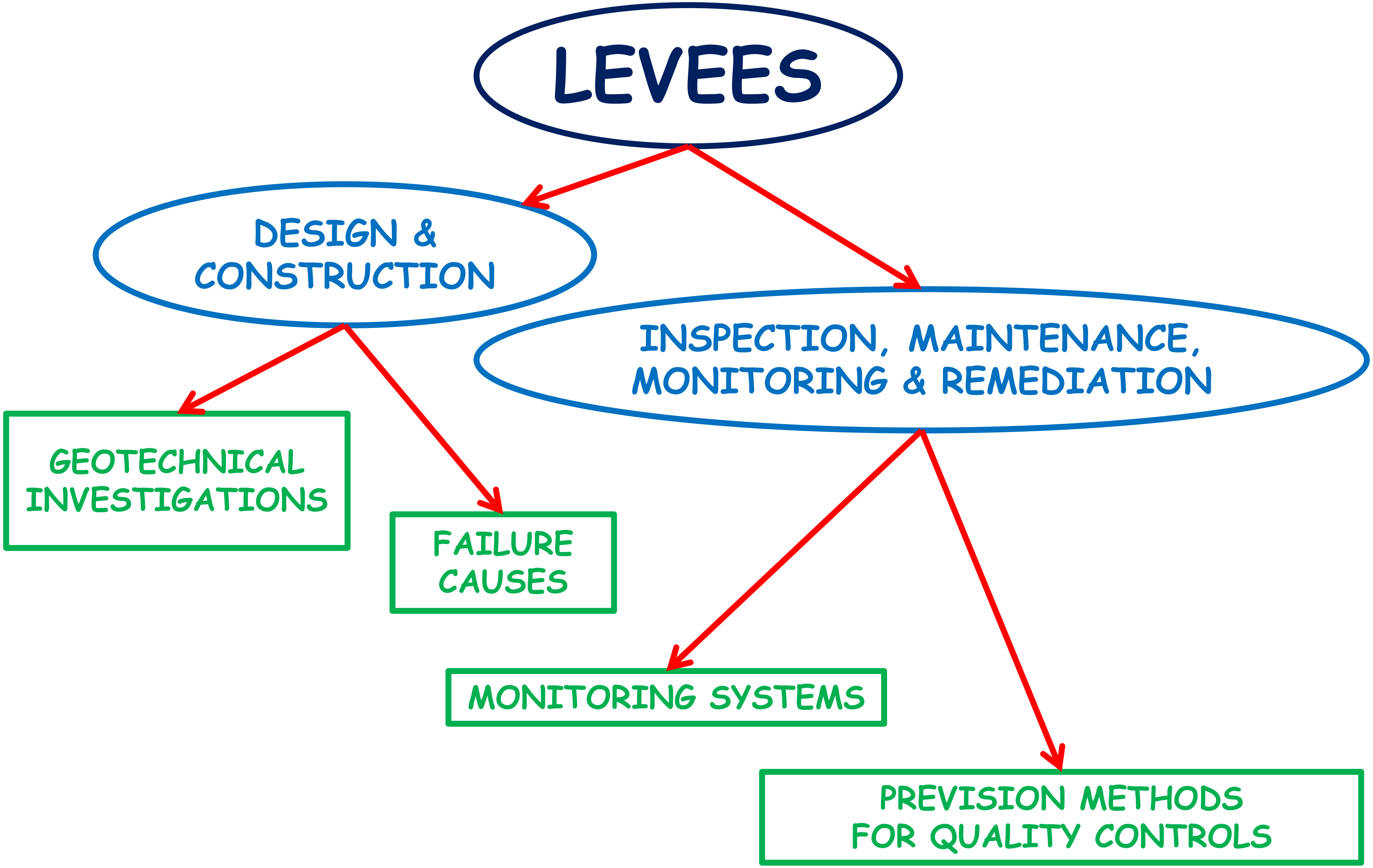
University of Pisa – June 30th, 2017

ON LEVEES

Relevant research activities at the University of Pisa
(B. Cosanti; D. Lo Presti ; N. Squeglia)

Barbara Cosanti, Ph.D.



LEVEES

DESIGN & CONSTRUCTION

INSPECTION, MAINTENANCE, MONITORING & REMEDIATION

GEOTECHNICAL INVESTIGATIONS

FAILURE CAUSES

MONITORING SYSTEMS

PREVISION METHODS FOR QUALITY CONTROLS

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Design & Constructions:

GEOTECHNICAL INVESTIGATIONS

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DESIGN OF THE GEOTECHNICAL CAMPAIGN

Notable extension
(levees run for many km)

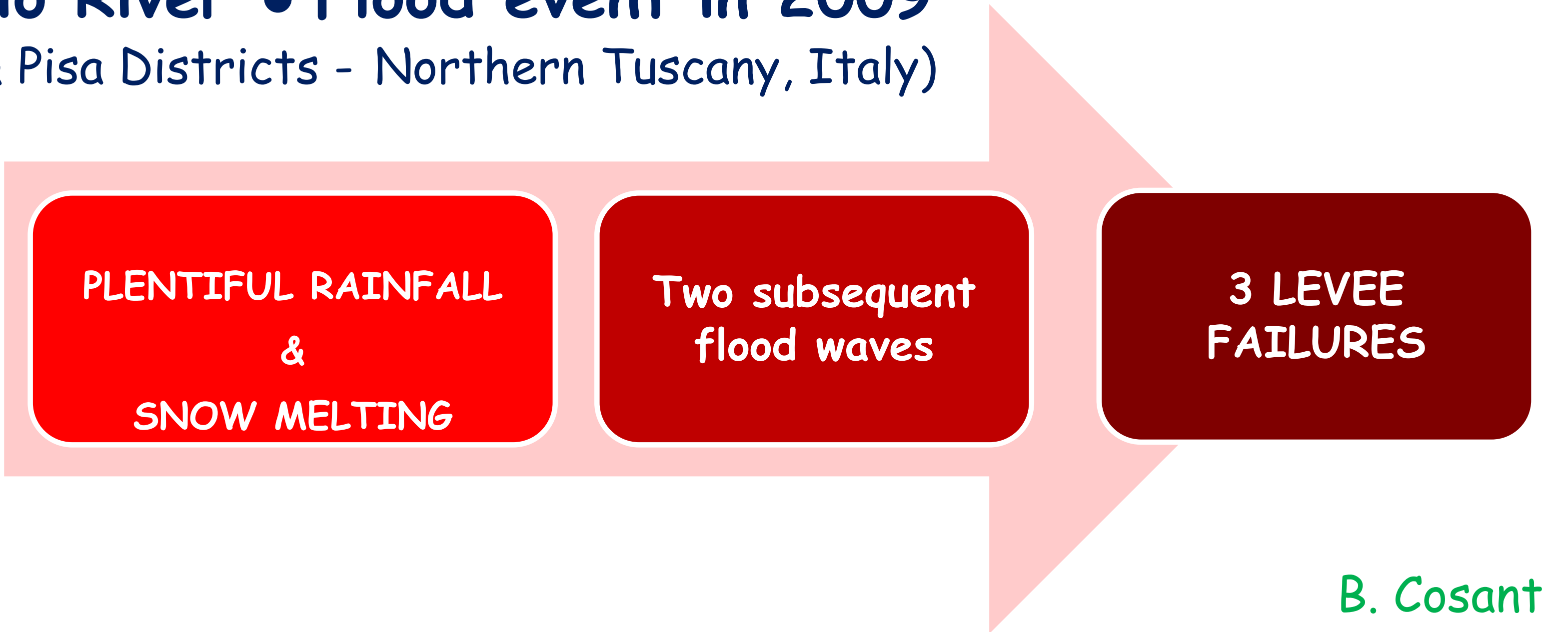
High level of detail required

→ **Considerable expertise & flexible budgets**

Need for: **CRITERIA FOR A COST-EFFECTIVE INVESTIGATION**

Serchio River • Flood event in 2009

(Lucca & Pisa Districts - Northern Tuscany, Italy)



PLENTIFUL RAINFALL
&
SNOW MELTING

Two subsequent flood waves

3 LEVEE FAILURES

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TWO INVESTIGATION CAMPAIGNS

1

- TO CLARIFY THE CAUSES OF FAILURE
- TO DESIGN APPROPRIATE REPAIR OF THE FAILURES

~ 3 km

2

- TO DEFINE THE LEVEE SYSTEM CONDITIONS
- TO IDENTIFY THE RISK AREAS
- BUDGET PLANNING FOR LEVEE IMPROVEMENT

~ 30 km

GEOTECHNICAL INVESTIGATIONS

1 ~ 3 km

- 4 boreholes (15 m depth)
  (4 Shelby samples retrieved from each borehole for laboratory testing)
- 15 CPTu (10 m depth)
  (for every CPTu 1 or 2 dissipation tests carried out in the foundation soil).
- 15 continuous sampling (4 m depth) carried out using a specially devised micro-stratigraphic sampler
  (AF shallow core system, Principe et al. 1997)
  (sample compaction measuring each 50 cm)

2 ~ 30 km

- 35 boreholes*
  For each borehole:
  - 4 Osterberg samples retrieved for laboratory testing
  - 2 Casagrande piezometer installations
  - 4 Lafranc tests
- CPTu (20 m depth) every 200 m
- 2D Electric Resistivity Tomography (ERT) every 200 m carried out along cross sections of the embankment

** In the district of Lucca all the boreholes were carried out from the embankment bank because of the limited width of the crest*

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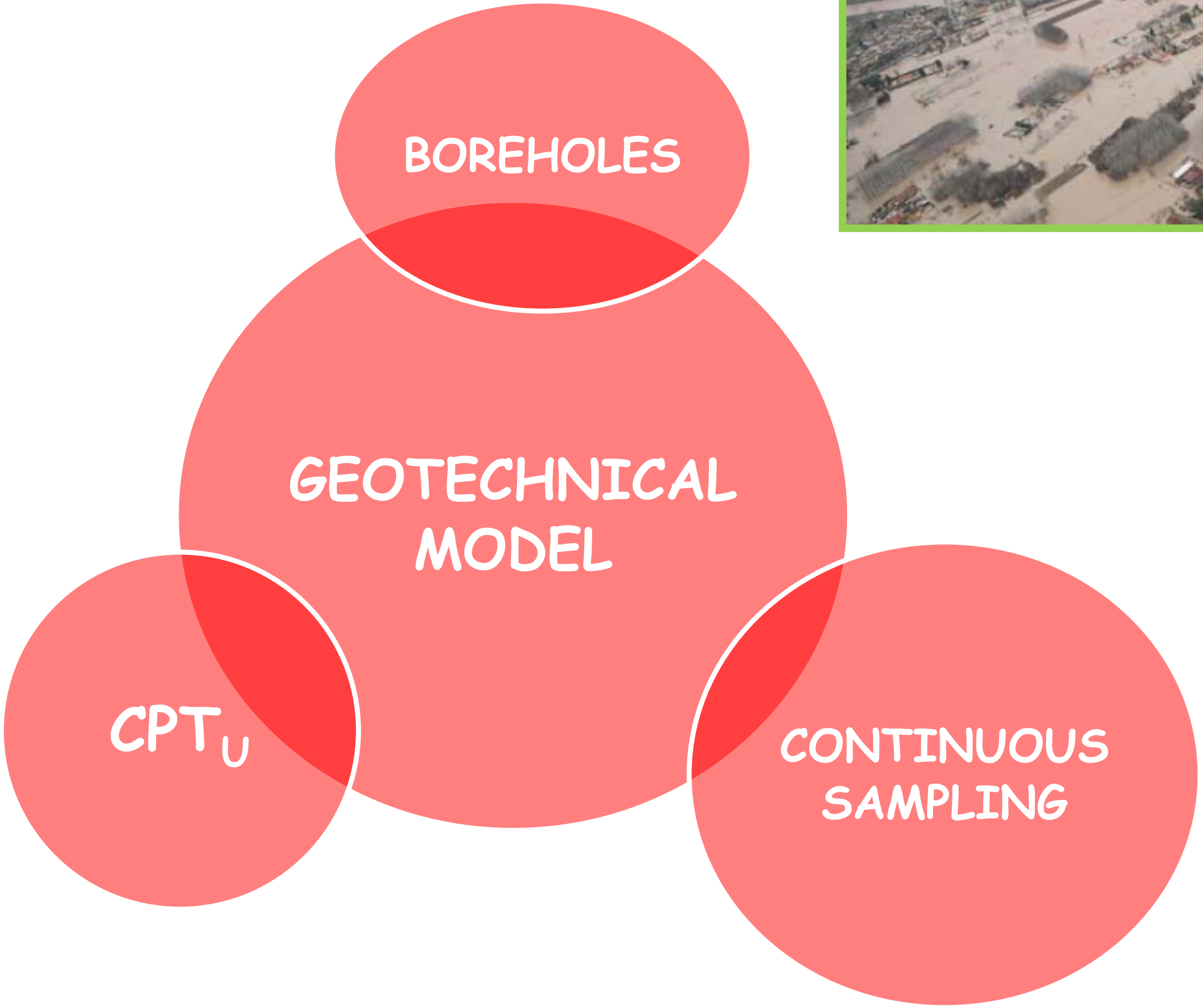
1 FAILURE AREA



BOREHOLES

GEOTECHNICAL MODEL

CPT_U

CONTINUOUS SAMPLING

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NATURAL UNIT WEIGHT

Failure area

γ_n

CONTINUOUS SAMPLES

SHELBY SAMPLES »

NATURAL UNIT WEIGHT [kN/m³]			
	Sandy silt	Silty sand	Sand
Continuous samples	12.8	12.3	17.7
Shelby samples	19.6	19.1	18.5

Very low values but consistent with the results of CPTu indicating D_R of about 10%

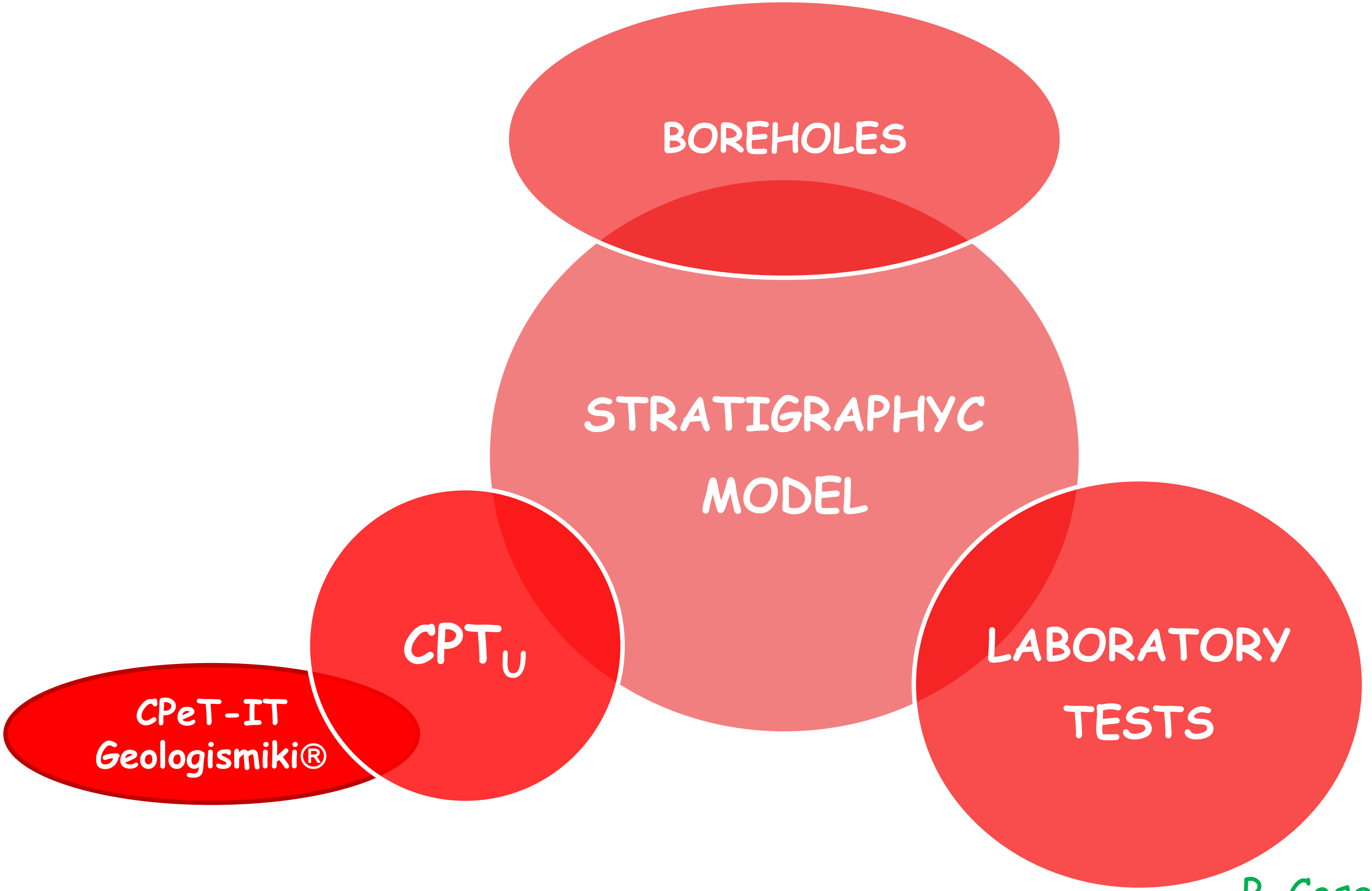
- Following investigation campaign:

  ~~**Shelby**~~ **Osterberg** ✓

- Very loose soils

Likely internal erosion phenomenon

2 WHOLE LEVEE SYSTEM



BOREHOLES

STRATIGRAPHYC MODEL

CPT_U

LABORATORY TESTS

CPeT-IT Geologismiki®

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STRATIGRAPHIC MODEL

- LABORATORY TESTS → 4 SOIL GROUPS based on laboratory grain size distributions → % finer than the No.200 sieve

- BOREHOLE-LOGS — Vs — SOIL GROUPS defined by laboratory grain size distributions

  → Correspondence

- PROVE CPT_U → Identification of the SBT lithology corresponding to each soil group

SOIL GROUP	BOREHOLE-LOG	SBT LITHOLOGY
>60% (clay >10%)	Clayey sandy silt	Clay
35÷60% (clay <10%)	Sand with clayey silt	Clayey silt Clay and silty clay
10÷35%	Silty sand	Sandy silt
<10%	Sand	Sand and silty sand
-	Gravel and coarse sand	-

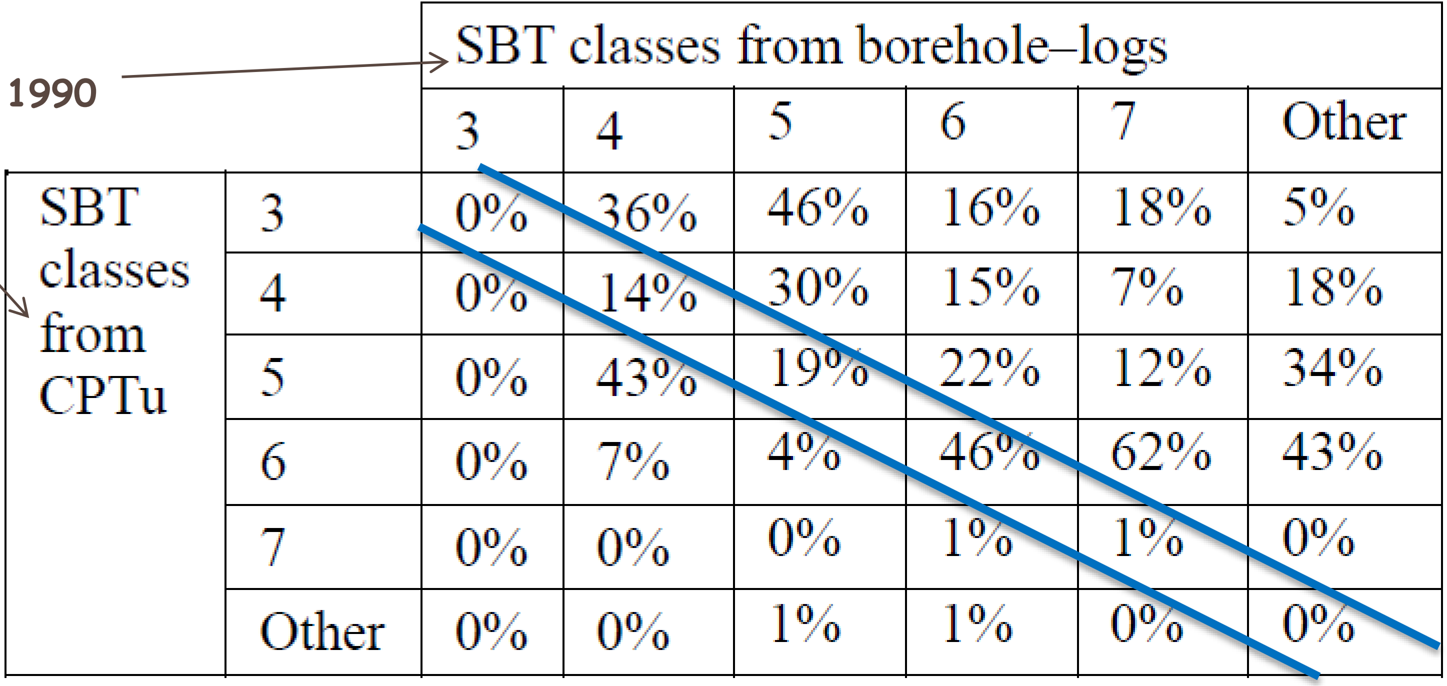
CPT_U INTERPRETATION

CPT_U vs BOREHOLES

% of success of CPT_u to give the same classification as from borehole-logs

$$= \frac{\text{length of correctly identified soil layers}}{\text{total length of layers belonging to that class}}$$

Robertson, 1990



		SBT classes from borehole–logs					
		3	4	5	6	7	Other
SBT classes from CPTu	3	0%	36%	46%	16%	18%	5%
	4	0%	14%	30%	15%	7%	18%
	5	0%	43%	19%	22%	12%	34%
	6	0%	7%	4%	46%	62%	43%
	7	0%	0%	0%	1%	1%	0%
	Other	0%	0%	1%	1%	0%	0%

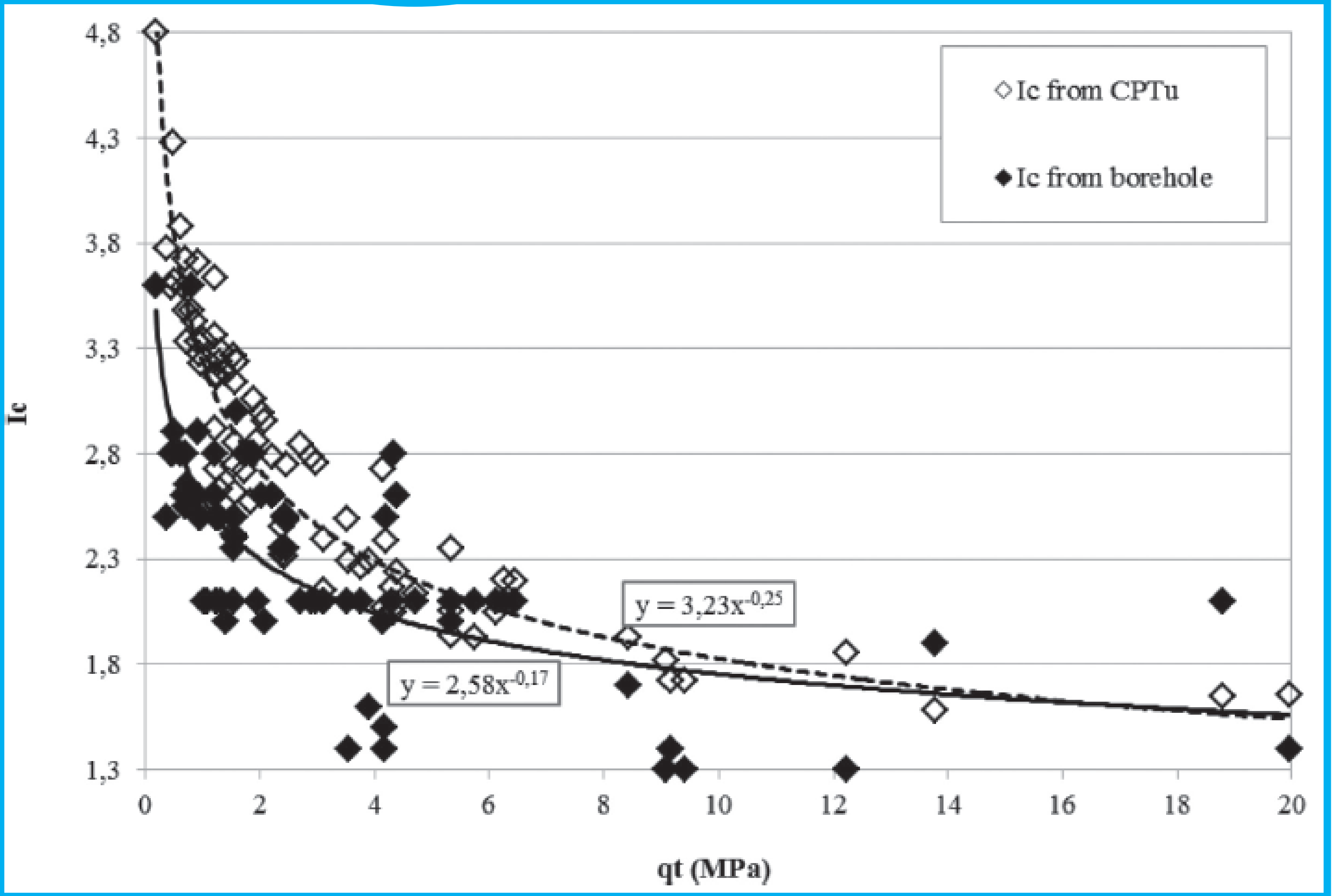
⇒ CPTu

- economical and expeditious tool
- results need to be calibrated against borehole-logs

“arbitrary” Ic value
associated to soil description

CPT_U
vs
BOREHOLES

Borehole #	Soil classification from borehole (AGI 1997)	Ic from borehole	Ic from CPTu	ΔIc	SBTn	Soil classification from CPTu
1	Clayey and sandy sil Silty sand Silty sand Sand, gravel and fir Silty sand					
2	Fine sand with silt Silty sand					
3	Clayey and sandy sil					
	Clayey and sandy sil Silty sand (5<clay<1 Silty sand					
4	Silty sand Sand, gravel and fir Sand Clayey and sandy sil					
5	Sand with silt Silt with clay Silty sand Sand Silt with clay/clay w					
6	Sand with silt/silt w Silt with clay Silty sand Clayey and sandy sil Silty sand					
7	Silty sand Medium silty sand					
	Sand, gravel and fine gravel	1.30	1.82	0.52	6	San



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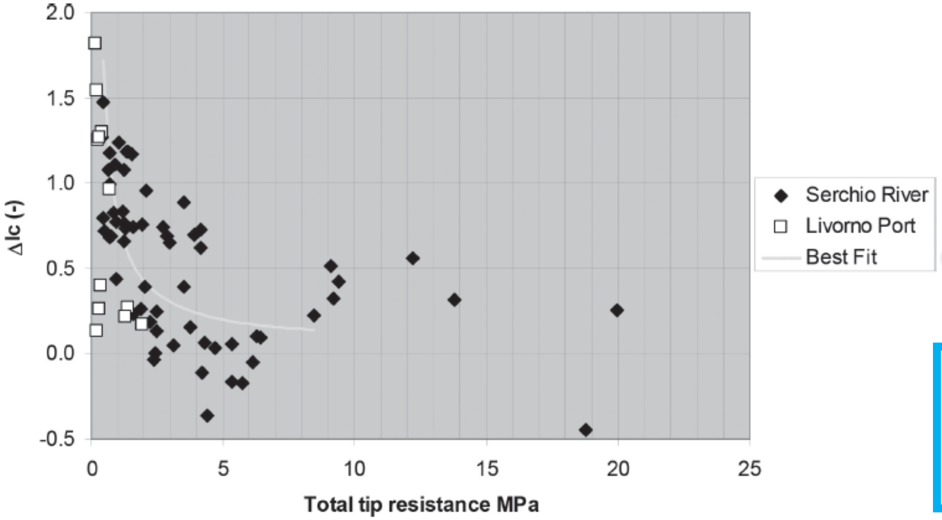
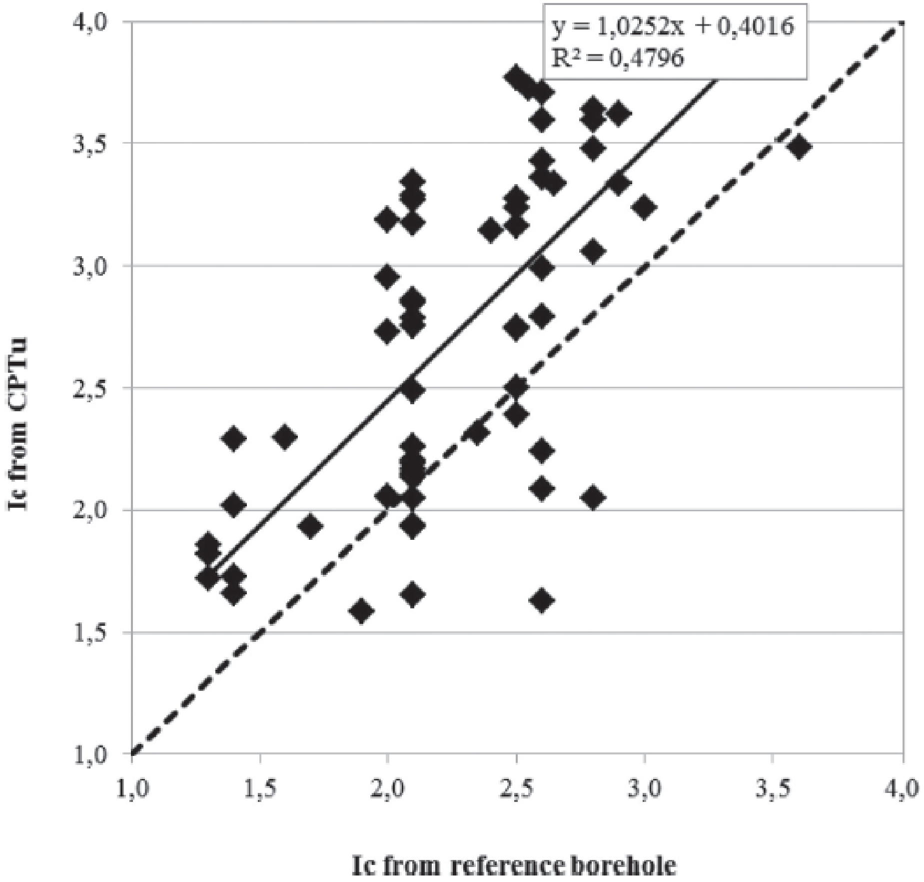
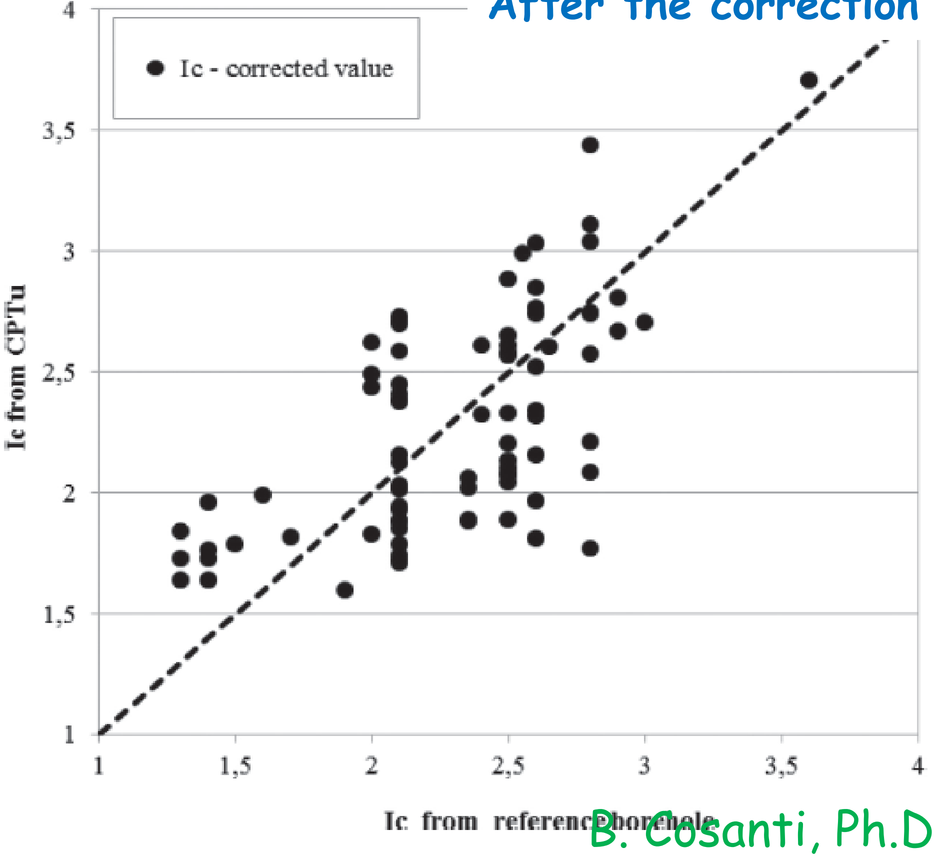
CPT_U vs BOREHOLES



$$\Delta I_c = 0.05 + \frac{0.75}{q_t}$$



After the correction



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Design & Constructions:

FAILURE CAUSES

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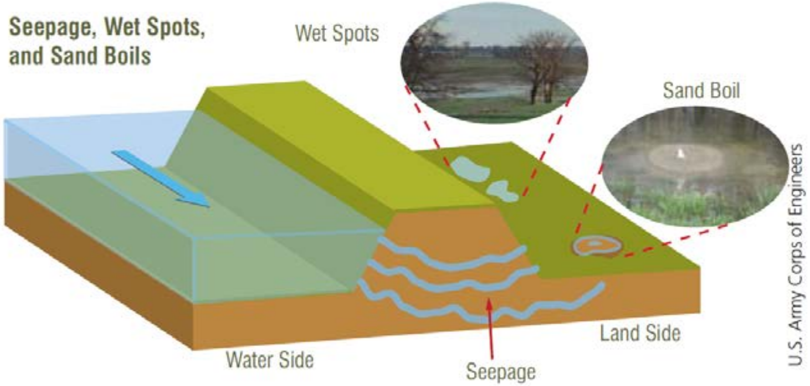
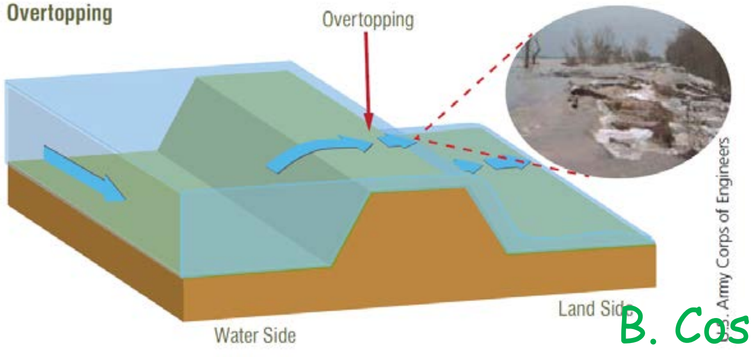
MAIN CAUSES OF FAILURE

- MECHANICAL FAILURE
- INTERNAL EROSION
- OVERTOPPING & EXTERNAL EROSION



U.S. Army Corps of Engineers



U.S. Army Corps of Engineers

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Mapping risky areas

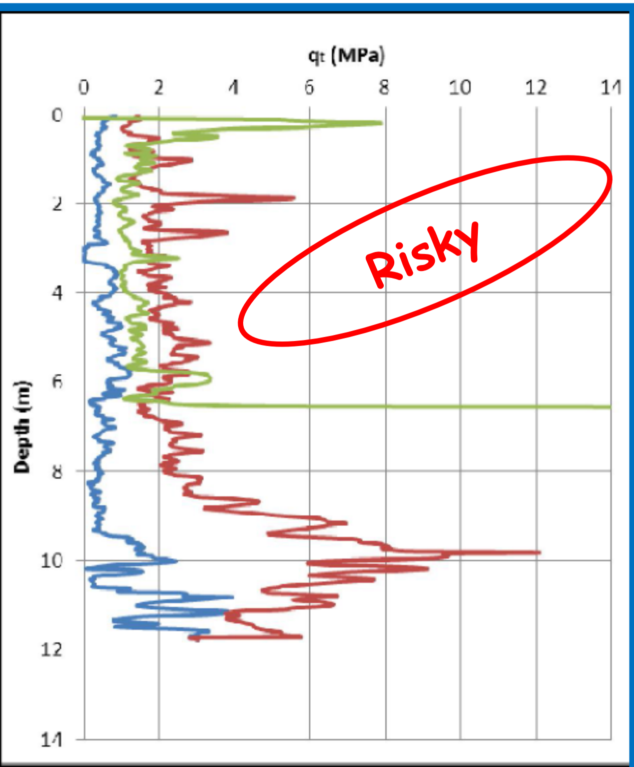
BUDGET PLANNING
FOR LEVEE
IMPROVEMENT

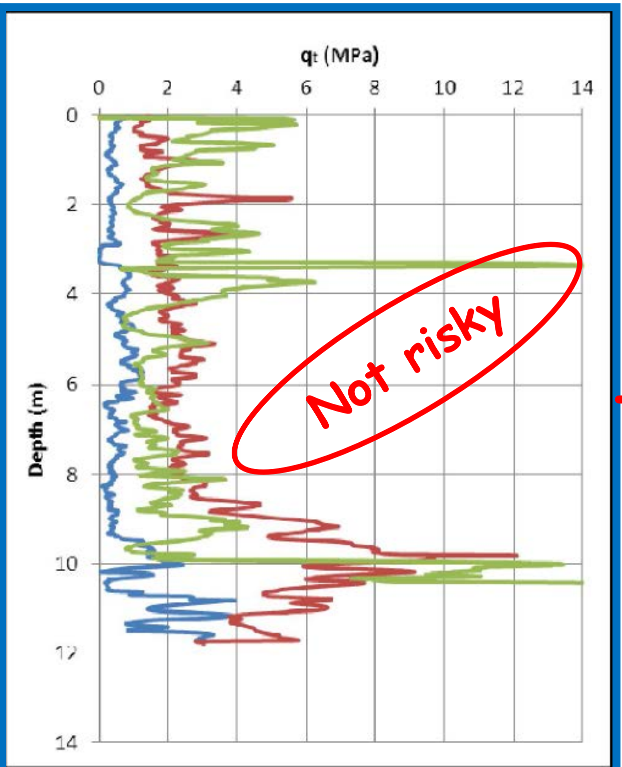
q_t profiles from CPTu carried out close to the December 2009 failure areas were assumed as reference

q_t <

MINIMUM & MAXIMUM ENVELOPES OF qt

assumed as reference for the CPTUs
carried out along
the whole levee system





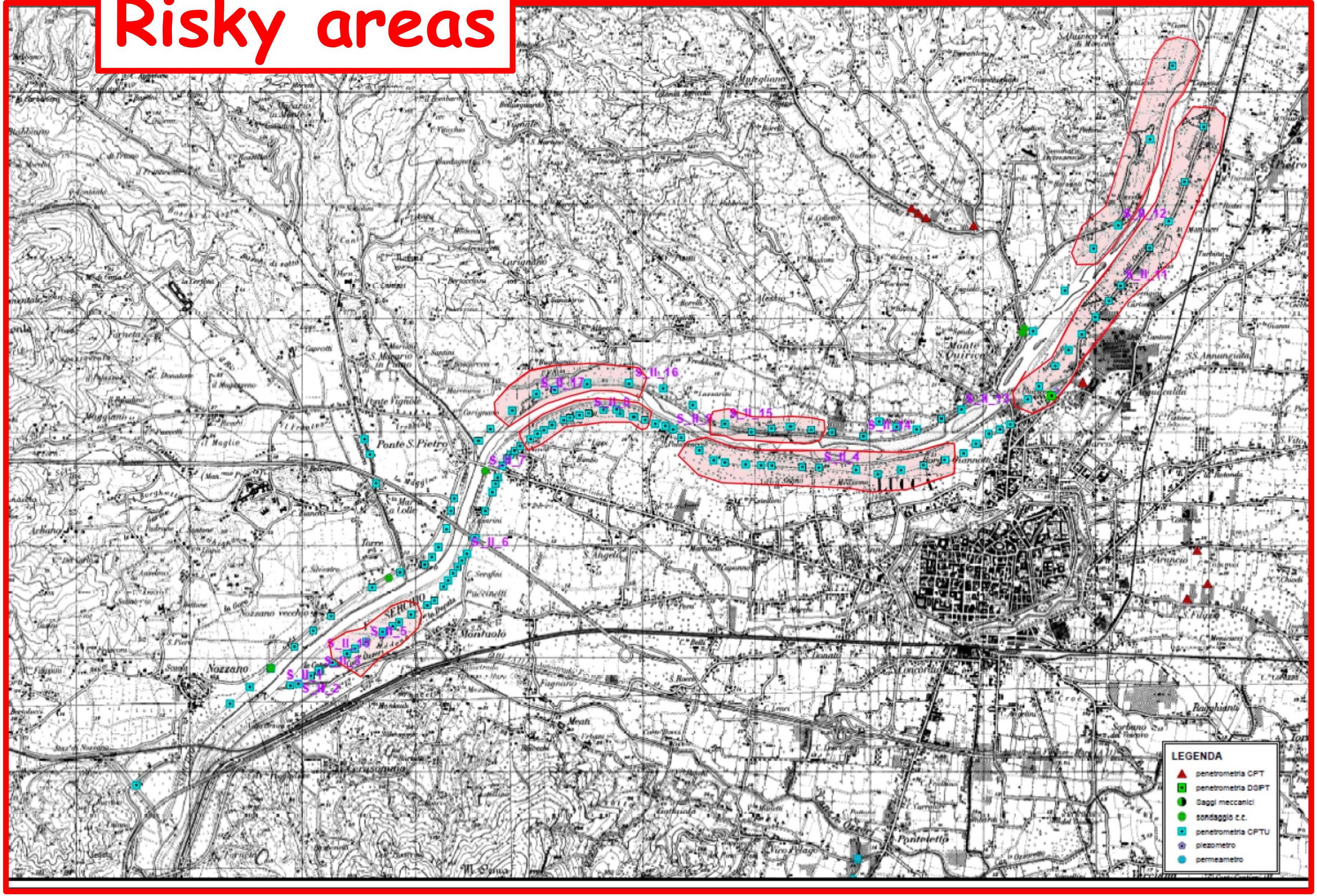
qt profile that falls in
between the MIN & MAX
ENVELOPES
⇒ particularly low
soil resistance :

Risky section

qt profile close to or
higher than the
MAX ENVELOPE:

Not risky section

Risky areas


S_II_16
S_II_17
S_II_8
S_II_9
S_II_15
S_II_14
S_II_13
S_II_12
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S_II_4
S_II_7
S_II_6
S_II_5
S_II_18
S_II_3
S_II_1
S_II_2
Ponte S.Pietro
Nozzano
Montuolo
Monte Quirico
LUCCA
LEGENDA
penetrometria CPT
penetrometria DSPT
Saggi meccanici
sondaggio c.c.
penetrometria CPTU
piezometro
permeametro

STABILITY ANALYSES

MECHANICAL FAILURE

CRITICAL CROSS SECTIONS
- GEOMETRIC CRITERIA $< B/H$
- Mechanical & hydraulic characteristics → Presence of a high permeability stratum in between two permeable strata

ULTIMATE LIMIT STATES
- Safety conditions against potential HEAVE failure (HYD, NTC 2008)
  - $1.3u \leq 0.9\sigma_{v0}$
- Mechanical failure under seepage conditions

FLOW CONDITIONS
- Steady state → LIMIT EQUILIBRIUM METHOD
  - SLIDE (RocScience)
  - SEEP/W & SLOPE/W (GEO-SLOPE)
  - PC STABL 5M (Achilleos, 1988)
- Transient → FINITE ELEMENT METHOD
  - PLAXFLOW & PLAXIS

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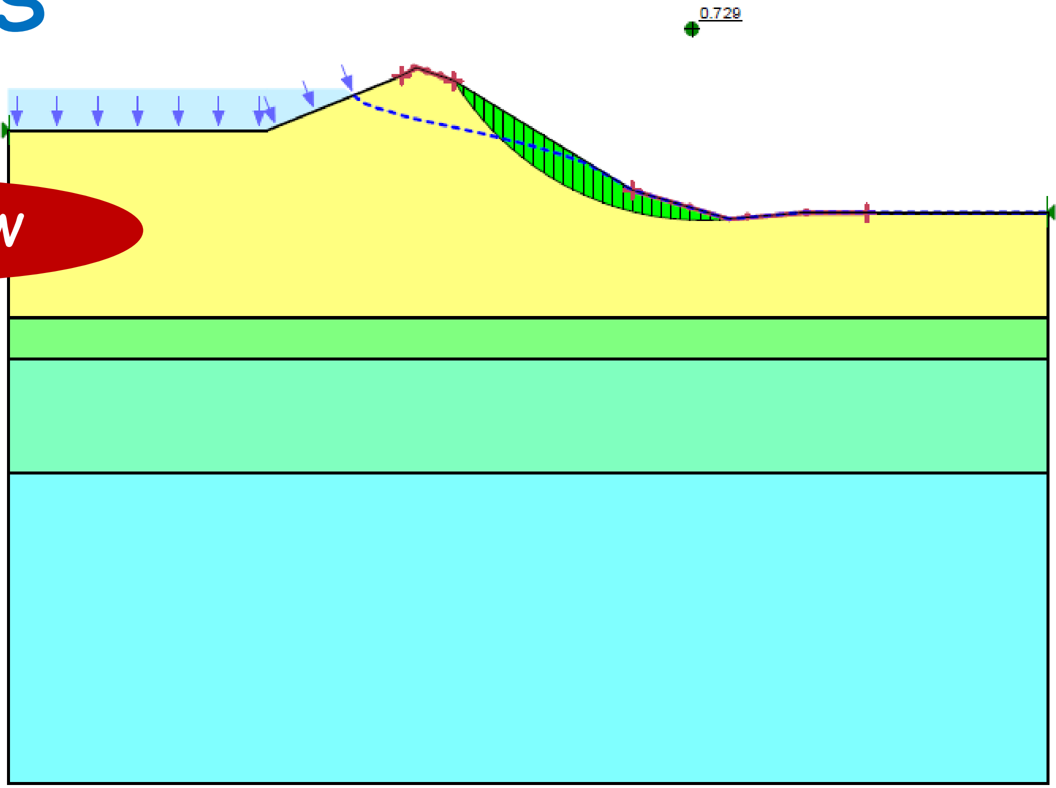
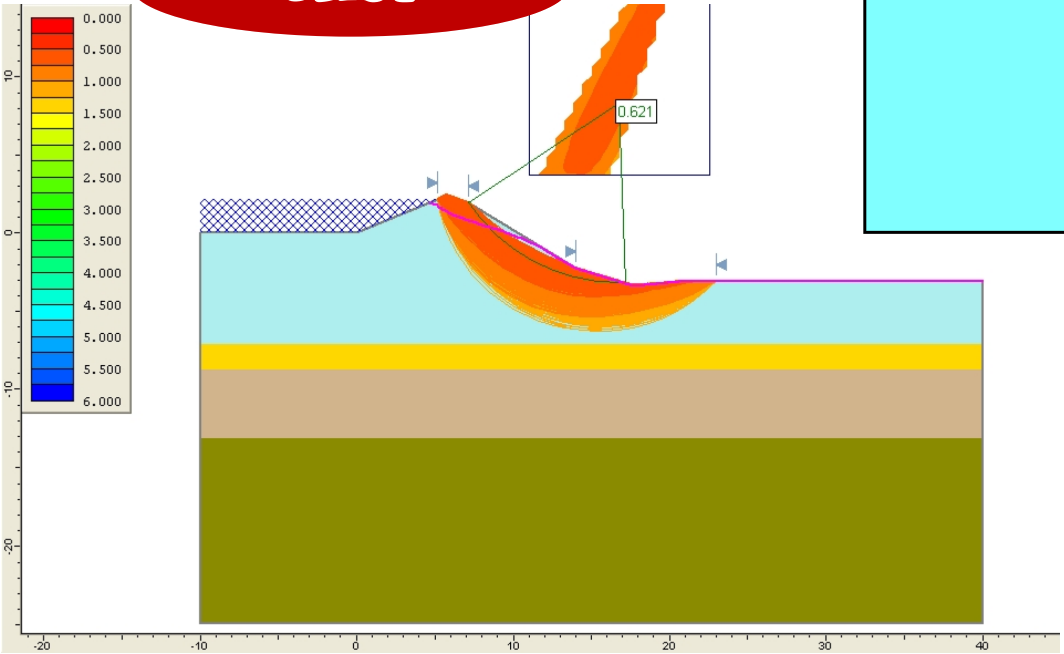
STABILITY ANALYSES

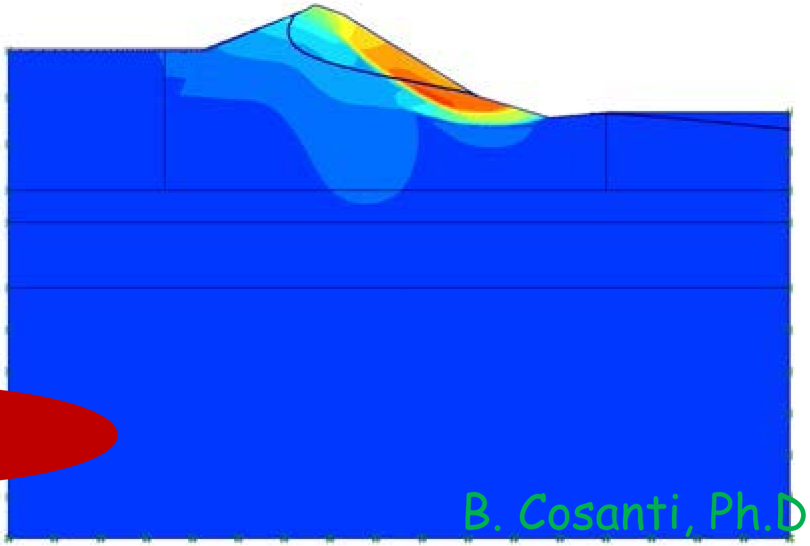
SLOPE/W



SLIDE



PLAXIS



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STABILITY ANALYSES: stationary flow

SECTION	SAFETY FACTOR		
	SLIDE	PC-STABL	SLOPE-W
9 dx LUCCA	0.621	0.76	0.729
13 dx LUCCA	0.677	0.87	0.655
25 dx LUCCA	0.560	0.62	0.640
39 sx LUCCA	0.819	0.89	0.898
51 sx LUCCA	0.676	0.71	0.710
57 sx LUCCA	0.746	0.78	0.798
4 PISA	1.264	1.40	1.318
27 PISA	1.047	1.19	1.132
32 PISA	0.728	0.99	0.760
48 PISA	0.794	1.02	0.828
51 PISA	0.761	1.09	0.763
57 PISA	0.905	0.93	0.906

✓Bishop simplified method

✓Water level coincident with the embankment crest on the riverside and with the ground level on the countryside

Unconfined seepage analysis

Seepage forces are not considered
(water table level indication)

FS<1

SECTIONS CANNOT SUSTAIN THE FLOW

- ✓ Very similar failure surfaces
- ✓ Comparable safety factors

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STABILITY ANALYSES:

steady state Vs transient flow

Steady state flow → None of examined “risky sections” can sustain the flow

Transient flow (FEM analyses)

→ Partial saturation of the embankment soil mainly contributes to its stability in the absence of filtration, leading to acceptable safety margins

→ 10 days are necessary to approach the steady state flow conditions

permanent flow condition is generally too cautious

BUT (probably) it was reached during December 2009 event

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INTERNAL EROSION

✓construction details unknown

✓ limited available data → boreholes carried out from the levee bank (unreachable levee crest: width between 1.2-3 m) ⇒ lack of grain distribution curves from samples retrieved from the embankment body in the Lucca District

INTERNAL EROSION RISK

↓

INTERNAL STABILITY ASSESSMENT

↓

- Terzaghi
- **Suffusion risk and self-filtering properties**
- Kezdi
- Kenney & Lau
- Burenkova
- USACE
- Isotomina

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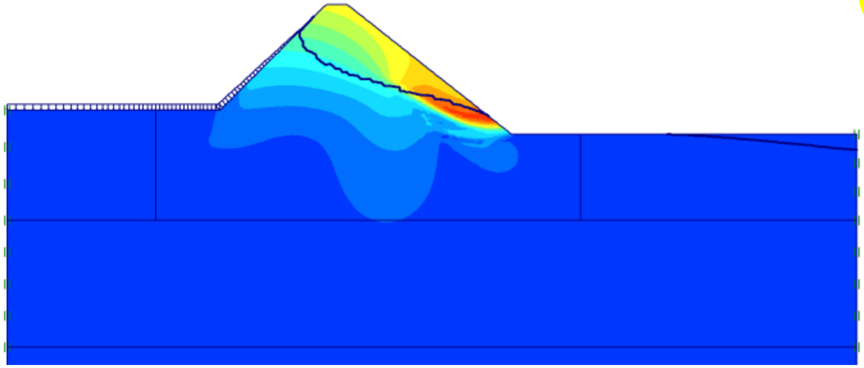
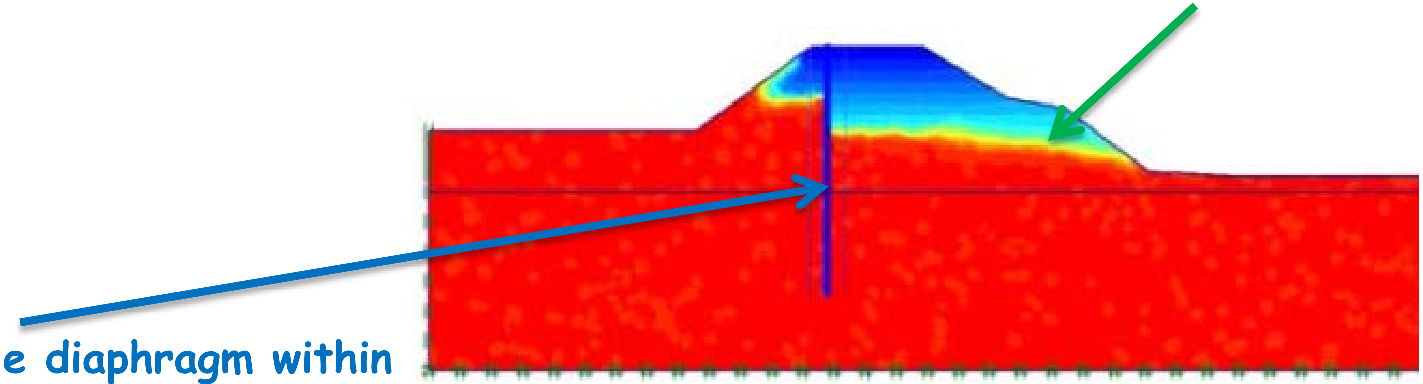
Analysed soils do not seem to be particularly prone to internal erosion phenomena

but

- ✓ Limited number of data
- ✓ Impossibility to exclude presence of anomalies and heterogeneities within the embankments
- ✓ No filters



cross-section geometry of the embankment modified by adding a berm



metallic sheet pile diaphragm within the body of the embankment

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OVERTOPPING & EXTERNAL EROSION

Case history on the effect of overtopping on a trial embankment in stabilized soil

Levee resiliency during overtopping

experimental full scale embankment

Quarry waste from a limestone quarry (CP)

45% calcite

CL (USCS)
A6 (AASHTO, UNI CNR 10006)
k = $1{,}6 \cdot 10^{-7}$ cm/s
LL=30%; PI=12%
w_{opt}=12%; γ_{dmax}=20 kN/m^3 (Modified Proctor)

stabilised soil used for the repair of the Serchio River levees

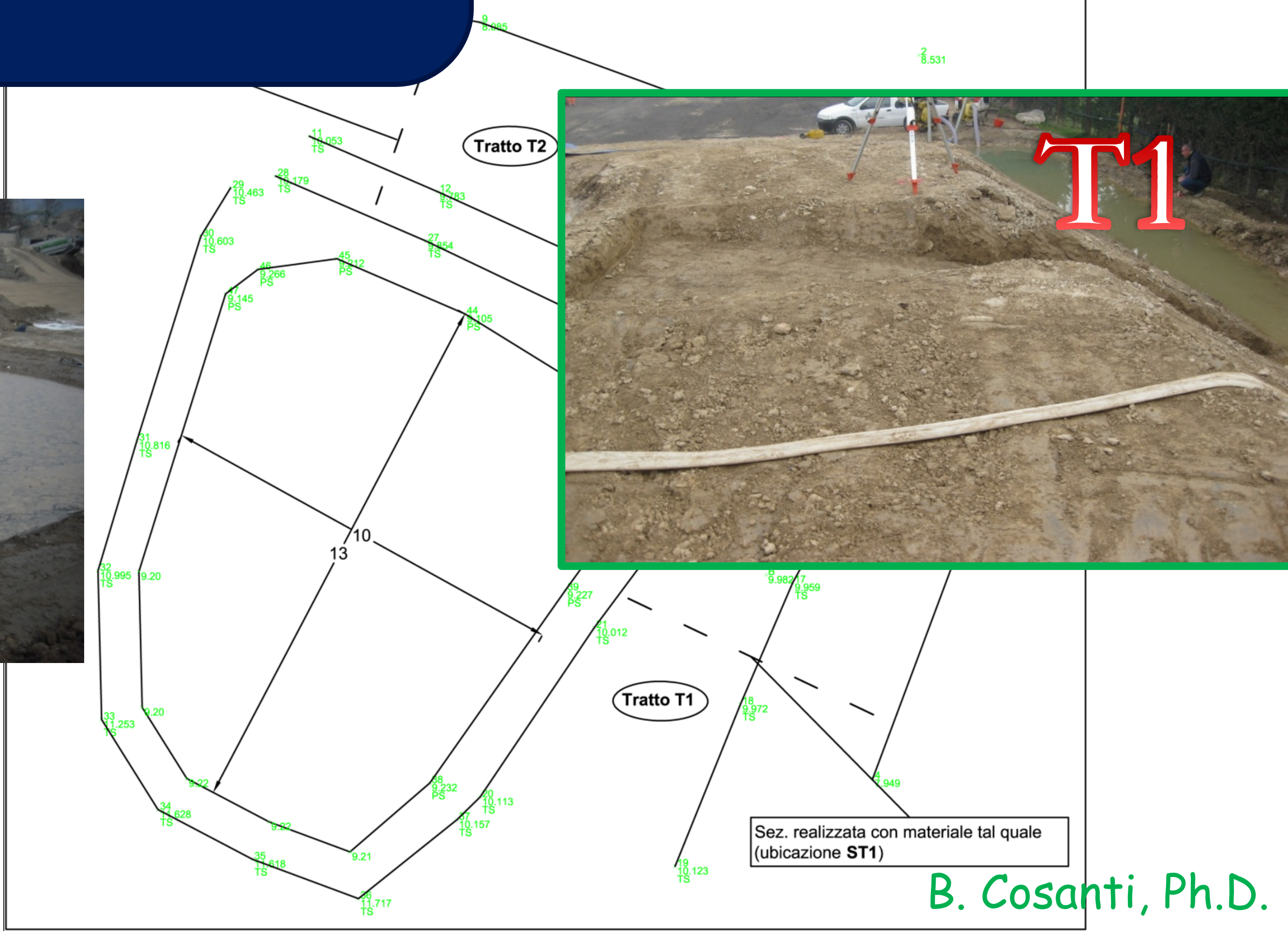
CROSS SECTION → h=2.6m; slope=1/2-2.5

PLAN SHAPE → the embankment enclosed a reservoir

TWO TEST SECTIONS:

T1 → CP

T2 → CP + 2% lime



Sez. realizzata con materiale tal quale (ubicazione **ST1**)

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OVERTOPPING TESTS

- ✓ 6 hours
- ✓ 15 cm or more of sheet-flow overtopping

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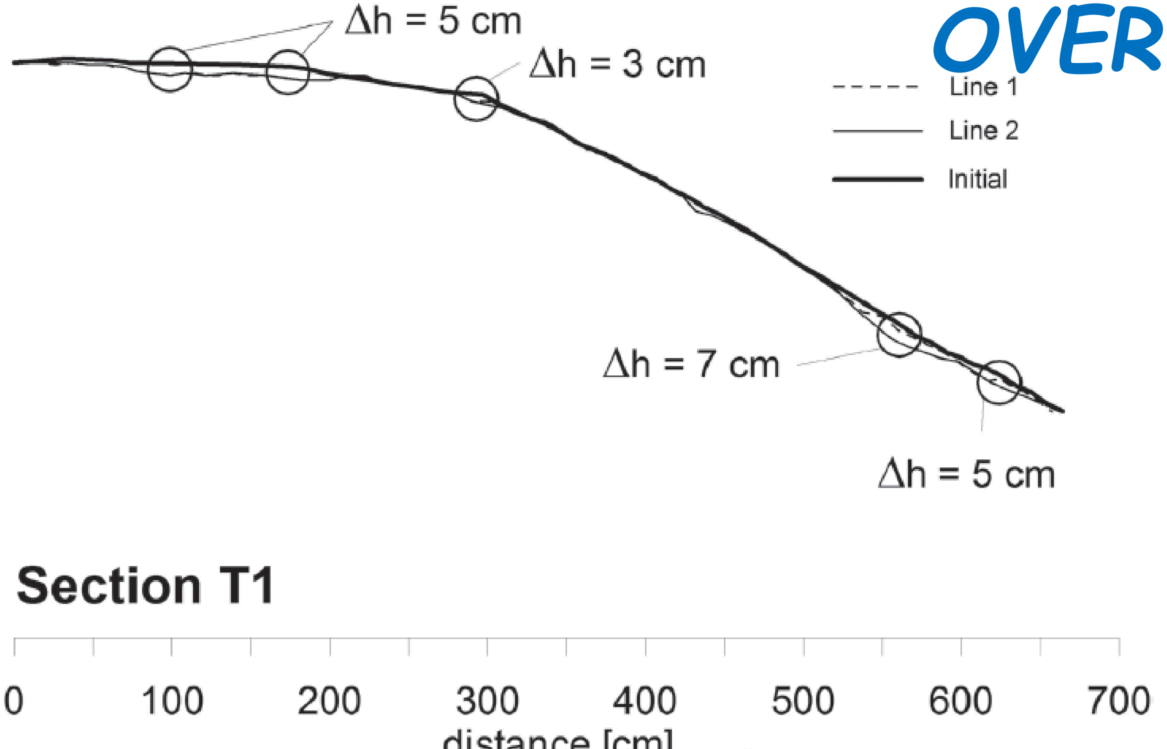
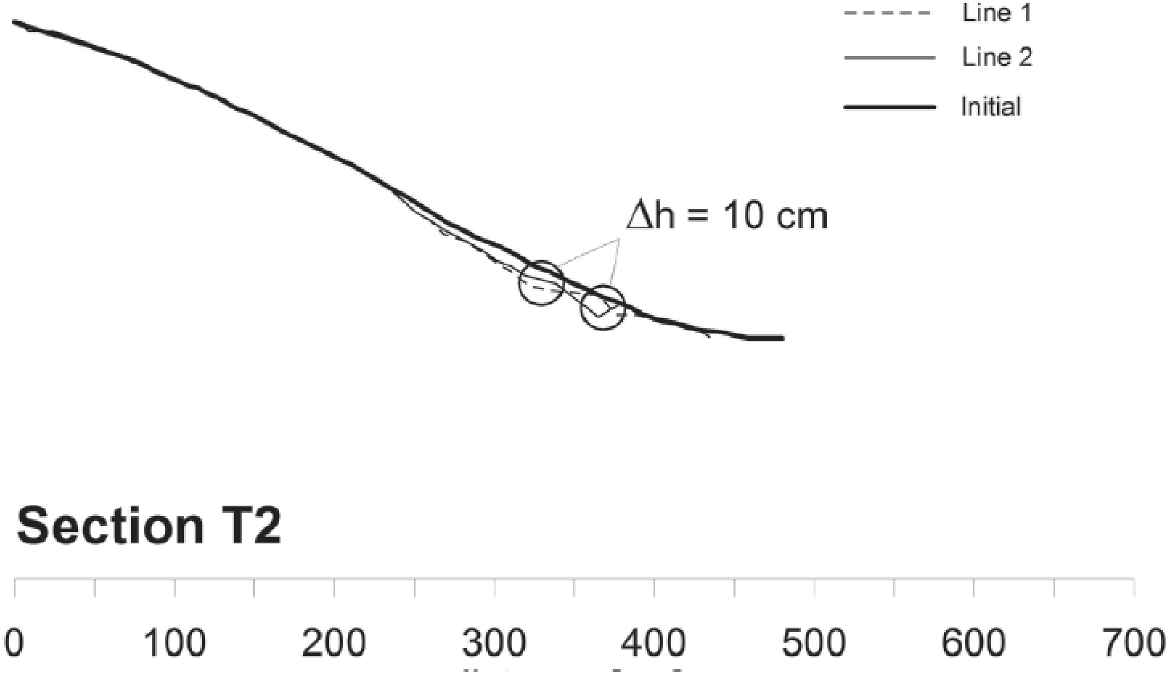
OVERTOPPING TESTS





Inspection, Maintenance, Monitoring & Remediation:

MONITORING SYSTEMS

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Seepage through embankment and foundation soils

MONITORING SYSTEM

“Bottacci”

installed within the real scale embankment of a detention basin

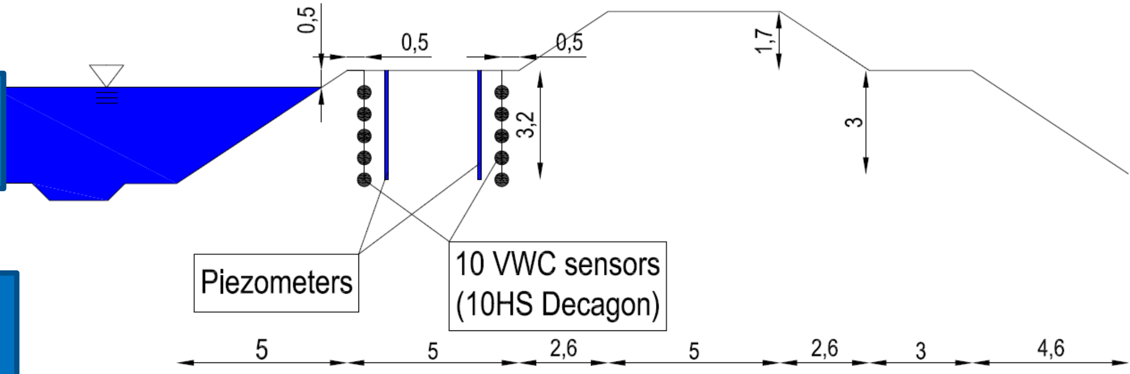
1. to realistically evaluate hydraulic and saturation conditions
2. to calibrate stability analyses under unsteady flow conditions
3. to assess the effectiveness of possible countermeasure

PLASTIC DIAPHRAGM
(dry mechanical mixing)

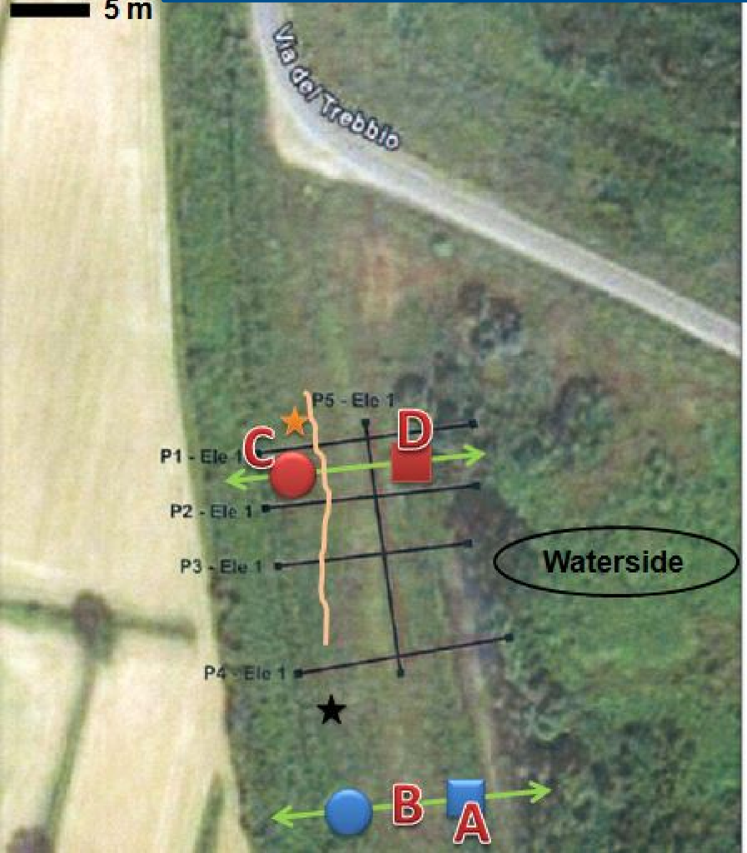
MONITORING SYSTEM

instrumented section

CROSS SECTION SCHEME



Investigation & section location



LEGEND:

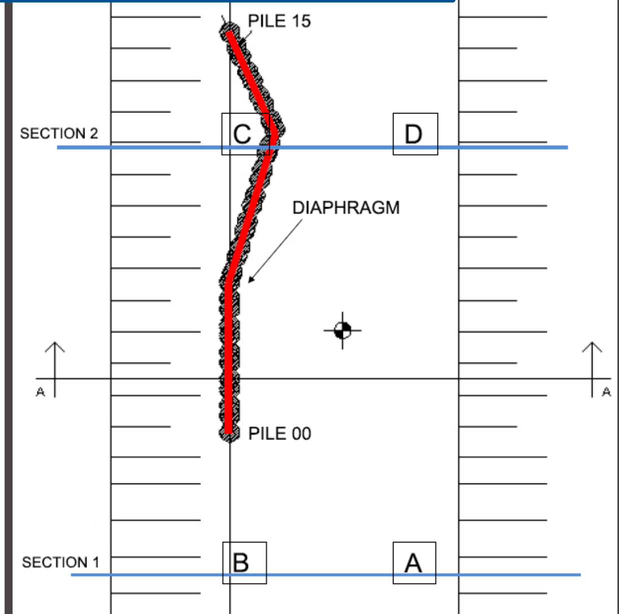
- ★ CPTu P1
- ★ CPTu P2
- ● CPT SB
- ● CPT SA
- ■ Borehole SB
- ■ Borehole SA
- A B C D 10 HS sensor group location
- ↔ cross sections
- diaphragm

CAPACITIVE SENSORS

10HS *Decagon Devices*

dielectric permittivity → VWC

plastic diaphragm location



MONITORING SYSTEM

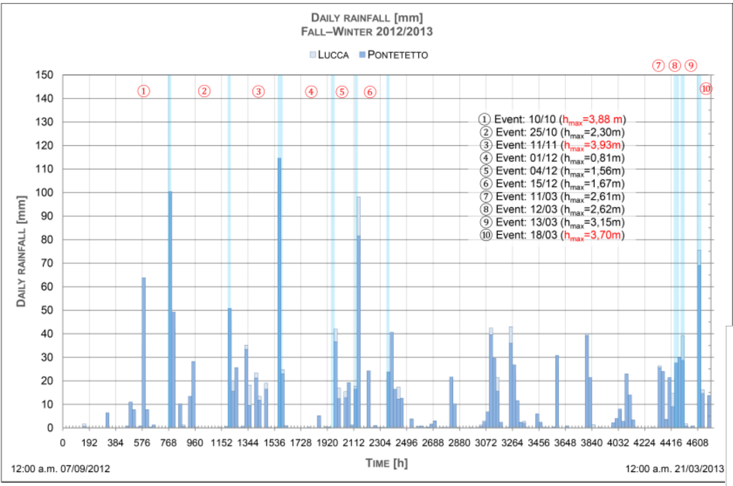
MONITORING CAMPAIGN
Observation time:
7/09/2012 – 7/09/2013

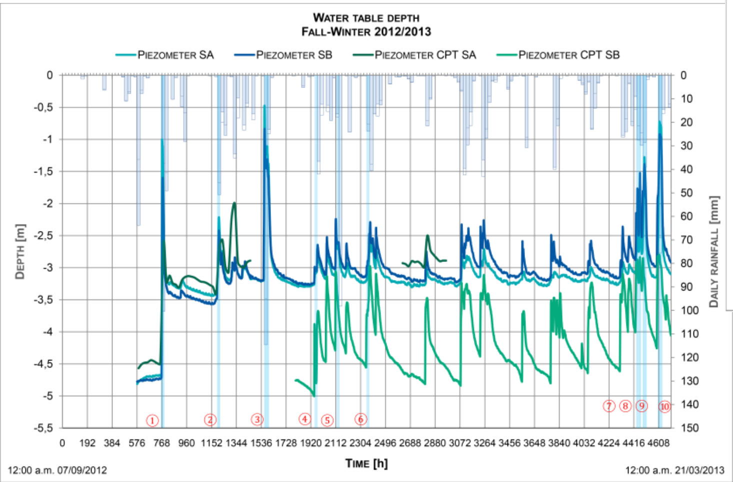
daily rainfall data

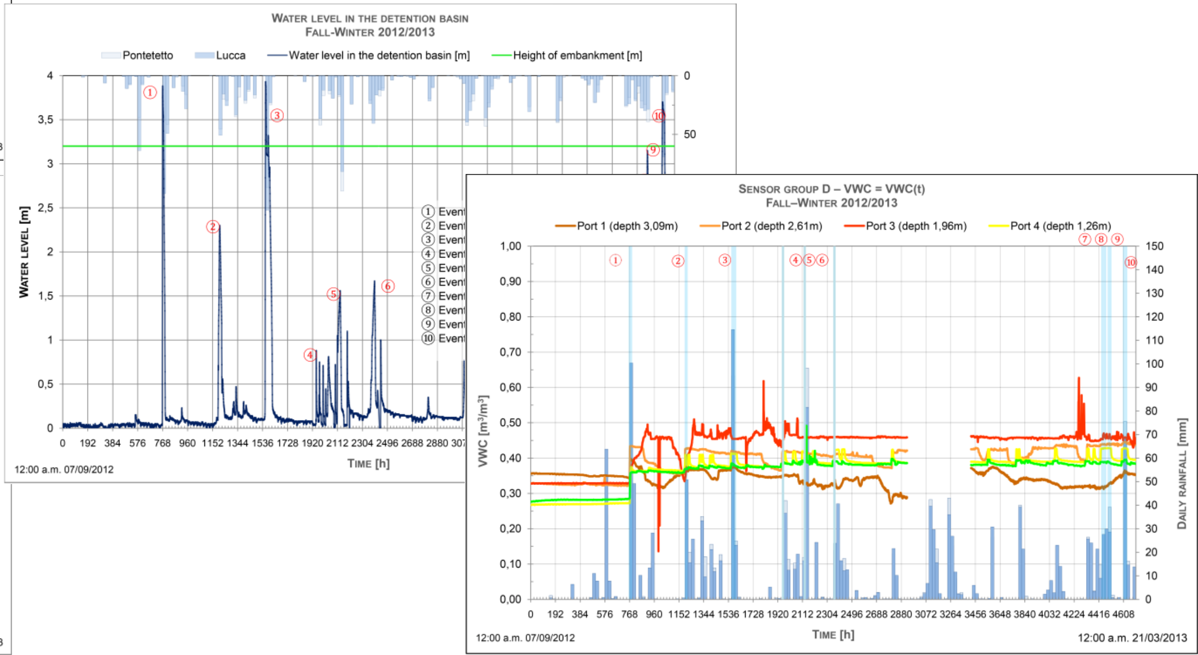
groundwater levels
4 open standpipe piezometers

water levels in the detention basin

VWC *10HS Decagon sensors located in positions A, B, C, D*



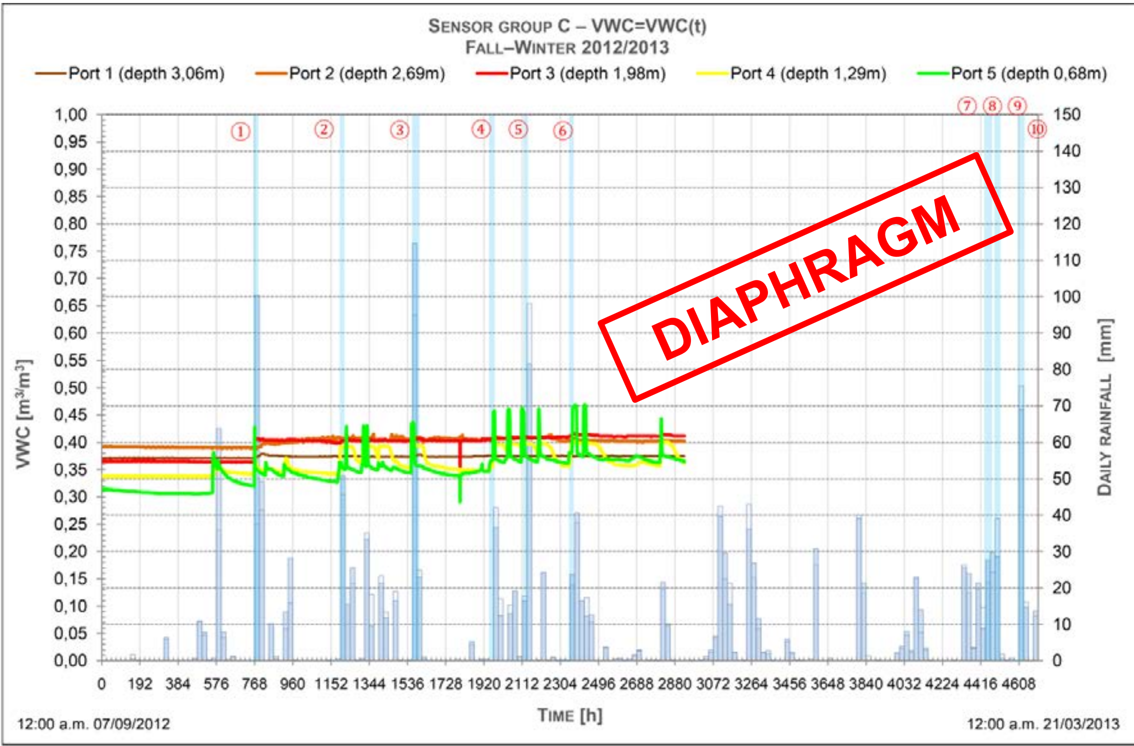


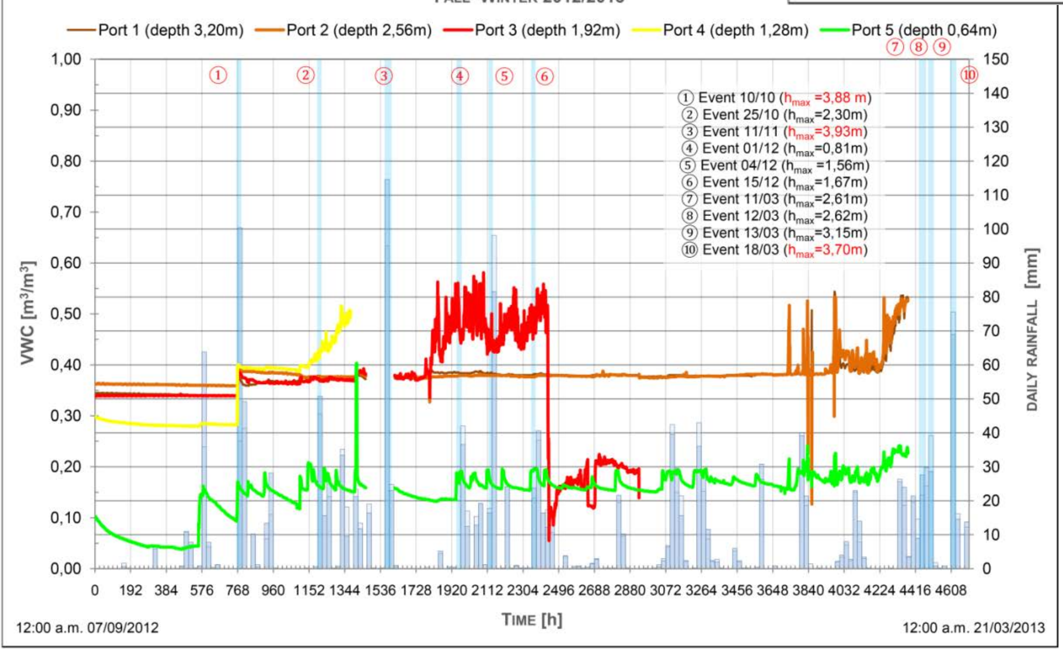


MONITORING CAMPAIGN

Observation time:
7/09/2012 – 7/09/2013

- ✓ Shallower moisture sensors are especially sensitive to the water infiltration after rainfall
- ✓ Diaphragm effectiveness





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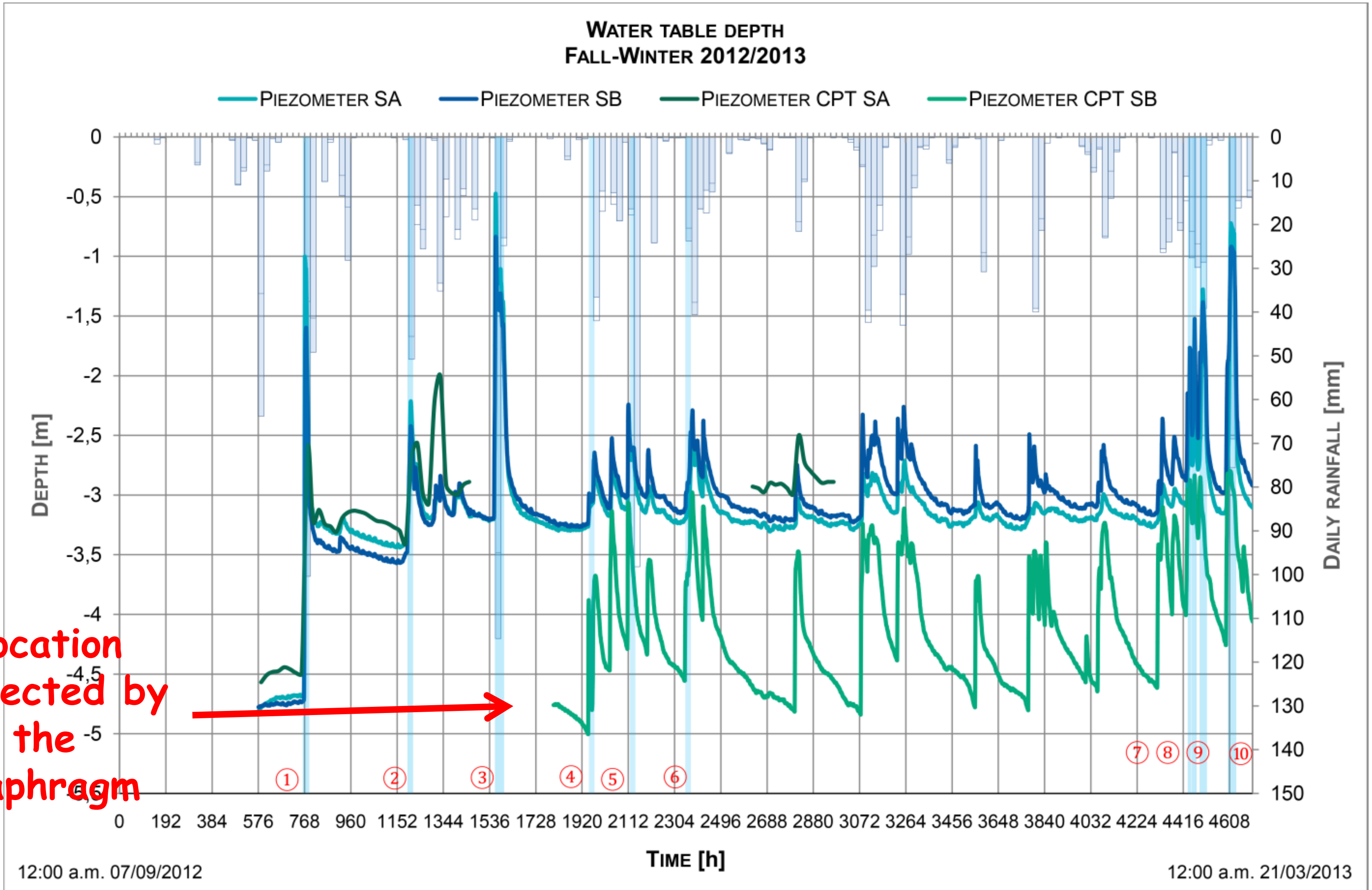
MONITORING CAMPAIGN

Observation time:
7/09/2012 – 7/09/2013

✓ diaphragm effectiveness



Location protected by the diaphragm

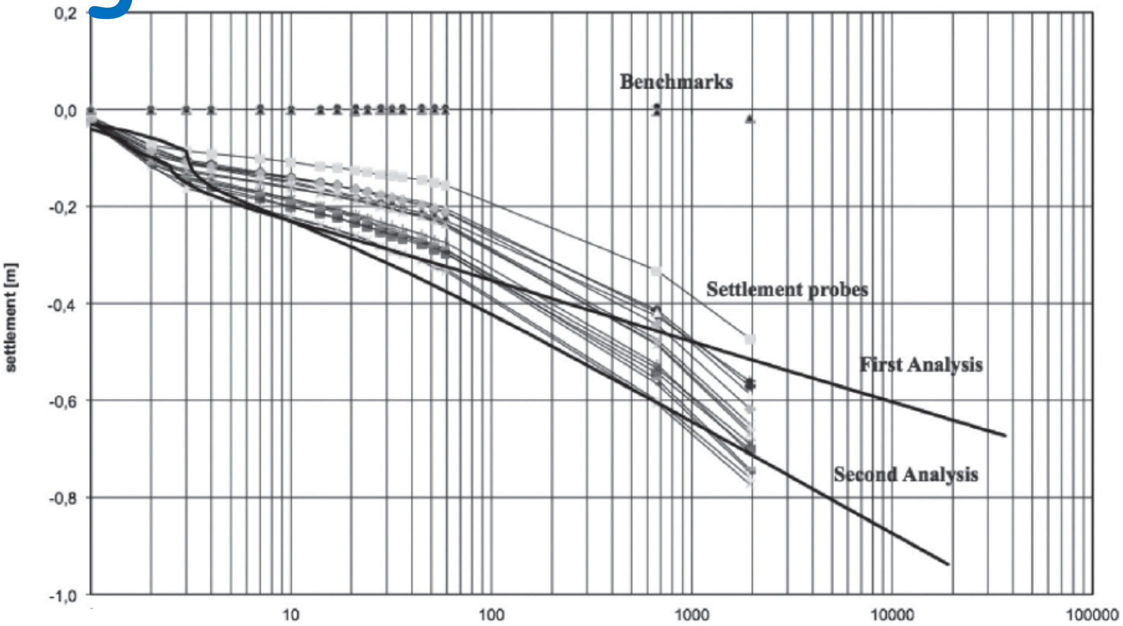
On levee monitoring:

FULL-SCALE TRIAL EMBANKMENT

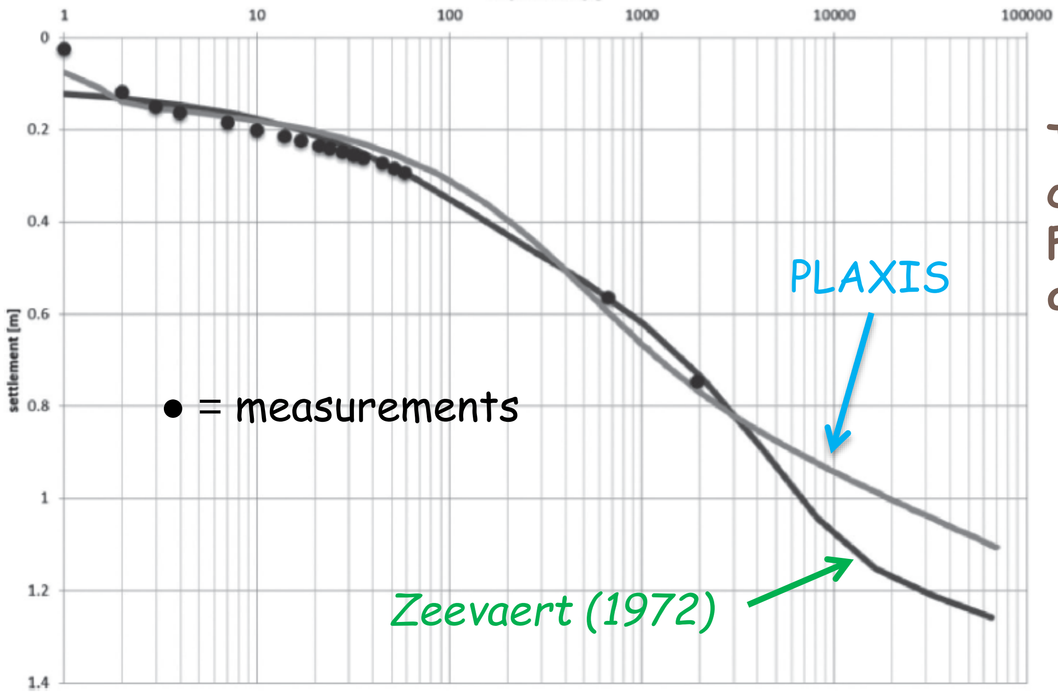
Embankments of a lamination basin for the flood risk mitigation

**FOUNDATION SOIL:
very compressible peaty soil**

MAIN GEOTECHNICAL ISSUES:
- ✓ loss of stability induced by the failure of the foundation soil
- ✓ loss of stability/serviceability because of (excessive) settlements



SETTLEMENTS MONITORING FOR FIVE YEARS



The measured settlements were compared against the results of a 2D FEM analysis and a 1D simplified approach

**Need for full-scale experiments
in order to highlight the actual behaviour of soil**

Inspection, Maintenance, Monitoring & Remediation:

PREVISION METHODS FOR QUALITY CONTROLS

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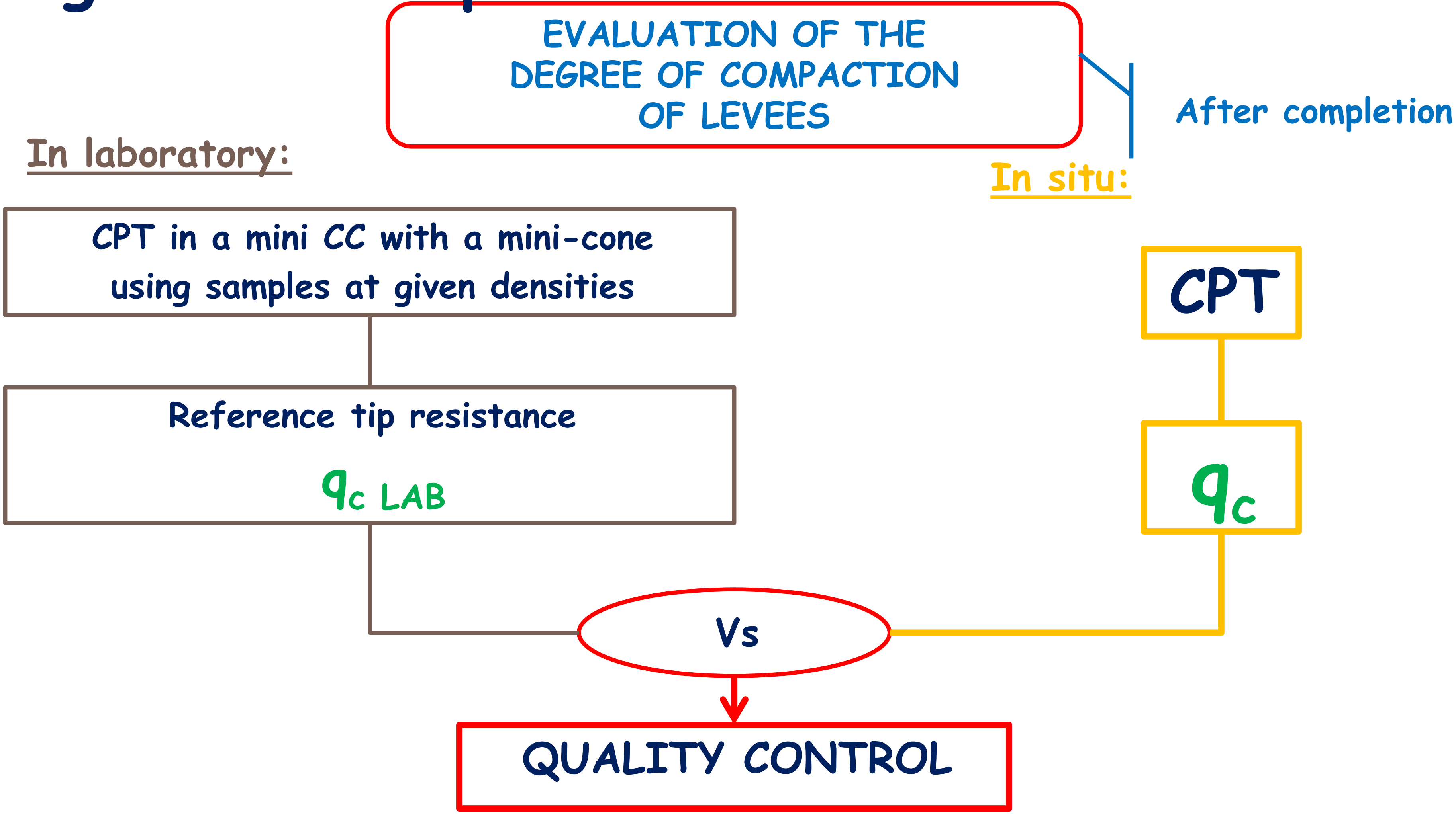
CPT-based method for evaluating the degree of compaction



EVALUATION OF THE DEGREE OF COMPACTION OF LEVEES

After completion

In laboratory:

CPT in a mini CC with a mini-cone using samples at given densities

Reference tip resistance

$q_{c\ LAB}$

In situ:

CPT

q_c

Vs

QUALITY CONTROL

- ✓ EXISTING LEVEES → DRY DENSITY
- ✓ NEW LEVEES → EXPECTED q_c CORRESPONDING TO A PRESCRIBED DRY DENSITY

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THE EQUIPMENT


10/05/2013 10:33

Aluminum mold:
Diameter = 320 mm; Height = 210 mm

Mini-cone:
8 mm diameter
Load cell located above the cone

Top boundary → rigid
Lateral & bottom boundaries → flexible
(provided with latex membranes)

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TESTED MATERIALS

TICINO SAND → PRELIMINARY CHECK OF THE EQUIPMENT

SILT MIXTURES

SILT MIXTURES

USED FOR THE CONSTRUCTION OF NEW LEVEES AND FOR THE REFURBISHMENT OF EXISTING STRUCTURES

SIEVED TO ELIMINATE THE FRACTION WITH $\phi > 2$ mm

Soil	γ_{dmax} kg/m^3	w_{opt} %	e_{opt}	$(Sr)_{opt}$ %	LL	PL	PI	AASHTO M 145	Gs	d_{50} mm
FR	2047	9.43	0.33	78	26÷31	18÷24	7÷10	A4÷A6	2.72	0.002÷0.025
PC	1950	10.7	0.39	74	25	19	6	A4	2.71	0.085
DD	1820	13.1	0.49	73	31.5	23.5	8	A4	2.71	0.01
TC	1895	12	0.42	77	25	6	19	A6	2.69	0.02

PARTIALLY SATURATED SILT MIXTURES

- ✓ Samples are reconstituted in 5 layers in a stainless steel mold
- ✓ The soil is prepared at a given w and compacted to a given γ_d using static compaction
- ✓ The compaction effort, required to consolidate each layer and the whole sample, is recorded:

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

EXPERIMENTAL PROGRAM

Soil type	Boundary stresses		Unit weight			Water content				
Abbreviation	σ'_v [kPa]	σ'_h [kPa]	γ_d [kN/m³]	γ_{dmax} [kN/m³]	γ_d/γ_{dmax}	w [%]	w_{opt} [%]	E [MJ/m³]	σ'_{pmax} [kPa]	Qc [MPa]
DD	30	30	14.56	17.85	0.82	13.2	13.1	0.395	8224	2.807
DD	50	50	14.56	17.85	0.82	13.2		0.238	6157	1.786
DD	80	80	14.56	17.85	0.82	13.2		0.299	6752	1.512
DD	30	30	16.38	17.85	0.92	13.2		1.324	24474	4.751
DD	50	50	16.38	17.85	0.92	13.2		1.413	24523	4.063
DD	80	80	16.38	17.85	0.92	13.2		1.501	24523	4.990
PC	30	30	15.60	19.13	0.82	10.8	10.7	0.62	13731	3.274
PC	50	50	15.60	19.13	0.82	10.8		0.697	14712	3.648
PC	80	80	15.60	19.13	0.82	10.8		0.545	13731	3.850
PC	30	30	17.55	19.13	0.92	10.8		2.407	39627	7.191
PC	50	50	17.55	19.13	0.92	10.8		2.76	40707	7.877
PC	80	80	17.55	19.13	0.92	10.8		2.211	36979	7.603
FR	30	30	18.50	2.05	0.92	12.0	9.43	4.123	46864	6.533
FR	30	30	18.50	2.05	0.92	12.0		3.315	43136	6.535
FR	30	30	18.50	2.05	0.92	12.0		2.938	37465	6.767
FR	30	30	18.00	2.05	0.90	12.0		1.735	22730	3.254
FR	30	30	18.00	2.05	0.90	12.0		1.735	24005	3.568
FR	30	30	18.00	2.05	0.90	12.0		1.828	24400	4.056
FR	30	30	16.00	2.05	0.80	12.0		0.511	8608	1.843
FR	30	30	16.00	2.05	0.80	12.0		0.463	8313	1.736
FR	30	30	16.00	2.05	0.80	12.0		0.475	7823	2.022
FR	30	30	16.00	2.05	0.80	4.0		0.26	10103	2.036
FR	30	30	16.00	2.05	0.80	4.0		0.307	9809	1.479
FR	30	30	16.00	2.05	0.80	4.0		0.346	10790	1.827
FR	30	30	16.00	2.05	0.80	8.0		0.579	15990	3.077
FR	30	30	16.00	2.05	0.80	8.0		0.622	15891	2.533
FR	30	30	16.00	2.05	0.80	8.0		0.564	15303	2.455

FINE-GRAINED SOILS

partially saturated

Boundary conditions:BC1

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%

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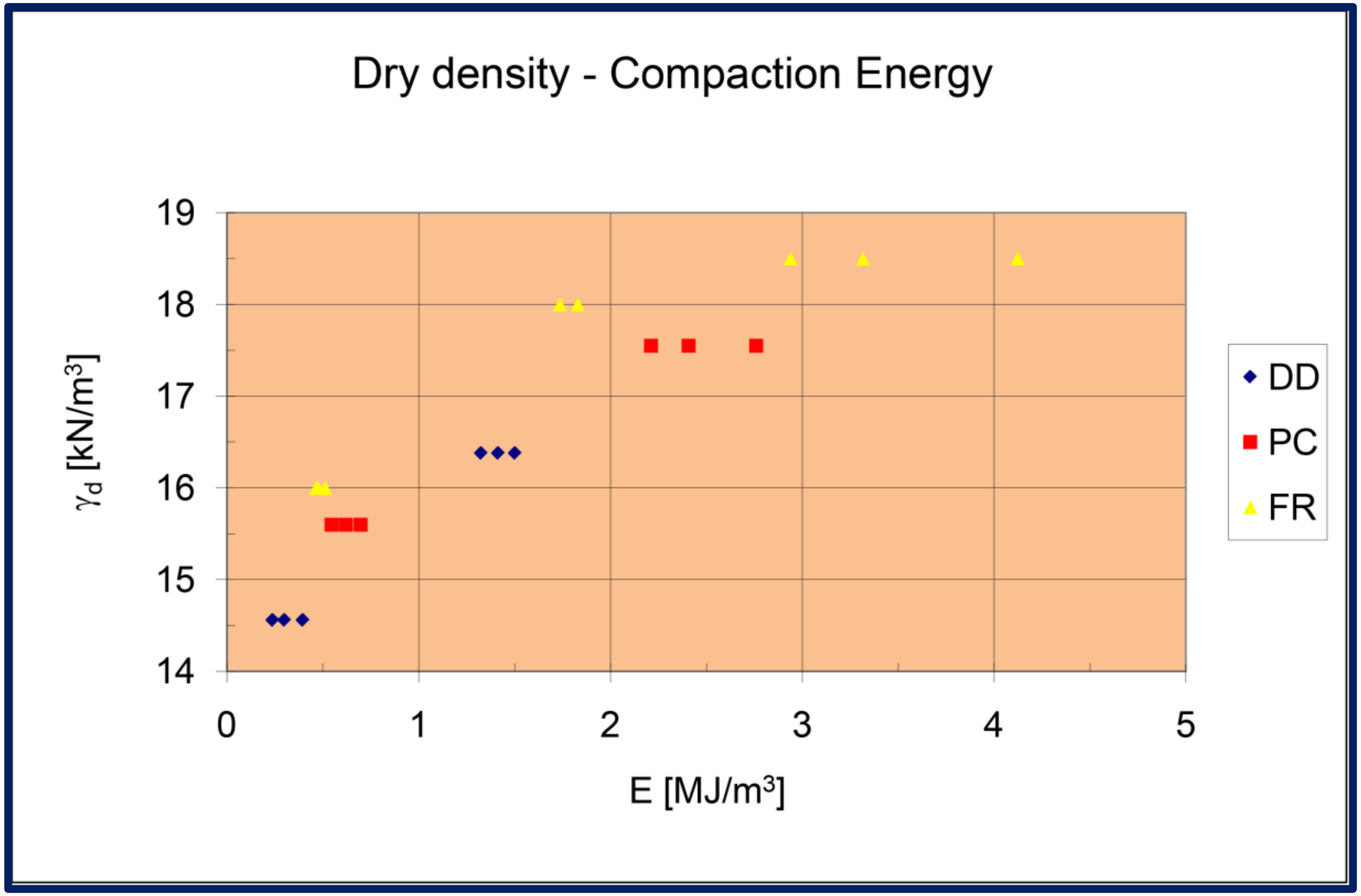
TEST RESULTS

FINE-GRAINED SOILS

partially saturated



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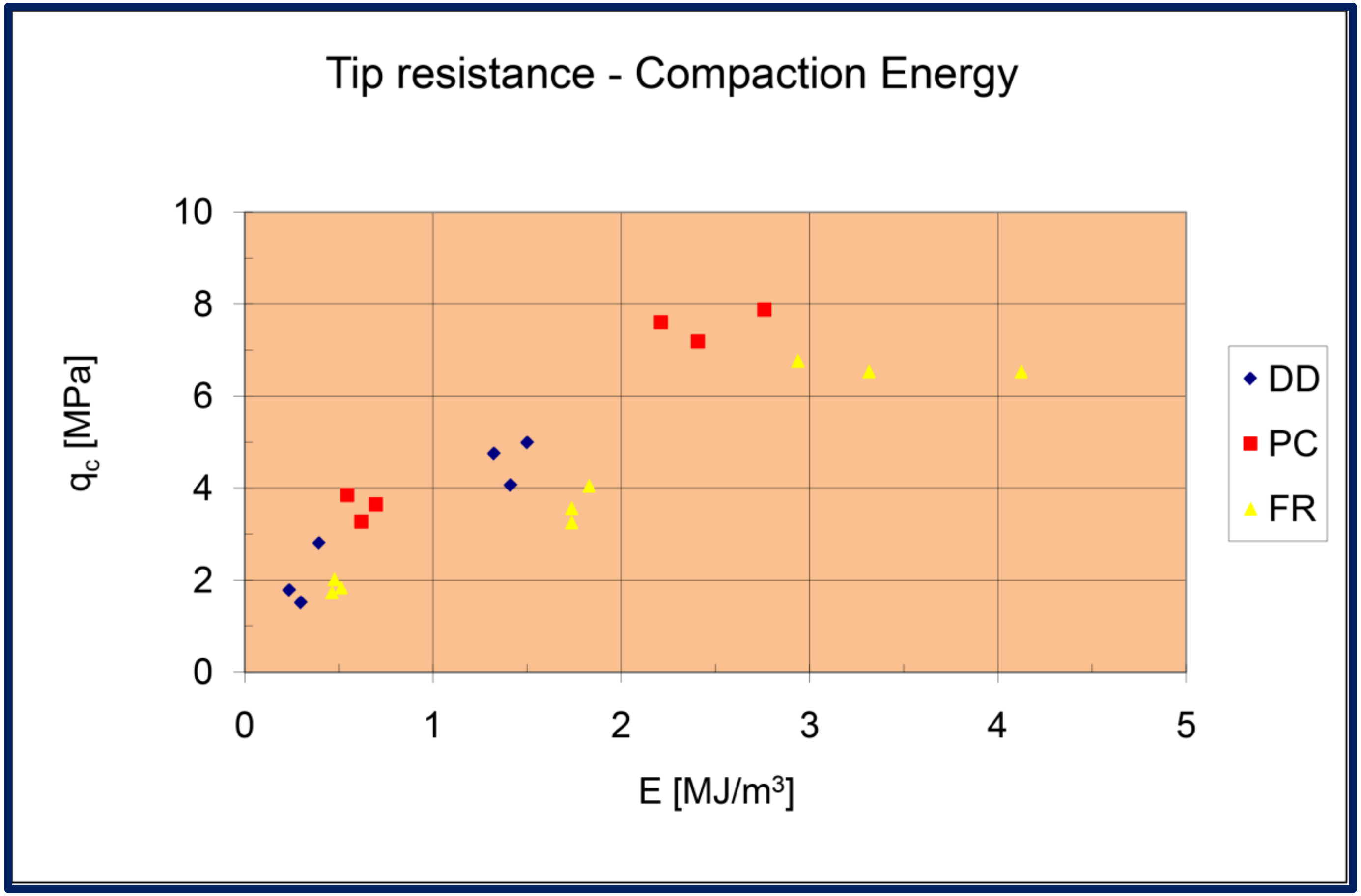
TEST RESULTS

FINE-GRAINED SOILS

partially saturated



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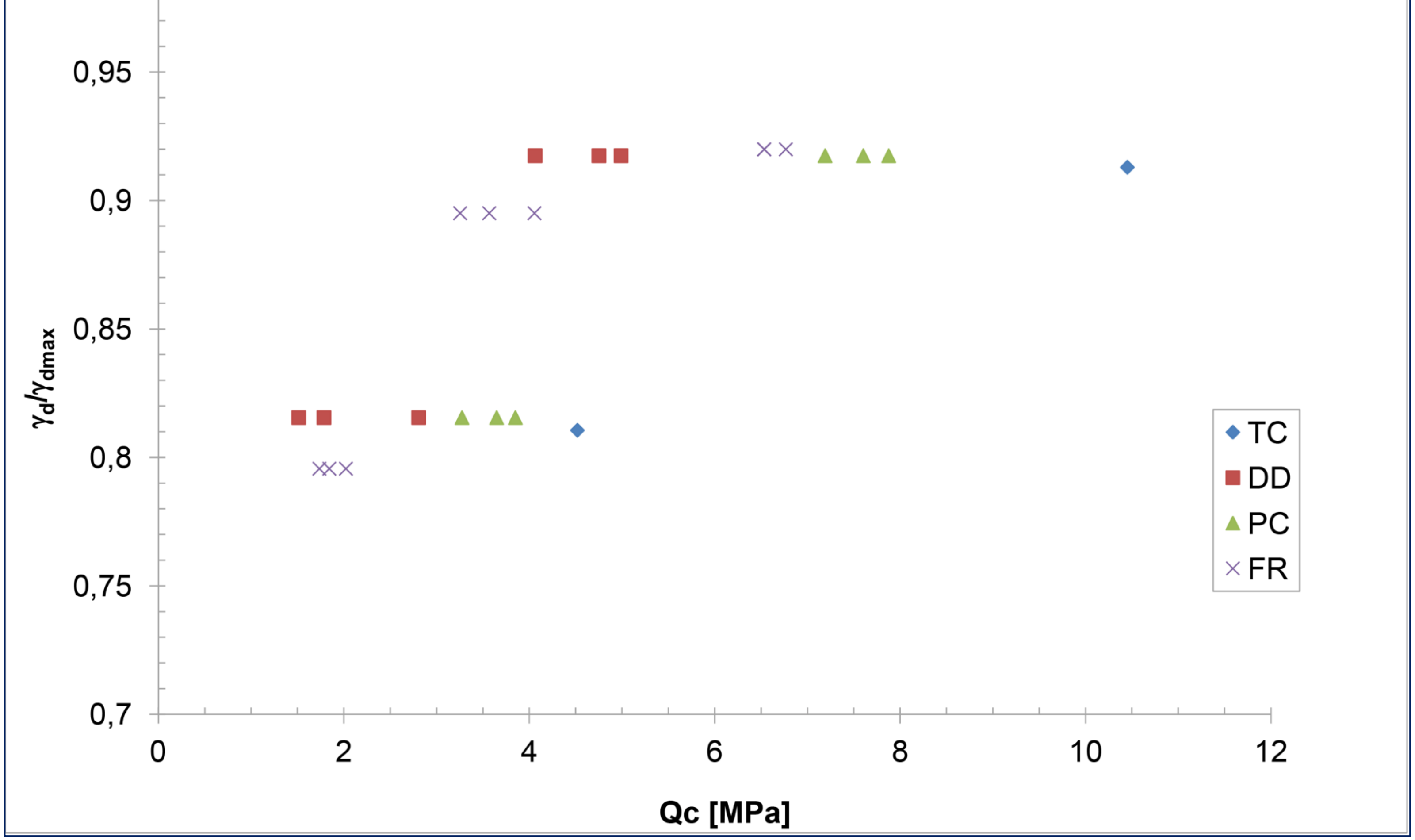
TEST RESULTS

FINE-GRAINED
SOILS

partially
saturated



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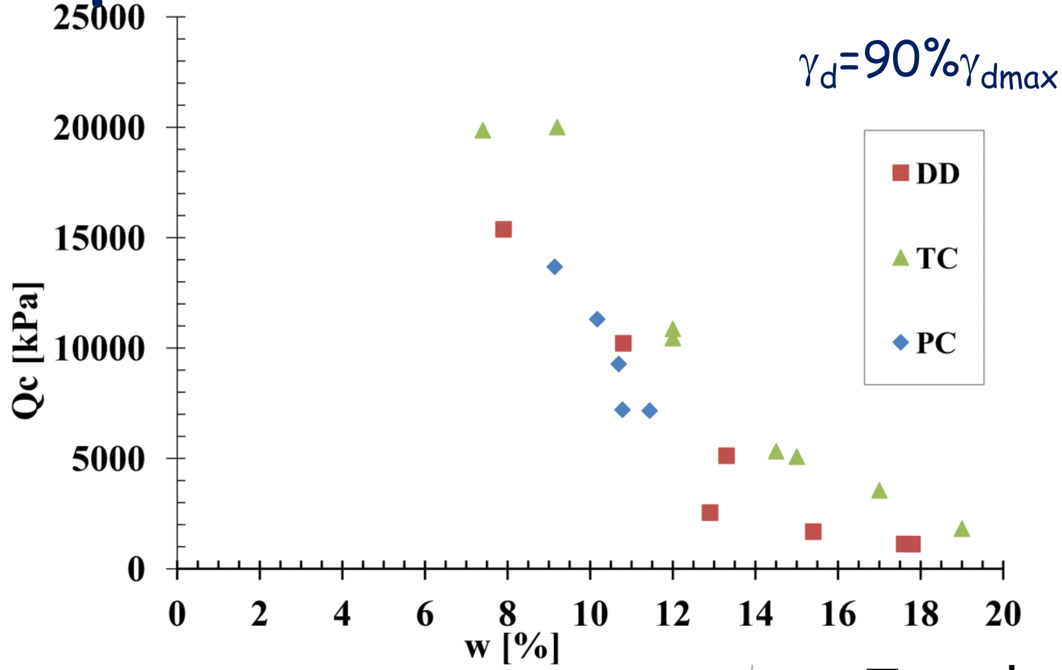
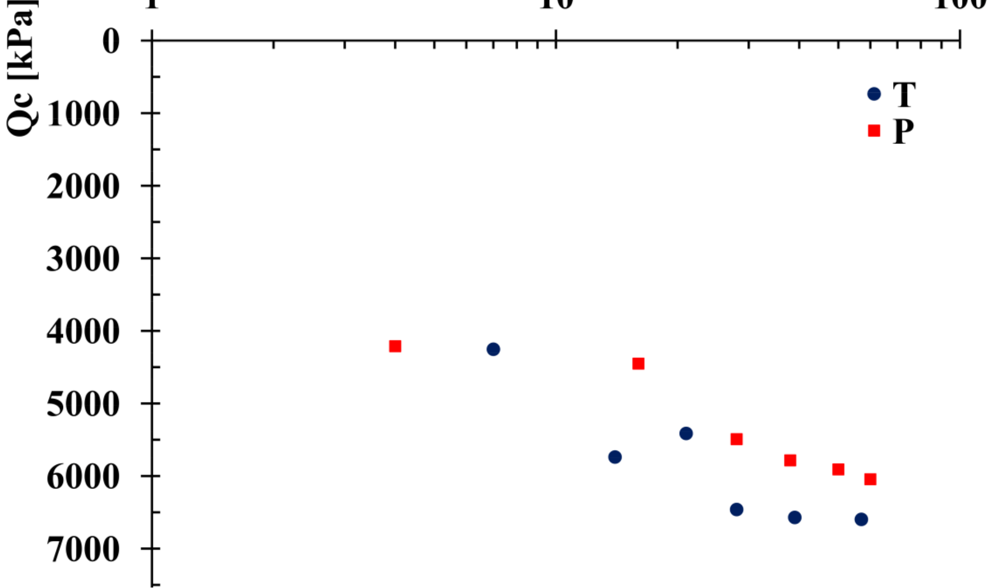
Water content after sample formation & elapsed time effects



$\gamma_d = 90\%\gamma_{dmax}$ (modified Proctor)

$w = w_{opt}$ = constant over the time

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



Practical application of the method:

FOR A GIVEN SOIL:

Define a design compaction degree

↓

Reconstitute a sample at the given dry density and water content

↓

Repeat tests (in the CC on the same sample) with variable water contents after sample formation

↓

Experimental determination
(for the given degree of compaction) of the
DESIGN CURVE
tip resistance vs. water content
after sample formation

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Thank you for your attention

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