JORNADA TÉCNICA 15/09/2009 BARCELONA

El ensayo presiométrico en el proyecto geotécnico

La experiencia francesa para las cimentaciones (Visión general ?)

Roger FRANK

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

I. Design of foundations with 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. Link with present European standards

I. Design of foundations with the Ménard pressuremeter : general

R Frank La experiencia francesa : Visión general, Jornada El ensayo presiométrico, UPC, Barcelona, 15/09/2009

Pressuremeter probe placement method (AFNOR Standard, 1991, after LCPC, 1971)

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	—
— sous la nappe	—	R	—	O°	O°	O°	—	—	—
Sables lâches — au-dessus de la nappe	R	R	O	O°	—	O°	—	—	—
— 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+
— saines	/	/	/	R	R	R	/	/	/

Légende :

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

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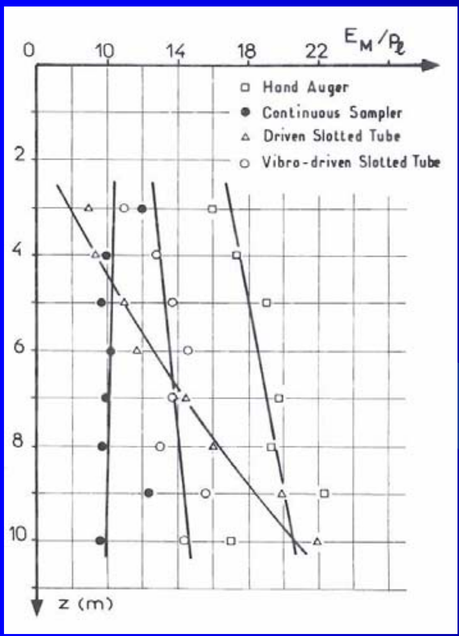
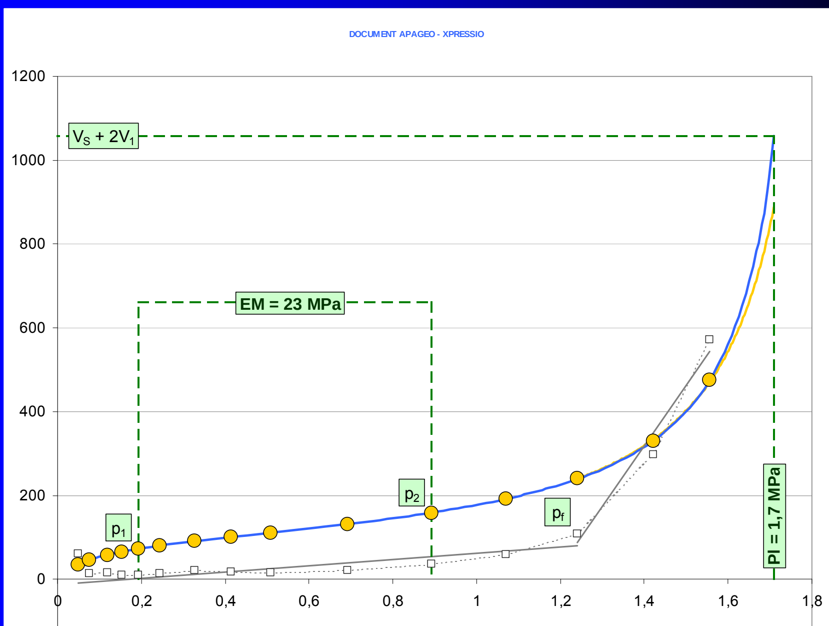
Influence of placement method

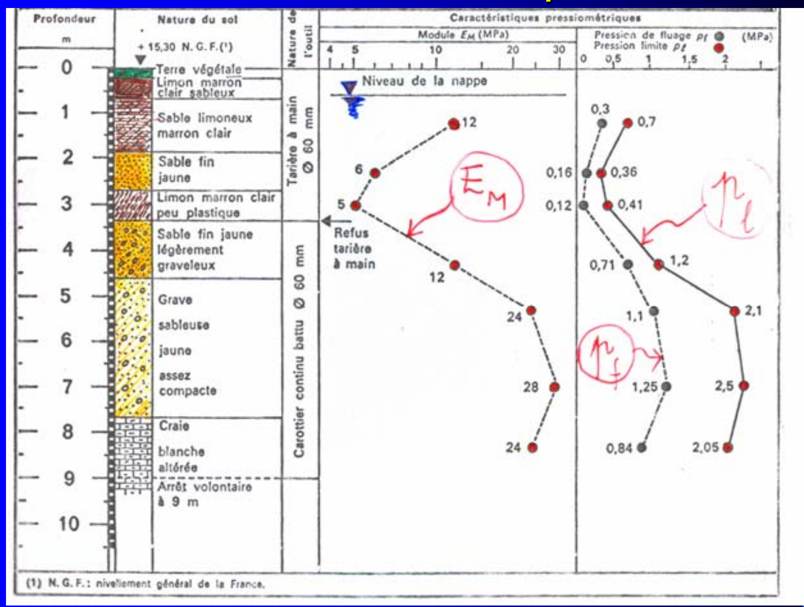


St-Malo de Phily sand

(after Jézéquel, Lemasson & Touzé, 1968)



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)

R_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

- **indirect** method ('analytical')

« going back » to elementary soil parameters,
In particular :

c_u, c', ϕ', etc.

and using classical rules ….

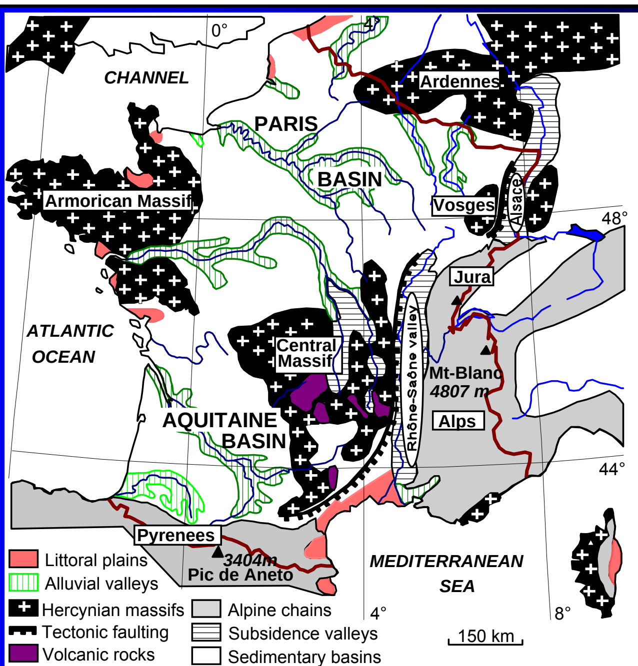


Table 2 Field and laboratory tests feasability after Bustamante & Gianeselli (2006)

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

- 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

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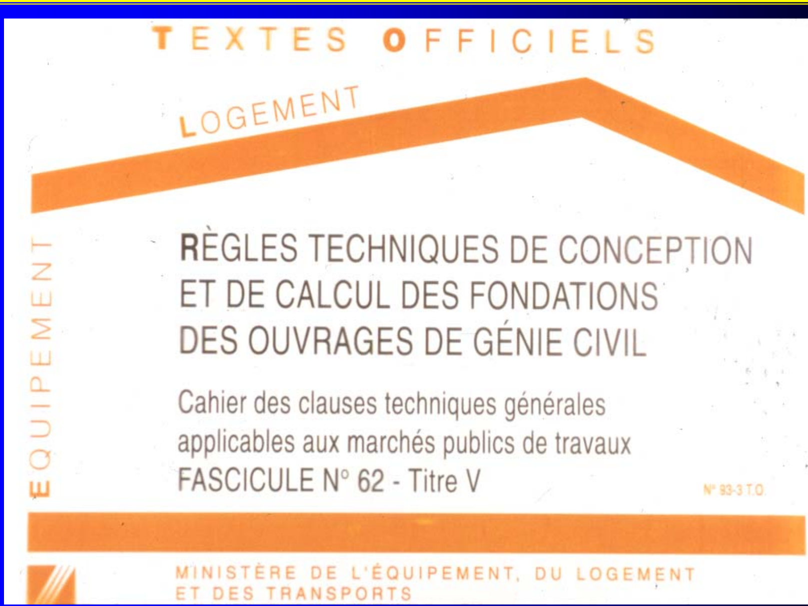
A specific vision for foundations …



TEXTES OFFICIELS

LOGEMENT

EQUIPEMENT

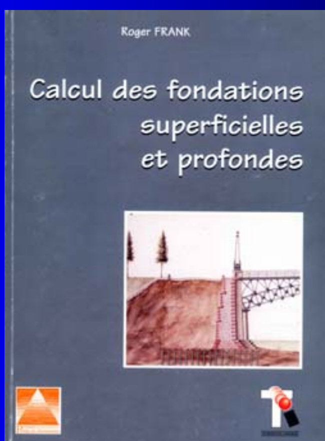
RÈGLES TECHNIQUES DE CONCEPTION
ET DE CALCUL DES FONDATIONS
DES OUVRAGES DE GÉNIE CIVIL

Cahier des clauses techniques générales
applicables aux marchés publics de travaux
FASCICULE N° 62 - Titre V

N° 93-3 T.O.

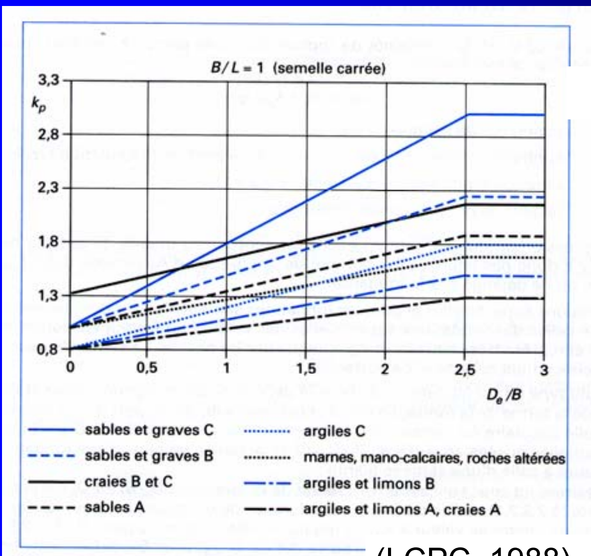
MINISTÈRE DE L'ÉQUIPEMENT, DU LOGEMENT
ET DES TRANSPORTS

Reference (for more details…)



II. Bearing capacity and settlement of shallow foundations

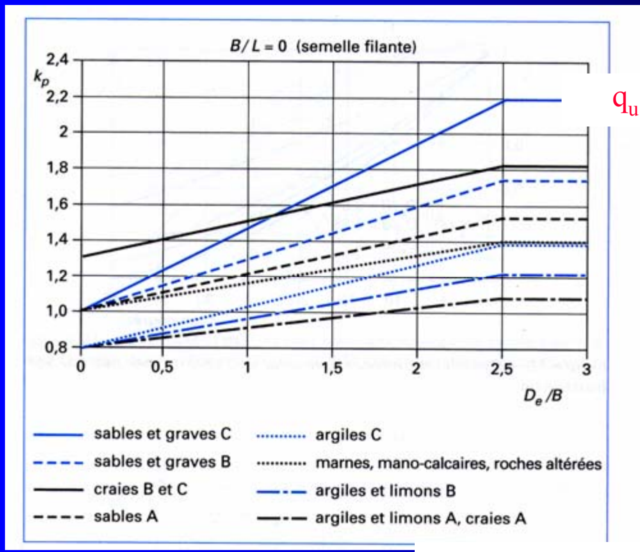
Bearing factors for square or circular footings



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

(LCPC, 1988)

Bearing factors for strip footings



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

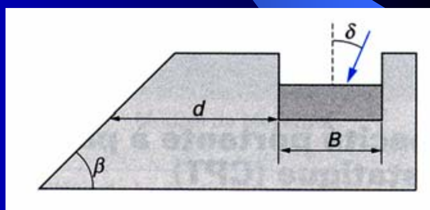
(LCPC, 1988)

Design bearing capacity

Reference stress $q_{réf}$:

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

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



And

γ_q = 2 for ULS

γ_q = 3 for SLS

Ménard’s formula for settlement

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

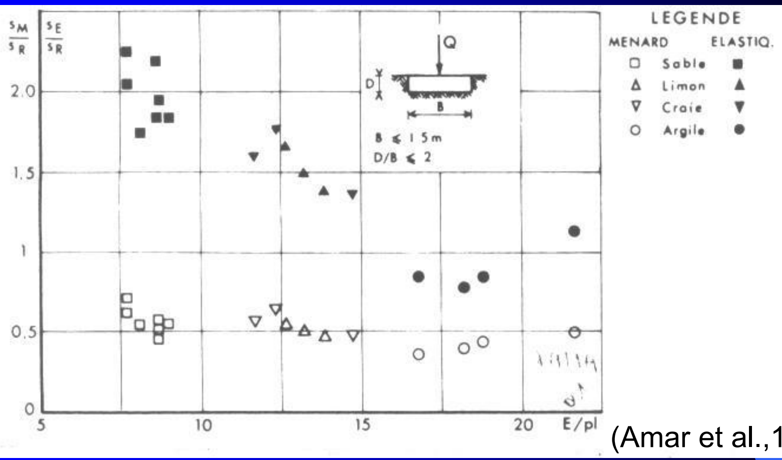
$s_c = (q - \sigma_v)\,\lambda_c B\alpha/9E_c$ is the volumetric settlement

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

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

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

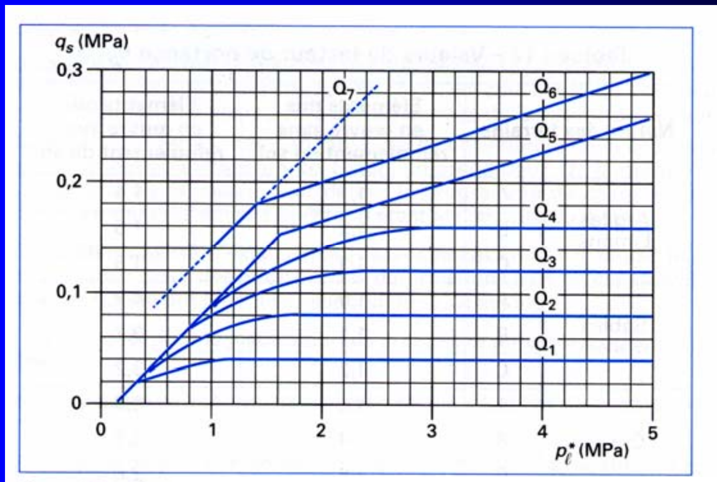
Table of bearing factors k_p

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)

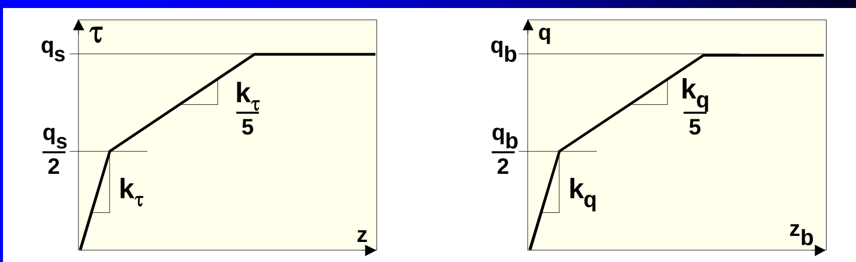
Type of pile	CLAY & SILT			SAND & GRAVEL			CHALK			MARL		ROCK
	A	B	C	A	B	C	A	B	C	A	B	C
Drilled no mud	Q_1	Q_1 Q_2 (1)	Q_2 Q_3 (1)	-			Q_1	Q_3	Q_4 Q_5 (1)	Q_3	Q_4 Q_5 (1)	Q_6
Drilled with mud	Q_1	Q_1 Q_2 (1)		Q_1	Q_2 Q_1 (2)	Q_3 Q_2 (2)	Q_1	Q_3	Q_4 Q_5 (1)	Q_3	Q_4 Q_5 (1)	Q_6
Drilled, removed casing	Q_1	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.

IV. Settlement of piles & laterally loaded piles

Settlement of piles

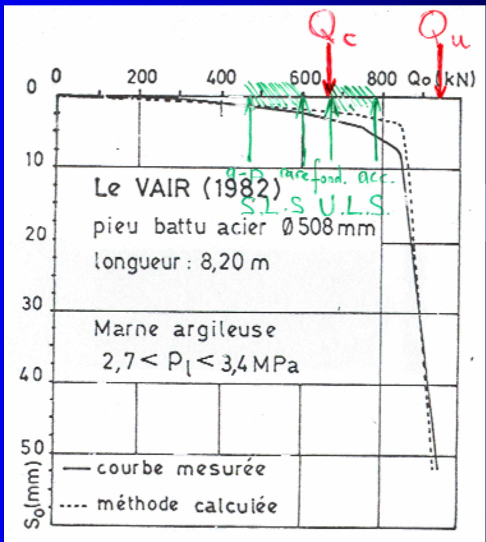
T-z curves from Ménard pressuremeter modulus $\mathbf{E_M}$



for fine grained soils :
k_τ = 2.0 E_M/B and k_q = 11.0 E_M/B
for granular soils
k_t = 0.8 E_M/B and k_q = 4.8 E_M/B

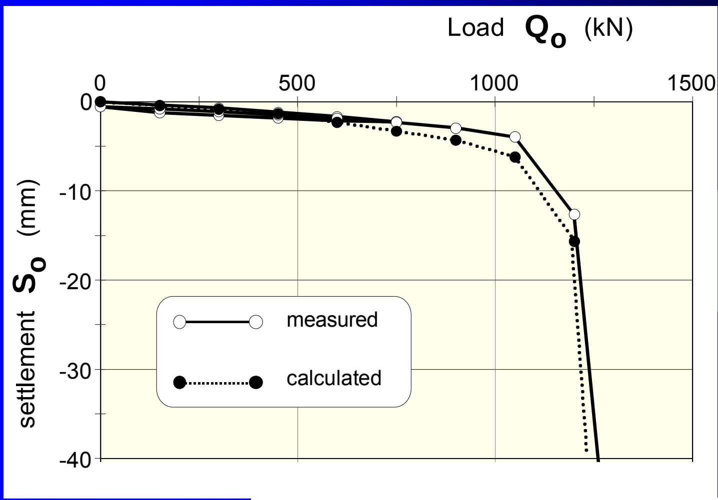
(after Frank et Zhao, 1982)

Example : driven pile in marl (Le Vair)



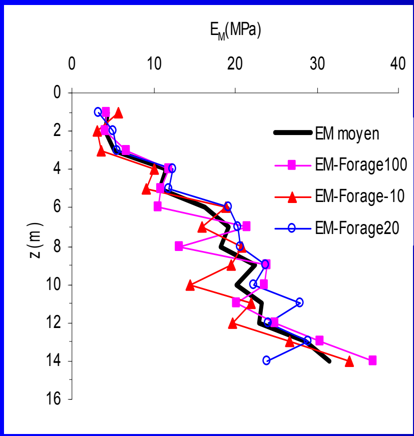
(after Bustamante, Frank & Gianeselli, 1989)

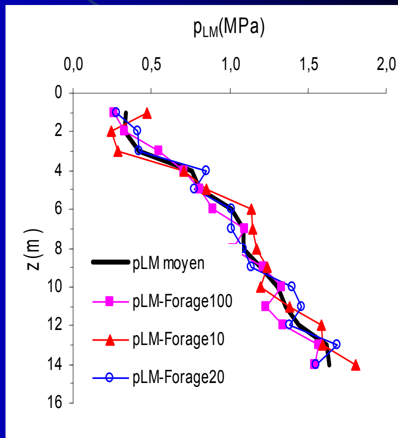
Example : screw pile in Ypresian clay (Belgium)



(Bustamante & Gianeselli, 1993)

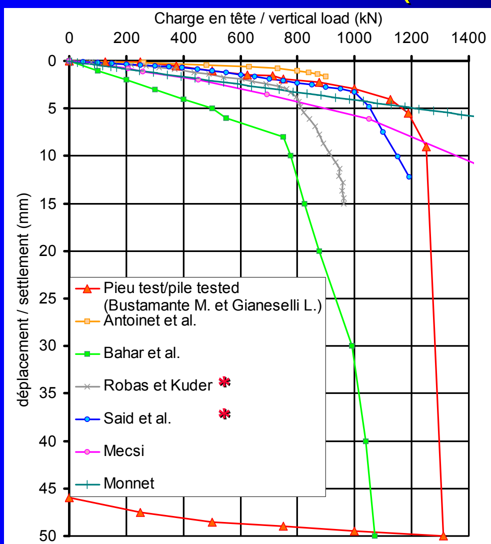
Example : CFA pile in silt and clay (Northern France) B = 0.5 m ; D = 12 m (ISP5 exercise, 2005)





(Reiffsteck, 2005)

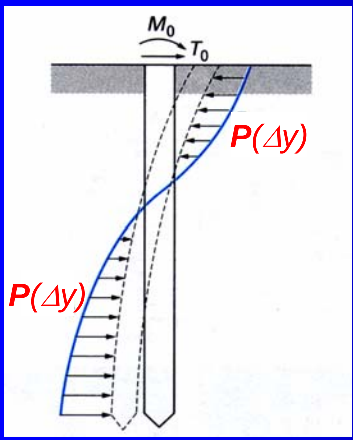
Results of the contest (ISP5)…



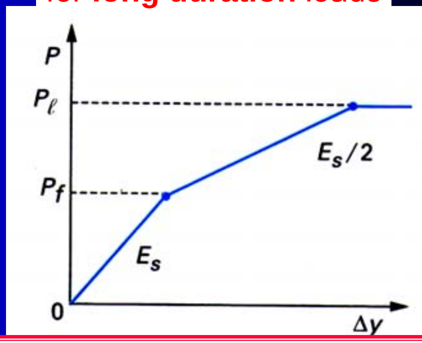
* using Frank & Zhao (1982)

(Reiffsteck, 2005)

Laterally loaded piles : the Ménard subgrade reaction modulus method



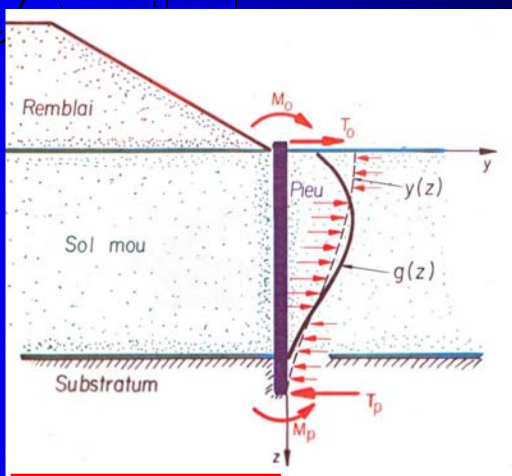
Reaction curve P-Y
for **long duration** loads



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

E_s = Ménard reaction modulus

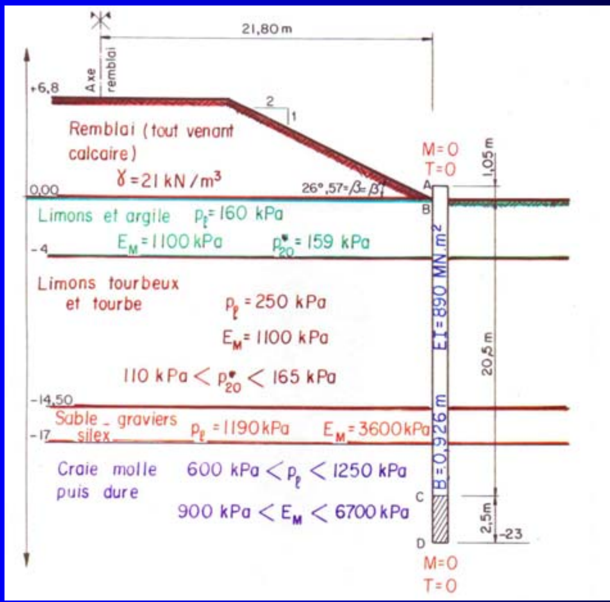
Extension to transverse thrusts

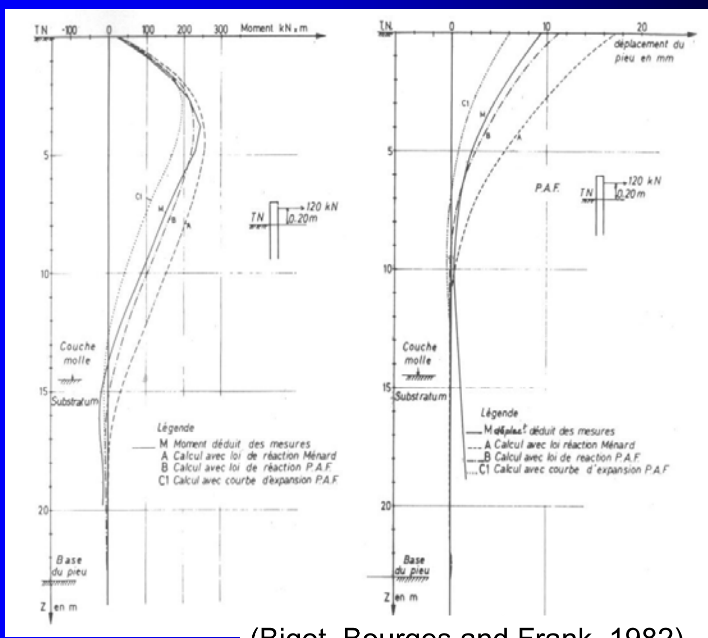


$$EI \frac{d^4y}{dz^4} + P(\mathbf{y} - \mathbf{g}) = 0$$

(LCPC, 1981)

Example : the Provins pile





(Bigot, Bourges and Frank, 1982)

V. Link with present European standards

Eurocode 7 'Geotechnical design'

- Part 1 : General rules (EN 1997-1)
  (issued in november 2004)
- Part 2 : Ground investigaton and testing (EN 1997-2)
  (issued in March 2007)

Geotechnical investigation and testing – Field testing - Ménard pressuremeter test

- EN ISO 22476-4

Project for European standard under publication

Conclusions

- 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 !
Gracias por su atención !

Acknowledgments :

CEDEX
CENTRO DE ESTUDIOS
Y EXPERIMENTACIÓN
DE OBRAS PÚBLICAS

UPC

ECOLE NATIONALE
DES PONTS ET CHAUSSEES

Standards

- NF P 94-110-1

Standard in use in France presently.
Data recording is mandatory

- EN ISO 22476-4

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

Allowed boring techniques

Table C.2 — Guidelines for pressuremeter probe placement techniques

Boring technique / Soil Type	Probe placing without soil displacement														Probe placing with full soil displacement
	$1< d_t/d_c \le 1,15$														$(d_t/d_c \approx 0)$
	Rotary Drilling					Rotary percussion			Pushing, driving or vibrodriving					.	Full displac.
	HA	CFA *	ADM*	DTM	CD	RP	RPM	STDT M	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
	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

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.

Expansion curve and pressuremeter test results

Ménard pressuremeter limit pressure

p_{LM} for $V = V_c + 2\,V_1$

Ménard pressuremeter modulus

$$E_M = 2(1+\nu)\left(v_S + \frac{v_1 + v_2}{2}\right)\frac{p_2 - p_1}{v_2 - v_1}$$

From Lamé's solution $\frac{\delta r}{r} = \frac{1+\nu}{E_M}.\delta p$

E_M/p_{LM} = 7 to 12

< 7 : loose or remoulded soils

>12 : overconsolidated or dense soils

Correlations with other tests

- c_u from MPM pressuremeter :

$$\boxed{c_u = \frac{p_l - p_o}{5{,}5}}$$

in fact : $p_l = c_u\,[1 + \mathit{ln}\,(1 + G/c_u)] + p_o$

- CPT penetrometer – MPM pressuremeter :
  - clays : $q_c/p_l = 3$
  - silts : $q_c/p_l = 6$
  - sands : $q_c/p_l = 9$

Bearing factors

Tableau 6 – Facteur de portance pressiométrique [1]			
Type de sol	Expression de k_p	$k_{p\ max}$ (semelle carrée)	$k_{p\ max}$ (semelle filante)
Argiles et limons A, craies A	$0{,}8\left[1+0{,}25\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	1,30	1,10
Argiles et limons B	$0{,}8\left[1+0{,}35\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	1,50	1,22
Argiles C	$0{,}8\left[1+0{,}50\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	1,80	1,40
Sables A	$\left[1+0{,}35\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	1,88	1,53
Sables et graves B	$\left[1+0{,}50\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	2,25	1,75
Sables et graves C	$\left[1+0{,}80\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	3,00	2,20
Craies B et C	$1{,}3\left[1+0{,}27\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	2,18	1,83
Marnes, marno-calcaires, roches altérées	$\left[1+0{,}27\left(0{,}6+0{,}4\,\frac{B}{L}\right)\frac{D_e}{B}\right]$	1,68	1,41

Failure stress for inclined load and near a slope

$$q_\ell = q_0 + i_{\delta\beta}\, k_p\, p^*_{\ell e}$$

$i_{\delta\beta}$ = reduction factor

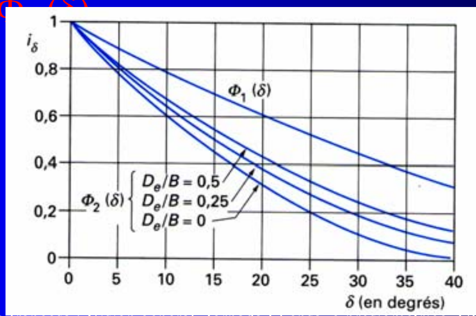
Inclined load on horizontal ground

- Cohesive soils (clays, silts, marls) , chalks, calcareous marls and weathered rocks :

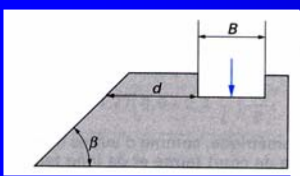
  $i_\delta = \Phi_1(\delta)$

- Granular soils (sands and gravels)

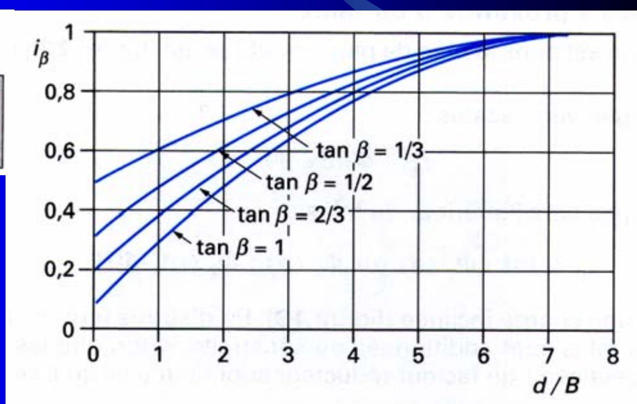
  $i_\delta = \Phi_2(\delta)$



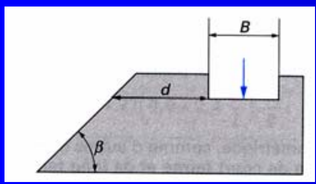
Vertical load, near a slope, no embedment

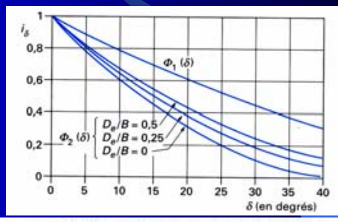


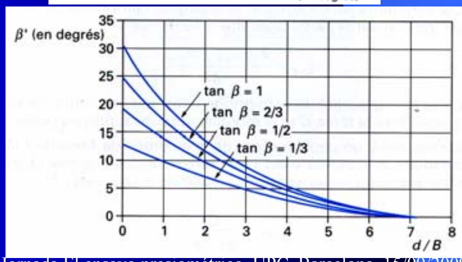
$i_\beta = \Psi(\beta, d/B)$



Vertical load, near a slope, with embedment







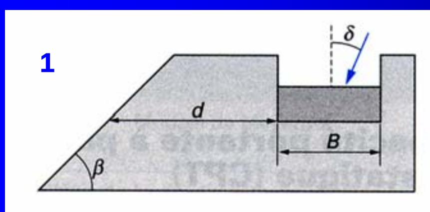
$i_\beta = \Psi\ (\beta, d/B)$

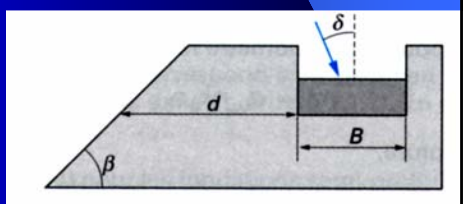
$\beta' = 45(1 - i_\beta^{\ 1/2}\ )$

$i_{\ \delta\beta} = \Phi_{\ 2}(\beta')$

Failure stress for inclined load, near a slope

- 1. Inclination towards the exterior of the slope $i_{\delta\beta} = \Phi_{\ 2}(\delta + \beta)$
- 2. Inclination towards the interior of the slope $i_{\delta\beta} = \inf\{\Phi_{\ 1}(\delta)\ or\ \Phi_{\ 2}\ (\delta)\ ;\ \Phi_{\ 2}\ (|\beta' - \delta|)\}$





λ_c et λ_d Shape coefficients

L/B	cercle	carré	2	3	5	20
λ_c	1,00	1,10	1,20	1,30	1,40	1,50
λ_d	1,00	1,12	1,53	1,78	2,14	2,65

Conventional categories in F 62-V

SOIL		TYPE	p_{1e} (MPa)
Clay & Silt	A	Soft	<0.7
	B	stiff	1.2-2
	C	hard(clay)	>2.5
Sand & Gravel	A	loose	<0.5
	B	medium	1-2
	C	dense	>2.5
Chalk	A	soft	<0.7
	B	weathered	1-2.5
	C	dense	>3
Marl & Calcareous Marl	A	soft	1.5-4
	B	dense	>4.5
Weak Rock	A	Weathered	2.5-4
	B	Fragmented	>4.5

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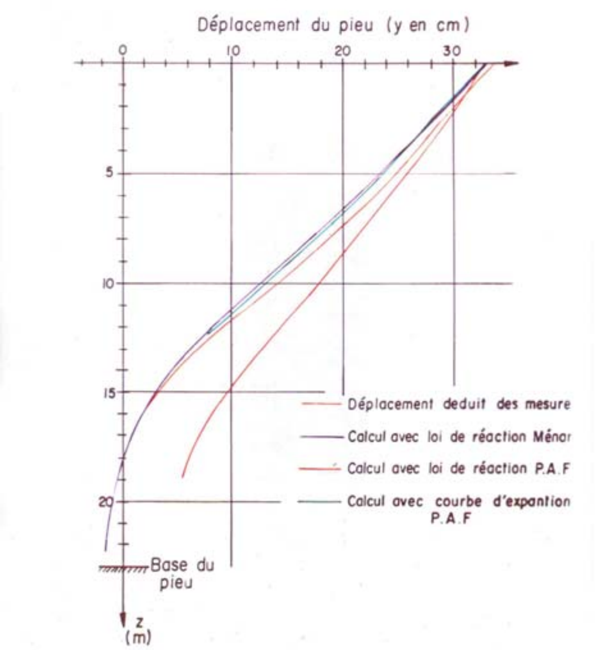


DEPLACEMENT DU PIEU AU 29/10/74

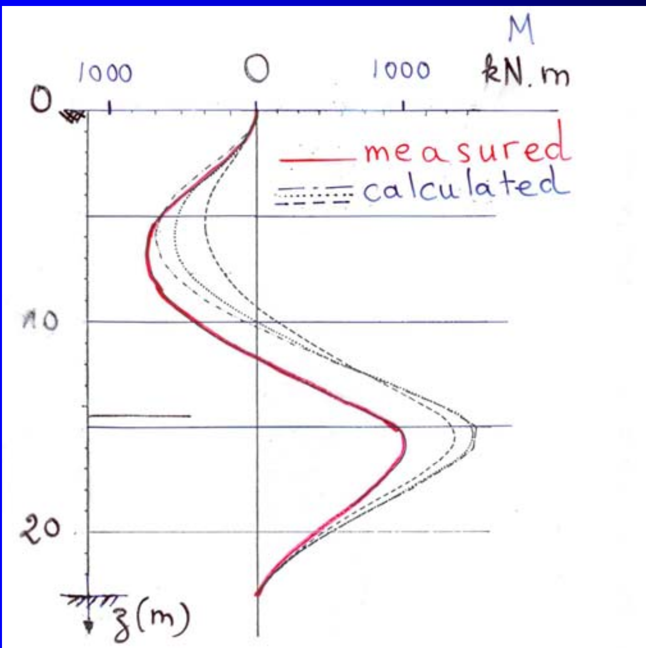


Fig. 19 Moments dans le pieu au 29.10.74, phase 3

Eurocode 7-1

Section 3 Geotechnical parameters - 3.3 Evaluation of geotechnical parameters

3.3.10.5 Pressuremeter test

(1)P In assessing the values of the limit pressure and the pressuremeter modulus, the following features shall be taken into account:

— the type of equipment;

— the procedure used to install the pressuremeter in the ground.

(2) Test curves, which exhibit more than a moderate degree of disturbance should not be used. Where the limit pressure is not reached during the test, a moderate and conservative extrapolation of the curve may be used to estimate it. For tests in which only the initial part of the pressuremeter curve is determined, general correlations or, preferably, local correlations from the same site may be used conservatively to estimate the limit pressure from the pressuremeter modulus.

Annex E (informative) A sample semi-empirical method for bearing resistance estimation..

Annex F (informative) Sample methods for settlement evaluation....

Eurocode 7-2

- Ménard pressuremeter (MPM), more generally prebored pressuremeters (PBP)
- Self-boring pressuremeters (SBP)
- Full displacement pressuremeters (FDP)

Also,

- Flexible dilatometer tests (FDT)
  (for rock RDT and soil SDT)

Eurocode 7-2 (cntd)

- 2 procedures :
- to obtain E_M and p_{LM}
- to obtain other stiffness and strength parameters

- Corrections for
- Membrane stiffness
- Membrane compression and thinning, or
- System expansion

Table 4.1 – A list of additional plots

Probe	Ground type	Abscissa	Ordinate
Radial displacement type			
Self-bored, Pushed in	All	Cavity strain for each arm	Applied pressure
Prebored	All	Cavity strain for each pair of arms	Applied pressure
Self bored	All	initial cavity strain for each arm	Applied pressure
All	All	Cavity strain for unload- reload cycle for each arm	Applied pressure
All	Clay	Logarithm of cavity strain for each arm	Applied pressure
All	Sands	Natural logarithm of current cavity strain for each arm	Natural logarithm of effective applied pressure
Volume displacement type (except MPM) [a)]			
Prebored	All	volume change	Applied pressure
Prebored	All	rate of change of volume	Applied pressure

[a)] For MPM tests the pressure is plotted as abscissa and the volume change as ordinate.

Use of test results and derived values

- Indirect method : derivation of (c_u, G, etc.) to be performed for the particular test and equipment

- Direct method : all the features of the method should be taken into account

In informative annexes : examples of calculation models :

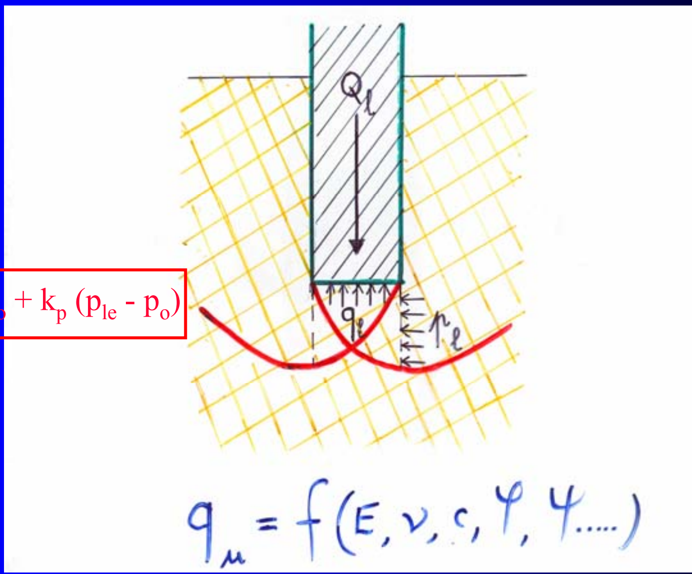
Spread foundations :

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

Pile bearing resistance (Annex E.3)

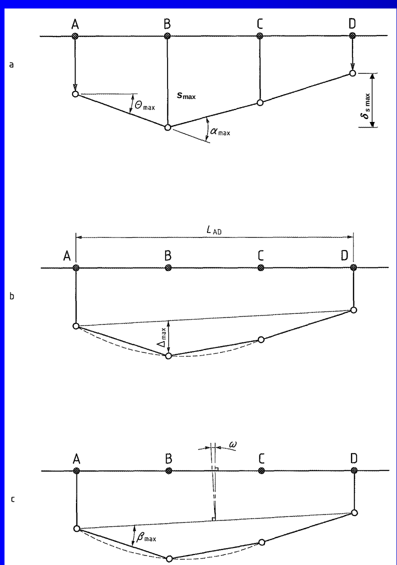
(Annexes E.1, E.2 and E.3 are the models of Fascicule 62-V presented above)

Bearing capacity : the pressuremeter 'faith'



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

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

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	A	soft	1.5 - 4	-
Calcareous marl	B	dense	> 4.5	-
Rock	A	weathered (1)	2.5 - 4	-
	B	fragmented	> 4.5	-

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

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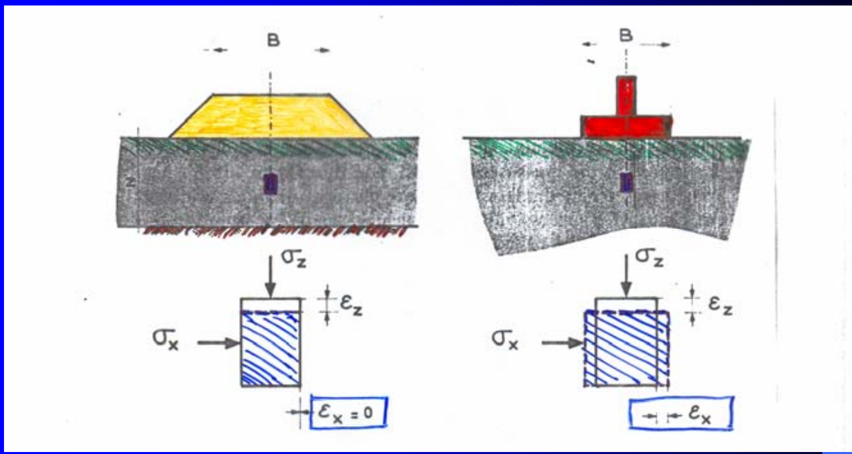
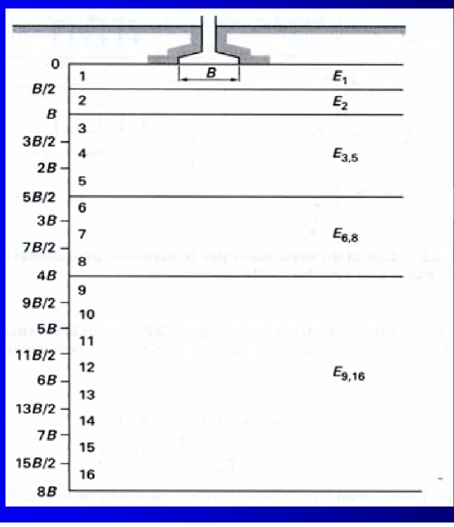
Pressuremeter method for settlement prediction



Selection of moduli E_c and E_d



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

Design bearing capacity

Creep load

ND piles : $Q_c = Q_p / 2 \quad + Q_s / 1{,}5$

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 $- Q_{tc}/1.4$)

PIVER programme is based on the analytical solution of

$$ES \cdot \frac{d^2 s}{dz^2} + T = 0$$

$$ES \cdot \frac{d^2 s}{dz^2} - P.t(s) = 0$$

which is $s = a.\cosh(mz) + b.\sinh(mz) - \frac{A}{B},\ for\ B \neq 0$

with $m = \sqrt{PB / ES} = a$

and $s = az + b + \frac{PA}{ES} \cdot \frac{z^2}{2},\ for B = 0$

Then we solve : $M . X = Y$

PILATE programme is based on the analytical solution of :

$$E_p I_p \frac{d^4 y^i}{dz^4} + E_s^{ti} y^i = E_s^{ti} g - P_0^i$$