

Chapitre III : Soil Compaction

3.1 Compaction Theory

3.2 Laboratory Compaction Tests (Standard and Modified Proctor Tests)

3.3 Equipment and Special Methods for In-Situ Compaction

3.4 Compaction Requirements and Quality Control



3.1 Compaction Theory

Compaction is the set of mechanical operations (application of mechanical energy) aimed at increasing the density of a soil. By doing so, the soil's texture becomes tighter, which reduces deformations and settlements, increases soil density, and improves its load-bearing capacity. Structures commonly affected by compaction include road embankments, earth dams, and airfields.

Mechanical densification of soil can lead to:

- Modification of grain size distribution.
- Modification of water content.
- Reduction or elimination of settlement risks.

- Increase in soil strength and slope stability.
- Improvement of bearing capacity.
- Limitation of volume changes caused by freezing, swelling, and shrinkage.

Proctor demonstrated that compaction depends on four parameters: dry unit weight of the soil, water content, compaction energy, and soil type (grain size distribution, mineralogy, etc.).

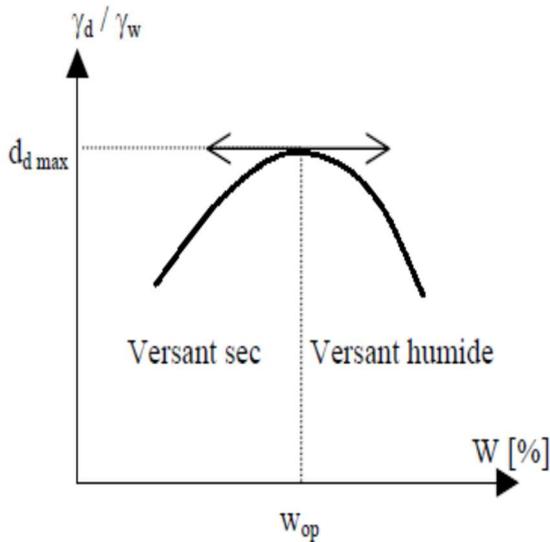


Fig. 3.1 : Compaction Curve

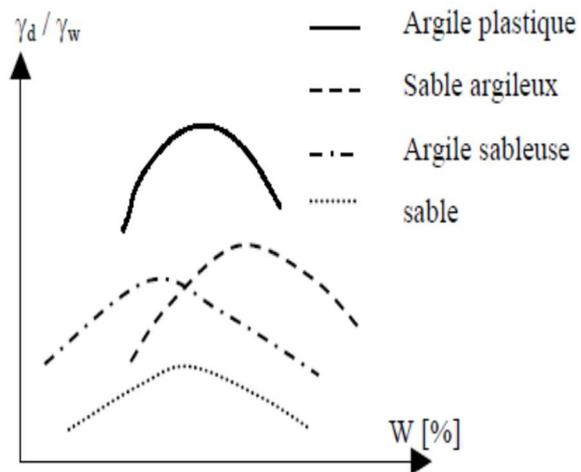


Fig. 3.2 : Influence of soil type

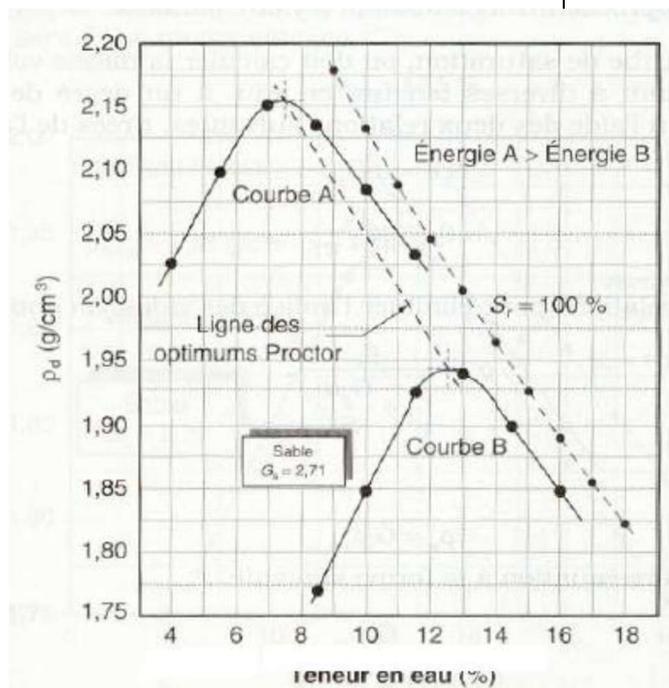


Fig. 3.4 : Saturation Curve

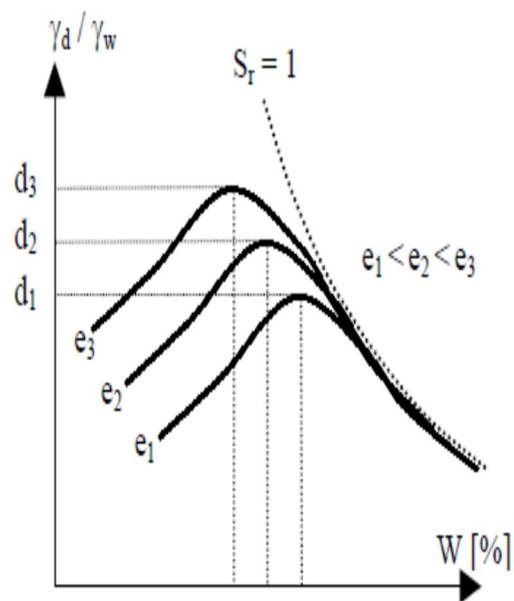


Fig. 3.3 : Influence of compaction energy

Compaction increases soil stability and its load-bearing capacity, but it also alters certain soil properties. The most affected are the soil structure, permeability, swelling and shrinkage behavior, compressibility, and shear strength.

3.2 Laboratory Compaction Tests (Proctor and CBR Tests)

3.2.1 Purpose of the Test

The purpose of the Proctor test is to determine the optimum water content (w_{opt}) for a given embankment soil and under defined compaction conditions, which leads to the best possible compaction or maximum bearing capacity.

The test consists of compacting the soil sample to be studied in a standardized mold using a standardized rammer, following a well-defined procedure, and then measuring its water content and dry unit weight after compaction (see Fig.3.5).

The test is repeated several times on samples prepared at different water contents. This results in several points on a curve ($w ; \gamma_d$); the curve is then plotted and shows a maximum, where the x-coordinate corresponds to the optimum water content (w_{opt}) and the y-coordinate to the optimum dry density (γ_{dopt}).

3.2.2 Types of Molds

Two types of molds with different dimensions are used for these tests:

The Proctor mold ($\Phi_{\text{mold}} = 101.6 \text{ mm} / H_{\text{soil}} = 117 \text{ mm}$) is used when the material is sufficiently fine (no particles larger than 5 mm; $\Phi \leq 5 \text{ mm}$).

The CBR mold (California Bearing Ratio) is used for materials with particle sizes greater than 5 mm and less than 20 mm ($\Phi_{\text{mold}} = 152 \text{ mm} / H_{\text{soil}} = 152 \text{ mm}$).

With each of these molds, depending on the chosen standard compaction energy, one can perform:

- the Standard Proctor Test (typically used for compaction works in building construction and/or dams),
- and the Modified Proctor Test (mainly used for road construction compaction works).

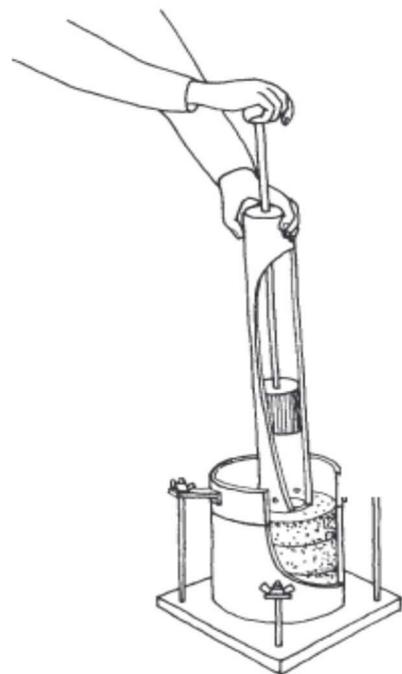


Fig.3.5 : Proctor test

The table below specifies the conditions for each test.

Table 3.1: Conditions for Standard and Modified Proctor Tests

Proctor test	Rammer weight (Kg)	Drop Height (cm)	Number of blows per layer	Number of layers	Compaction energy (kJ/dm ³)
Standard (Normal)	2.490	30.50	25 (Proctor mold)	3	0.59
			55 (CBR mold)	3	0.53
Modified	4.540	45.70	25 (Proctor mold)	5	2.71
			55 (CBR mold)	5	2.41

3.3 Equipment and Special In-Situ Compaction Methods

3.3.1 Common Compaction Methods

The most common compaction techniques involve the use of:

a. Vibration: For granular and loose soils, efficient compaction is achieved by vibration using:

- Hand-held vibrating plates
- Self-propelled vibrating rollers
- Pneumatic-tire rollers
- Large free-falling weights

b. Pneumatic Rammers: Used for the compaction of thin soil layers:

- **Explosion rammers** (commonly known as "jumping jacks") for cohesive or non-cohesive soils over small areas
- **2 to 3-ton tampers** mounted on mobile cranes, suitable for all soil types, though mainly used for small surface areas

c. Smooth Rollers: Used for cohesive, non-clayey soils

d. Pneumatic-Tire Rollers: Best for compacting non-cohesive soils

e. Sheepsfoot Rollers: Designed for cohesive soils, particularly necessary for clayey soils

f. Vibratory Equipment (rollers, plates, etc.): Effective for coarse-grained soils such as sands and gravels

3.3.2 Special Compaction Methods

For thick soil layers, dynamic compaction methods are used, including:

a. Compaction by Explosives

- **Point-source explosives:** Used for loose soils, compaction is achieved by generating a shock compression wave
- **Linear explosives:** Applied to cohesive soils, involving the placement of sand columns to densify the soil

b. Vibroflotation Compaction This technique induces alternating stresses and deformations, which rearrange soil particles.

- **Vibrating tubes:** Used for highly permeable materials
- **Ballasted columns:** Columns formed from compacted granular materials, typically applied in cohesive soils

c. Dynamic Compaction Suitable for all soil types. It involves applying high-energy impacts to the ground surface (free fall of a mass ranging from **10 to 30 tons**, or exceptionally **up to 140 tons**, from a height of **15 to 30 meters**). The depth of influence is given by Léonard et al. (1980) using the formula: $D = \frac{1}{2} \sqrt{(w \cdot h)}$ (in meters), where **w** is the falling mass in tons and **h** is the drop height in meters.

3.4 Compaction Requirements and Quality Control

Despite the wide variety of compaction equipment available, several key factors influence the effectiveness of a machine on a given soil. These include:

- Soil-related factors: such as type and moisture content
 - Equipment and process-related factors: including number of passes, speed, contact pressure, frequency, and vibration intensity
- Regardless of the equipment used,

on-site compaction should always be done in thin layers:

- **20 to 30 cm thick** for roadworks
- **10 to 15 cm thick** for building works

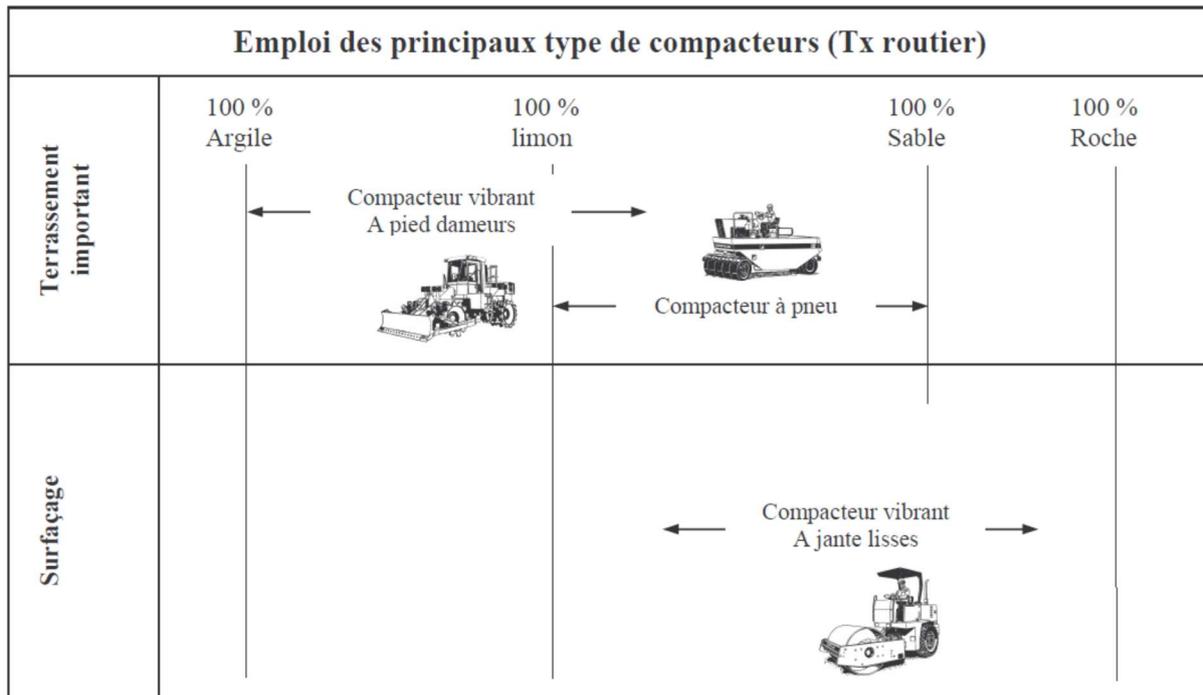


Fig. 3.6: Application Range of Main Compaction Equipment (Roadworks)

3.4.1. Trial Section Concept: A large part of the difficulties in earthworks projects stems from the fact that the placement of soil (e.g., embankments) often depends on atmospheric conditions at the time of construction. The trial section allows, prior to the opening of an earthworks site, the determination of compaction parameters related to the equipment used and the soil conditions at the time of the work (water content, equipment speed, number of passes, etc.), with the aim of achieving the required compaction (specified compaction).

3.4.2. Influence of Equipment Speed: For a given machine and fixed quality requirements, there is an optimal speed, depending on the thickness of the layer and the nature of the material, that allows for maximum compaction. The stricter the quality requirements, the lower the optimal travel speed. In general, it should not exceed 8 km/h, and for vibrating compactors, it is around 5 km/h.

3.4.3 Influence of the Number of Passes: The optimal number of passes depends on speed, layer thickness, and soil type. It typically ranges from 3 to 8, but can go up to 12. If the required compaction is not achieved after 12 passes, the compactor is considered unsuitable.

3.4.4 Degree of Compaction (Dc): It is calculated as the ratio between the dry density on site (γ_{d_site}) and the optimum Proctor dry density (γ_{d_opt}): $Dc = \gamma_{d_site} / \gamma_{d_opt}$

It is expressed as a percentage and must be $\geq 95\%$ (often 98%) to be acceptable. The higher the D_c , the more effective the compaction.

3.4.5. Membrane Densitometer: Used to measure the apparent unit weights of soils (wet γ or dry γ_d) in place, before swelling or after settlement or compaction. The test involves digging a cavity, collecting and weighing all the extracted material, and then measuring the volume of the cavity using a membrane densitometer. The device is equipped with a piston which, under the action of the operator, displaces a volume of water into a flexible, watertight membrane that conforms to the shape of the cavity. A graduated rod allows the volume to be read directly (see Fig. 3).

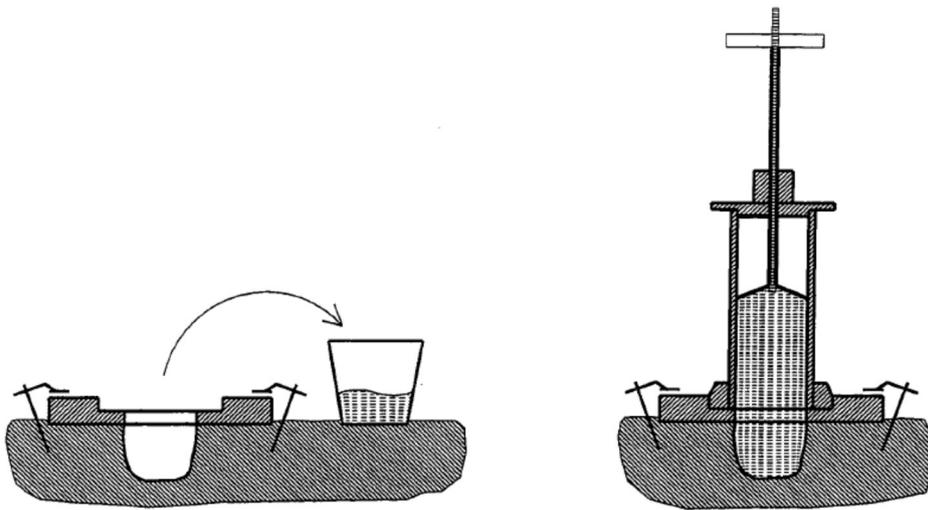
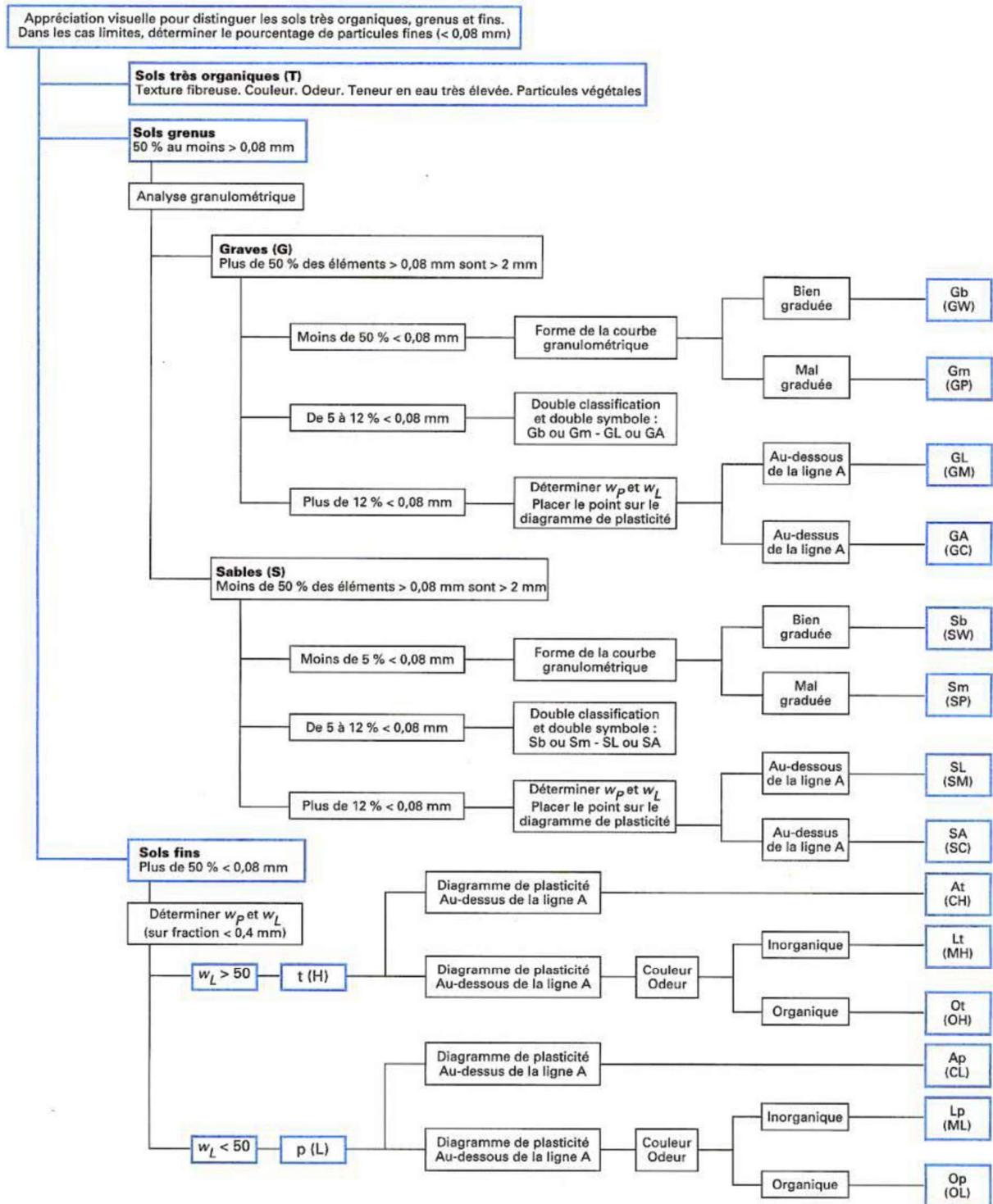
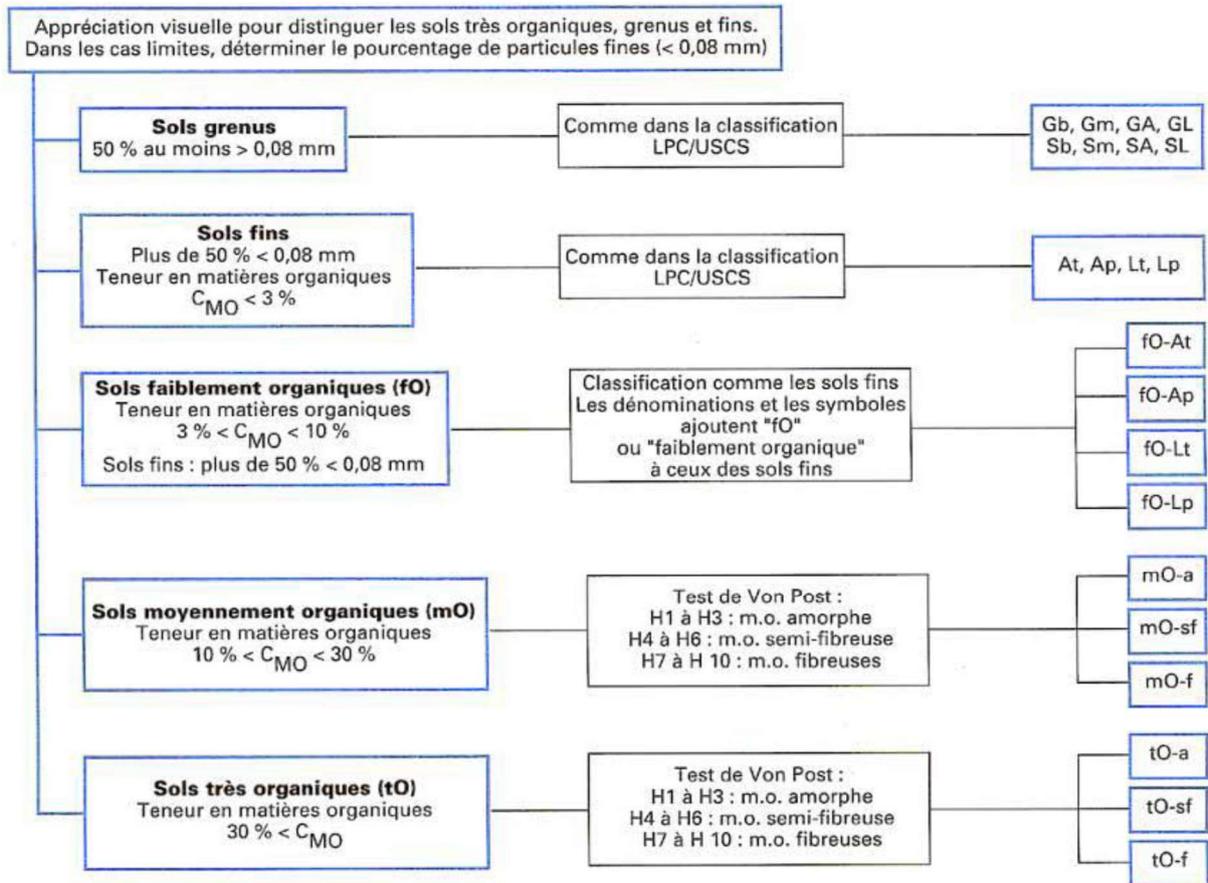


Fig. 3. .Membrane densitometer

Appendix 1 – Laboratory Soil Classification According to LPC/USCS



Appendix 2 – Modified LPC Soil Classification



Compaction Equipment



Tamping rammer



Roller à deux cylindres



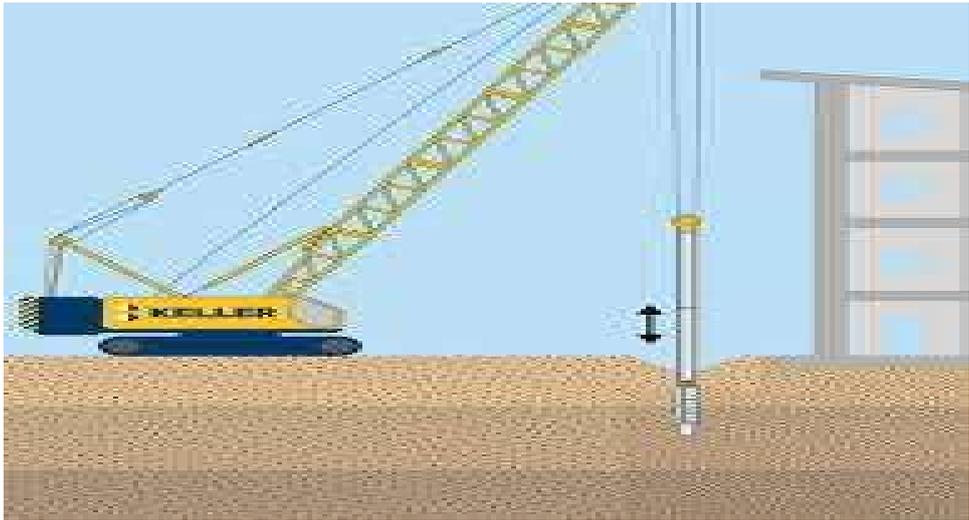
Roller à cylindres de diamètres différents



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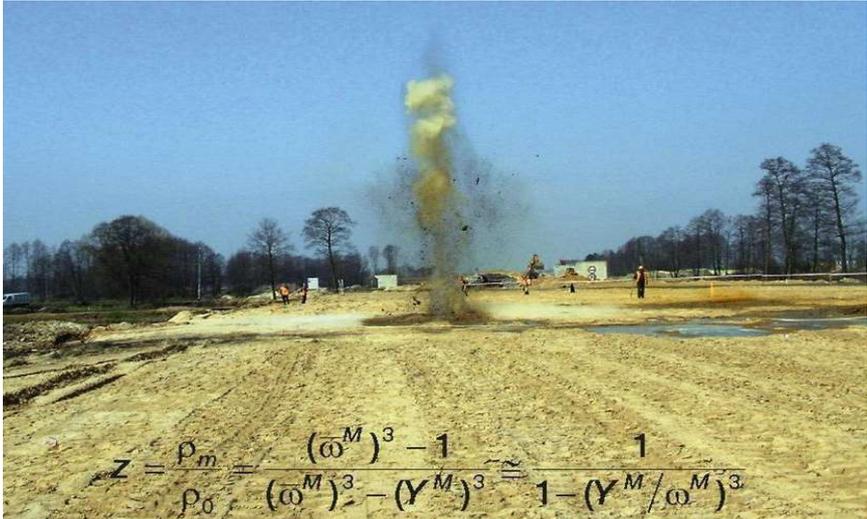
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Vibroflotation

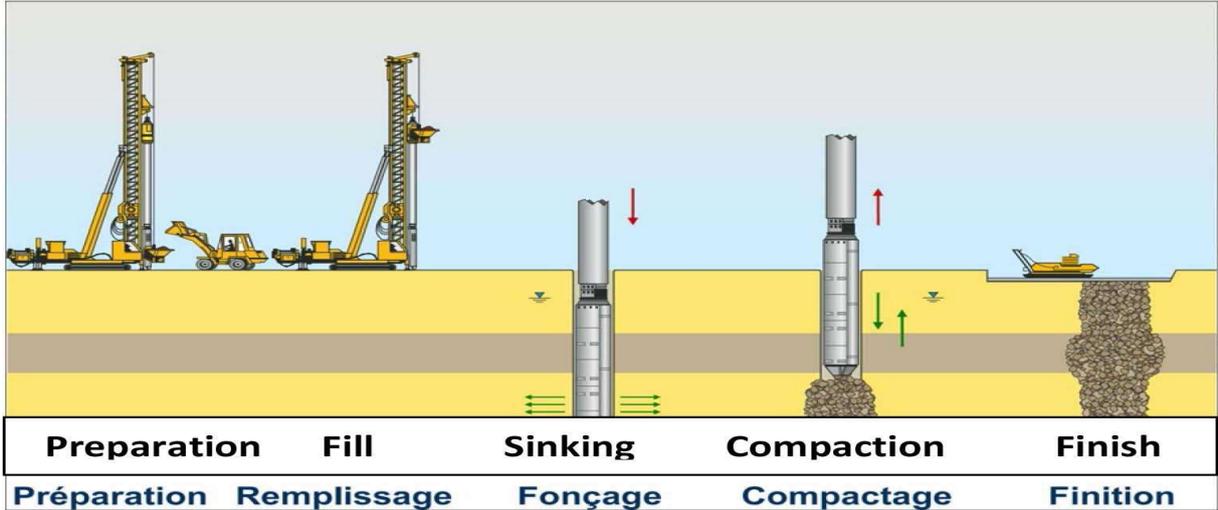


Dynamic compaction

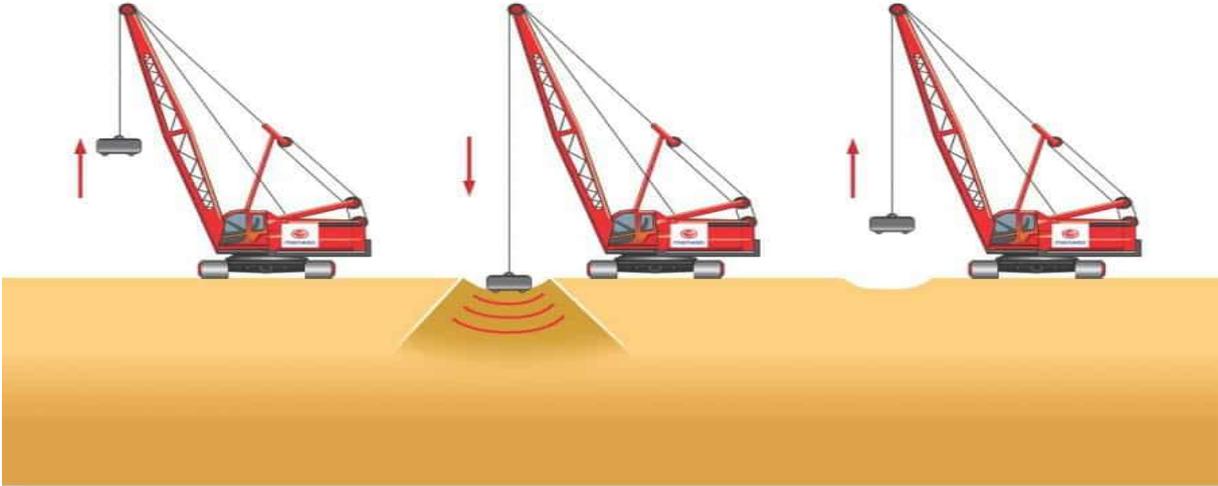


$$z = \frac{\rho_m}{\rho_0} = \frac{(\omega^M)^3 - 1}{(\omega^M)^3 - (Y^M)^3} \approx \frac{1}{1 - (Y^M / \omega^M)^3}$$

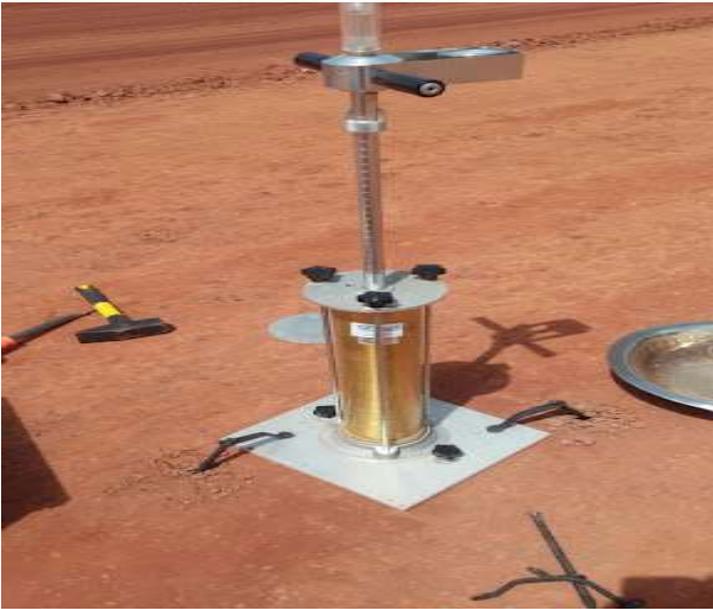
Compaction by Explosive



Ballasted columns



Dynamic compaction



Densitometre