GEOTECHNICAL ENGINEERING – PART I

Contents

1.1 INTRODUCTION

1.1.1 CONTENTS

This chapter is divided into two parts:

- **Part I** focuses on straightforward yet rigorous procedures (i.e., adhering to current technical standards) for characterizing the geotechnical properties of soil;
- **Part II** covers practicals applications through quick and easy methods.

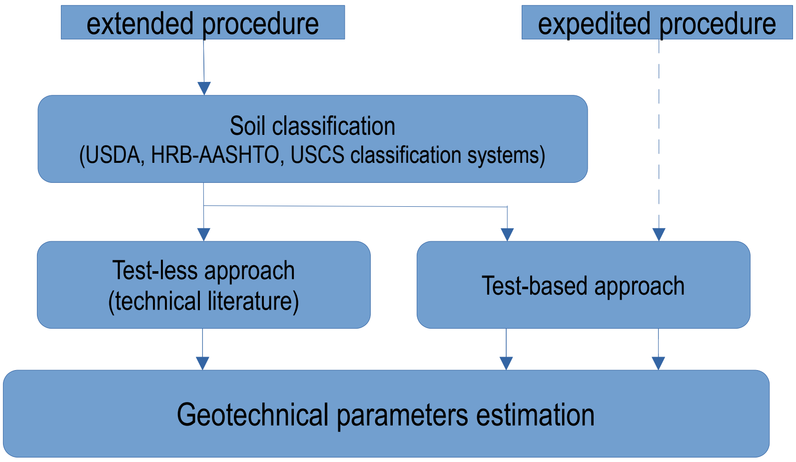
1.1.2 GEOTECHNICAL PROPERTIES EVALUATION PROCEDURES

The purpose of this document is to provide simple, quick, and reliable methods for determining soil geotechnical properties.

There are basically two procedures.

A) The **extended procedure** involves two phases: soil classification followed by parameter extrapolation from technical literature (test-less approach). Filed tests can also be performed to validate the obtained results. This method is mainly recommended for earthworks such as dam or levee construction.

B) The **expedited procedure**, easier and quicker than the previous one, involves parameter evaluation through field tests (test-based approach). This method is quite time-saving and the most common method in emergency contexts, especially for structure sizing purposes.



Procedures for geotechnical parameters estimation.

The extended procedure consists of the following stages:

- **soil classification**. Its main purpose is the identification of the ASTM-USCS class of the soil. This classification can be determined directly or indirectly through correspondence with other (simpler) classification systems such as USDA or AASHTO.
- **geotechnical parameters estimation**. Once the ASTM-USCS class is identified, the most probable values of geotechnical parameters can be easily extrapolated from the technical literature.

The expedited procedure consists of the following stages:

- **field tests**: rudimentary penetration tests and infiltration tests.
- **geotechnical parameters estimation**, through straightforward elaboration of the obtained results.

1.2 GENERAL

term	definition	formula	unit of measure
Porosity	percentage ratio of the volume of the voids V_v to the total volume of the sample V	$n = V_v / V$	[%]
Void ratio	ratio of the volume of the voids V_v to the volume of the solids V_s	$e = V_v / V_s$	-
Specific volume	ratio of the total volume of the sample v to its volume of the solids V_s	$v = V / V_s$	-
Degree of saturation	percentage ratio of the volume of free water contained V_w to total volume of the voids V_v	$S_r = V_w / V_v$	[%]
Moisture content	percentage ratio of the weight of water contained P_w to the weight of the sollid part P_s	$w = P_w / P_s$	[%]
Bulk Unit weight	ratio of the weight of the sample P to its volume V	$\gamma_{bulk} = P / V$	[kN/m^3]
Dry unit weight	ratio of the weight of the solid part P_s to its volume V when S_r = 0%	$\gamma_d = P_s / V$	[kN/m^3]
Saturated unit weight	ratio of the weight of the solid part P_s to its volume V when S_r = 100%	$\gamma_{sat} = P / V$ when S_r = 100%	[kN/m^3]
Unit weight of solid part	ratio of the weight of the solid part P_s to its volume V_s	$\gamma_s = P_s / V_s$	[kN/m^3]
Submerged unit weight	saturated unit weight γ_{sat} minus unit weight of the water γ_w	$\gamma' = \gamma_{sat} - \gamma_w$	[kN/m^3]
Relative density or density index	ratio of maximum void ratio minus void ratio to maximum void ratio minus minimum void ratio	$D_R = (e_{max} – e) / (e_{max} - e_{min})$	[%]
Liquid limit	State in which the soil has the minimum moisture content to allow to close a groove engraved according to the standard test of the Casagrande		
Plastic limit	State in which the soil has the minimum moisture content to allow to mold a 3 mm diameter stick		
Plasticity index	Difference, expressed in percentage, between the moisture contents in liquid and plastic limit	$PI = w_L - w_P$	[%]

Table 1: definitions of the main geotechnical parameters

1.3 SOIL CLASSIFICATION

1.3.1 METHODS OF EMPIRICAL IDENTIFICATION OF SOILS – INTRODUCTION

"Empirical methods are processes aimed at identifying soil types and facilitating the evaluation of their key geotechnical parameters. The most commonly used classifications, listed in increasing order of complexity, are:

- **USDA Classification system**
  sedimentation / settling test
- **HRB-AASHTO classification system (UNI-CNR 10006 - EN ISO 14688-1:2017)**
  sieve analysis (three sizes), two manipulative and one visual tests
- **ASTM D2488 (USCS) calssification system**

  sieve analysis (four sizes), four manipulative and one visual tests.

A summary table of the methods is shown below.

Classification system	Coarse contents analysis	Fine contents analysis
USDA	sedimentation / settling test	
HRB-AASHTO (UNI-CNR 10006 - EN ISO 14688-1:2017)	Sieve analysis mesh 2 mm (n.7 UNI – No.10 ASTM) mesh 0.4 mm (n.22 UNI) mesh 0.075 mm (n.37 UNI – No.200 ASTM)	dilatancy test toughness test organic / inorganic identification
ASTM D2488 (USCS)	Sieve analysis mesh 75 mm (3 in.) mesh 4.75 mm (No.4 ASTM) mesh 0.425 mm (No.35 ASTM) mesh 0.075 mm (n.37 UNI – No.200 ASTM)	dry strenght test dilatancy test toughness test plasticity test organic / inorganic identification

Table 2: comparison between different methods of soil classification

1.3.2 SETTLING TEST – USDA CLASSIFICATION SYSTEM (U.S. DEPARTMENT OF AGRICULTURE)

This classification method was primarily developed for agricultural purposes. The following practice is a simplified procedure that does not correspond to the recommendations provided by the USDA. For the USDA's recommended method, please continue reading.

The test is straightforward, but has the following limitations:

- it does not enable to estimate the gravel content;
- it does not offer any information about particle size of sand;
- It tends to underestimate clay content, as complete sedimentation may require a significant amount of time.

1.3.2.1 Practice

1. Fill 1/3 up tp 1/2 of clear glass / plastic jar (cylinder-shaped, if possible) with the soil to be analysed;
2. Fill almost all the remaining space with water (leave enough space for shaking);
3. Shake the jar et let the particles settle;
4. Directly mark on the jar the levels of the settled material at the times indicated in the following table;

Material	Settling time (approximately)
Sand	1 to 5 minutes
Silt	30 minutes – 2 hours
Clay	24 – 48 h

5. Measure the thickness of the layers and calculate the percentages of their volume;

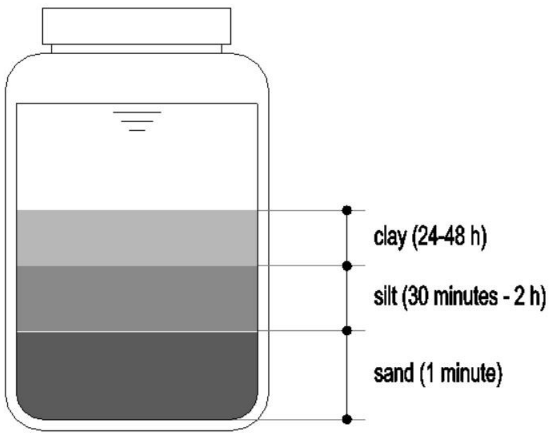


Figure 1: settling / sedimentation test

6. Once the percentages of sand, silt and clay have been given, the soil class is inferred from the USDA texture diagram below and determine the soil class.

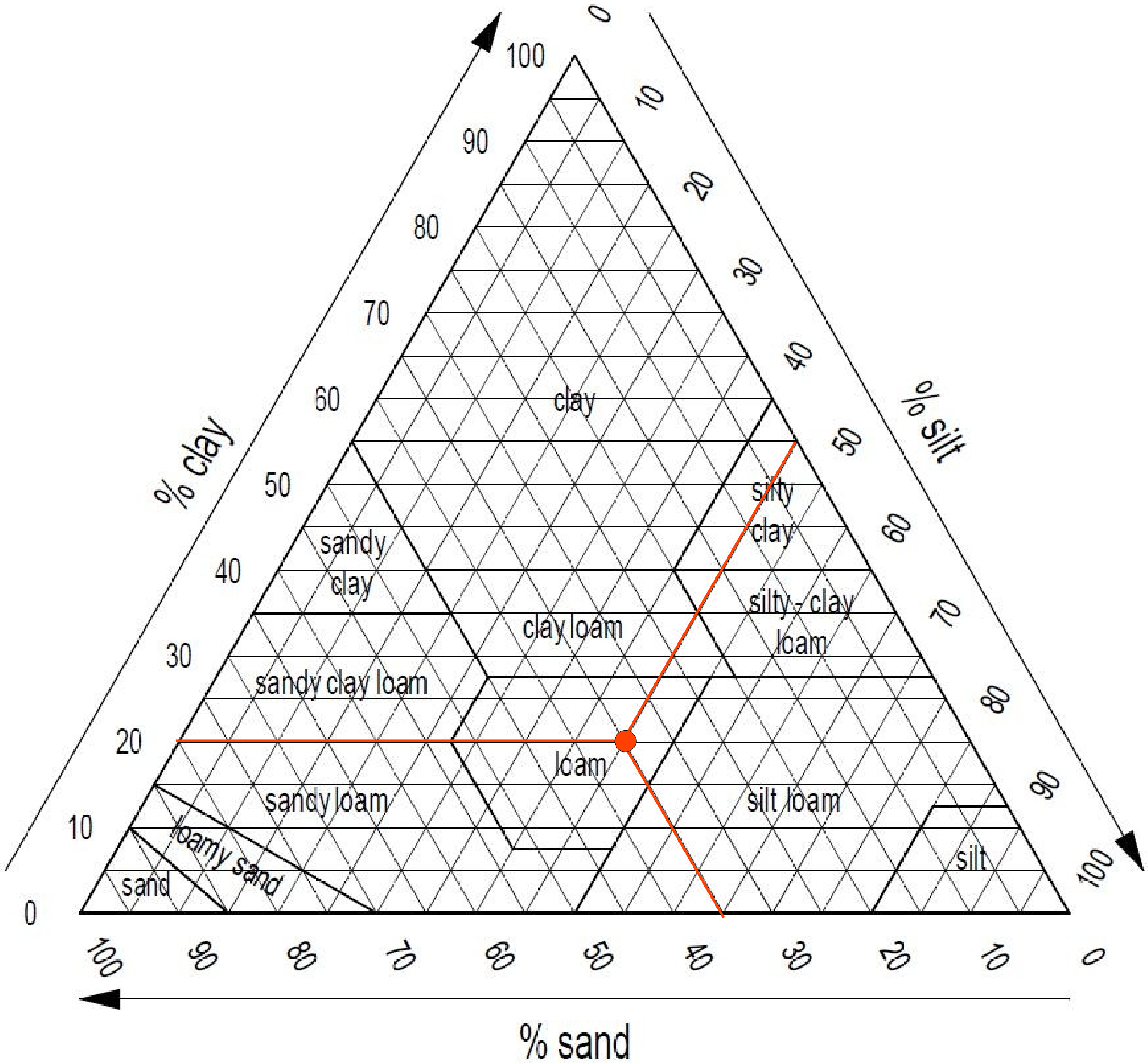


Figure 2: USDA soil texture diagram (example with 45% sand – 55% silt 20% clay soil sample)

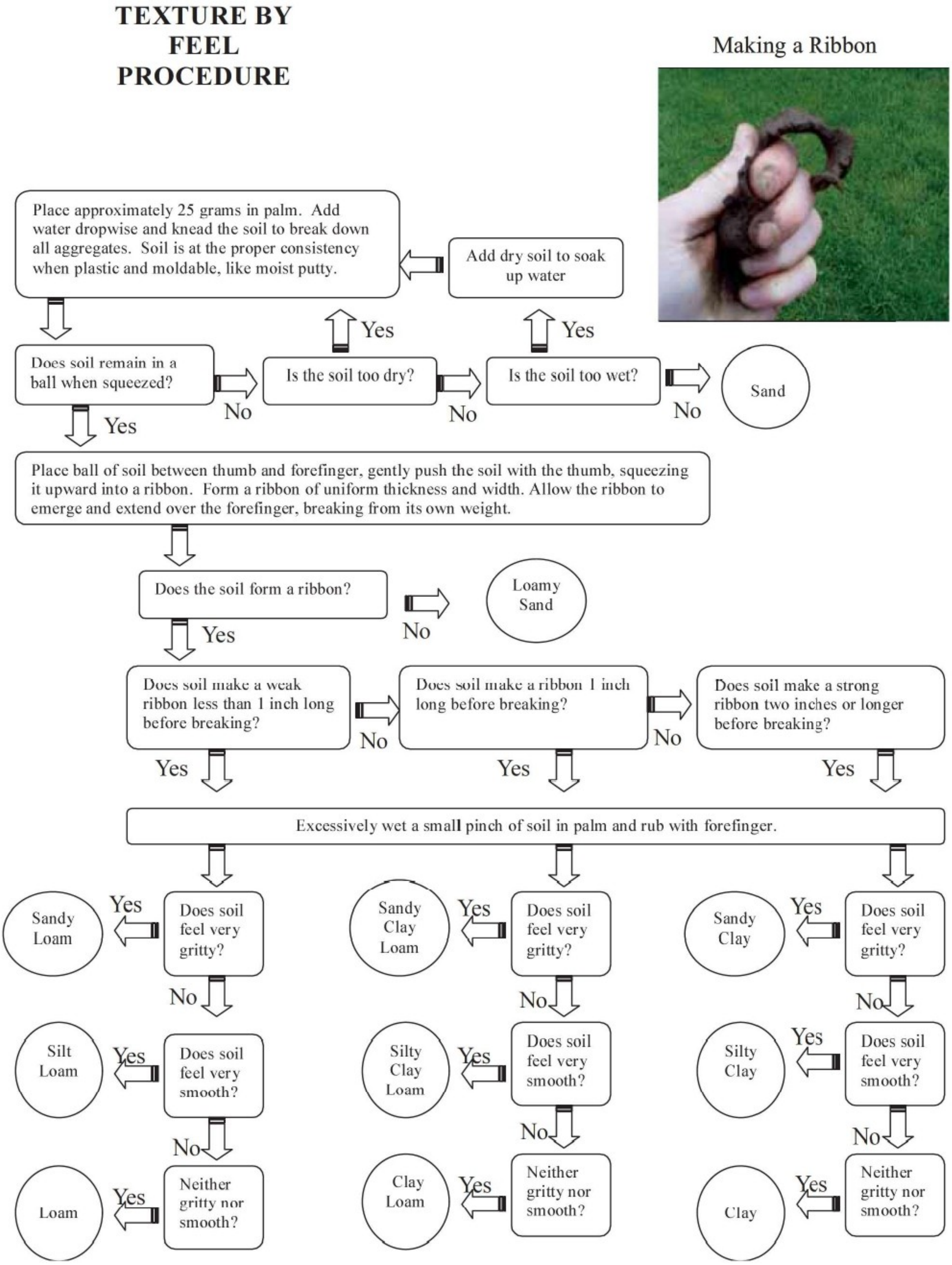


Figure 3: USDA soil survey standard practice (from USDA, *Soil Quality Teat Kit Guide,* 2001).

1.3.3 HRB-AASHTO CLASSIFICATION SYSTEM (UNI-CNR 10006-2002)

This classification method was primarily developed for road engineering purposes, but it can also be properly utilized for dam or levee works. Accurate performance requires a sieve test and various manipulative tests.

This standard has been replaced by the EN ISO 14688-1:2017.

With the field tests it is possible to identify the following soil categories:

- A1 stone fragments, gravel and sand
- A2 silty or clayey gravel and sand
- A3 fine sand
- A4-A5 silt
- A6-A7 clay
- A8 peat and organic soil

General classification	**Granular Materials (35% or less passing the 0.075 mm / No. 200 sieve)**							**Silt-Clay Materials (>35% passing the 0.075 mm / No. 200 sieve)**					**Peat and organic soil**
Group	A 1		A 3	A 2				A 4	A 5	A 6	A 7		A 8
Sub-group	A 1-a	A 1-b		A 2-4	A 2-5	A 2-6	A 2-7				A 7-5	A 7-6	
Sieve analysis Percent passing 2 mm / No. 2 % 0.425 mm / No. 40 % 0.075 mm / No. 200 %	≤ 50 ≤ 30 ≤ 15	- ≤ 50 ≤ 25	- > 50 ≤ 10	- - ≤ 35	- - ≤ 35	- - ≤ 35	- - ≤ 35	- - > 35	- - > 35	- - > 35	- - > 35	- - > 35	
Characteristic of fraction passing sieve 0.425 mm / No. 40 Liquid limit (LL) Plasticity index (IP)	- ≤ 6		- N.P.	≤ 40 ≤ 10	> 40 ≤ 10	≤ 40 > 10	> 40 > 10	≤ 40 ≤ 10	> 40 ≤ 10	≤ 40 > 10	> 40 > 10	> 40 > 10 IP≤LL-30	> 40 > 10 IP≤LL-30
Group index	0		0	0	0	≤ 4	≤ 4	≤ 8	≤ 12	≤ 16	≤ 20		
Usual types of significant constituent materials	Stone fragments, gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soil		Clayey soil			Peat or generic organic soil
General rating as a subgrade (without ice)	Excellent to good							Fair to poor					No to use
Effect of frost on the bearing qualities of the subgrade soil (1)	None or slight			Medium				Very high		Medium	High	Medium	
Shrinkage or swelling (1)	None			None or slight				Slight or medium		High	High	Very high	
Permeability (1)	High			Medium or low						None or low			
On-site soil identification (1)	Particles easily detectable to the naked eye		Harsh to the touch, in a granular state when dry	Most of the particles are detectable to the naked eye. Harsh to the touch. Medium or high tenacity when dry indicates the presence of clay				Reactive to dilatancy test. Pulverulent or with little tenacity when dry. Not easily moldable when wet		Not reactive to dilatancy test. Tenacity when dry. Easily moldable into thin sticks when wet.			Fibrous, brown to black. Easily identifiable by sight.

(1) UNI-CNR 10006-2002

Table 3: HRB-AASHTO classification chart

1.3.3.1 Practice

The method consists of the following procedure.

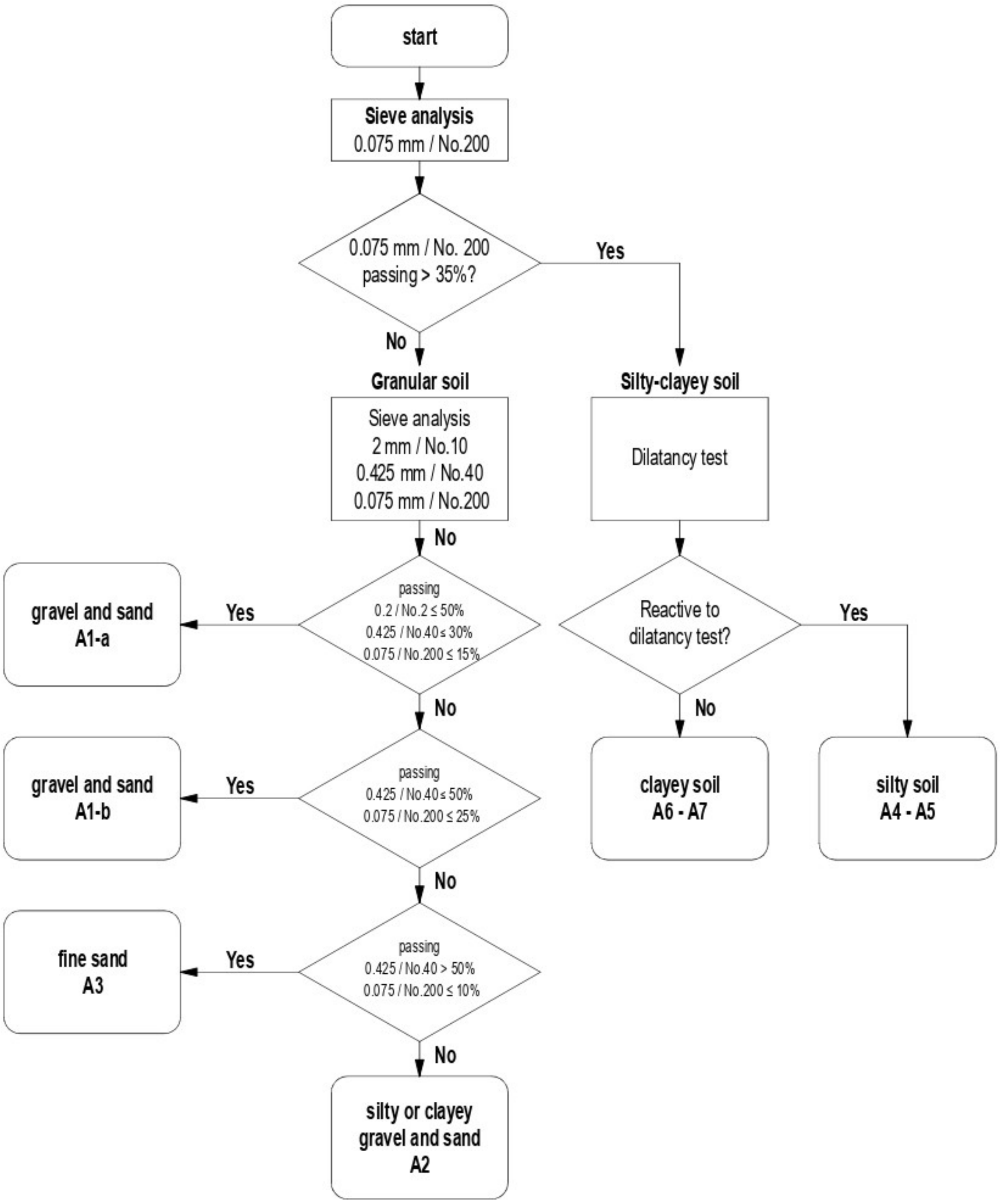


Table 4: HRB-AASHTO classification procedure

1. Perform a sieve analysis with the following sieve sizes:
   - mesh 2 mm (No.10 ASTM E 11-70)
   - mesh 0.425 mm (No.40 ASTM E 11-70)
   - mesh 0.075 mm (No.200 ASTM E 11-70)

   If the percent passing through the sieve No. 200 / 0.075 mm is greater than 35%, the soil is defined as **silty-clay**, otherwise **granular;**
2. If the soil is granular, with the sieve analysis it is possible to identify only the (sub)groups: A1-a, A1-b, A2 and A3;

3. If the soil is silty-clay the following tests have to been performed:
    - dilatancy test: mold a 25 mm diameter ball in the palm of one hand, add water, and flat it with a spatula. Then shake the sample by hitting with the other hand several times. If it releases water on its surface the soil is silty (A4-A5 group), otherwise clayey (A6-A7 group).

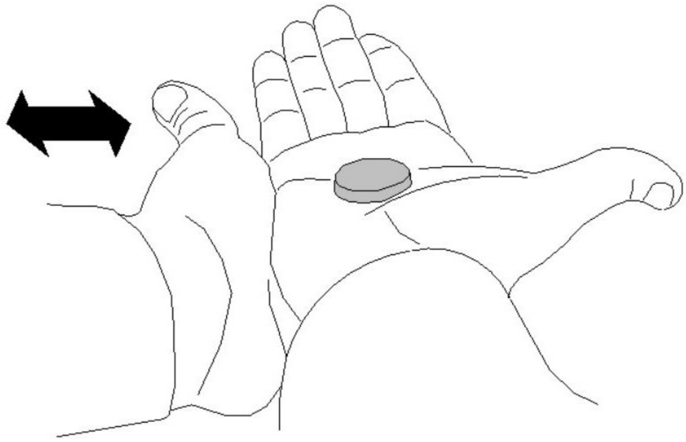


Figure 4: dilatancy test

    - toughness test: asses how hard is make a 3 mm diameter stick. Easier it is to mold, greater the contents in clay.

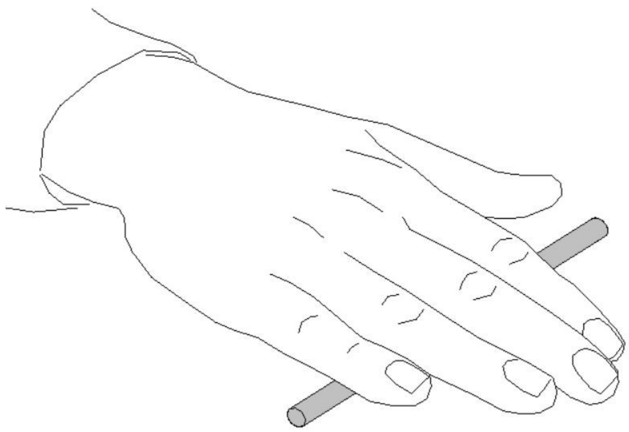


Figure 5: toughness test

    - a visual test that aims to asses if soil is inorganic or not. In the latter case the sample is dark, fibrous and probably lighter.

1.3.4 ASTM D2488 Classification System[1]

This soil classification is more detailed and complex than previous ones and requires more field tests. Specifically, the operator must perform a sieve analysis with four sizes and three manipulative tests.

Before introducing the procedure, note that the classification categorizes particles according to the following table:

Definition	Categories	Size range [mm]	ASTM sieve size	Plasticity properties
Boulders		>300	12 inches	-
Cobbles		75-300	3 – 12 inches	-
Gravel	coarse gravel	19 – 75	¾ - 3 inches	-
	fine gravel	4.75 - 19	No.4 – ¾	-
Sand	coarse sand	2.00 – 4.75	No.10 – No.4	-
	medium sand	0.425 – 2.00	No.40 – No.10	-
	fine sand	0.075-0.425	No.200 – No.40	-
Silt	inorganic silt	<0.075	passing No.200	PI ≥ 4[2], [P; w_l] above “A” line
	organic silt	<0.075	passing No.200	as above, with $w_{l,a} < 0.75\ w_{l\,b}$
Clay	inorganic clay	<0.075	passing No.200	PI ≥ 4, [P; w_l] below “A” line
	organic clay	<0.075	passing No.200	as above, with $w_{l,a} < 0.75\ w_{l\,b}$

1.3.4.1 Practice

Preparation

1. Perform a sieve analysis with the following sieve sizes:
   - mesh 75 mm (3 in.)
   - mesh 4.75 mm (No.4 ASTM E 11-70)
   - mesh 0.425 mm (No.35 ASTM E 11-70)
   - mesh 0.075 mm (n.37 UNI 2332 – No.200 ASTM E 11-70)
2. Remove from the sample the portion retained by the 75 mm / 3 in mesh sieve (boulders and cobbles), noting its percentage (in volume);
3. Estimate the percentages of gravel (4.75 – 75 mm), sand (0.075 – 4,75 mm) and fine soil (< 0.075 mm), approximating them by multiple of 5%. If a portion is smaller than 5% it will be indicated as *trace*;
4. If the portion of fine material is more than 50%, the soil must be defined as *fine-grained soil*, otherwise *coarse-grained soil*. Continue following the procedure corresponding to the type of soil identified.

1 Also known as United Soil Classification System (USCS)

2 PI: Plasticity Index (see “General”)

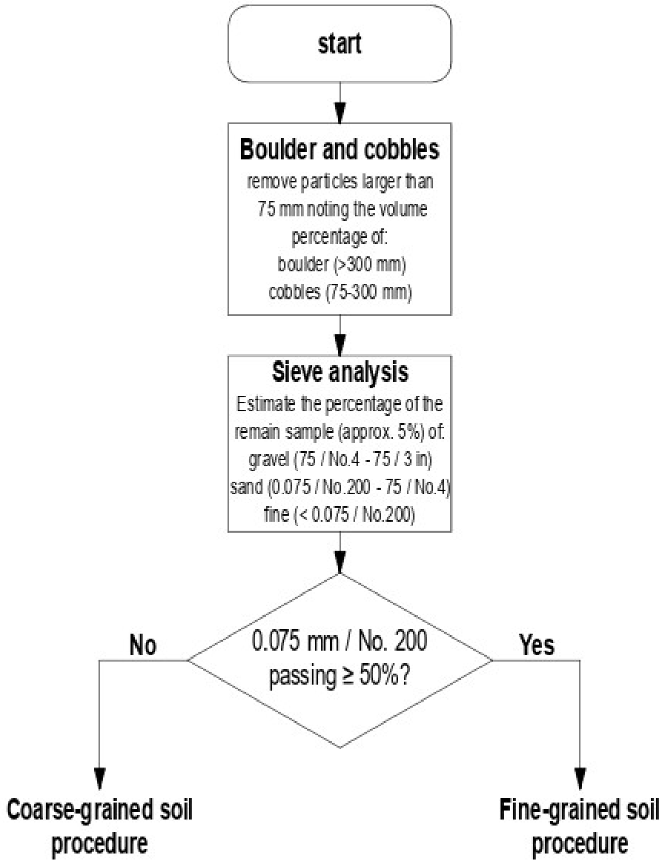


Table 5: ASTM classification procedure

Procedure for fine-grained soil classification

a) Remove particles larger than the No. 40 sieve (medium sand and larger) until a specimen equivalent to about a handful of material is available;

b) Dry strength test

- Mold a 25 mm / 1 in. diameter ball (adding water if necessary);
- From the previous material, make three 12 mm / ½ in diameter balls;
- Dry the samples at temperature not higher than 60°. If natural lumps about 12 mm size are found, use them in place of balls;
- Press the samples with fingers and identify their reaction from the table below.

Dry strength	Criteria
None	The dry specimen crumbles into powder with mere pressure of handling
Low	The dry specimen crumbles into powder with some finger pressure
Medium	The dry specimen breaks into pieces or crumbles with considerable finger pressure
High	The dry specimen cannot be broken with finger pressure. Specimen will break into pieces between thumb and a hard
Very high	The dry specimen cannot be broken between the thumb and a hard surface

c) Dilatancy test

- Mold a 25 mm / 1 in. diameter ball, adding water if necessary. Sample must be soft but not sticky;
- Flat the sample on the palm of one hand with a spatula or a knife;
- Shake horizontally, striking the side of the hand vigorously against the other hand several times. Note the reaction of water appearing on the surface of the soil;
- Squeeze the sample by closing the hand or pinching the soil between the fingers, and note the reaction in accordance with the criteria in the table below. The reaction is the speed with which water appears while shaking, and disappears while squeezing.

Dilatancy	Criteria
None	No visible change in the specimen
Slow	Water appears slowly on the surface of the specimen during shaking and does not disappear or disappears slowly upon squeezing
Rapid	Water appears quickly on the surface of the specimen during shaking and disappears quickly upon squeezing

d) Toughness test

- Use the same sample of the dilatancy test to mold a 3 mm diameter stick;
- Fold the stick several times, continue to roll until it begins to break into smaller parts (condition that occurs at the plasticity index). Note the energy necessary to continue rolling in this condition in accordance to the table below.

Toughness	Criteria
Low	Only slight pressure is required to roll the thread near the plastic limit. The thread and the lump are weak and soft
Medium	Medium pressure is required to roll the thread to near the plastic limit. The thread and the lump have medium stiffness
High	Considerable pressure is required to roll the thread to near the plastic limit. The thread and the lump have very high stiffness

e) Plasticity test

- During the toughness test, note the tendency of the sample to be molded, according to the table below:

Plasticity test	Criteria
Nonplastic	A 1⁄8 in. (3-mm) thread cannot be rolled at any water content
Low	The thread can barely be rolled and the lump cannot be formed when drier than the plastic limit
Medium	The thread is easy to roll and not much time is required to reach the plastic limit. The thread cannot be rerolled after reaching the plastic limit. The lump crumbles when drier than the plastic limit
High	It takes considerable time rolling and kneading to reach the plastic limit. The thread can be rerolled several times after reaching the plastic limit. The lump can be formed without crumbling when drier than the plastic limit

f) Identification of inorganic / organic soils

Organic soils usually have:

- a strong organic odor;
- dark brown to black color, that could become lighter if exposed to the air;
- a spongy consistency during the toughness test;
- not high toughness or plasticity.

g) Group identification

Classifying soil according the table below:

Group	sigla	Dry strength	Dilatancy	Toughness and plasticity
silt	ML	None to low	Slow to rapid	Low or nonplastic
low plasticity or lean clay	CL	Medium to high	None to slow	Medium
high plasticity or elastic silt	MH	Low to medium	None to slow	Low to medium
high plasticity or fat clay	CH	high to very high	None	High
organic silt or clay	OL/OH		Identified as organic soil	

h) If greater precision is required, continue the identification according to the chart below.

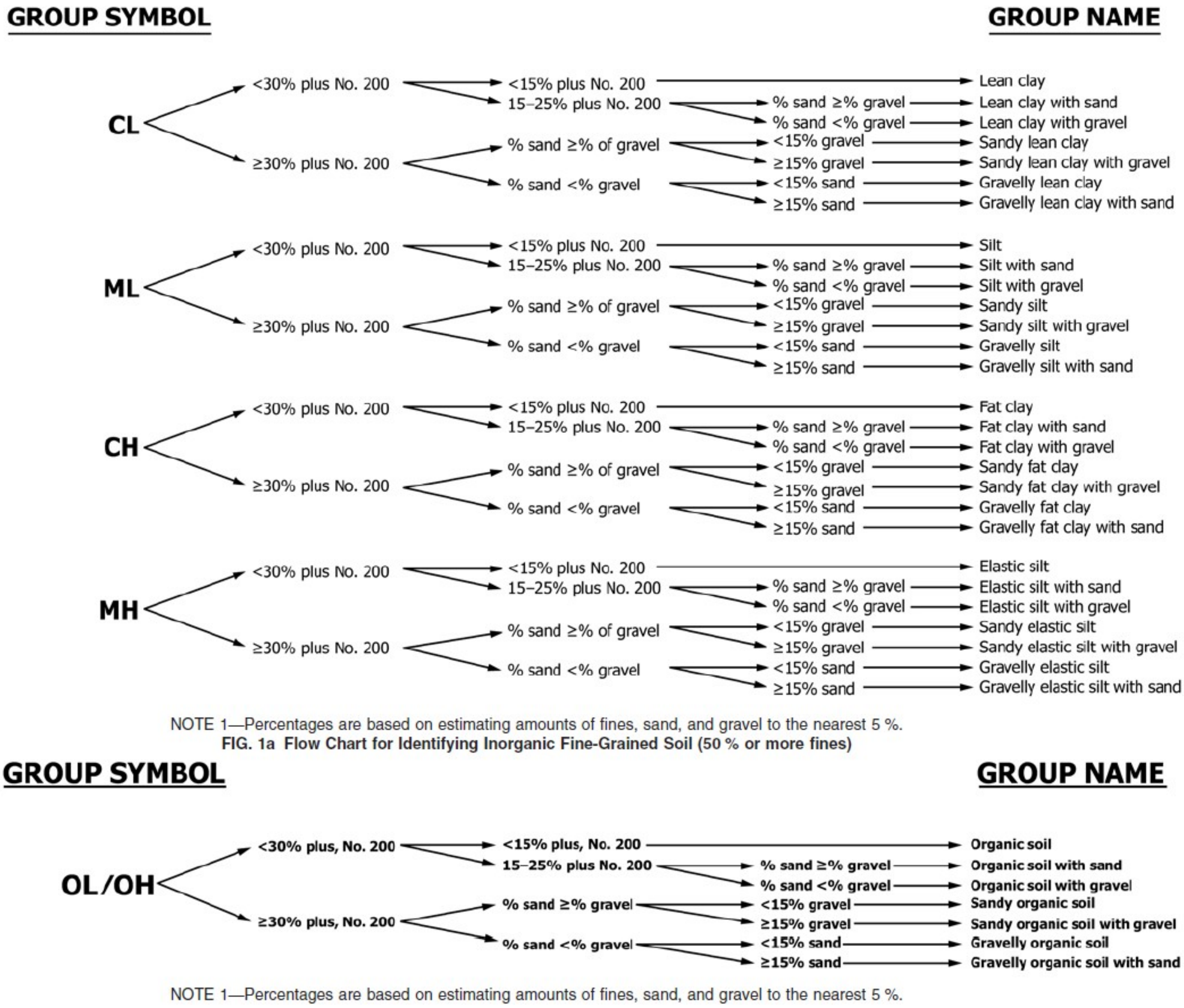


Figure 6: fine-grained soil classification chart

Procedure for coarse-grained soil classification

a) Soil is defined as sand if *sand* percentage is greater than gravel percentage, otherwise it must be defined as *gravel*;

b) If fine-particle percentage is not smaller than 10%, it must be classified according to the fine-soil procedure previously described above;

c) The soil is defined as *well-graded gravel or sand* (GW o SW) if:
- the range between the minimum and the maximum particle size is large;
- and there is a considerable percentage of intermediate particle sizes.

The soil is defined as *poorly-graded gravel or sand* (GP o SP) if:
- one particle size is most relevant above the others;
- altough the particle size range is large, some sizes are obviously missing.

d) the soil identification must be performed according the char below.

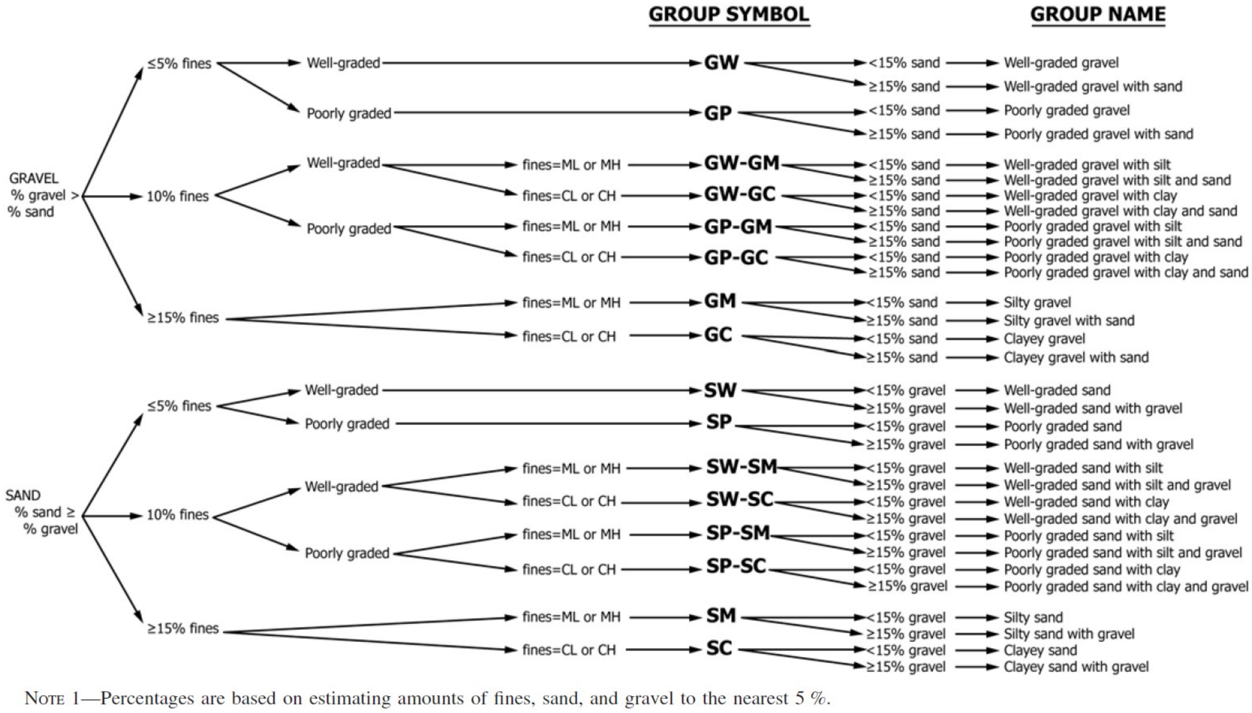


Figure 7: coarse-grained soil classification chart

1.3.5 COMPARISON TABLES BETWEEN CLASSIFICATION SYSTEMS

The purpose of this chapter is to provide conversion tables between different soil classification systems. Although the direct application of the USCS method is recommended, it is common practice (and time-saving) to use simpler methods such as the USDA, and then convert the identified class accordingly.

1.3.5.1 AASHTO – USCS correlation

Soil Group in AASHTO System	Comparable Soil Groups in USCS		
	Most Probable	Possible	Possible but Improbable
A-1-a	GW, GP	SW, SP	GM, SM
A-1-b	SW, SP, GM, SM	GP	—
A-3	SP	—	SW, GP
A-2-4	GM, SM	GC, SC	GW, GP, SW, SP
A-2-5	GM, SM	—	GW, GP, SW, SP
A-2-6	GC, SC	GM, SM	GW, GP, SW, SP
A-2-7	GM, GC, SM, SC	—	GW, GP, SW, SP
A-4	ML, OL	CL, SM, SC	GM, GC
A-5	OH, MH, ML, OL	—	SM, GM
A-6	CL	ML, OL, SC	GC, GM, SM
A-7-5	OH, MH	ML, OL, CH	GM, SM, GC, SC
A-7-6	CH, CL	ML, OL, SC	OH, MH, GC, GM, SM

Table 6: AASHTO to USCS conversion (Das 2009, extract from *USCS and the USDA Soil Classification System* – USACE ERDC 2015)

Soil Group in USCS	Comparable Soil Groups in AASHTO System		
	Most Probable	Possible	Possible but Improbable
GW	A-1-a	—	A-2-4, A-2-5, A-2-6, A-2-7
GP	A-1-a	A-1-b	A-3, A-2-4, A-2-5, A-2-6, A-2-7
GM	A-1-b, A-2-4, A-2-5, A-2-7	A-2-6	A-4, A-5, A-6, A-7-5, A-7-6, A-1-a
GC	A-2-6, A-2-7	A-2-4	A-4, A-6, A-7-6, A-7-5
SW	A-1-b	A-1-a	A-3, A-2-4, A-2-5, A-2-6, A-2-7
SP	A-3, A-1-b	A-1-a	A-2-4, A-2-5, A-2-6, A-2-7
SM	A-1-b, A-2-4, A-2-5, A-2-7	A-2-6, A-4	A-5, A-6, A-7-5, A-7-6, A-1-a
SC	A-2-6, A-2-7	A-2-4, A-6, A-4, A-7-6	A-7-5
ML	A-4, A-5	A-6, A-7-5, A-7-6	—
CL	A-6, A-7-6	A-4	—
OL	A-4, A-5	A-6, A-7-5, A-7-6	—
MH	A-7-5, A-5	—	A-7-6
CH	A-7-6	A-7-5	—
OH	A-7-5, A-5	—	A-7-6
Pt	—	—	—

Table 7: USCS to AASHTO conversion (Das 2009, extract from *USCS and the USDA Soil Classification System* – USACE ERDC 2015)

1.3.5.2 USDA – USCS correlation

USDA Classification	USCS classification						Consensus
	SSURGO (2014) *Table 8* WES (1961) *Table 9* Wilson et al. (1965) *Table 10* Rollings and Rollings (1996) *Table 11* Curtis (2005) *Table 12*		Ayers et al. (2011) *Table 13*		Baylot et al. (2013) *Table 14*	FASST (2004) *Table 15*	
	MP	P	MP	P	MP	MP	
Sand	SM	SP-SM	SW, SP	–	SP	SP	SP
Loamy Sand	SM	CL	SM	SC	SM	SM	SM
Sandy Loam	SM	ML, CL	SM	–	SC	SM	SM
Sandy Clay Loam	CL	SC	SC	–	SC	SC	SC
Sandy Clay	SC, CL	–	SC	CL	SC	SC	SC,
Loam	CL	ML	ML	–	CL	ML	CL
Silt Loam	CL	ML	ML	–	SM	ML	ML
Silt	ML	–	ML	–	ML	ML	ML
Clay Loam	CL	–	CL, MH	–	CL	CL	CL
Silty Clay Loam	CL	ML, CH	MH	–	CL	CL	CL
Clay	CH, CL	GC	CH	CL	CH	CH	CH
Silty Clay	CH, CL	–	CL, MH	–	CL	CH	CH

MP: most probable attribution P: probable attribution

Table 8: USDA to USCS conversion (extract from *USCS and the USDA Soil Classification System* – USACE ERDC 2015)

1.4 EVALUATION OF MAIN GEOTECHNICAL PARAMETRES

1.4.1 INTRODUCTION

As mentioned many times previously, there are basically two approaches for the rapid estimation of geotechnical parameters:

- test-less approach: this involves correlating the USCS soil class with the most probable values available in technical literature;
- test-based method, this roughly estimates the soil parametres trough site tests.

The undrained shear strength c_u and the degree of compaction cannot be evaluated without tests, due to their correlation with the local settlement process.

1.4.1.1 Testless approach

Once the USCS class is determined (or estimated), the tables below can be used to find the most probable corresponding parameter values.

Unit weight

Soil type	USCS class	Unit weight [kN/m³] Loose wet	Loose saturated	Dense wet	Dense saturated	Reference
Gravel	GP – GW	16.0	20.0	18.0	21.0	[2 cited by 1]
Well graded sand with gravel	SW	19.0	21.5	21.0	23.0	[2 cited by 1]
Coarse and medium sand	SP	16.5	20.0	18.5	21.5	[2 cited by 1]
Well-graded sand	SW	18.0	20.5	21.0	22.5	[2 cited by 1]
Fine or silty sand	SP – SM	17.0	20.0	19.0	21.5	[2 cited by 1]
Silt	ML	12,0	12,5	17,5	21,0	[4]
Elastic silt	MH	12,0	12,0	17,5	21,0	[4]
Very soft clay	CL – CH	14.0		18.0		[3 cited by 1]
Soft clay	CL – CH	15.0		19.0		[3 cited by 1]
Firm clay	CL – CH	16.5		20.5		[3 cited by 1]
Stiff clay	CL – CH	18.0		22.0		[3 cited by 1]
Hard clay	CL – CH	21.0		24.0		[3 cited by 1]
Organic silt	OM	14.0		21.0		[6]
Organic clay	OC	13.0		20.0		[6]
Peat	Pt	3,0	12,0	9,0	15,0	[1], [5]

References:
1. https://www.abg-geosynthetics.com/soil-properties-unit-weight.html
2. British Standards Institution, BS 8002:1994 - *Code of Practice for Earth Retaining Structures;*
3. British Standards Institution, BS 8002:2015 - *Code of Practice for Earth Retaining Structures;*
4. Coduto, 2001 cited by Elvesier Science, *Geotechnolohy Compendium*, 2000;
5. Eurocode 1991-1-1 *Actions on structures - Part 1-1: Densities, self-weight, imposed loads for buildings*, 2004;
6. NAVFAC DM 7.1 cited by http://www.geotechnicalinfo.com/soil_unit_weight.html

Angle of friction

Description	USCS class	Soil friction angle [°]			Reference
		min	max	specific value	
Well graded gravel, sandy gravel, with little or no fines	GW	33	40	-	[1],[2]
Poorly graded gravel, sandy gravel, with little or no fines	GP	32	44	-	[1]
Sandy gravels - Loose	(GW, GP)	-	-	35	[3 cited in 6]
Sandy gravels - Dense	(GW, GP)	-	-	50	[3 cited in 6]
Silty gravels, silty sandy gravels	GM	30	40	-	[1]
Clayey gravels, clayey sandy gravels	GC	28	35	-	[1]
Well graded sands, gravelly sands, with little or no fines	SW	33	43	-	[1]
Well-graded clean sand, gravelly sands - Compacted	SW	-	-	38	[3 cited in 6]
Well-graded sand, angular grains - Loose	(SW)	-	-	33	[3 cited in 6]
Well-graded sand, angular grains - Dense	(SW)	-	-	45	[3 cited in 6]
Poorly graded sands, gravelly sands, with little or no fines	SP	30	39	-	[1], [2]
Poorly-garded clean sand - Compacted	SP	-	-	37	[3 cited in 6]
Uniform sand, round grains - Loose	(SP)	-	-	27	[3 cited in 6]
Uniform sand, round grains - Dense	(SP)	-	-	34	[3 cited in 6]
Sand	SW, SP	37	38	-	[7]
Loose sand	(SW, SP)	29	30	-	[5 cited in 6]
Medium sand	(SW, SP)	30	36	-	[5 cited in 6]
Dense sand	(SW, SP)	36	41	-	[5 cited in 6]
Silty sands	SM	32	35	-	[1]
Silty clays, sand-silt mix - Compacted	SM	-	-	34	[3 cited in 6]
Silty sand - Loose	SM	27	33	-	[3 cited in 6]
Silty sand - Dense	SM	30	34	-	[3 cited in 6]
Clayey sands	SC	30	40	-	[1]
Calyey sands, sandy-clay mix - compacted	SC	-	-	31	[3 cited in 6]
Loamy sand, sandy clay Loam	SM, SC	31	34	-	[7]
Inorganic silts, silty or clayey fine sands, with slight plasticity	ML	27	41	-	[1]
Inorganic silt - Loose	ML	27	30	-	[3 cited in 6]
Inorganic silt - Dense	ML	30	35	-	[3 cited in 6]
Inorganic clays, silty clays, sandy clays of low plasticity	CL	27	35	-	[1]
Clays of low plasticity - compacted	CL	-	-	28	[3 cited in 6]
Organic silts and organic silty clays of low plasticity	OL	22	32	-	[1]
Inorganic silts of high plasticity	MH	23	33	-	[1]
Clayey silts - compacted	MH	-	-	25	[3 cited in 6]

Description	**USCS class**	**Soil friction angle [°]**			**Reference**
		min	**max**	**specific value**	
Silts and clayey silts - compacted	ML	-	-	32	[3 cited in 6]
Inorganic clays of high plasticity	CH	17	31	-	[1]
Clays of high plasticity - compacted	CH	-	-	19	[3 cited in 6]
Organic clays of high plasticity	OH	17	35	-	[1]
Loam	ML, OL, MH, OH	28	32	-	[7]
Silt Loam	ML, OL, MH, OH	25	32	-	[7]
Clay Loam, Silty Clay Loam	ML, OL, CL, MH, OH, CH	18	32	-	[7]
Silty clay	OL, CL, OH, CH	18	32	-	[7]
Clay	CL, CH, OH, OL	18	28	-	[7]
Peat and other highly organic soils	Pt	0	10	-	[2]

References:
data are extracted from http://geotechdata.info/parameter/angle-of-friction.

1. Swiss Standard SN 670 010b, *Characteristic Coefficients of soils, Association of Swiss Road and Traffic Engineers;*
2. Jon W. Koloski, Sigmund D. Schwarz, and Donald W. Tubbs, *Geotechnical Properties of Geologic Materials, Engineering Geology in Washington*, Volume 1, Washington Division of Geology and Earth Resources Bulletin 78, 1989, Link;
3. Carter, M. and Bentley, S. (1991). *Correlations of soil properties*. Penetech Press Publishers, London;
4. Meyerhof, G. (1956). P*enetration tests and bearing capacity of cohesionless soils*. J Soils Mechanics and Foundation Division ASCE, 82(SM1);
5. Peck, R., Hanson,W., and Thornburn, T. (1974). *Foundation Engineering Handbook*. Wiley, London;
6. Obrzud R. & Truty, A. *The Hardening soil model – a pratical guidebook* Z Soil.PC 100701 report, revised 31.01.2012;
7. Minnesota Department of Transportation, *Pavement Design*, 2007

Cohesion (drained conditions)

Description	USCS class	Cohesion [kPa]			Reference
		min	max	specific value	
Well graded gravel, sandy gravel, with little or no fines	GW	-	-	0	[1],[2],[3],
Poorly graded gravel, sandy gravel, with little or no fines	GP	-	-	0	[1],[2],[3]
Silty gravels, silty sandy gravels	GM	-	-	0	[1]
Clayey gravels, clayey sandy gravels	GC	-	-	20	[1]
Well graded sands, gravelly sands, with little or no fines	SW	-	-	0	[1],[2],[3]
Poorly graded sands, gravelly sands, with little or no fines	SP	-	-	0	[1],[2],[3]
Silty sands	SM	-	-	22	[1]
Silty sands - Saturated compacted	SM	-	-	50	[3]
Silty sands - Compacted	SM	-	-	20	[3]
Clayey sands	SC	-	-	5	[1]
Clayey sands - Compacted	SC	-	-	74	[3]
Clayey sands -Saturated compacted	SC	-	-	11	[3]
Loamy sand, sandy clay Loam - compacted	SM, SC	50	75	-	[2]
Loamy sand, sandy clay Loam - saturated	SM, SC	10	20	-	[2]
Sand silt clay with slightly plastic fines - compacted	SM, SC	-	-	50	[3]
Sand silt clay with slightly plastic fines - saturated compacted	SM, SC	-	-	14	[3]
Inorganic silts, silty or clayey fine sands, with slight plasticity	ML	-	-	7	[1]
Inorganic silts and clayey silts - compacted	ML	-	-	67	[3]
Inorganic silts and clayey silts - saturated compacted	ML	-	-	9	[3]
Inorganic clays, silty clays, sandy clays of low plasticity	CL	-	-	4	[1]
Inorganic clays, silty clays, sandy clays of low plasticity - compacted	CL	-	-	86	[3]
Inorganic clays, silty clays, sandy clays of low plasticity - saturated compacted	CL	-	-	13	[3]
Mixture if inorganic silt and clay - compacted	ML-CL	-	-	65	[3]
Mixture if inorganic silt and clay - saturated compacted	ML-CL	-	-	22	[3]
Organic silts and organic silty clays of low plasticity	OL	-	-	5	[1]
Inorganic silts of high plasticity - compactd	MH	-	-	10	[1]
Inorganic silts of high plasticity - saturated compacted	MH	-	-	72	[3]
Inorganic silts of high plasticity	MH	-	-	20	[3]
Inorganic clays of high plasticity	CH	-	-	25	[1]
Inorganic clays of high plasticity - compacted	CH	-	-	103	[3]
Inorganic clays of high plasticity - satrated compacted	CH	-	-	11	[3]
Organic clays of high plasticity	OH	-	-	10	[1]
Loam - Compacted	ML, OL, MH, OH	60	90	-	[2]

Description	USCS class	Cohesion [kPa]			Reference
		min	max	specific value	
Loam - Saturated	ML, OL, MH, OH	10	20	-	[2]
Silt Loam - Compacted	ML, OL, MH, OH	60	90	-	[2]
Silt Loam - Saturated	ML, OL, MH, OH	10	20	-	[2]
Clay Loam, Silty Clay Loam - Compaced	ML, OL, CL, MH, OH, CH	60	105	-	[2]
Clay Loam, Silty Clay Loam - Saturated	ML, OL, CL, MH, OH, CH	10	20	-	[2]
Silty clay, clay - compacted	OL, CL, OH, CH	90	105	-	[2]
Silty clay, clay - saturated	OL, CL, OH, CH	10	20	-	[2]
Peat and other highly organic soils	Pt	-	-	-	-

Note: KPa = 100 DaN/mq = 0.01 DaN/cmq
References:
data are extracted from http://geotechdata.info/parameter/cohesion

1. Swiss Standard SN 670 010b, *Characteristic Coefficients of soils, Association of Swiss Road and Traffic Engineers;*
2. Minnesota Department of Transportation, *Pavement Design*, 2007;
3. NAVFAC Design Manual 7.2 - *Foundations and Earth Structures*,SN 0525-LP-300-7071, revalited by change 1 September 1986

Permeability

Description	USCS	min (m/s)	max (m/s)	Specific value (m/s)	Reference
Well graded gravel, sandy gravel, with little or no fines	GW	5.00E-04	5.00E-02	-	[1]
Poorly graded gravel, sandy gravel, with little or no fines	GP	5.00E-04	5.00E-02	-	[1]
Silty gravels, silty sandy gravels	GM	5.00E-08	5.00E-06	-	[1]
Alluvial sand and gravel	(GM)	4.00E-04	4.00E-03	-	[2 & 3 in 4]
Clayey gravels, clayey sandy gravels	GC	5.00E-09	5.00E-06	-	[1]
Well graded sands, gravelly sands, with little or no fines	SW	1.00E-08	1.00E-06	-	[1]
Very fine sand, very well sorted	(SW)	-	-	8.40E-05	[5]
Medium sand, very well sorted	(SW)	-	-	2.23E-03	[5]
Coarse sand, very well sorted	(SW)	-	-	3.69E-01	[5]
Poorly graded sands, gravelly sands, with little or no fines	SP	2.55E-05	5.35E-04	-	[1], [2 & 3 in 4]
Clean sands (good aquifers)	(SP-SW)	1.00E-05	1.00E-02	-	[5]
Uniform sand and gravel	(SP-GP)	4.00E-03	4.00E-01	-	[2 & 3 in 4]
Well graded sand and gravel without fines	(GW-SW)	4.00E-05	4.00E-03	-	[2 & 3 in 4]
Silty sands	SM	1.00E-08	5.00E-06	-	[1]
Clayey sands	SC	5.50E-09	5.50E-06	-	[1], [5]
Inorganic silts, silty or clayey fine sands, with slight plasticity	ML	5.00E-09	1.00E-06	-	[1]
Inorganic clays, silty clays, sandy clays of low plasticity	CL	5.00E-10	5.00E-08	-	[1]
Organic silts and organic silty clays of low plasticity	OL	5.00E-09	1.00E-07	-	[1]
Inorganic silts of high plasticity	MH	1.00E-10	5.00E-08	-	[1]
Inorganic clays of high plasticity	CH	1.00E-10	1.00E-07	-	[1]
Compacted silt	(ML-MH)	7.00E-10	7.00E-08	-	[2 & 3 in 4]
Compacted clay	(CL-CH)	-	1.00E-09	-	[2 & 3 in 4]
Organic clays of high plasticity	OH	5.00E-10	1.00E-07	-	[1]

References:
data are extracted from http://geotechdata.info/parameter/permeability

1. Swiss Standard SN 670 010b, Characteristic Coefficients of soils, Association of Swiss Road and Traffic Engineers;
2. Carter, M. and Bentley, S. (1991). Correlations of soil properties. Penetech Press Publishers, London;
3. Leonards G. A. Ed. 1962, Foundation ENgineering. McGraw Hill Book Company;
4. Dysli M. and Steiner W., 2011, Correlations in soil mechanics, PPUR;
5. West, T.R., 1995. Geology applied to engineering. Prentice Hall, 560 pp.

1.4.1.2 Test-based approach

Introduction

The procedure consists of two different tests:

1. a penetration test, which differs for coarse-grained soils and mixed/fine-grained soils. For coarse-grained soils, the friction angle is estimated through a preliminary evaluation of relative density. For mixed/fine-grained soils, cohesion is estimated through a preliminary evaluation of the degree of compaction;
2. An infiltration test, which involves measuring the percolation rate, is conducted to determine the soil's permeability.

Penetration test

Coarse-grained soils

Perform the test with a 2.5 Kg hand hammer, a 12 mm (½ in) diameter rod and a 50 mm (2 in) square wooden peg.

The table below is conceived for sands. In the case of gravel, add 4° to the friction angle values.

Density	**Visual assessment**[3]	**D_R [%] (Meyerhof)**[4]	**Friction angle φ (Meyerhof, 1974)**
Very loose	A 12 mm (½ in) diameter rod can be pushed easily by hand into soil.	< 20	< 30°
Loose	Soil can be excavated with a spade. A 50 mm (2-in), square, wooden peg can easily be driven to a depth of 150 mm (6 in).	20 - 40	30° - 35°
Medium dense	Soil is easily penetrated with a ½-in rod driven with a 5-lb hammer.	40 - 60	35° - 38°
Dense	Soil requires a pick for excavation. A 50 mm (2-in), square, wooden peg is hard to drive to a depth of 150 mm (6 in).	60 - 80	38° - 41°
Very dense	Soil is penetrated only a few cm with a ½-in rod driven with a 5-lb hammer.	> 80	41° - 44°

Note: relative density is the ratio : $D_R = (e_{max} – e) / (e_{max} – e_{min})$ where e is the void ratio: $e = V_v / V_s$.

3 *Soil Properties and Special Geotechnical Problems Related to Stream Stabilization Projects,* Technical Supplement 14A Part 654 National Engineering Handbook (2007)

4 *Bearing capacity of soil*, Engineer Manual 1110-1-1905 Department of the Army U.S. Army Corps of Engineers (1992).

Fine-graded soils or mixed soils

The test can be easily performed with just by hand.

Saturated consistency	Visual assessment[5]	Estimated undrained shear strength c_u	Drained cohesion c’
Very soft	Thumb will penetrate greater than 25 mm (1 in). Soil is extruded between fingers	0 – 12 kPa	-
Soft	Thumb will penetrate about 25 mm (1 in). Soil molded by light finger pressure.	12 – 24 kPa	-
Medium	Thumb will penetrate about 6 mm (¼ in). Soil molded by strong finger pressure.	24 – 48 kPa	-
Stiff	Indented with thumb.	48 – 96 kPa	2.4 – 4.8 kPa
Very stiff	Indented by thumb nail.	96 – 192 kPa	4.8 kPa
Hard	Not indented by thumb nail.	> 192 kPa	4.8 kPa

Note: KPa = 100 DaN/mq = 0.01 DaN/cmq

The friction angle is related to the plasticity index, which cannot be easily estimated through visual field tests. As a precaution, $\Phi = 22°$ can be assumed.

Infiltration test

An infiltration test can be easily performed in the field using rudimentary means. As will be shown later, the test requires complete saturation of the ground, which can take a considerable amount of time in fine-grained soils.

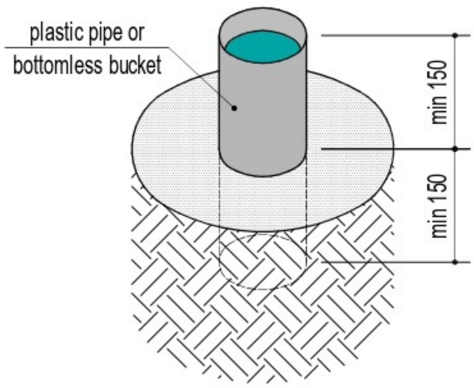


Figure 8: infiltration test

- Drive a plastic cylindrical surface into the soil to a minimum depth of 150 mm, leaving at least 150 mm above the surface. A 100 mm diameter pipe or a bottomless bucket can be adequately used for this purpose.

  It is recommended to avoid using unlined holes in the ground, as infiltration through vertical walls can significantly affect the results by overestimating the permeability.
- Ensure complete saturation of the soil at the bottom of the pipe by filling it with water and waiting for the water to fully infiltrate;

5 *Soil Properties and Special Geotechnical Problems Related to Stream Stabilization Projects,* Technical Supplement 14A Part 654 National Engineering Handbook (2007)

- Once the soil has been saturated, the test can begin. Pour a measured quantity of water into the pipe and measure the thickness of the water layer above the soil surface. Record the water level drop at regular intervals of time. If the soil has been adequately saturated, the infiltration rate should remain approximately constant during the test;
- The permeability can be determined by calculating the ratio between the initial water depth and the time necessary for its complete percolation.

1.5 APPENDIX 1:SIEVE ANALYSIS

1.5.1.1 Procedure

The suggested minimum set of sieve sizes is: 4.75 mm (No. 4), 2.00 mm (No. 10), 0.425 mm (No. 40), and 0.075 mm (No. 200).
Ensure the sample is completely dry. Carefully break down any clayey lumps before starting the test.

- Record the total weight of the sample;
- Arrange the sieves in a stack, with the largest mesh size on top and the smallest mesh size (pan) at the bottom;
- Shake the sieve stack thoroughly;
- Record the weight of the material retained on each sieve and, consequently, the passing percentage;
- Plot the data on a graph, with the vertical axis representing the percentage passing and the horizontal axis (preferably on a logarithmic scale) representing the sieve size.

1.5.1.2 Data elaborating

From the graph, the sizes corresponding to any passing percentage can be easily calculated by interpolation.
It is standard practice to use the following expression:

D_x in millimetres where *x* is the passing percentage.

Usual parameters include D_{60} and D_{10}, where the latter is defined as *Effective Size* (ES).

The Sort Coefficient (SC) or Uniform Coefficient is defined as the ratio:

$$SC = D_{60} / D_{10}$$

A higher SC indicates a wider range of particle sizes, suggesting a more poorly graded (well-graded) soil, while a lower SC indicates a narrower range of particle sizes, suggesting a more uniformly graded (poorly graded) soil.
Another relevant parameter is the Coefficient of Curvature C_c which provides information about the distribution uniformity between the smallest and the largest particle sizes in the soil. It is defined as:

$$C_c = D_{30}^2 / (D_{10}\, D_{60}).$$

The USCS defines soil as well-graded when:

$$SC > 4 \text{ for gravel or } SC > 6 \text{ for sand,}$$
$$\text{and } 1 < C_c < 3.$$

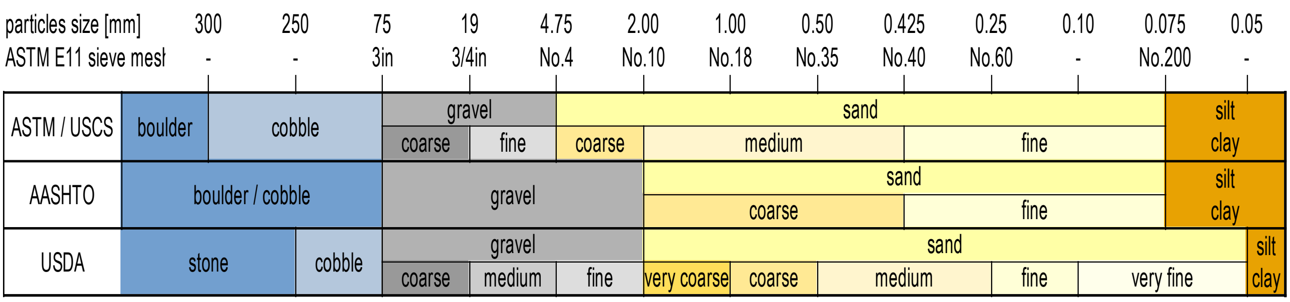


Figure 9: comparison between different soil classification systems

Mesh size	ASTM E11 Mesh	ISO 3310 Size	UNI 2331/2332 Mesh	TYLER Mesh	BS-410 Mesh	DIN-4188 mm
125.0mm	5in	125.0mm				125.0mm
112.0mm		112.0mm	-	-	-	112.0mm
106.0mm	4.24in	106.0mm	-	-	-	106.0mm
100.0mm	4in	100.0mm	-	-	-	100.0mm
90.0mm	3 1/2in	90.0mm	-	-	-	90.0mm
80.0mm		80.0mm	-	-	-	80.0mm
75.0mm	3in	75.0mm	-	-	-	75.0mm
71.0mm		71.0mm	-	-	-	71.0mm
63.0mm	2 1/2in	63.0mm	-	-	-	63.0mm
56.0mm	-	56.0mm	-	-	-	56.0mm
53.0mm	2.12in	53.0mm	-	-	-	53.0mm
50.0mm	2in	50.0mm	-	-	-	50.0mm
45.0mm	1 3/4in	45.0mm	-	-	-	45.0mm
40.0mm	-	40.0mm	-	-	-	40.0mm
37.5mm	1 1/2in	37.5mm	-	-	-	37.5mm
35.5mm	-	35.5mm	-	-	-	35.5mm
31.5mm	1 1/4in	31.5mm	-	-	-	31.5mm
28.0mm	-	28.0mm	-	-	-	28.0mm
26.5mm	1.06in	26.5mm	-	-	-	26.5mm
25.0mm	1in	25.0mm	-	-	-	25.0mm
22.4mm	7/8in	22.4mm	-	-	-	22.4mm
20.0mm	-	20.0mm	-	-	-	20.0mm
19.0mm	3/4in	19.0mm	-	-	-	19.0mm
18.0mm	-	18.0mm	-	-	-	18.0mm
16.0mm	5/8in	16.0mm	-	-	-	16.0mm
14.0mm	-	14.0mm	-	-	-	14.0mm
13.2mm	0.530in	13.2mm	-	-	-	13.2mm
12.5mm	1/2in	12.5mm	-	-	-	12.5mm
11.2mm	7/16in	11.2mm	-	-	-	11.2mm
10.0mm	-	10.0mm	-	-	-	10.0mm
9.5mm	3/8in	9.5mm	-	-	-	9.5mm
9.0mm	-	9.0mm	-	-	-	9.0mm
8.0mm	5/16in	8.0mm	-	-	-	8.0mm
7.1mm	-	7.1mm	-	-	-	7.1mm
6.7mm	0.265in	6.7mm	-	-	-	6.7mm
6.3mm	1/4in	6.3mm	-	-	-	6.3mm
5.6mm	No.3 1/2	5.6mm	-	No.3	No.3	5.6mm
5.0mm	-	5.0mm	-	-	-	5.0mm
4.75mm	No.4	4.75mm	-	No.4	No.3.5	4.75mm
4.50mm	-	4.50mm	-	-	-	4.50mm
4.00mm	No.5	4.00mm	No.1	No.5	No.4	4.00mm
3.55mm	-	3.55mm	-	-	-	3.55mm
3.35mm	No.6	3.35mm	No.2	No.6	No.5	3.35mm
3.15mm	1/8in*	3.15mm	No.3	-	-	3.15mm
2.80mm	No.7	2.80mm	No.4	No.7	No.6	2.80mm
2.50mm	-	2.50mm	No.5	-	-	2.50mm
2.36mm	No.8	2.36mm	No.6	No.8	No.7	2.36mm
2.24mm	-	2.24mm	-	-	-	2.24mm
2.00mm	No.10	2.00mm	No.7	No.9	No.8	2.00mm
1.80mm	-	1.80mm	-	-	-	1.80mm
1.70mm	No.12	1.70mm	No.8	No.10	No.10	1.70mm
1.60mm	-	1.60mm	No.9	-	-	1.60mm
1.40mm	No.14	1.40mm	No.10	No.12	No.12	1.40mm
1.25mm	-	1.25mm	No.11	-	-	1.25mm
1.18mm	No.16	1.18mm	No.12	No.14	No.14	1.18mm
1.12mm	-	1.12mm	-	-	-	1.12mm
1.00mm	No.18	1.00mm	No.13	No.16	No.16	1.00mm

Table 9: standard sieve sizes (mesh size ≥ 1 mm)

Mesh size	ASTM E11 Mesh	ISO 3310 Size	UNI 2331/2332 Mesh	TYLER Mesh	BS-410 Mesh	DIN-4188 mm
900µm	-	900µm	-	-	-	900µm
850µm	No.20	850µm	No.14	No.20	No.18	850µm
800µm	-	800µm	No.15	-	-	800µm
750µm	-	750µm	No.16	-	-	750µm
710µm	No.25	710µm	No.17	No.24	No.22	710µm
630µm	-	630µm	No.18	-	-	630µm
600µm	No.30	600µm	No.19	No.28	No.25	600µm
560µm	-	560µm	-	-	-	560µm
500µm	No.35	500µm	No.20	No.32	No.30	500µm
450µm	-	450µm	-	-	-	450µm
425µm	No.40	425µm	No.21	No.35	No.36	425µm
400µm	-	400µm	No.22	-	-	400µm
355µm	No.45	355µm	No.23	No.42	No.44	355µm
315µm	-	315µm	No.24	-	-	315µm
300µm	No.50	300µm	No.25	No.48	No.52	300µm
280µm	-	280µm	-	-	-	280µm
250µm	No.60	250µm	No.26	No.60	No.60	250µm
224µm	-	224µm	-	-	-	224µm
212µm	No.70	212µm	No.27	No.65	No.72	212µm
200µm	-	200µm	No.28	-	-	200µm
180µm	No.80	180µm	No.29	No.80	No.85	180µm
160µm	-	160µm	No.30	-	-	160µm
150µm	No.100	150µm	No.31	No.100	No.100	150µm
140µm	-	140µm	-	-	-	140µm
125µm	No.120	125µm	No.32	No.115	No.120	125µm
112µm	-	112µm	-	-	-	112µm
106µm	No.140	106µm	No.33	No.150	No.150	106µm
100µm	-	100µm	No.34	-	-	100µm
90µm	No.170	90µm	No.35	No.170	No.170	90µm
80µm	-	80µm	No.36	-	-	80µm
75µm	No.200	75µm	No.37	No.200	No.200	75µm
71µm	-	71µm	-	-	-	71µm
63µm	No.230	63µm	No.38	No.250	No.240	63µm
56µm	-	56µm	-	-	-	56µm
53µm	No.270	53µm	-	No.270	No.300	53µm
50µm	-	50µm	No.39	-	-	50µm
45µm	No.325	45µm	-	No.325	No.350	45µm
40µm	-	40µm	No.40	-	-	40µm
38µm	No.400	38µm	-	No.400	No.400	38µm
36µm	-	36µm	-	-	-	36µm
32µm	No.450	32µm	-	-	No.440	32µm
28µm	-	-	-	-	-	28µm
25µm	No.500	25µm	-	No.500	No.500	25µm
22µm	-	-	-	-	-	22µm
20µm	No.635	20µm	-	No.625	No.625	20µm
15µm	-	-	-	No.800	No.800	15µm
10µm	-	10µm	-	No.1250	No.1250	10µm
5µm	-	5µm	-	No.2500	No.2500	5µm

Table 10: standard sieve sizes (mesh size < 1 mm)

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