WORKSHOP ON PENETRATION TESTING
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Auditorium Opera Primaziale, Pisa

AN INNOVATIVE METHOD TO EVALUATE DEGREE OF COMPACTION OF RIVER EMBANKMENTS USING CPT

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Presentation outline

1 Introduction

Compaction = Densification of soil by removing air voids using mechanical equipment

Objectives

- ✓Improving soil strength by increasing the unit weight
- ✓Increasing the bearing capacity of foundations
- ✓Decreasing the undesirable settlement of structures
- ✓Control undesirable volume changes
- ✓Reduction in hydraulic conductivity
- ✓Increasing the stability of slopes

River embankments

DESIGN

Saturated for only a short period of time

↓

POOR ATTENTION

CAUSES of FAILURE

Different erosion mechanisms and slope instability

↓

POOR DEGREE OF COMPACTION = PREDISPOSING FACTOR

ASSESSMENT of the SAFETY DEGREE

Definition of design values for strength and permeability characteristics

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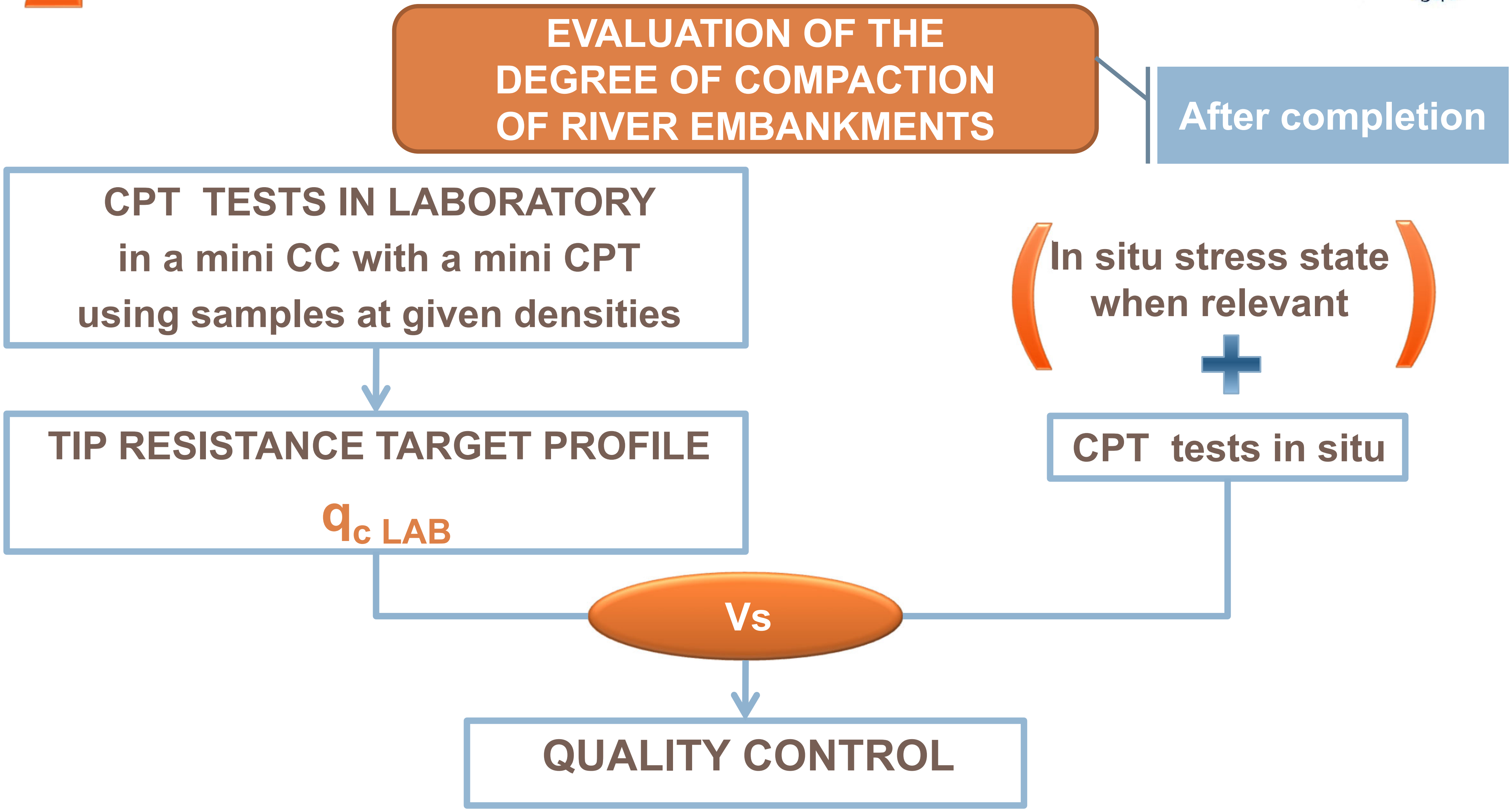
DEPENDENCY ON THE DEGREE OF COMPACTION

NEED FOR AN EXPEDITIOUS AND ACCURATE METHOD TO EVALUATE DEGREE OF COMPACTION

2 The method



- ✓ Existing embankments: evaluation of the degree of compaction
- ✓ Embankments under construction: it is possible (a–priori) to establish which is the expected q_c corresponding to a prescribed density

3 Hypotheses

I. The tip resistance is not affected by the tip diameter

≅ q_c from CPT (d= 35.7 mm)

≅ q_{cLAB} from mini-CPT (d= 8 mm)

Even if:

$V_{mini\text{-}CPT} = 1/4 \cdot V_{CPT}$

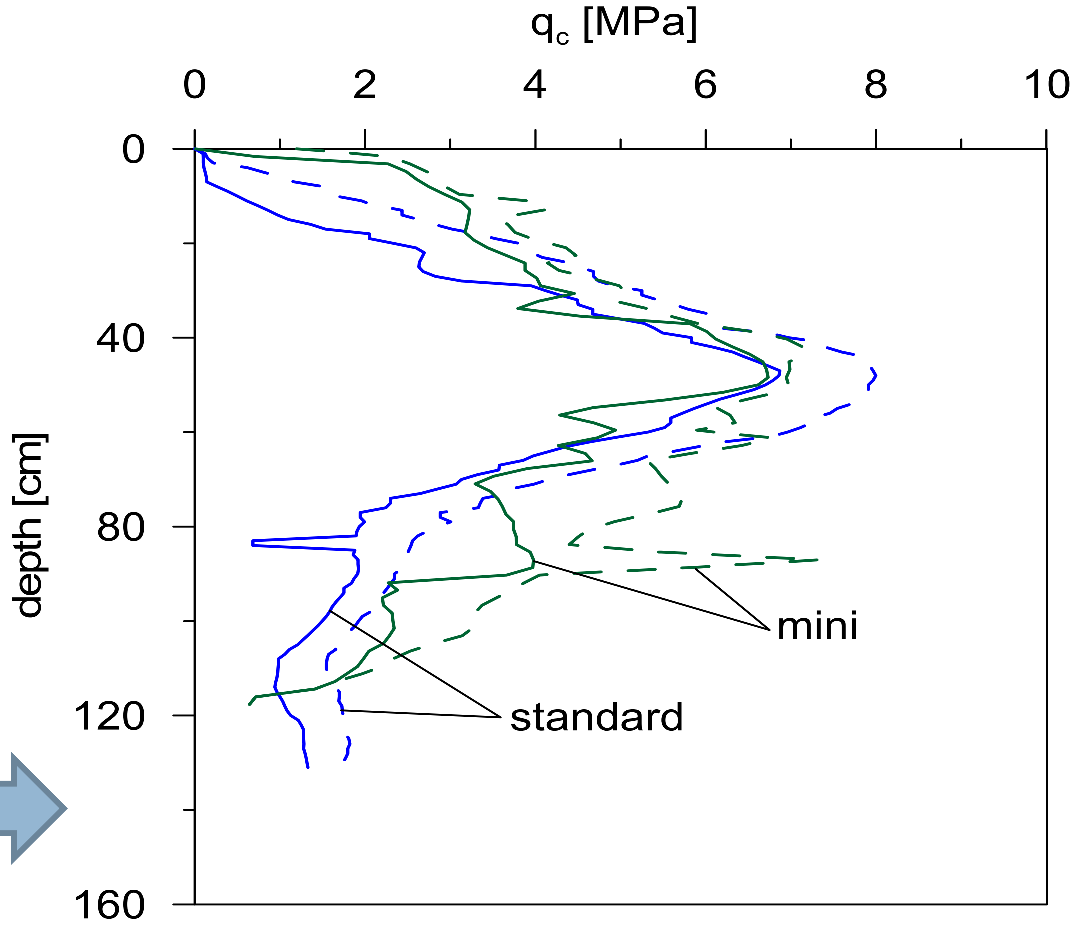
$$V = \frac{v \cdot d}{c_v}$$

Normalized velocity

(Finnie & Randolph, 1994)

Where:
v: velocity of the penetrometer
d: diameter of the penetrometer
c_v: coefficient of consolidation of the soil

UNSATURATED SILT MIXTURES



3 Hypotheses

II. FOR DRY SAND →

$$q_c = C_0 \cdot \sigma'^{C1}_{v0} \cdot \sigma'^{C2}_{h0} \cdot e^{C_3 \cdot D_R}$$

(Baldi et al. 1986, Jamiolkowski et al. 1988, Garizio 1997, Jamiolkowski et al. 2000, 2001)

III. IN SITU STRESS STATE →

- Estimate of the vertical effective stress component σ_v
- At-rest earth pressure coefficient → DMT test

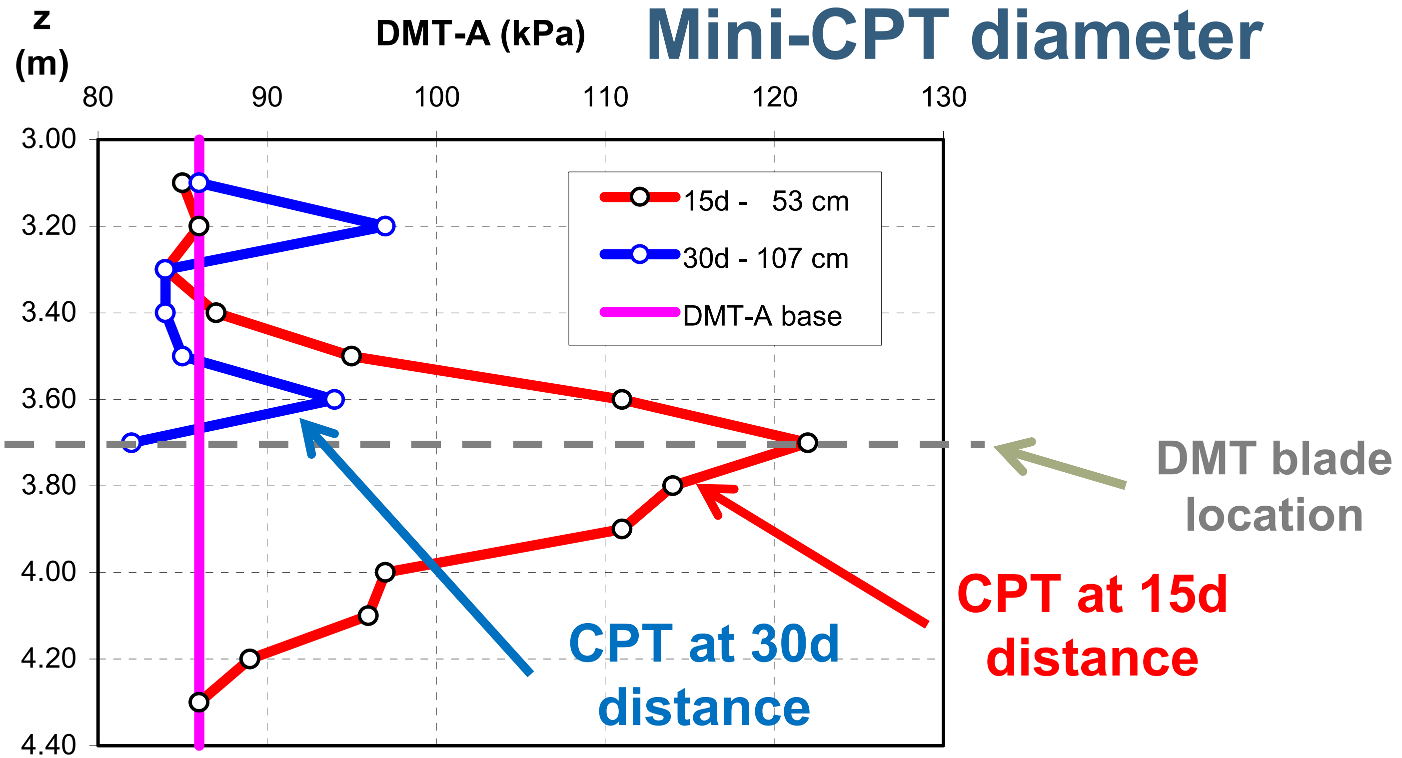
$$K_0 = 0.376 + 0.095 \cdot K_D + 0.0046 \frac{q_c}{\sigma'_{v0}}$$

(Jamiolkowski et al. 1988)

3 Hypotheses

IV. The effects of the mini–chamber sizes can be considered negligible if:

$$\frac{\text{CC diameter}}{\text{Mini-CPT diameter}} = 40$$



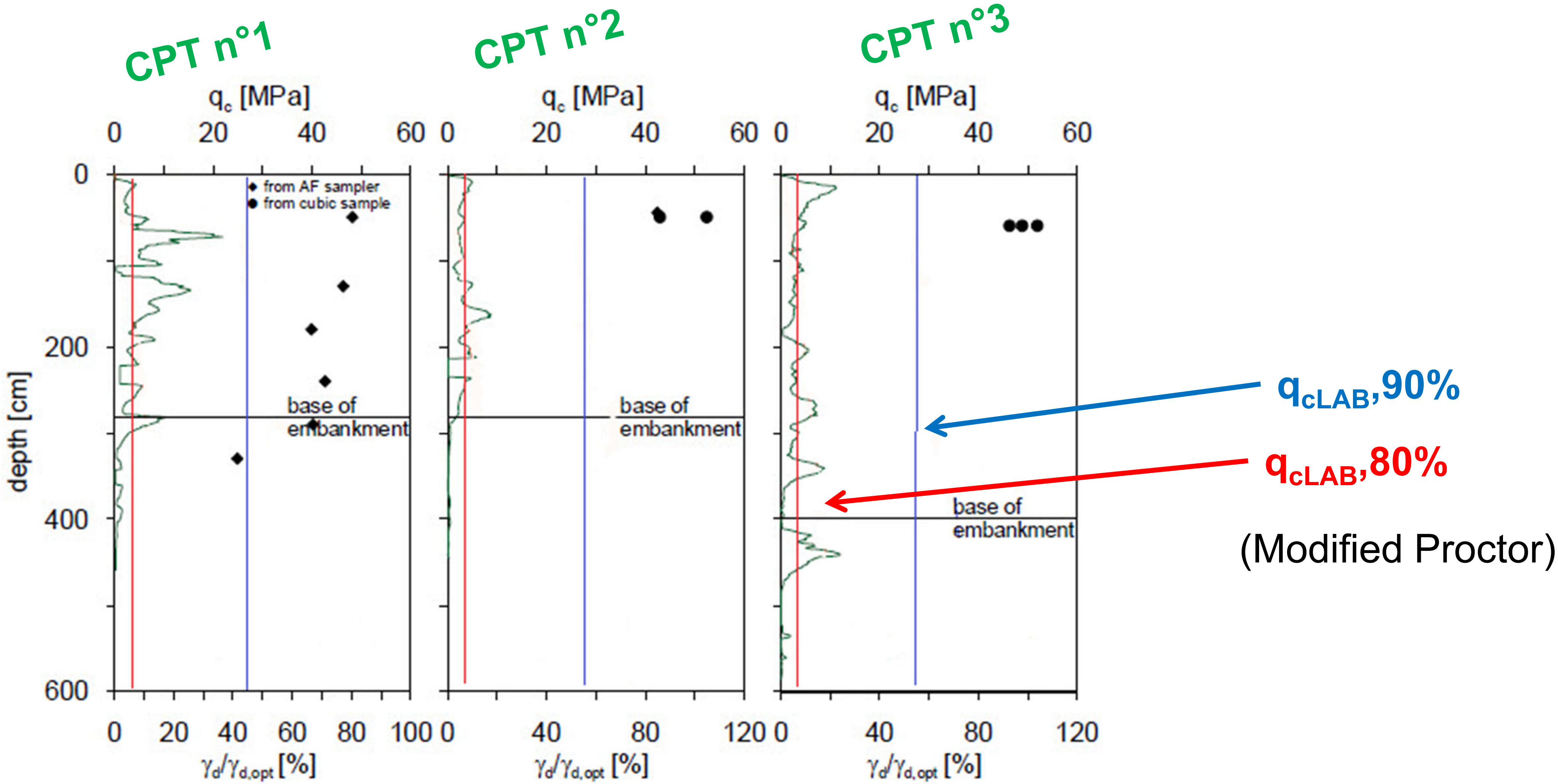
When the horizontal distance between DMT and CPT is ≥ 20 times the cone diameter the DMT is no more sensitive to the passage of the cone

V. It is acceptable:

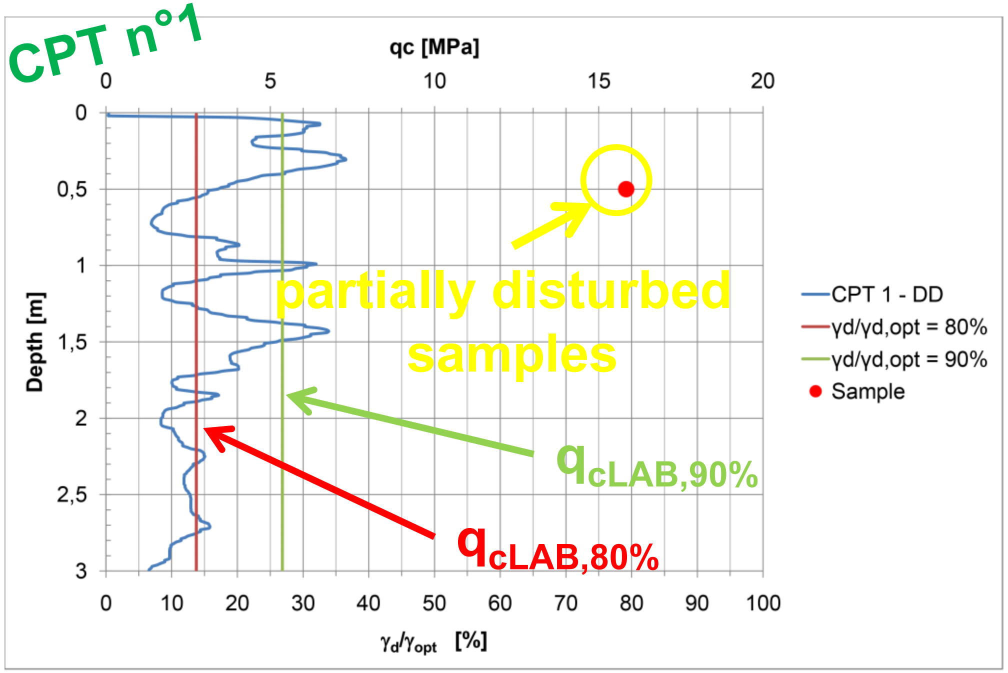
$$\frac{\text{Mini-CPT diameter}}{\text{Diameter of the biggest particle}} \geq 4$$

3 Hypotheses

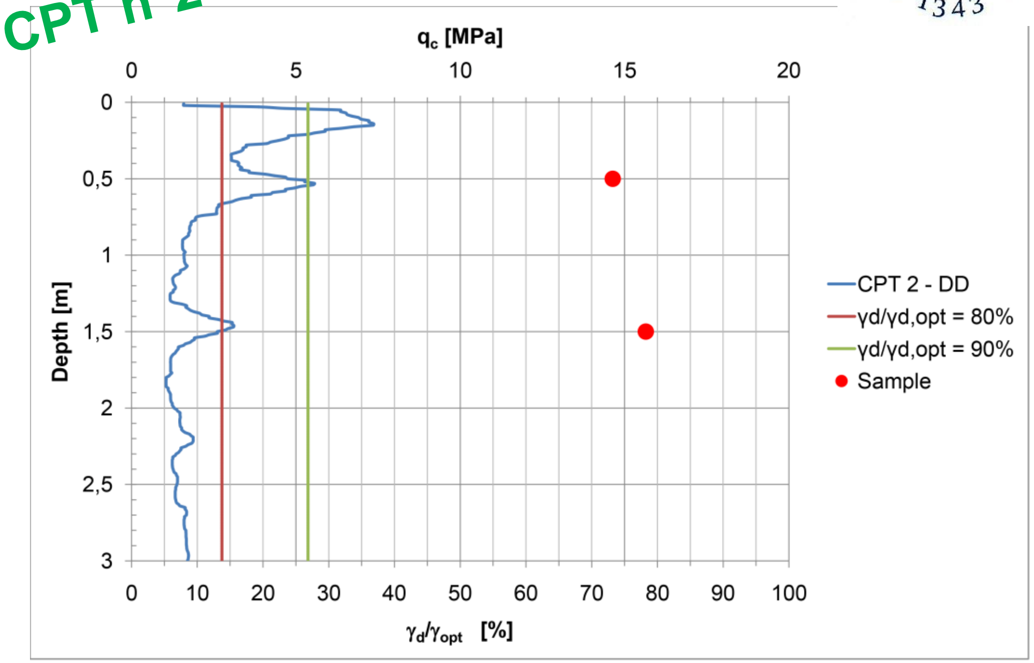
The method has been successfully used in some case histories



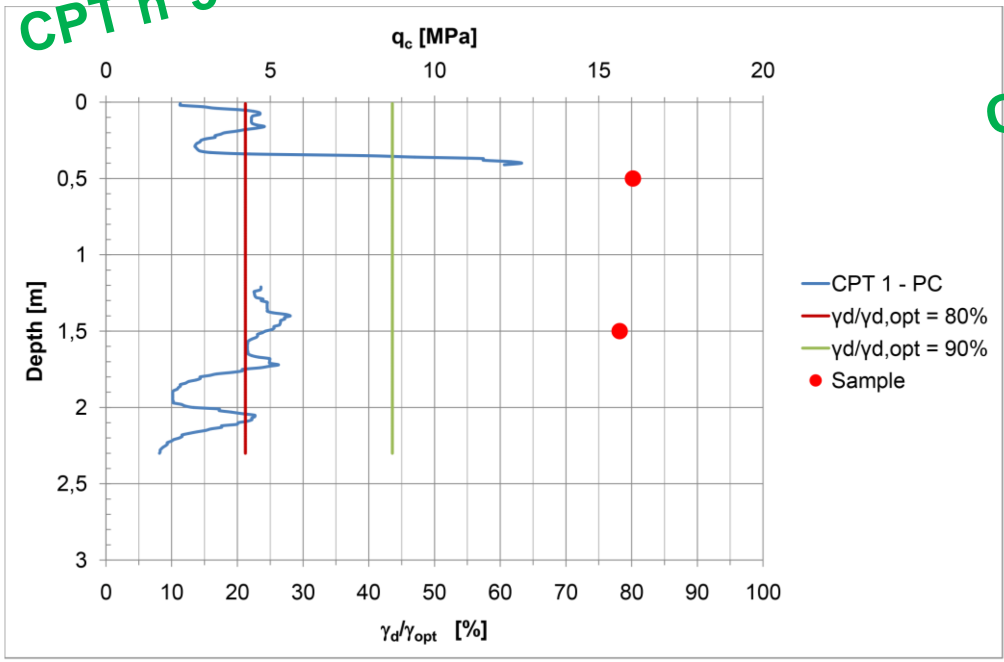
CPT n°1



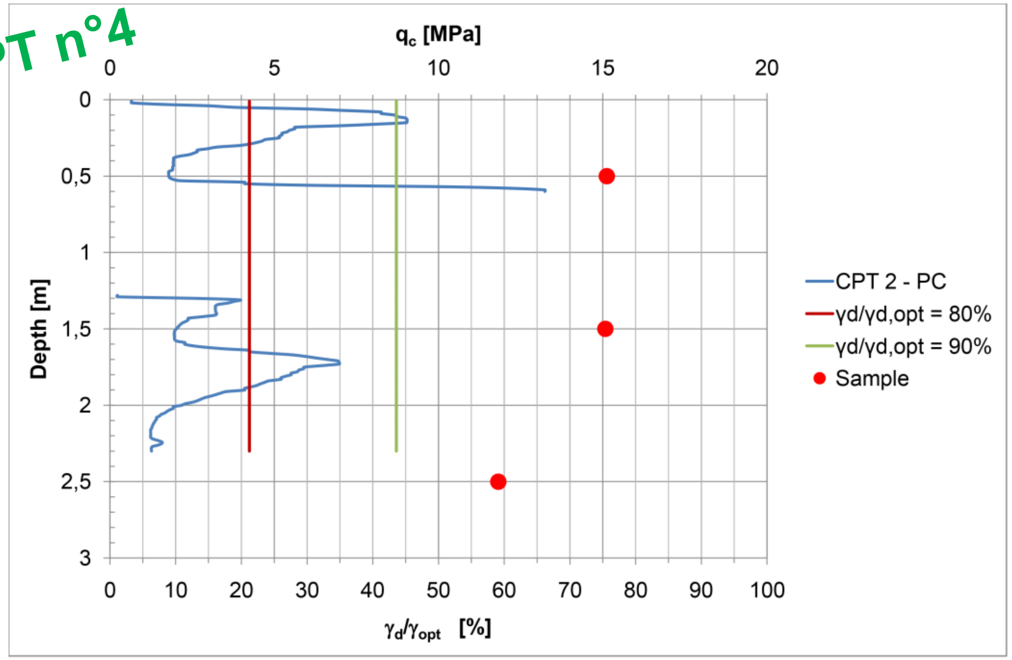
CPT n°2



CPT n°3



CPT n°4



4 The equipment

Developed by the Geotechnical Laboratory of the University of Pisa in partnership with Pagani Geotechnical Equipment

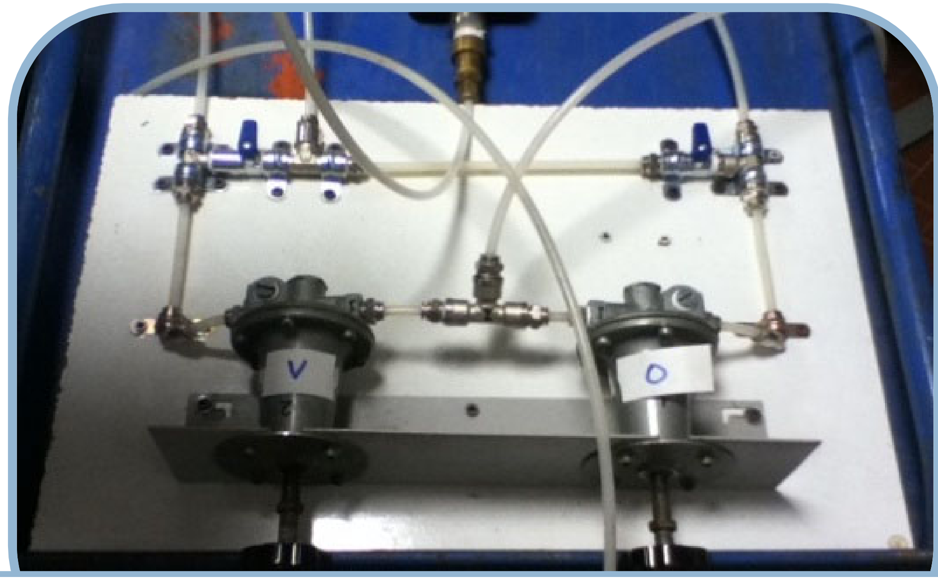
THE EQUIPMENT

Diameter = 320 mm; Height = 210 mm

Top boundary → rigid
Lateral and bottom boundaries → flexible → provided with latex membranes

THE EQUIPMENT

The membranes allow the independent application of horizontal and vertical stresses through a compressed air system.



Manual air pressure regulators for the vertical and horizontal stresses.

All the possible chamber boundary conditions can be applied:

- **BC1 = σ_h = cost; σ_v = cost**
- **BC2 = ε_h = 0; ε_v = 0**
- **BC3 = ε_h = 0; σ_v = cost**
- **BC4 = σ_h = cost; ε_v = 0.**

THE EQUIPMENT

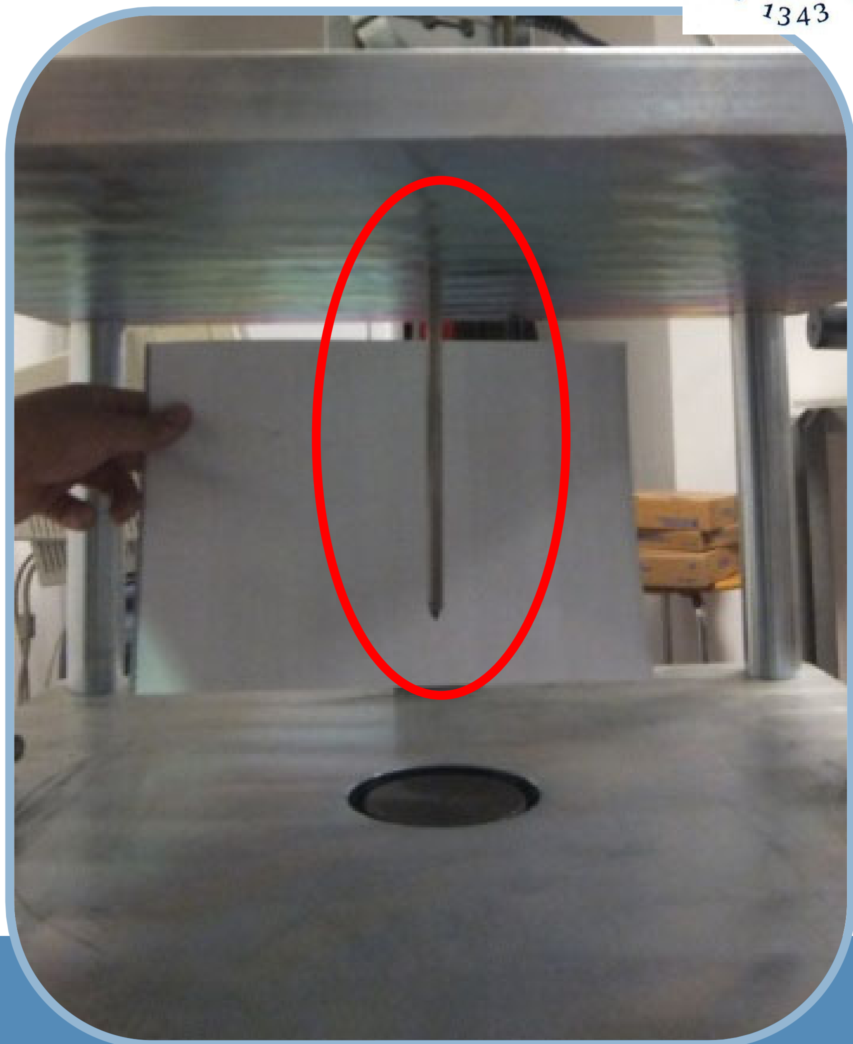
step by step electric motor

aluminum frame

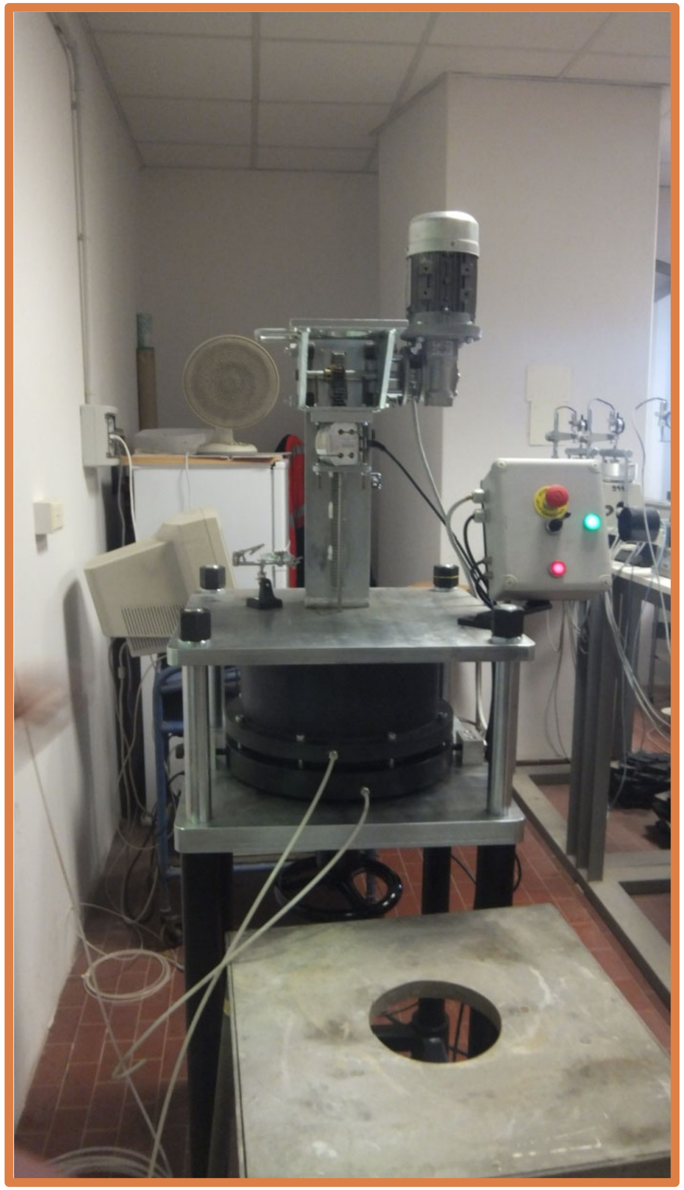
locking system

IN SUPREMÆ DIGNITATIS 1343

THE EQUIPMENT



Mini CPT:
- 60° conical tip
- cone diameter = 8 mm
- external sleeve
- standard rate of 20 mm/s
- load cell external to the cone



5 Laboratory tests

CRUSHED SAND
(Calibration material)

d_{50} = 0,5 mm C_u = 2
γ_{min} = 1,419 kg/dm^3 ; γ_{max} = 1,663 kg/dm^3

Dry sand samples are reconstituted inside the CC to a given D_R by pluvial deposit.

FINE GRAINED SOILS
(Building materials)

Only the particle size fraction which pass the 2 mm sieve

DD	A4; γ_{dmax} = 18.2 kN/m^3; w_{opt}=13.2%
PC	A4; γ_{dmax} = 19.5 kg/m^3; w_{opt}=10.8%
FR	A6; γ_{dmax} = 20.5 kN/m^3; w_{opt}=9.43%

partially saturated

FINE GRAINED SOILS

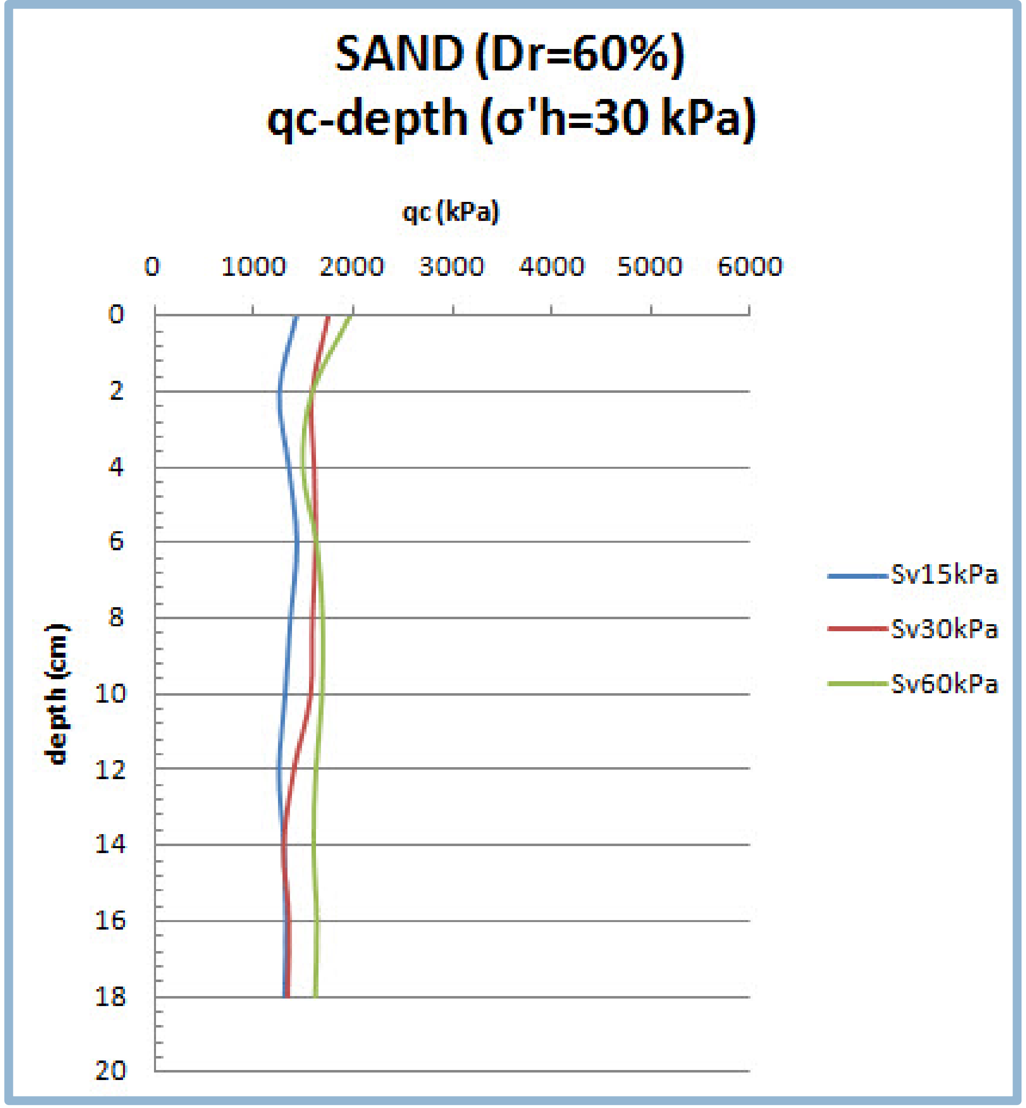
- ✓ Fine grained soil samples are reconstituted in 5 layers at a known unit weight using static compaction (hydraulic ram) in a mold
- ✓ The compaction effort, required to consolidate each layer and the sample, is registered:

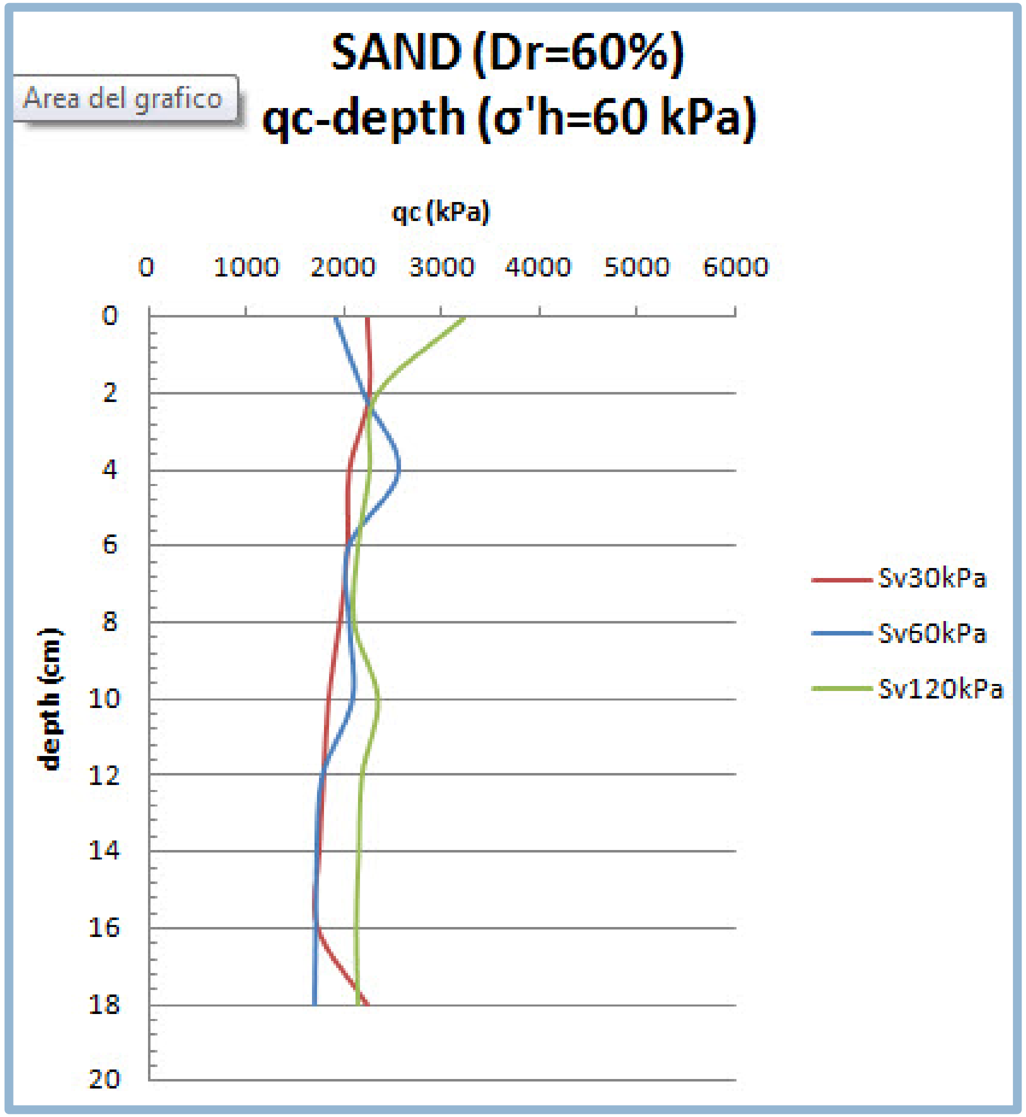
$$E = \left(1/2 \cdot \sum_{i=1}^{5} F_i \cdot \delta_i\right)/\sum_{i=1}^{5} V_i$$

dry sand

TIP RESISTANCE STRESS DEPENDENCE

σ'_h = costant

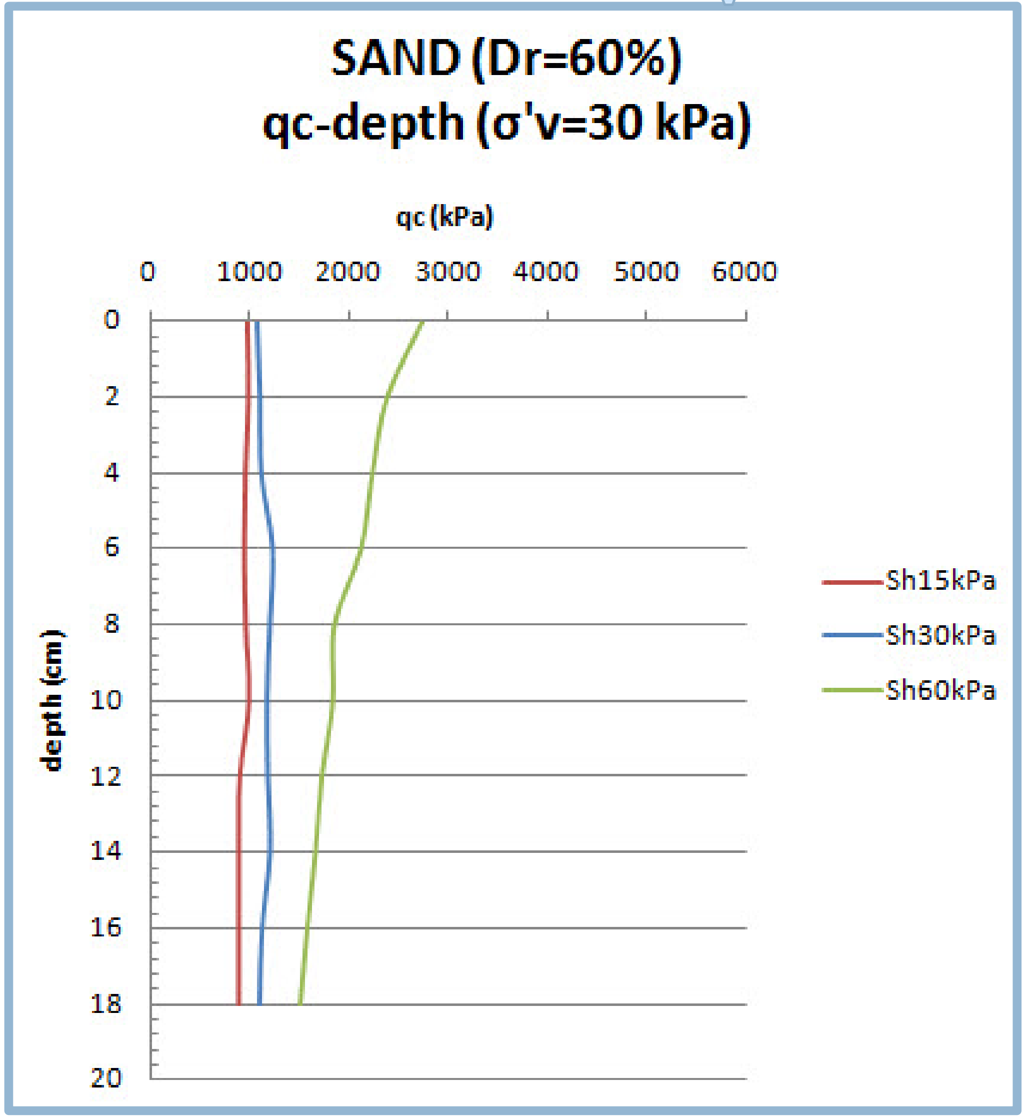


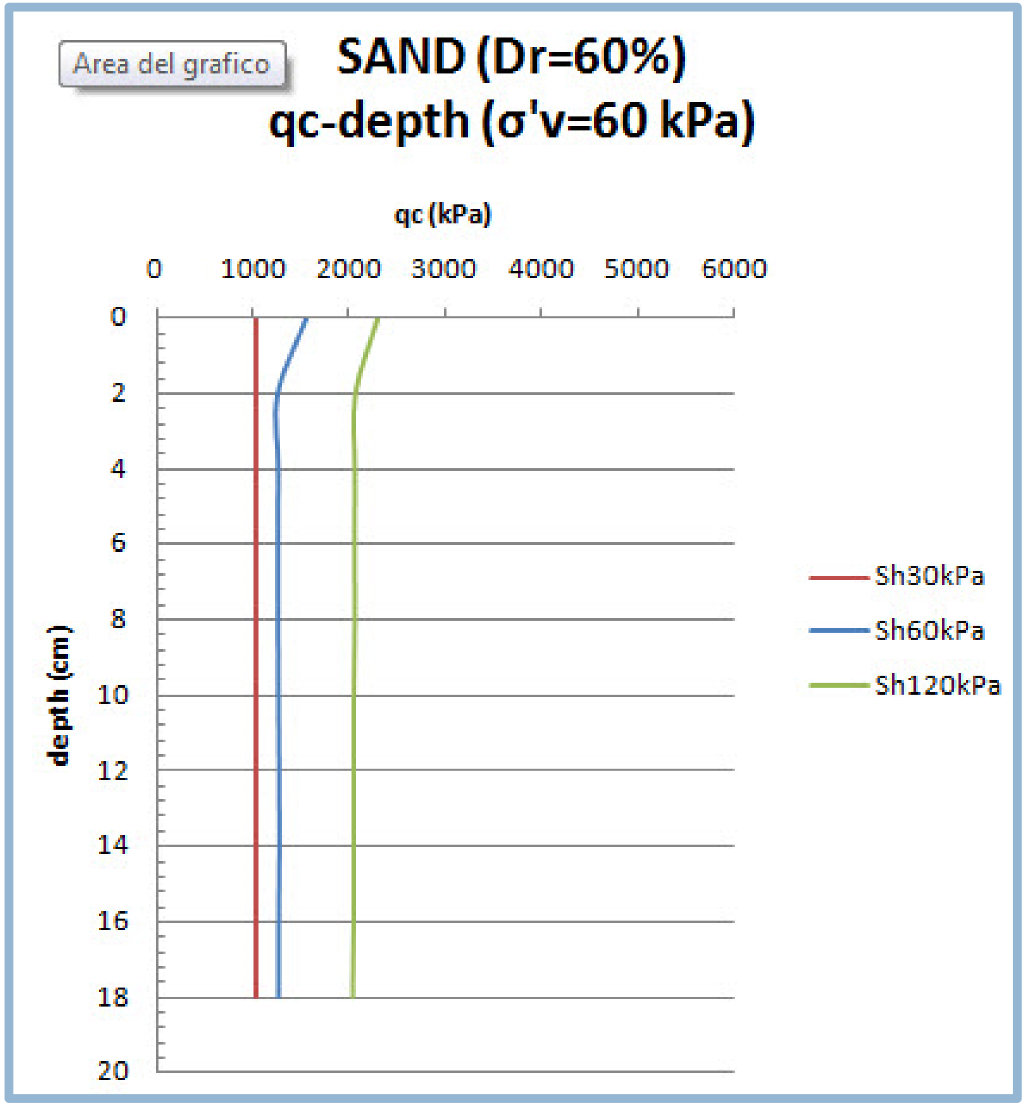


dry sand

TIP RESISTANCE STRESS DEPENDENCE

σ'_v = costant





Sabbia asciutta

D_R = 60%

(d_{50}= 0.5 mm; C_U= 2)

$q_{c\,LAB}$ [kPa]	σ'$_h$ [kPa]	σ'$_v$ [kPa]	C_1	C_2
1293		15		
1490	30	30	0.17	0
1641		60		
1984		30		
1905	60	60	0.11	0
2305		120		
949	15			
1925	30	30	0	0.51
1168	60			
1041	30			
1290	60	60	0	0.50
2080	120			

TIP RESISTANCE STRESS DEPENDENCE

$$q_c = C_0 \cdot \sigma'^{C1}_{v0} \cdot \sigma'^{C2}_{h0} \cdot e^{C_3 \cdot D_R}$$

AT A GIVEN D_R VALUE σ_h IS THE MOST INFLUENTIAL PARAMETER ON q_{cLAB}

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Material	q_{cLAB} [kPa]	E [MJ/m^3]	γ_d [kN/m^3]	γ/γ_{opt}	σ'_v [kPa]	σ'_h [kPa]	σ'_p [kPa]	w [%]
DD	2807	0,395	14,56	0,82	30	30	8224	13,2
DD	1786	0,238	14,56	0,82	50	50	6157	13,2
DD	1512	0,300	14,56	0,82	80	80	6753	13,2
DD	4751	1,324	16,38	0,92	30	30	24475	13,2
DD	4063	1,413	16,38	0,92	50	50	24524	13,2
DD	4990	1,501	16,38	0,92	80	80	24524	13,2
PC	3274	0,620	15,6	0,82	30	30	13732	10,8
PC	3648	0,697	15,6	0,82	50	50	14713	10,8
PC	3850	0,545	15,6	0,82	80	80	13732	10,8
PC	7191	2,407	17,55	0,92	30	30	39628	10,8
PC	7877	2,759	17,55	0,92	50	50	40707	10,8
PC	7603	2,211	17,55	0,92	80	80	36979	10,8
FR	6533	4,124	18,5	0,92	30	30	46864	12
FR	6535	3,316	18,5	0,92	30	30	43137	12
FR	6767	2,938	18,5	0,92	30	30	37465	12
FR	3254	1,735	18	0,90	30	30	22731	12
FR	3568	1,735	18	0,90	30	30	24006	12
FR	4056	1,828	18	0,90	30	30	24401	12
FR	1843	0,511	16	0,80	30	30	8608	12
FR	1736	0,463	16	0,80	30	30	8314	12
FR	2023	0,475	16	0,80	30	30	7824	12
FR	2036	0,260	16	0,80	30	30	10104	4
FR	1479	0,307	16	0,80	30	30	9810	4
FR	1827	0,346	16	0,80	30	30	10791	4
FR	3077	0,579	16	0,80	30	30	15990	8
FR	2533	0,622	16	0,80	30	30	15892	8
FR	2455	0,565	16	0,80	30	30	15303	8

DD; PC; →

$\gamma_d = 80 \div 92\% \gamma_{dmax}$ (Modified Proctor)

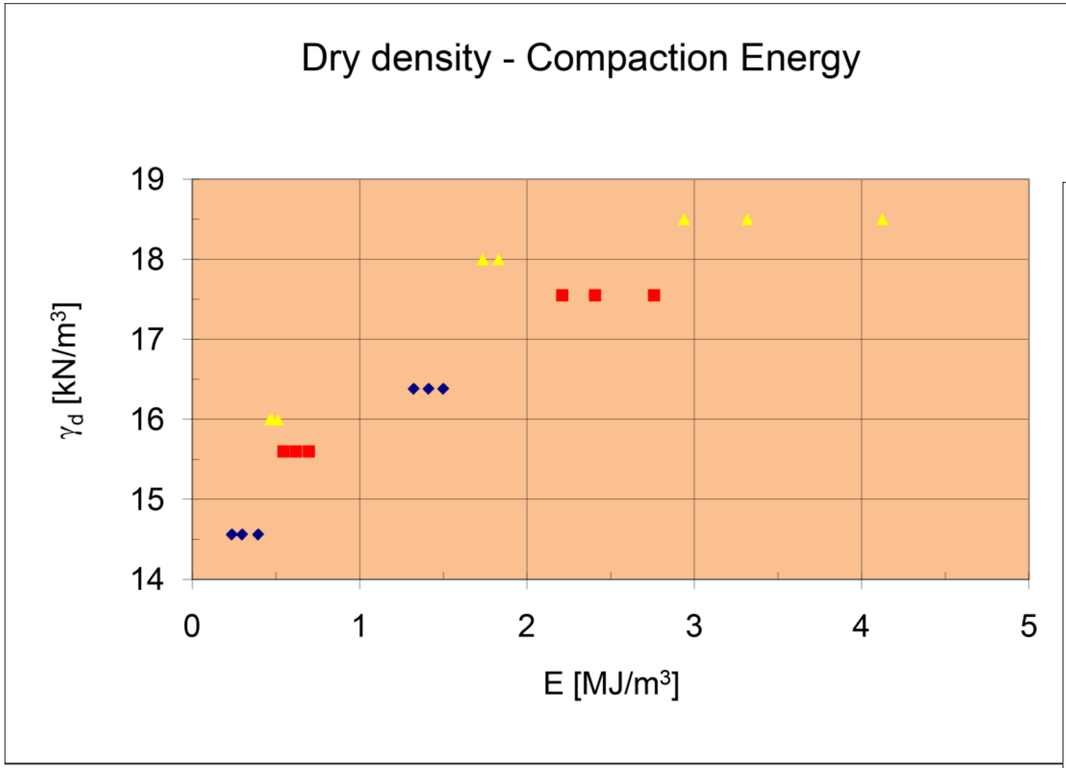
$w = w_{opt}$

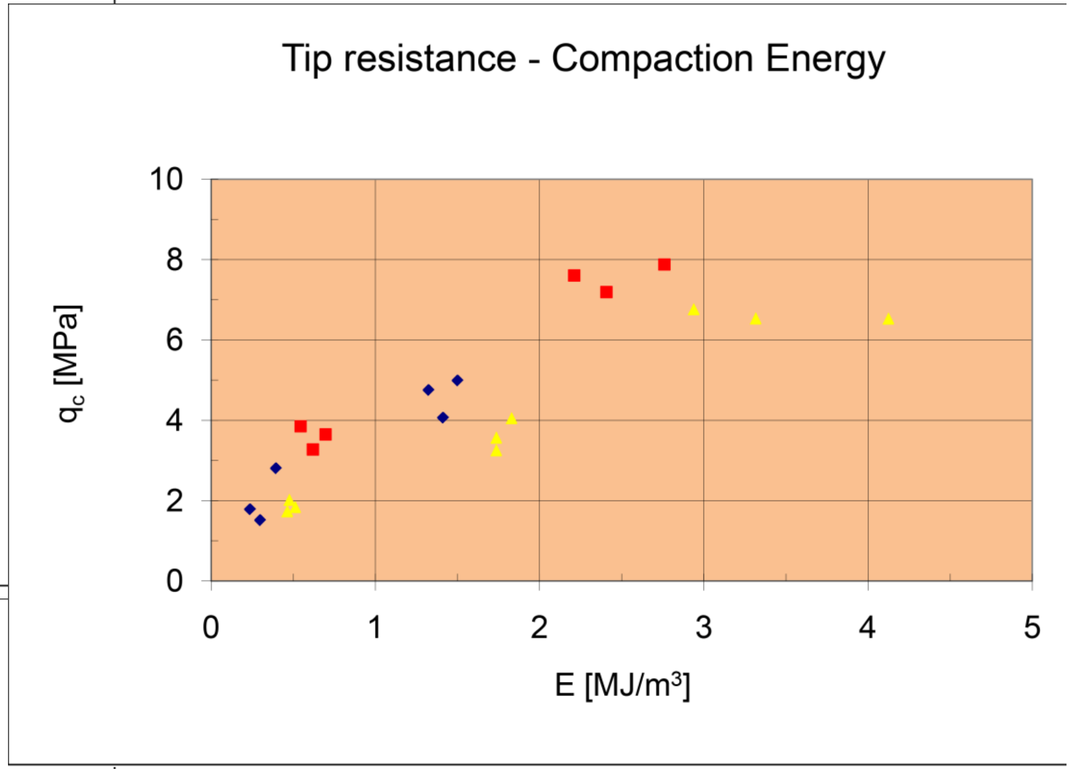
FR →

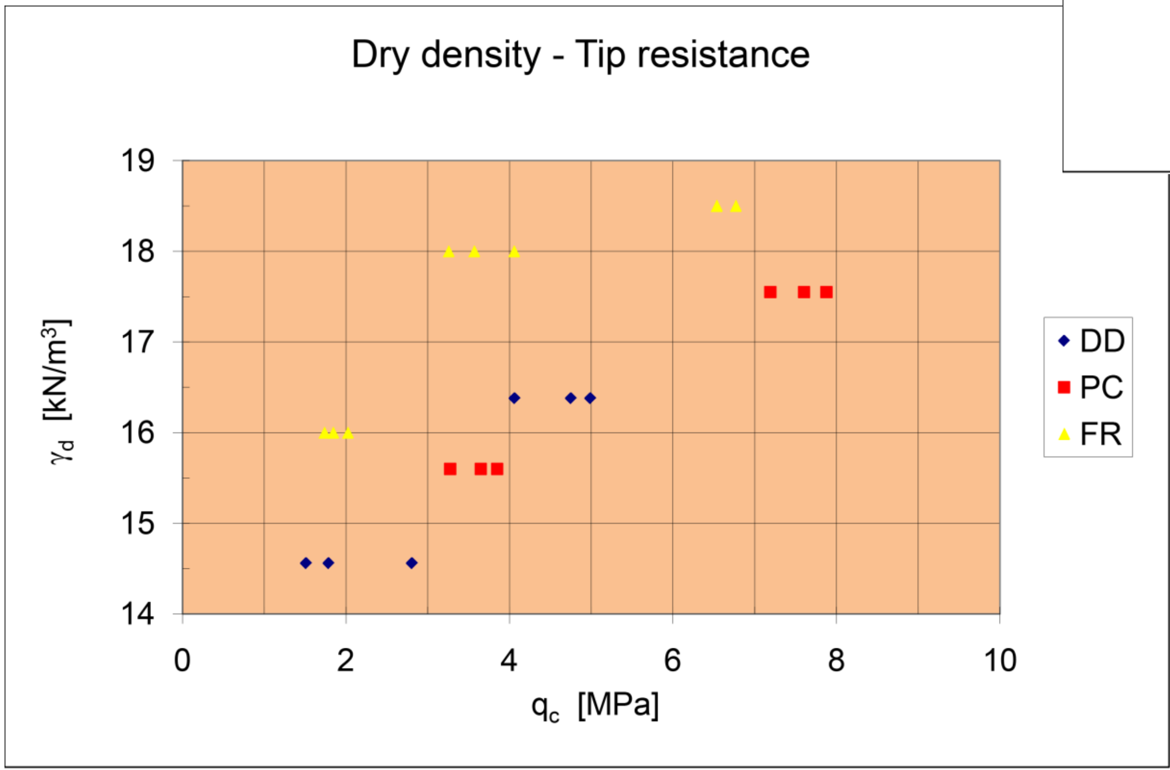
$\gamma_d = 80\% \gamma_{dmax}$ (Modified Proctor)

w= 4; 8; 12%

Suction → evaluated according to Aubertin et al. (2003)

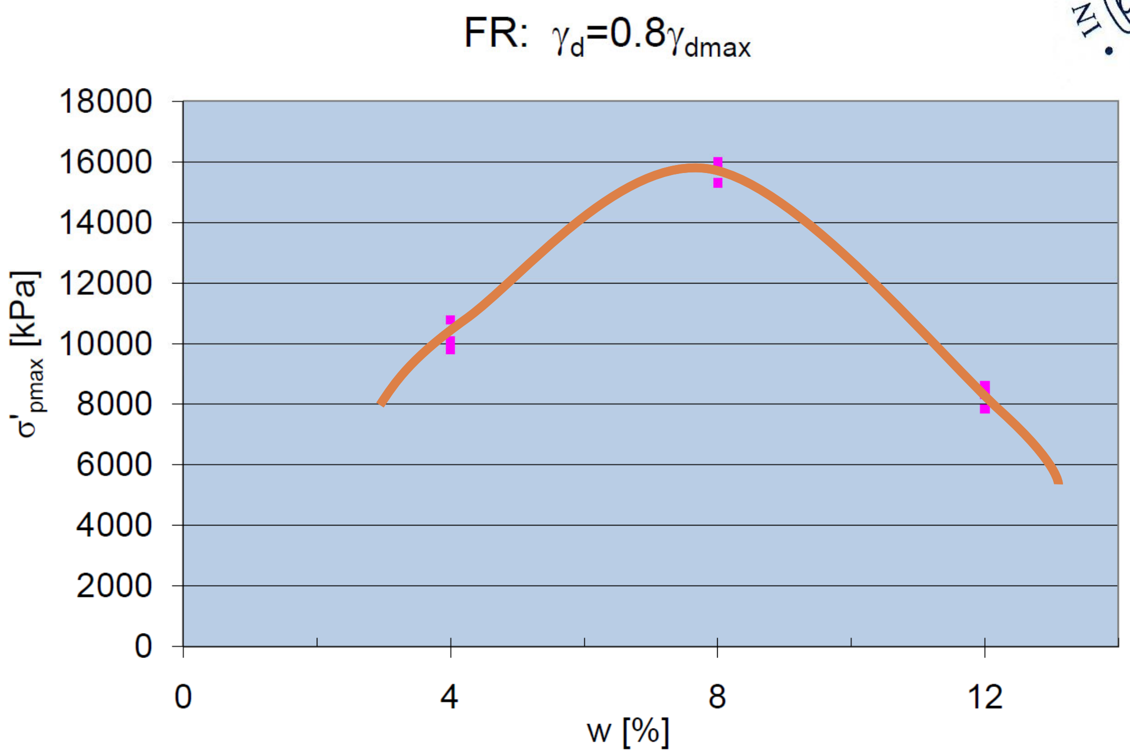


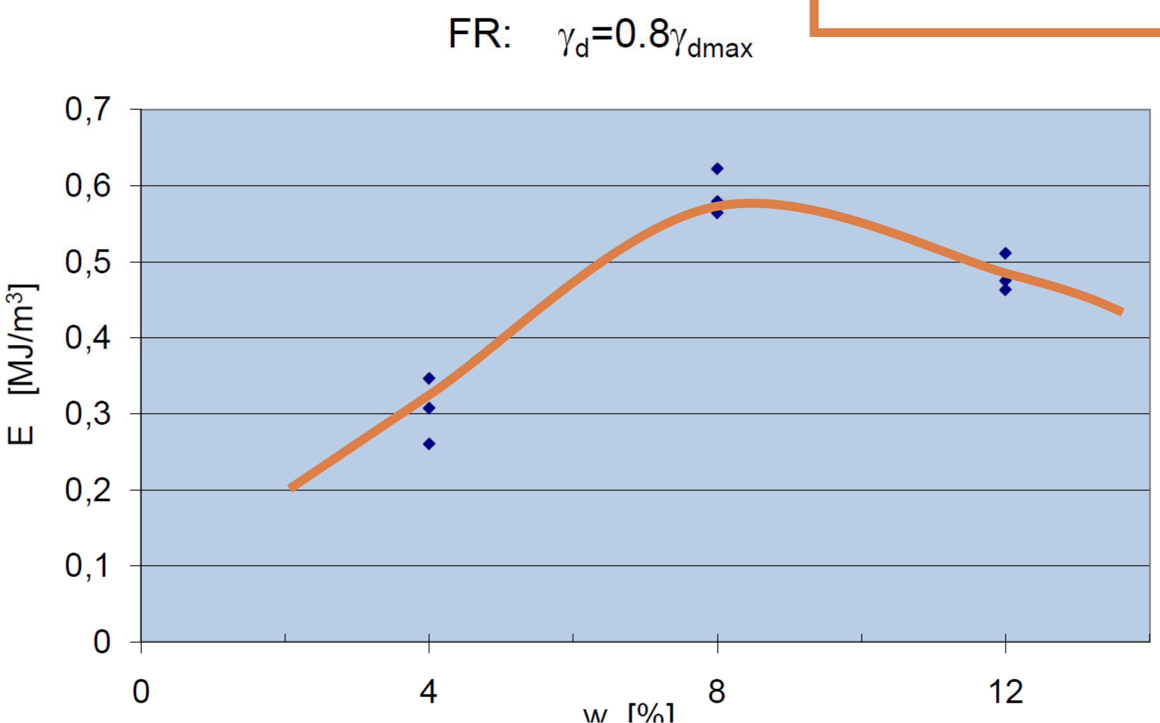


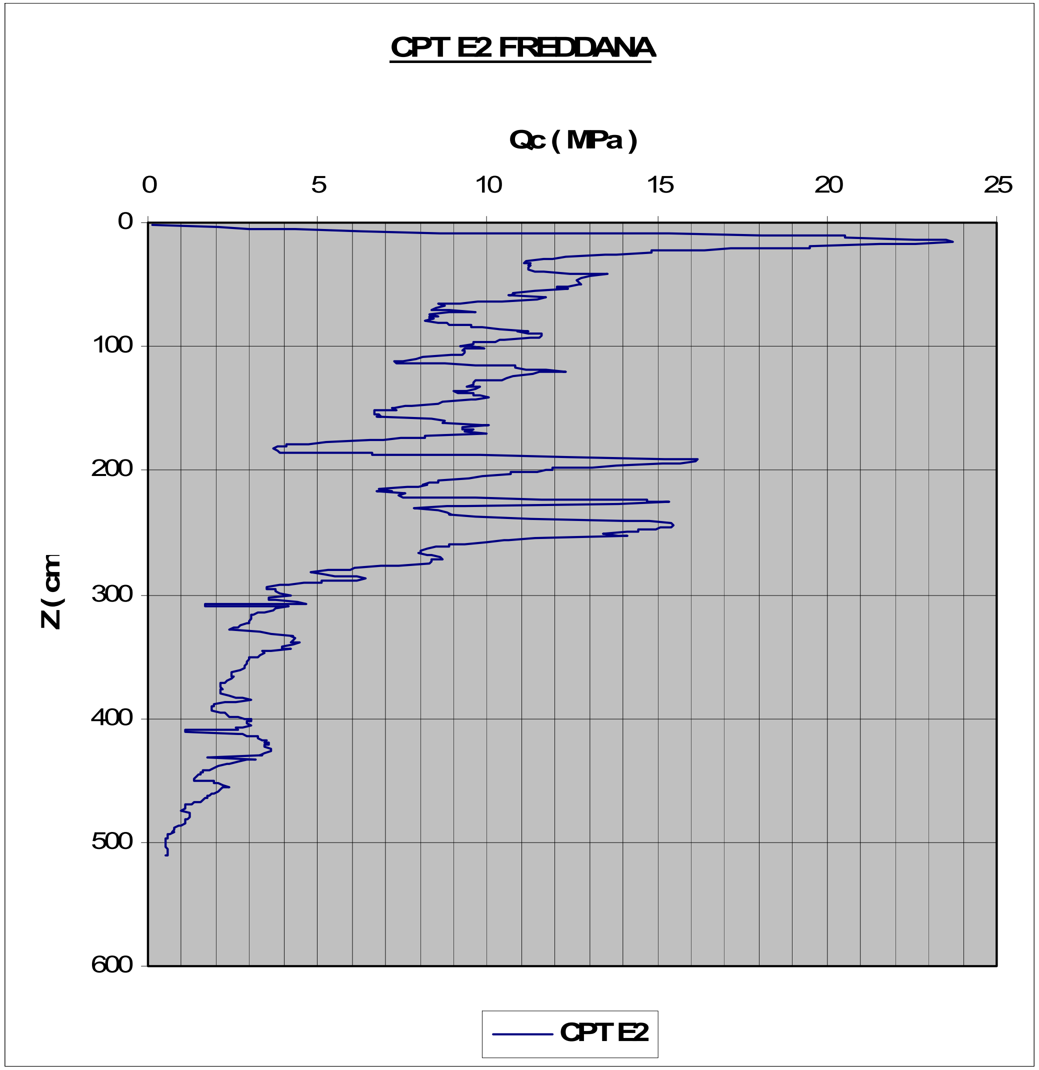


There is a clear relationship between tip resistance – degree of compaction – compaction energy, while, confinement pressures and suction have little effect on the tip resistance

FR →
$\gamma_d = 80\%\gamma_{dmax}$ (Modified Proctor)
w= 4; 8; 12%
($w_{opt} \cong 10\%$)







Very high values of q_c in the shallower layers of the embankments

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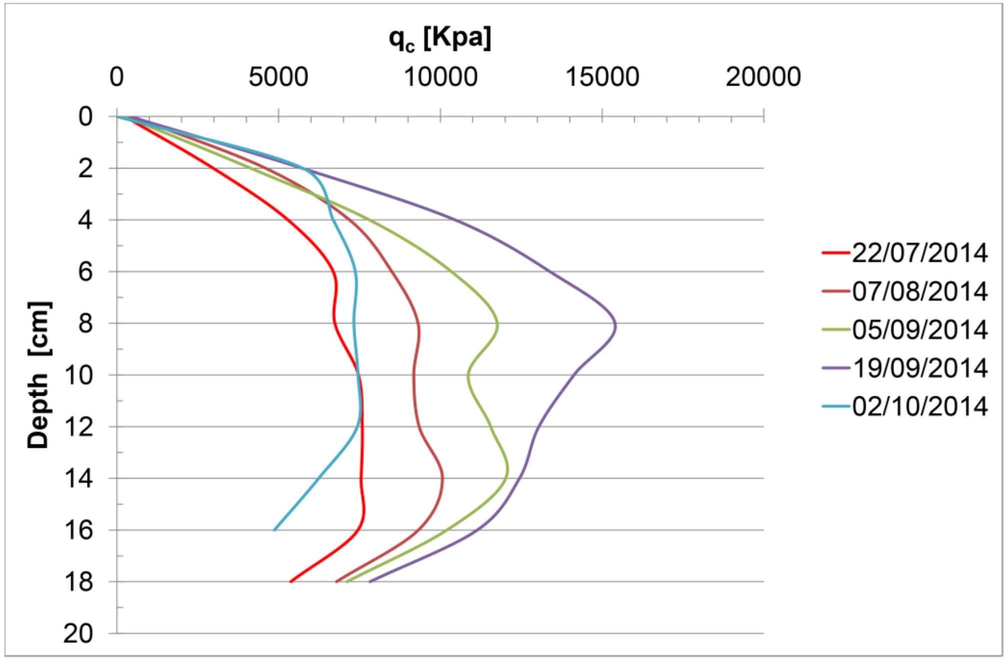
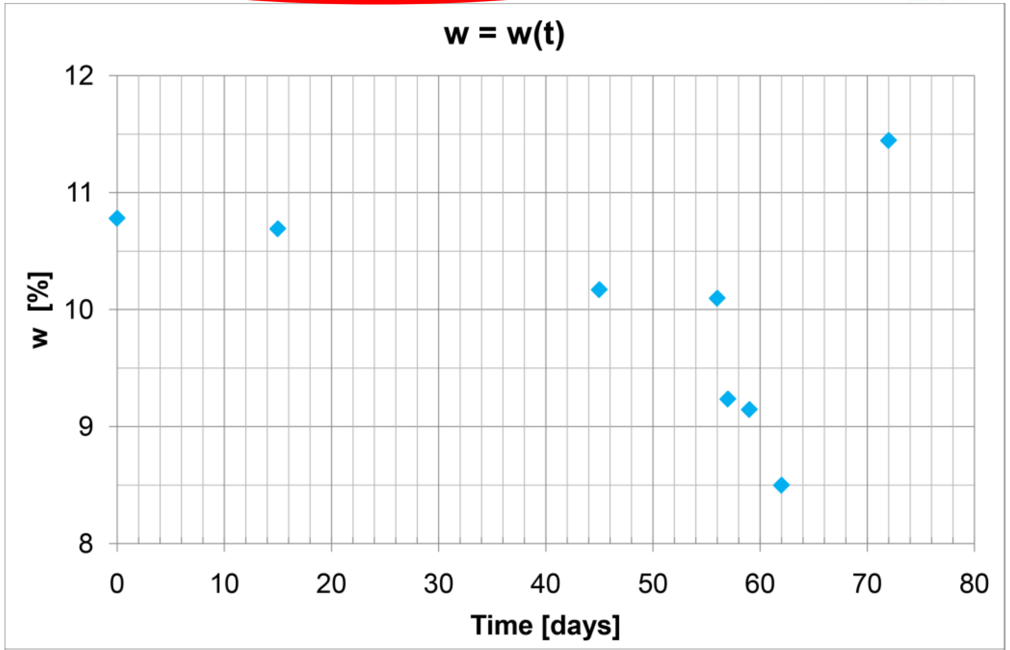
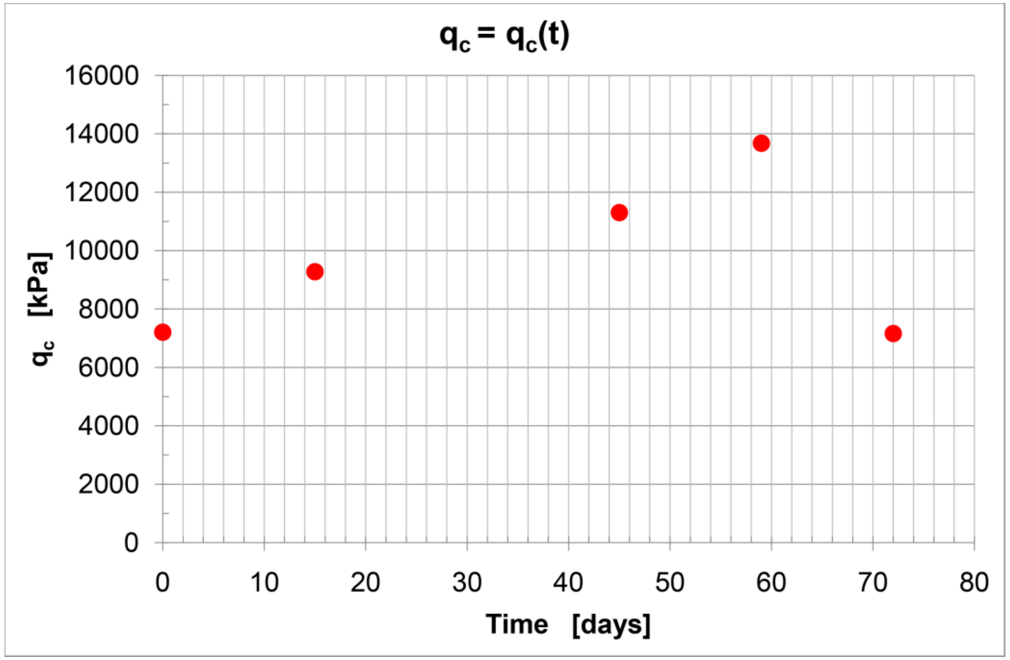
EVAPO - TRANSPIRATION PHENOMENA (DESSICATION)

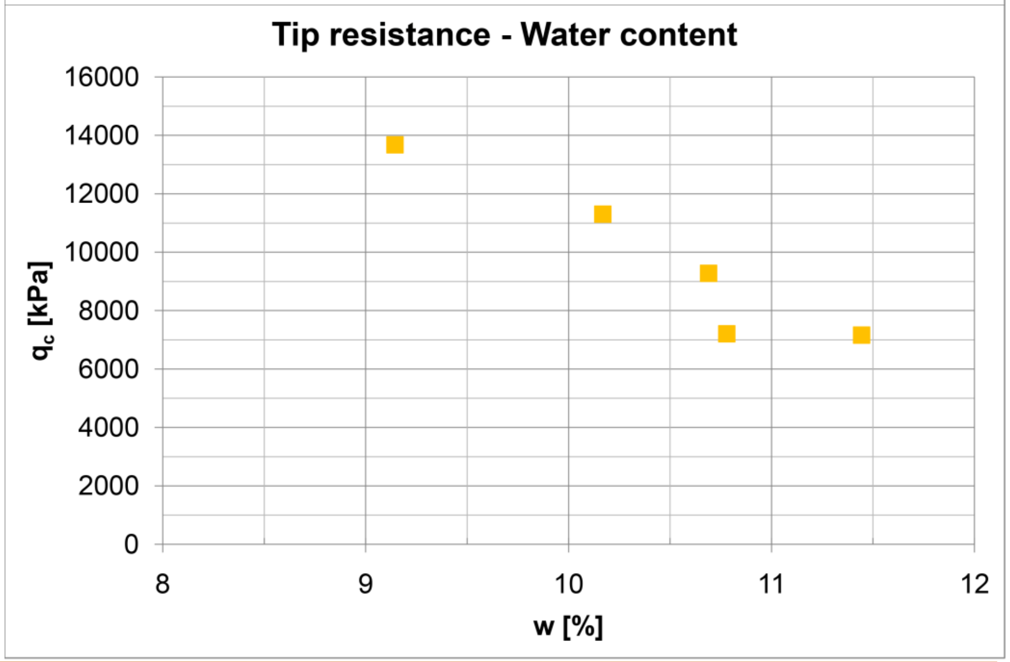
Variation of tip resistance with water content

Laboratory tests

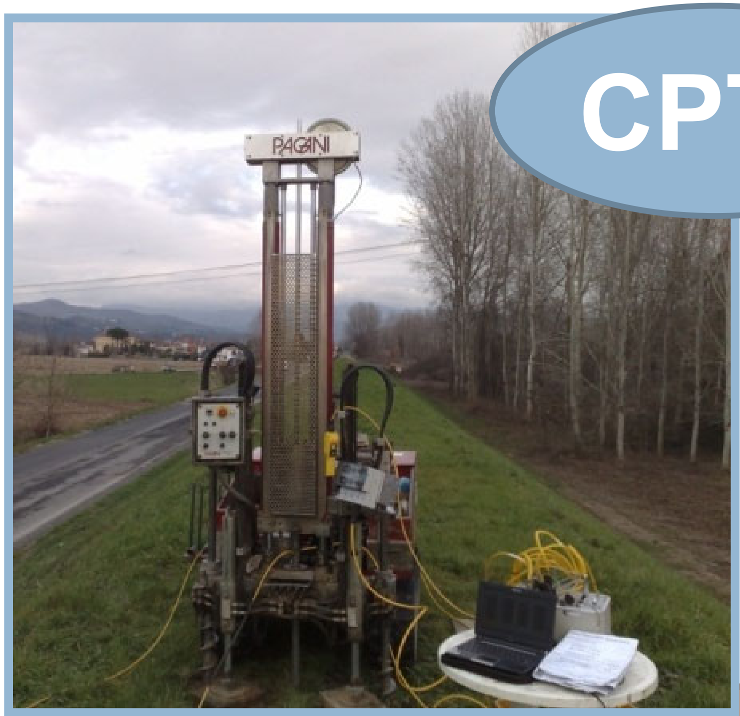








CPTu



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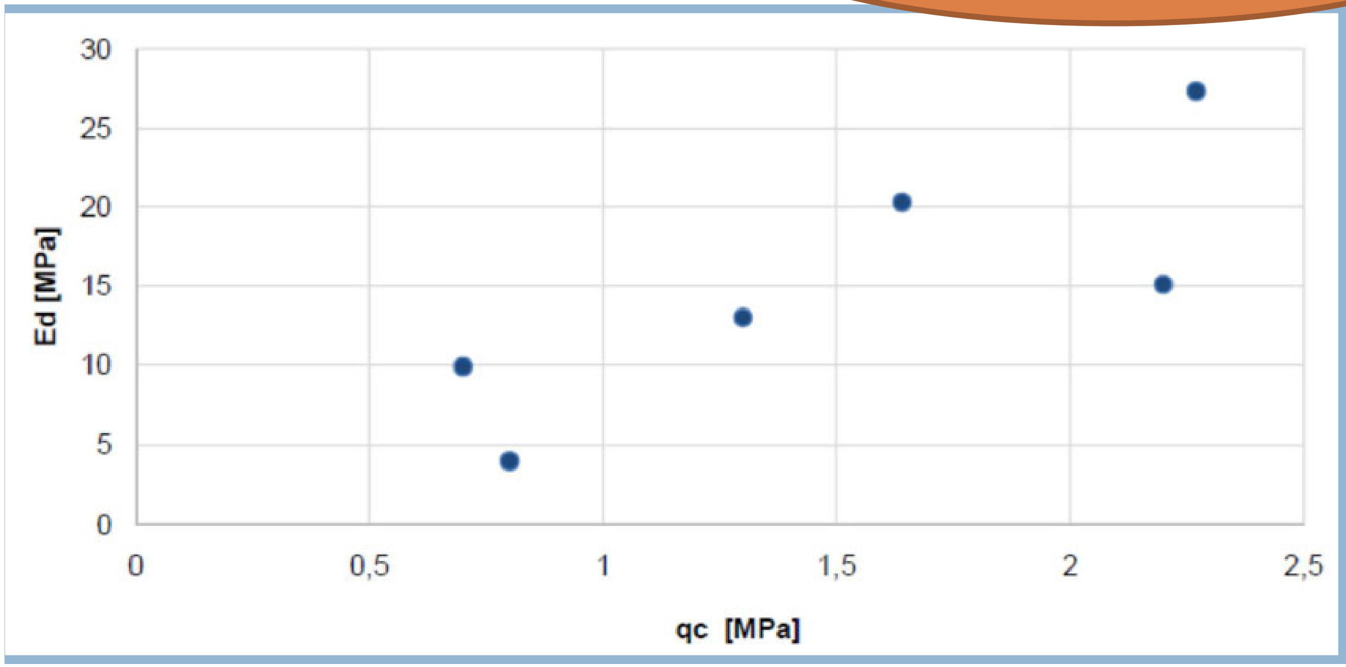
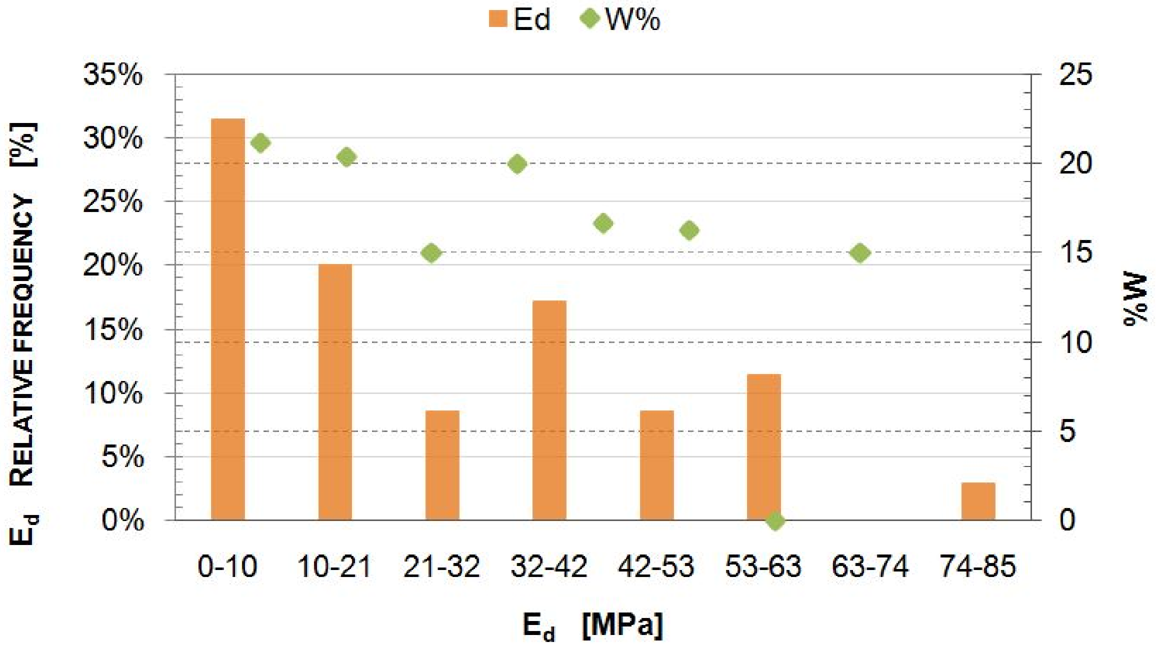
LFWD

Correlation between E_d and q_c

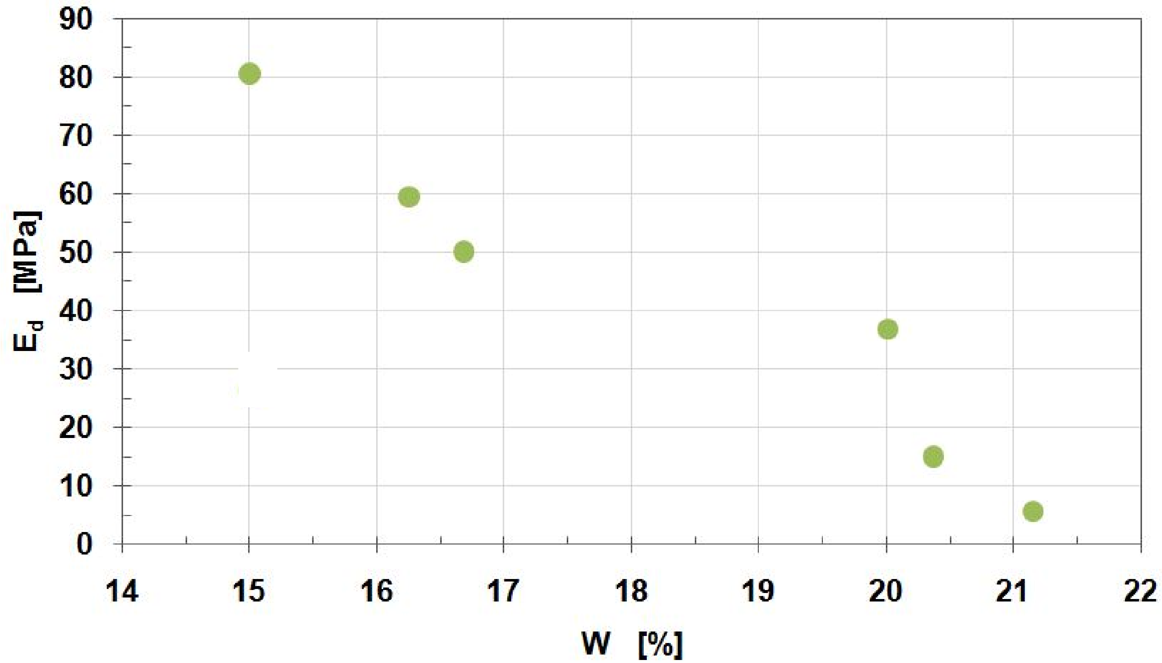


Average q_c measured within the influence depth for the LFWD (approximately 1.5 times the diameter of the loading plate = 45cm)

Simple prevision method for quality control



As the water content decreases, E_d value increases



Conclusions

DRY SANDS

$$q_c = f\,(\sigma'_h)$$

PARTIALLY SATURATED FINE GRAINED SOILS

$$q_c = f\left(\begin{matrix}\text{COMPACTION ENERGY}\\ w\end{matrix}\right)$$

For a given soil and water content:

✓ a correlation exists between q_c and soil density that can be used to define a target tip resistance profile

✓ it is possible to predict the dry density from the measured q_c irrespective of the boundary stresses

TIP RESISTANCE INCREASES WITH TIME BECAUSE OF DESSICATION

Thank you

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