Chapter II: Soil Identification and Classification

II.1 Physical Characteristics

II.1.1 Elementary Soil Model: A soil is composed of solid grains, water, and air. Each phase can be grouped into a unique partial volume with a unit cross-section. The following notations are used:

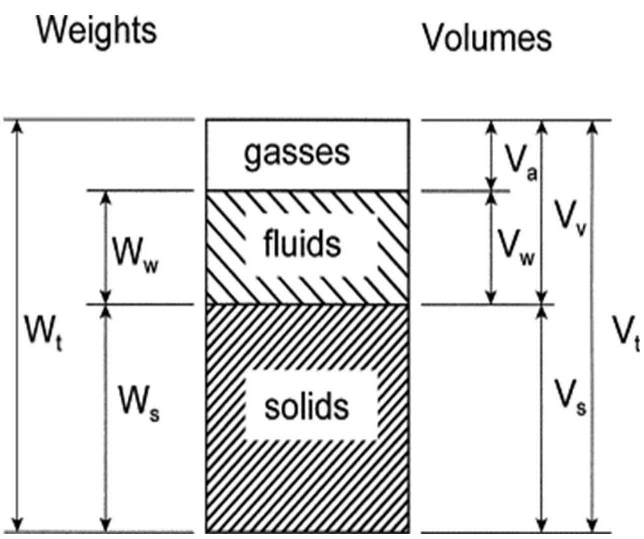


Fig. II.1: Conventional Representation of a Soil Volume (Weight and Volumes of Different Phases)

Conventional Notations:

- **W**: Total weight of the soil
- **Ws**: Weight of solid particles
- **Ww**: Weight of water
- **V**: Total (apparent) volume
- **Vs**: Volume of solid particles
- **Vv**: Volume of voids between particles
- **Vw**: Volume of water
- **Va**: Volume of air

With the following relations:

- **W = Ws + Ww**
- **Vv = Vw + Va**
- **V = Vs + Vv = Vs + Vw + Va**

We also define the unit weights, which, along with the weights and volumes, constitute:

a- Dimensional Parameters (Unit Weights):

- **The unit weight of solid particles** (the material forming the solid grains), denoted as **γs** : **γs = Ws/Vs** ; saand et clay = 26 à 27 kN/m^3.
- **The unit weight of water**, denoted as **γw**: **γw = Ww/Vw** = 9,81 kN/m^3. It is often approximated as **γw** = 10 kN/m^3.

- **The unit weight of soil** (also called **apparent unit weight** or **moist unit weight**), denoted as **γ**: It is the ratio of the total weight (solid particles and water) to the total volume of soil. **$\gamma = W/V$** ; sand = 17 à 20kN/m3, clay = 16 à 22kN/m^3.
- **The dry unit weight of soil**, denoted as **γd**: **$\gamma d = Ws/V$** ; sand= 14 à 18k N/m3, clay = 10 à 20 kN/m3. If the soil is dry: $\gamma = \gamma d$.
- **The saturated unit weight of soil**, denoted as **γsat**: When all voids are completely filled with water: **$\gamma sat = W/V$** = $(Ws + \gamma w.Vv)/V$. Sand and clay: 19 to 22 kN/m³
- **The submerged unit weight of soil**, denoted as **γ'**: It is considered when the soil is fully submerged. It accounts for the presence of water filling all voids and the Archimedes' buoyancy force: **$\gamma' = \gamma sat - \gamma w$**. Sand and clay: 9 to 12 kN/m³.

$\gamma' = \gamma sat - \gamma w = \gamma' = (\gamma s - \gamma w)(1\text{-}n)$. We also have the relation: **$\gamma' = \gamma_d \left(1 - \frac{\gamma w}{\gamma s}\right)$**

- **The concept of mass density**, denoted as **ρi**, is also introduced, and more rarely, the **density relative to water**, denoted as **Di**:

Density: $Di = \gamma i/\gamma w$ ⇒ **Dry density**: $Dd = \gamma d/\gamma w$.

b- Dimensionless Parameters (State Parameters): These parameters indicate the proportions of the different phases in a soil. They are very important and highly variable.

- **Porosity**, denoted as **n**, represents the amount of voids, which determines whether the soil is in a loose or dense state. It is defined as the ratio of the volume of voids to the total volume**: $n=Vv/Vn$** ; **Sand**: **n = 0.25 to 0.5, Clay**: **n = 0.20 to 0.80** Porosity is always less than **1** and can also be expressed as a percentage.
- **Void ratio**, denoted as **e**, has a similar meaning to porosity. It is defined as: **$e=Vv/Vs$;** Sand: e = 0.5 to 1, Clay: e = 0.3 to 1.
- **Water content**, denoted as **w**, is defined as the ratio of the weight of water to the weight of solid particles in a given soil volume. It is expressed as a percentage: **$w=Ww/Ws\times100w$**, Sand: w = 1 to 15%, Clay: w = 10 to 20%.
- The **degree of saturation**, denoted as **Sr**, indicates the proportion of voids that are filled with water. It is defined as the ratio of the volume of water to the volume of voids and is expressed as a percentage: %. $Sr = Vw/Vv$ .100. The degree of saturation can range from **0%** (dry soil) to **100%** (saturated soil).

- **Relative density or density index**, denoted as **Id**, is defined by the following expression: $I_d = (e_{max} - e)/(e_{max} - e_{min})$

Where:

- **emin**: Void ratio corresponding to the densest state.
- **emax**: Void ratio corresponding to the loosest state.
- **e**: Void ratio of the soil in its natural state.

Table II.1 : Soil Density State for Granular Soils

I_d	**Soil Density State for Granular Soils**
0-15	Very loosely compacted
15-35	Loosely compacted
35-65	Moderately
65-85	compacted
85-100	very Compacted

II.1.2 Relationships Between Parameters

All the previously defined parameters are not independent. The most important relationships between these different parameters are given as follows:

Moist unit weight (γ)		Dry unit weight (γ_d)		Saturated unit weight (γ_{sat})	
Given	**Relationship**	**Given**	**Relationship**	**Given**	**Relationship**
w, G_s, e	$\frac{(1+w)G_s\gamma_w}{1+e}$	γ, w	$\frac{\gamma}{1+w}$	G_s, e	$\frac{(G_s+e)\gamma_w}{1+e}$
S, G_s, e	$\frac{(G_s+Se)\gamma_w}{1+e}$	G_s, e	$\frac{G_s\gamma_w}{1+e}$	G_s, n	$[(1-n)G_s+n]\gamma_w$
w, G_s, S	$\frac{(1+w)G_s\gamma_w}{1+\frac{wG_s}{S}}$	G_s, n	$G_s\gamma_w(1-n)$	G_s, w_{sat}	$\left(\frac{1+w_{sat}}{1+w_{sat}G_s}\right)G_s\gamma_w$
w, G_s, n	$G_s\gamma_w(1-n)(1+w)$	G_s, w, S	$\frac{G_s\gamma_w}{1+\left(\frac{wG_s}{S}\right)}$	e, w_{sat}	$\left(\frac{e}{w_{sat}}\right)\left(\frac{1+w_{sat}}{1+e}\right)\gamma_w$
S, G_s, n	$G_s\gamma_w(1-n)+nS\gamma_w$	e, w, S	$\frac{eS\gamma_w}{(1+e)w}$	n, w_{sat}	$n\left(\frac{1+w_{sat}}{w_{sat}}\right)\gamma_w$
		γ_{sat}, e	$\gamma_{sat}-\frac{e\gamma_w}{1+e}$	γ_d, e	$\gamma_d+\left(\frac{e}{1+e}\right)\gamma_w$
		γ_{sat}, n	$\gamma_{sat}-n\gamma_w$	γ_d, n	$\gamma_d+n\gamma_w$
		γ_{sat}, G_s	$\frac{(\gamma_{sat}-\gamma_w)G_s}{(G_s-1)}$	γ_d, S	$\left(1-\frac{1}{G_s}\right)\gamma_d+\gamma_w$
				γ_d, w_{sat}	$\gamma_d(1+w_{sat})$

II.2 Granulometric Characteristics

II.2.1 Granulometric Analysis and Sedimentometry (NF P 94-056 & -057)

The purpose of granulometric analysis is to determine the weight proportions of grains of different sizes in the soil. It is carried out by:

- **Sieving** (square-mesh sieves) for grains with a diameter greater than **80 µm**.
- **Sedimentometry** for finer grains. This test involves allowing a soil suspension to settle at the bottom of a water-filled test tube. The finer the grains, the slower the settling velocity, in accordance with **Navier-Stokes' law** on the falling velocity of spherical particles in water. By measuring the suspension density at varying time intervals, the proportion of grains of each diameter can be calculated.

A convenient way to represent the results of granulometric analysis is the **granulometric curve**. This curve shows, for each particle size, the **percentage** of particles of that size or smaller, expressed as a percentage of the total dry mass of the studied sample. The curve is plotted on **semi-logarithmic coordinates**.

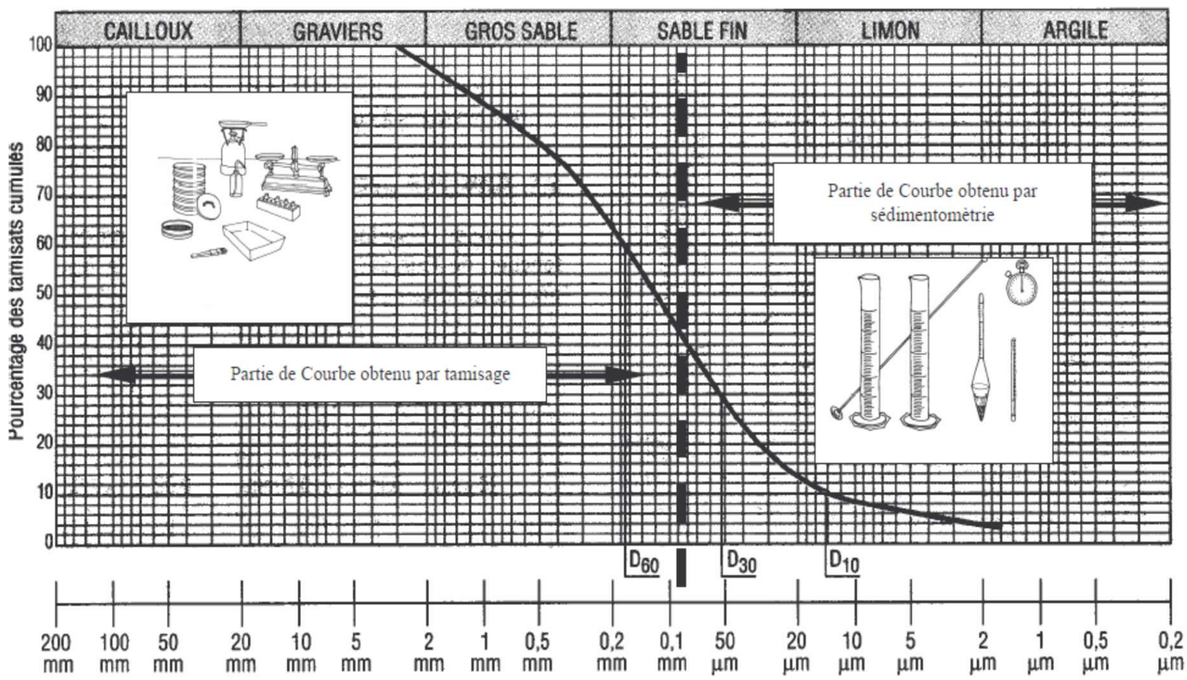


Fig. 2.2 Granulometric Curves.

II.2.2 Interpretation of Granulometric Curves

At first glance, a **granulometric curve** allows the identification of the different soil types present in the analyzed sample. By examining the curve, one can determine the respective proportions of **gravel, sand, silt, and clay**, expressed as percentages. Once these proportions are known, it becomes possible to classify the soil using a standard naming method, as indicated in **Table 2.2**. For example, if a soil sample consists of: **27% gravel**, **38% sand**, **29% silt**, **6% clay**, It is classified as **silty gravelly sand with traces of clay**.

Table 2.2: Soil Naming Based on the Proportion of Soil Types

Proportion of soil des types	Terminology	Examples
> 35% 20% à 35% 10% à 20% < 10%	Name Adjectif some traces	Gravel, sand, silt, etc. Gravelly, sandy, etc. some silt, some sand, etc. with traces of clay, silt, etc.

The **granulometry** of a soil can be characterized by the **coefficient of uniformity** (*Hazen's coefficient*) and the **coefficient of curvature**:

a- Coefficient of Uniformity (Cu) This coefficient expresses the **gradation spread** of the granulometric curve: $Cu=D60/D10$

Where:

- $\mathbf{D_{60}}$ = Effective particle diameter corresponding to **60% passing**.
- $\mathbf{D_{10}}$ = Effective particle diameter corresponding to **10% passing**.

Based on the value of the **coefficient of uniformity**, five soil gradation classes can be identified (**Table II.2**).

Table II.2: Soil Gradation Classes

Coefficient of uniformity	Gradation Classes
$Cu \leq 2$ $2 < Cu \leq 5$ $5 < Cu \leq 20$ $20 < Cu \leq 200$ $200 < Cu$	Very well-graded. well-graded. Moderatly graded. Poorly graded. Very Poorly graded.

b- Coefficient of Curvature (Cc)

This coefficient describes the shape of the grain size distribution curve: $\mathbf{Cc = (D_{30})^2/(D_{10} \times D_{60})}$

Where:

- D_{30} = Effective particle diameter corresponding to 30% passing.

When certain conditions on Cu and Cc are met ($1 \leq Cc \leq 3$), the soil is said to be well-graded, meaning its particle size distribution is well spread, without dominance of any particular fraction.

If the grain size distribution is discontinuous (Cc < 1 or Cc > 3), with a predominant particle fraction, the soil is considered poorly graded.

II.3 Consistency of Fine Soils (Atterberg Limits)

II.3.1 Definition

The consistency of cohesive soils, such as clays and silts, depends on their water content and determines their resistance to deformation. As the water content increases, the cohesion between particles decreases, leading to softer consistency and greater soil deformability.

The four main consistency states of cohesive soils, classified in order of increasing water content, are:

1. **Solid State:** Particles are in tight contact, with very thin adsorbed water films. The soil has high shear strength and low deformability under load. It behaves in a brittle manner, similar to a brick.
2. **Semi-Solid State:** A slight increase in water content causes adsorbed water films to thicken slightly. The soil shrinks when drying and may crack under loads.
3. **Plastic State:** A higher water content increases the distance between particles. The soil becomes malleable, deforming without cracking under small loads. Its consistency varies from soft butter to firm clay.
4. **Liquid State:** At very high water content, cohesion between particles is almost completely lost. The soil behaves like a viscous liquid, with consistency ranging from thick soup to soft butter.

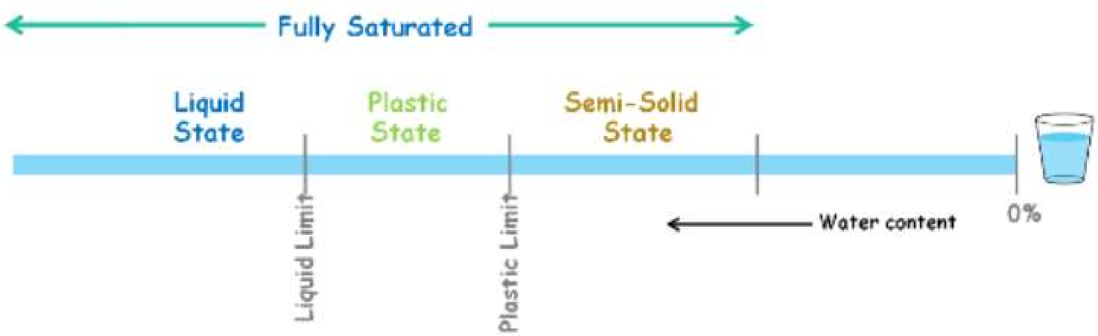


Fig.2.3 States of Consistency

II.3.2 Atterberg Limits

The Atterberg limits define the transitions between the consistency states of soils based on their water content:

- **Shrinkage Limit (ws):** The threshold beyond which the soil changes volume, separating the solid state from the semi-solid state.
- **Plastic Limit (wp):** The threshold where the soil loses its plasticity and cracks under low stress, separating the semi-solid state from the plastic state.
- **Liquid Limit (wl):** The threshold where the soil becomes fluid, separating the plastic state from the liquid state.

II.3.3 Plasticity and Liquidity Index

- **Plasticity Index (Ip)** is defined as the difference between the liquid limit (wl) and the plastic limit (wp): **Ip (%) = wl – wp**

This index measures the range of water content within which the soil remains in a plastic state.

Table 2.3 Classification of Clay Based on the Plasticity Index (Ip).

Plasticity index (Ip)	Soil state
0-5	Non-plastic
5-15	Low plasticity
15-40	Plastic
>40	Highly plastic

- **The Liquidity Index (I_L)** determines the consistency state of a soil by comparing its natural water content (w) to its plastic and liquid limits. It is calculated using the following formula: $I_L = (w - wp) / Ip$

Based on the liquidity index value, the soil can be classified as follows:

- $I_L > 1$: Soil in a liquid state
- $0 < I_L < 1$: Soil in a plastic state
- $I_L = 0$: Soil at the plastic limit
- $I_L < 0$: Soil in a semi-solid or solid state

The Consistency Index (Ic) is a derived indicator that characterizes the water state of a soil: $Ic = \frac{wl-w}{wl-wp} = \frac{wl-w}{Ip}$

II.3.4 The Plasticity Chart

In 1932, Casagrande proposed a plasticity chart (Fig. 2.5) to identify fine-grained soils based on the Atterberg limits. The chart is divided into two zones by Line A, with each zone further subdivided into three regions according to the soil's plasticity.

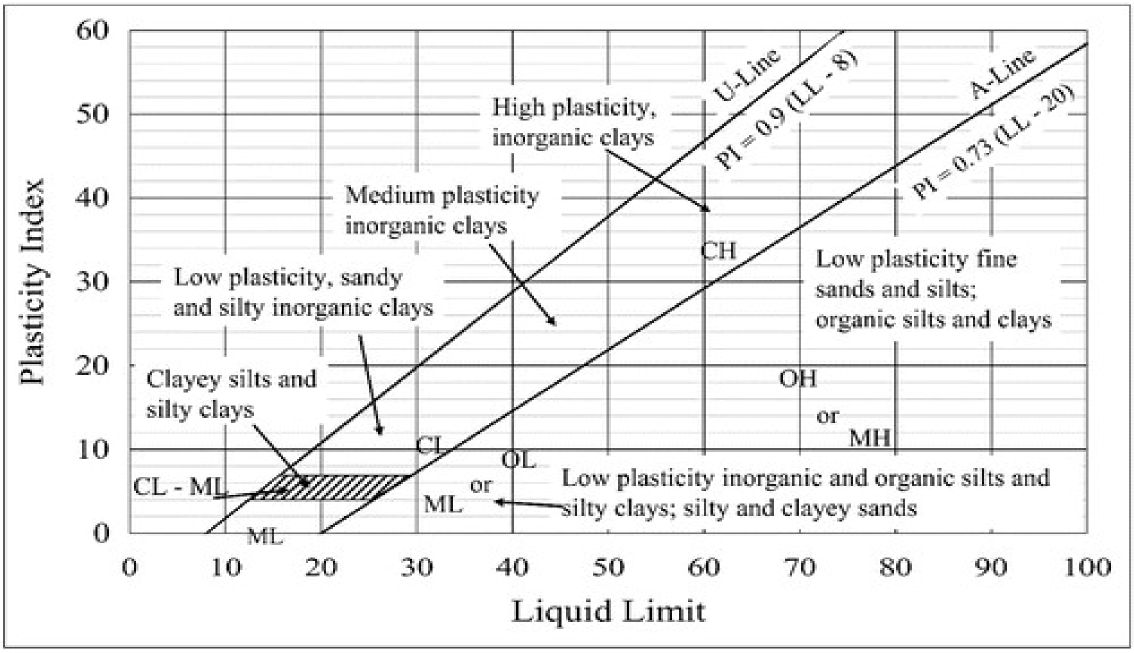


Fig.2.5 : Plasticity chart (After Casagrande, 1948).

II.4 Geotechnical Classification of Soils

To solve soil mechanics problems, it is crucial not only to characterize soils but also to classify them into groups with similar behaviors. This classification helps predict soil behavior and ensures the reliability and durability of infrastructures. Various soil classification systems exist worldwide.

II.4.1 LPC/USCS Soil Classification

The **LPC classification (1965)** is based on standard soil identification tests and includes the following criteria:

- **Grain size distribution criteria:**

- Percentages of **gravel, sand, and fine particles** (passing through **2 mm and 0.08 mm sieves**).
- Shape of the **particle size distribution curve**, using:
    - **Uniformity coefficient (Cu)** (Hazen's coefficient).
    - **Curvature coefficient (Cc)**.

- **Plasticity characteristics:**

- **Liquid limit (wL)** and **plasticity index (IP)**, with reference to **Line A**, defined by the equation:

$IP=0.73(w_L-20)$ *(Casagrande's equation)*

- **Organic matter content.**

Soil classification can also be performed through visual observation and simple field tests.

Tab.2.4: Soil Groups.

Soil Elements	Soil Granularity	Soil Plasticity
G: Gravel. Gravel is the main fraction **S**: Sand. Sand is the main fraction. **M**: Silt or silty. **C**: Clay or clayey. **Pt**: Peat. **O**: Organic. The soil contains organic matter	**W**: Well-graded **Pt**: Poorly graded	**H**: Highly plastic **I**: Medium plasticity **L**: Low plasticity

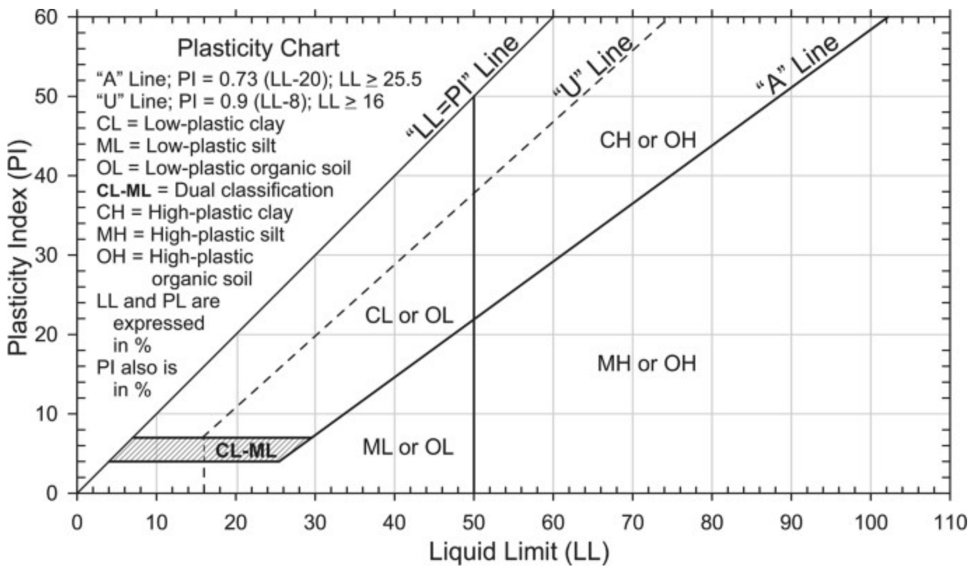


Fig. 2.6: LPC Classification of Fine Soils in the Laboratory – Plasticity Chart.

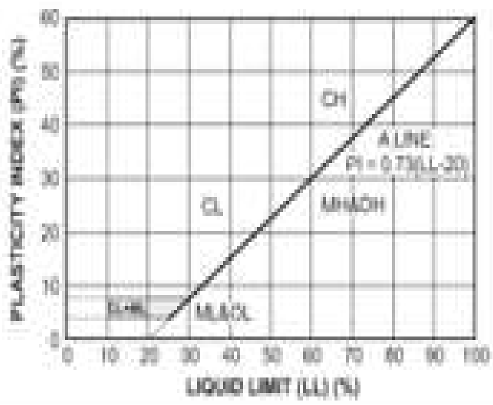
Tab.2.4: Classification of Coarse-Grained Soils (More than 50% of Particles > 0.08 mm)

UNIFIED SOIL CLASSIFICATION AND SYMBOL CHART			LABORATORY CLASSIFICATION CRITERIA	
COARSE-GRAINED SOILS (more than 50% of material is larger than No. 200 sieve size.)				
GRAVELS More than 50% of coarse fraction larger than No. 4 sieve size	Clean Gravels (Less than 5% fines)			
	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	GW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}^2}{D_{10} \times D_{60}}$ between 1 and 3
	GP	Poorly-graded gravels, gravel-sand mixtures, little or no fines	GP	Not meeting all gradation requirements for GW
	Gravels with fines (More than 12% fines)			
	GM	Silty gravels, gravel-sand-silt mixtures	GM	Atterberg limits below "A" line or P.I. less than 4 — Above "A" line with P.I. between 4 and 7 are borderline cases requiring use of dual symbols
	GC	Clayey gravels, gravel-sand-clay mixtures	GC	Atterberg limits above "A" line with P.I. greater than 7 — Above "A" line with P.I. between 4 and 7 are borderline cases requiring use of dual symbols
SANDS 50% or more of coarse fraction smaller than No. 4 sieve size	Clean Sands (Less than 5% fines)			
	SW	Well-graded sands, gravelly sands, little or no fines	SW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}^2}{D_{10} \times D_{60}}$ between 1 and 3
	SP	Poorly graded sands, gravelly sands, little or no fines	SP	Not meeting all gradation requirements for GW
	Sands with fines (More than 12% fines)			
	SM	Silty sands, sand-silt mixtures	SM	Atterberg limits below "A" line or P.I. less than 4 — Limits plotting in shaded zone with P.I. between 4 and 7 are borderline cases requiring use of dual symbols.
	SC	Clayey sands, sand-clay mixtures	SC	Atterberg limits above "A" line with P.I. greater than 7 — Limits plotting in shaded zone with P.I. between 4 and 7 are borderline cases requiring use of dual symbols.
FINE-GRAINED SOILS (50% or more of material is smaller than No. 200 sieve size.)				
SILTS AND CLAYS Liquid limit less than 50%	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity		
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays		
	OL	Organic silts and organic silty clays of low plasticity		
SILTS AND CLAYS Liquid limit 50% or greater	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts		
	CH	Inorganic clays of high plasticity, fat clays		
	OH	Organic clays of medium to high plasticity, organic silts		
HIGHLY ORGANIC SOILS	PT	Peat and other highly organic soils		

Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows:

Less than 5 percent	GW, GP, SW, SP
More than 12 percent	GM, GC, SM, SC
5 to 12 percent	Borderline cases requiring dual symbols

PLASTICITY CHART

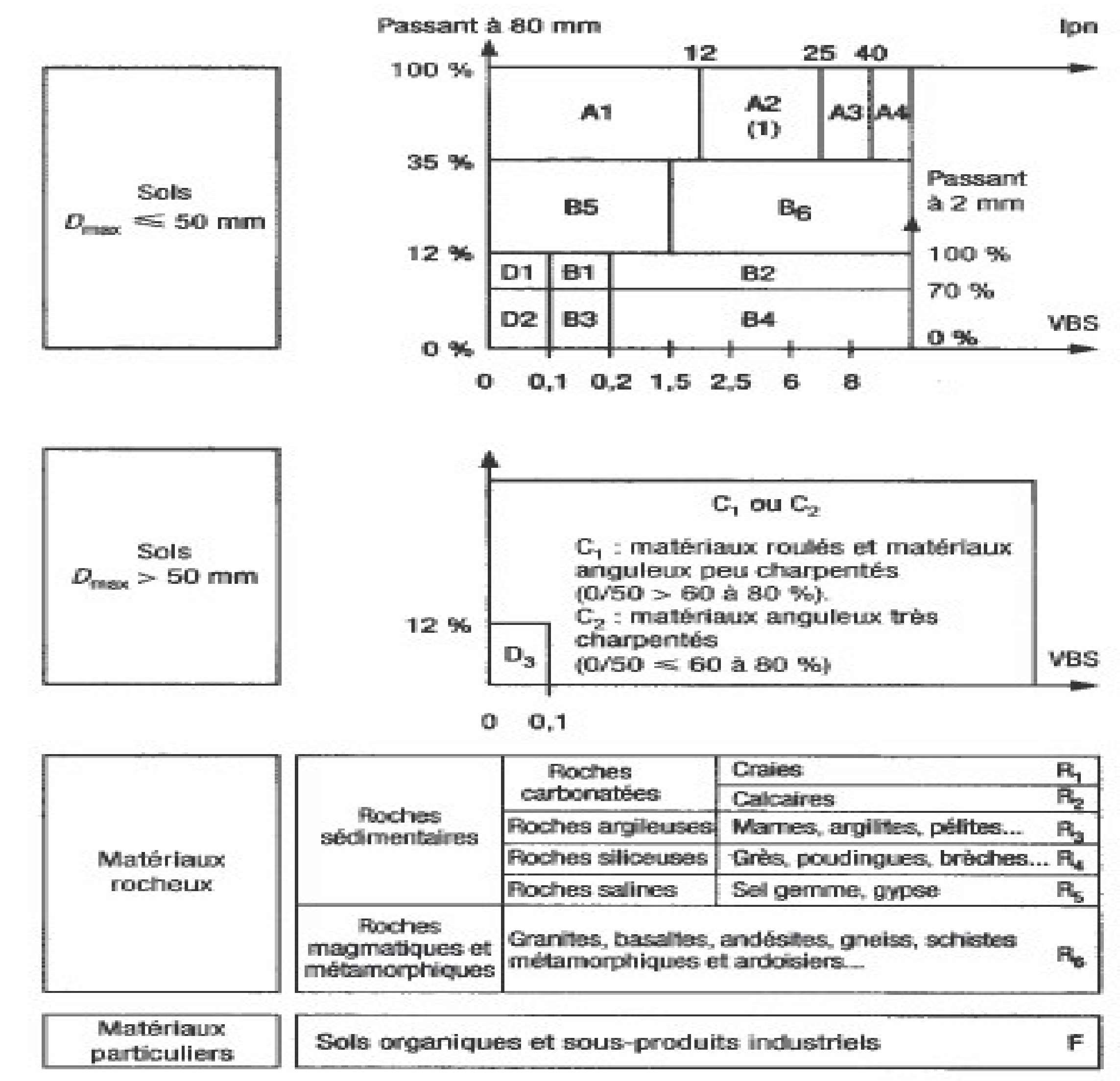


II.4.2 GTR Classification

This classification is the only one with real practical interest and is widely used in **earthworks**. Its application is detailed in the **Technical Guide for Embankment Construction and Subgrade Layers**. For this reason, it is referred to as the **GTR classification**.

Tab. 2.5: GTR Classification (SETRA).

CLASSE	Définition	Caractéristique	Sous-classe
A	Sols fins	$D_{max} \leq 50mm$ et passant à $80\mu m > 35\%$	A1 à A4 selon VBS ou I_p
B	Sols sableux et graveleux avec fines	$D_{max} \leq 50mm$ et passant à $80\mu m \leq 35\%$	B1 à B6 selon VBS ou I_p et tamisat
C	Sols comportant des fines et des gros éléments	$D_{max} > 50mm$ et passant à $80\mu m > 12\%$ ou passant à $80\mu m \leq 12\%$ + VBS>0,1	30 sous-classes selon VBS, I_p et tamisat à 50 mm
D	Sols insensibles à l'eau avec fines	VBS≤ 0,1 et passant à $80\mu m \leq 12\%$	D1 à D3
R	Matériaux rocheux	Voir la norme NF P 11-300	
F	Sols organiques et sous-produits industriels	Voir la norme NF P 11-300	
D_{max} = diamètre pour lequel 95% des grains du sol ont une dimension inférieure (soit D_{95} si la courbe granulométrique est disponible, sinon appréciation visuelle de la dimension des plus gros éléments			


Passant à 80 mm
Ipn
100 %
12
25
40
A1
A2
(1)
A3
A4
35 %
B5
B6
Passant
à 2 mm
12 %
100 %
D1
B1
B2
70 %
D2
B3
B4
VBS
0 %
0 %
0
0,1
0,2
1,5
2,5
6
8
Sols
D_{max} ≤ 50 mm
Sols
D_{max} > 50 mm
C_1 ou C_2
C_1 : matériaux roulés et matériaux anguleux peu charpentés (0/50 > 60 à 80 %).
C_2 : matériaux anguleux très charpentés (0/50 ≤ 60 à 80 %)
12 %
D_3
VBS
0
0,1
Matériaux rocheux
Roches sédimentaires
Roches carbonatées
Craies
R_1
Calcaires
R_2
Roches argileuses
Marnes, argilites, pélites...
R_3
Roches siliceuses
Grès, poudingues, brèches...
R_4
Roches salines
Sel gemme, gypse
R_5
Roches magmatiques et métamorphiques
Granites, basaltes, andésites, gneiss, schistes métamorphiques et ardoisiers...
R_6
Matériaux particuliers
Sols organiques et sous-produits industriels
F