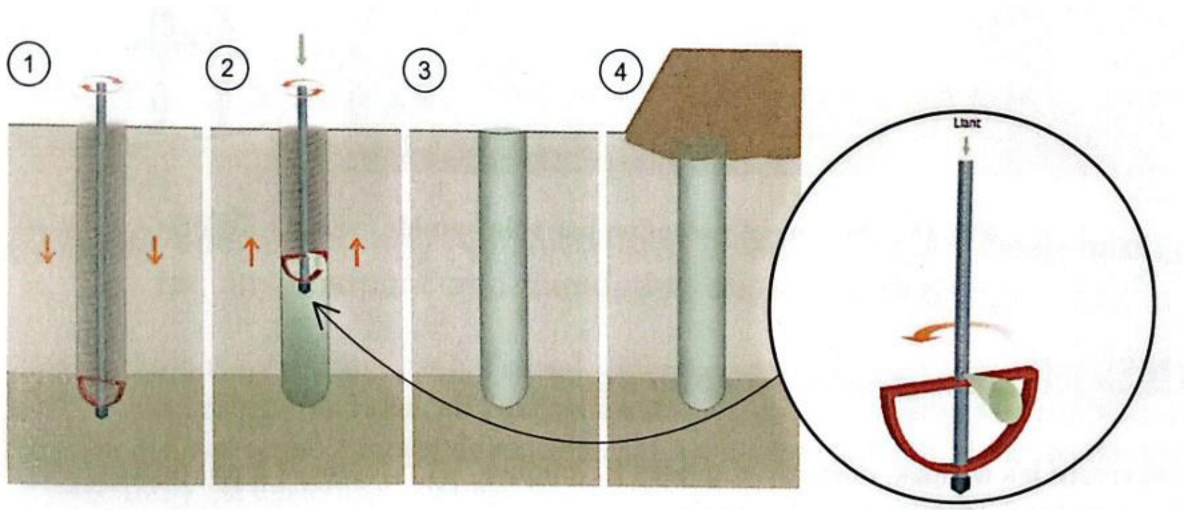


Figure V.9. Diagram of dry execution (Keller)

This technique is often used to produce columns of treated soil.

- **Wet Method**

In the wet method, the binder is injected in the form of a grout prepared in a mixing plant and then injected into the soil during mixing.

The operation is illustrated in Figure V.10.

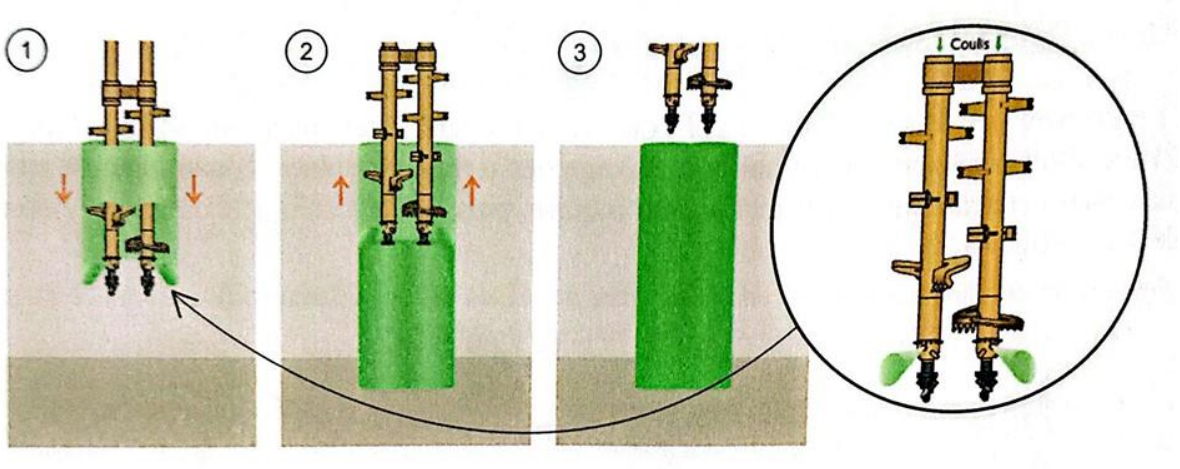


Figure V.10. Diagram of wet execution (Keller)

This method is now the most widespread because it allows better control of the mixture and binder dosage.

V.3.3. Types of Structures Constructed

DMM makes it possible to construct different forms of stabilized elements in the ground.

The possible configurations are illustrated in Figure V.11.

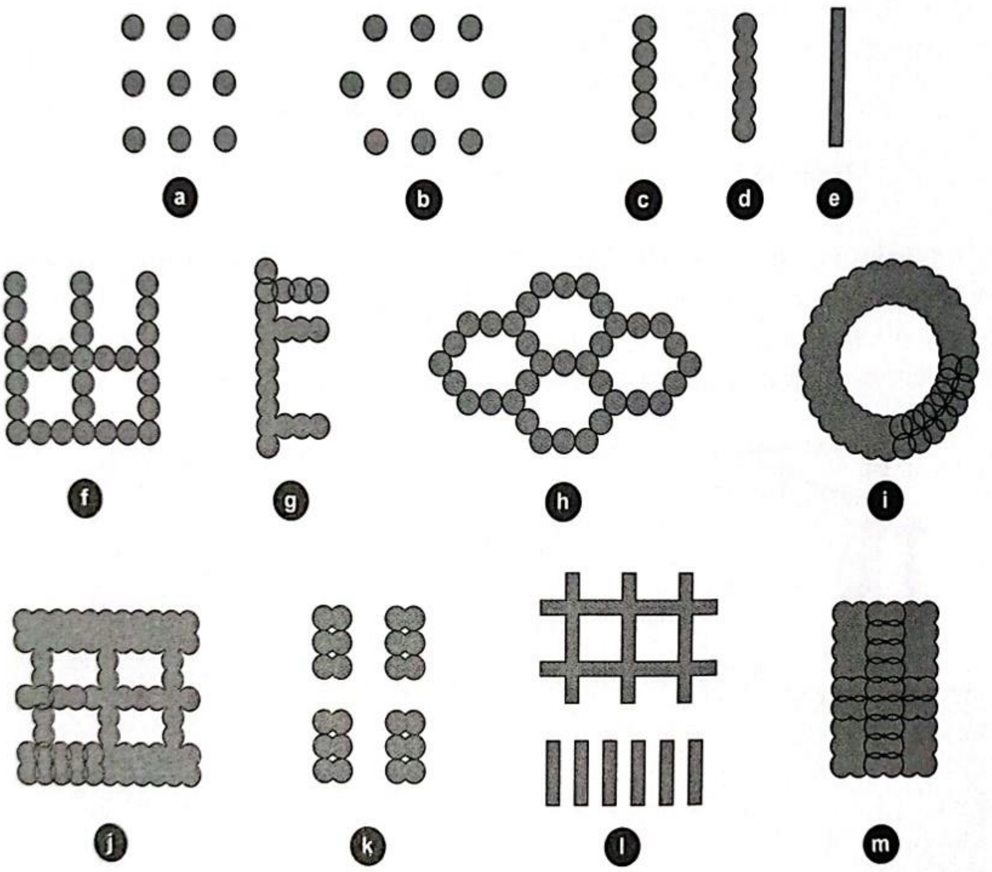


Figure V.11. Examples of DMM installation patterns (Topolnicki, 2016)

The main types of structures are:

- Isolated columns,
- Panels or barrettes,
- Continuous walls,
- Three-dimensional networks,
- Mass treatments.

These configurations make it possible to adapt the technique to different geotechnical conditions.

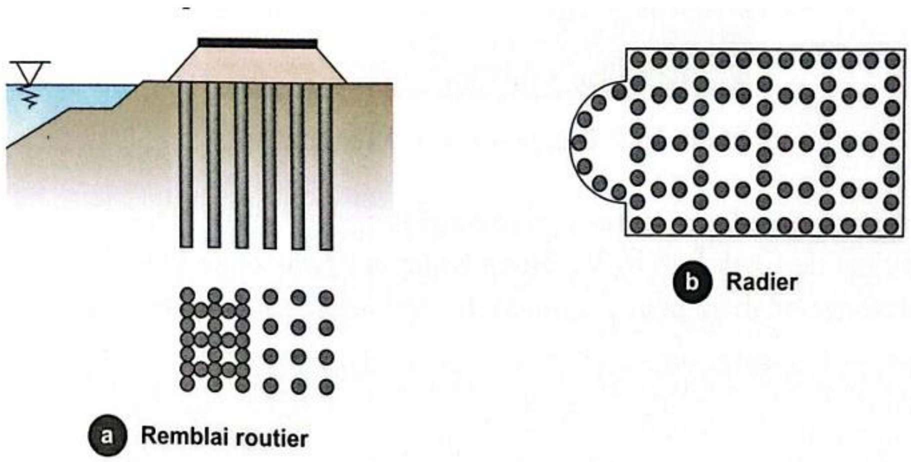
V.3.4. Fields of Application

DMM is used in many civil engineering projects to improve compressible soils.

The most common applications are:

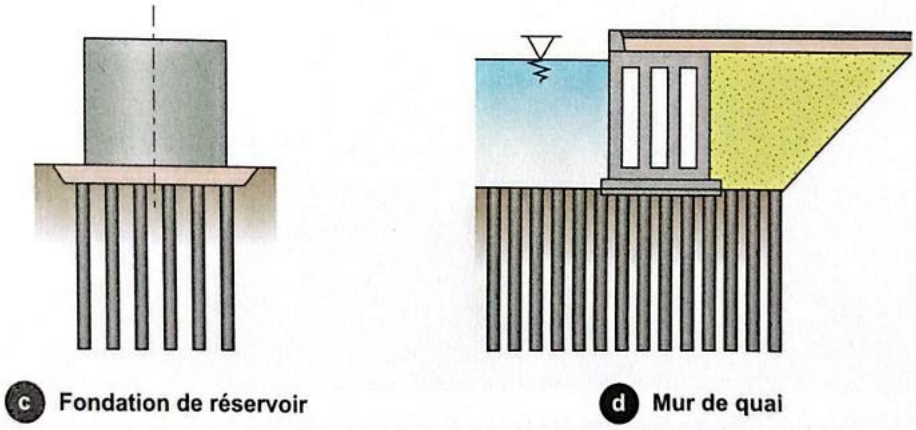
- Improvement of structure foundations,
- Stabilization of embankments and slopes,
- Construction of retaining walls,
- Construction of watertight cut-off walls,
- Reduction of liquefaction risk.

Some examples of applications are illustrated in Figure V.12.



a Remblai routier

b Radier



c Fondation de réservoir

d Mur de quai

Figure V.12. Examples of DMM applications

The technique is used both for land works and maritime works, particularly in ports and reclaimed land.

V.3.5. Soilmix Material and Binders Used

The material obtained after treatment is called soilmix. It is a mixture of the natural soil and a hydraulic binder.

The properties of soilmix mainly depend on:

- Soil type,
- Binder dosage,
- Water content,
- Mixing energy.

The influence of binder dosage on the strength of the material is illustrated in Figure V.13.

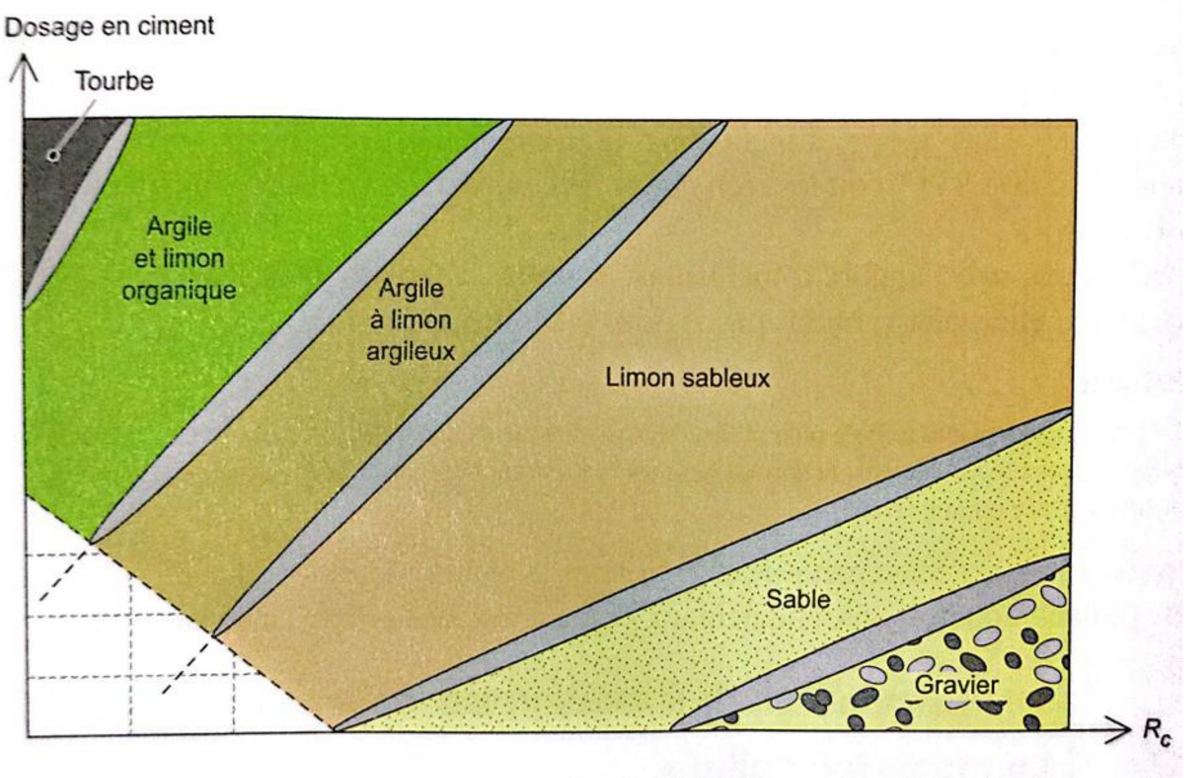


Figure V.13. Binder dosage and strength of soilmix as a function of soil type (Soletanche Bachy)

The most commonly used binders are cement and lime, to which industrial by-products such as slag or fly ash may be added.

V.3.6. Advantages and Limitations

Advantages

DMM presents several advantages:

- Significant improvement in soil strength,
- Possible treatment of very soft or organic soils,
- Possibility of constructing different reinforcement structures,
- Low vibrations during the works.

Limitations

Certain limitations must be taken into account:

- Difficulty in treating soils containing blocks or coarse gravels,
- Need to control binder dosage,
- Possible heterogeneity of the mixture if execution is not mastered.

V.3.7. Selection Criteria for the Technique

DMM is particularly suited when:

- The soil is cohesive and compressible,
- Deep improvement is necessary,
- Conventional densification techniques are not effective.

It now constitutes an effective solution for foundation reinforcement, embankment stabilization, and treatment of soft soils.

V.4. Jet Grouting

V.4.1. Introduction and General Principle

Jet grouting is a soil improvement technique consisting of disaggregating the soil in place using very high-pressure fluid jets, then mixing this soil with a cement grout in order to form a soil-cement column.

The process is based on the use of high-energy jets, generally greater than 20 MPa, capable of cutting the soil and mixing it with the injected grout. This technique makes it possible to create columns or elements of treated soil having significantly improved mechanical properties.

The execution principle of a column is illustrated in Figure V.14.

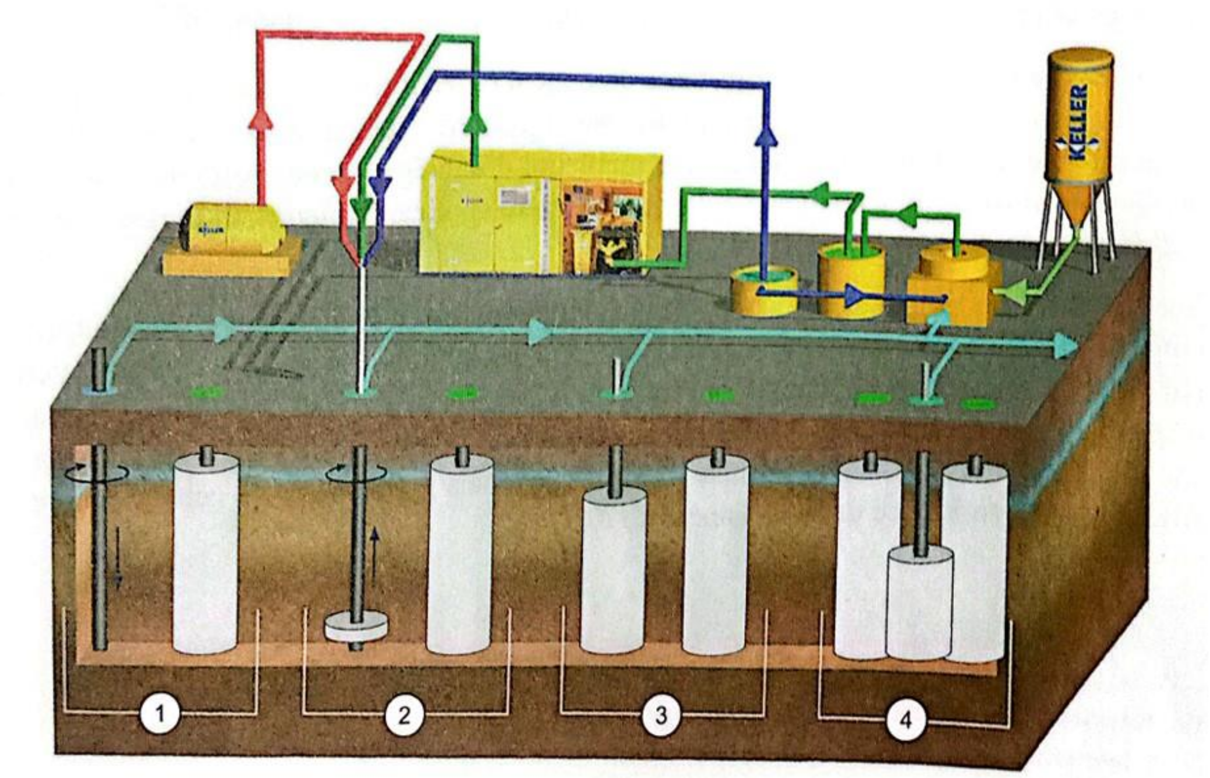


Figure V.14. Execution phases of a jet grouting column (Keller)

The figure shows the different steps of the process: drilling, pressure jet injection, and formation of the soil-cement column during withdrawal of the tool.

V.4.2. Operating Principle

Jet grouting is based on three main phenomena:

- Disaggregation of the soil by a high-pressure jet,
- Mixing of the soil with the cement grout,
- Withdrawal of the tool allowing progressive formation of the column.

The injection system may use different fluids (grout, water or air) depending on the technique used. The choice of the system depends in particular on:

- The geotechnical characteristics of the soil,
- The diameter of the columns to be constructed,
- The mechanical properties required.

V.4.3. Fields of Application

Jet grouting is used for soil improvement and the construction of geotechnical structures.

It allows in particular:

- Improvement of compressible soils,
- Construction of deep foundations,
- Construction of retaining structures,
- Reduction of liquefaction risk.

An example of improvement of a deep soil layer is illustrated in Figure V.15.

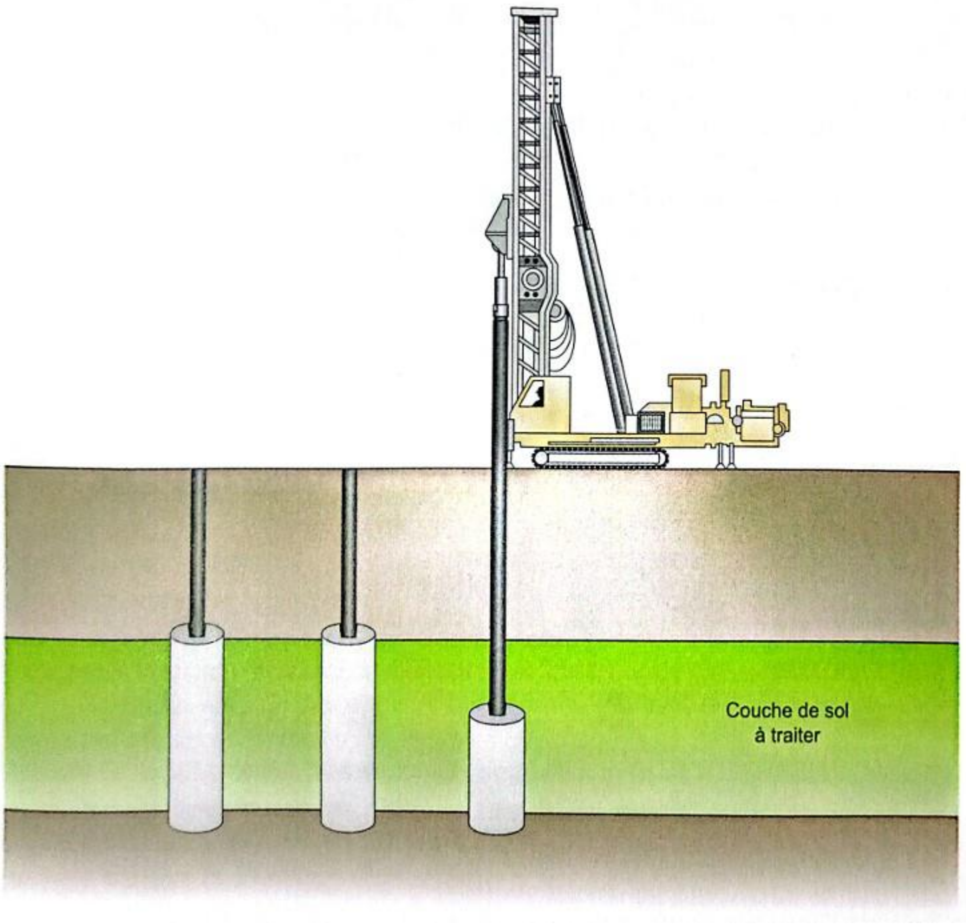


Figure V.15. Treatment of a deep soil layer to be improved overlain by a layer of good soil

The technique thus makes it possible to treat a soil layer located beneath more resistant ground.

V.4.4. Applications for Watertightness and Structures

Jet grouting is widely used to construct watertight structures in underground works.

The main applications are:

- Bottom plugs for excavations,
- Watertight cut-off walls,
- Watertight curtains for dams,
- Containment of pollution,
- Limitation of groundwater flow.

These applications are illustrated in Figure V.16.

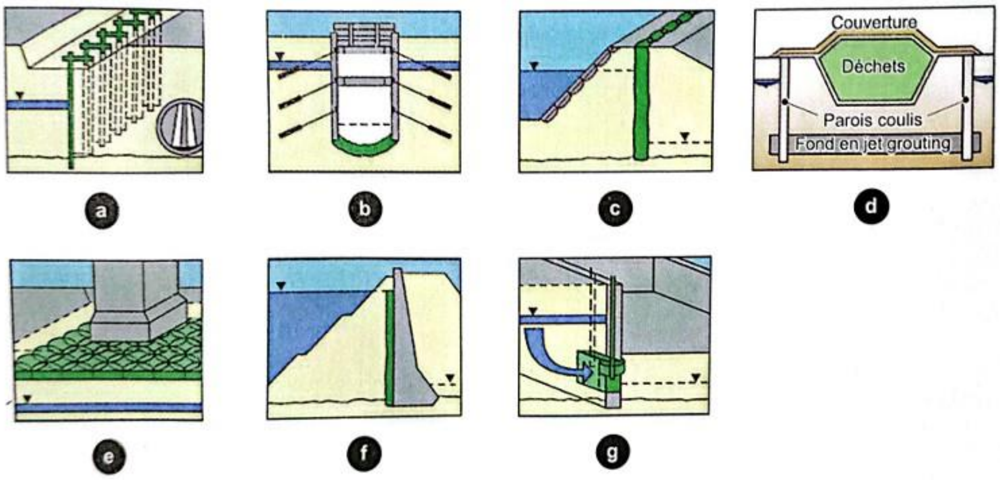


Figure V.16. Applications of jet grouting for watertightness (Keller and Ménard)

The technique makes it possible to construct continuous watertight structures through the overlapping of columns.

V.4.5. Jet Grouting Techniques

Several techniques are used depending on the number of injected fluids.

The main techniques are:

- Single jet: injection of cement grout only,
- Double jet: injection of grout and air,
- Triple jet: injection of water, air and grout.

The different techniques are illustrated in Figure V.17.

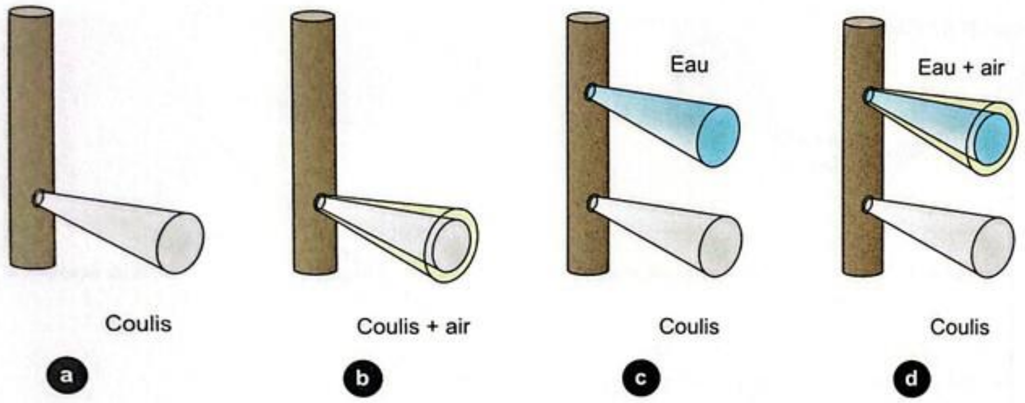


Figure V.17. The different jet grouting techniques

The choice of the technique directly influences the diameter of the columns and the quality of the soil-cement mixture.

V.4.6. Geometry of Constructed Elements

The elements constructed by jet grouting may take different forms depending on the movement of the tool and the configuration of the injection nozzles.

The main shapes are:

- Cylindrical columns,
- Half-columns,
- Quarter-columns,
- Panels or lamellae.

These different shapes are illustrated in Figure V.18.

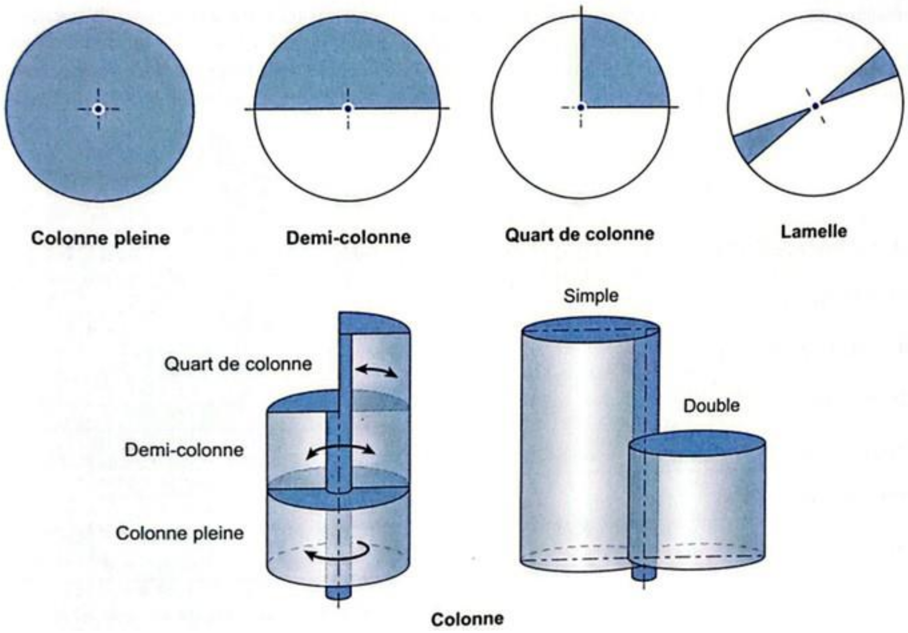


Figure V.18. Combinations made from elementary shapes (Keller)

The combination of several columns makes it possible to create continuous cut-off walls or complex structures.

V.4.7. Advantages and Limitations of the Technique

Advantages

Jet grouting presents several important advantages:

- Applicable to almost all types of soils,
- Possibility of deep treatment,
- Construction of effective watertight structures,
- Possible use in areas with difficult access.

The technique also makes it possible to treat a weak soil layer located beneath a more resistant layer.

Limitations

Certain limitations must be taken into account:

- Relatively high cost of the technique,
- High consumption of cement grout,
- Need to manage spoil and grout returns,
- Difficulty of precise control of the diameter of the columns.

V.4.8. Selection Criteria for the Technique

Jet grouting is generally chosen when:

- The soil is heterogeneous or poorly permeable,
- Localized deep improvement is necessary,
- Watertight structures must be constructed,
- Conventional grouting techniques are insufficient.

The technique is often used for underground works, foundations, and hydraulic structures.

V.4.9. Conclusion

Jet grouting is a soil improvement technique based on the use of very high-pressure jets allowing the soil to be disaggregated and mixed with a cement grout in order to form soil-cement columns.

This method makes it possible to construct reinforcement structures, watertight cut-off walls, and improved foundations, even under difficult geotechnical conditions.

Its effectiveness mainly depends on:

- The pressure and energy of the jet,
- The type of soil treated,
- The technique used (single, double or triple jet),
- The control of execution parameters.

V.5. Compaction Grouting

V.5.1. Introduction and General Principle

Compaction grouting is a soil improvement technique consisting of injecting a very stiff mortar into the soil under pressure through tube boreholes, in order to cause densification of the ground in place.

This technique, developed in the 1950s, is used both for soil improvement and underpinning of existing foundations.

The injected mortar progressively forms grout bulbs that compress the surrounding soil and increase its density. Figure V.19 illustrates a grout bulb injected into a loose sand.

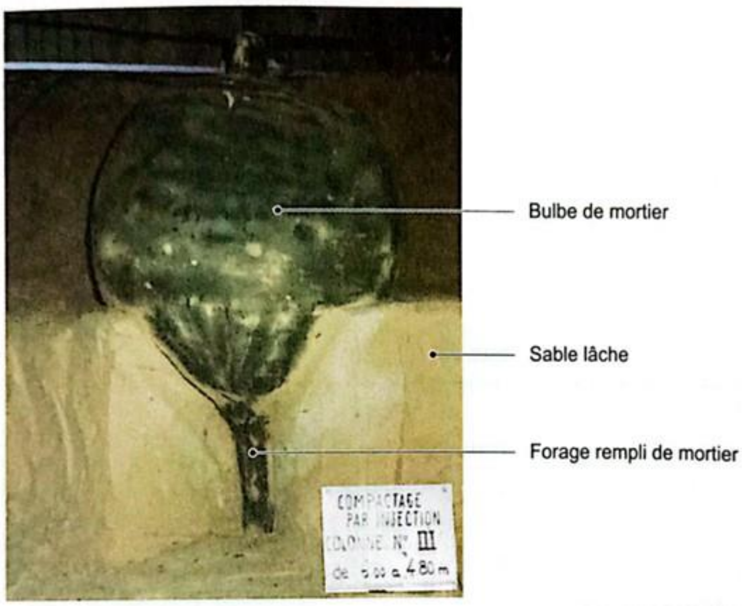


Figure V.19. Grout bulb injected into a loose sand (CEBTP, 1987)

V.5.2. Operating Principle

Compaction grouting is carried out from tube boreholes into which a very stiff mortar is injected under pressure in successive stages.

Each injection creates a grout bulb that compacts the surrounding soil and improves its mechanical properties.

The implementation of the process is illustrated in Figure V.20.

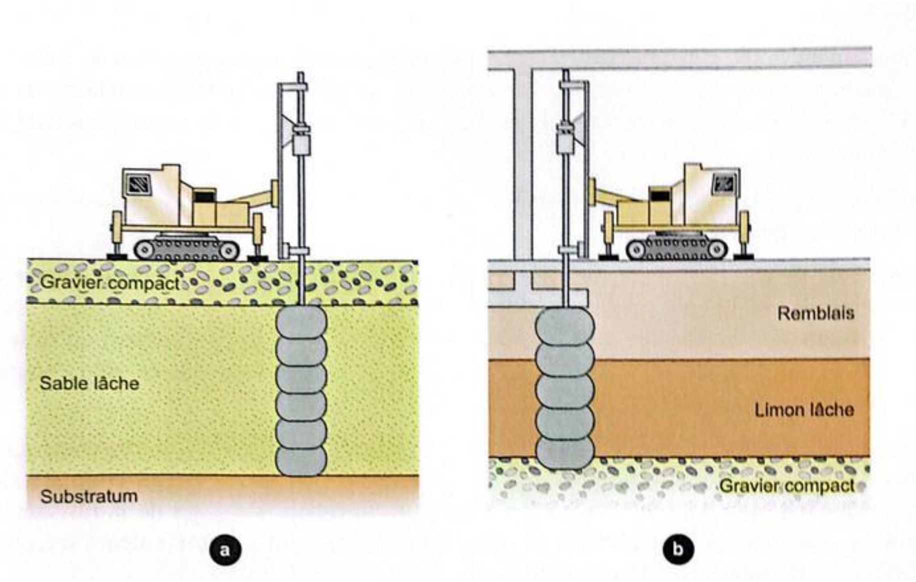


Figure V.20. Implementation diagrams. (a) Soil improvement; (b) Underpinning (Keller)

As illustrated in the figure, the technique can be used for:

- Soil improvement,
- Underpinning of existing foundations.

V.5.3. Fields of Application

Compaction grouting is used mainly for:

- Densifying loose or compressible soils,
- Strengthening existing foundations,
- Filling cavities or sinkholes,
- Reducing settlements of structures.

An example of cavity treatment is illustrated in Figure V.21.

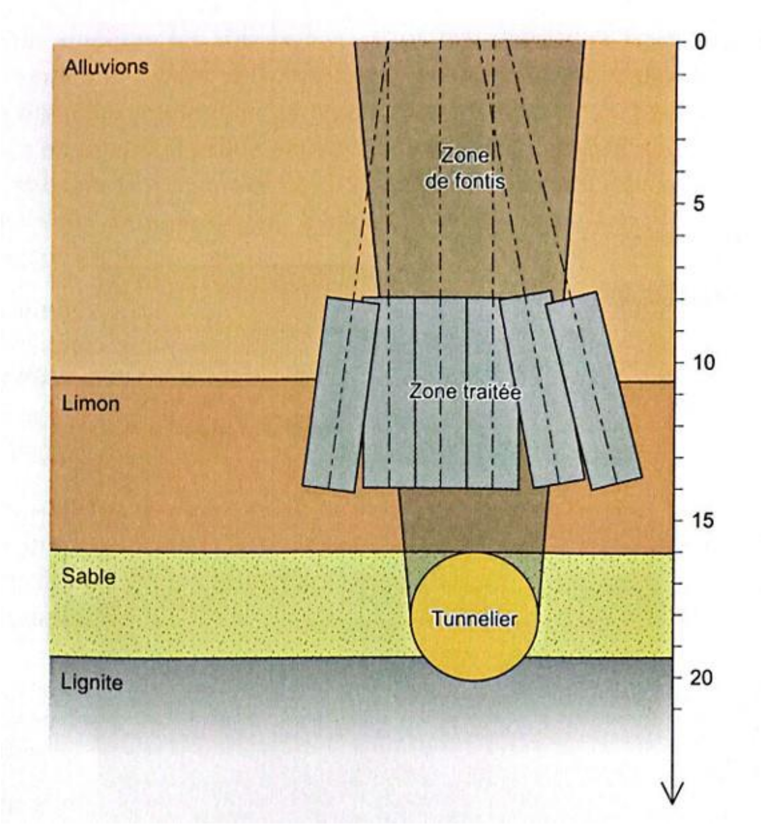


Figure V.21. Treatment of a sinkhole during the passage of a tunnel boring machine (Soletanche Bachy)

The technique is also used for underpinning foundations, as presented in Figure V.22.

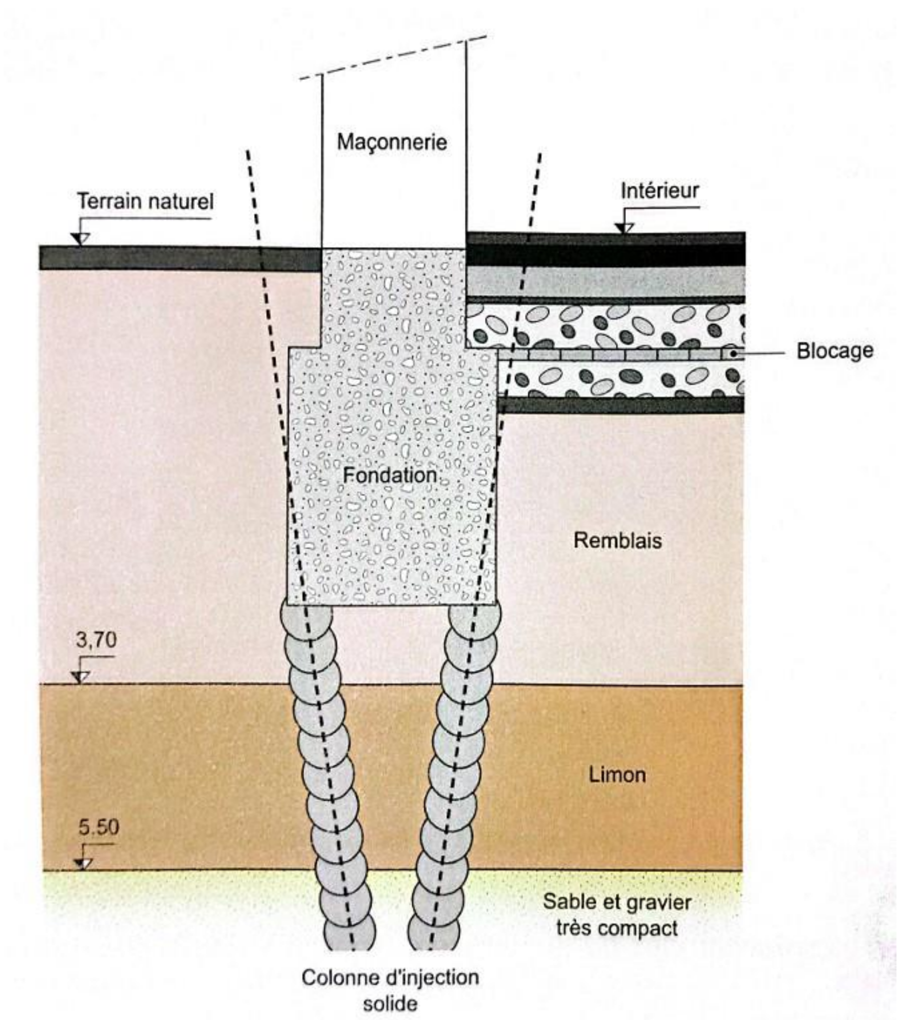


Figure V.22. Underpinning of semi-deep foundations (Keller)

V.5.4. Design and Dimensioning

The design of the treatment requires good geotechnical investigation of the site (CPT, pressuremeter, SPT).

The main design parameters are:

- Injection grid,
- Injection pressure,
- Volume of mortar injected,
- Mortar incorporation ratio.

The arrangement of injection points is represented in Figure V.23.

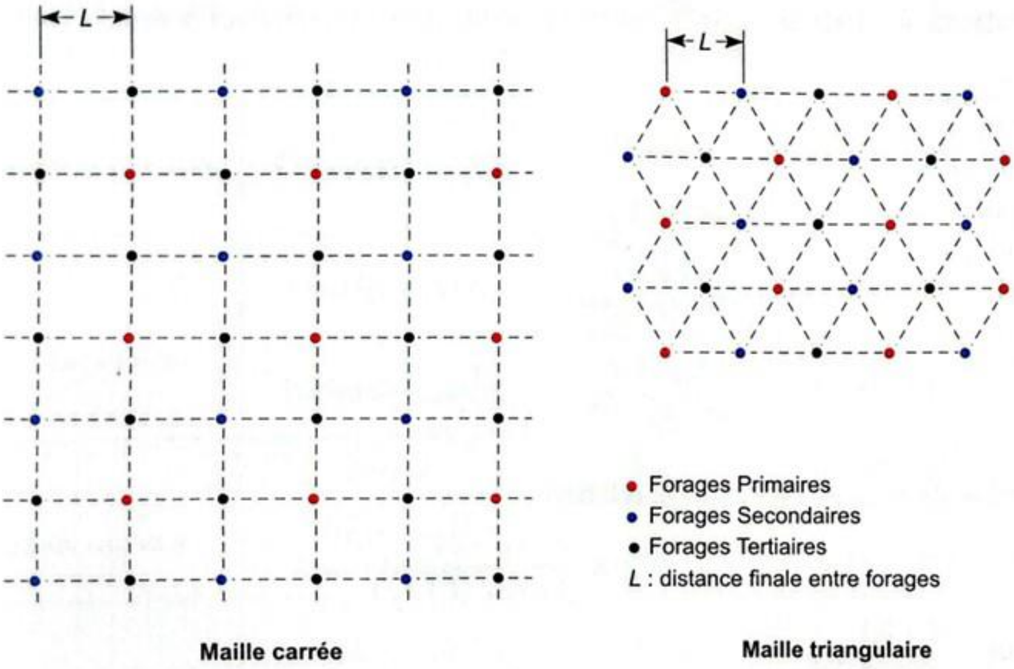


Figure V.23. Description of grid patterns

The radius of influence depends on the nature of the soil and generally varies between 0.2 m and 1.5 m.

V.5.5. Execution and Control

Injection is carried out in successive stages from bottom to top, each injection forming a grout bulb compacting the soil.

During the works, the injection parameters are recorded in order to control the quality of the treatment (see Figure V.24).

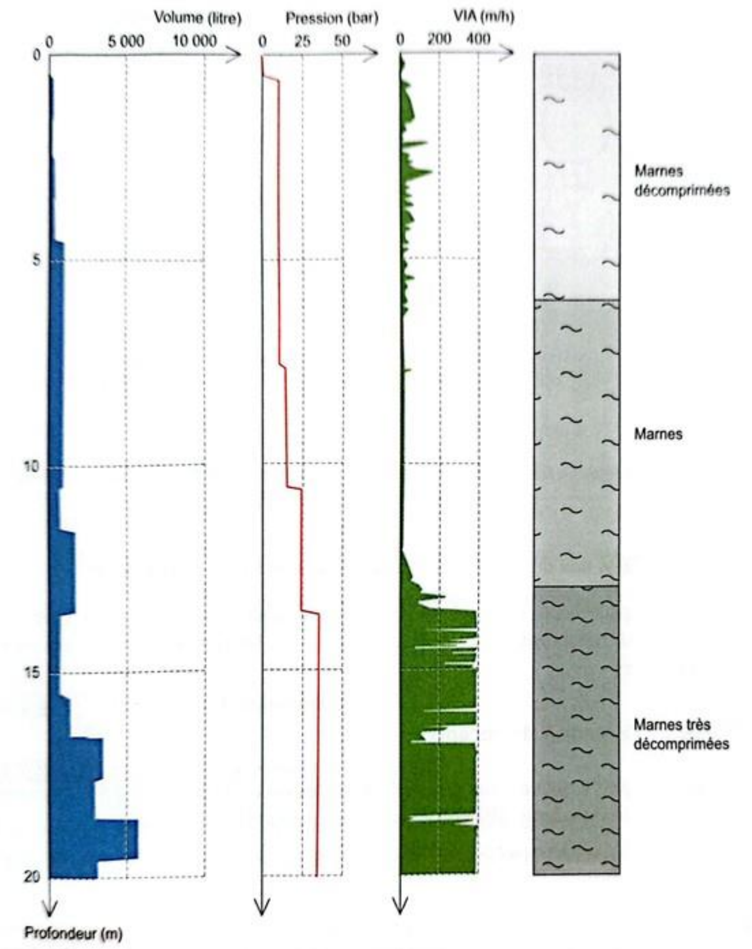


Figure V.24. Recording of volume, pressure, and VIA ratio parameters

Improvement of the soil is verified by geotechnical tests before and after treatment, as illustrated in Figure V.25.

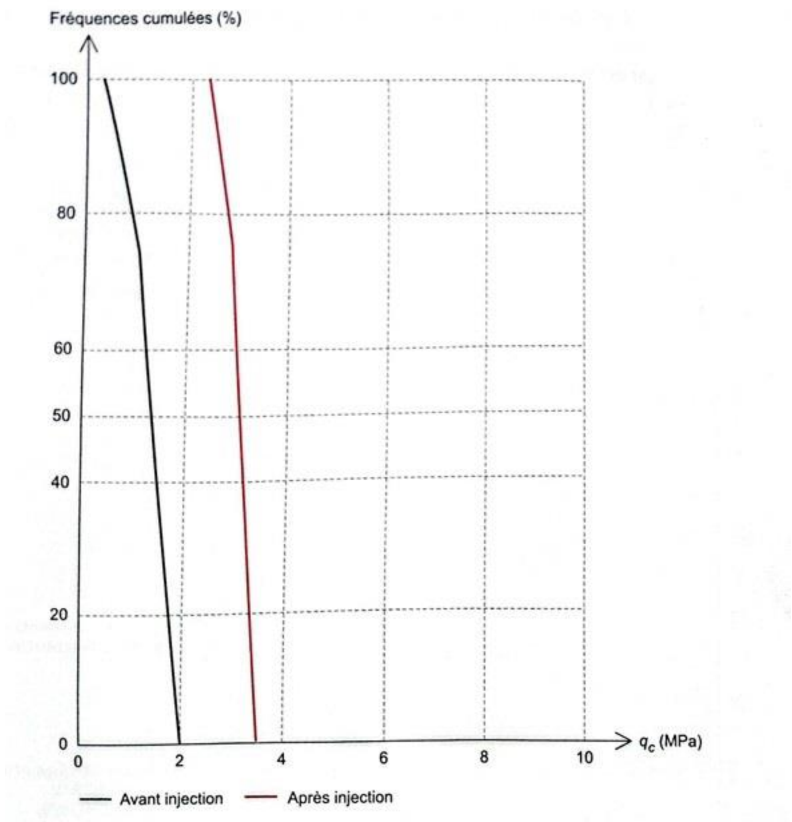


Figure V.25. Curves of cumulative frequencies of cone resistance

The results generally show a significant increase in soil resistance after injection.

V.5.6. Advantages and Limitations of the Technique

Advantages

Compaction grouting presents several advantages:

- Effective improvement of loose soils,
- Possibility of intervention beneath existing structures,
- Precise control of injected volumes,
- Limitation of spoil.

Limitations

Certain limitations must be taken into account:

- Reduced efficiency in very compact soils,
- Risk of ground heave,
- Relatively high cost for large-area treatments.

Selection Criteria

Compaction grouting is particularly suited when:

- The soils are loose or compressible,
- The works must be carried out beneath existing structures,
- Localized and controlled treatment is necessary.

It is therefore widely used for underpinning and stabilization of foundations.

V.6. Expansive Resin Injection

V.6.1. Introduction and General Principle

Expansive resin injection is a soil improvement technique consisting of injecting into the ground a polyurethane resin that expands strongly during its chemical reaction, causing densification of the soil and an increase in its bearing capacity.

This method is used as an alternative to conventional underpinning techniques, because it allows rapid, minimally invasive, and localized intervention beneath existing structures.

The resin is injected in liquid form through injection tubes introduced into the soil. During the chemical reaction, the resin polymerizes and expands, generating a pressure that compacts the surrounding soil.

The general principle of the process is illustrated in Figure V.26.

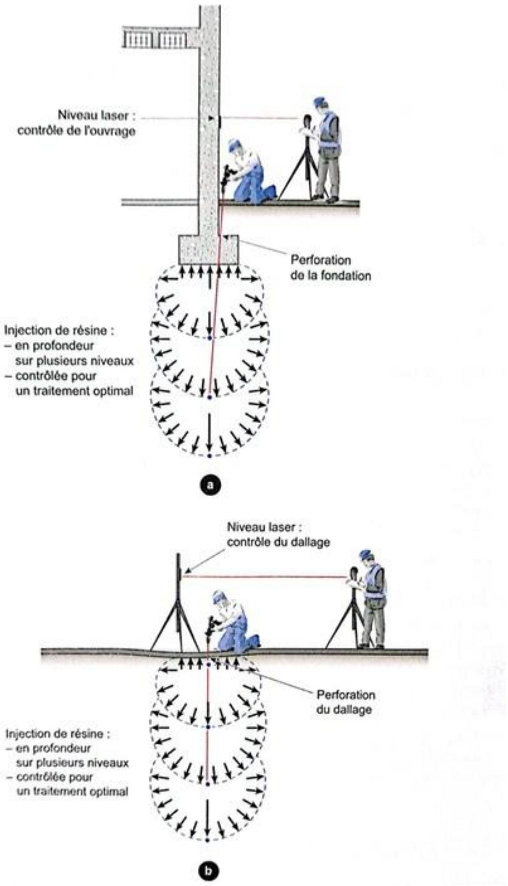


Figure V.26. Principles of a soil treatment by expansive resin injections, beneath foundations (a) and beneath slabs (b)

V.6.2. Operating Principle

The resin used is composed of two liquid components that react chemically when mixed. This reaction causes significant volumetric expansion and rapid hardening.

During its expansion, the resin develops a swelling pressure that acts on the soil and causes:

- Densification of the soil,
- Increase in confinement stresses,
- Improvement of mechanical characteristics.

The balance between resin pressure and soil confinement stress is illustrated in Figure V.27.

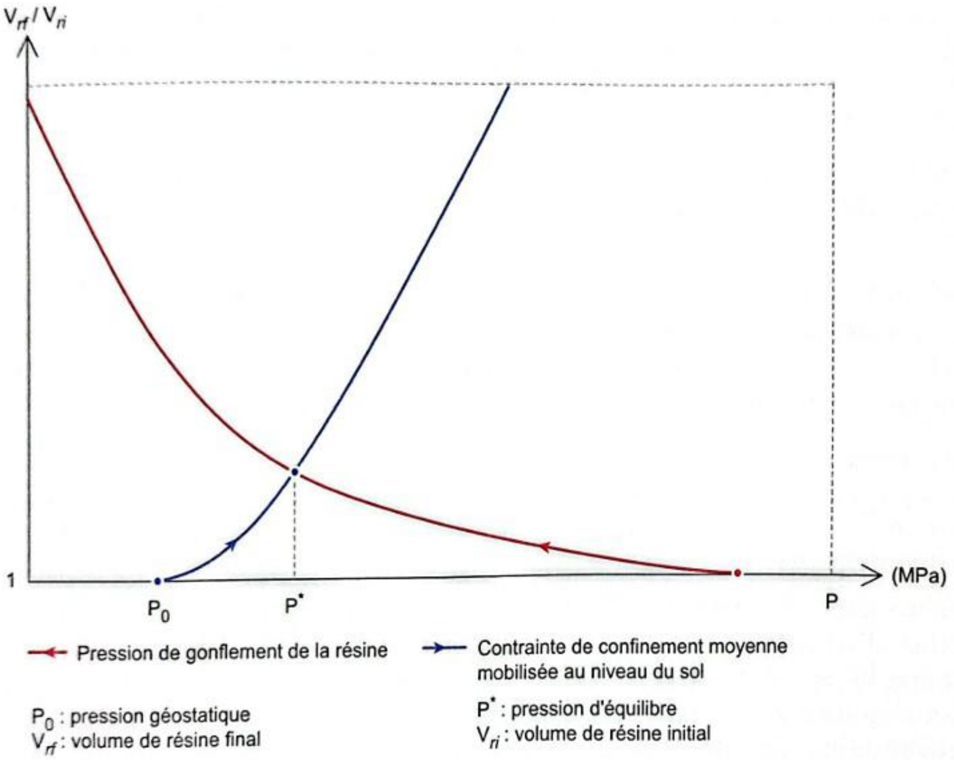


Figure V.27. Balance between the pressure developed by the resin during its expansion and the confinement stress of the soil (Dominijanni and Manassero, 2015)

V.6.3. Fields of Application

Expansive resin injection is used mainly for:

- Improving the mechanical characteristics of the soil,
- Reducing permeability,
- Treating soils sensitive to shrink–swell behavior,
- Re-levelling settled structures.

The improvement capacity depends in particular on the swelling pressure of the resin and on the characteristics of the soil (see Figure V.28).

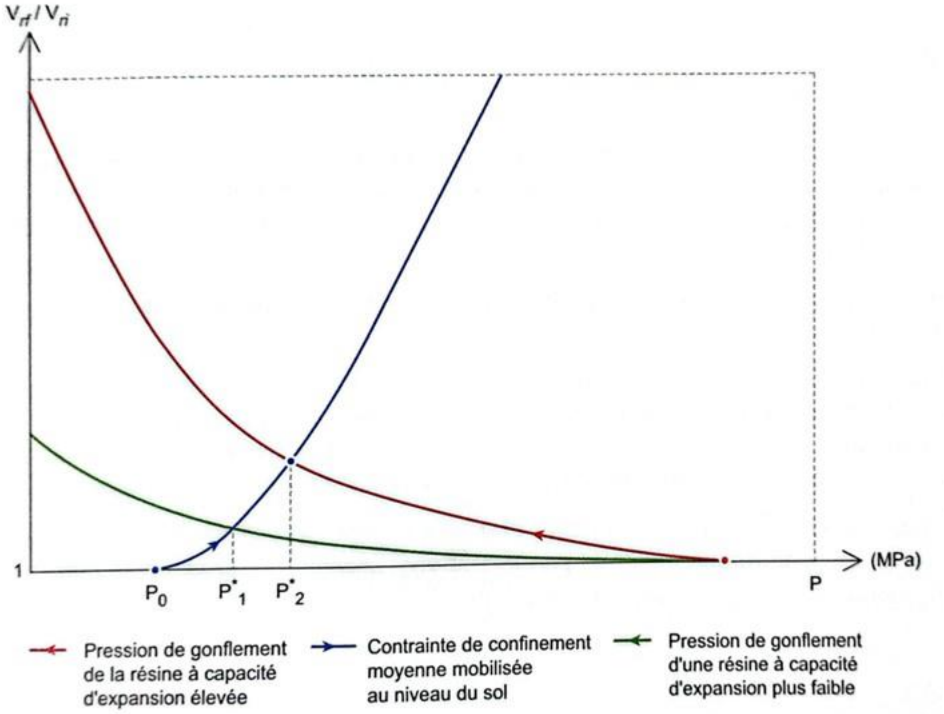


Figure V.28. Evolution of $P*$ as a function of the limiting swelling pressure of the resin and the confinement stress of the soil (Dominijanni and Manassero, 2015)

V.6.4. Properties of the Expansive Resin

The resins used are generally polyurethane resins, characterized by:

- High volumetric expansion,
- Rapid polymerization,
- Significant mechanical strength.

The swelling pressure developed by the resin depends on its density and chemical formulation. Figure V.29 presents an example of the evolution of the swelling pressure of a high-performance polyurethane resin as a function of its unit weight.

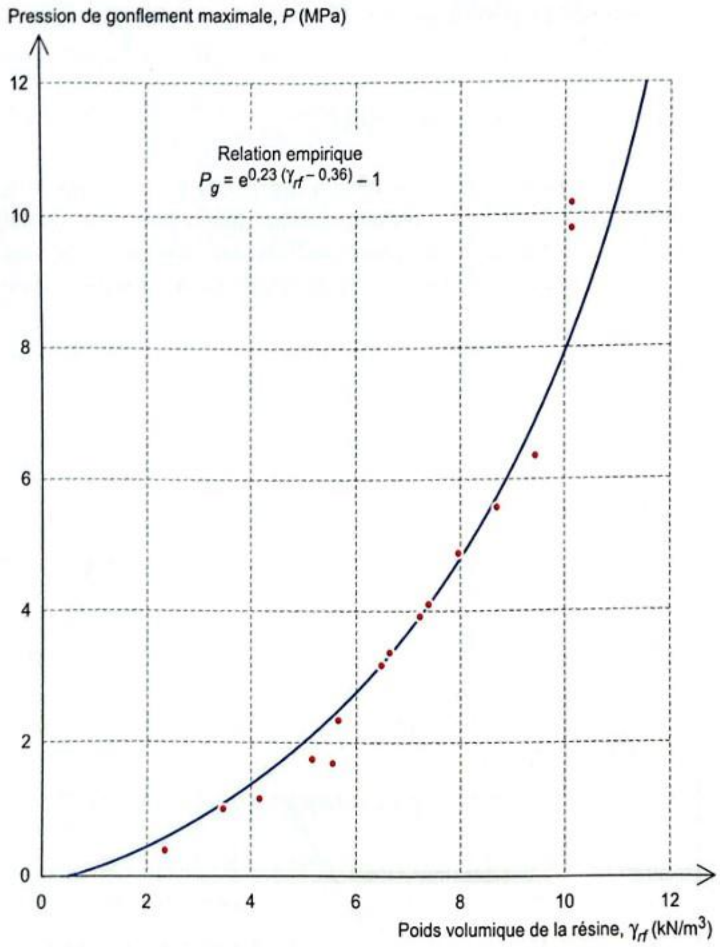


Figure V.29. Example of the evolution of the swelling pressure of a high-performance polyurethane resin as a function of its unit weight (Favaretti et al., 2004, cited by Dominijanni and Manassero, 2015)

V.6.5. Diffusion of the Resin in the Soil

The mechanism of action depends on the nature of the soil.

- **Coarse Soils (Sands and Gravels)**

The resin diffuses mainly into the soil voids and causes densification by expansion.

- **Fine Soils (Silts and Clays)**

The resin acts rather by fracturing the soil, creating a network of fissures that increases the strength of the ground.

This mechanism is illustrated in Figure V.30.

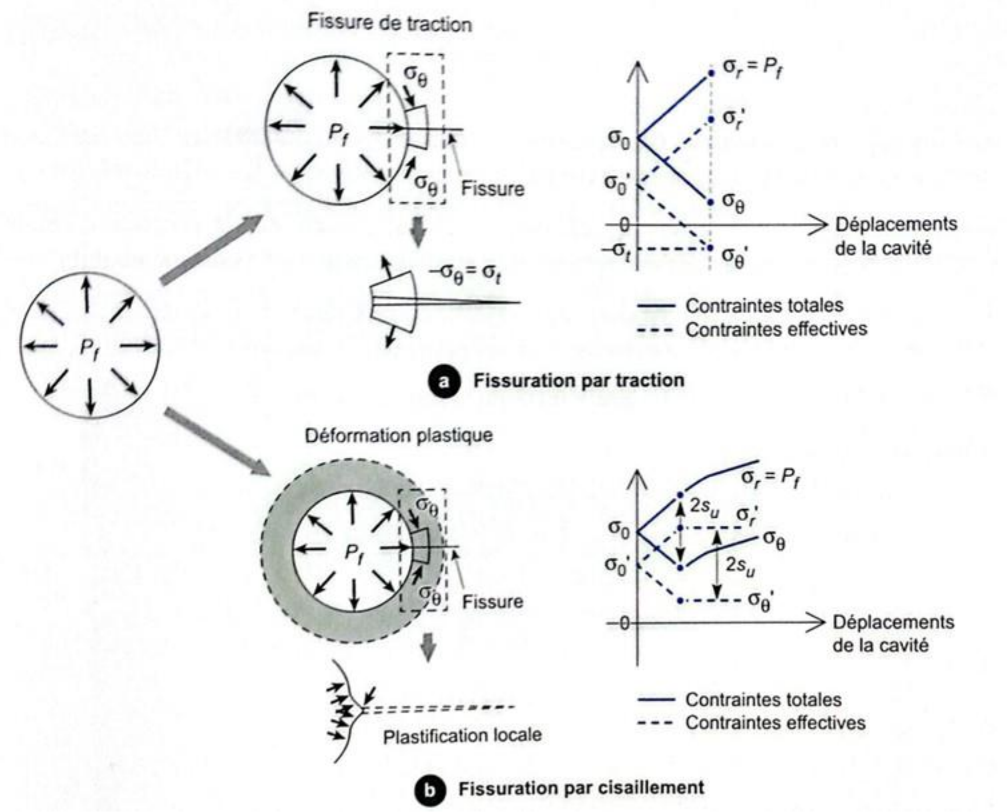


Figure V.30. Soil fracturing (under undrained conditions) during injection into a cavity of a pressurized fluid (Mitchell and Soga, 2005)

V.6.6. Advantages, Limitations and Selection Criteria

Advantages

Expansive resin injection presents several advantages:

- Rapid and minimally intrusive technique,
- Possibility of intervention beneath existing structures,
- Localized and controlled improvement of the soil.

Limitations

Certain limitations must be taken into account:

- Generally limited treatment depth,
- Efficiency dependent on soil characteristics,
- Risk of excessive heave if injection is not well controlled.

Selection Criteria

This technique is particularly suited when:

- The works must be carried out without significant excavation,
- Settlements are localized,

- Rapid intervention is necessary beneath existing structures.

It is therefore widely used for the stabilization of foundations, slabs, and infrastructures.

V.7 Comparison of Injection-Based Ground Improvement Techniques

Table V.1 summarizes the comparison between the different injection-based ground improvement techniques presented in this chapter.

The comparison highlights their main principles, fields of application, advantages, limitations, and selection criteria, helping to determine the most appropriate technique according to the soil conditions and the objectives of the ground treatment.

Table V.1. Comparison of Injection-Based Ground Improvement Techniques

Technique	Principle	Suitable Soils	Main Objective	Advantages	Limitations	Selection Criteria
Biological Methods	Biologically induced cementation of soil particles	Sands and granular soils	Soil stabilization and permeability reduction	Environmentally friendly	Still under development	Projects requiring minimal chemical additives
Cement and Chemical Grouting	Injection of grout to fill voids in the soil	Fissured or granular soils	Strengthening and waterproofing	Widely used technique	Difficult control of grout propagation	Permeable soils requiring local improvement
Deep Mixing Method (DMM)	In situ mixing of soil with binders (e.g., cement)	Soft clays	Increase soil strength	Very effective for soft soils	Specialized equipment required	Highly compressible cohesive soils
Jet Grouting	High-pressure injection creating soil-cement columns	Various soil types	Ground strengthening and waterproofing	Highly versatile	High cost	Works beneath existing structures or in restricted sites
Compaction Grouting (Solid Injections)	Injection of stiff mortar to compact surrounding soil	Compressible soils	Settlement reduction	Effective localized improvement	Difficult monitoring	Stabilization of existing structures
Expansive Resin Injection	Injection of expanding resin that compacts the soil	Soils beneath foundations	Stabilization and lifting of structures	Rapid intervention	Limited depth of treatment	Rehabilitation of existing buildings and foundations

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