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NOVEL METHODOLOGY FOR DETERMINING THE MECHANICAL CHARACTERISTICS OF COARSE-GRAINED SOILS

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Abstract

Coarse-grained soils are a type of soil frequently found in civil engineering projects, and their mechanical characterization still presents a real challenge. They are composed by elements of different dimensions (from a few microns to tens of centimeters), and can be of very varied nature (clay, sand, gravel, pebbles, etc.). The mechanical characterization of coarse-grained soils is very difficult because of the presence of large elements. In order to be able to characterize them in the laboratory by means of conventional size devices, it is very important to study the influence of significant parameters on the mechanical behavior of coarse-grained soils (the volume fraction, particle size distribution and spread, consolidation level and initial state of the matrix), using the large-sized triaxial testing device. In this paper, we will propose a methodology for evaluating the mechanical characteristics of coarse-grained soils based on soil granulometric reconstruction procedures. The method we have named GALA is based on the use of polynomial correlations between the strength increase due to inclusions and the volume fraction f_v and the particle spread (d_{min}/d_{max}) of inclusions. We were able to apply this new method to a natural soil. The results showed the relevance of our method.

Keywords:

Coarse-grained soil;
Matrix;
Inclusions;
Mechanical characterization;
Granulometric reconstitution.

1 Introduction

The great difficulty in the study of coarse-grained soils results from the presence of elements of large size, which do not permit to test a representative volume of material in the classic test devices [1]. This is why granulometric reconstitution methods are used, which are: capping and substitution [2].

The capping method consists of removing the large elements and testing this capped soil, Fig. 1, [2, 3]. This reduces both the volume fraction of inclusions f_v and the particle size distribution (d_{min}/d_{max}). Indeed, the decrease in the volume fraction f_v of the inclusions decreases the shear strength of the coarse-grained soil. On the other hand, the shear strength is higher for a tight granulometric spread. Thus, the rate of decrease in strength as a function of f_v is more significant than the rate of increase when moving from a large to a tight granulometric spread. Therefore, using this method leads to an underestimation of the mechanical characteristics of the coarse-grained soil [2].

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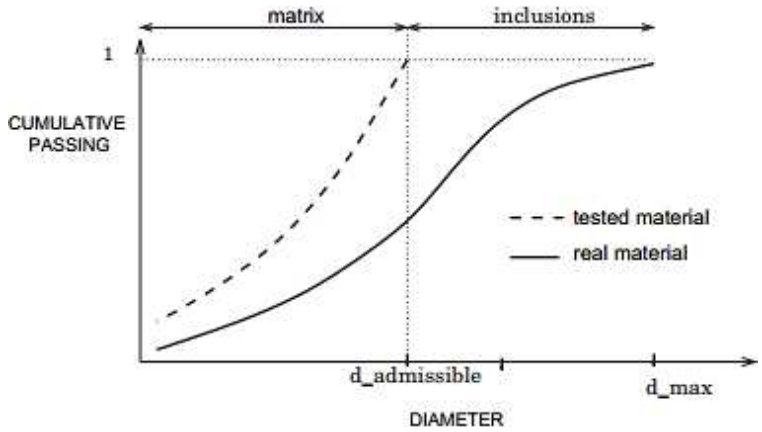

Fig. 1: Schematic diagram of the capping method [2].

The second method, called substitution, consists in replacing the inclusions with elements of smaller size, Fig. 2, [3]. In this case, we keep the same volume fraction f_v of the inclusions, but we decrease their size d_{max} and their granulometric spread, d_{min}/d_{max}. In addition, since it has been observed that the shear strength increases with the decrease of the granulometric spread of the inclusions, then this method tends to overestimate the mechanical characteristics of the coarse-grained soil [3, 4].

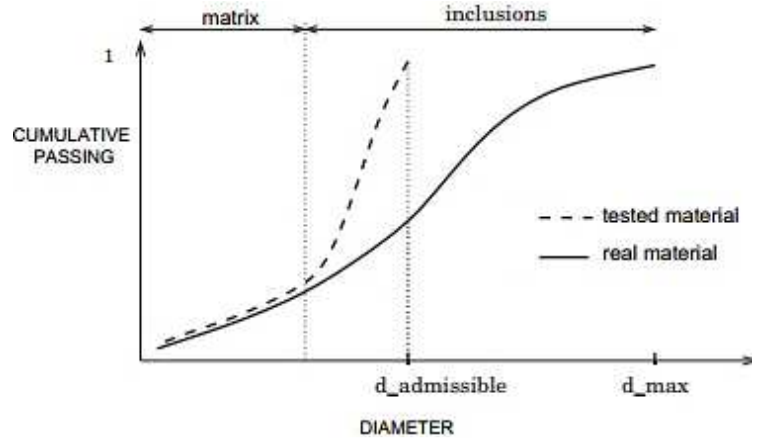

Fig. 2: Schematic diagram of the substitution method [2].

Consequently, none of the two methods is suitable for evaluating the characteristics of real coarse-grained soil. With the capping method, we are on the safe side; however, this is not the case with the substitution method. That is why we tried to develop a new procedure for the characterization of coarse-grained soils in the laboratory.

2 The GALA method

The study of a reference coarse-grained soil allows an understanding of the importance of inclusions f_v, their size d_{max}, and their granulometric spread d_{min}/d_{max}, on the mechanical behavior of this type of soil [4].

Now, we can develop a method to determine the mechanical characteristics of coarse-grained soils in the laboratory, using the large-sized triaxial testing device on a capped material.

This new method will take into account:

- The effect of the size d_{max} of the inclusions at the same granulometric spread d_{min}/d_{max}
- The effect of the granulometric spread d_{min}/d_{max},
- The effect of the volume fraction of inclusions f_v.

2.1 The Influence of the size d_{max} of the inclusions

The first analysis focused on the influence of the maximum diameter d_{max} of the inclusions. Fig. 3 shows the variation of the increase in shear strength of coarse-grained soils ($\Delta\ (q_{max}/q_{mat,max})$) as a

function of d_{max} of inclusions. With q_{max} is the shear strength of the complete soil, and $q_{mat,max}$ is the shear strength of the matrix.

Δ ($q_{max}/q_{mat,max}$): increase in shear strength of the complete soil compared to the matrix alone. Fig. 3 shows that the maximum inclusion size d_{max} has no significant influence on the shear strength, which was also stated by other authors, e. g. [4-7].

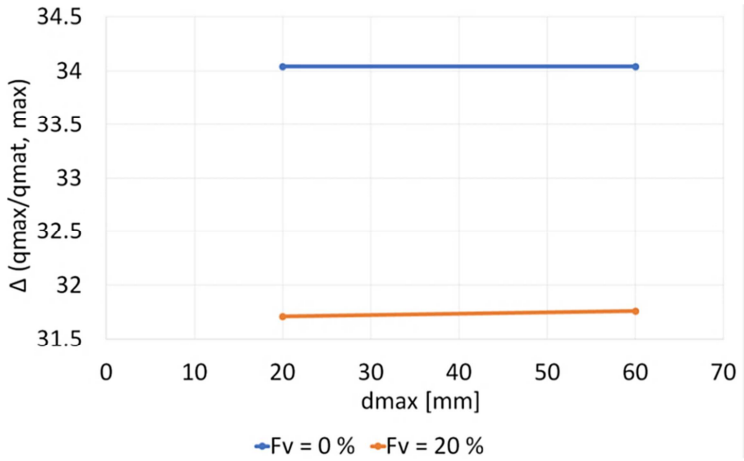

Fig. 3: Shear strength increase as a function of maximum inclusion size d_{max} for constant d_{min}/d_{max} spread.

2.2 The influence of the granulometric spread of the inclusions d_{min}/d_{max}

In Fig. 4, it can be seen that the increase in shear strength increases with the increase in granulometric spread d_{min}/d_{max} [8, 9] (an increase of about 20 % for d_{min}/d_{max} = 0.80).

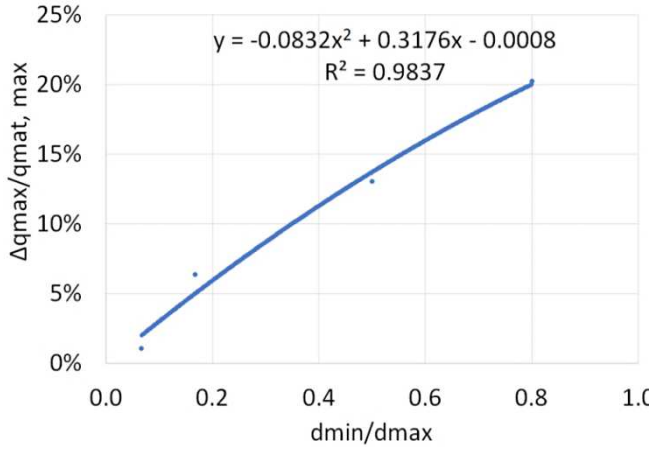

Fig. 4: Increase in shear strength as a function of granulometric dispersion d_{min}/d_{max}.

We also observe a polynomial correlation between the increase in shear strength and the granulometric spread d_{min}/d_{max}, of the form:

$$\frac{\Delta q_{max}}{q_{mat,max}} = a \times \left(\frac{d_{min}}{d_{max}}\right)^2 + b \times \left(\frac{d_{min}}{d_{max}}\right). \quad (1)$$

2.3 The influence of the volume fraction of the inclusions f_v

We can see from Fig. 5 that the increase in shear strength increases as the volume fraction of inclusions increases [11-12] (an increase of about 40 % for the soil containing sand and 35 % of 8/10 mm gravel).

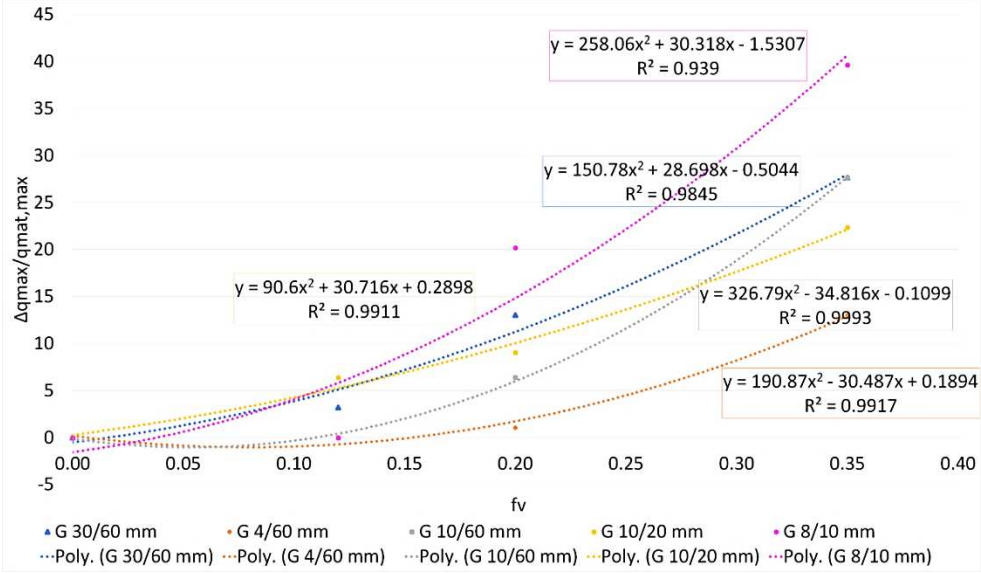

Fig. 5: Shear strength increase as a function of the volumetric volume fraction f_v of the different types of coarse-grained soils studied.

We also notice a polynomial correlation between the increase in soil shear strength and the volume fraction of the form:

$$\frac{\Delta q_{\max}}{q_{mat,\max}} = c \times (f_v)^2 + d \times (f_v). \quad (2)$$

Table 1 gives the values of the coefficients *c* and *d* for the different types of coarse-grained soils studied.

Table 1: Values of the coefficients *c* and *d* as a function of the granulometric spread of the inclusions d_{min}/d_{max}.

Gravels	d_{min}/d_{max}	*c*	*d*
G30/60	0.5	150.78	28.698
G10/20	0.5	90.6	30.716
G10/60	0.17	326.79	-34.816
G4/60	0.07	190.87	-30.487
G8/10	0.8	258.06	30.318

2.4 The GALA method

The GALA method consists in:

- Collect coarse-grained soil samples on site,
- Identify the natural material collected,
- Identify the matrix and the inclusions (choice of a capping threshold),
- Perform a series of triaxial tests on the matrix with the same density as in situ,
- Add the result of the increase of the shear strength of the large clipped elements to the value obtained from the triaxial test on the matrix:

$$q_{\text{compl soil,max}} = q_{mat,\max} + \Delta q_{\max}, \quad (3)$$

$$\Delta q_{\max}: q_{\text{compl soil,max}} - q_{mat,\max}, \quad (4)$$

where:

$q_{compl\ soil,\max}$ - maximum shear strength of the complete coarse-grained soil;
$q_{capped\ soil,\max}$ - maximum shear strength of the capped soil;
$\Delta q_{\max}$ - increase in shear strength of the complete soil compared to the matrix alone (clipped soil), obtained using the correlations presented above.

The level of capping is decided so that the volume proportion f_v of large elements is less than 35 %. Indeed, when fv exceeds 35 %, the gravels touch each other and form a "macro granular" structure [13], which will control the overall behavior. Thus, the inclusions are no longer embedded in the matrix, a difference in behavior is observed between $f_v \leq 35$ % and $f_v > 35$ % [14, 15].

At this point, the d_{min}/d_{max} value of the inclusion part can be obtained. The shear strength of the natural soil is then determined from the strength of the matrix part only. Fig. 6 shows the evolution of the coefficients *c* and *d* (from equation (2)) as a function of the granulometric spread of the inclusions d_{min}/d_{max}. We find that the best correlations are of the polynomial form:

$$c = 212.29 \cdot (\frac{d_{\min}}{d_{\max}})^2 - 135 \cdot \left(\frac{d_{\min}}{d_{\max}}\right) + 235.35, \quad (5)$$

and

$$d = -113.89 \cdot \left(\frac{d_{\min}}{d_{\max}}\right)^2 + 180.08 \cdot \left(\frac{d_{\min}}{d_{\max}}\right) - 41.736, \quad (6)$$

where d_{min}/d_{max} is granulometric spread of the inclusions.

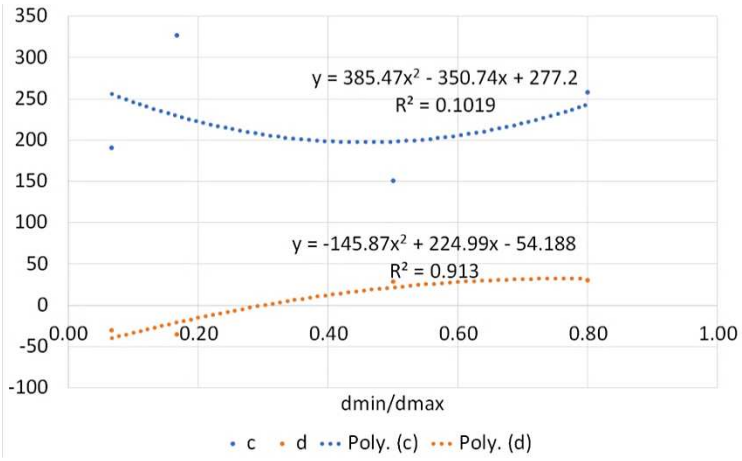

Fig. 6: Correlation of the coefficients *c* and *d* as a function of d_{min}/d_{max}.

3 Application of the Gala method to a natural coarse-grained soil

3.1 Materials used

The method will be applied to characterize sand-lime gravel, Fig. 7. Table 2 presents the characteristics of the soil.



Fig. 7: Natural coarse-grained soil.

Table 2: The characteristics of the natural soil used.

Atterberg's limits NF P 94-051			**Proctor NF P 94-093**	
W_L [%]	W_P [%]	I_P [%]	W_{OPN} [%]	ρ_d OPN [g/cm^3]
22	16	6	8	2.07

First, we will apply the method to the multi-threshold capped soil, and determine its shear strength. Then, we evaluate this method for the complete soil by performing a large-sized triaxial testing device of 300 mm.

The granulometric spread of the studied soil, Fig. 8, is obtained by carrying out a granulometric analysis by sifting for the elements of diameter higher than 0.08 mm (French Norms NF P 94-056), and by sedimentometry for the particles of diameter lower than 0.08 mm (NF P 94-057).

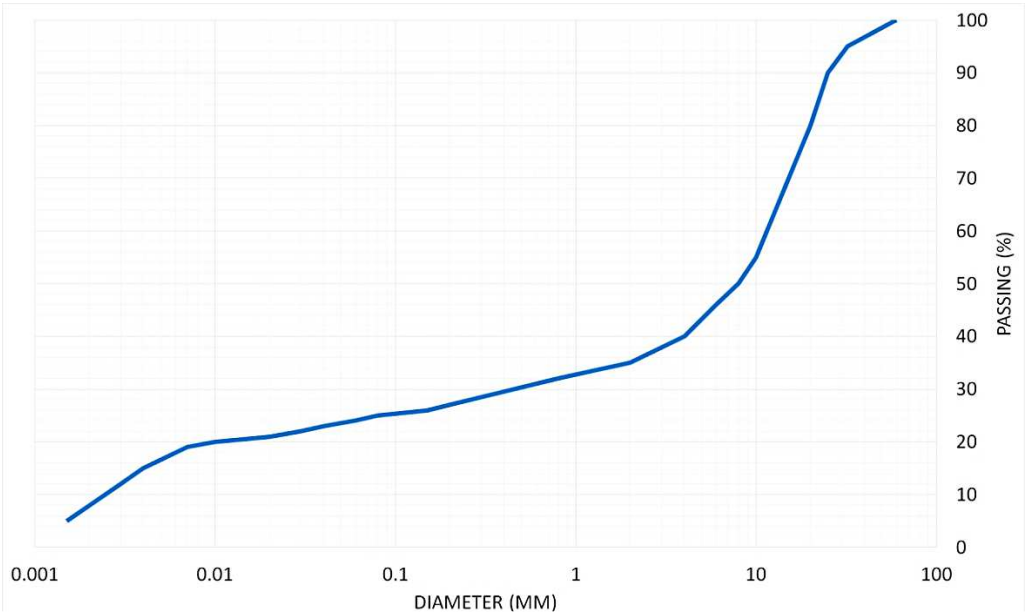

Fig. 8: The granulometric curve of the studied soil.

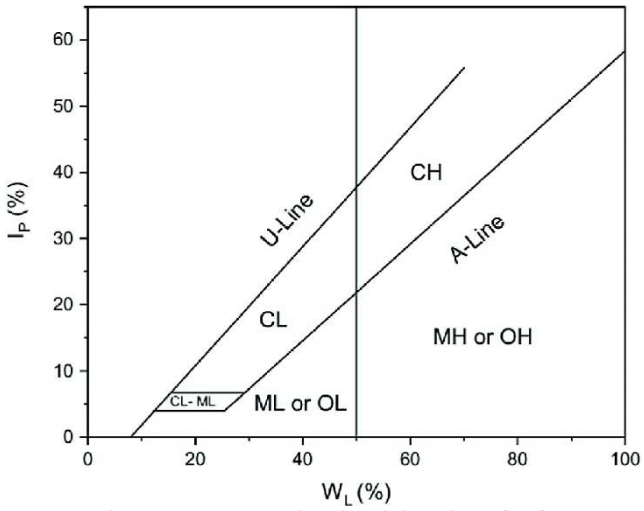

Fig. 9: Casagrande plasticity chart [10]:

CL - Inorganic clays of low plasticity; CH - Inorganic clays of high plasticity; ML - Inorganic silts of low plasticity, MH - Inorganic silts of high plasticity, OH - High plasticity organic, OL - Low plasticity organic clay [10]. The soil studied is silty gravel with low plasticity, according to the LCPC classification [10], Fig. 9, and the granulometric curve.

3.2 Identification of the matrix and inclusions

We have opted to study three thresholds of capping:

- Capping at 20 mm: The particles between 20 mm and 60 mm are removed. Therefore, the matrix is composed by the 0/20 mm elements (capped soil), and the inclusions are represented by the 20/60 mm particles: the volume fraction f_v of the inclusions is 19 % (< 35 %).
- Capping at 16 mm: We remove the particles between 16 mm and 60 mm. Therefore, the matrix is composed by the 0/16 mm elements (capped soil), and the inclusions are represented by the

16/60 mm particles: the volume fraction f_v of the inclusions is 25.40 % (< 35 %).

- Capping at 10 mm: The particles between 10 mm and 60 mm are removed. Therefore, the matrix is composed by the 0/10 mm elements (capped soil), and the inclusions are represented by the 10/60 mm particles: the volume fraction f_v of the inclusions is 38 % (> 35 %).

3.3. Triaxial tests Ø 100 mm on the matrix phase

Depending on the level of capping, we performed a series of triaxial tests in the laboratory. The consolidation stress applied for all tests is 100 kPa.

The dry density of the matrix is identical to that when mixed with the inclusions (complete soil) [3] ρ_d = 1.96 g/cm^3 and w = 7.8 %, corresponding to 95 % of the Proctor optimum. The density condition is the same too [16-18]. So, to calculate ρ_d, mat of the capped soil we have:

$$V_{total} = V_{capped\ soil} + V_{incl}, \tag{7}$$

where:
V_{total} - total volume of the specimen,
$V_{capped\ soil}$ - volume of the matrix (grains and void),
V_{incl} - volume of inclusions,

This corresponds to:

$$V_{total} = \frac{m_{capped\ soil}}{\rho_{capped\ soil}} + \frac{m_{inc}}{\rho_{inc}}, \tag{8}$$

where:
m - capped soil: the mass of the capped soil (matrix),
m_{inc} - the mass of inclusions,
m_{total} - the mass of the complete soil (matrix + inclusions).

We define f_m as the massive volume fraction of the inclusions, such that:

$$m_{inc} = f_m \cdot m_{total}, \tag{9}$$

and

$$m_{capped\ soil} = (1 - f_m) \times m_{total}\ . \tag{10}$$

Therefore, we will have:

$$V_{total} = m_{total}\left(\frac{1-f_m}{\rho_{capped\ soil}} + \frac{f_m}{\rho_{inc}}\right). \tag{11}$$

So, the density of the complete soil is:

$$\rho_{total} = \frac{1}{\left(\frac{1-f_m}{\rho_{capped\ soil}} + \frac{f_m}{\rho_{inc}}\right)}\ . \tag{12}$$

Then the density of the capped soil is:

$$\rho_{capped\ soil} = \frac{1-f_m}{\left(\frac{1}{\rho_{total}} + \frac{f_m}{\rho_{inc}}\right)}\ . \tag{13}$$

Therefore, the dry density of the clipped soil (matrix) $P_{d.capped\ soil}$ can be obtained from $P_{d.capped\ soil}$.

As the dry density of the capped soil changes with the level of capping, the table below shows the characteristics of the triaxial tests performed in the laboratory.

Fig. 10 shows the results obtained in terms of shear curves. An increase in the stress deviator is observed with the capping threshold. So, capping leads to an underestimation of the shear characteristics of coarse-grained soils [19, 20].

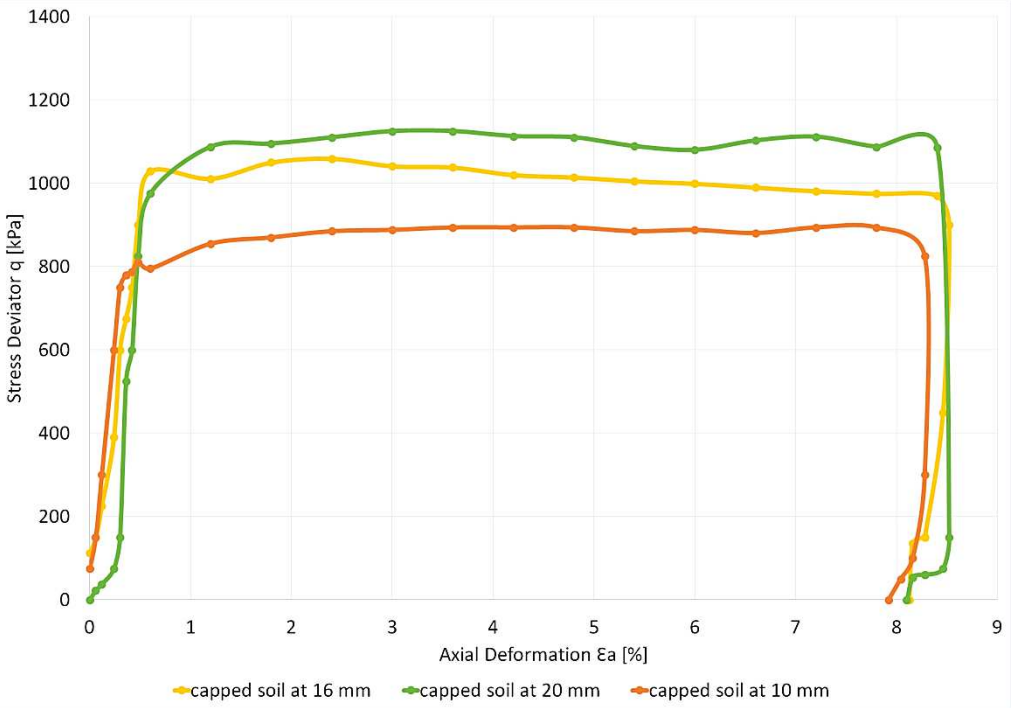

Fig. 10: The effect of capping on the mechanical behavior of capped natural coarse-grained soil.

Table 3: Characteristics of the Ø100 mm triaxial tests performed in the laboratory.

Soil	$\rho_{d,mat}$ [g/cm^3]	W [%]	σ'_c [kPa]	q [kPa]
Natural soil capped at 20 mm	1.89	7.8	100	1110.00
Natural soil capped at 20 mm	1.89	7.8	100	1116.00
Natural soil capped at 10 mm	1.76	7.8	100	885.00
Natural soil capped at 10 mm	1.76	7.8	100	904.50
Natural soil capped at 16 mm	1.85	7.8	100	1050.00

3.4 Calculation of the shear strength of the complete soil using the GALA method

Based on the results of triaxial tests performed in the laboratory on capped soils, the increase in shear strength of capped inclusions is calculated from equations (2), (5), and (6). Therefore, we obtain the resistance of the complete soil by using the equation (3). Table 4 presents the results obtained by the GALA method.

Table 4: Values of the shear strengths of the complete soil obtained using the GALA method.

Soil	Matrix	Inclusions			c	d	$q_{mat,max}$	$\Delta q_{max}/q_{mat,max}$	Δq_{max}	$q_{complete\ soil,max}$
		d_{min}	d_{max}	f_v						
Capped soil at 20 mm	Particles 0/20 mm	20	60	19 %	203.117	4.601	1110.00	8.21	91.09	1201.09
Capped soil at 20 mm	Particles 0/20 mm	20	60	19 %	203.117	4.601	1116.00	8.21	91.59	1207.59
Capped soil at 10 mm	Particles 0/10 mm	10	60	38 %	229.451	-20.742	885.00	25.25	223.47	1108.47
Capped soil at 10 mm	Particles 0/10 mm	10	60	38 %	229.451	-20.742	904.50	25.25	228.39	1132.89
Capped soil at 16 mm	Particles 0/16 mm	16	60	26 %	211.081	-4.564	1050.00	13.08	137.37	1187.37

4 Characterization of the complete coarse-grained soil with the large-sized triaxial testing device 100 mm

Now, in order to evaluate the method, we have proposed, we have carried out tests on the complete soil with the large-sized triaxial testing device with the same consolidation stress used in the classic triaxial device σ_c = 100 kPa. The dry density is kept constant ρ_d = 1.96 g/cm^3.

We realized two repeatability tests on the natural soil. As can be seen in Fig. 11, there is a difference between the two tests due to the difficulties of reconstituting the samples and also to the compaction method.

From these tests, the repeatability band of the natural soil (the envelope of the curves corresponding to these tests) is determined. This band will be used later and will allow to conclude on the influence of capping on the behavior of coarse-grained soils and to evaluate the GALA method.

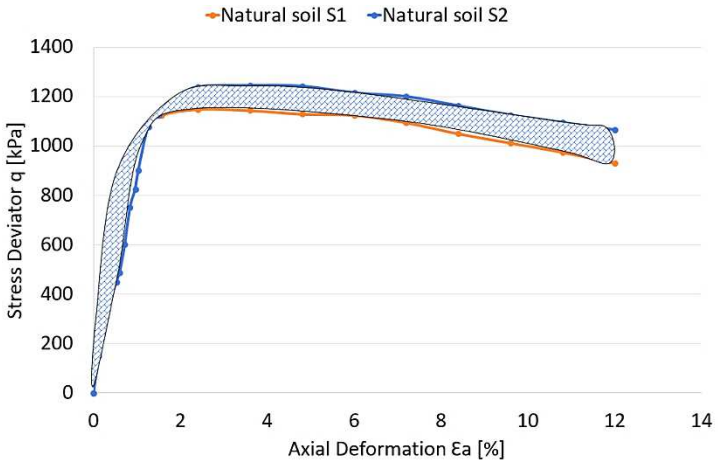

Fig. 11: Repeatability tests on natural soil.

5 Comparison of results and discussion

In Fig. 12, the shear curves of the capped soils (obtained from the conventional triaxial device), and the shear curve of the complete soil (obtained using the large-sized triaxial testing device) with the repeatability band are grouped together. It can be seen that clipping generally decreases the shear strength (all curves are below the repeatability band).

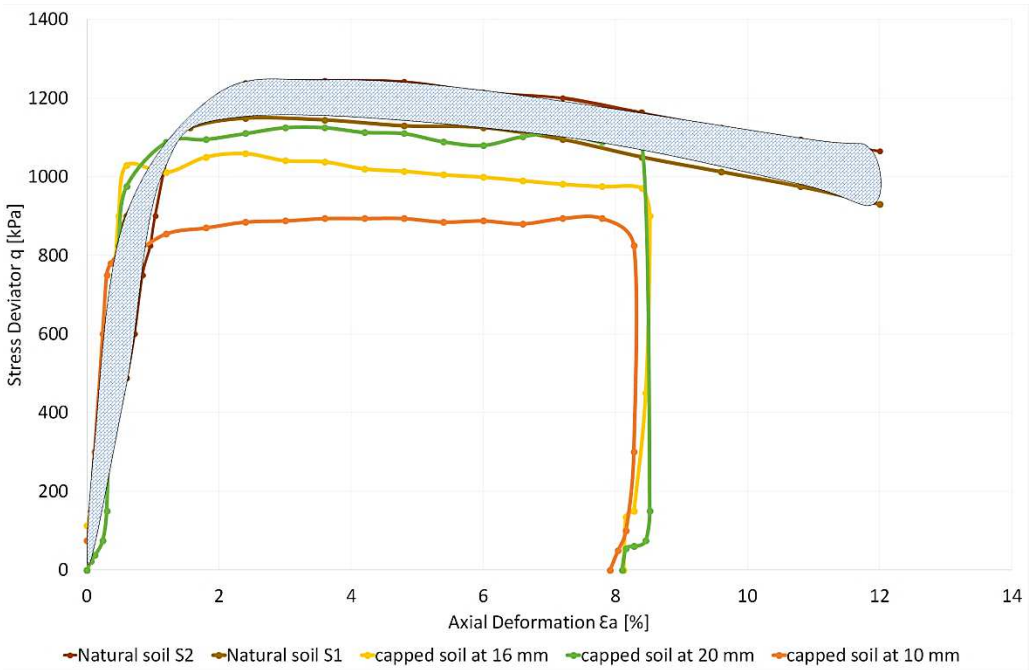

Fig. 12: Comparison between the results obtained on the complete coarse-grained soil and on the clipped coarse-grained soil.

In order to evaluate our method, we presented the values of the maximum shear strength q_{max} for all the clipped soils and the repeatability band of the natural soil, Fig. 13. It can be seen that for the 16 mm and 20 mm capped soils, the resistance values are within the repeatability band, contrary to the 10 mm capped soil (the values are below the band).

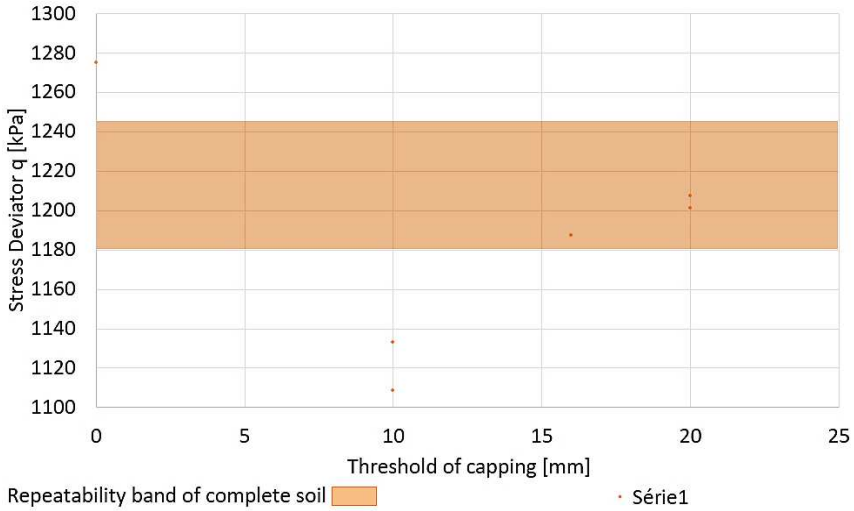

Fig. 13: Theoretical" shear strength values for different full soil capping thresholds.

Fig. 13 shows that the method gives good results for the soil clipped at 20 mm; both "theoretical" values are in the expected band. Then, we find the same result for the soil clipped at 16 mm. However, for the soil clipped at 10 mm, we find that the values of the stress deviator are below the repeatability band. At this clipping threshold, the volume fraction of clipped particles f_v is greater than 35 % (f_v = 38 %); therefore, the criteria is not respected.

6 Conclusion

To be able to characterize coarse-grained soils in the laboratory with a representative volume of the soil, we use large devices. However, this alternative remains limited by the high costs of the devices.

Currently, so-called granulometric reconstruction methods are used to test coarse-grained soils in the laboratory by conventional devices. The capping method consists in removing the large elements and testing just the matrix. The substitution method consists in replacing the large elements by elements of smaller size.

In this article, we have shown that these methods give different and sometimes opposing results: The capping method leads to an underestimation of the mechanical characteristics of the coarse-grained soil, while the substitution method tends to overestimate them.

All the results obtained in the parametric study of coarse-grained soils allowed us to propose a new methodology of mechanical characterization of coarse-grained soils in the laboratory, using the large-sized triaxial testing device on a capped material.

This new method takes into account:

- The effect of the size d_{max} of the inclusions at the same granulometric spread $d_{min}/d_{max.}$
- The effect of the granulometric spread $d_{min}/d_{max.}$
- The effect of the volume fraction of inclusions f_v.

The maximum inclusion size d_{max} has no significant influence on the shear strength. However, we have proved polynomial correlations between the increase in strength due to the inclusions and the volume fraction f_v and the granulometric spread d_{min}/d_{max} of inclusions.

We were able to apply this new method to natural soil, silty gravel with low plasticity. We have opted to study three thresholds of capping: Capping at 20 mm, 16 mm, and 10 mm. An increase in the stress deviator is observed with the capping threshold.

The results showed the relevance of our method: the method gives good results for the soil clipped at 20 mm; both "theoretical" values are in the expected band. Then, we find the same result for the soil clipped at 16 mm. However, for the soil clipped at 10 mm, we find that the values of the stress deviator are below the repeatability band. At this clipping threshold, the volume fraction of clipped particles f_v is greater than 35 % (f_v = 38 %); therefore, the criteria is not respected.

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