РОССИЙСКОЕ ОБЩЕСТВО ПО МЕХАНИКЕ ГРУНТОВ, ГЕОТЕХНИКЕ И ФУНДАМЕНТОСТРОЕНИЮ
RUSSIA SOCIETY FOR SOIL MECHANICS, GEOTECHNICS AND FOUNDATION ENGINEERING

Gersevanovskie Chteniya
Laboratory and in-situ soil investigation
Moscow, 15 April 2009

Design of foundations in France with the use of Ménard pressuremeter tests (MPM)

Roger FRANK

Ecole nationale des ponts et chaussées
UR Navier, CERMES (ENPC-LCPC), Paris

École des Ponts ParisTech

I. The Ménard pressuremeter : general

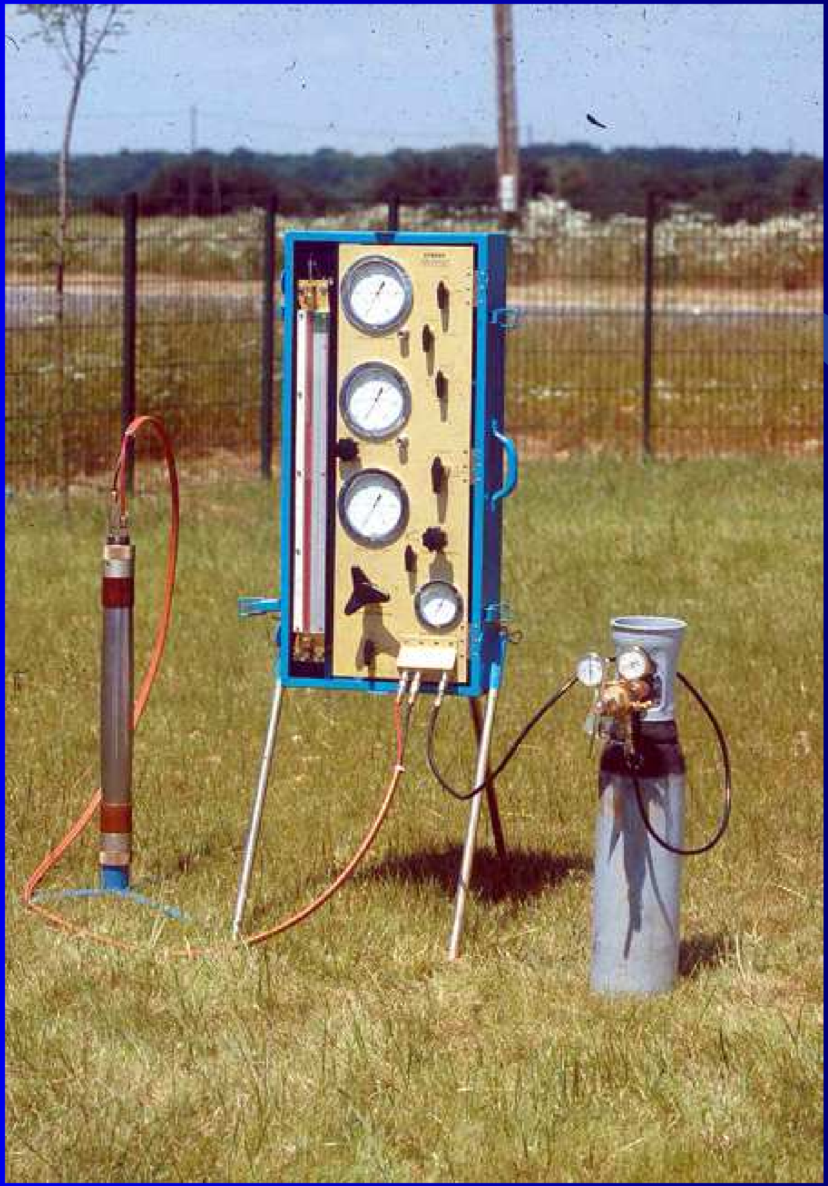
II. Bearing capacity and settlement of shallow foundations

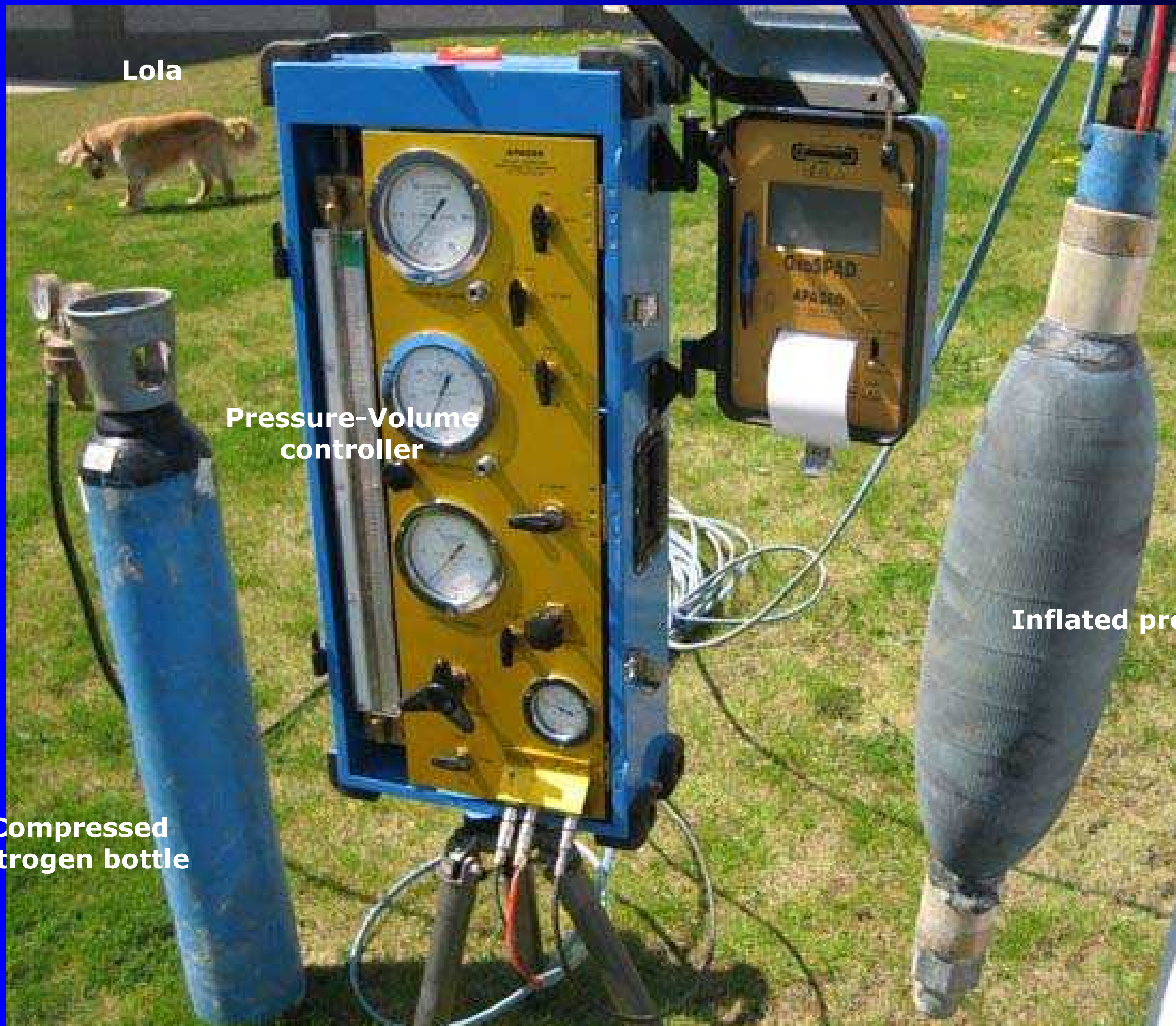
III. Bearing capacity of piles

IV. Settlement of piles & laterally loaded piles

V. Annexes in Eurocode 7 – Part 2

I. The Ménard pressuremeter : general




Lola
Pressure-Volume controller
Inflated probe
Compressed nitrogen bottle

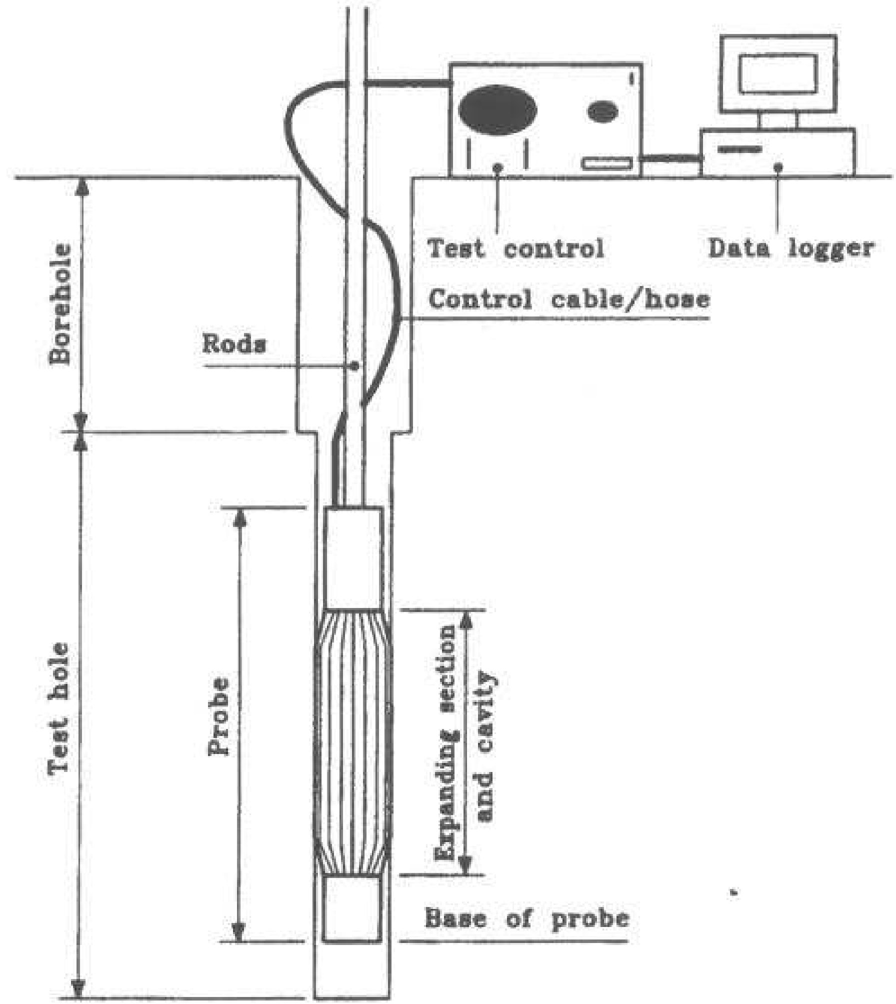


Figure 4.1: Key features of a pressuremeter

(from ENV 1997-3, 1999)

Pressuremeter probe placement techniques (AFNOR Standard, 1991)

Tableau C.1 — Méthodes de réalisation des forages pressiométriques

Nature des terrains	Forage préalable								Refoulement
	Rotation *					Battage et autres			
	T.S.	T.IN °	THC	O. DG. IN	CAR.	ROTOP.	CAR. BAT.	CAR.VBF	TF BAT/VBF
Vase et argile molles	—	R	—	O °	—	—	O poinç	—	—
Argiles moyennement compactes	R	R	R	R °	—	O °	—	—	—
Argiles compactes marnes raides	/	/	R	R	R °	O °	—	—	—
Limons — au-dessus de la nappe	R	O	R	O °	—	O °	O	O	—
Limons — sous la nappe	—	R	—	O °	O °	O °	—	—	—
Sables lâches — au-dessus de la nappe	R	R	O	O °	—	O °	—	—	—
Sables lâches — sous la nappe	—	R	—	O °	—	O °	—	—	O
Sables moyennement compacts et compacts	R	R	R	R °	—	R °	O	O	O +
Sols grossiers : graviers, galets ; argiles à silex, etc.	/	/	O	O °	/	R °	O	O	O +
Roches — altérées	/	/	R	R	O	R °	O	O	O +
Roches — saines	/	/	/	R	R	R	/	/	/

Légende :

R	Recommandé	T.S.	Tarière à sec	T.IN. °	Tarière avec injection de boue de forage
O	Toléré	THC	Tarière hélécoïdale continue à sec	CAR.	Carottier
—	Non toléré	O. DG.	Outil désagrégateur	IN	Avec injection de boue
/	Inadapté	ROTOP.	Rotopercussion	poinç	Carottier à parois minces foncé
		BAT.	Battage	VBF	Vibrofonçage
		TF	Tube fendu		

Allowed boring techniques (prEN ISO 22476-4)

Table C.2 — Guidelines for pressuremeter probe placement techniques

	Probe placing without soil displacement														Probe placing with full soil displacement
Boring technique	1< d_t/d_c ≤ 1,15														(d_t/d_c ≈0)
	Rotary Drilling					Rotary percussion			Pushing, driving or vibrodriving					.	Full displac.
Soil Type	HA	CFA *	ADM*	DTM	CD	RP	RPM	STDTM	PS	DS	VDS				DST
Sludge and soft clay	-	-	***°	**°	-■		-	-	*** TWS	-					*■
Soft to medium stiff clayey soils	**■	**■	***°	***°	**■	-	*■°	*°	*■	*	-			-	
Stiff clayey soils		***	**■°	***°	***°	*■	**°	**■°	-	*■	-			-	
Silty soils: - above water table	**	**	***°	**°	**■°	-	*°	**°	*■	*	*		-	-	-
- below water table	-	-	**■°	*■°	*■°	-	*°	**▲°	-	-	-				*■
Loose sandy soils: - above water table	**	**	***■°	**°	*	-	*°	*°	-■	-	-		-	-	-
- below water table	-	-	**°	*■°	-■	-	*°	*▲°	-■	-	-				*■+

Allowed boring techniques (cntd)

Medium dense and dense sandy soils	**	***	***°	***°	* °	*	**°	**▲ °	-	*	*				**■+
Coarse soils: gravels, cobbles		-■	-■°	** °	-■	*	*** °	*■°		*	*				***■+
Coarse soils with cohesion (e.g. boulder clay)		*	*°	**°	**■ °	*	*** °	*■ °		*	*				
Loose non homogeneous soils, non textbook soils (e.g. tills, some alluvial deposits, man made soils, treated or untreated fills ...)		*	*°	**°	* °	*	**°	**■ °	-	*	*				**■+
Weathered rock, Soft rock		**	**°	***°	**■ °	*■	**°	**■ °		*■	*■			-	
Rock (*see note below*)				***°	***°	***	*** °					*■			

NOTE In rocks or any material with creep pressure exceeding 5 MPa, Ménard pressuremeter tests can be carried out .. However the corresponding test procedure and test interpretation are not covered by this standard.

Caption

✱✱✱	Recommended	ADM	Auger with drilling mud	PS	Pushed sampler
✱✱	Suited	HA	Hand auger (post-hole or small helical type)	DS	Driven sampler
✱	Acceptable			VDS	Vibro driven sampler
-	Not suited	CFA	Continuous flight auger (in the dry)	STDTM	Slotted tube with inside disintegrating tool and mud circulation
(grey box)	Not covered by this standard	DTM	Disintegrating tool (e.g. drag bit, rock roller bits,...) with mud circulation	DST	Driven slotted tube
		CD	Core drilling	TWS	Thin wall sampler
		RP	Rotary percussion	PFCO	Probe with flexible cover and open tapered shoe
		RPM	Rotary percussion with mud		

■	Depending on the actual site conditions and on the evaluation of the operator -
*	Rotation speed should not exceed 60 rpm and tool diameter not be more than 1,15 d_c
°	Slurry circulation: pressure should not exceed 500 kPa and the flowrate 15 l/min. The flow may be temporarily interrupted if necessary.
▲	With special care meaning add a guard tube at the toe of the slotted tube, carry out the tests while going down, keep slurry level in casing higher than water table level.
+	Pilot hole with possible preboring techniques: DTM, , RP,RPM,

Drilling stage length (prEN ISO 22476-4)

Table C.1 — Maximum continuous drilling or driving stage length before testing

Soil type	Maximum continuous drilling stage length (m)		
	Rotary drilling	Rotary percussion	Pushing, driving and vibrodriving[b]
Sludge and soft clay, soft clayey soil	1[a]	----	1[a]
Medium stiff clayey soils	2	2	3
Stiff clayey soils	5	4	4
Silty soils:			
- above ground water table	4	3	3
- below water table	2[a]	1[a]	---
Loose sandy soils:			
- above ground water table	3	2	---
- below water table	1[a]	1[a]	---
Medium dense and dense sandy soils	5	5	4
Coarse soils: gravels, cobbles	3	5	3
Coarse soils with cohesion	4	5	3
Loose non homogeneous soils, non text book soils	2	3	2
Weathered rock, soft rock	4	5	3
Solid rock	c	c	---

a Or the required interval between two successive tests.

b Not applicable to STDTM technique.

c Maximum length is a function of the number of tests in a working shift.

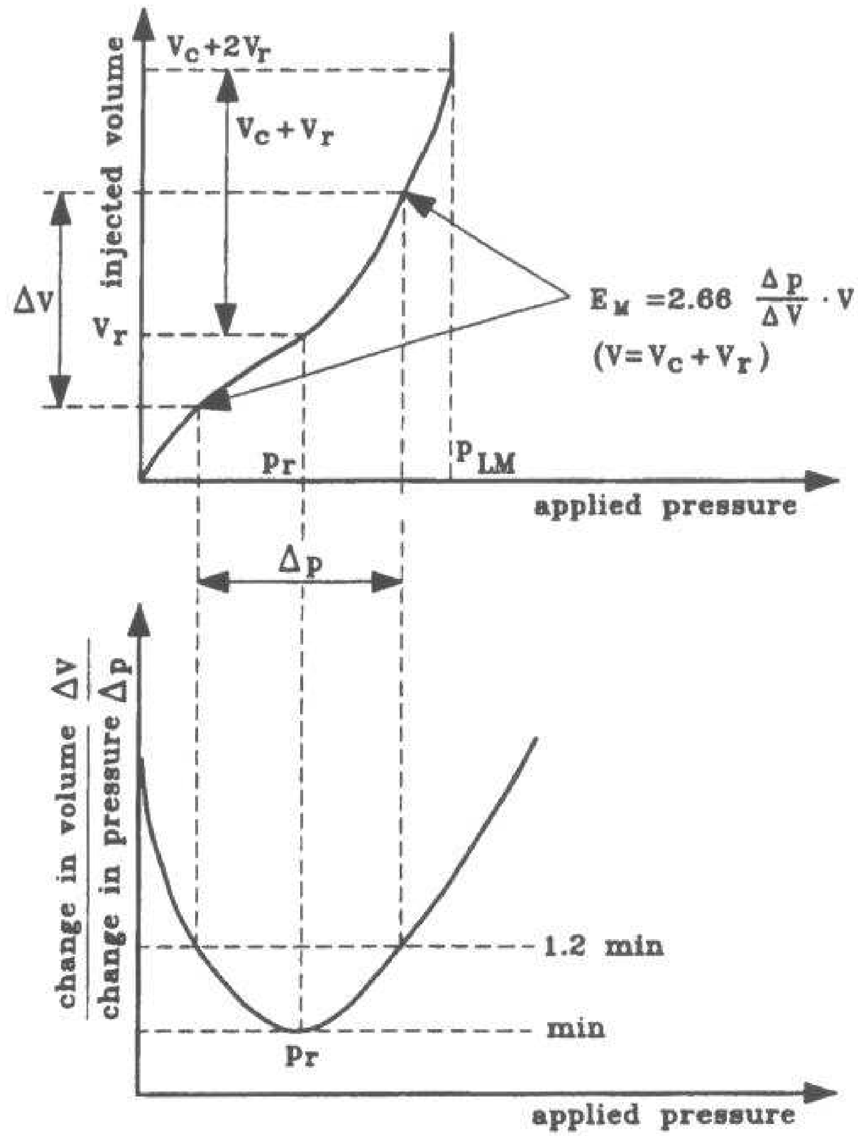
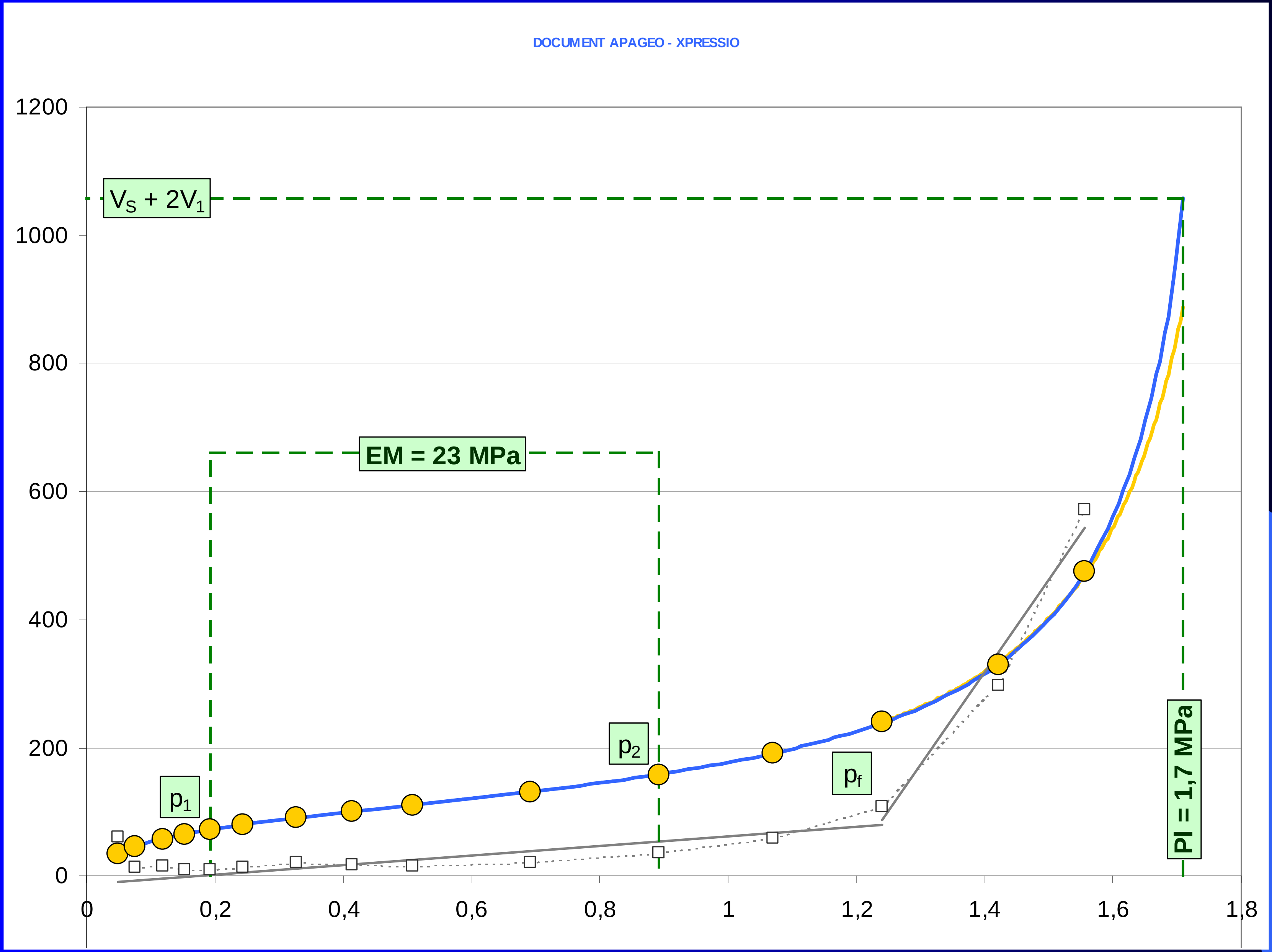
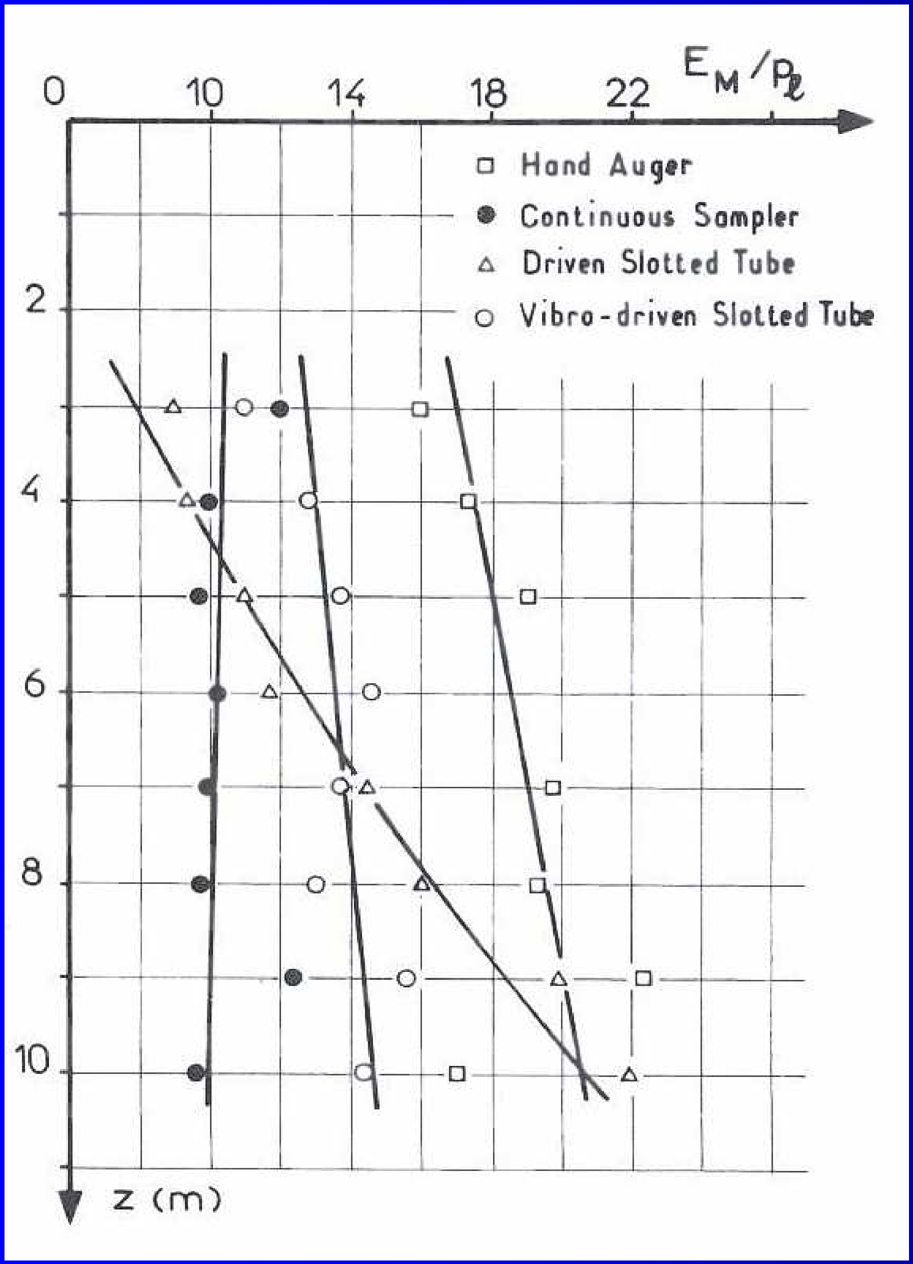


Figure 4.3: Interpretation of E_M and p_{LM} for an MPM test

(from ENV 1997-3, 1999)


DOCUMENT APAGEO - XPRESSIO
1200
1000
800
600
400
200
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
$V_S + 2V_1$
EM = 23 MPa
p_1
p_2
p_f
PI = 1,7 MPa



Influence of placement method

St-Malo de Phily sand

(after Jézéquel, Lemasson & Touzé, 1968)

Standards

- NF P 94-110-1

Standard in use in France presently.
Data recording is mandatory

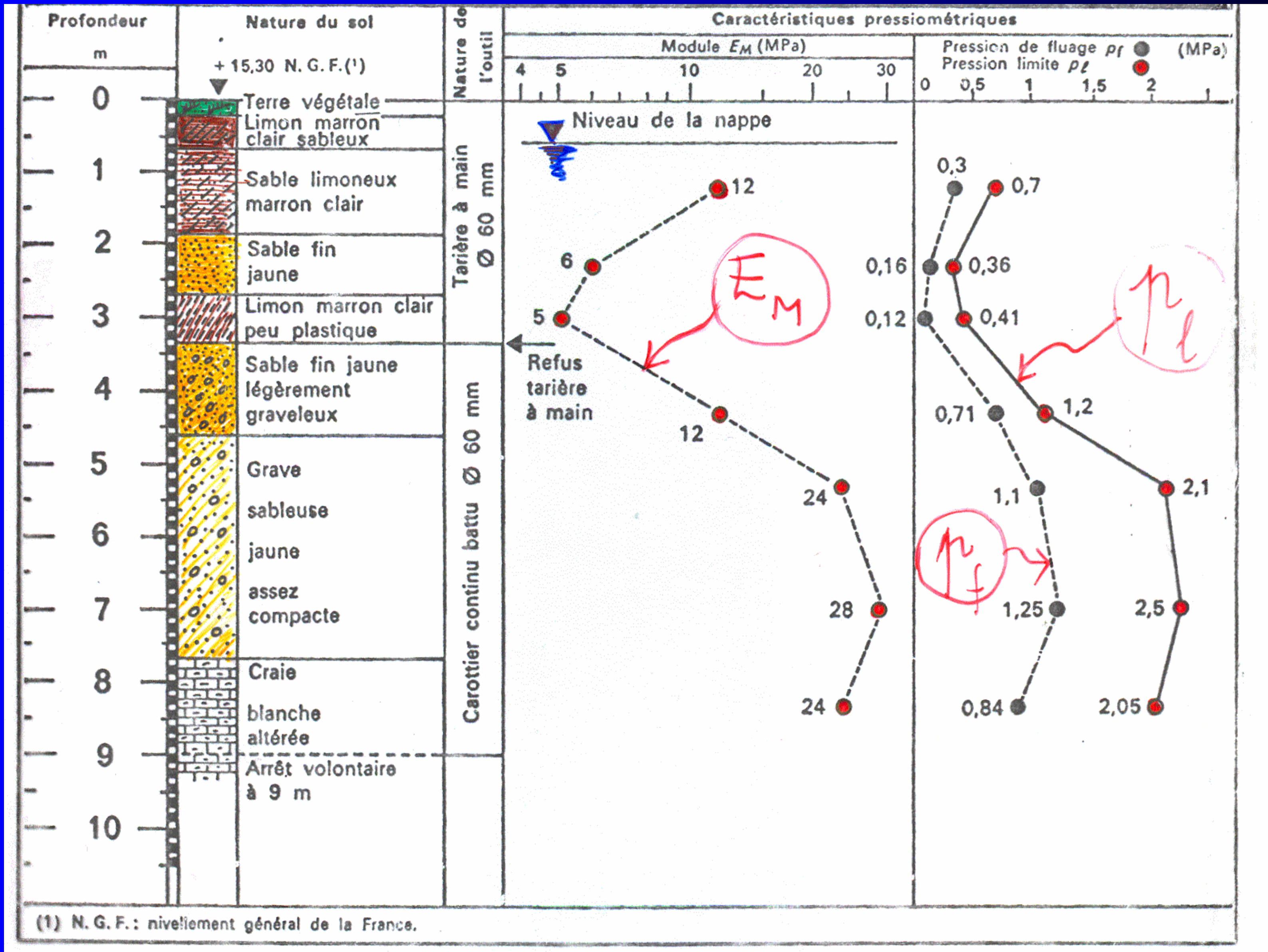
- EN ISO 22476-4

Project for European standard under publication. Data recording is optional (procedure B)

- ASTM D-4719

American standard (1987)

Pressuremeter soil profile



Use of in situ test results

- The **direct** method ('semi-empirical') should be preferred
  i.e direct rules for determining the bearing capacity of foundations from the test results :
  (and possibly the displacements)

q_d, N, q_c, etc.

Specific advantages of the Pressuremeter

with the limit pressure p_{LM} **:**

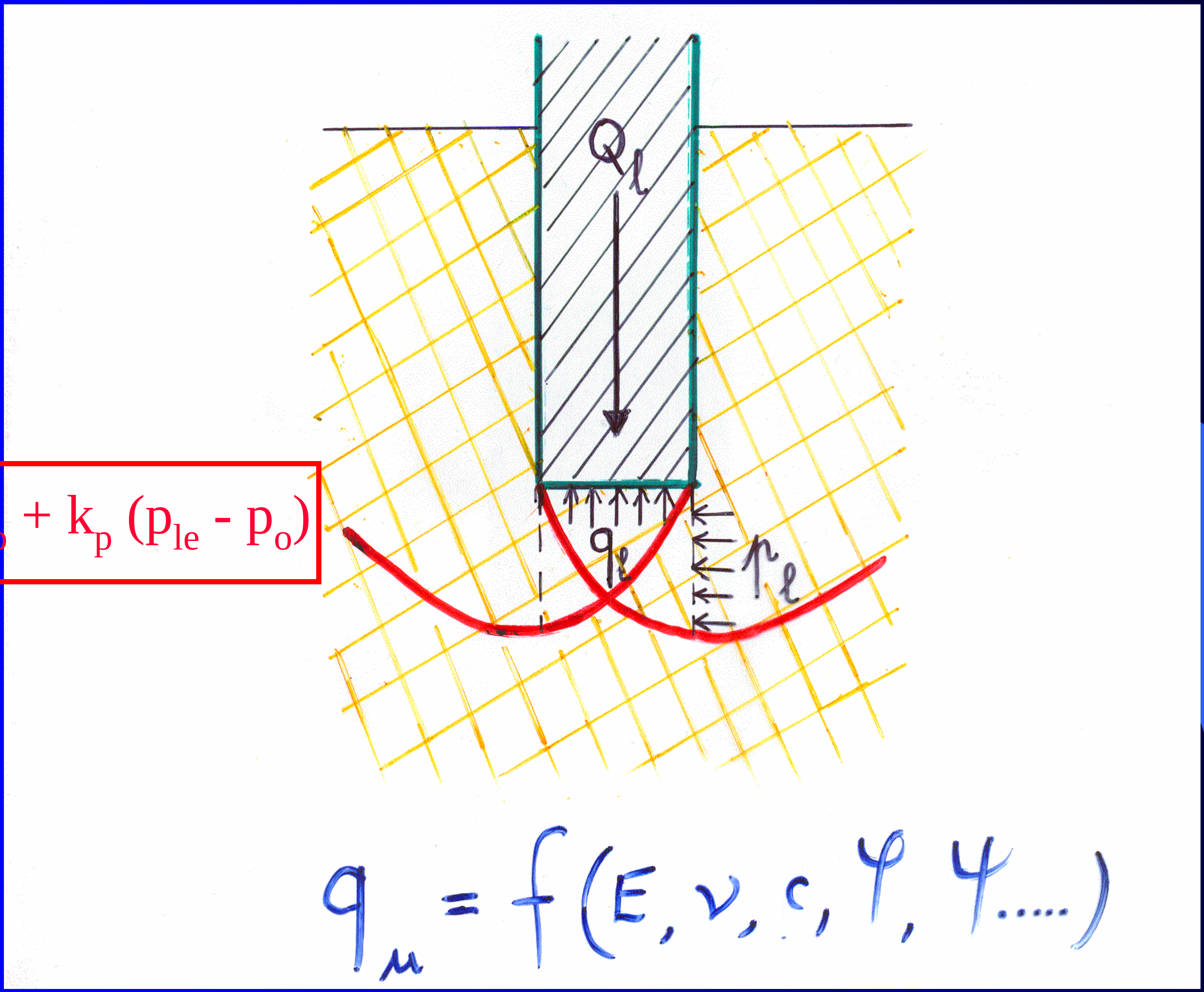
- bearing capacity of shallow foundations (q_p)
- axial bearing capacity of deep foundations (q_p and q_s)

With the pressuremeter modulus E_M **:**

- settlement of shallow foundations (s)
- analysis of the behaviour of deep foundations under transverse loading

Bearing capacity : the pressuremeter 'faith'

$$q_u = q_o + k_p\,(p_{le} - p_o)$$



Pressuremeter proves its worth in London's Docklands

By Duncan Nicholson, Tim Chapman and Paul Morrison, Arup Geotechnics.

GROUND ENGINEERING MARCH 2002

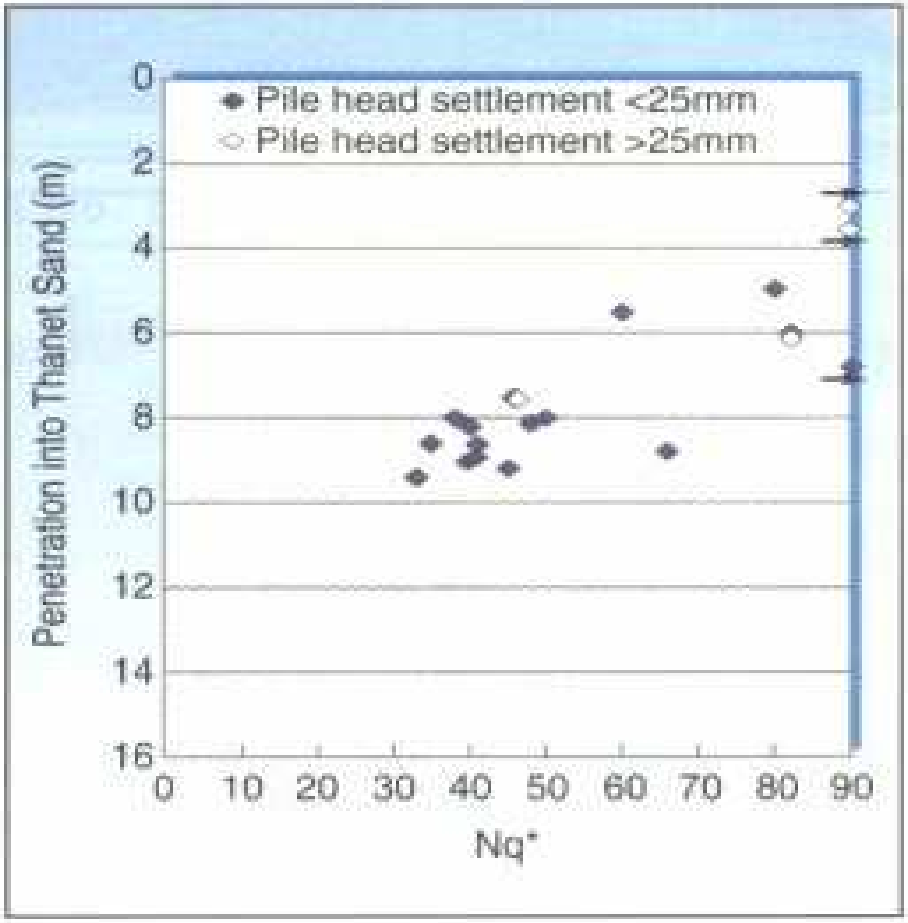


Figure 8: Pile test results in Thanet Sand.

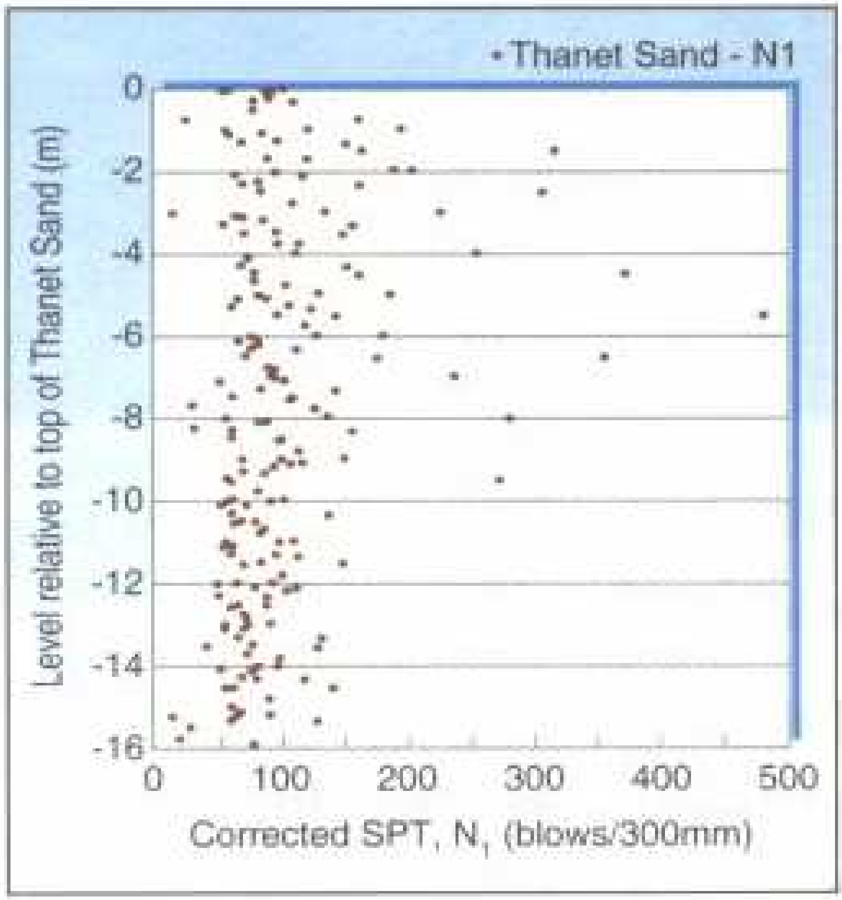


Figure 2: North Quay corrected SPT data for Thanet Sand.

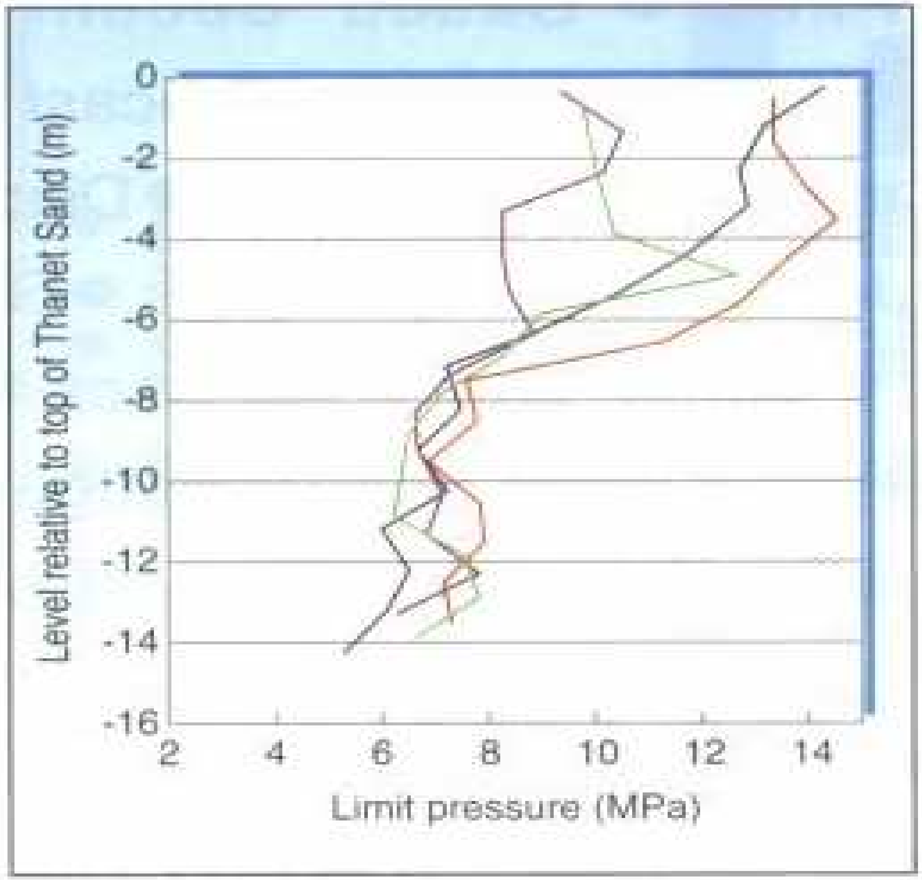


Figure 3: North Quay Menard Pressuremeter tests in Thanet Sand.

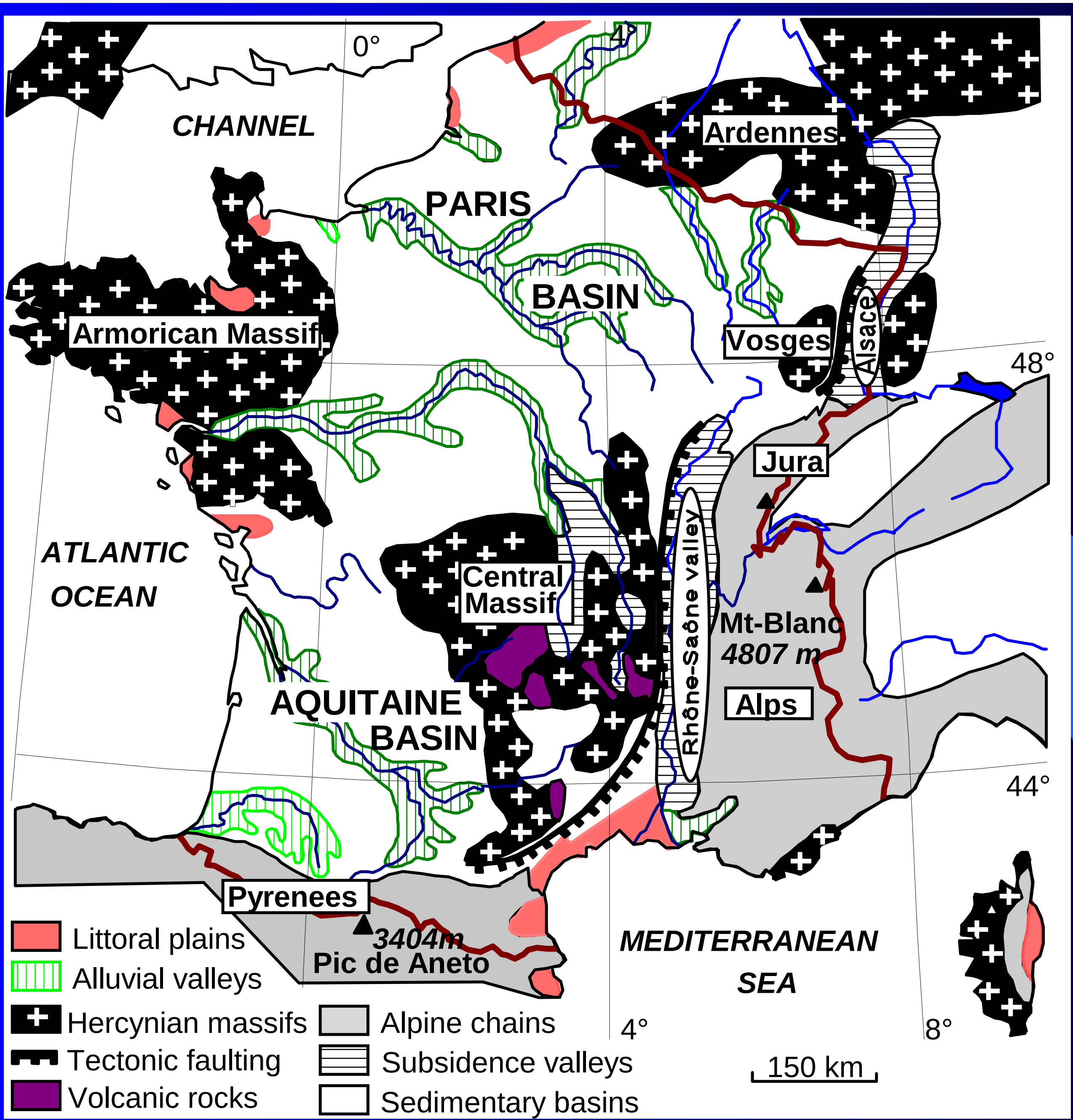

0°
4°
CHANNEL
PARIS
BASIN
Ardennes
Vosges
Alsace
Armorican Massif
48°
Jura
ATLANTIC
OCEAN
Central
Massif
Rhône-Saône valley
Mt-Blanc
4807 m
Alps
AQUITAINE
BASIN
44°
Pyrenees
3404m
Pic de Aneto
MEDITERRANEAN
SEA
Littoral plains
Alluvial valleys
Hercynian massifs
Tectonic faulting
Volcanic rocks
Alpine chains
Subsidence valleys
Sedimentary basins
4°
8°
150 km

Table 2 Field and laboratory tests feasability after Bustamante & Gianeselli (2006)

Test	carried out to full design length (1)	incomplete test (2)	not carried out (3)	not applicable (4)
PMT pressuremeter (p_l)	155	3	46	0
CPT (q_c)	60	79	23	42
laboratory tests (c_u, c', φ')	21	67	69	47
SPT (N)	26	54	72	52

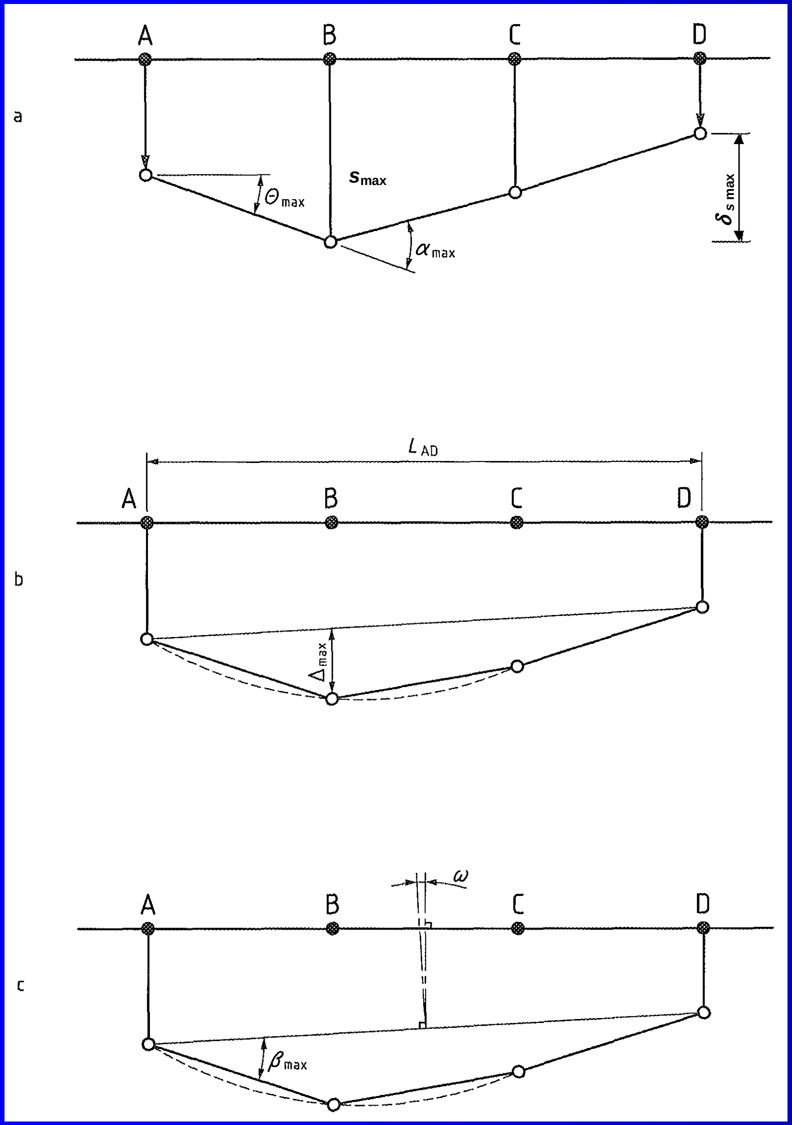
(1) including the full length of pile + additional metres below the pile point

(2) due to premature refusal for CPT; sampling not possible for laboratory tests; soil strength too high for SPT

(3) feasible but not planned when the investigation campaign was decided

(4) considered from the beginning as inadequate with respect to soil nature or strength

Allowable settlements of structures



- settlement *s*, differential settlement δs, rotation θ and angular strain α
- relative deflection Δ and deflection ratio Δ/L
- ω and relative rotation (angular distortion) β

(after Burland and Wroth, 1975)

Foundations of buildings (Eurocode 7, 1994)

- Serviceability limit states (SLS) : $\beta_{max} \approx$ 1/500
- Ultimate limit states (ULS) : $\beta_{max} \approx$ 1/150
- $s_{max} \approx$ 50 mm $\delta_{smax} \approx$ 20 mm

Foundations of bridges

Moulton (1986) for 314 bridges in the US and Canada :

* $\beta_{max} \approx$ 1/250 (continuous deck bridges)

and $\beta_{max} \approx$ 1/200 (simply supported spans)

* $s_{Hmax} \approx$ 40 mm

In France, in practice :

ULS : $\beta_{max} \approx$ 1/250

SLS : $\beta_{max} \approx$ 1/1000 à 1/500

- The pressuremeter test can be performed in all types of soils and soft rocks

- It provides the soil engineer with both a failure parameter and a deformation parameter measured in situ

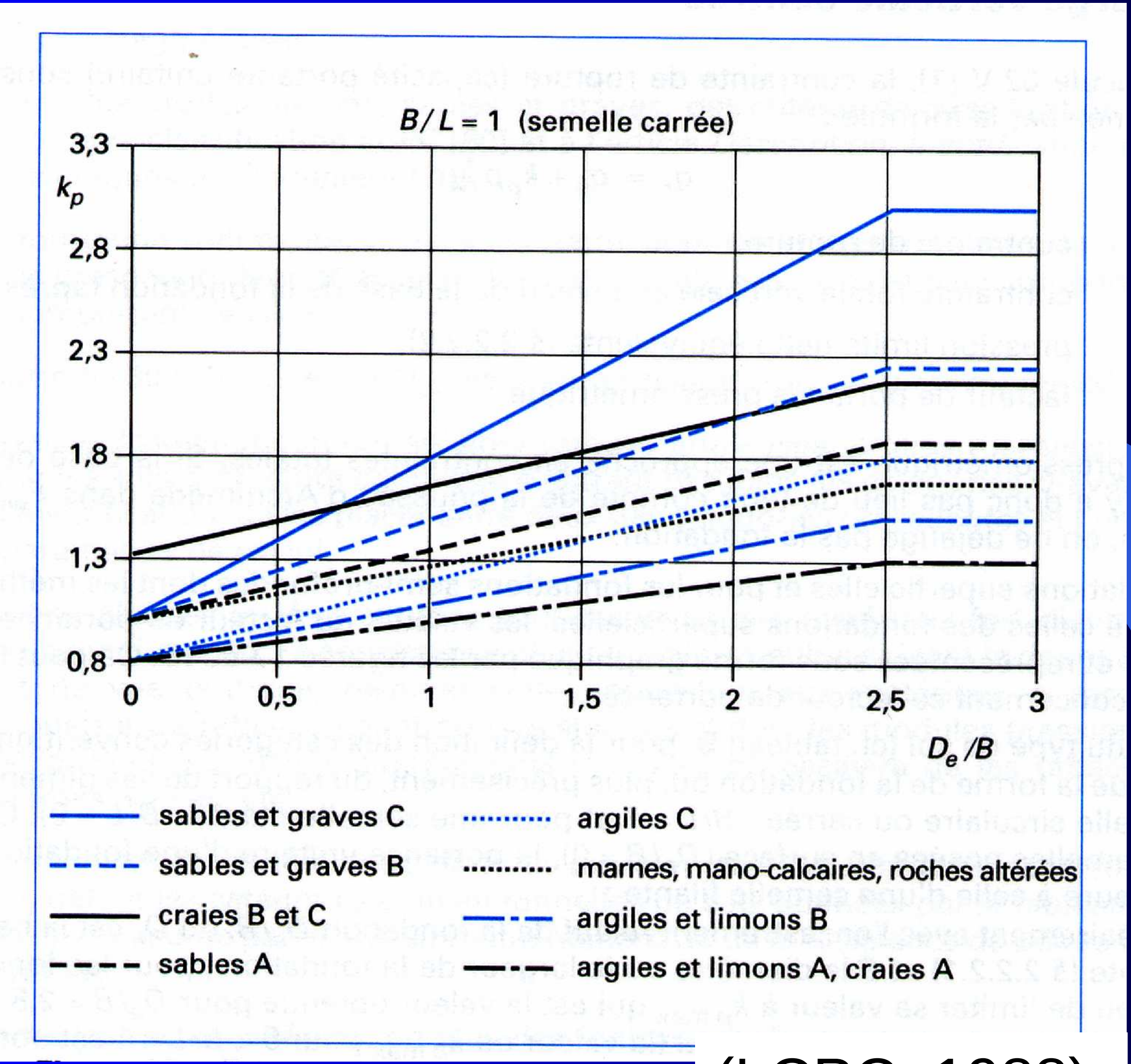
Conventional categories in F 62-V

Soil type			p_l (MPa)	q_c (MPa)
Clay Silt	A	soft	< 0.7	< 3
	B	stiff	1.2 - 2	3 - 6
	C	hard(clay)	> 2.5	> 6
Sand Gravel	A	loose	< 0.5	< 5
	B	medium	1- 2	8 - 15
	C	dense	> 2.5	> 20
Chalk	A	soft	< 0.7	< 5
	B	weathered	1 - 2.5	> 5
	C	dense	> 3	-
Marl Calcareous marl	A	soft	1.5 - 4	-
	B	dense	> 4.5	-
Rock	A	weathered (1)	2.5 - 4	-
	B	fragmented	> 4.5	-

(1) use the value of the most similar soil.

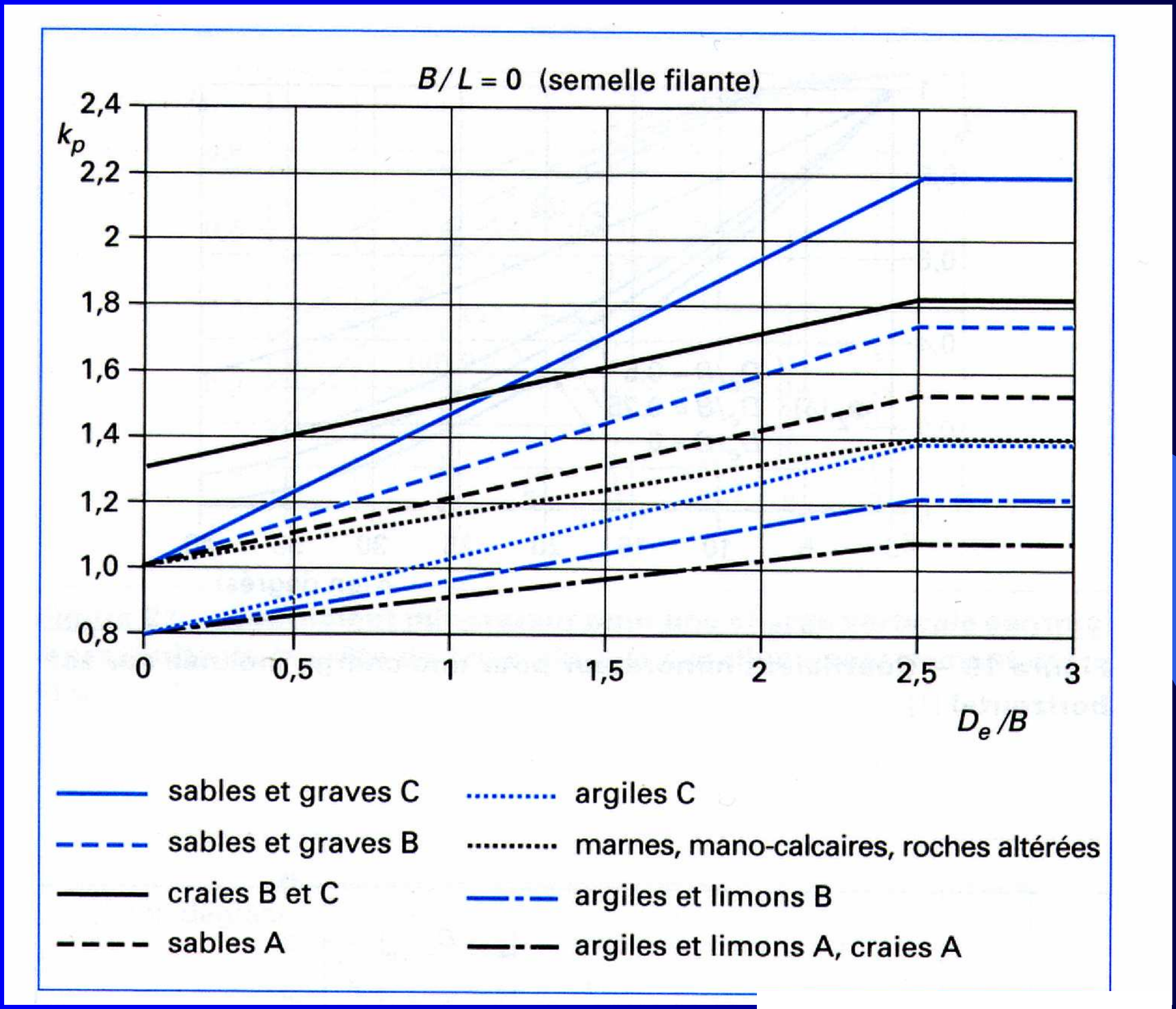
II. Bearing capacity and settlement of shallow foundations

Bearing factors for square or circular footings



(LCPC, 1988)

Bearing factors for strip footings



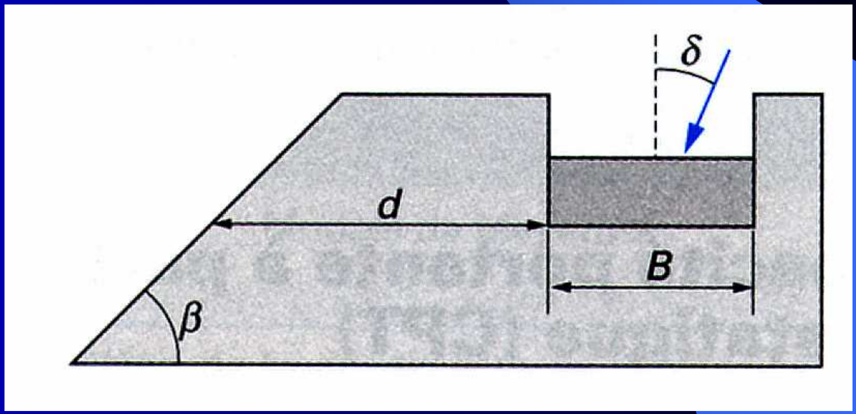
(LCPC, 1988)

Design bearing capacity

Reference stress $q_{réf}$:

$$q_{réf} \leqslant \frac{1}{\gamma_q} k_p p^*_{\ell e} i_{\delta\beta} + q_0$$

$i_{\delta\beta}$ reduction factor depends on β, δ, d/B_e, D_e/B_e

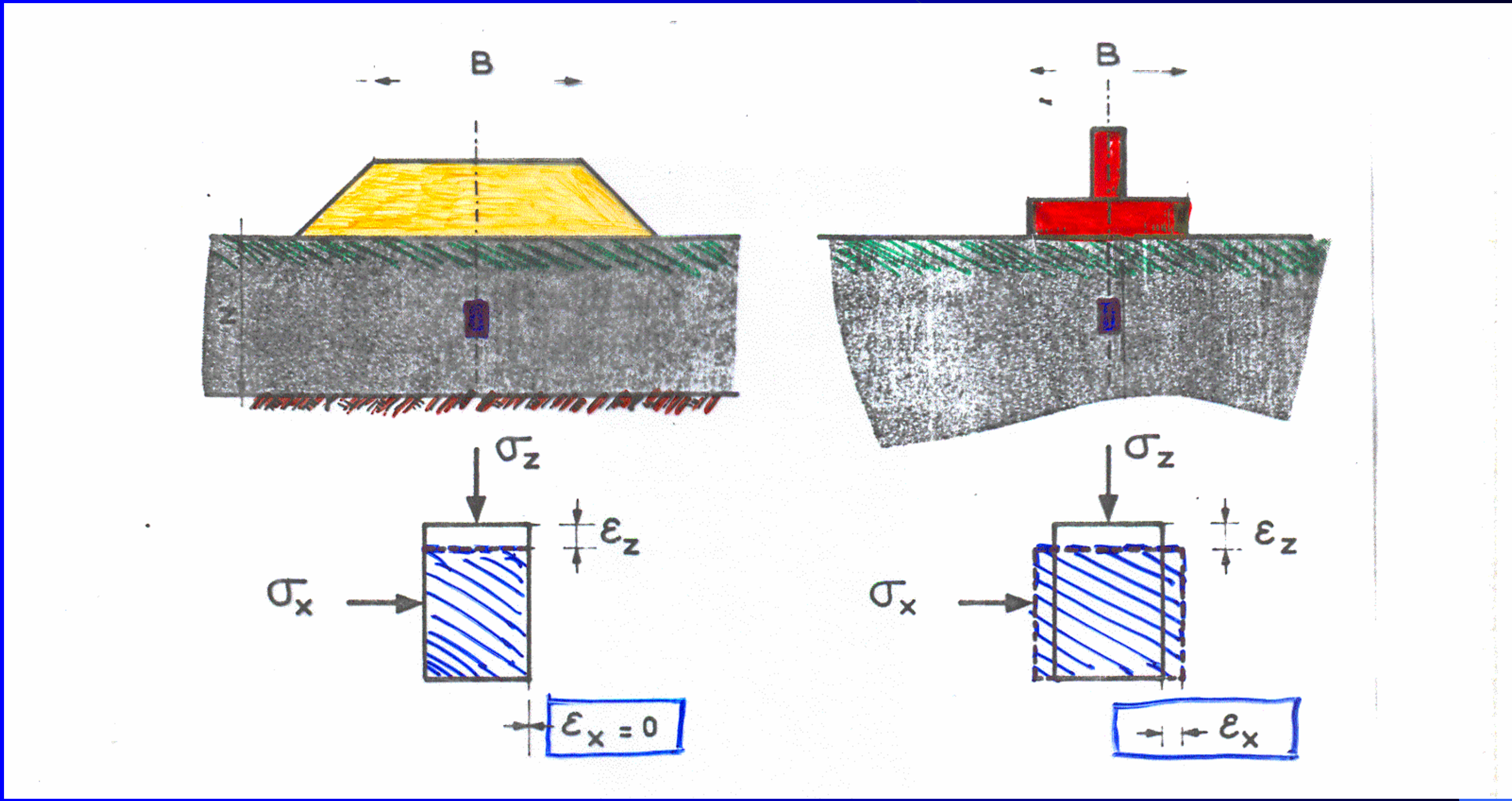


And

$\gamma_q = 2$ for ULS

$\gamma_q = 3$ for SLS

Pressuremeter method for settlement prediction



Ménard's formula for settlement

$$s(10\text{ years}) = s_c + s_d$$

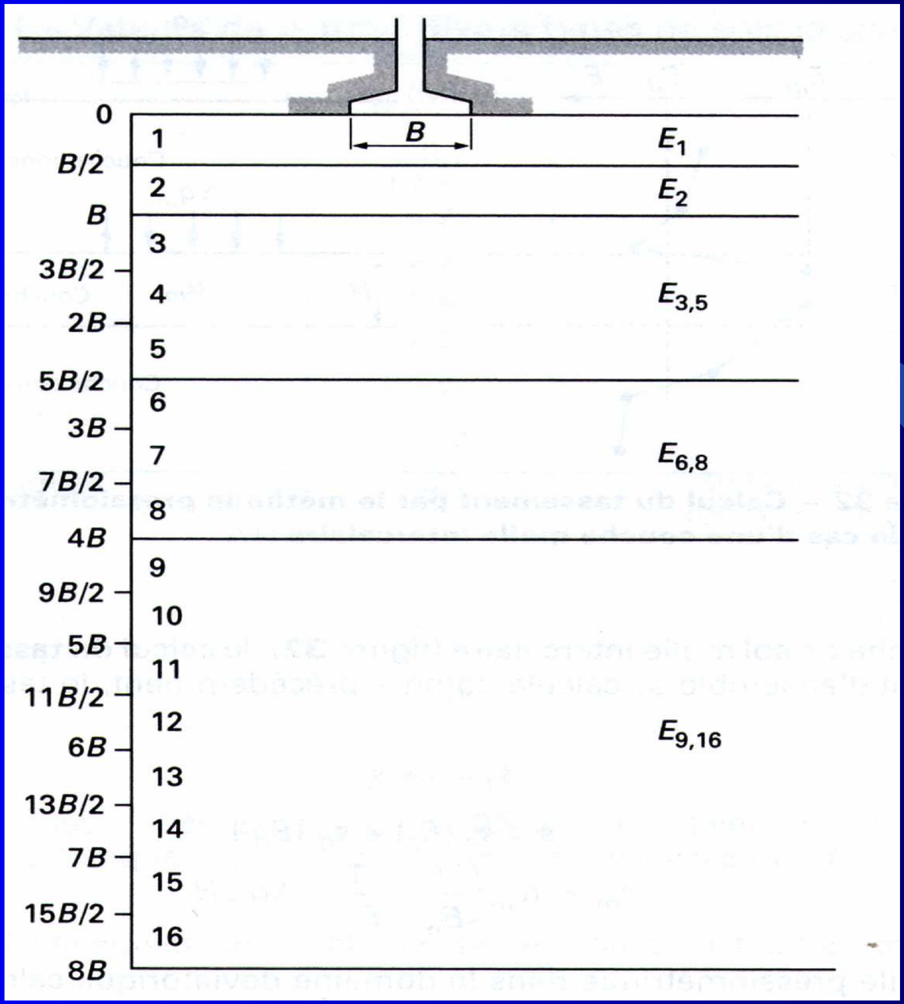
$s_c = (q - \sigma_v)\,\lambda_c B\alpha/9E_c$ is the volumetric settlement

$s_d = 2\,(q - \sigma_v)\,B_0(\lambda_d B/B_0)^{\alpha}/9E_d$ is the deviatoric settlement

Rheological coefficient α

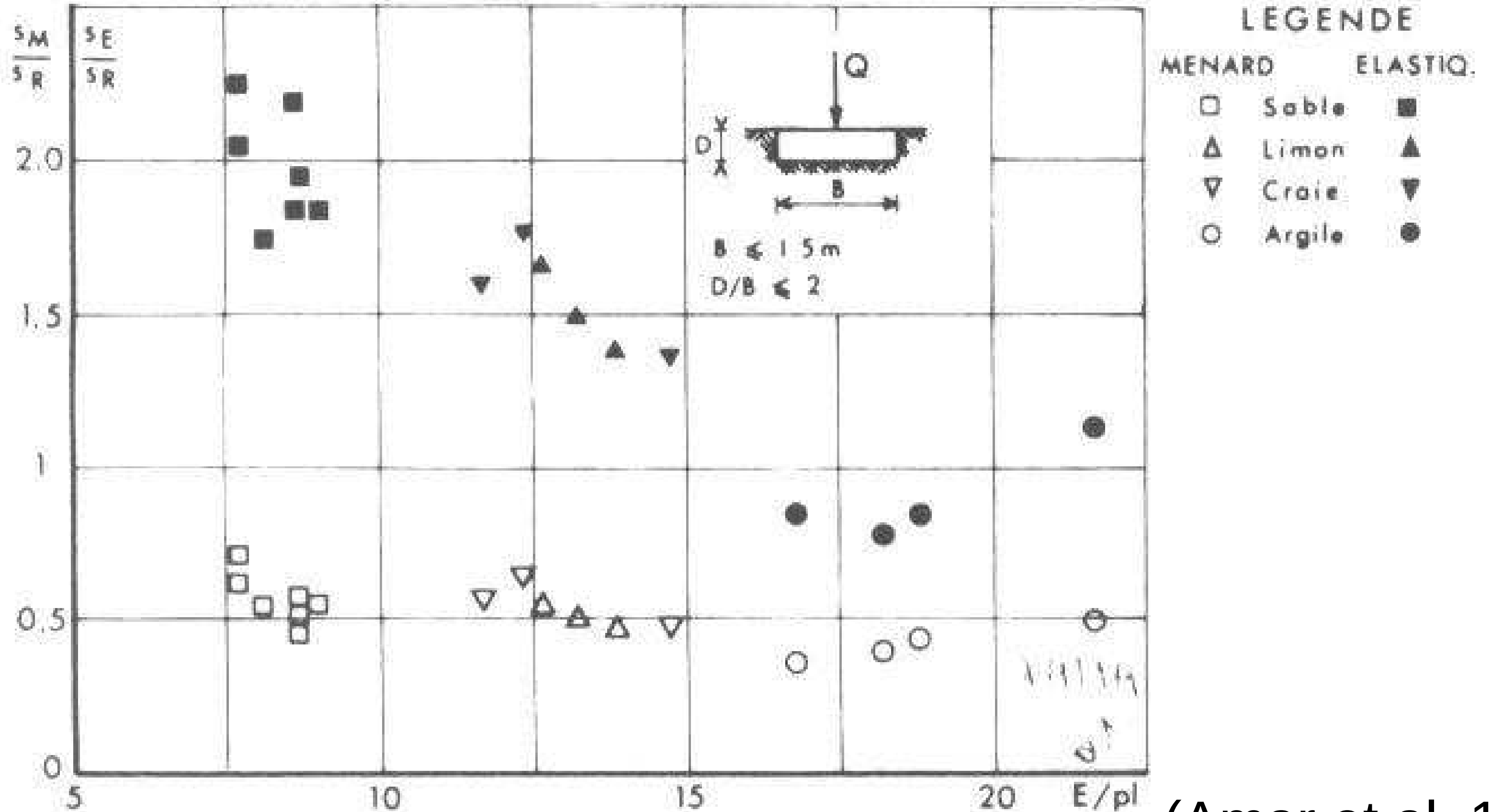
Type	Tourbe	Argile		Limon		Sable		Sable et gravier		Type	Roche
	α	E/p_ℓ	α	E/p_ℓ	α	E/p_ℓ	α	E/p_ℓ	α		α
Surconsolidé ou très serré		> 16	1	> 14	2/3	> 12	1/2	> 10	1/3	Très peu fracturé..........	2/3
Normalement consolidé ou normalement serré....................	1	9 à 16	2/3	8 à 14	1/2	7 à 12	1/3	6 à 10	1/4	Normal	1/2
Sous-consolidé altéré et remanié ou lâche...............		7 à 9	1/2	5 à 8	1/2	5 à 7	1/3			Très fracturé ..	1/3
										Très altéré	2/3

Selection of moduli E_c and E_d



$$E_c = E_1 \text{ and } \quad \frac{4}{E_d} = \frac{1}{E_1} + \frac{1}{0{,}85\ E_2} + \frac{1}{E_{3,5}} + \frac{1}{2{,}5\ E_{6,8}} + \frac{1}{2{,}5\ E_{9,16}}$$

Experimental assessment



(Amar et al.,1987)

Comparions of estimated 10 year settlements under $q_u/2$ from measurements, Ménard formula and elasticity theory

III. Bearing capacity of piles

(Bustamante & Gianeselli, 1982, under revision, see Bustamante & Gianeselli, 2006, 2008)

Pressuremeter method : point resistance

$$q_u = q_o + k_p\,(p_{le} - p_o)$$

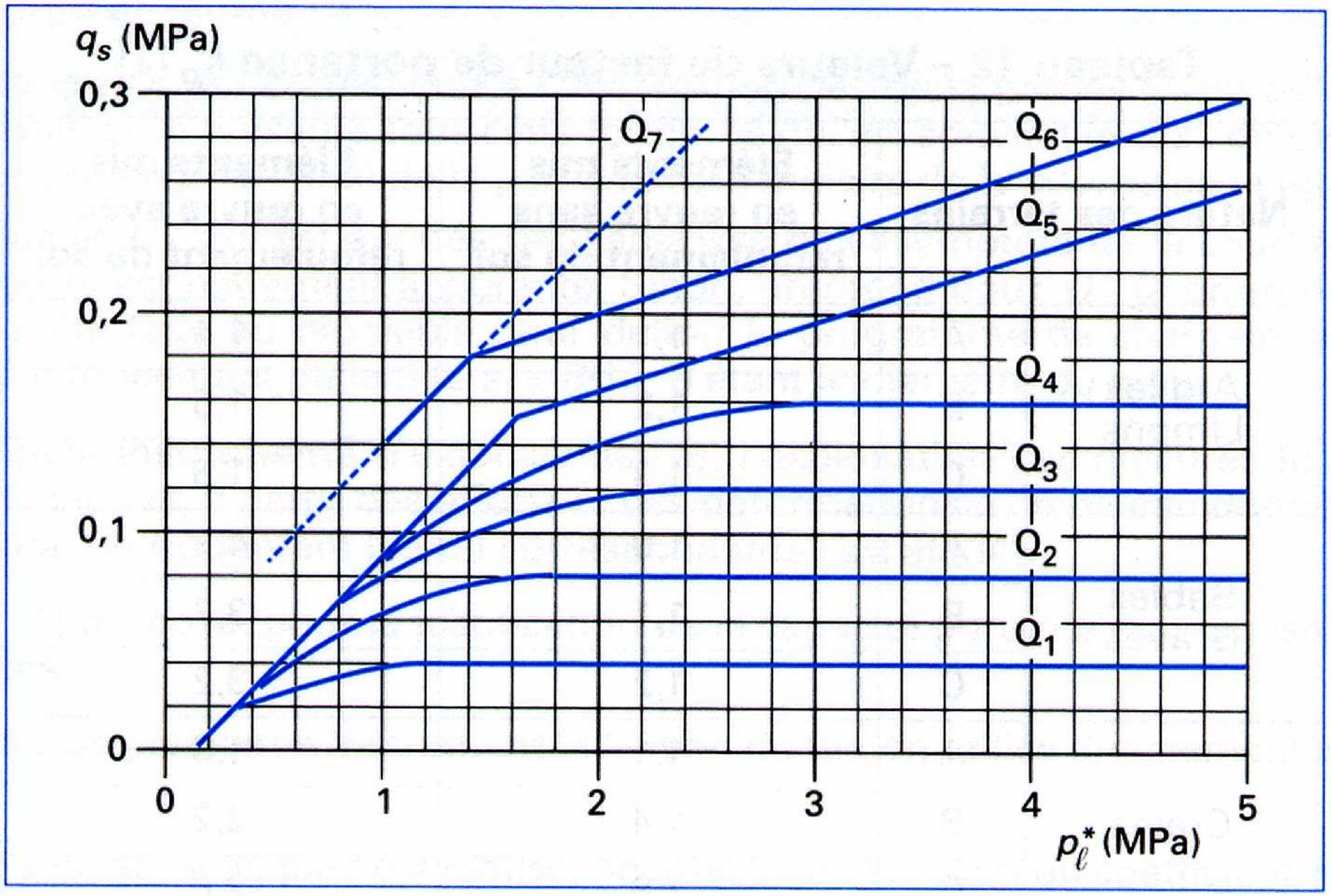
Table of bearing factors k_p

SOIL		NON DISPLACEMENT PILE	DISPLACEMENT PILE
Clay & Silt	A	1.1	1.4
	B	1.2	1.5
	C	1.3	1.6
Sand & Gravel	A	1.0	4.2
	B	1.1	3.7
	C	1.2	3.2
Chalk	A	1.1	1.6
	B	1.4	2.2
	C	1.8	2.6
Marl & Calcareous Marl	A	1.8	2.6
	B		
Weak Rock	A	1.1 to 1.8	1.8 to 3.2
	B		

(after Bustamante and Gianeselli, 1982)

Pressuremeter method : unit shaft friction

q_s = f (soil, p_l*; pile + specific conditions)



(after Bustamante and Gianeselli, 1982)

Type of pile	CLAY & SILT			SAND & GRAVEL			CHALK			MARL		ROCK
	A	B	C	A	B	C	A	B	C	A	B	C
Drilled no mud	Q_1	Q_1 Q_2 (1)	Q_2 Q_3 (1)	-			Q_1	Q_3	Q_4 Q_5 (1)	Q_3	Q_4 Q_5 (1)	Q_6
Drilled with mud	Q_1	Q_1 Q_2 (1)		Q_1	Q_2 Q_1 (2)	Q_3 Q_2 (2)	Q_1	Q_3	Q_4 Q_5 (1)	Q_3	Q_4 Q_5 (1)	Q_6
Drilled, removed casing	Q_1	Q_1		Q_1	Q_2 Q_1 (2)	Q_3 Q_2 (2)	Q_1	Q_3	Q_3 Q_4 (3)	Q_3	Q_4	-
Drilled, permanent casing	Q_1			Q_1		Q_2	(4)			Q_2	Q_3	-
Piers (5)	Q_1	Q_2		-			Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
Steel driven closed-ended	Q_1	Q_2		Q_2		Q_3	(4)			Q_3	Q_4	Q_4
Driven concrete	Q_1	Q_2		Q_3			(4)			Q_3	Q_4	Q_4
Driven moulded	Q_1	Q_2		Q_2		Q_3	Q_1	Q_2	Q_3	Q_3	Q_4	-
Driven coated	Q_1	Q_2		Q_3		Q_4	(4)			Q_3	Q_4	-
Low pressure injected	Q_1	Q_2		Q_3			Q_2	Q_3	Q_4	Q_5		-
High pressure injected (6)	-	Q_4	Q_5	Q_5		Q_6	-	Q_5	Q_6	Q_6		Q_7 (7)

(1)trimmed and grooved at the end of drilling (2)for long piles (longer than 30 m) (3)dry excavation, no rotation of casing (4)in chalk, qs can be very low for some types of piles ; a specific study is needed (5)without permanent casing (rough pile walls) (6)low rate injection and repeated grouting at selected depths (7)(6)plus preliminary treatment of fissured or fractured masses and filling of cavities.

Design bearing capacity

Creep load

ND piles : $Q_c = Q_p / 2 + Q_s / 1,5$

D piles : $Q_c = Q_p / 1,5 + Q_s / 1,5$

Ultimate limit states :

- fundamental combinations :

$$-Q_{tu} / 1.4 \leq Q_d \leq Q_u / 1.4$$

- accidental combinations :

$$-Q_{tu} / 1.3^* \leq Q_d \leq Q_u / 1.2$$

(* for micropiles the minimum is : : $-Q_{tu} / 1.2$)

Serviceability limit states :

- rare combinations :

$$-Q_{tc} / 1.4^* \leq Q_d \leq Q_c / 1.1$$

- quasi-permanent combinations:

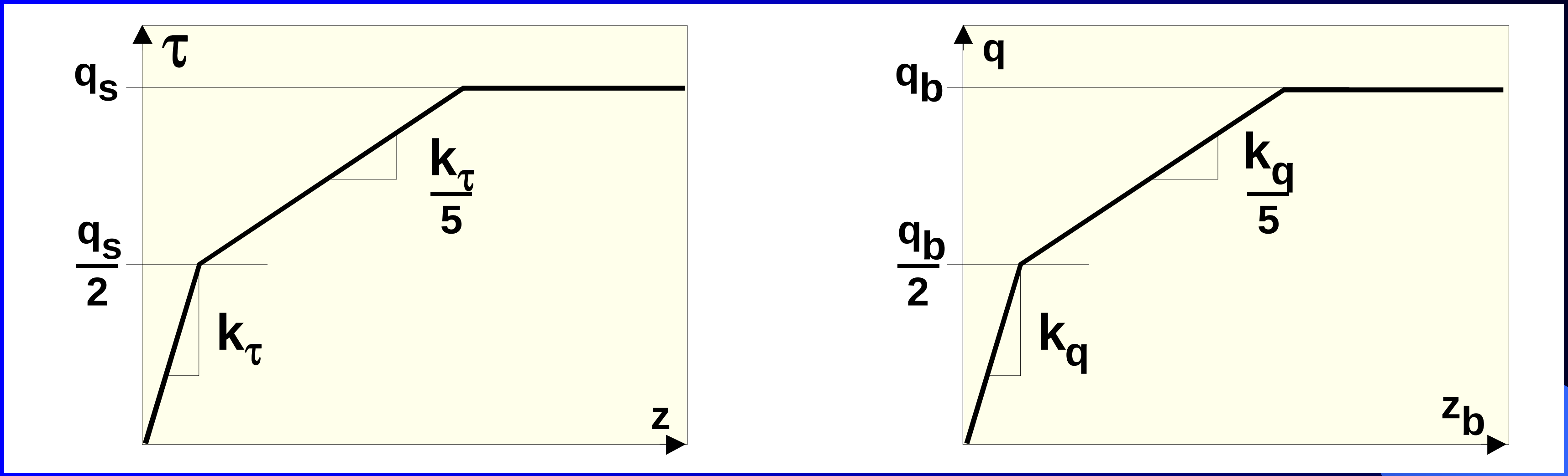
$$-0^{**} \leq Q_d \leq Q_c / 1.4$$

(for micropiles: * the minimum is $-Q_{tc}/1.1$; ** the minimum is $-Q_{tc}/1.4$)

IV. Settlement of piles & laterally loaded piles

Settlement of piles

T-z curves from Ménard pressuremeter modulus E_M



for fine grained soils :

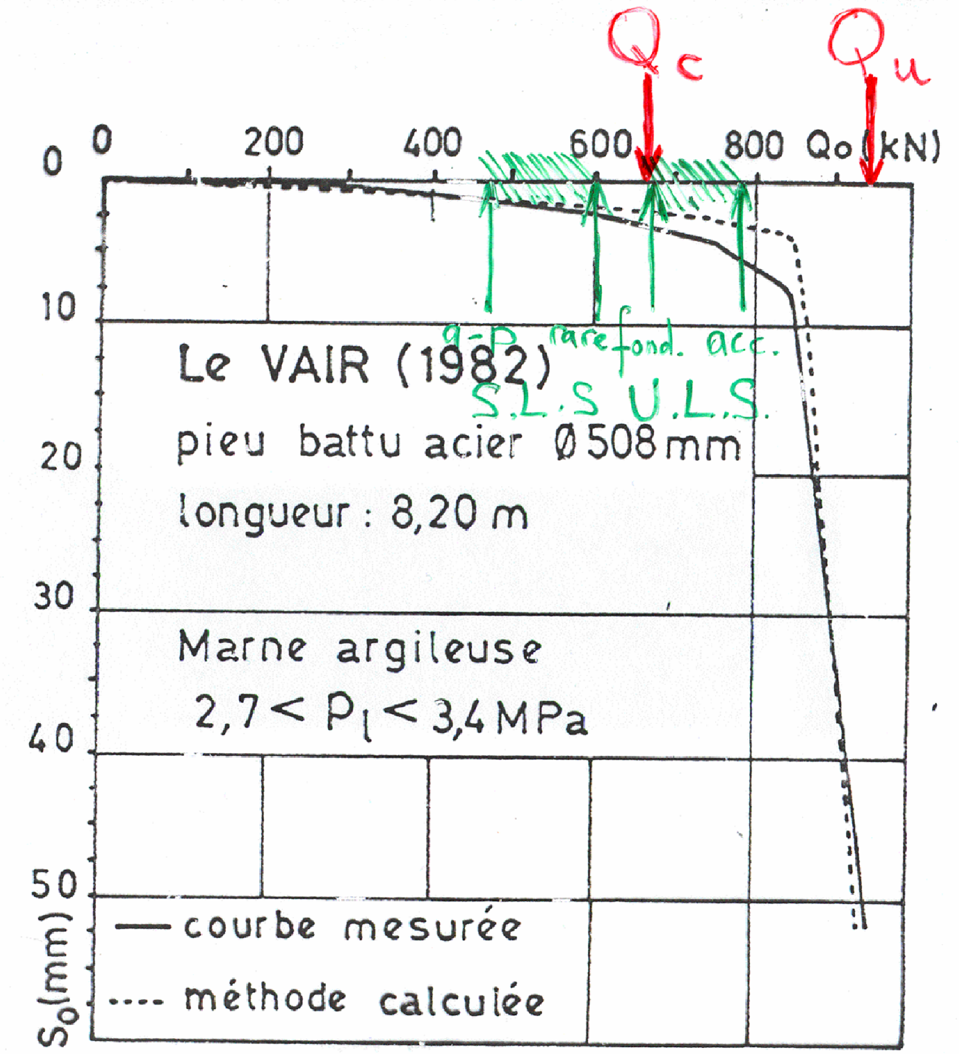
k_τ = 2.0 E_M/B and k_q = 11.0 E_M/B

for granular soils

kt = 0.8 E_M/B and k_q = 4.8 E_M/B

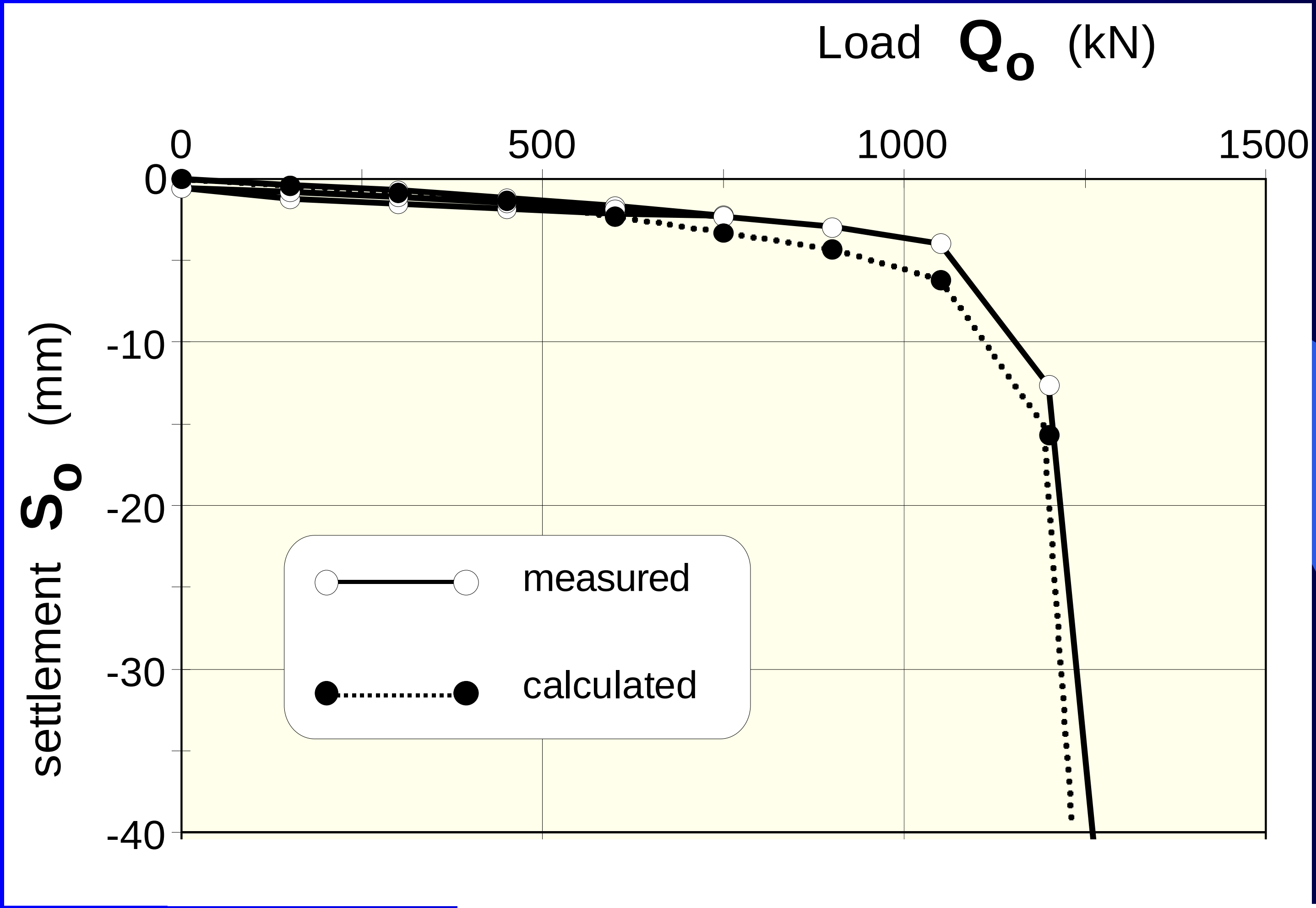
(after Frank et Zhao, 1982)

Example : driven pile in marl (Le Vair)



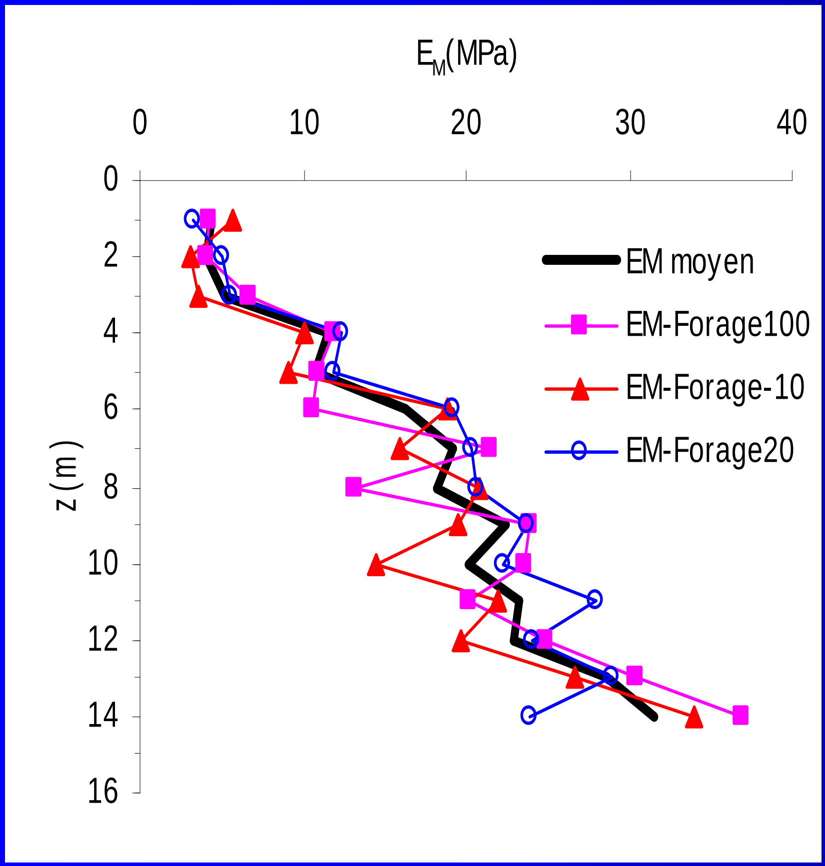
(after Bustamante, Frank & Gianeselli, 1989)

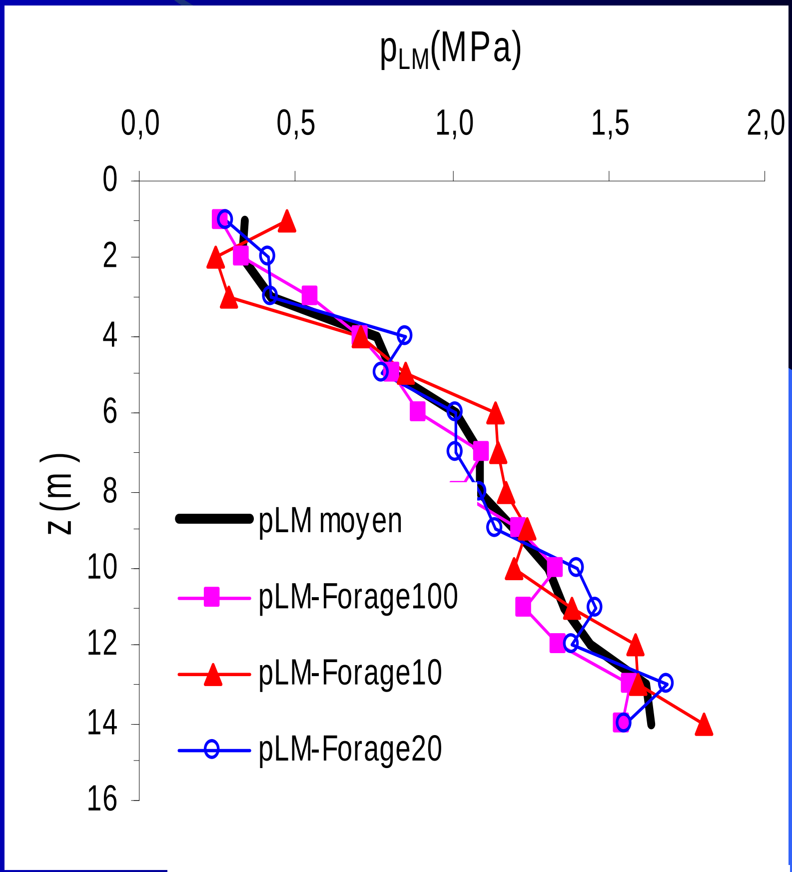
Example : screw pile in Ypresian clay (Belgium)



(Bustamante & Gianeselli, 1993)

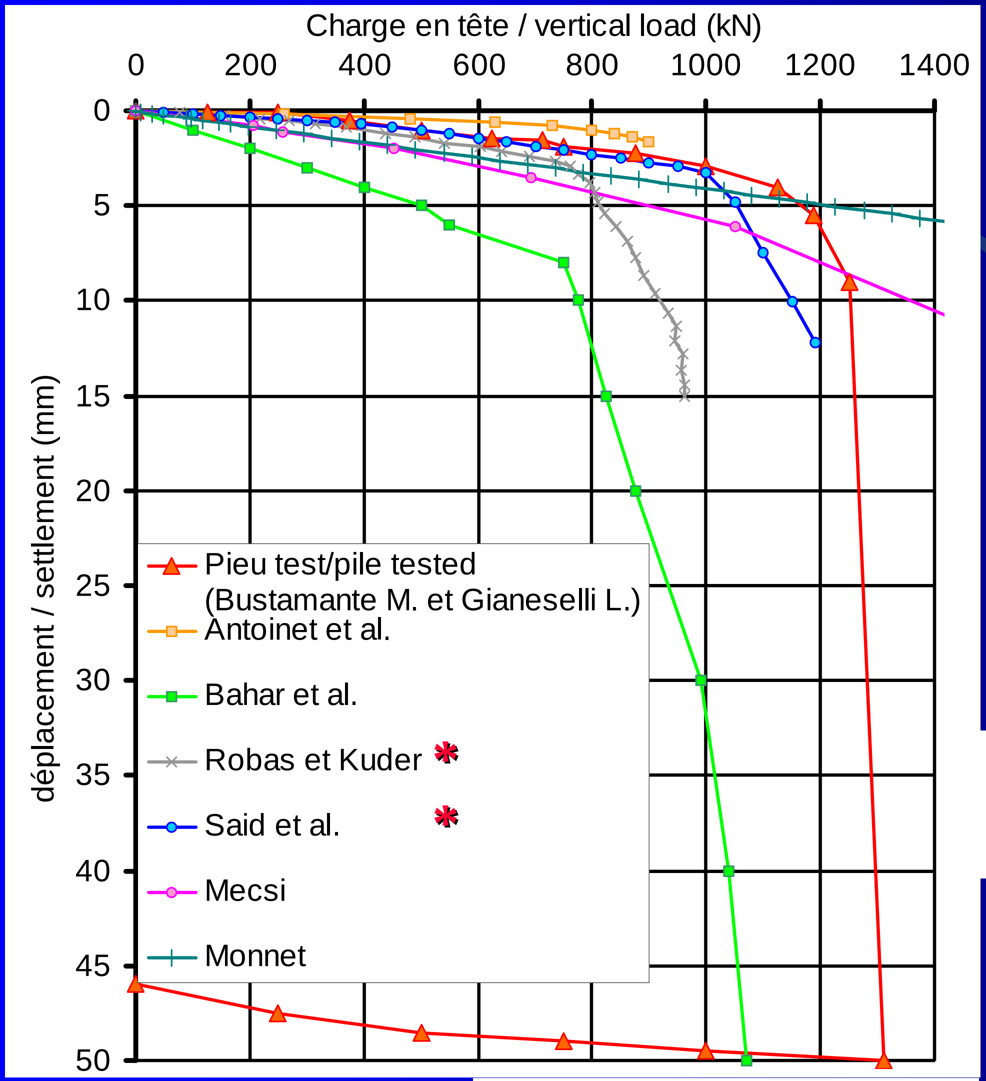
Example : CFA pile in silt and clay (Northern France) B = 0.5 m ; D = 12 m (ISP5 exercise, 2005)





(Reiffsteck, 2005)

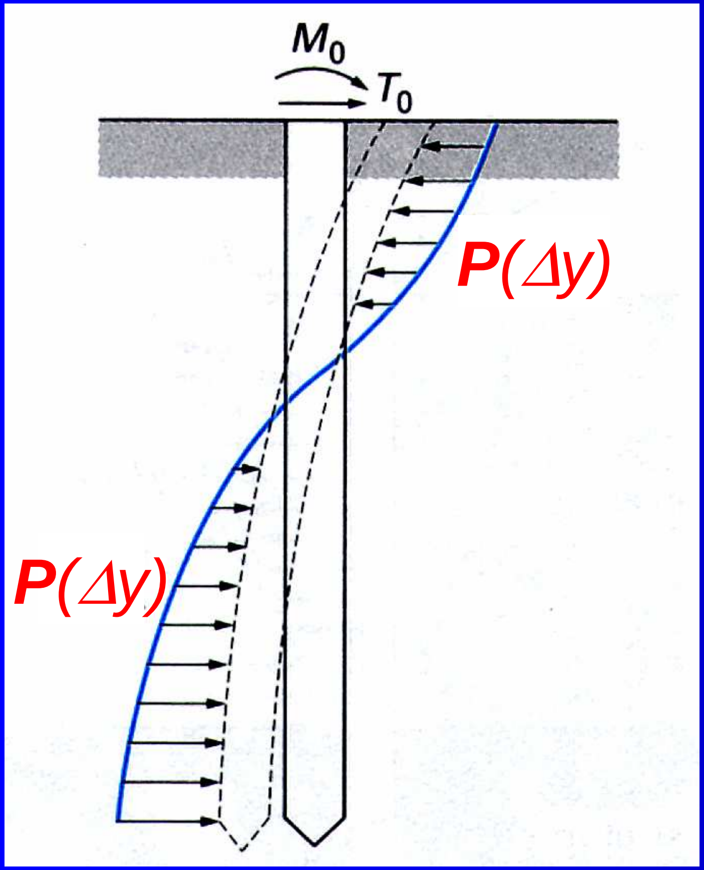
Results of the exercise (ISP5)…



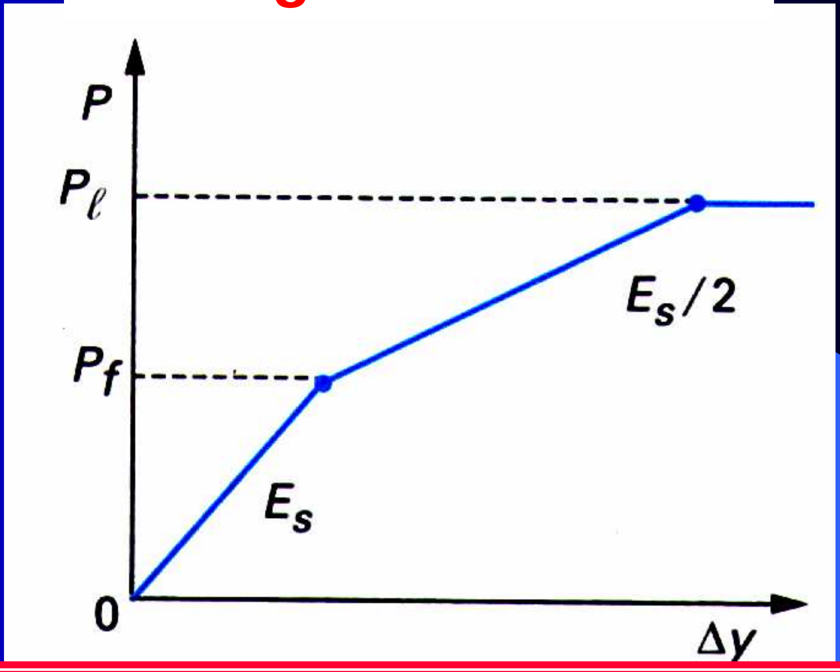
* using Frank & Zhao (1982)

(Reiffsteck, 2005)

Laterally loaded piles : the Ménard subgrade reaction modulus method



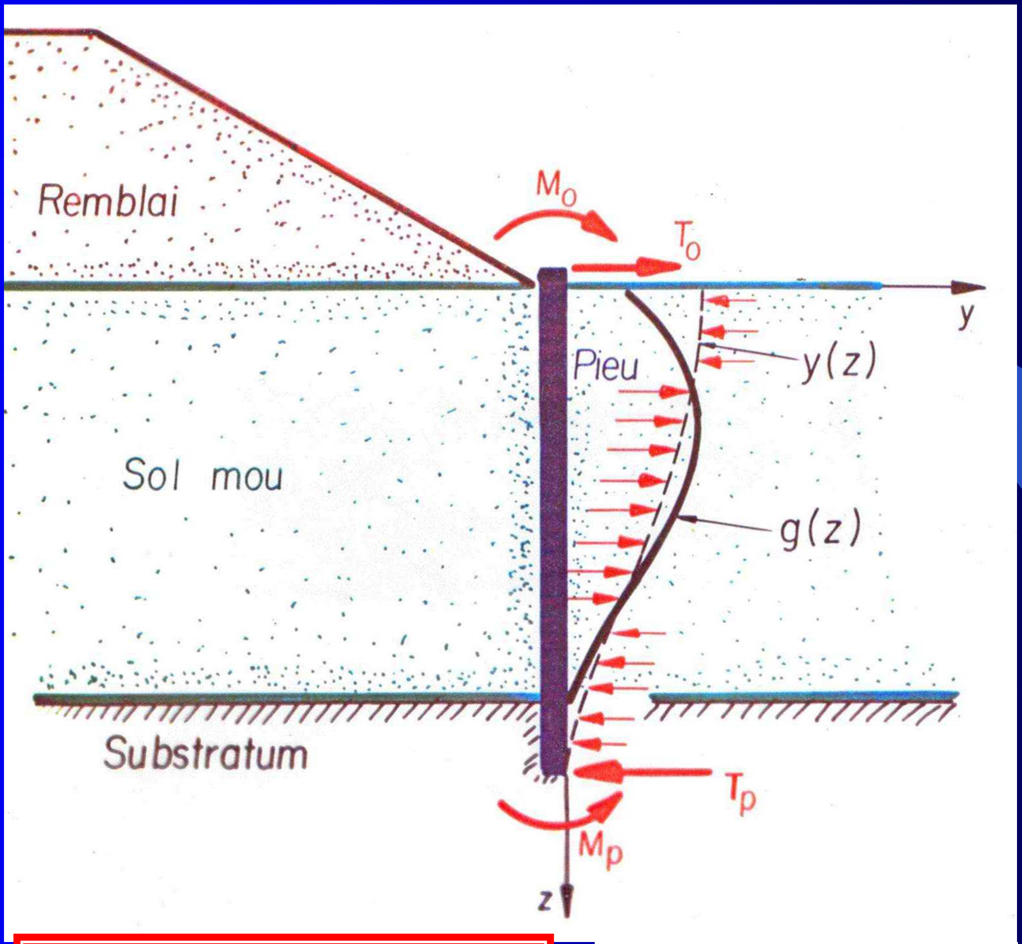
Reaction curve P-Y
for **long duration** loads



$$E_s = E_M \frac{18}{4(2{,}65\ B/Bo)^{\alpha}\ Bo/B + 3\alpha}$$

E_s = Ménard reaction modulus

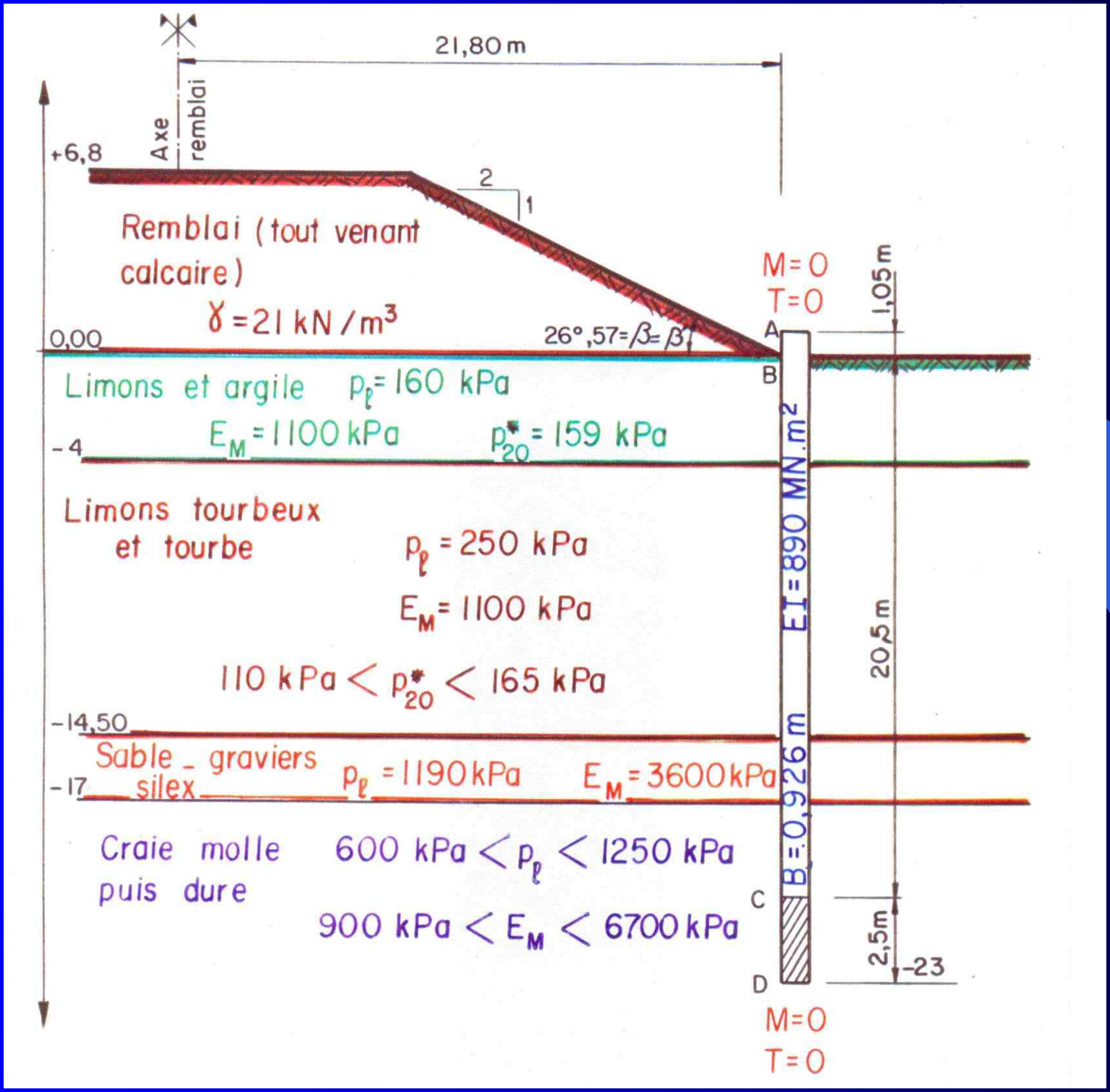
Extension to lateral thrusts

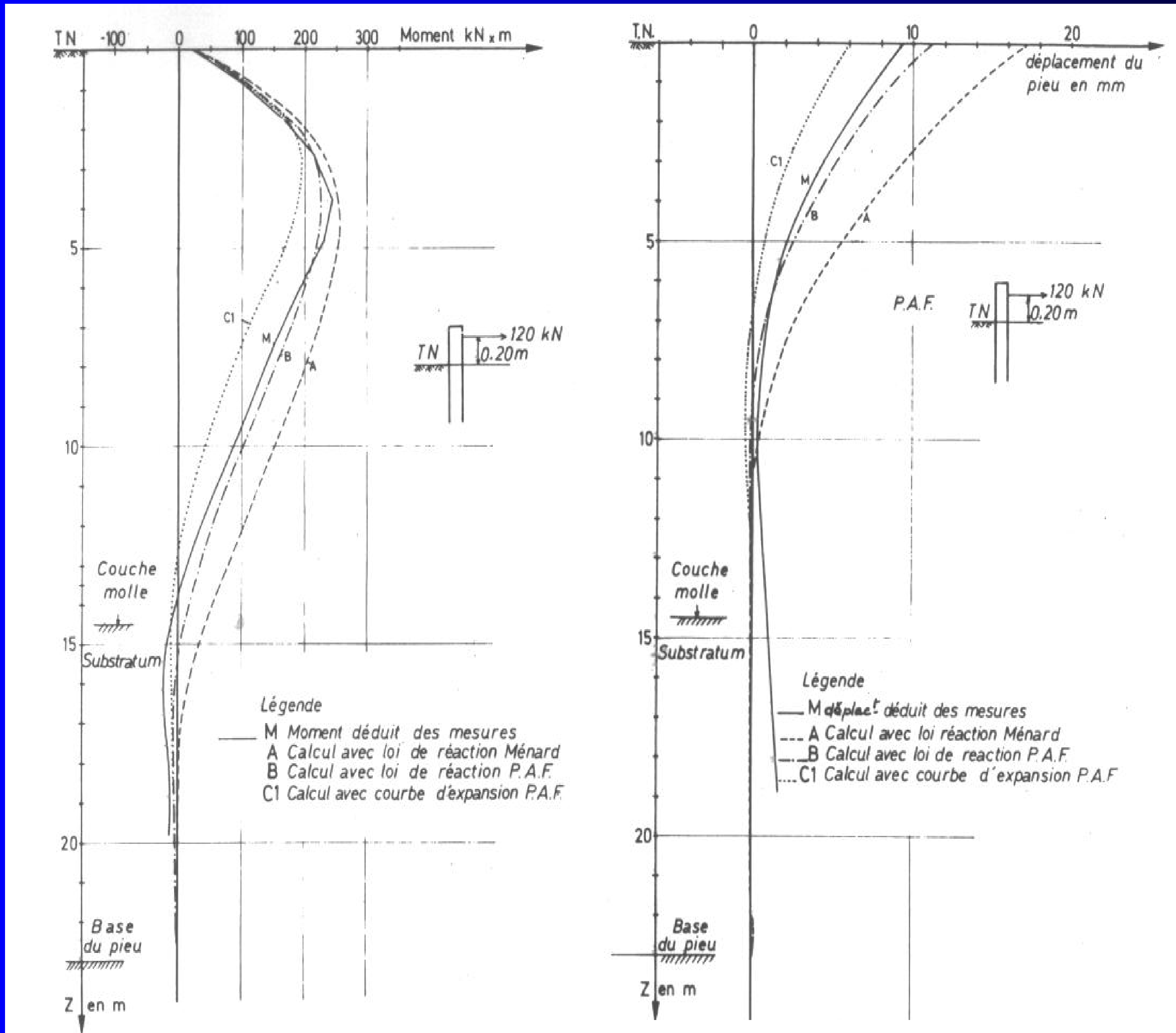


$$EI \frac{d^4y}{dz^4} + P(\mathbf{y} - \mathbf{g}) = 0$$

(LCPC, 1981)

Example : the Provins pile





(Bigot, Bourges and Frank, 1982)

V. Annexes in Eurocode 7 – Part 2

In informative annexes : examples of calculation models :

Spread foundations :

- Bearing resistance (Annex E.1)
- Settlement (Annex E.2)

Pile bearing resistance (Annex E.3)

(Annexes E.1, E.2 and E.3 are the models of Fascicule 62-V presented above)

Conclusions for MPM

- Ménard pressuremeter tests can be performed in all soils and soft rocks
- It provides for a deformation as well as for a failure parameters
- These parameters, used with simple rules, charts or softwares (for t-z or p-y approaches) can solve most of the current problems of shallow and deep foundations
- This vision is fully compatible with Eurocode 7...

The rest is a matter of engineering judgement !

Thank you for your attention !
Большое спасибо !

Acknowledgments :

РОССИЙСКОЕ ОБЩЕСТВО ПО МЕХАНИКЕ ГРУНТОВ, ГЕОТЕХНИКЕ И ФУНДАМЕНТОСТРОЕНИЮ
RUSSIA SOCIETY FOR SOIL MECHANICS, GEOTECHNICS AND FOUNDATION ENGINEERING

École des Ponts
ParisTech