TECHNICAL UNIVERSITY OF CONSTRUCTIONS BUCHAREST

Faculty of Hydrotechnics

Criteria for verifying the improvement of collapsible soils as established by specific geotechnical tests

Research Report no. 3

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1. INTRODUCTION

The thesis is developed in order to contribute at the establishment of criteria for verifying the improvement of water sensitive soils (PSU) and to develop correlations between in situ and laboratory test in order to optimize the certification of their desensitization. In this regard, considering my direct involvement for a long period of time at a project located in the south-east of the country, close to the city Constanta.

The project had as object the construction of approximately 22 km of highway with a width of 26m, 26 bridges and 5 interchanges. Preliminary geotechnical investigations performed revealed the existence of a layer up to 12m thick of loess soils, generally having water sensitivity on the first 6m.

Research report number 3 includes results of the in situ and laboratory tests performed.

2. PREZENTAREA GENERALĂ A PROIECTULUI

The project had as object the construction of approximately 22 km of highway with a width of 26m, 26 bridges and 5 interchanges. Preliminary geotechnical investigations performed revealed the existence of a layer up to 12m thick of loess soils, generally having water sensitivity on the first 6m, placed on a layer of red clays with calcareous concretions. After depth of about 28 m it is found up to 40 m deep the bedrock consisting of degraded limestone in clay mass.

On this soil, for the construction of the highway, embankments of 5 - 11 m height are provided. Due to the nature and the state of thickening of the first layer of land, it was necessary to improve the land to a depth of 6m. The improvement was achieved by intensive dynamic compaction.

The improvement of the land aimed at reducing the risk of collapse of the loess, limiting the differentiated settlements and increasing the load-bearing capacity.

Dynamic compaction was performed on an area of approximately 240.000 m^2.

In order to verify the efficiency of the ground improvement by dynamic compaction and to establish improvement criteria and correlations of the physical and mechanical parameters, an extensive testing program was executed. This program included in situ and laboratory tests performed both before and after ground improvement.

3. TESTING PROGRAM

The testing program includes the performance and analysis of 95 CPTs and 8 geotechnical borings in 4 areas of the project covering a total area of 94,200m2. Were analysed a total of 68 undisturbed and 68 disturbed samples.

For each analysed area, several static cone penetration tests (CPT) and laboratory tests were performed as well as disturbed and undisturbed samples were taken (both before and after ground improvement).

The tests performed include the determination of the following parameters:

- Granulometry;
- Humidity (w);
- Saturation degree (Sr);
- Atterberg limits, plasticity index (Ip) and consistency index (Ic);
- Porosity (n);
- Pore index (e);
- Dry density (ρd);
- Additional settlement index (im300) and deformation modulus (E200-300) in natural state and at saturation.

In order to consider that loess is no longer collapsible the following criteria were established (Manea et al., 2012):

- Decreasing the additional settlement index im300 < 2%
- Increasing the dry density ρd > 1,6g/cm3
- Reduction of the porosity n < 40%
- Increasing the average odometer modulus E200-300 at natural moisture and saturation
- Increasing the average cone resistance qc > 2,5MPa

In addition, the following conditions must be met also in order to certify the quality of the works (Manea et al., 2012):

- im300îmb / im300nat < 1;
- ρdîmb / ρdnat > 1;
- nîmb /nnat < 1;
- E200-300îmb / E200-300nat > 1;
- E200-300îmbwsat / E200-300natwsat > 1;
- qcmedîmb / qcmednat > 1.

For the global characterization of the soil, comparisons of the average values of the determined parameters were performed.

The composition and nature of the materials were analysed using the fingerprint-based methodology and the similarity criterion (NP 126/2010).

Correlations between the values of the edometric deformation modules and the specific values from the static cone penetration tests according to SREN 1997 - 2: 2007 were analysed.

4. OBTAINED RESULTS

4.1. Zone 1

Zone 1 has a length of 440m. The compacted area was 35,232m2. In this area, were executed two boreholes, with disturbed and undisturbed samples, one on the natural ground and one after improvement by dynamic compaction (DC). In addition were performed 13 CPTs in the natural soil and 14 in the improved soil.

Based on the analysis of the data obtained by processing laboratory samples, it is found that up to a depth of 6m the soil can be classified as sensitive to moisture according to the identification criteria provided in the technical requirements and detailed in previous chapters. All results are represented in the thesis graph in parallel (before and after improvement).

The tables below show the values of the parameters obtained from the laboratory tests performed before and after the improvement by DC and their average values per 6m.

ZONA 1							
Adâncime (m)	1N - în teren natural						
	i_{m300} (%)	I_c	Medie e	Medie ρ_d (g/cm^3)	Medie n (%)	$M_{200\text{-}300\ natural}$ (KPa)	$M_{200\text{-}300\ saturat}$ (KPa)
0,60			0,55	1,75	35,69		
1,20		0,75	0,55	1,75	35,63		
1,80			0,50	1,78	33,33		
2,40	4,83	0,74	0,90	1,41	47,30	4.830,02	4.081,60
3,00			0,57	1,73	36,34		
3,60	3,44	0,88	0,84	1,46	45,57	8.563,90	4.614,80
4,20			0,53	1,78	34,73		
4,80	4,46	1,00	0,83	1,46	45,15	5.342,10	4.251,10
5,40			0,54	1,73	35,18		
6,00	4,17	0,61	0,86	1,44	45,97	5.054,40	3.364,00
MEDIE	4,23	0,80	0,67	1,63	39,49	5.947,61	4.077,88

Tabel 4.1: Parametrii obținuți în laborator în teren natural, Zona 1

ZONA 1							
Adâncime (m)	**1C - în teren compactat**						
	i_{m300} (%)	**I_c**	**Medie e**	**Medie ρ_d (g/cm^3)**	**Medie n (%)**	**$M_{200-300\ natural}$ (KPa)**	**$M_{200-300\ saturat}$ (KPa)**
0,60							
1,20		0,87	0,58	1,72	36,77		
1,80			0,57	1,73	36,37		
2,40	0,00	0,83	0,58	1,69	36,85	14.397,00	11.424,00
3,00			0,58	1,72	36,63		
3,60	2,00	0,86	0,71	1,57	41,29	8.463,00	5.129,00
4,20			0,53	1,78	34,69		
4,80	3,23	0,86	0,79	1,50	43,90	5.857,20	4.082,00
5,40			0,64	1,63	39,04		
6,00	0,00	0,76	0,85	1,45	45,76	4.189,50	4.058,10
MEDIE	1,31	0,84	0,65	1,64	39,03	8.226,68	6.173,28

Tabel 4.2: Parametrii obținuți în laborator în teren compactat, Zona 1

The structural strength obtained by double edometric tests is shown in Table 4.3.

Adâncime (m)	$\sigma_{0\ natural}$ (kPa)	$\sigma_{0\ după\ CD}$ (kPa)
2,4	28	-
3,6	64	130
4,8	32	30
6	77	-

Tabel 4.3: Rezistența structurală σ_0 (kPa), Zona 1

Based on the average values, it is observed that the conditions for attesting the quality of the works is satisfied, even if locally (4.8 m) there are values that do not satisfy all the requirements.

Below are plotted in parallel (before and after improvement) the results obtained for the additional settlement index (im300), porosity (n) and dry density (ρd).

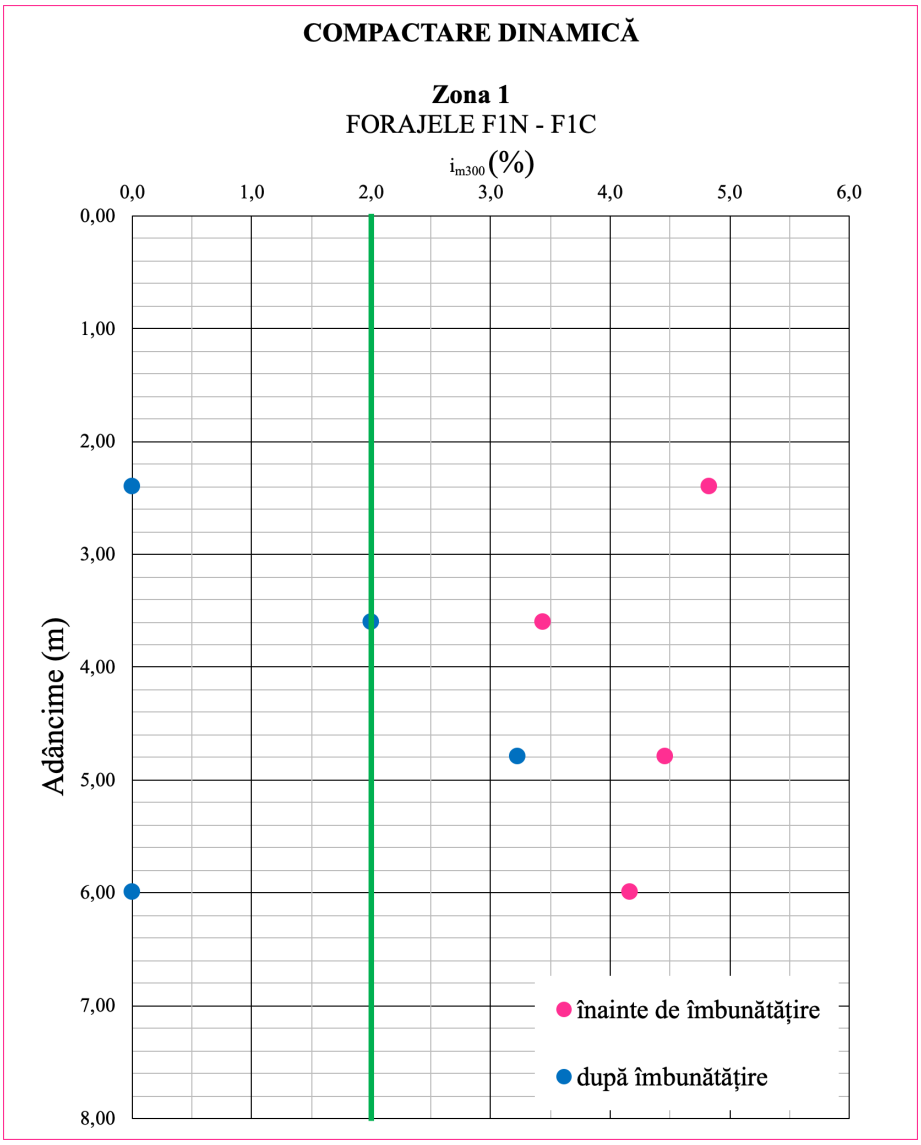

Figura 4.1: Reprezentarea grafică a indicilor tasării specifice la umezire (i_{m300}) obținuți prin încercări de laborator, Zona 1

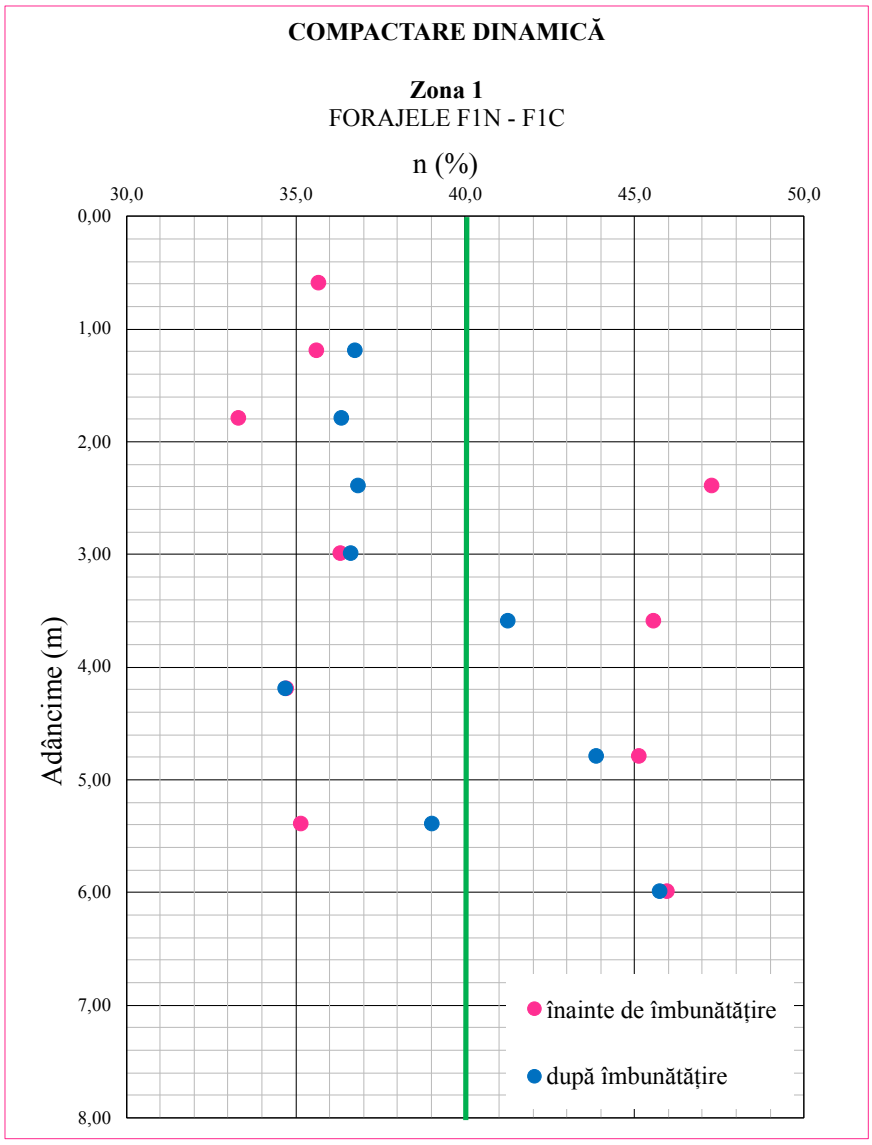

Figura 4.2: Reprezentarea grafică a porozităților (n) obținute prin încercări de laborator, Zona 1

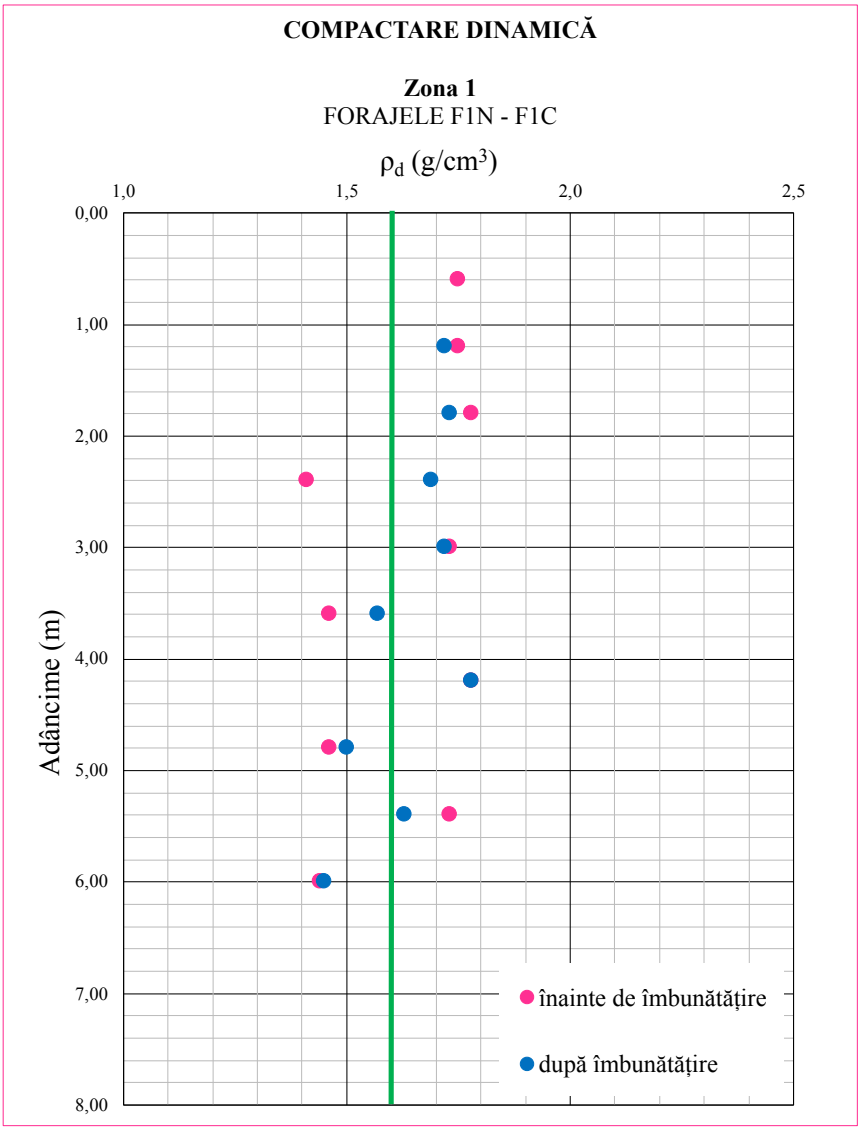

Figura 4.3: Reprezentarea grafică a densităților în stare uscată (ρ_d) obținute prin încercări de laborator, Zona 1

Raport între valorile compactate și cele naturale - ZONA 1						
i_{m300} (%)	**I_c**	**Medie e**	**Medie ρ_d (g/cm^3)**	**Medie n (%)**	**$M_{200\text{-}300\ natural}$ (KPa)**	**$M_{200\text{-}300\ saturat}$ (KPa)**
0,31	1,05	0,97	1,01	0,99	1,38	1,51
< 1		**<1**	**> 1**	**< 1**	**> 1**	**> 1**

Tabel 4.4: Rapoartele valorilor medii ale parametrilor obținuți prin încercări de laborator pe 6m, Zona 1

The edometric modules increased considerably after compaction on the first 4m, reaching a percentage of improvement of 70% for the edometric modules determined in the soil at natural humidity and at 90% for those determined in saturated soil. This aspect highlights the stronger effect of DC in the surface and median area of the improved layer (approximately 2/3 of the layer thickness).

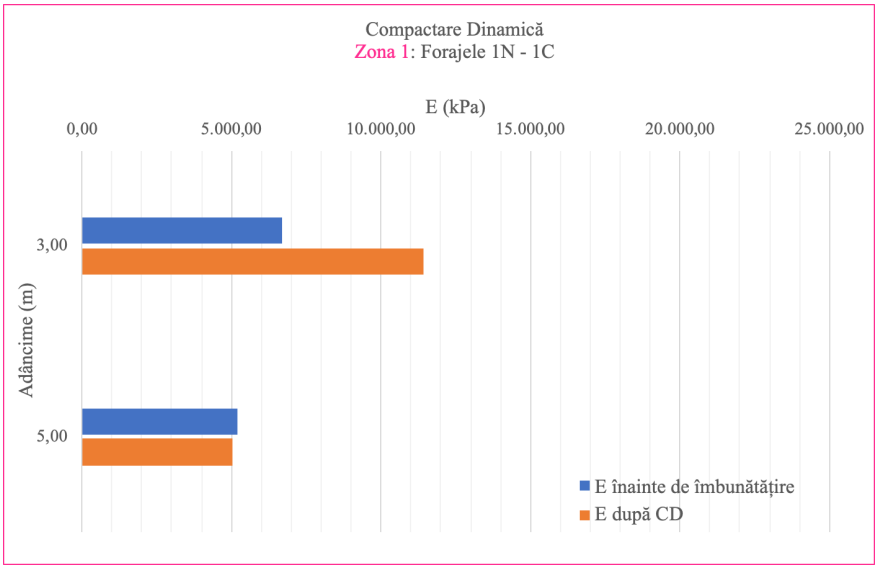

Figura 4.4: Reprezentarea grafică a modulilor edometrici $E_{200\text{-}300}$ obținuți prin încercări de laborator, Zona 1

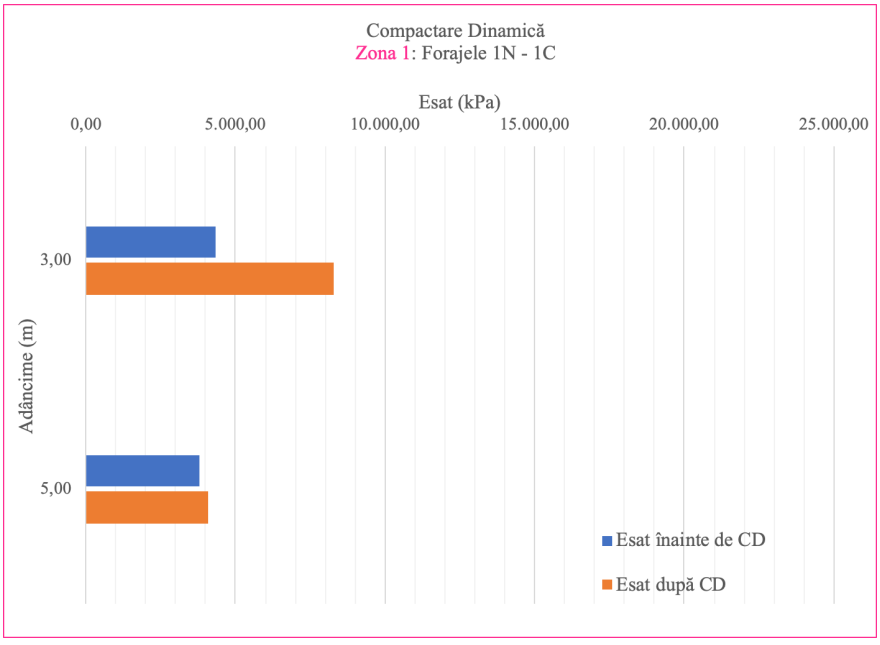

Figura 4.5: Reprezentarea grafică a modulilor edometrici saturați $E_{200\text{-}300sat}$ obținuți prin încercări de laborator, Zona 1

4.2. Zone 2

Zone 2 has a length of 510m. The compacted area measured 30.176m2. In this area, were executed two boreholes, with disturbed and undisturbed samples, one on the natural ground and one after improvement by dynamic compaction (DC). In addition were performed 21 CPTs in the natural soil and 21 in the improved soil.

ZONA 2							
Adâncime (m)	SPT 2N - în teren natural						
	i_{m300} (%)	I_c	Medie e	Medie ρ_d (g/cm^3)	Medie n (%)	$M_{200\text{-}300\ natural}$ (KPa)	$M_{200\text{-}300\ saturat}$ (KPa)
0,60			0,67	1,63	39,96		
1,50		0,78	0,60	1,71	37,31		
1,80			0,52	1,76	34,20		
2,40	4,72	0,78	0,85	1,45	46,04	7.848,20	3.455,50
3,00			0,65	1,65	39,45		
3,60	2,51	0,78	0,87	1,47	45,84	9.753,50	5.008,30
4,20			0,63	1,67	38,51		
4,80	1,76	0,94	0,61	1,67	37,72	14.548,00	7.035,20
5,40			0,53	1,74	34,78		
6,00	0,50	0,97	0,72	1,56	41,72	12.381,00	9.827,20
MEDIE 6m	2,37	0,85	0,67	1,63	39,55	11.132,68	6.331,55

Tabel 4.5: Parametrii obținuți în laborator în teren natural, Zona 2

ZONA 2							
Adâncime (m)	SPT 2C - în teren compactat						
	i_{m300} (%)	I_c	Medie e	Medie ρ_d (g/cm^3)	Medie n (%)	$M_{200\text{-}300\ natural}$ (KPa)	$M_{200\text{-}300\ saturat}$ (KPa)
0,60			0,48	1,84	32,51		
1,50			0,61	1,69	37,73		
1,80	0,10	0,81	0,52	1,79	34,30	21.462,00	12.683,00
2,40	0,00	0,97	0,49	1,82	32,99	12.440,00	10.769,00
3,00			0,45	1,87	31,12		
3,60	0,00	0,88	0,62	1,68	38,24	15.993,00	11.340,00
4,20	0,00	0,83	0,67	1,63	40,12	12.621,00	14.548,00
4,80	0,00	0,77	0,58	1,72	36,69	17.170,00	13.482,00
5,40			0,51	1,77	33,56		
6,00	2,45	1,00	0,64	1,66	39,06	15.895,00	9.717,00
MEDIE 6m	0,43	0,88	0,56	1,75	35,63	15.930,17	12.089,83

Tabel 4.6: Parametrii obținuți în laborator în teren compactat, Zona 2

Based on the analysis of the data obtained by processing laboratory samples, it is found that to a depth of 6m the soil can be classified as sensitive to moisture according to the identification criteria provided in the technical requirements and detailed in previous chapters. All results are represented in the thesis graph in parallel (before and after improvement).

The edometric modules increased considerably after compaction on the first 4m, reaching a percentage of improvement of 60% for the edometric modules determined in the soil at natural humidity and at 160% for those determined in saturated soil. This aspect highlights the stronger effect of DC in the surface and median area of the improved layer (approximately 2/3 of the layer thickness).

The structural strength obtained by double edometric tests is shown in the following table.

Adâncime (m)	$\sigma_{0\ natural}$ (kPa)	$\sigma_{0\ după\ CD}$ (kPa)
2,4	95	Nu este cazul
3,6	130	Nu este cazul
4,8	180	Nu este cazul
6	Nu este cazul	63

Tabel 4.7: Rezistența structurală σ_0 (kPa), Zona 2

Based on the analysis of the data obtained by processing laboratory samples, it is found that to a depth of 6m the soil can be classified as sensitive to moisture according to the identification criteria provided in the technical requirements and detailed in previous chapters. All results are represented in the thesis graph in parallel (before and after improvement).

Below are plotted in parallel (before and after improvement) the results obtained for the additional settlement index (im300), porosity (n) and dry density (ρd).

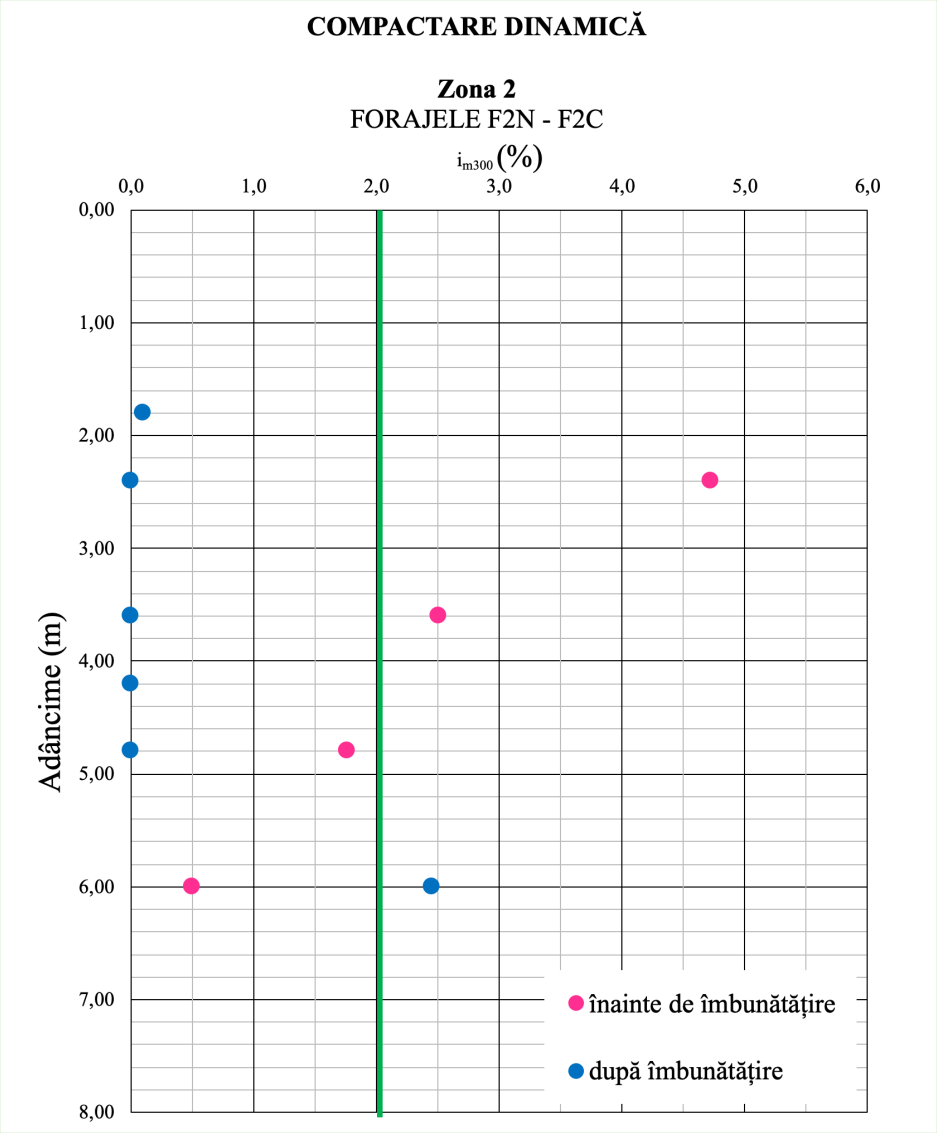

Figura 4.6: Reprezentarea grafică a indicilor tasării specifice la umezire (i_{m300}) obținuți prin încercări de laborator, Zona 2

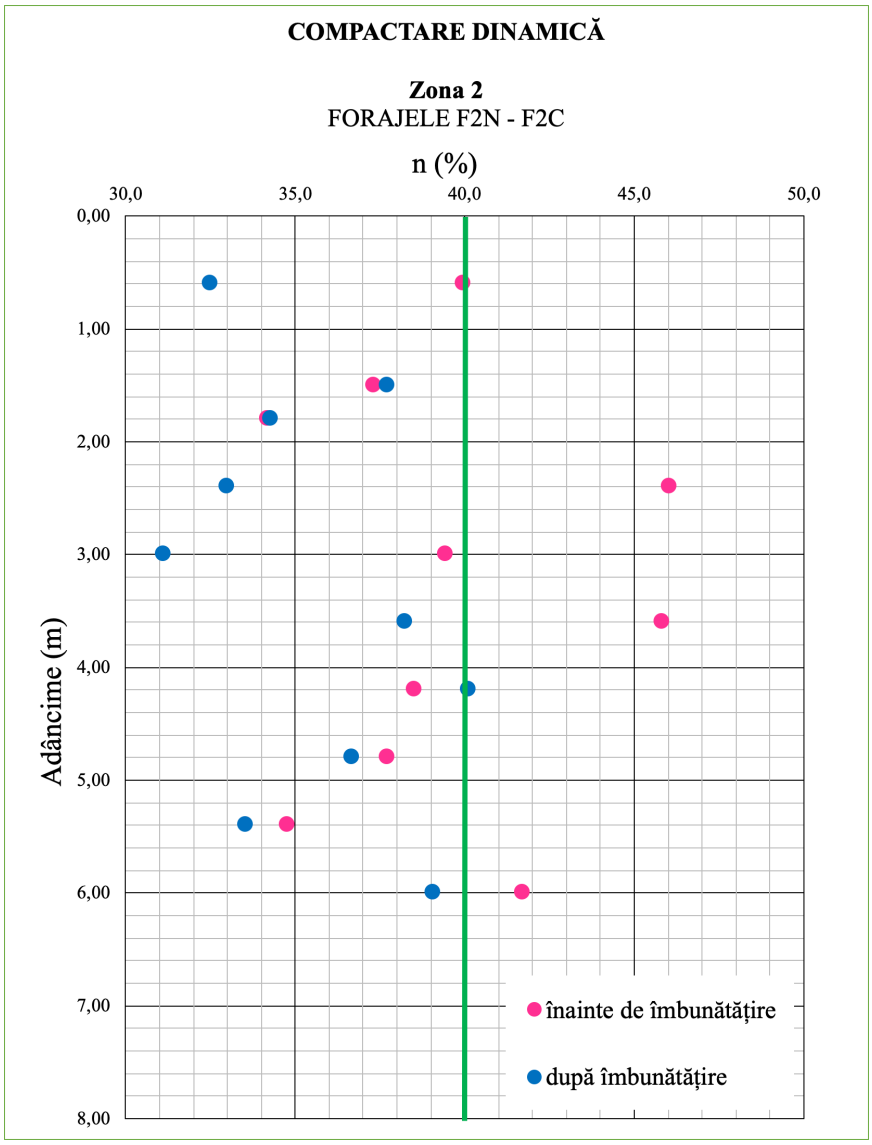

Figura 4.7: Reprezentarea grafică a porozităților (n) obținute prin încercări de laborator, Zona 2

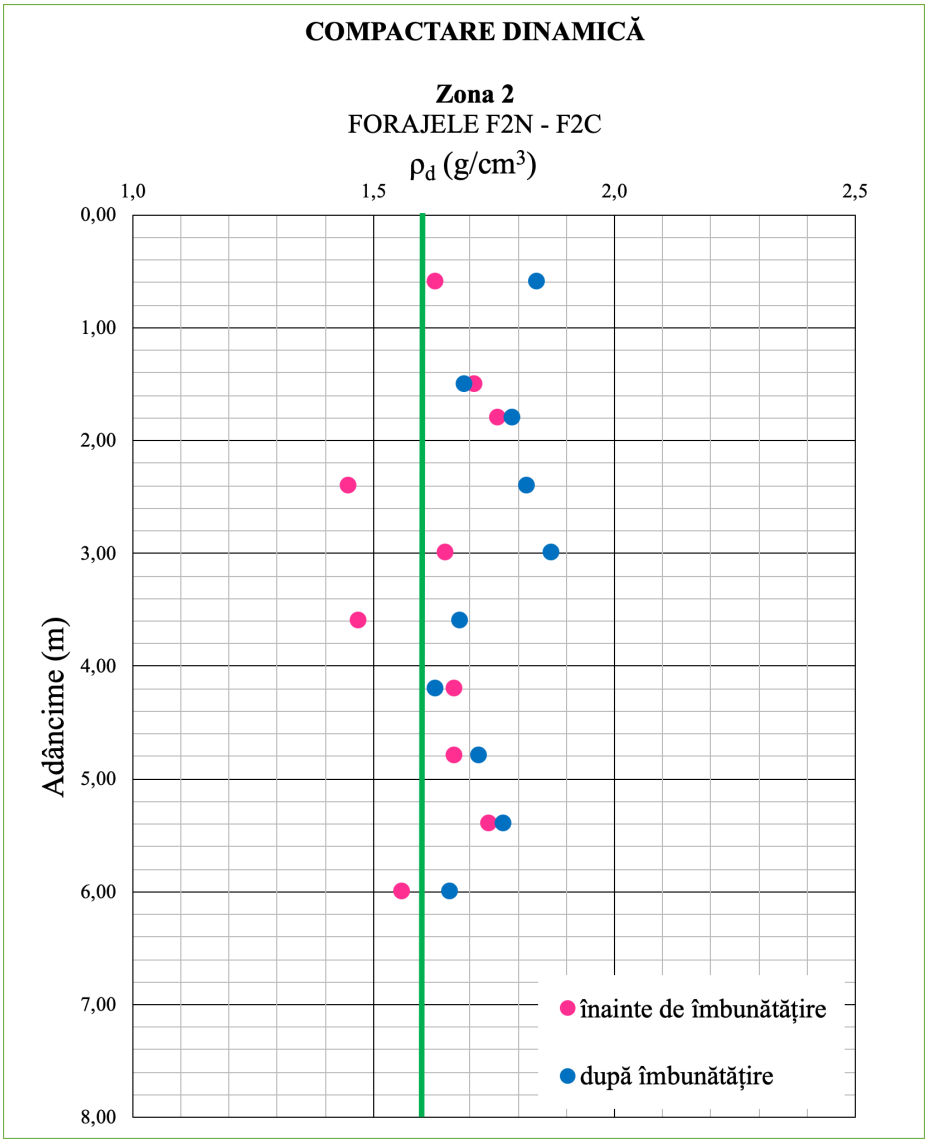

Figura 4.8: Reprezentarea grafică a densităților în stare uscată (ρ_d) obținute prin încercări de laborator, Zona 2

Raport între valorile compactate și cele naturale ZONA 2						
i_{m300} (%)	**I_c**	**Average e**	**Average ρ_d**	**Average n**	**$M_{2\text{-}3\ natural}$ (KPa)**	**$M_{2\text{-}3\ saturat}$ (KPa)**
0,18	1,04	0,84	1,07	0,90	1,43	1,91
< 1		**1<**	**> 1**	**< 1**	**> 1**	**> 1**

Tabel 4.8: Rapoartele valorilor medii ale parametrilor obținuți prin încercări de laborator pe 6m, Zona 2

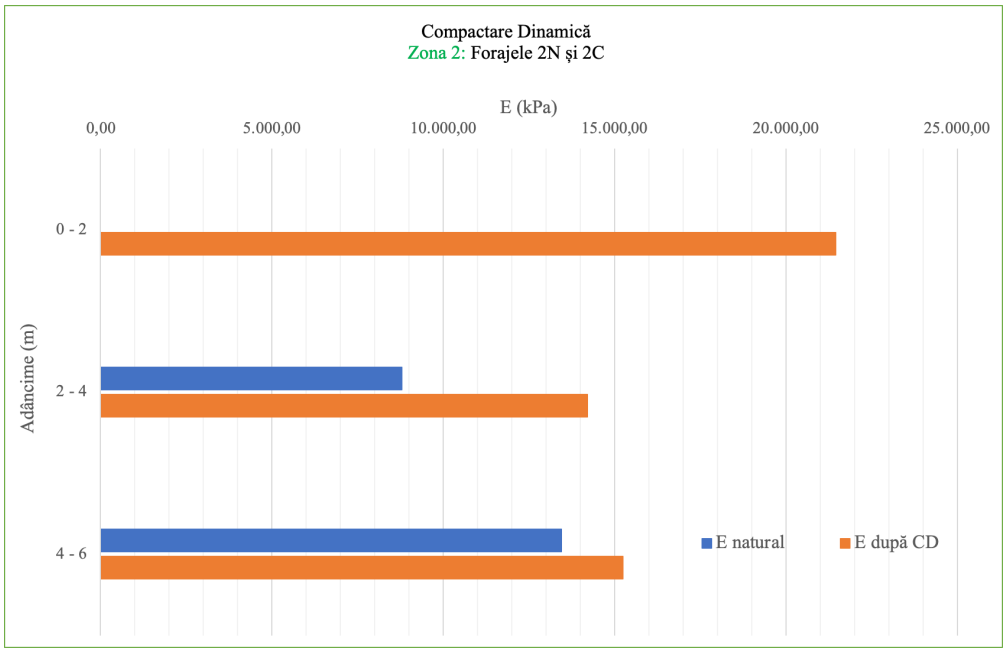

Figura 4.9: Reprezentarea grafică a modulilor edometrici la umiditate naturală $E_{200\text{-}300}$ obținuți prin încercări de laborator, Zona 2

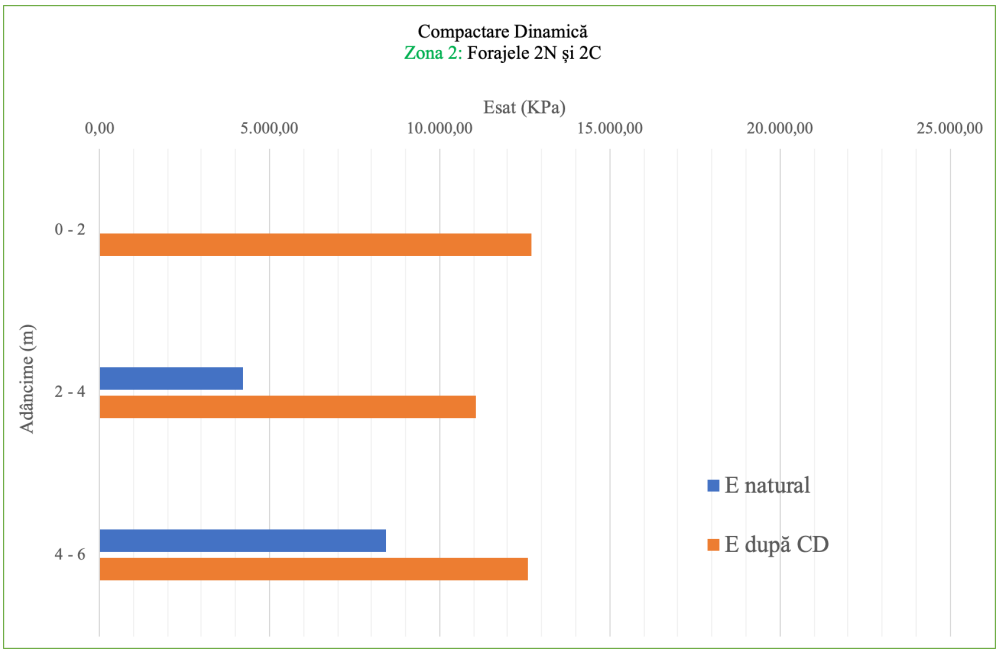

Figura 4.10: Reprezentarea grafică a modulilor edometrici la saturație $E_{200\text{-}300sat}$ obținuți prin încercări de laborator, Zona 2

From the cone penetration tests (CPT) results the following average values for the tip cone resistance qc:

Adâncime (m)	Medie $q_{c\ natural}$	Medie $q_{c\ CD/i}$	Procent îmbunătățire
0 - 2	1,1	3,9	255%
2 - 4	1,4	3,4	143%
4 - 6	1,7	2,8	65%
Medie	**1,4**	**3,4**	**143%**

Tabel 4.9: Valori medii pentru rezistența pe con q_c (MPa), Zona 2

4.3. Zone 3

Zone 3 has a length of 450m. The compacted area measured 22.500m2. In this area, were executed two boreholes, with disturbed and undisturbed samples, one on the natural ground and one after improvement by dynamic compaction (DC). In addition were performed 10 CPTs in the natural soil and 10 in the improved soil.

The tables below show the values of the parameters obtained from the laboratory tests performed before and after the improvement by DC and their average values per 6m.

Zona 3							
Adâncime (m)	F13 - în teren natural						
	i_{m300} (%)	I_c	Medie e	Medie ρ_d (g/cm^3)	Medie n (%)	$M_{200\text{-}300\ natural}$ (KPa)	$M_{200\text{-}300\ saturat}$ (KPa)
0,60	10,41	1,00	0,92	1,41	47,91	7.640,60	3.657,60
1,20	9,07	0,97	0,73	1,56	41,81	14.308,00	3.080,10
1,80	8,12	0,97	0,64	1,64	39,08	13.840,00	3.330,90
2,40	7,62	0,96	0,81	1,48	44,59	8.441,60	3.437,90
3,00	2,71	0,91	0,68	1,62	40,46	14.308,00	6.502,30
3,60	2,41	0,97	0,66	1,64	39,65	14.881,00	7.596,00
4,20	6,22	0,94	0,79	1,52	43,98	8.280,30	3.556,10
4,80	8,67	1,00	0,88	1,44	46,58	7.073,50	2.987,00
5,40	4,87	0,94	0,87	1,46	46,44	6.403,90	2.594,40
6,00	2,00	1,00	0,58	1,70	36,79	12.871,00	7.210,80
Medie	6,21	0,97	0,76	1,55	42,73	10.804,79	4.395,31

Tabel 4.10: Parametrii obținuți în laborator în teren natural, Zona 3

Zona 3							
Adâncime (m)	F12A - în teren compactat						
	i_{m300} (%)	I_c	Medie e	Medie ρ_d (g/cm^3)	Medie n (%)	$M_{200\text{-}300\ natural}$ (KPa)	$M_{200\text{-}300\ saturat}$ (KPa)
0,60							
1,20							
1,80		0,95	0,61	1,67	37,99	10.957,00	
2,40	0,00	0,98	0,56	1,74	35,84	13.409,00	9.723,30
3,00	0,45	0,79	0,61	1,67	38,06	11.082,70	8.458,00
3,60	0,25	0,80	0,56	1,72	36,07	11.954,00	10.081,00
4,20	0,43	0,76	0,70	1,59	41,00	10.501,00	8.354,80
4,80	0,00	0,76	0,71	1,57	41,54	10.228,00	9.252,70
5,40	1,24	0,83	0,68	1,60	40,35	11.116,00	7.415,90
6,00	2,00	0,86	0,65	1,62	39,48	10.952,00	5.816,60
Medie	0,62	0,84	0,64	1,65	38,79	11.274,96	8.443,19

Tabel 4.11: Parametrii obținuți în laborator în teren compactat, Zona 3

Based on the analysis of the data obtained by processing laboratory samples, it is found that to a depth of 6m the soil can be classified as sensitive to moisture according to the identification criteria provided in the technical requirements and detailed in previous chapters. All results are represented in the thesis graph in parallel (before and after improvement).

Below are plotted in parallel (before and after improvement) the results obtained for the additional settlement index (im300), porosity (n) and dry density (ρd).

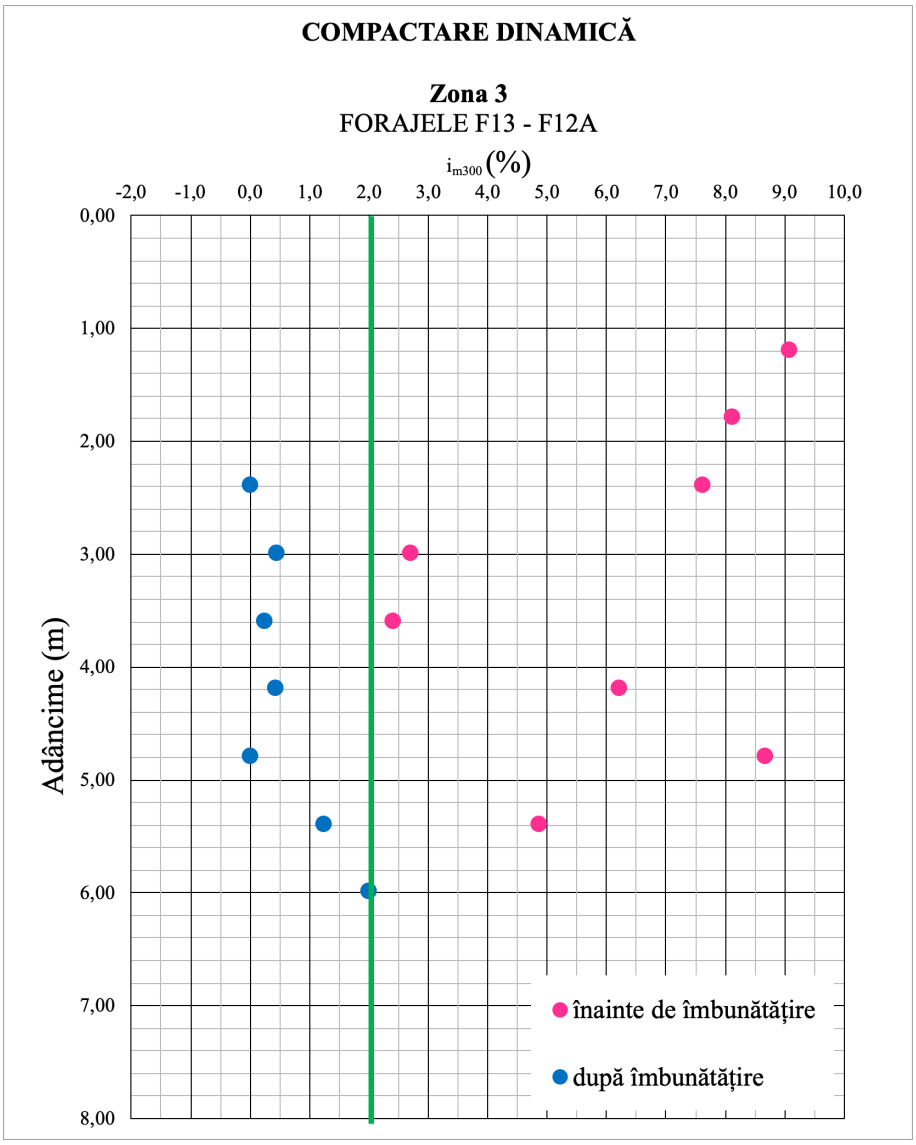

Figura 4.11: Reprezentarea grafică a indicilor tasării specifice la umezire (i_{m300}) obținuți prin încercări de laborator, Zona 3

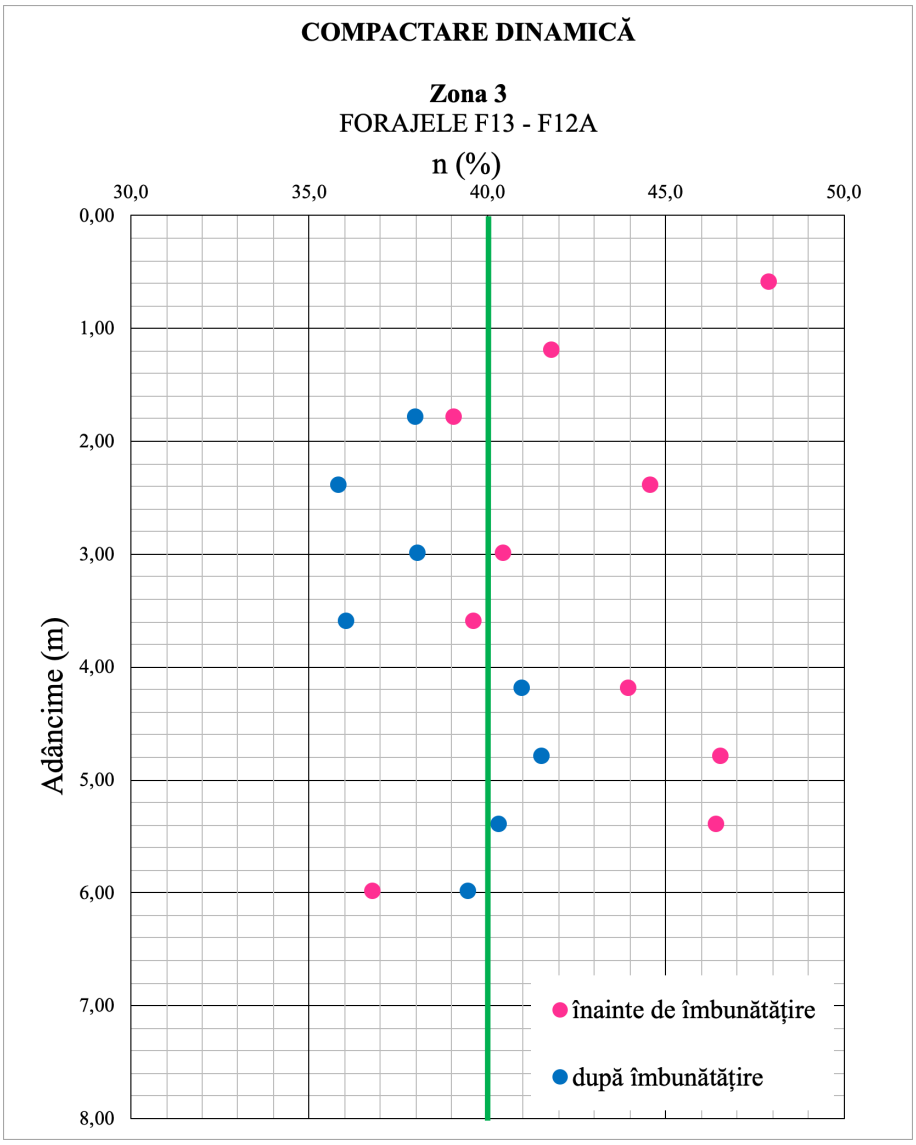

Figura 4.12: Reprezentarea grafică a porozităților (n) obținute prin încercări de laborator, Zona 3

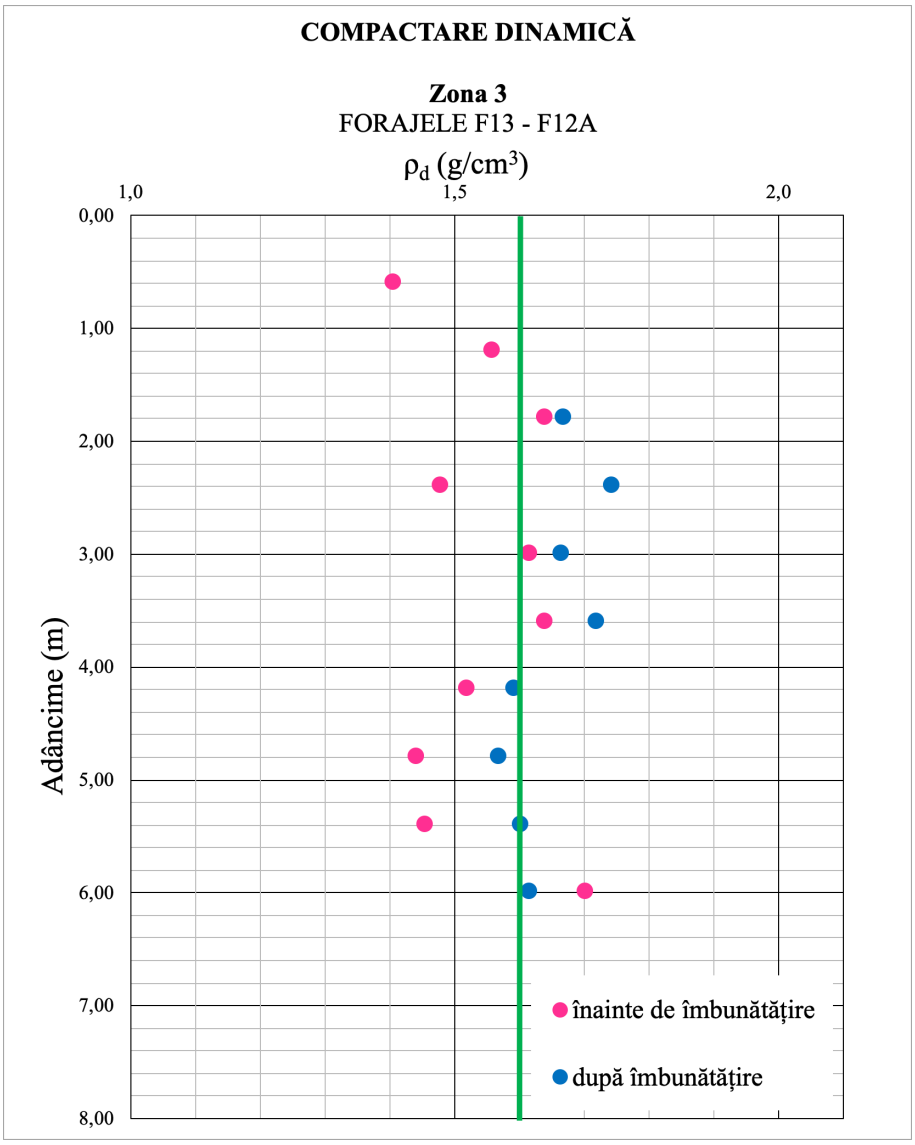

Figura 4.13: Reprezentarea grafică a densităților în stare uscată (ρ_d) obținute prin încercări de laborator, Zona 3

Raport între valorile compactate și cele naturale ZONA 3						
i_{m300} (%)	**I_c**	**Medie e**	**Medie ρ_d (g/cm^3)**	**Medie n (%)**	**$M_{200\text{-}300\ natural}$ (KPa)**	**$M_{200\text{-}300\ saturat}$ (KPa)**
0,10	0,87	0,84	1,07	0,91	1,04	1,92
< 1		**< 1**	**> 1**	**< 1**	**> 1**	**> 1**

Tabel 4.12: Rapoartele valorilor medii ale parametrilor obținuți prin încercări de laborator pe 6m, Zona 3

The structural strength obtained by double edometric tests is shown in the following table:

Adâncime (m)	$\sigma_{0\ natural}$ (kPa)	$\sigma_{0\ după\ CDI}$ (kPa)
0,6	16	nu este cazul
1,2	60	nu este cazul
1,8	58	nu este cazul
2,4	40	nu este cazul
3	102	nu este cazul
3,6	140	nu este cazul
4,2	30	nu este cazul
4,8	25	nu este cazul
5,4	95	235
6	150	65

Tabel 4.13: Rezistența structurală σ_0 (kPa), Zona 3

The edometric modules corresponding to the soil at natural humidity do not show significant changes after compaction. At saturation, the modules increase considerably after compaction.

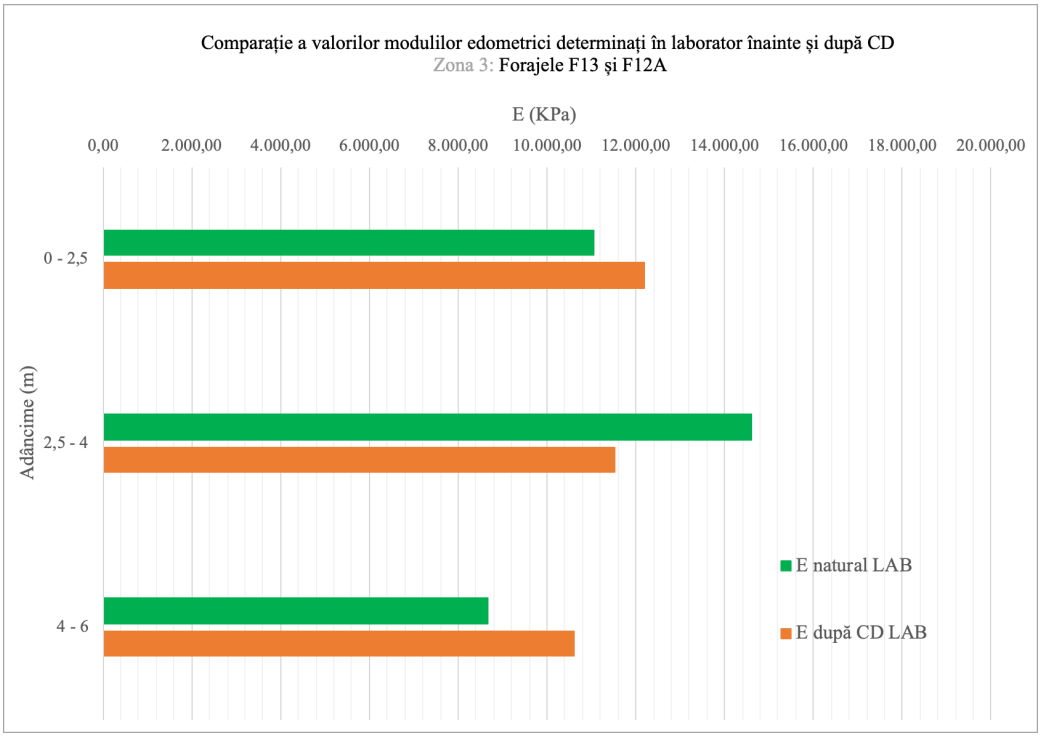

Figura 4.14: Reprezentarea grafică a modulilor edometrici la umiditate naturală $E_{200\text{-}300}$ obținuți prin încercări de laborator, Zona 3

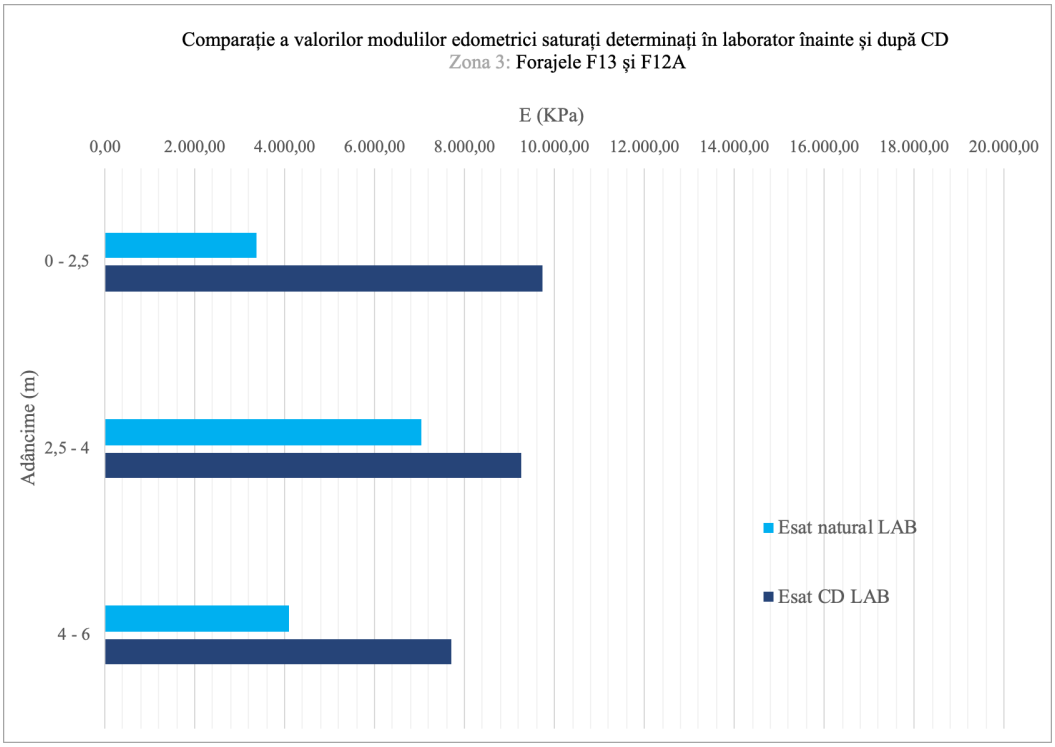

Figura 4.15: Reprezentarea grafică a modulilor edometrici la saturație $E_{sat200-300}$ obținuți prin încercări de laborator, Zona 3

From the cone penetration tests (CPT) results the following average values for the tip cone resistance qc:

Adâncime (m)	Medie $q_{c\ natural}$	Medie $q_{c\ CDI}$	Procent îmbunătățire
0 - 2,5	1,2	3,0	150%
2,5 - 4	1,6	3,5	119%
4 - 6	1,4	3,0	114%
Medie	**1,4**	**3,2**	**129%**

Tabel 4.14: Valori medii pentru rezistența pe con q_c (MPa), Zona 3

4.4. Zone 4

Zone 4 has a length of 140m. The compacted area measured 6.300m2. In this area, were executed two boreholes, with disturbed and undisturbed samples, one on the natural ground and one after improvement by dynamic compaction (DC). In addition were performed 3 CPTs in the natural soil and 3 in the improved soil.

ZONA 4						
Adâncime (m)	P4 - în teren natural					
	i_{m300} (%)	I_c	Medie e	Medie ρ_d (g/cm^3)	Medie n (%)	$M_{200\text{-}300\ natural}$ (KPa)
2,50	1,30	0,76	0,76	1,52	44,73	5.131,60
4,50	1,10	0,77	0,76	1,50	43,14	5.820,90
MEDIE	1,20	0,77	0,76	1,51	43,94	5.476,25

Tabel 4.15: Parametrii obținuți în laborator în teren natural, Zona 4

ZONA 4						
Adâncime (m)	F1DC - în teren compactat					
	i_{m300} (%)	I_c	Medie e	Medie ρ_d (g/cm^3)	Medie n (%)	$M_{200\text{-}300}$ natural
2,50	0,05	0,86	0,52	1,79	34,19	11.470,60
4,50	0,00	0,80	0,53	1,74	34,76	10.833,30
MEDIE	0,03	0,83	0,53	1,77	34,48	11.151,95

Tabel 4.16: Parametrii obținuți în laborator în teren compactat, Zona 4

Below are plotted in parallel (before and after improvement) the results obtained for the additional settlement index (im300), porosity (n) and dry density (ρd).

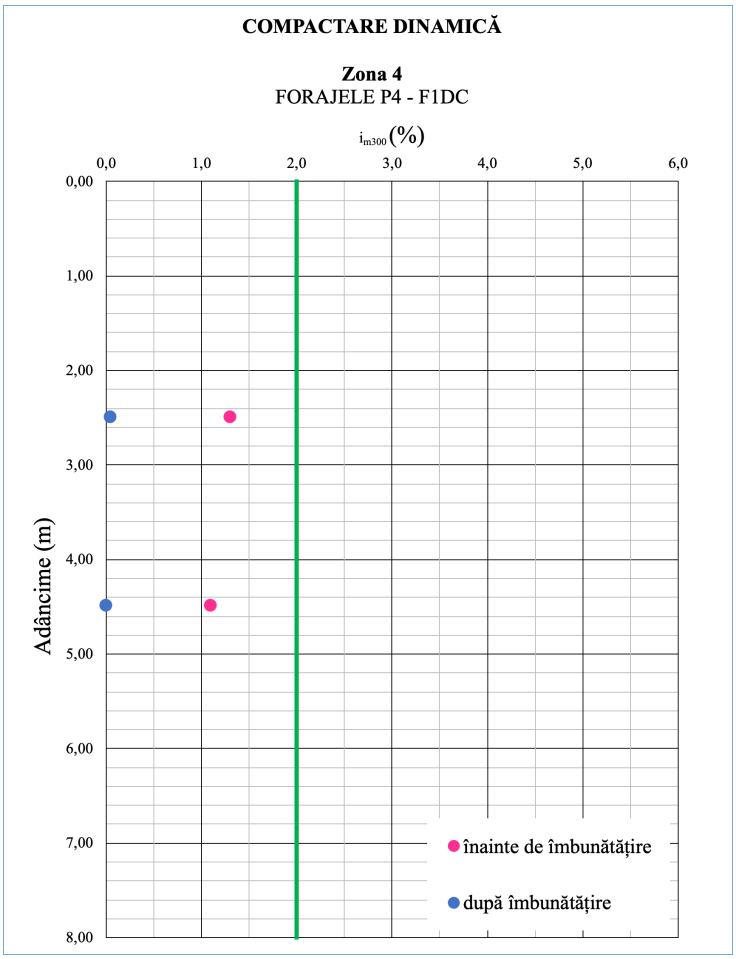

Figura 4.16: Reprezentarea grafică a indicilor tasării specifice la umezire (i_{m300}) obținuți prin încercări de laborator, Zona 4

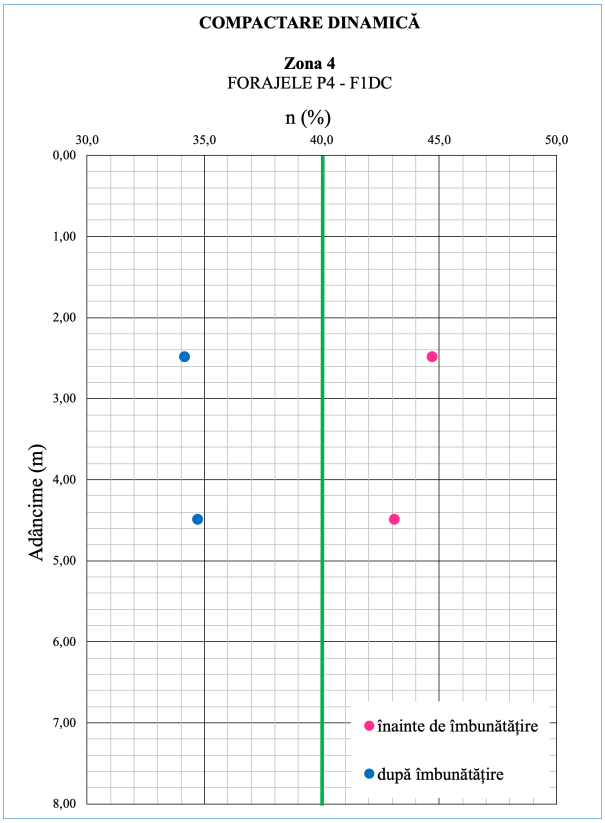

Figura 4.17: Reprezentarea grafică a porozităților (n) obținute prin încercări de laborator, Zona 4

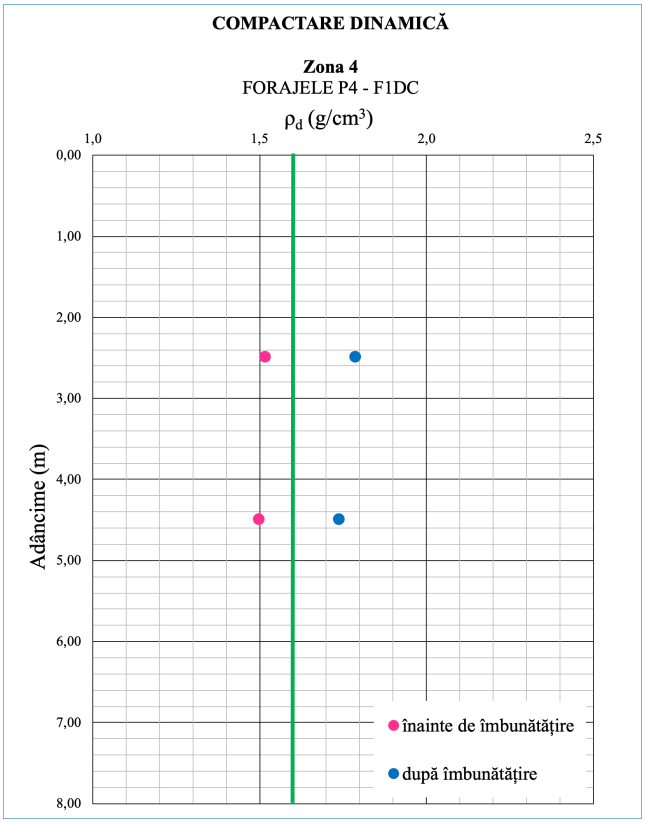

Figura 4.18: Reprezentarea grafică a densităților în stare uscată (ρ_d) obținute prin încercări de laborator, Zona 4

Raport între valorile compactate și cele naturale ZONA 4 P4 - F1DC					
i_{m300} (%)	**I_c**	**Medie e**	**Medie ρ_d (g/cm^3)**	**Medie n (%)**	**$M_{200\text{-}300\ natural}$ (KPa)**
0,02	1,08	0,69	1,17	0,78	2,04
< 1		**< 1**	**> 1**	**< 1**	**> 1**

Tabel 4.17: Rapoartele valorilor medii ale parametrilor obținuți prin încercări de laborator pe 6m, Zona 4

The edometric modules increased considerably after compaction reaching a percentage of improvement of 100%.

From the cone penetration tests (CPT) resulted an average value of the tip cone resistance qc of 1,5MPa and after inmprovement of 3 MPa.

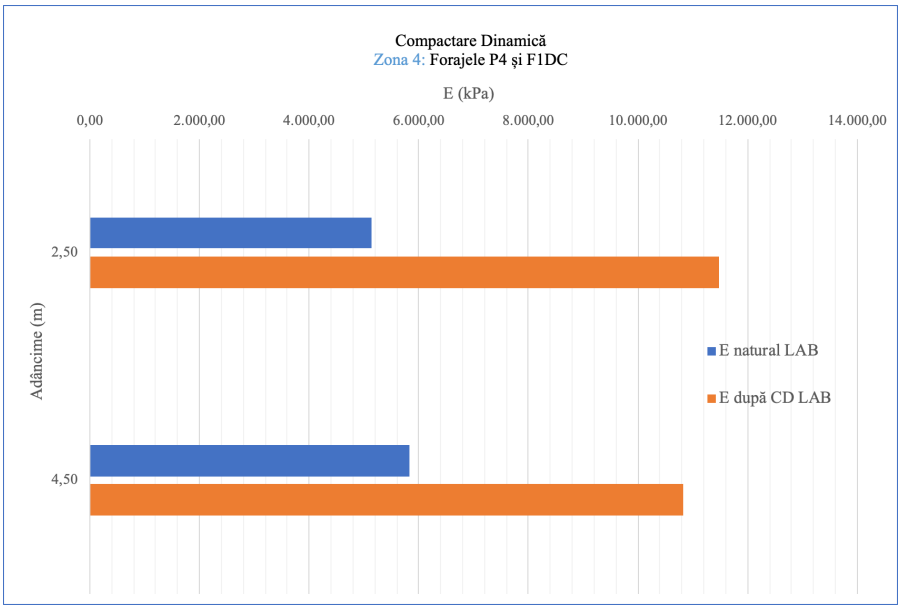

Figura 4.19: Reprezentarea grafică a modulilor edometrici $E_{200\text{-}300}$ obținuți prin încercări de laborator, Zona 4

5. CONCLUSIONS

On the site of the studied project, the foundation soil consists on the first 6m of loessoid soils sensitive to moisture. According to the project, it was necessary to improve this layer, respectively desensitization in relation to water. Intensive dynamic compaction technology was used for this purpose.

Through specific laboratory and in situ tests, the requirements for the improved soil parameters and the attestation of the quality of the works were established.

Laboratory tests have also shown a decrease in compressibility for improved soil reflected by increases in edometric modules. These changes in compressibility are differentiated by areas depending on the initial compressibility and local variations in the nature of the materials and the humidity.

Based on the geotechnical tests that have been performed, correlations of the mechanical parameters will be established in order to optimize the way of certifying their desensitization.

Is proposed a more efficient and faster methodology for attesting the PSU ground improvement:

a. Establishment of α at the site:

• Execution of laboratory tests to determine the physical and mechanical properties and determine the footprint of the soil in the area
• Performing static cone penetration tests (CPTs)

b. For the determination of the deformation modulus E for the improved PSU, only CPTs will be performed (without the need for further laboratory tests)

The methodology will be confirmed by analysing the obtained data.

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