5th Dr. Victor de Mello Goa Lecture
4th June 2022

Displacement of piles from pressuremeter test results – A summary of French research and practice

Roger Frank
Ecole des Ponts ParisTech, Navier-CERMES

Dr Victor de Mello

ISSMGE President
1981-1985

Courtesy : Luiz Guilherme de Mello

Introduction (MPM* and PAF*)

1. Axial displacements (settlements)

    1.1 t-z curves from MPM results and examples

    1.2 t-z curves from PAF results

        1.2.1 Theoretical background

        1.2.2 Examples

2. Lateral displacements

    2.1 p-y curves from MPM results

    2.2 p-y curves from PAF results: theoretical background

    2.3 Examples

3. Behaviour of « barrettes »

Conclusions

* MPM = Ménard (prebored) PressureMeter

* PAF = Pressiomètre AutoForeur (self-boring pressuremeter)

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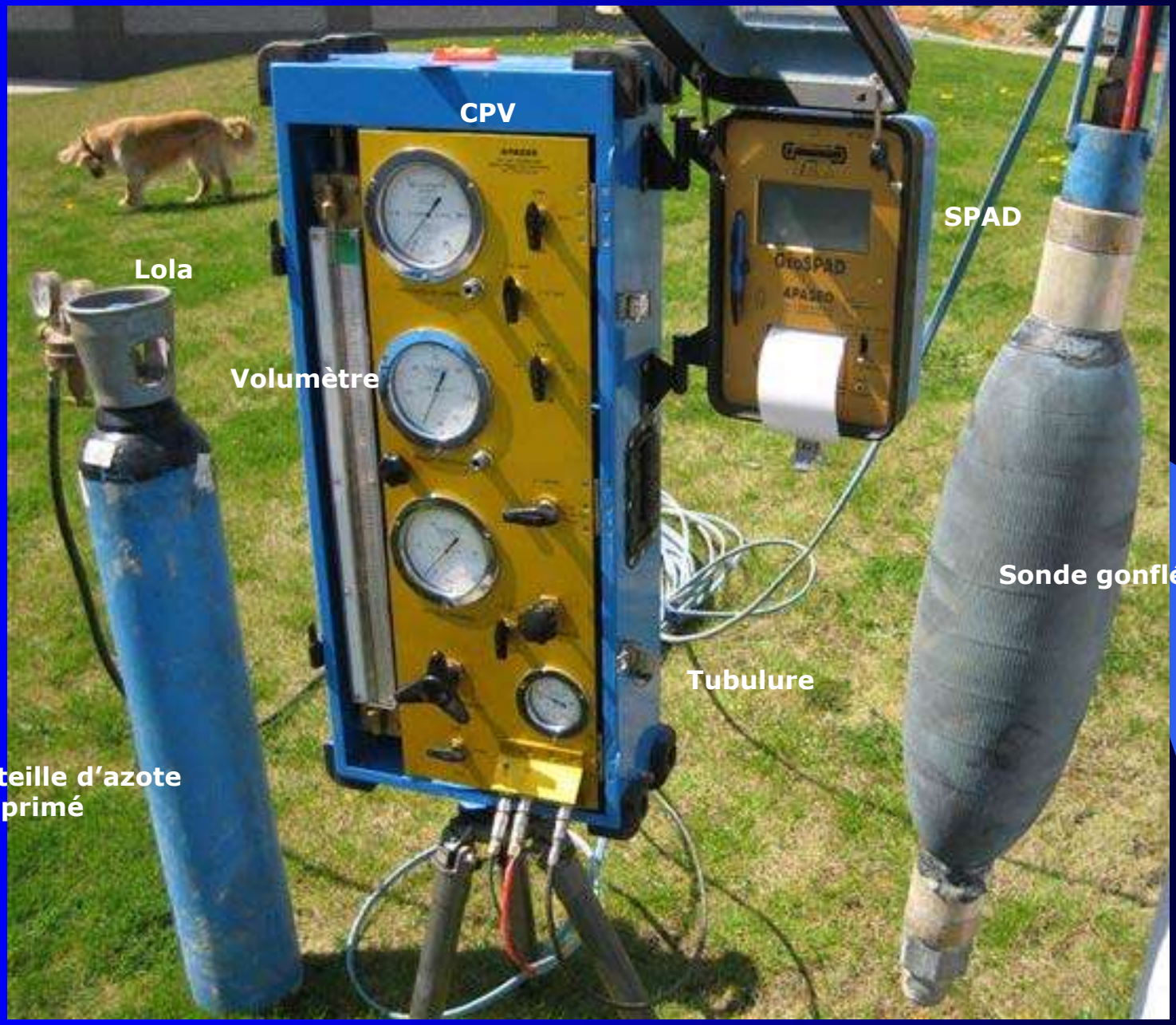
Conclusions


CPV
SPAD
Lola
Volumètre
Sonde gonflée
Tubulure
Bouteille d'azote comprimé

GeoSPAD
APAGEO
APAGEO
enard matériels

Standard for MPM:

Geotechnical investigation and testing. Field testing – Prebored pressuremeter test by Ménard procedure

BS EN ISO 22476-4 (September 2021)

Joint European/ISO standard

Table C.2 — Guidelines for pressuremeter probe placement technique

Boring technique → / Soil Type ↓	Probe placing without soil displacement										Probe placing by direct driving
	$1 < d_t/d_c \leq 1{,}08$										$d_t/d_c \approx 0$
	Rotary drilling				Rotary percussion			Tube pushing, driving or vibrodriving			Driven slotted tube.
	OHD *	HA/HAM *	CFA	CD	RP	RPM	STDTM	PT	DT	VDT	DST
Sludge and soft clay	✱✱°	✱✱✱°	—	—▪		—	—▪	✱✱✱ TWT	—		✱▪
Soft to firm clayey soils	✱✱✱°	✱✱✱°	✱✱▪	✱✱▪	—	✱▪°	✱°	✱▪	✱	—	
Stiff clayey soils	✱✱✱°	✱✱▪°	✱✱✱	✱✱✱°	✱▪	✱✱°	✱✱▪°	—	✱▪	—	
Silty soils:											
— above water table	✱✱°	✱✱✱°	✱✱	✱✱▪°	—	✱°	✱✱°	✱▪	✱	✱	—
— below water table	✱▪°	✱✱▪°	—	✱▪°	—	✱°	✱✱^°	—	—	—	✱▪
Loose sandy soils:											
— above water table	✱✱°	✱✱✱▪°	✱✱	✱	—	✱°	✱°	—▪	—	—	—
— below water table	✱▪°	✱✱°	—	—▪	—	✱°	✱^°	—▪	—	—	✱▪+
Medium dense and dense sandy soils	✱✱✱°	✱✱✱°	✱✱✱	✱°	✱	✱✱°	✱✱^°	—	✱	✱	✱✱▪+
Gravels, cobbles	✱✱°	—▪°	—▪	—▪	✱	✱✱✱°	✱▪°		✱	✱	✱✱✱▪+
Cohesive non-homogeneous soils (e.g. boulder clay)	✱✱°	✱°	✱	✱✱▪°	✱	✱✱✱°	✱▪°		✱	✱	
Loose non-homogeneous soils, other soils not specified above (e.g. tills, some alluvial deposits, man made soils, treated or untreated fills)	✱✱°	✱°	✱	✱°	✱	✱✱°	✱✱▪°	—	✱	✱	✱✱▪+
Weathered rock, weak rock	✱✱✱°	✱✱°	✱✱	✱✱▪°	✱▪	✱✱°	✱✱▪°		✱▪	✱▪	

Caption

Key

✱✱✱	Recommended	OHD	Open hole drilling.	PT	Pushed tube
✱✱	Suited	HA	OHD performed with a hand auger	TWT	Thin wall tube, pushed
✱	Acceptable	HAM	OHD performed with a hand auger and mud	DT	Driven tube
—	Not suited	CFA	Continuous flight auger	VDT	Vibrodriven tube
	Not covered by this standard	CD	Core drilling	DST	Driven slotted tube
		RP	Rotary percussion		
		RPM	Rotary percussion with mud		
		STDTM	Slotted tube with inside disintegrating tool and mud circulation		

▪ Depending on the actual site conditions and on the evaluation of the operator

• Rotation speed should not exceed 1 s^{-1} and tool diameter not be more than 1,15 d_c

◦ Slurry circulation: pressure should not exceed 500 kPa and the flow rate 15 l/min. The flow can be temporarily interrupted if necessary.

+ Pilot hole with possible preboring techniques: DST, RP and RPM

- Needs special care: 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

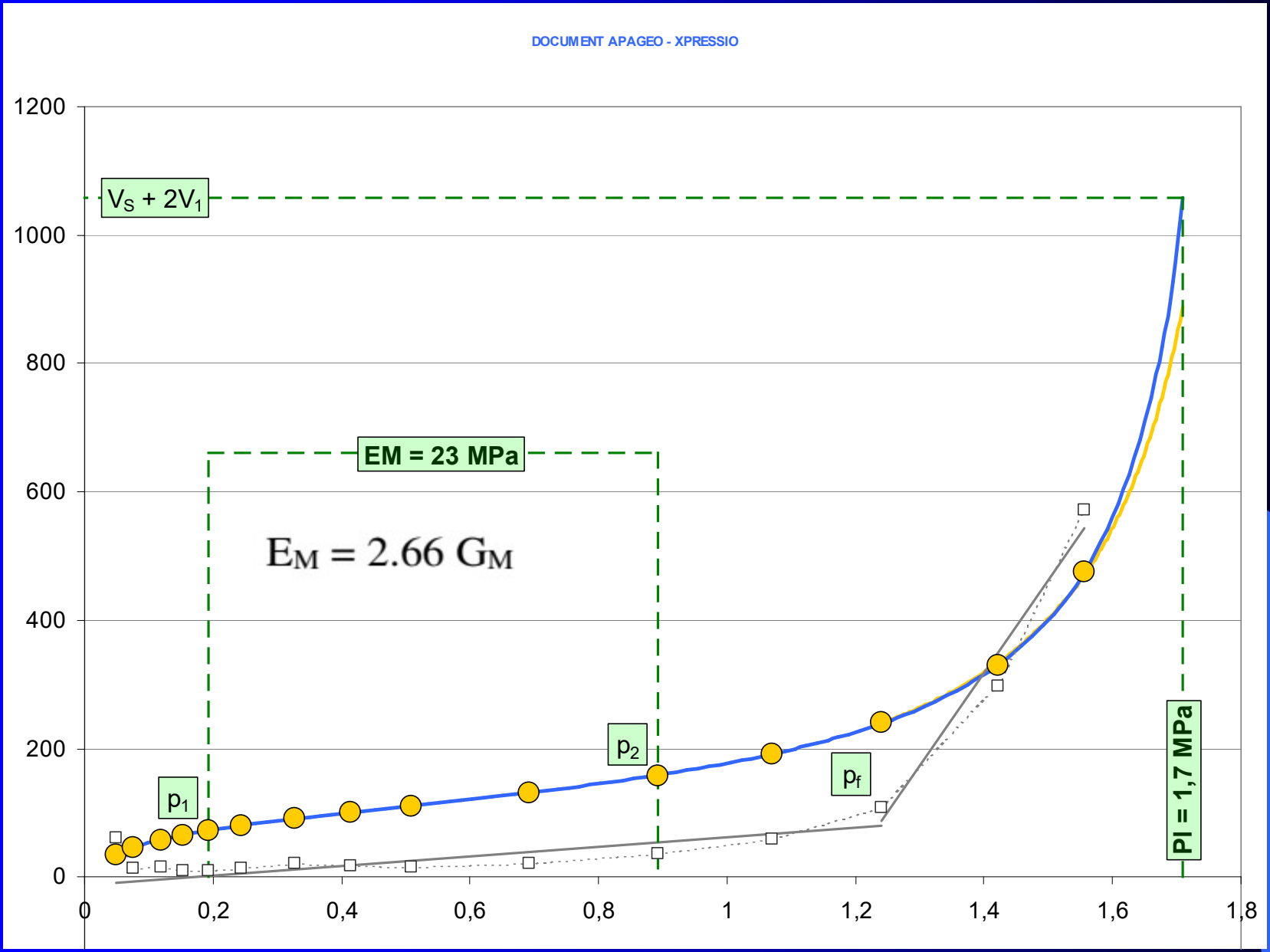
Table C.1 — Maximum continuous drilling or driving stage length before testing

Soil type	Maximum continuous drilling or tube driving stage length (m)		
	Adapted rotary drilling[b]	Rotary percussive drilling[b]	Smooth tube pushing, driving and vibrodriving[c]
Sludge and soft clay, soft clayey soil	1[a]	—	1[a]
Firm 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, other soils not specified above (e.g. tills, etc.)	2	3	2
Weathered rock, weak rock	4	5	3

[a] Or the required interval between two successive tests.

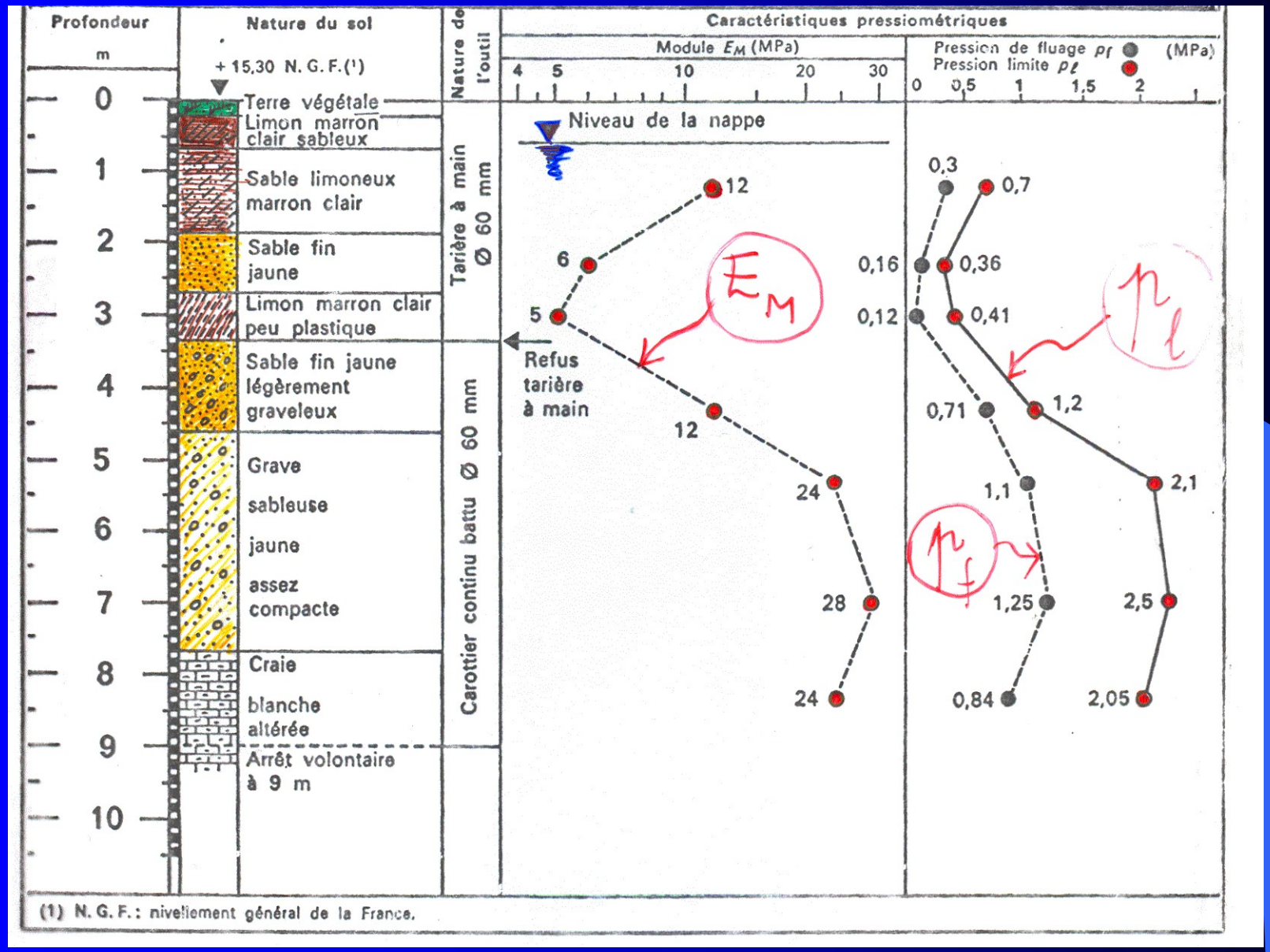
[b] Refer to Table C.2 for acceptable techniques.

[c] Not applicable to STDTM technique (see C.2.6.3).

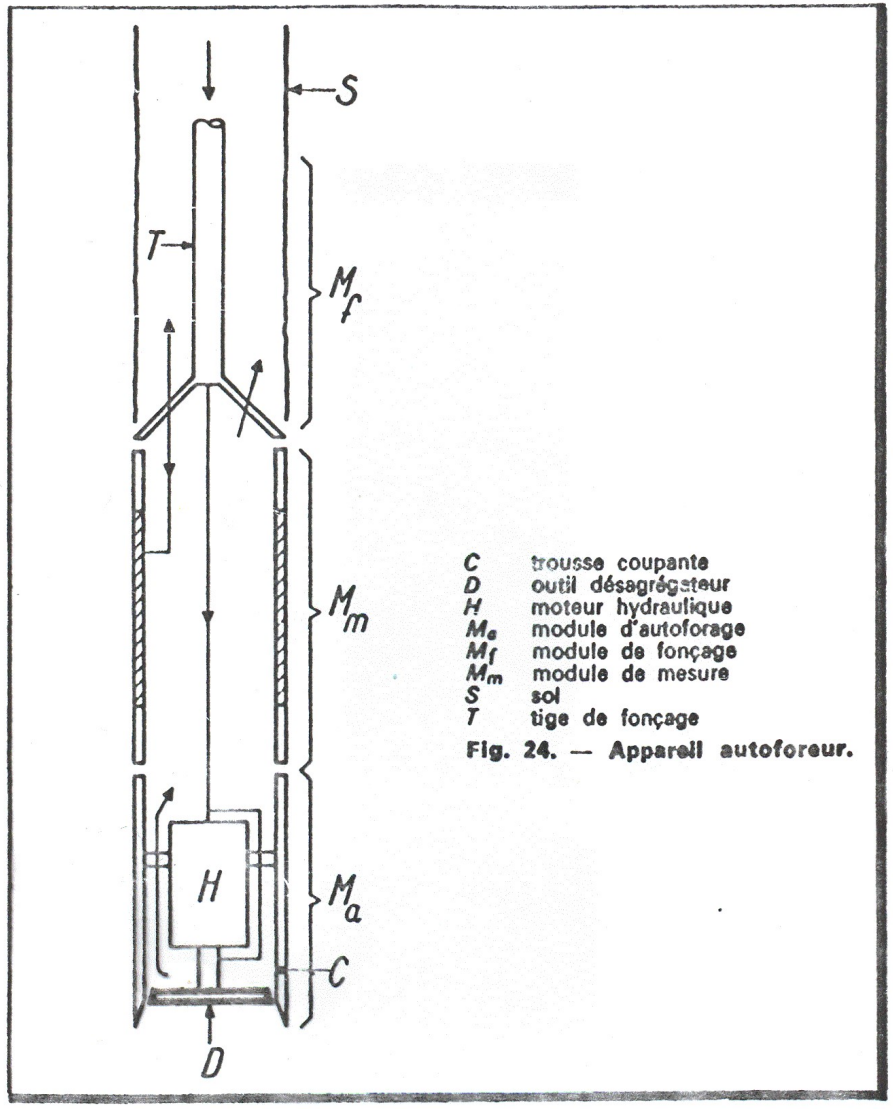

DOCUMENT APAGEO - XPRESSIO
1200
1000
800
600
400
200
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
$V_S + 2V_1$
EM = 23 MPa
$E_M = 2.66\ G_M$
p_1
p_2
p_f
Pl = 1,7 MPa

APAGEO

Pressuremeter soil profile



PAF : Self-boring pressuremeter … (Concorde <-> Airbus)



C trousse coupante
D outil désagrégateur
H moteur hydraulique
M_a module d'autoforage
M_f module de fonçage
M_m module de mesure
S sol
T tige de fonçage

Fig. 24. — Appareil autoforeur.

Standard for PAF (SBP):

Geotechnical investigation and testing. Field testing – Self-boring pressuremeter test

BS EN ISO 22476-6 (October 2018)

Joint European/ISO standard

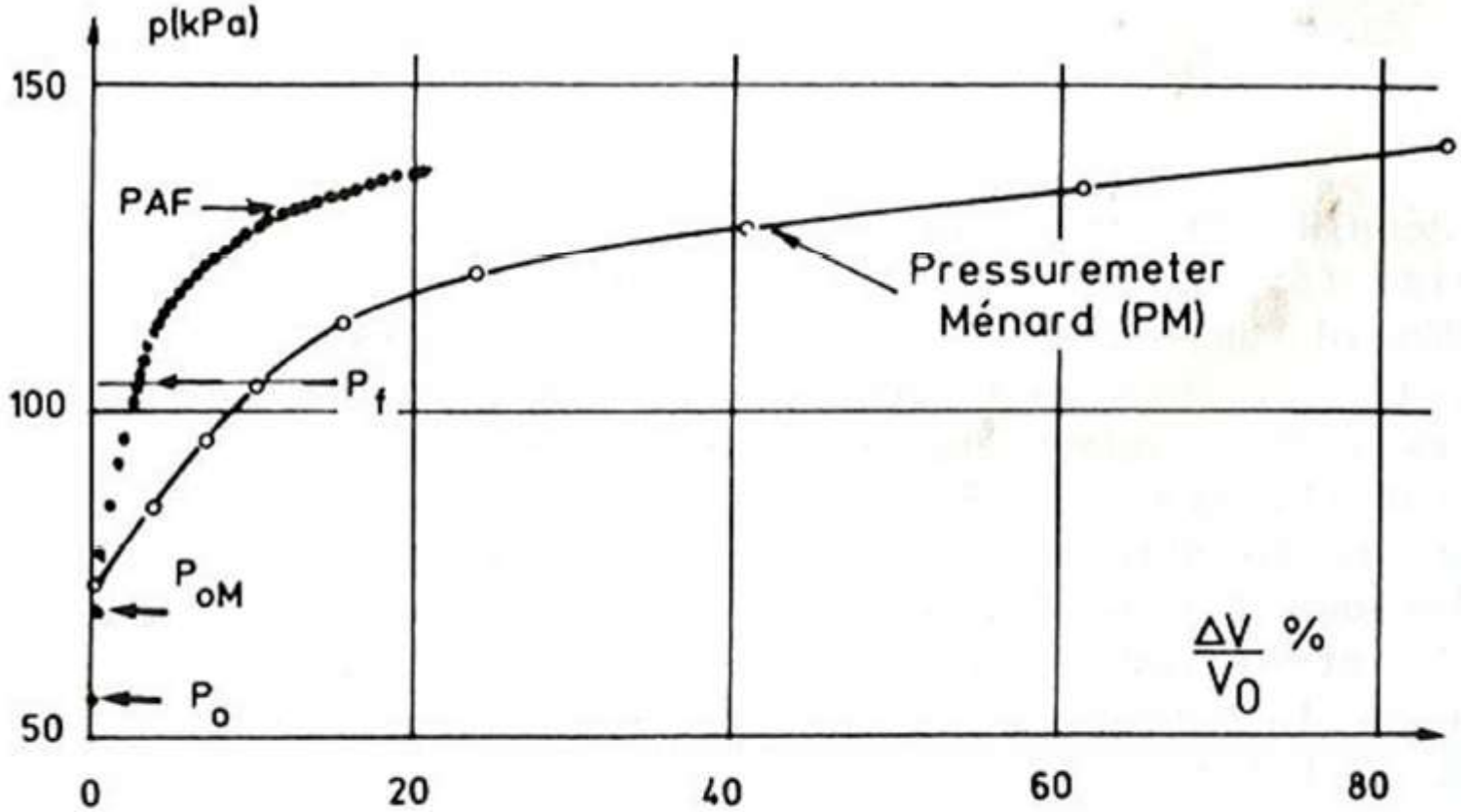


Figure 1 Typical pressuremeter MPM and PAF expansion curves (Baguelin et al. 1978)

Table 1 Correlations between PAF and MPM moduli (Jézéquel and Le Méhauté, 1979)

	$\frac{G_{p0}}{G_{p2}}$	$\frac{G_{p2}}{G_{p5}}$	$\frac{G_{p2}}{G_M}$	$\frac{G_{p5}}{G_M}$	$\frac{G_{p0}}{G_M}$
Clays	2.09	1.72	5.42	3.03	11.3
Sands	1.19	1.29	3.47	2.53	4.1

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Conclusions

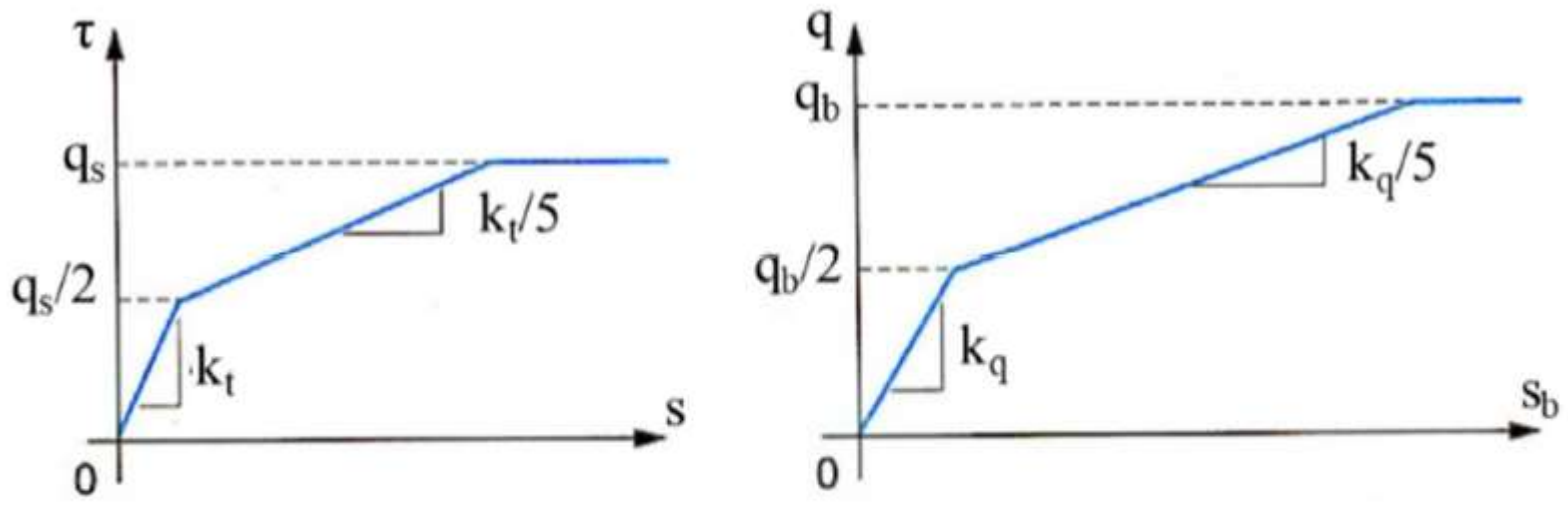

Figure 2 MPM τ-s (=t-z) and q-s_b (=q-z_b) curves (Frank and Zhao, 1982)

$k_\tau = 2.0\ E_M/(2r_0)$ and $k_q = 11.0\ E_M/(2r_0)$ for cohesive soils and soft rocks

$k_\tau = 0.8\ E_M/(2r_0)$ and $k_q = 4.8\ E_M/(2r_0)$ for granular soils

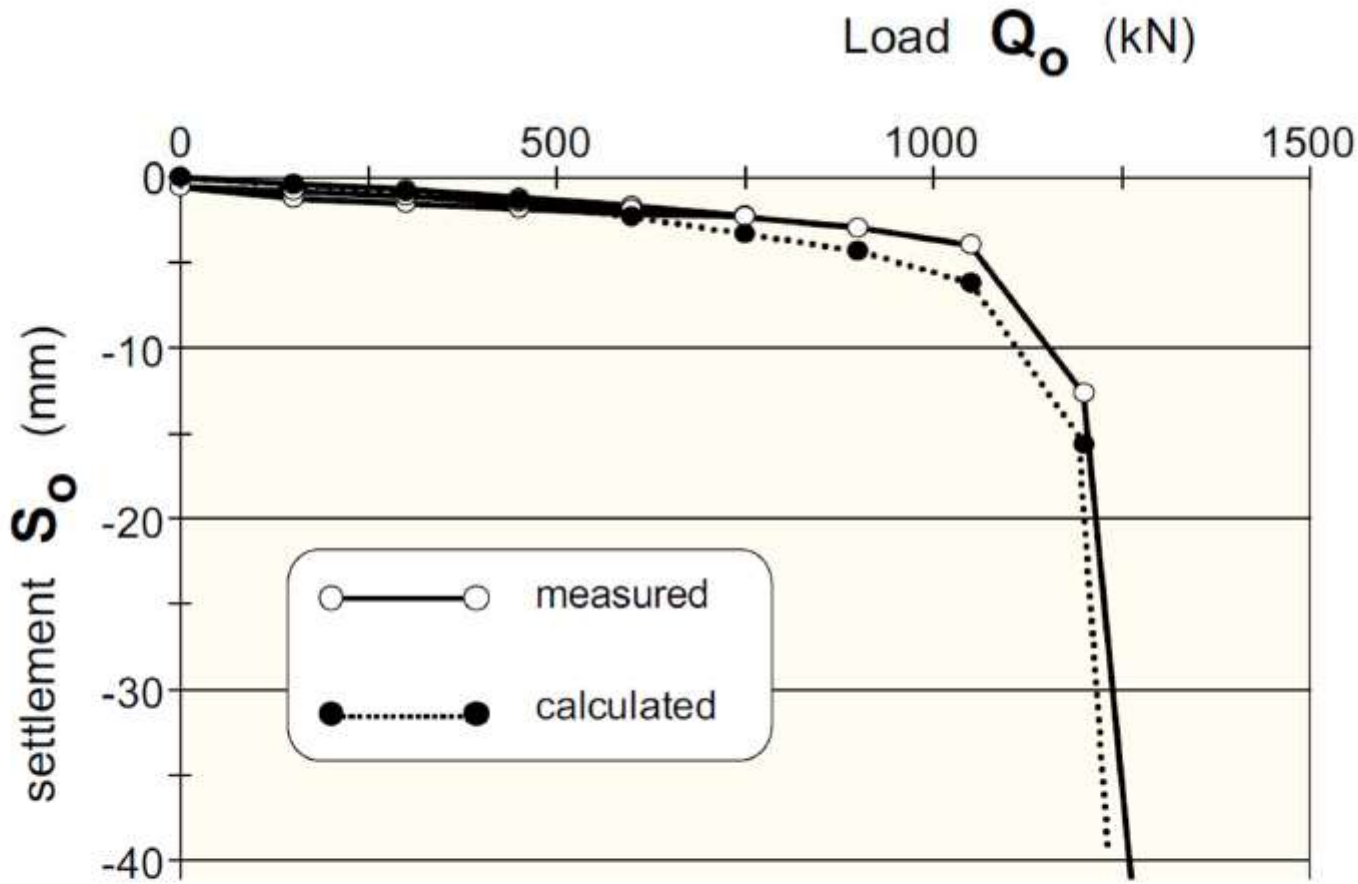

Figure 3 Comparison of measured and calculated load-settlement curves for the Koekelare pile (Bustamante and Frank, 1999)

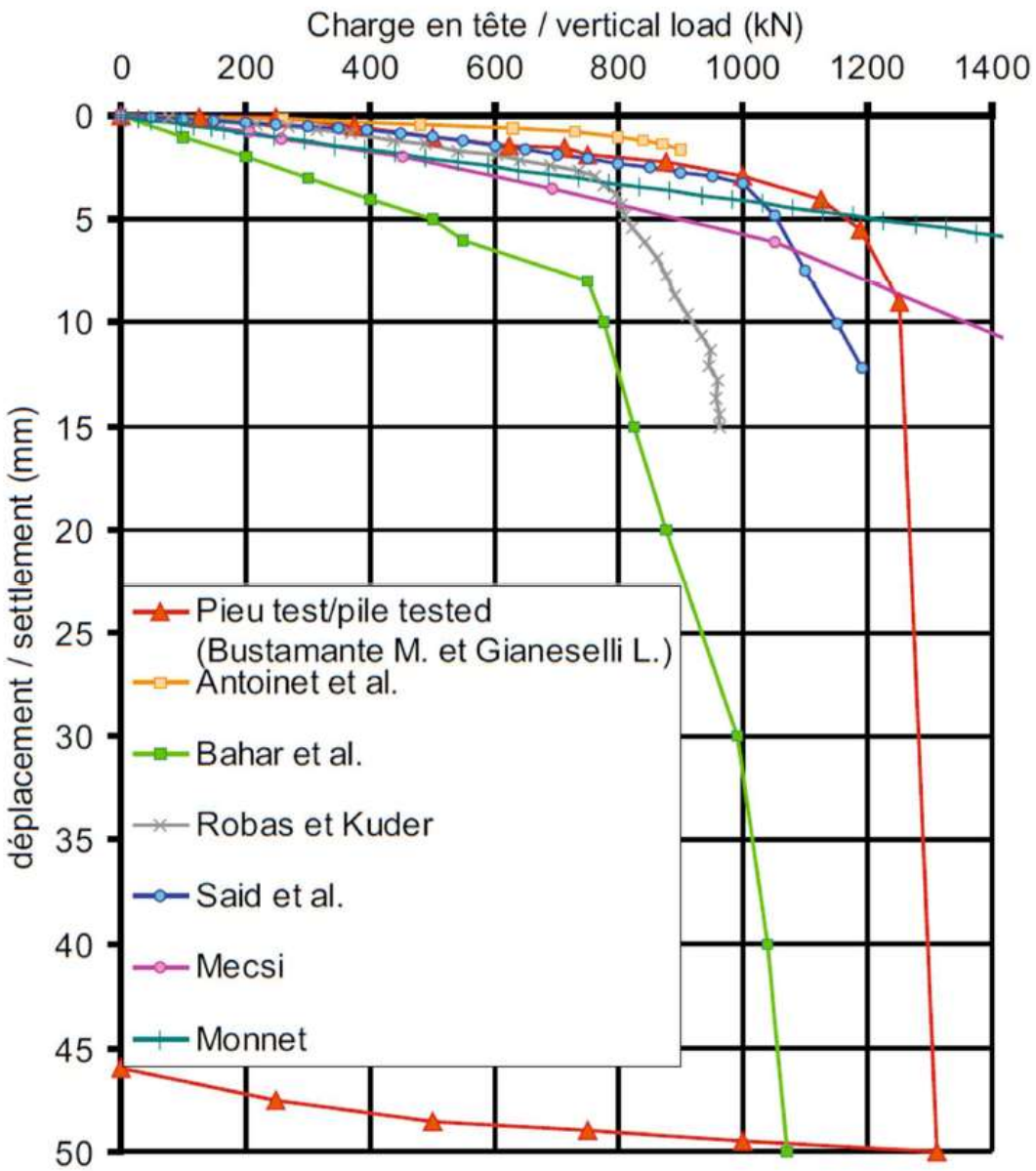

Figure 4 Comparison of the experimental curve with the participants' predictions (Reiffsteck, 2006)

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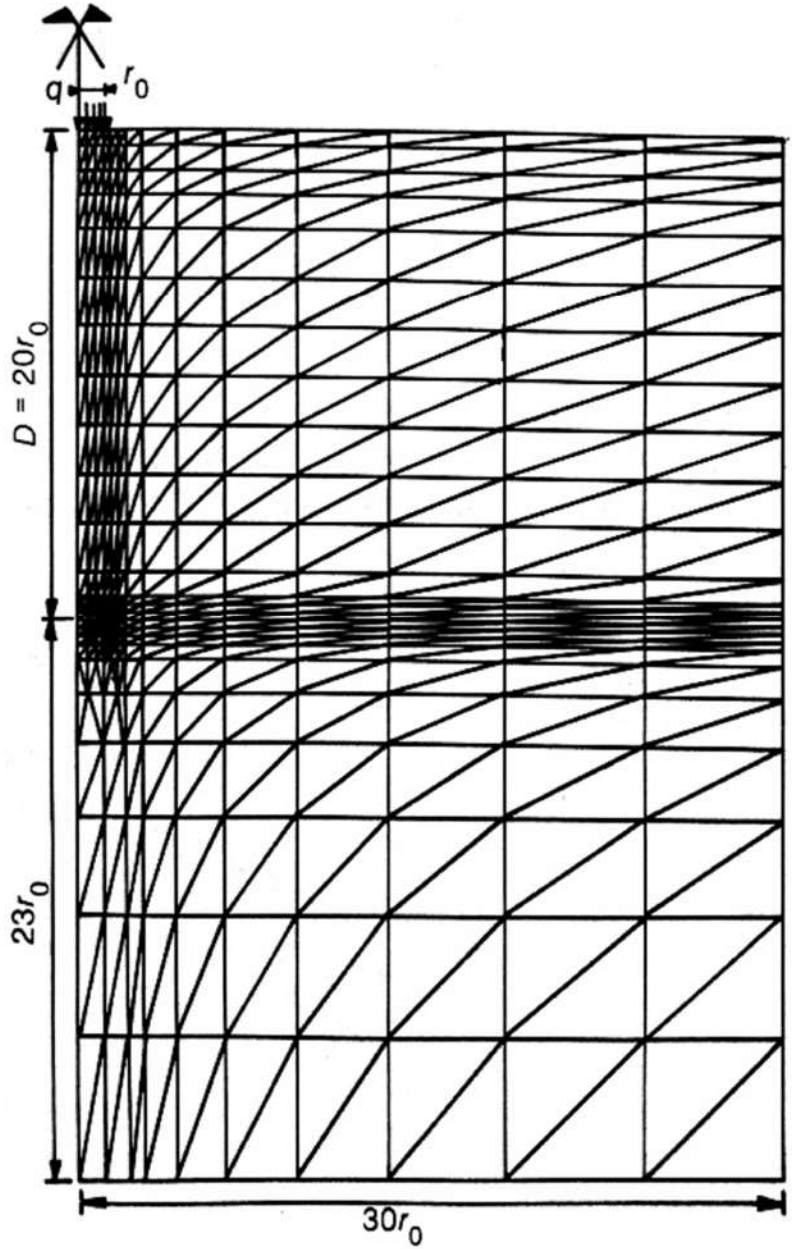


Figure 5 FEM mesh for the study of the mechanism of shaft friction of piles in isotropic linear elastic media (Frank, 1974)

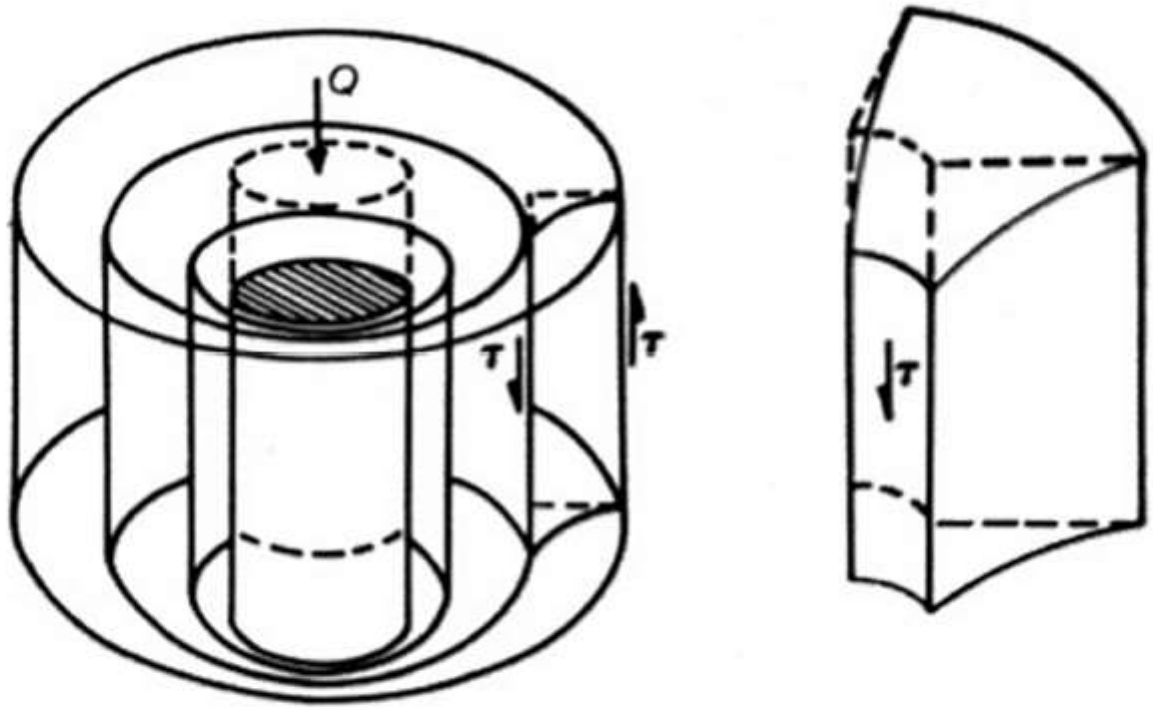
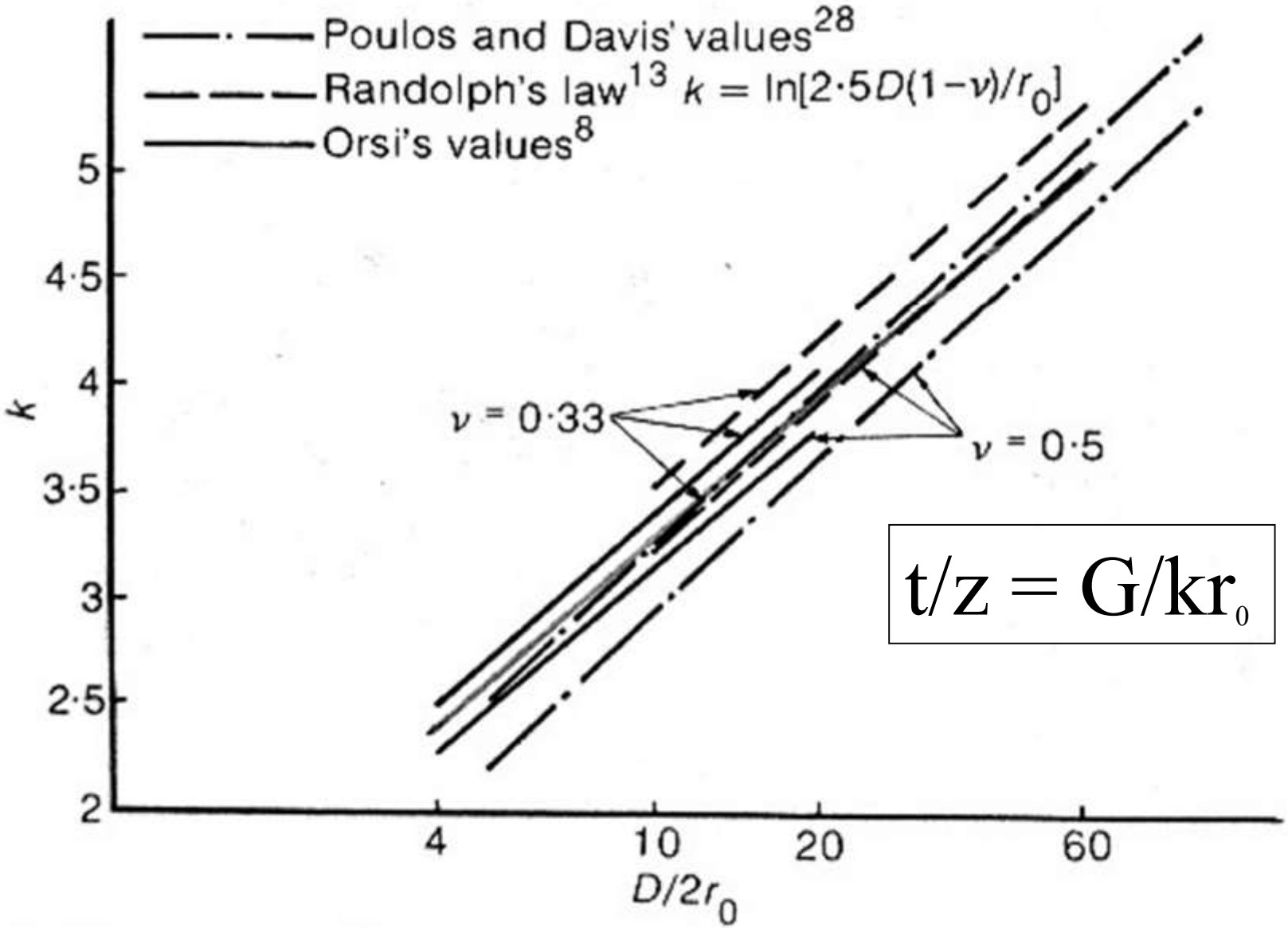


Figure 6 Sketch of the mechanism of pure shearing of vertical concentric annuli (Frank, 1974)

$$t/z = G/kr_0$$



$$t/z = G/kr_0$$

Figure 7 Parameter k as a function of $D/2r_0$ and ν (in isotropic elasticity) (Baguelin and Frank, 1980)

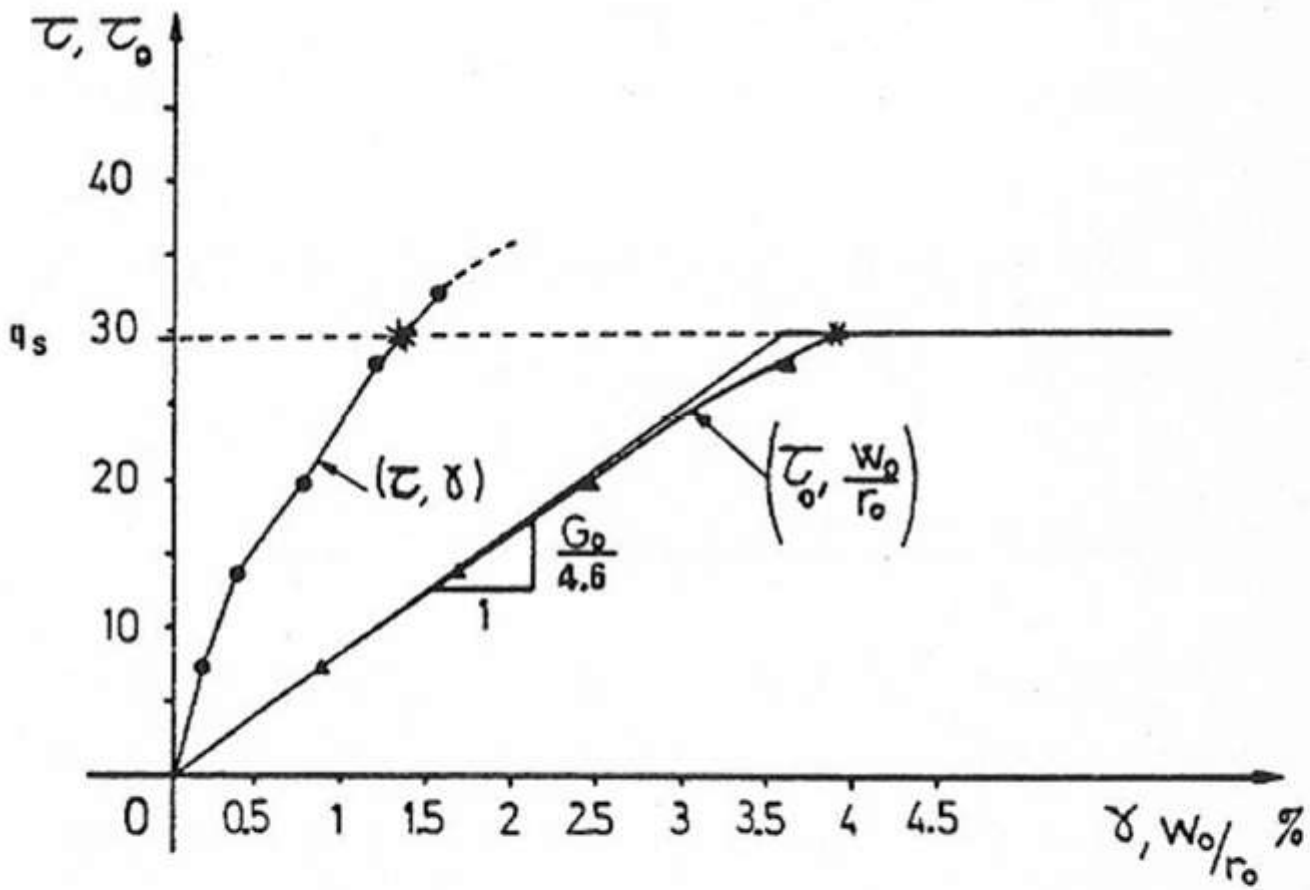


Figure 8 Shear curve (τ,γ) derived from a PAF expansion test and corresponding shaft friction curve (τ_0,w_0/r_0) at 3 m depth for the Plancoët pile (Baguelin et al., 1982).

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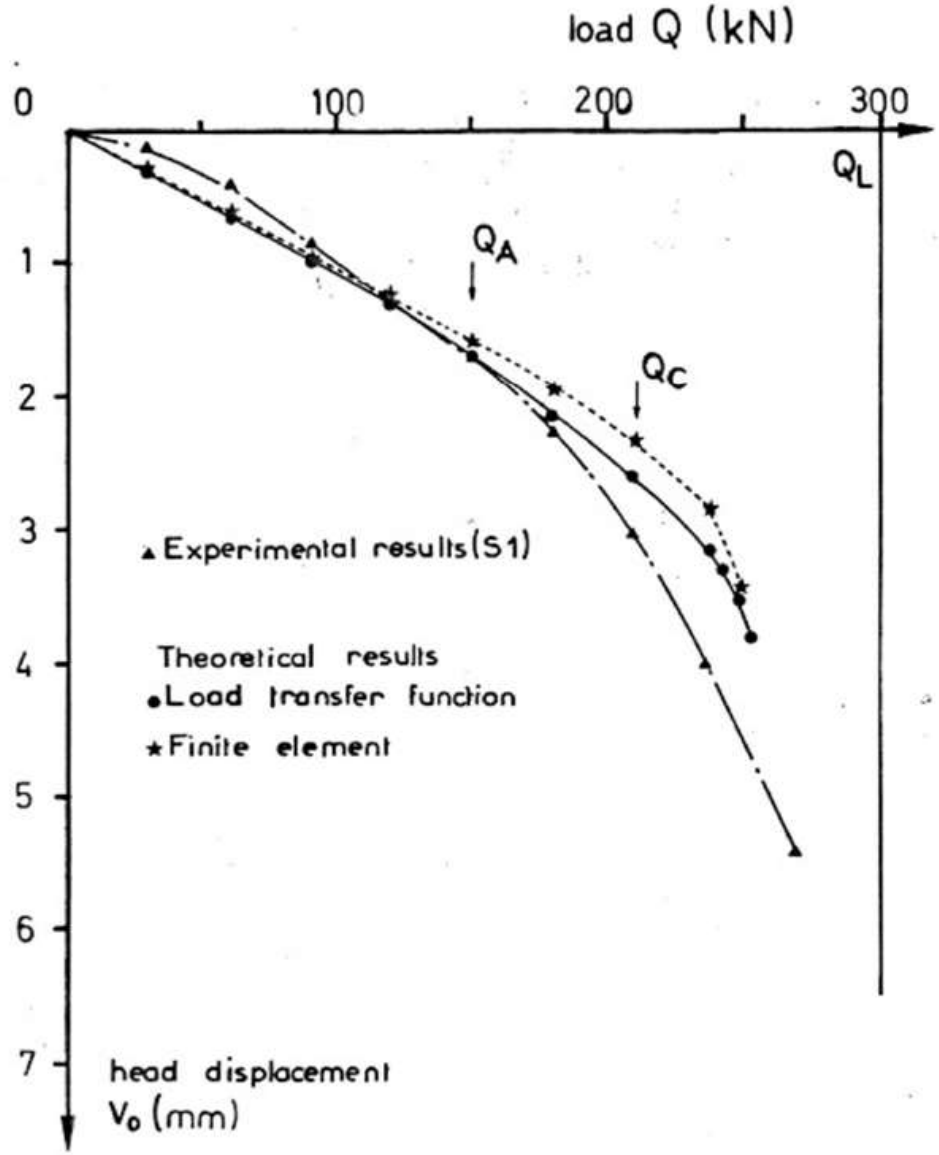

Figure 9 Comparison of measured and calculated load-settlement curves for the pull-out test at Cran

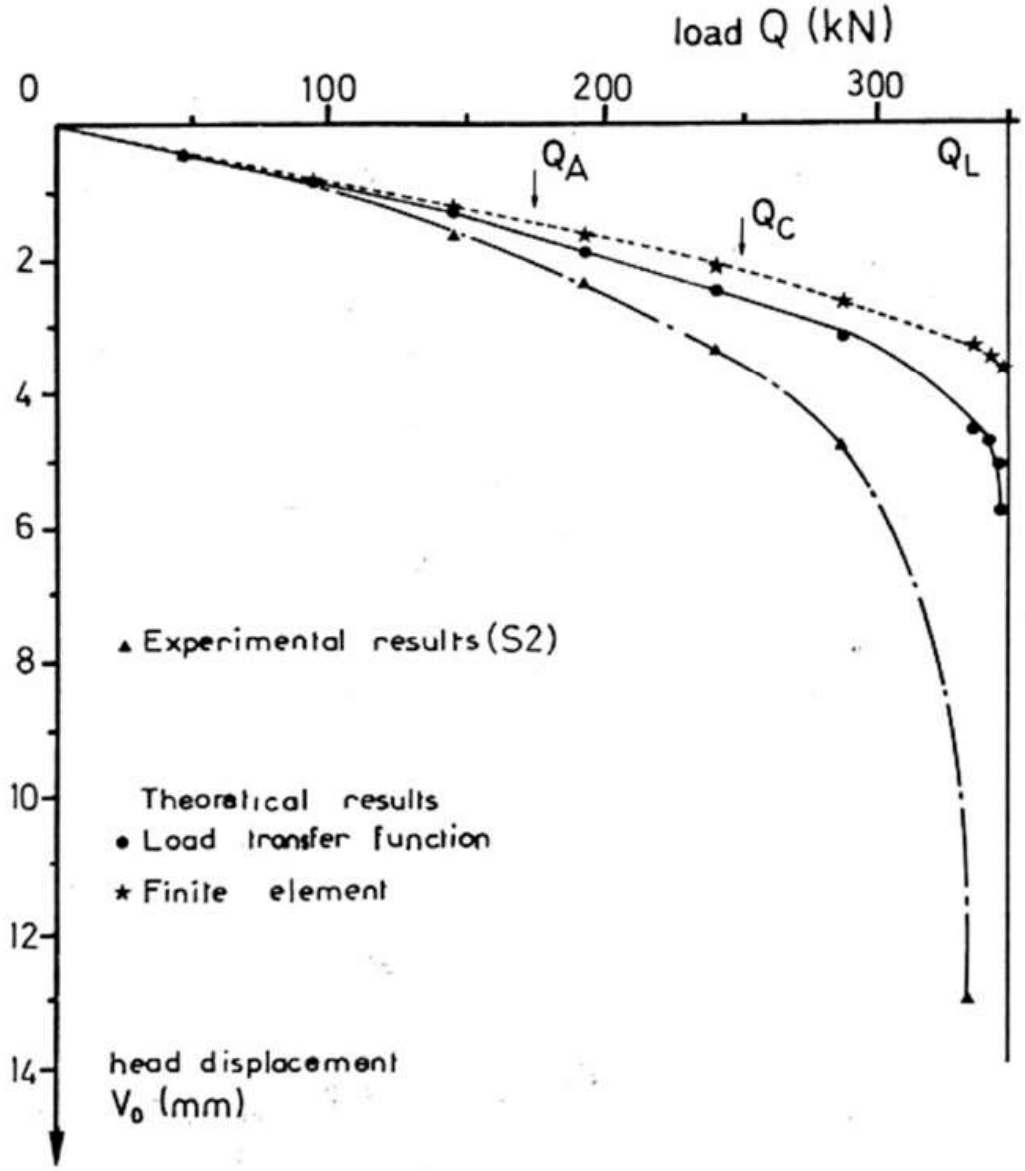

Figure 10 Comparison of measured and calculated load-settlement curves for the pull-out test at Plancoët

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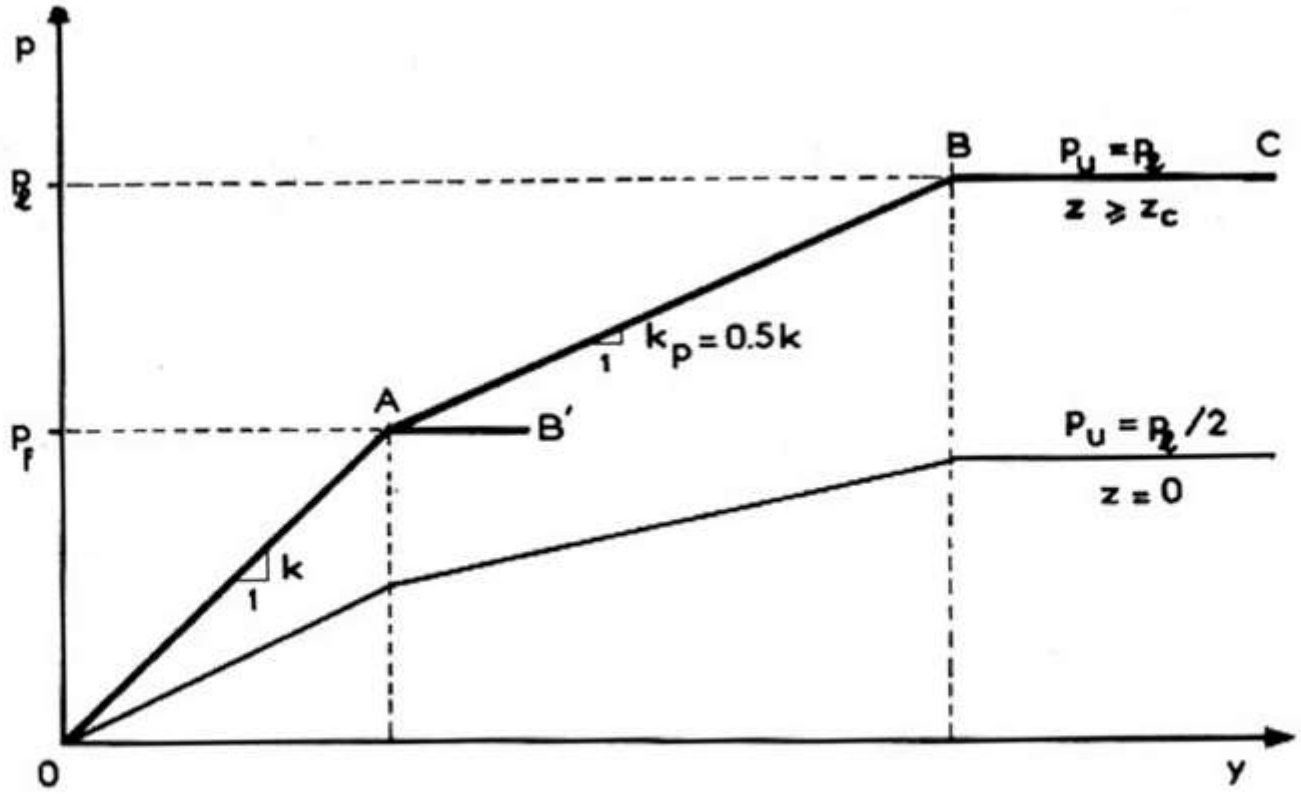

Figure 11 p-y reaction curve from MPM results for long duration loadings (Baguelin et al., 1978)

$E_{sM} = k_s B$ is obtained:

$$E_{sM} = E_M \frac{18\rho}{4(2{,}65\rho)^{\alpha} + 3\alpha\rho} \quad \text{with } \rho = \max\left(\frac{B}{B_0}; 1\right)$$

Table 2 Ratio E_{sM}/E_M for estimating the Ménard horizontal reaction modulus E_{sM} from the pressuremeter modulus E_M (Baguelin et al., 1978)

		$B < 0.6$ m	$B = 1.20$ m
Peat	$\alpha = 1$	1.33	1.33
Clay	$\alpha = 2/3$	1.9	2.25
Silt	$\alpha = 1/2$	2.3	3
Sand	$\alpha = 1/3$	2.8	4
Sand and gravel			

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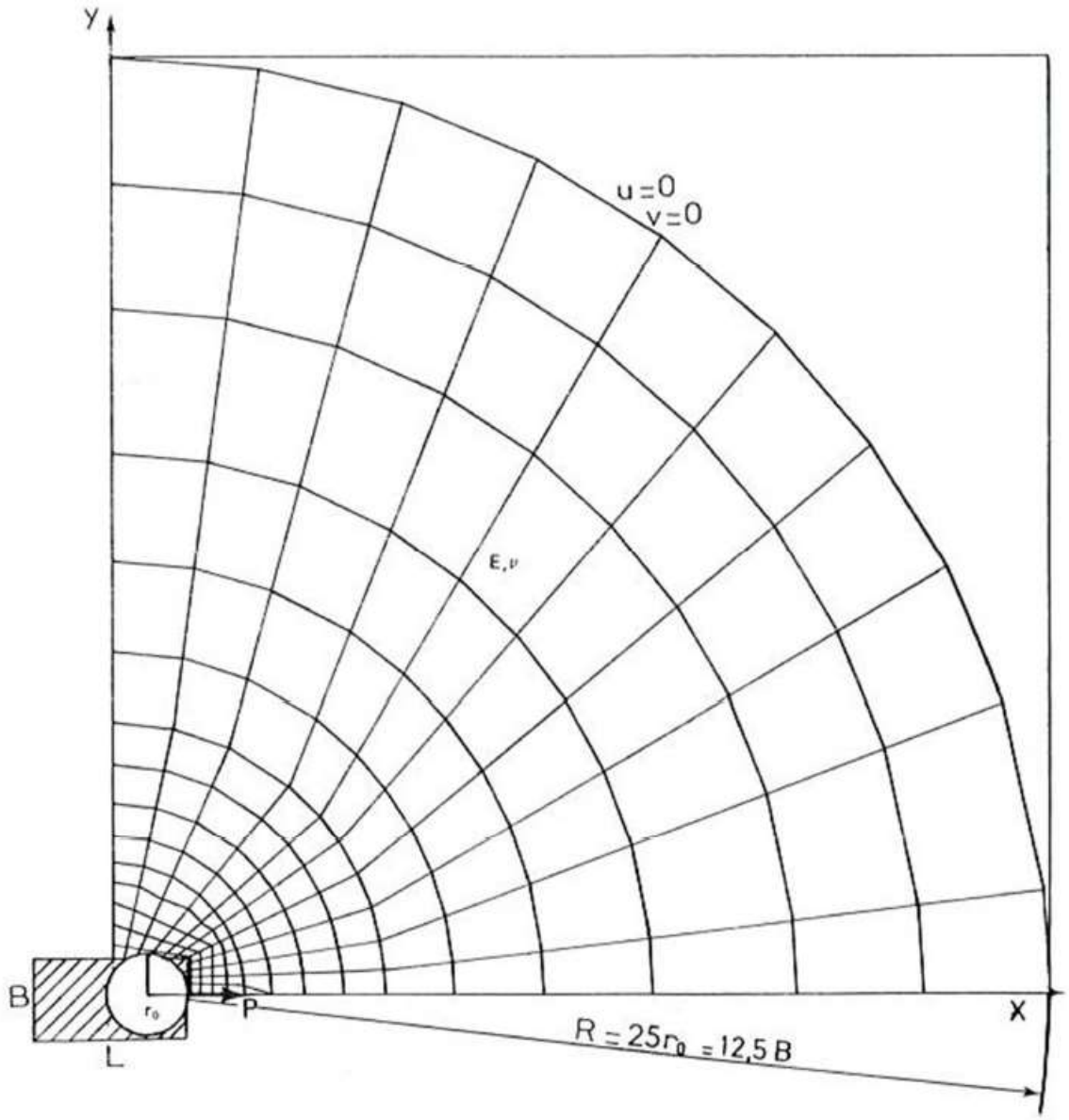

Figure 14 Bi-dimensional FEM mesh in isotropic linear elastic media for a cross-section L/B = 2 (Baguelin et al., 1979)

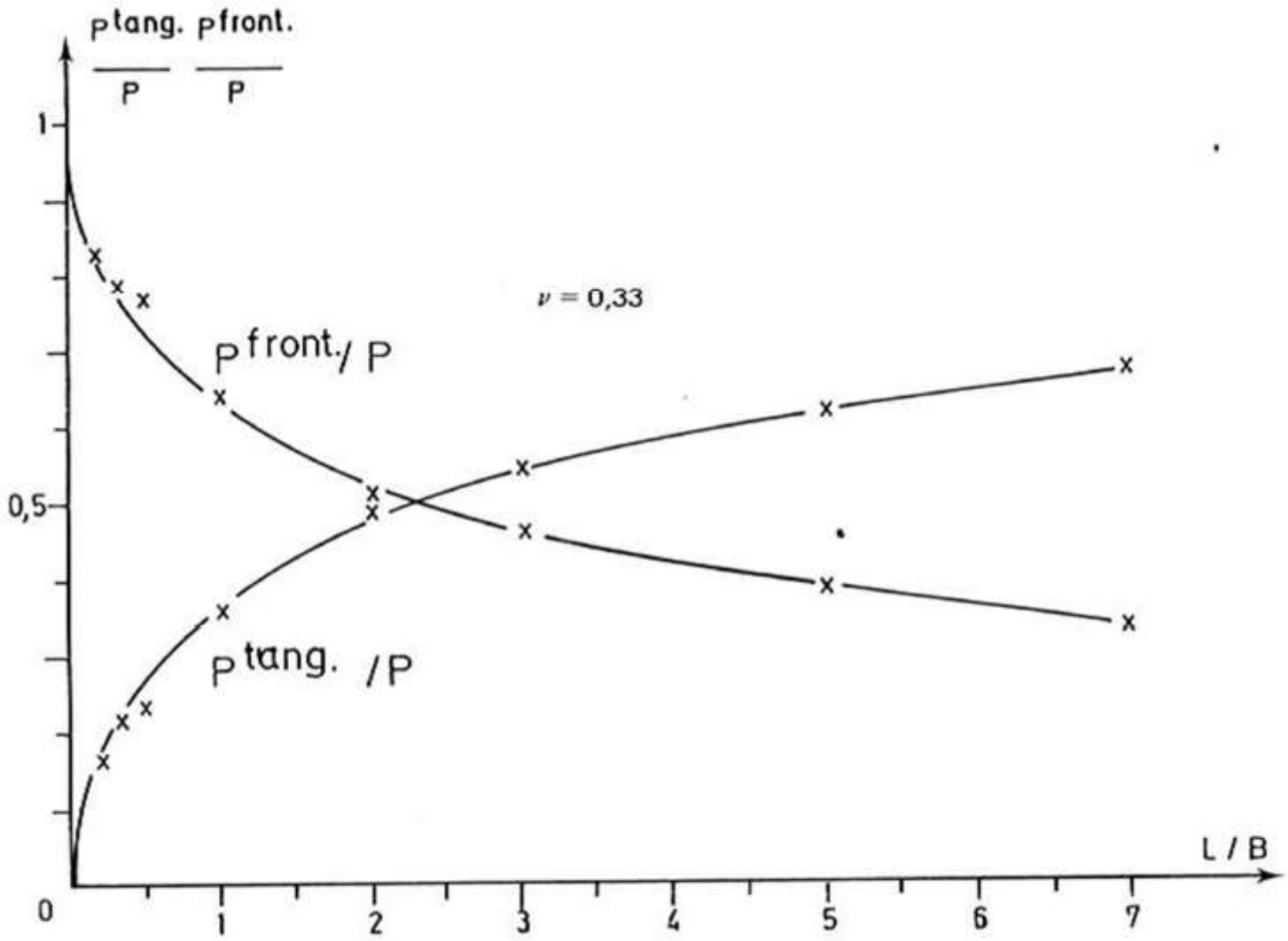

Figure 15 $P^{front.}$ and $P^{tang.}$ for $\nu = 0.33$ from 2D finite element calculations

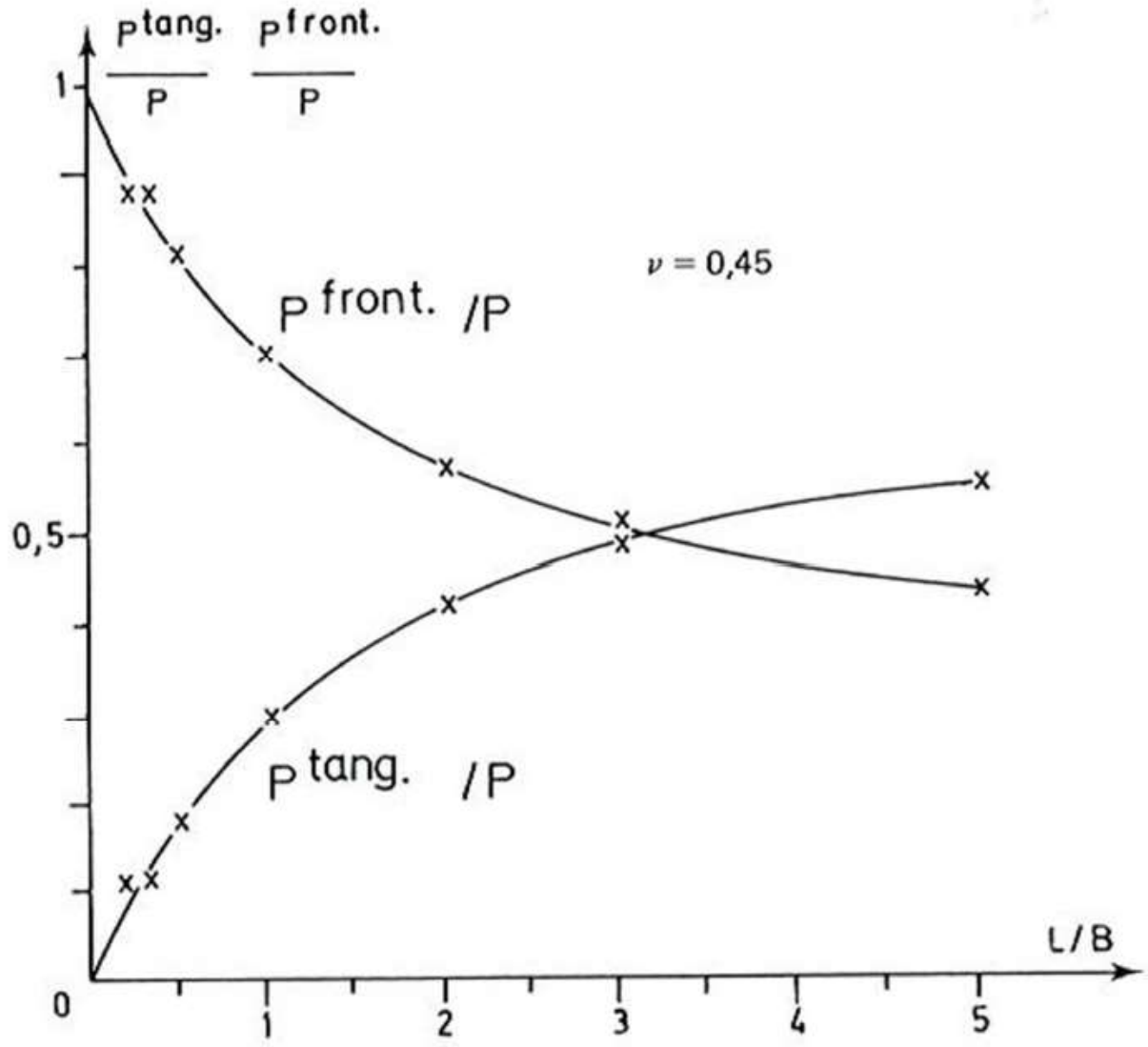

Figure 16 $P^{front.}$ and $P^{tang.}$ for $\nu = 0.45$ from 2D finite element calculations

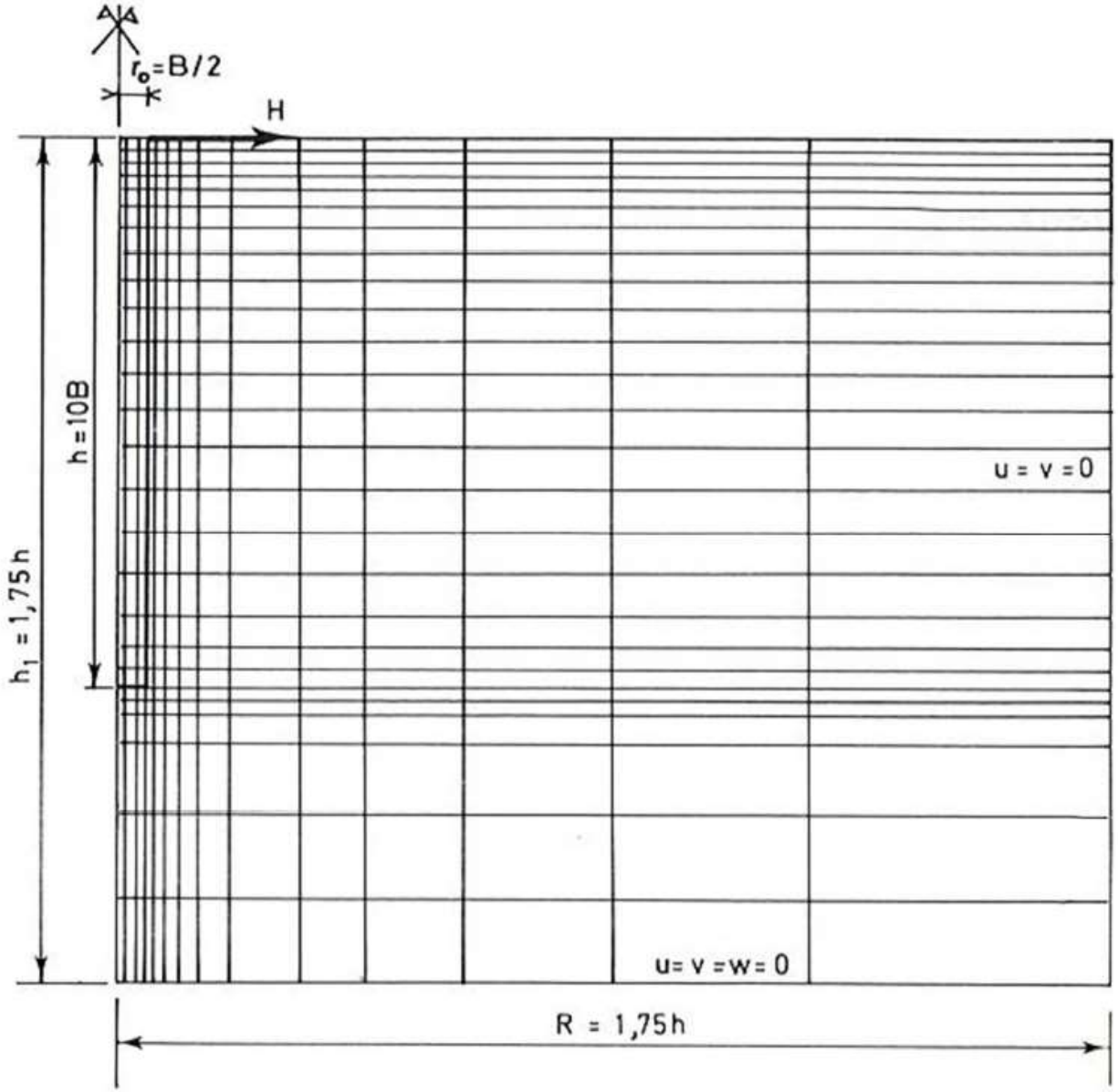

Figure 17 FEM mesh in isotropic linear elastic media for 3D study of laterally loaded piles for piles with $D/2r_0 = 10$

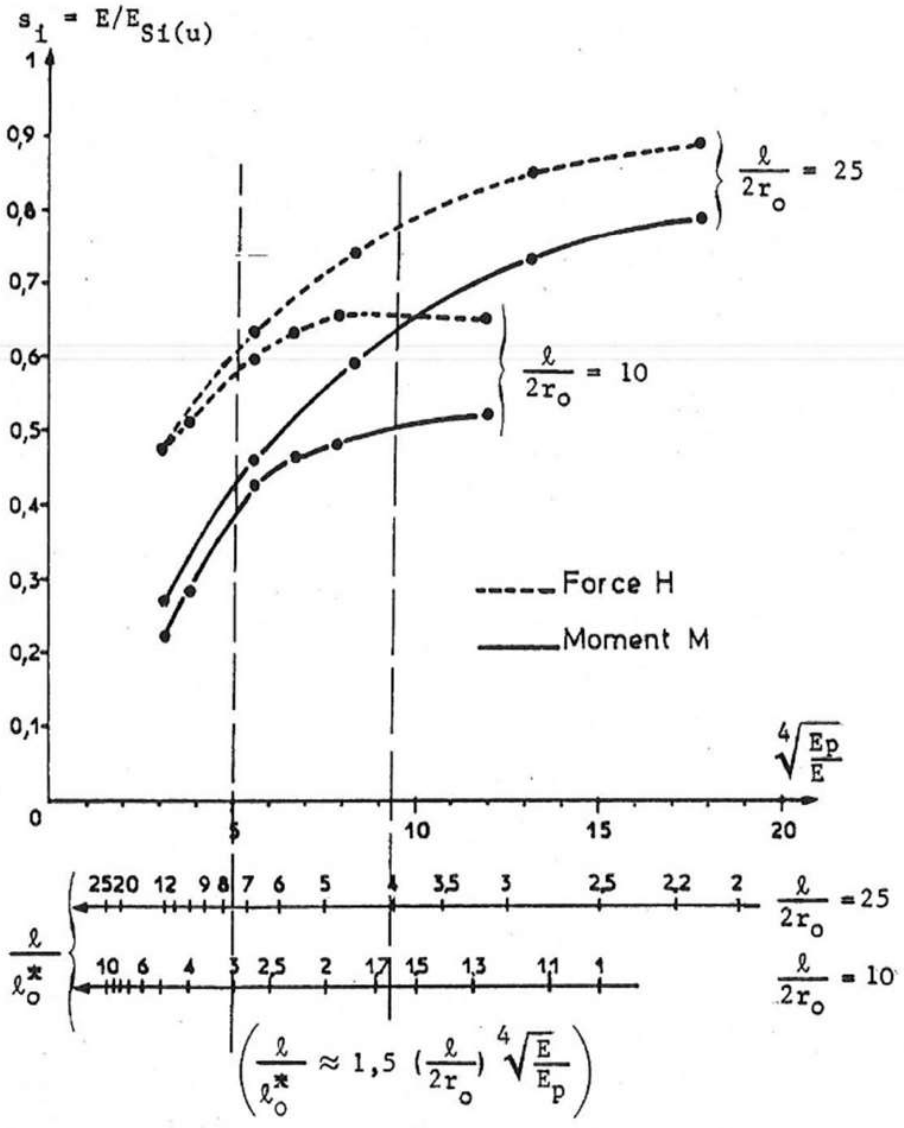

Figure 18 Equivalent horizontal reaction modulus in an intact soil $E_{si(u)}$ as a function of the slenderness ratio $l/2r_0$ (= $D/2r_0$), of the relative pile-soil stiffness E_p/E and of the head loading (H or M)

$s = E/Es(u) \sim 0.6\text{-}0.7$

$E_s \sim 4\,G$

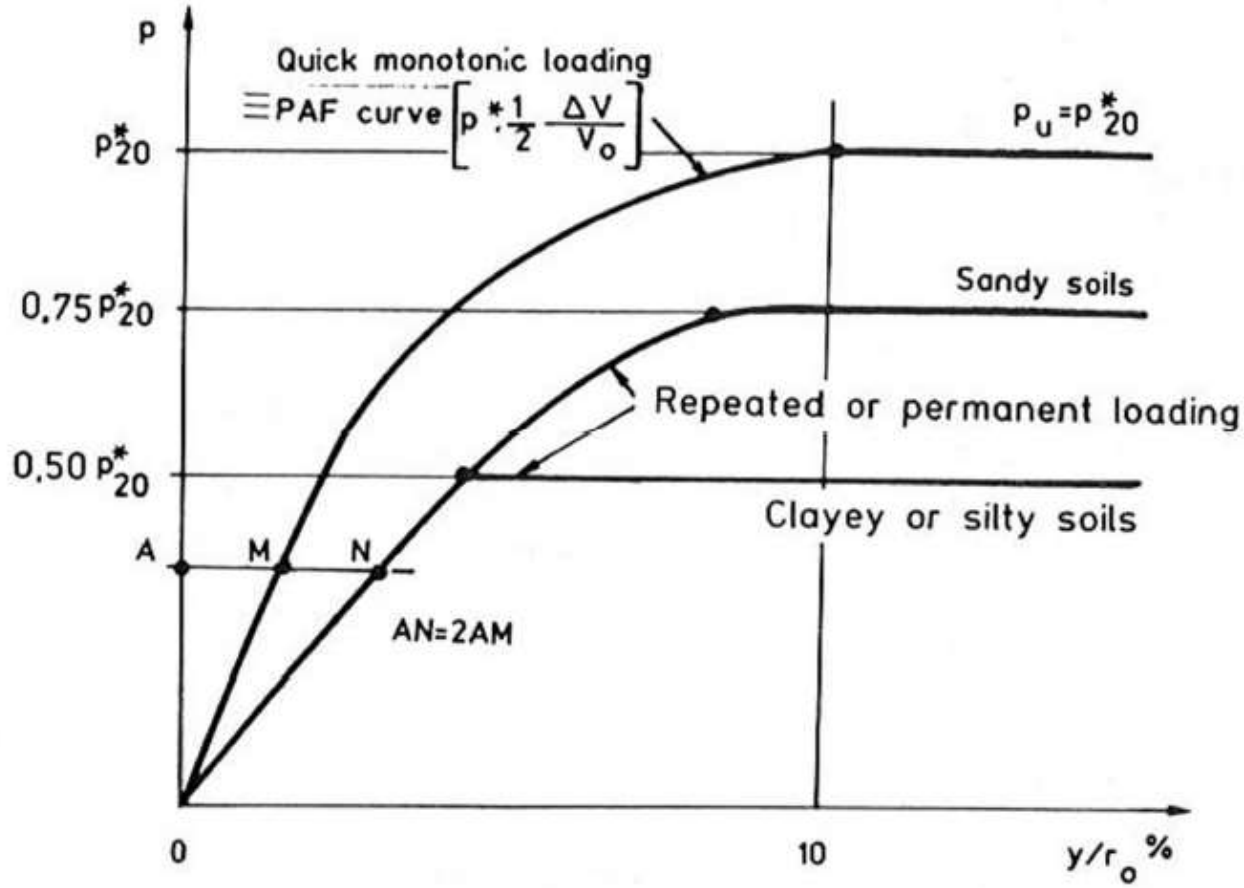

Figure 19 p-y curves derived from PAF expansion curves (Amar et al., 1981)

PAF expansion curve itself : $E_s = pB/y = p2r_0/y = 4\ G_p$

Repeated or permanent loadings: $E_s = 2\ G_p$

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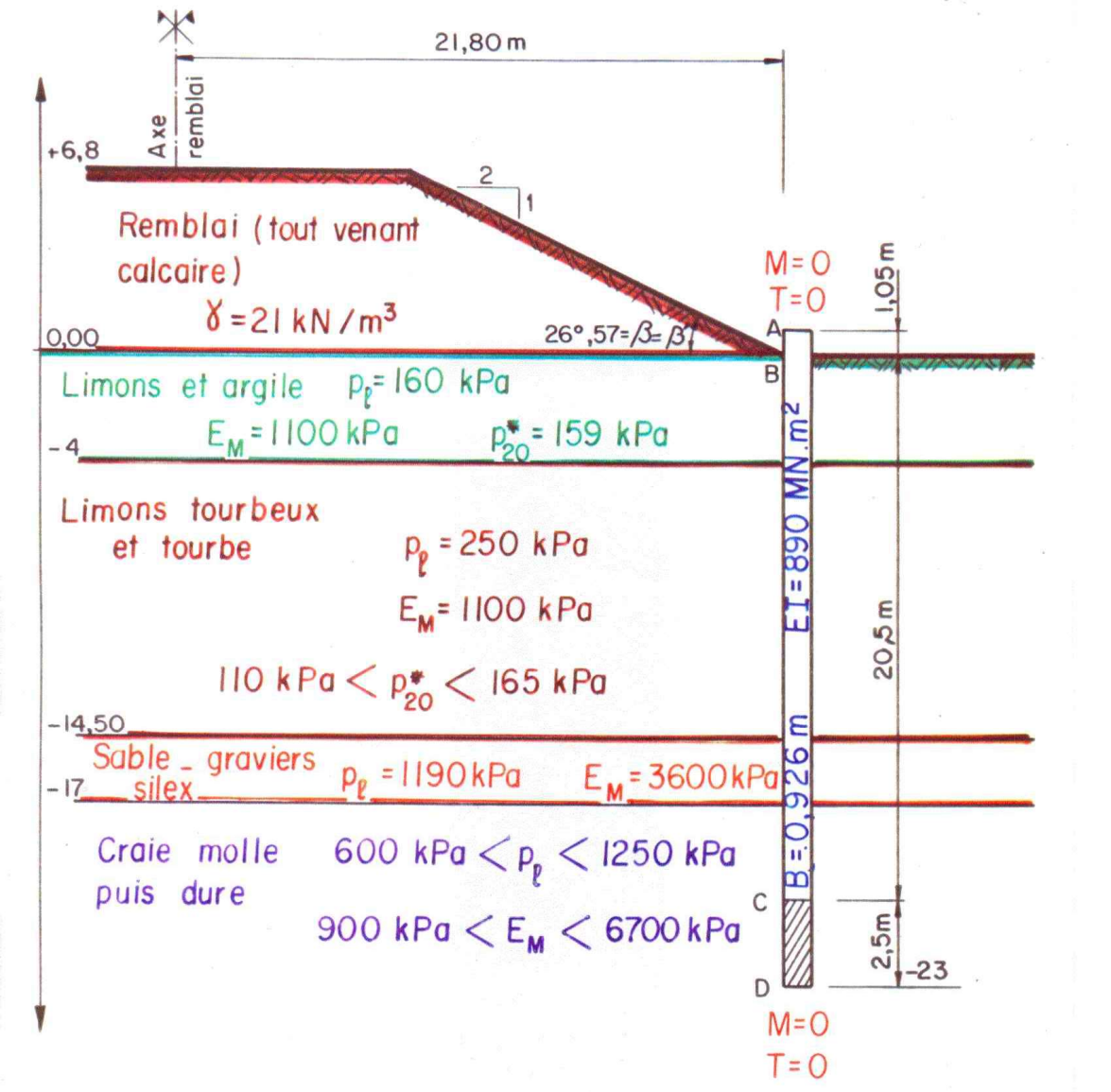
   - 2.3 Examples (Provins, Sallèdes)

3. Behaviour of « barrettes »

Conclusions

The experiment of Provins



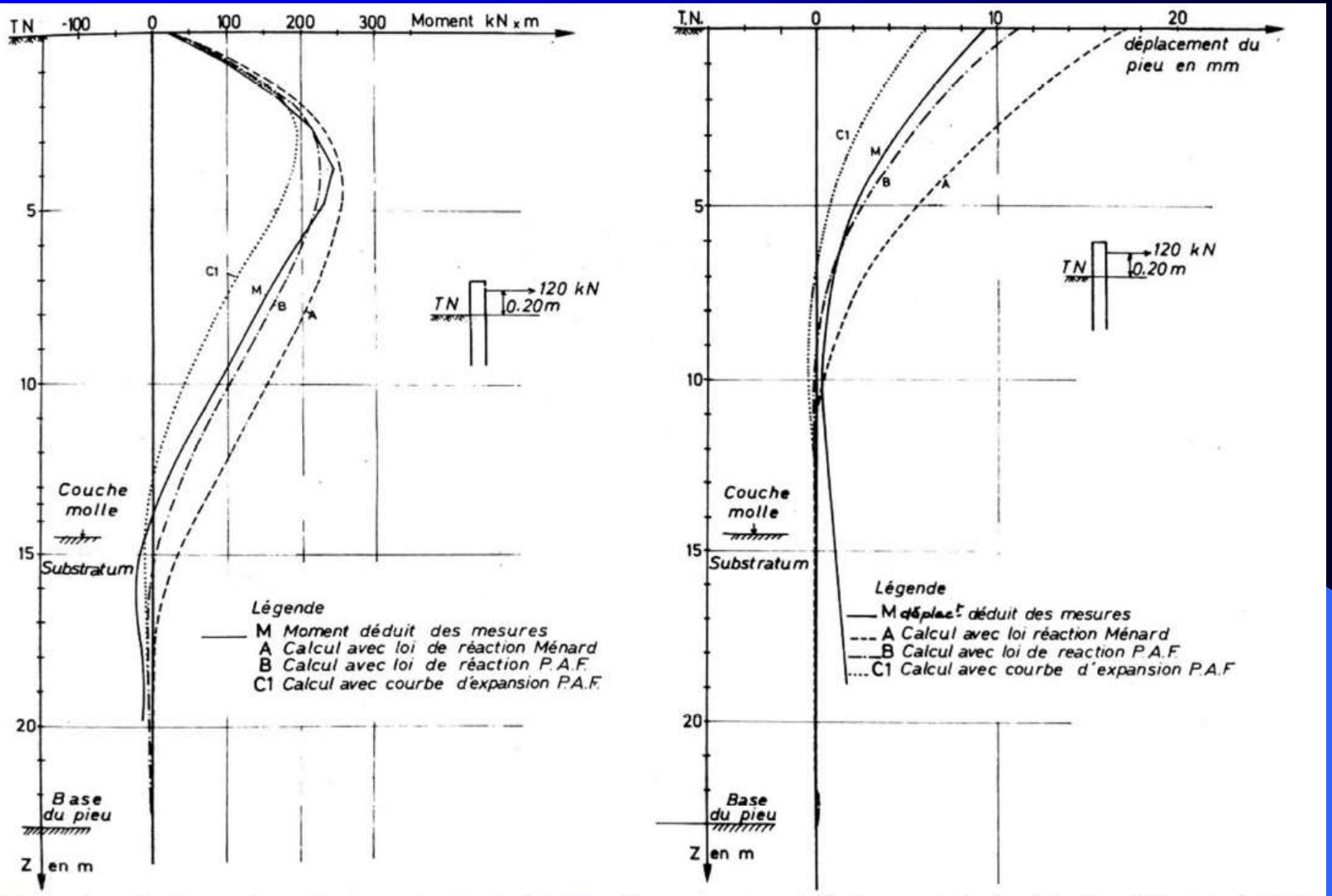


Figure 12 Provins pile. Comparison of measured and calculated bending moments and displacements for head loading (Bigot et al. 1982).

- method A, MPM reaction curves : $E_{sM} = k_s\ B = 2900$ kPa
- method C1, PAF reaction curves : $E_{sM} = k_s\ B = 11700$ kPa

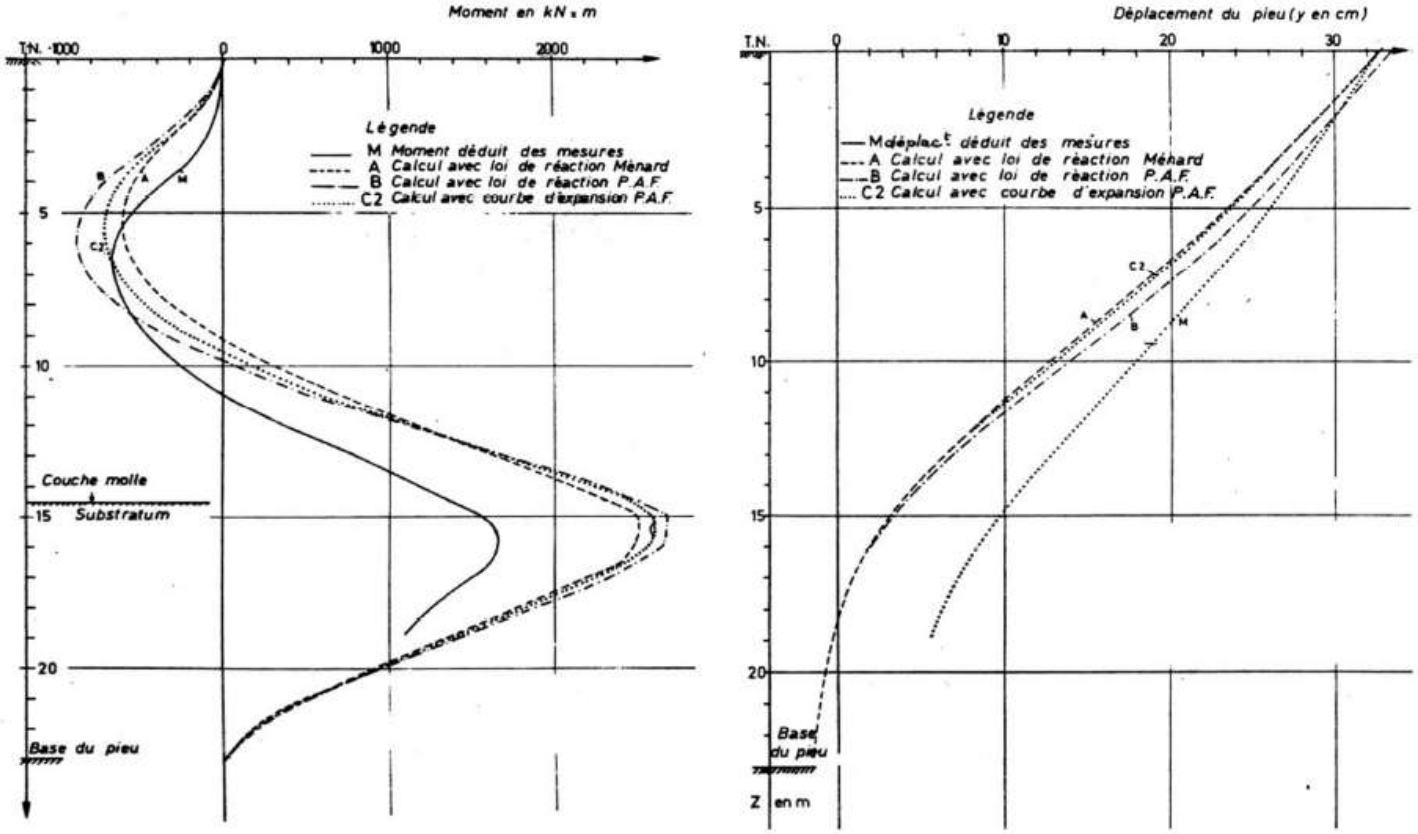


Figure 13 Provins pile. Comparison of measured and calculated bending moments and displacements after 3 months of consolidation under final height of embankment (Bigot et al. 1982)

- method A, MPM reaction curves : $E_{sM} = k_s B = 2900$ kPa
- method C2, PAF reaction curves : $E_{sM} = k_s B = 5850$ kPa

Frank R., Pouget P. (2008) "Experimental pile subjected to long duration thrusts due to a moving slope", Géotechnique 58, No. 8, October, London, pp. 645-658.

George Stephenson Medal, ICE, 2009

The experiment of Sallèdes

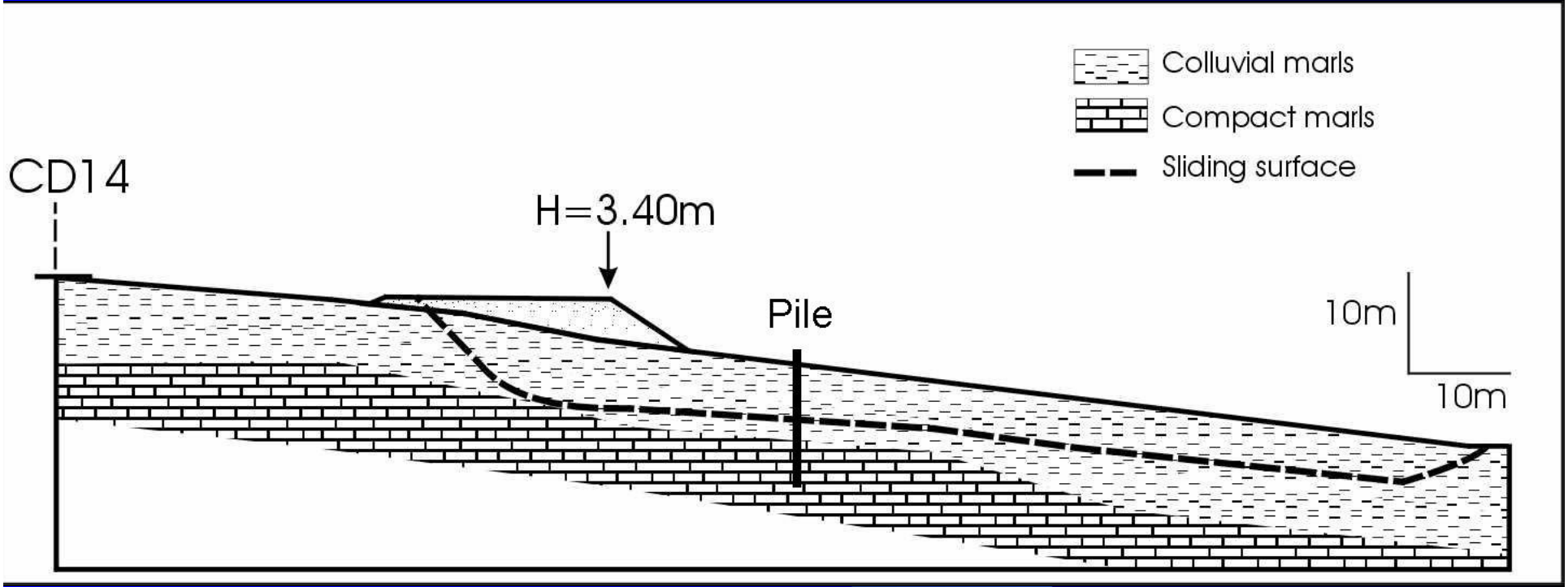


Table 1. Colluvial marls: main identification and shear strength properties

γ: kN/m^3	w: %	I_p: %	w_L: %	% < 2 μ	$CaCO_3$: %	c': kPa	φ': °
16 to 18	30 to 55	35 to 57	55 to 85	45 to 65	18 to 55	10–20	21–28

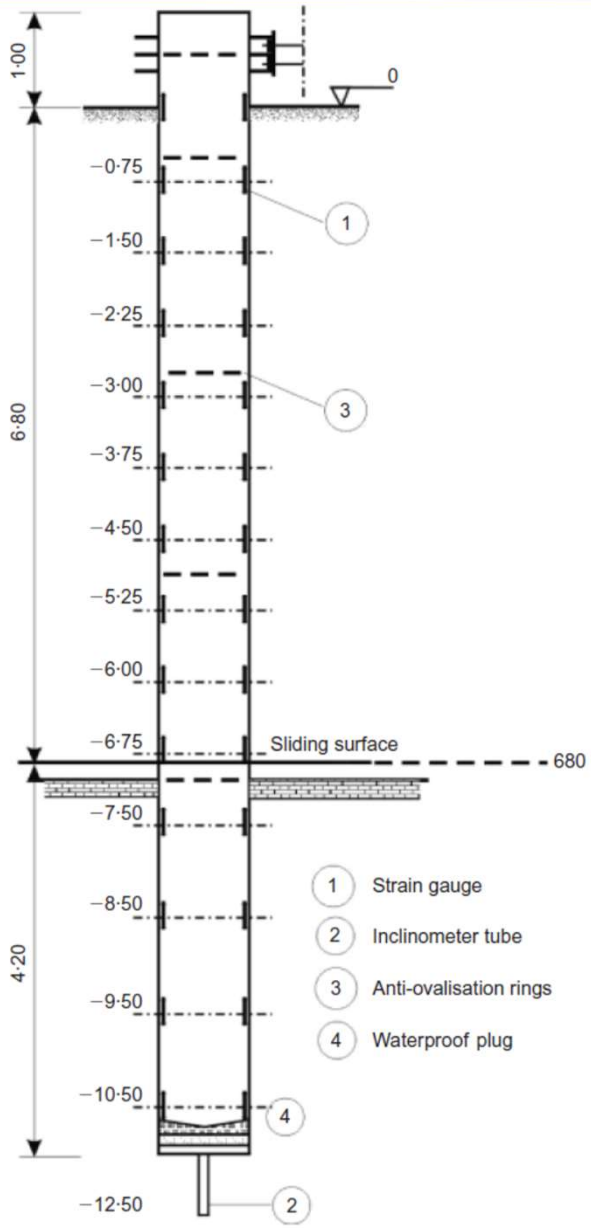
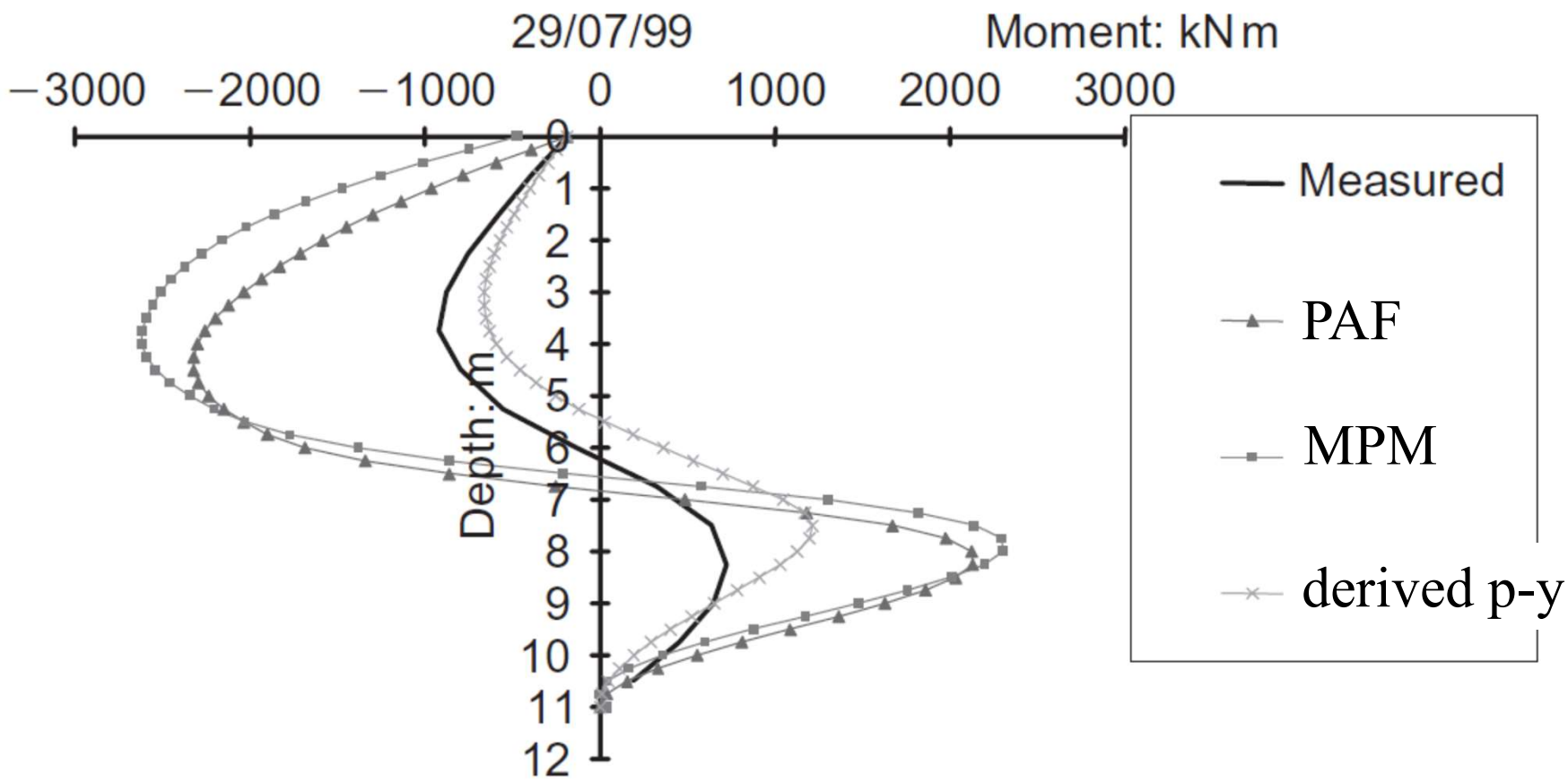


Fig. 9. Pile instrumentation

The experiment of Sallèdes



Bending moment measurements of 29 July 1999

Introduction (MPM and PAF)

1. Axial displacements (settlements)
   - 1.1 t-z curves from MPM results and examples
   - 1.2 t-z curves from PAF results
     - 1.2.1 Theoretical background
     - 1.2.2 Examples

2. Lateral displacements
   - 2.1 p-y curves from MPM results
   - 2.2 p-y curves from PAF results: theoretical background
   - 2.3 Examples

3. Behaviour of « barrettes »

Conclusions

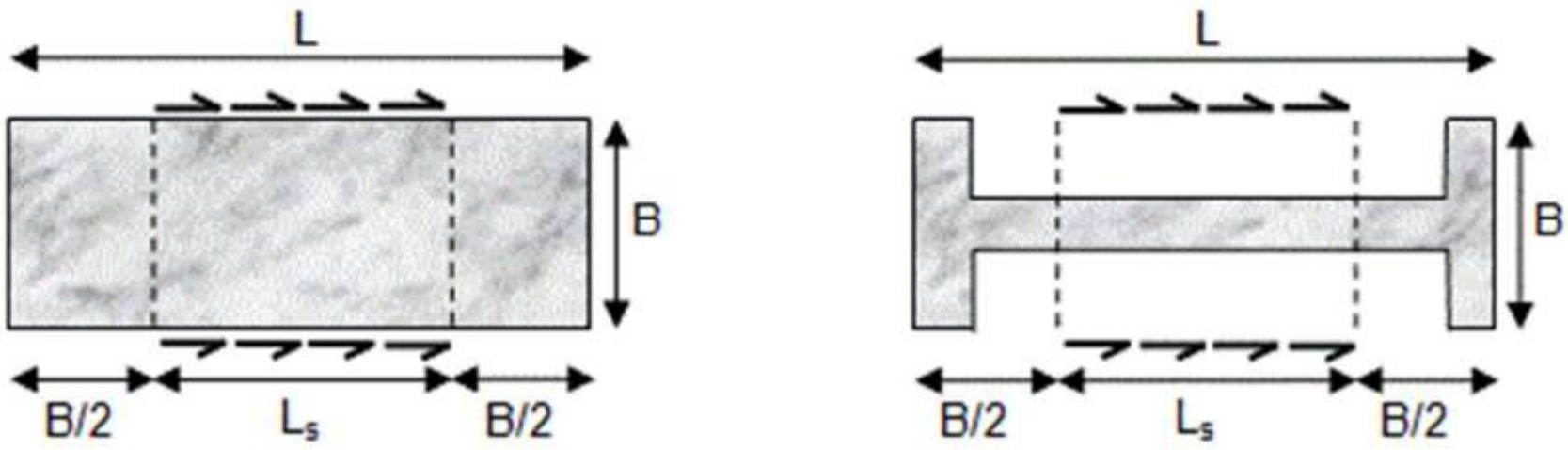


Figure 20 Design lengths for the reaction curves of "barrettes" (MELT, 1993, AFNOR, 2012)

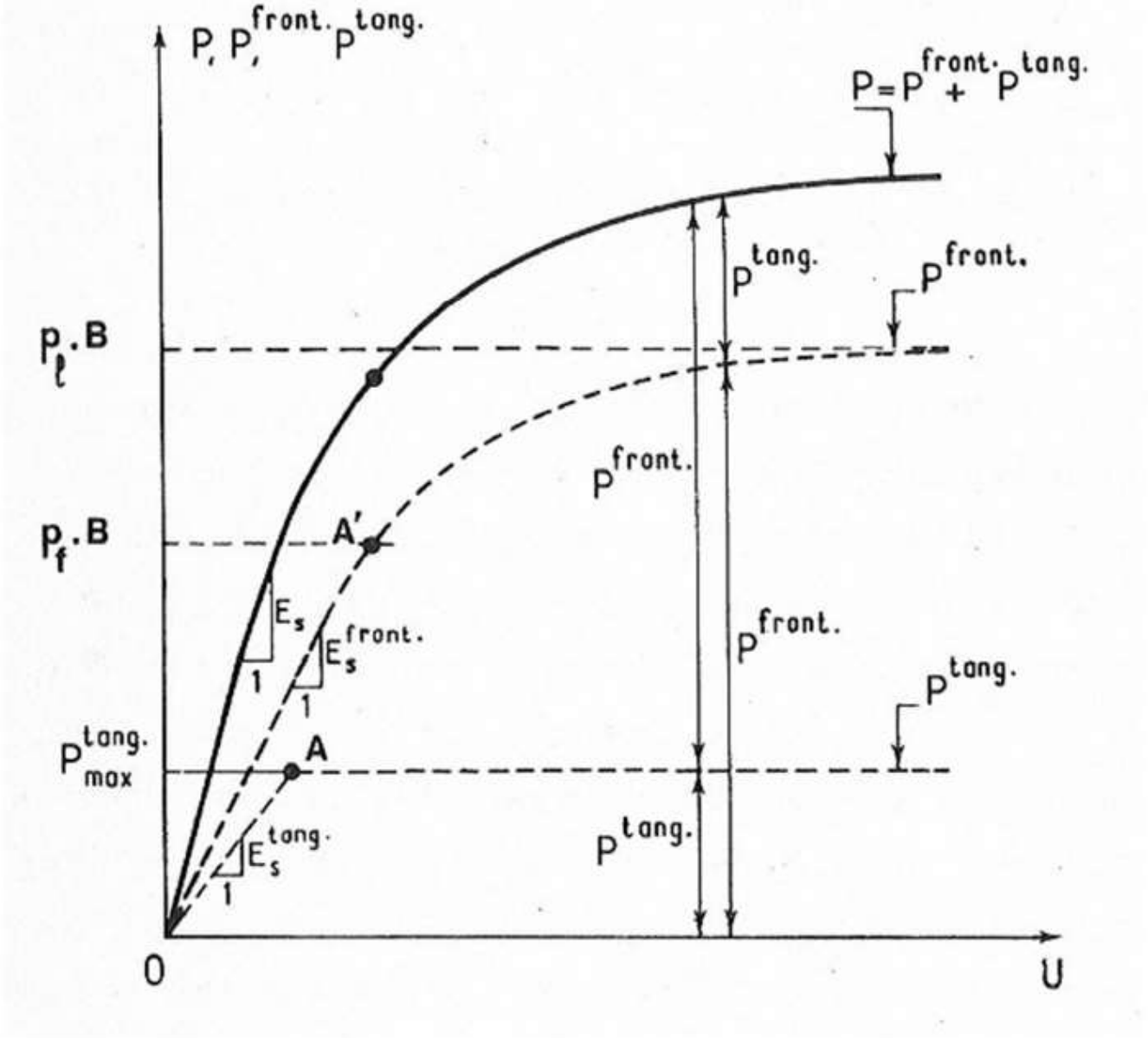


Figure 21 Lateral reaction curves for the design of "barrettes"

Introduction (MPM and PAF)

1. Axial displacements (settlements)
   - 1.1 t-z curves from MPM results and examples
   - 1.2 t-z curves from PAF results
     - 1.2.1 Theoretical background
     - 1.2.2 Examples

2. Lateral displacements
   - 2.1 p-y curves from MPM results
   - 2.2 p-y curves from PAF results: theoretical background
   - 2.3 Examples

3. Behaviour of « barrettes »

Conclusions

- MPM and PAF allow deformation parameters to be measured in situ
- a clear distinction should be made between the moduli obtained
- t-z and p-y curves can be assessed for the prediction of pile movements, including when there are soil lateral thrusts (and/or axial negative friction)
- the determination of the MPM curves is mainly empirical (full scale tests are used)
- the determination of the PAF curves is based on theoretical studies in linear isotropic elasticity
- short and long durations are/should be taken into account
- the theoretical studies help validating the approach
- the more full scale data are available, the better…!

Thank you for your attention !

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École des Ponts ParisTech

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