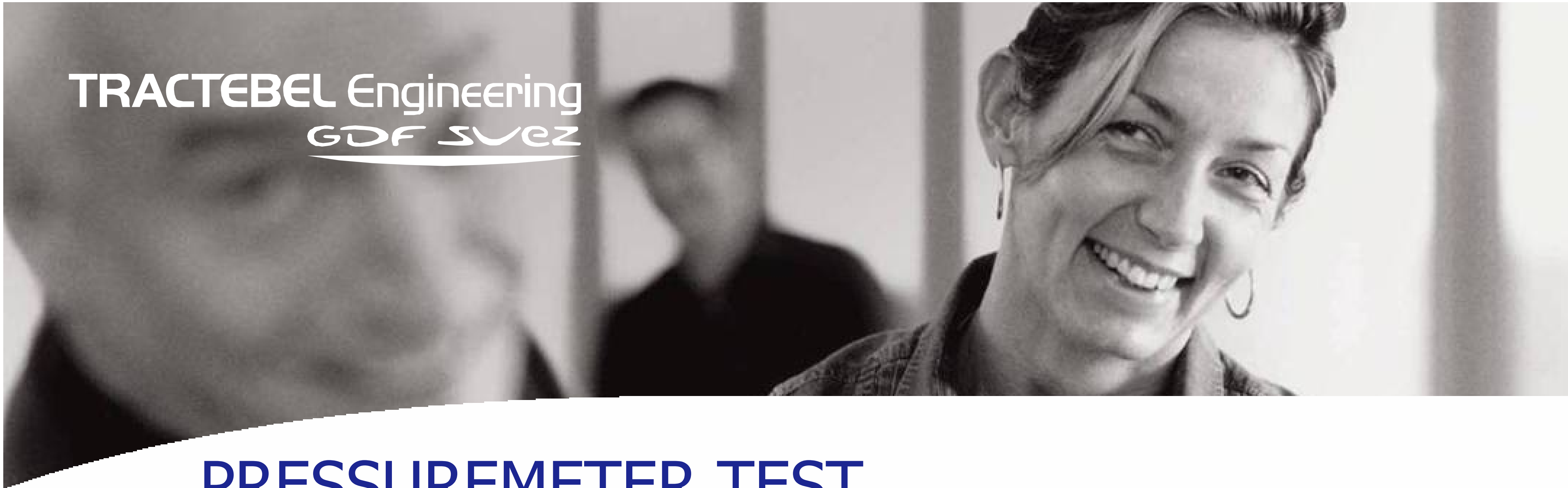

PRESSUREMETER TEST

Study case: Leuze-en-Hainaut wind farm wind turbines 9 & 10

Presentation for SBGIMR / BVGIRM

CHOOSE EXPERTS, FIND PARTNERS

P. Debauche & A. Roth

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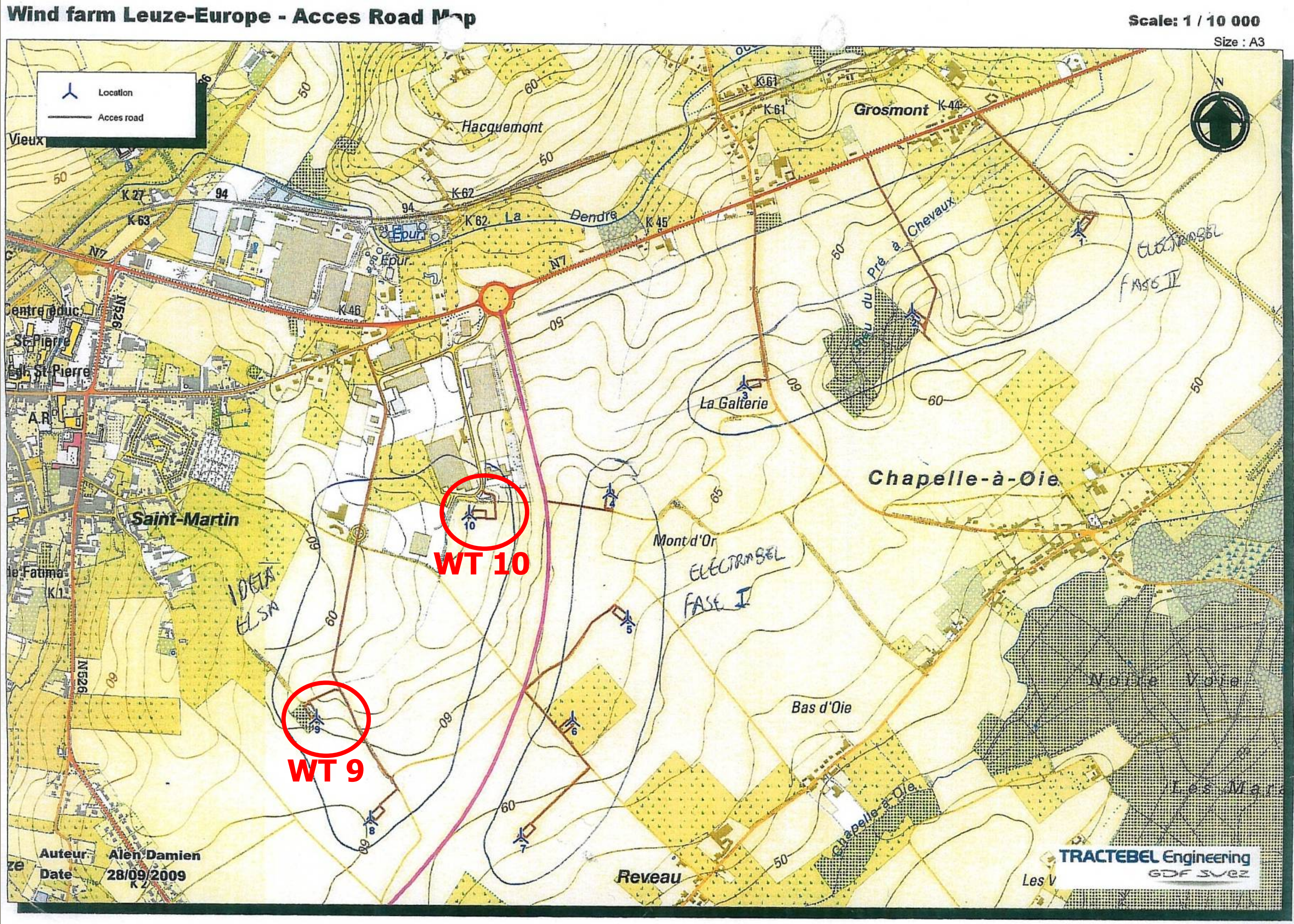
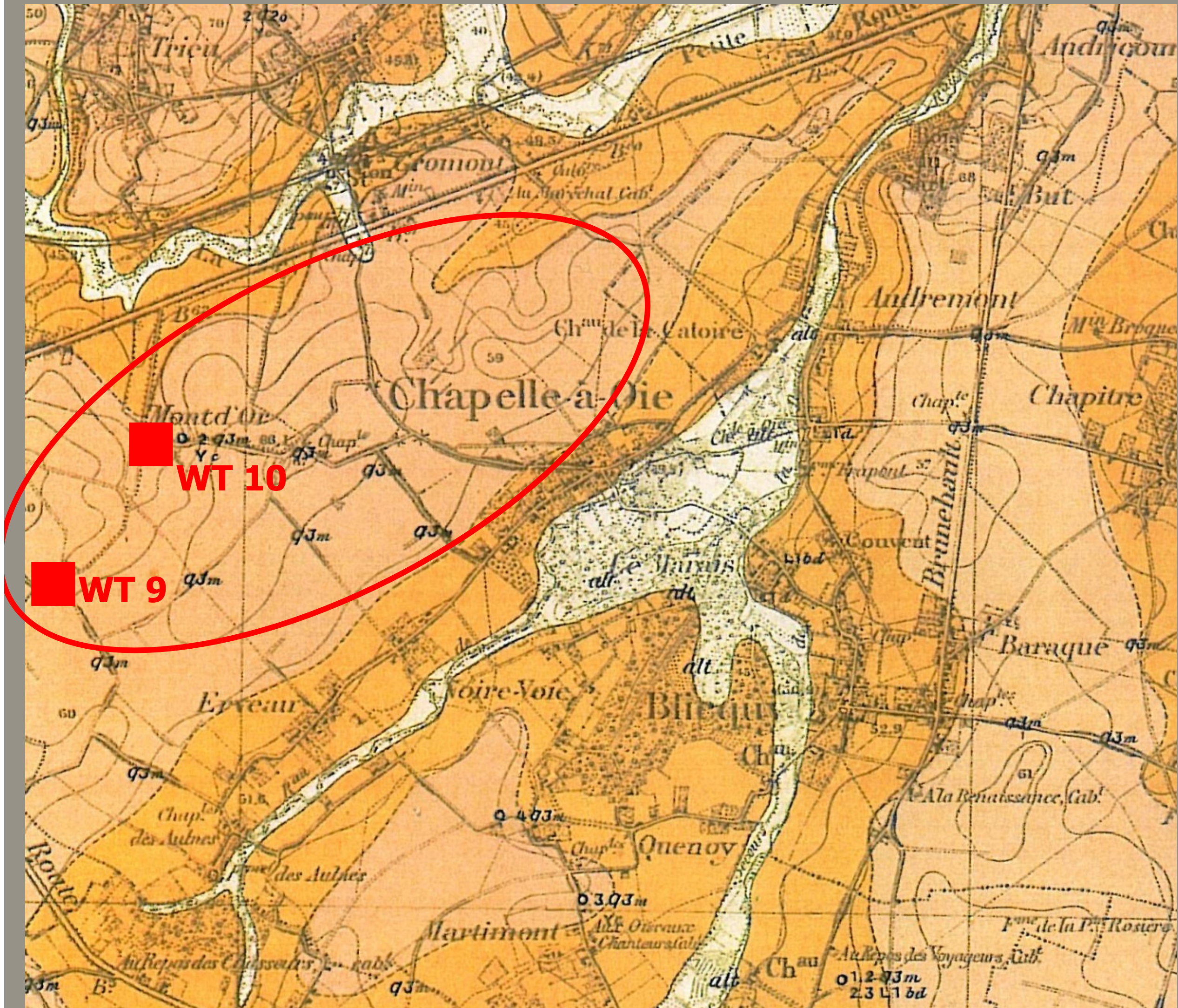
LEUZE-EN-HAINAUT WIND FARM LAYOUT



GEOLOGICAL MAP OF LEUZE-EN-HAINAUT



Groupe quaternaire : Hesbayen
q3m - limons brunâtres

Groupe tertiaire : Etage Yprésien
Yc – Argile sableuse ou plastique + septaria

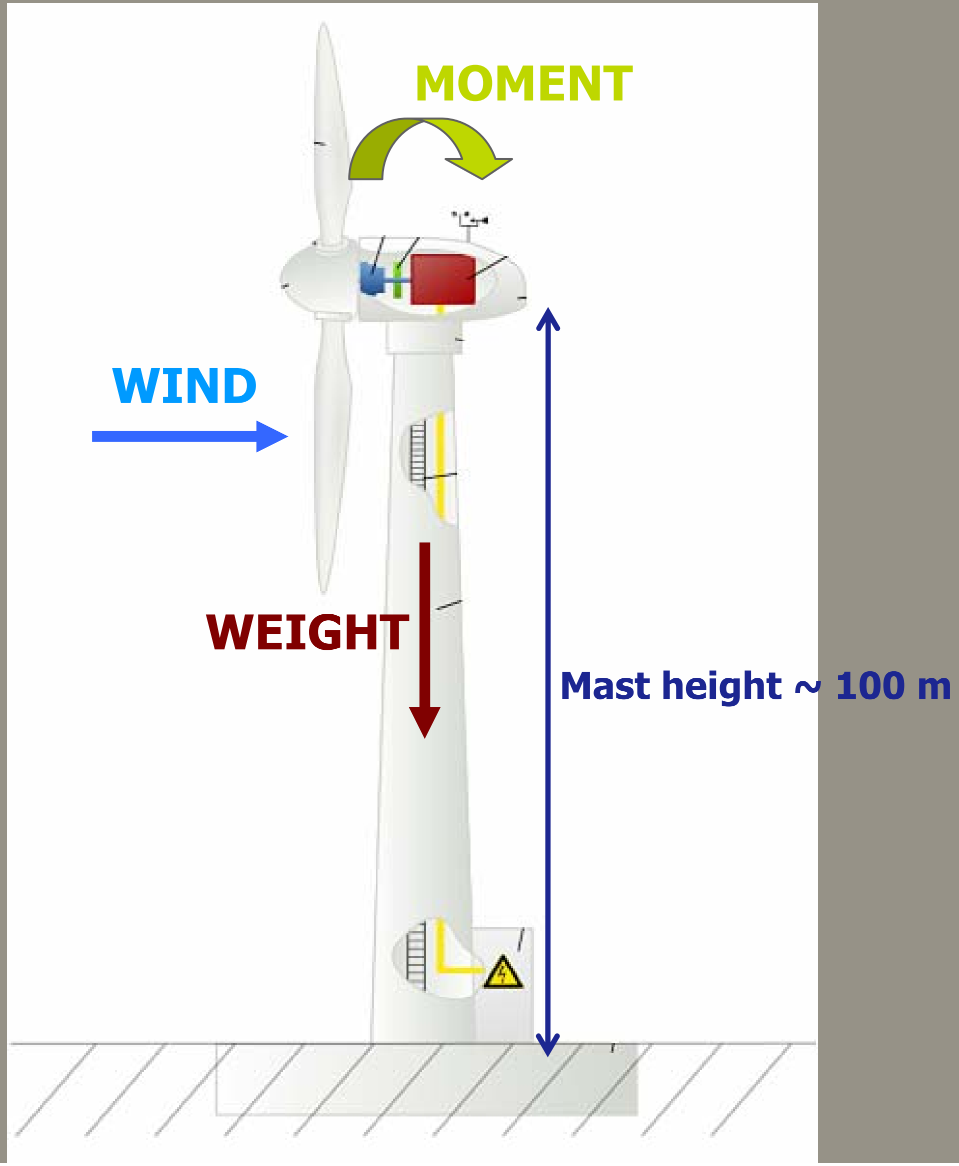
Groupe primaire : Etage Viséen
V1a – Calcaire noir et bleu foncé

ROLE OF WIND TURBINE FOUNDATION

Resist forces (vertical, horizontal and moment) and transmit them to competent bearing soil layers in depth (shallow or deep).

Sollicitations :

- **Wind**
- **Weight**
- **Seismic**

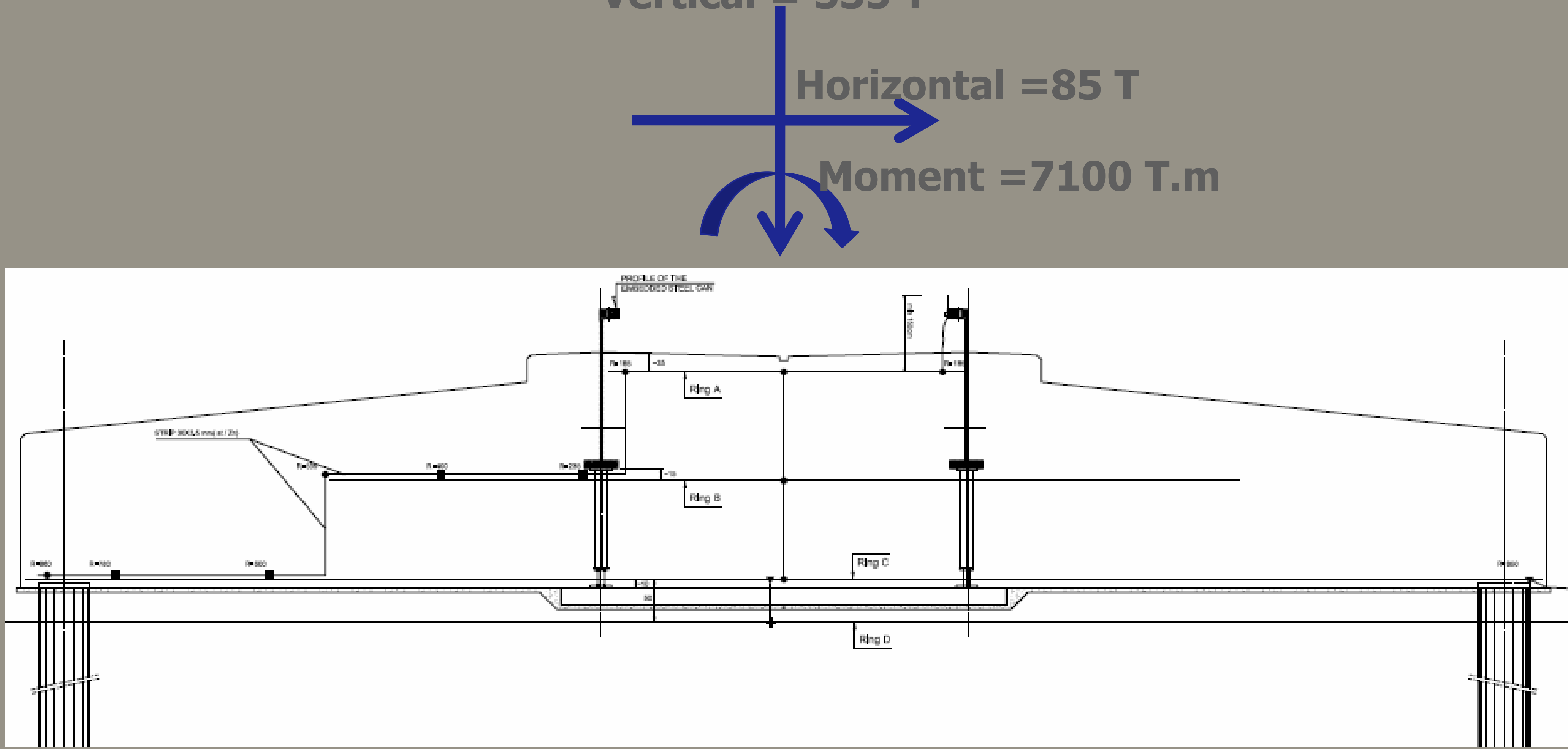


FORCES APPLIED ON FOUNDATION SLAB (SLS)

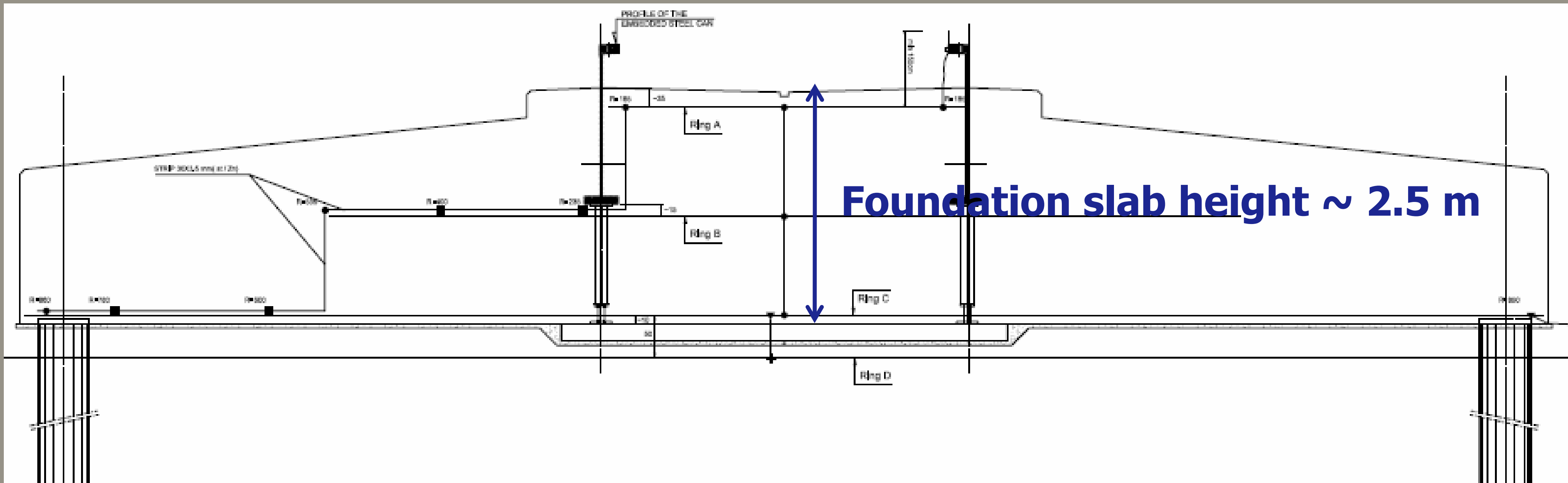
Vertical = 335 T

Horizontal =85 T

Moment =7100 T.m



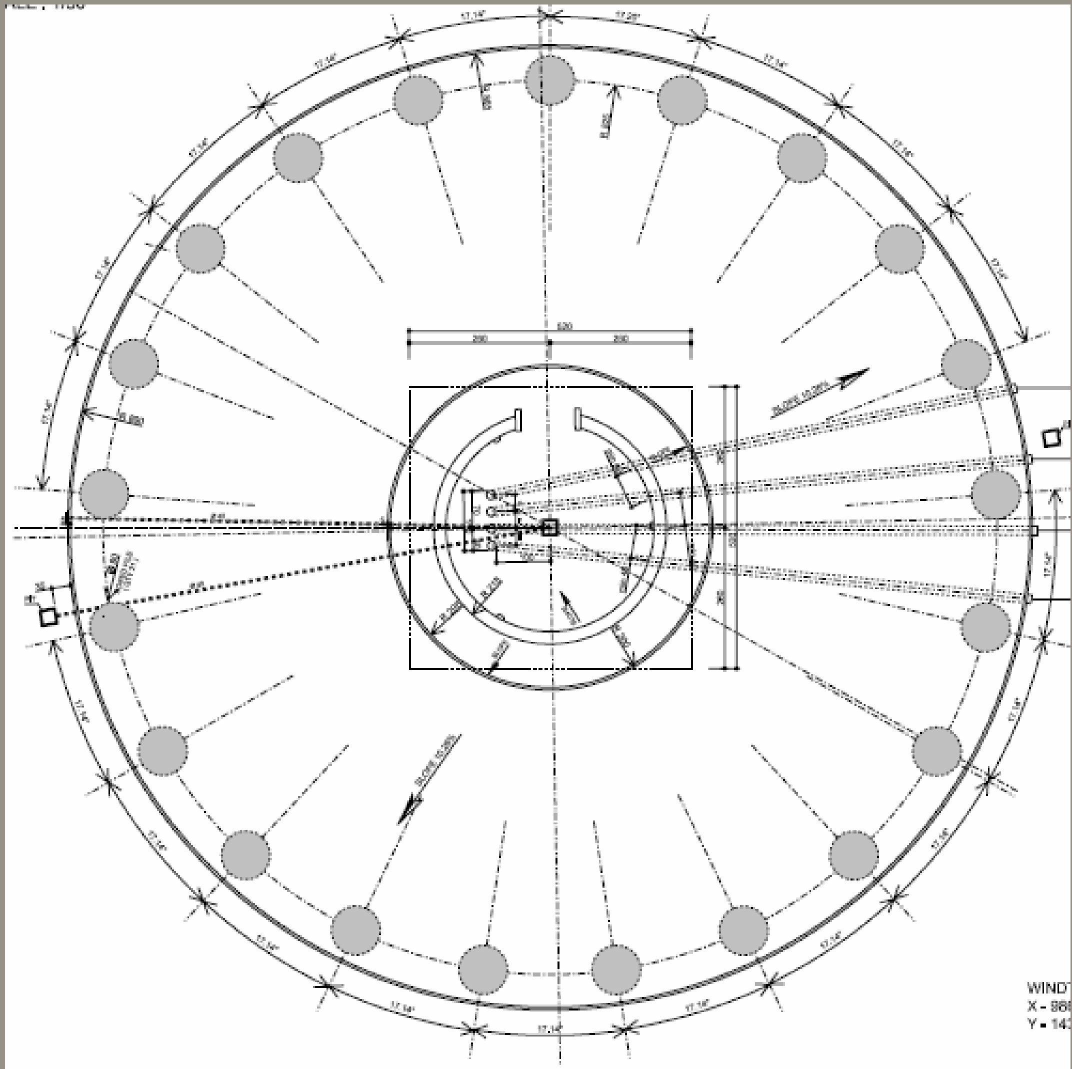
WIND TURBINE FOUNDATION LAYOUT (1)



Foundation slab diameter ~ 18 m

Foundation slab weight ~ 1300 tons

WIND TURBINE FOUNDATION LAYOUT (2)



Number of piles/WT: from 15 to 35

Piles diameter: from 50 to 100 cm

Piles length: from 10 to 25 m

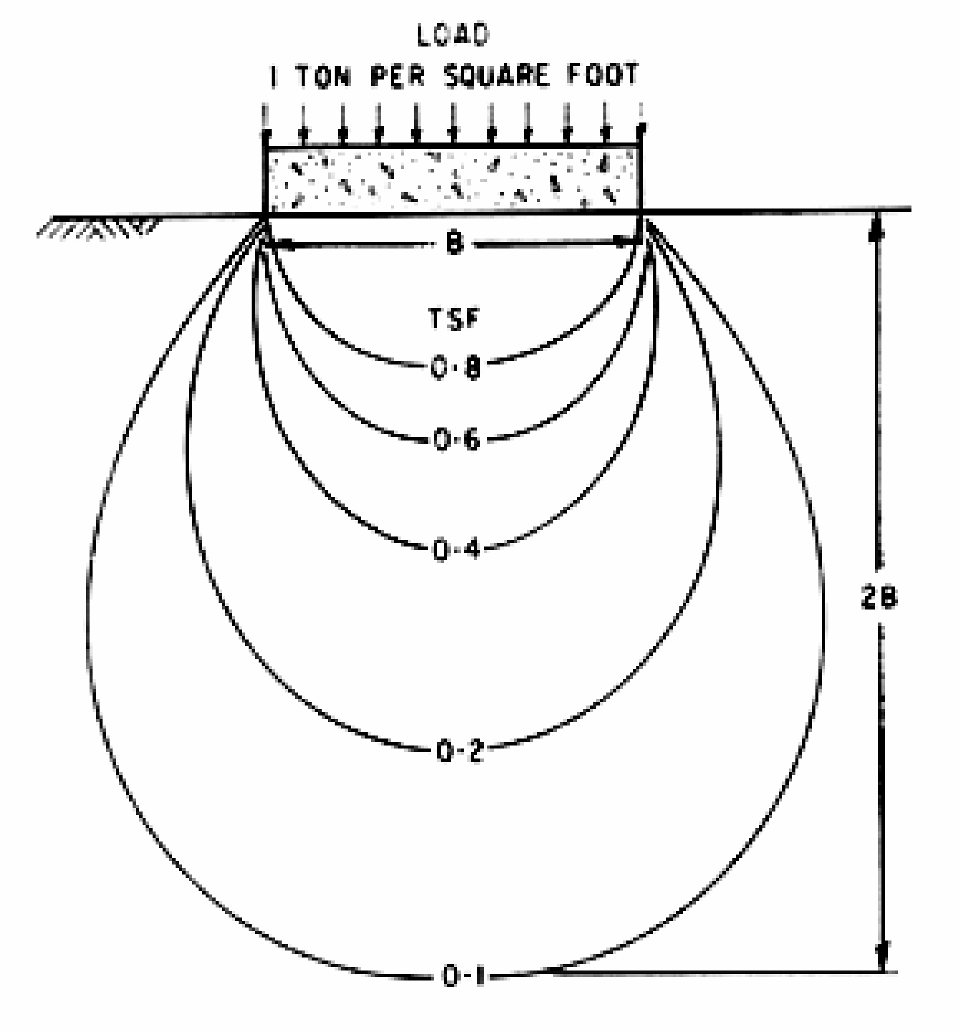
Factorized design loads per pile:

WT 9 & 10: 21 piles

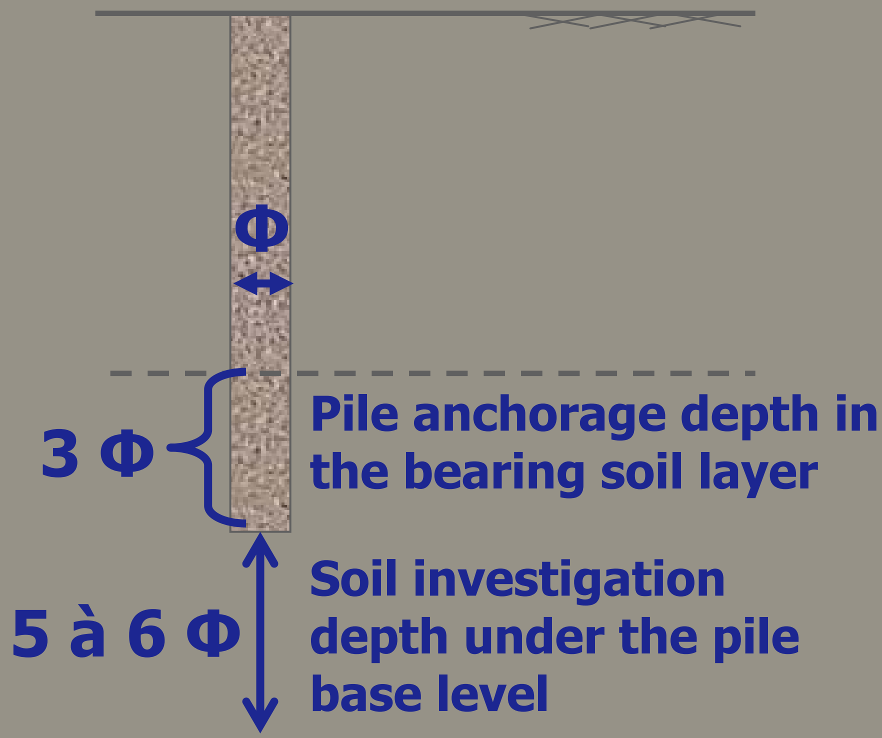
	SLS	ULS
Compression [T]	170	240
Traction [T]	50	100
Horizontal [T]	8	12

REQUIRED SOIL INVESTIGATION DEPTH

Superficial foundation



Deep foundation - piles



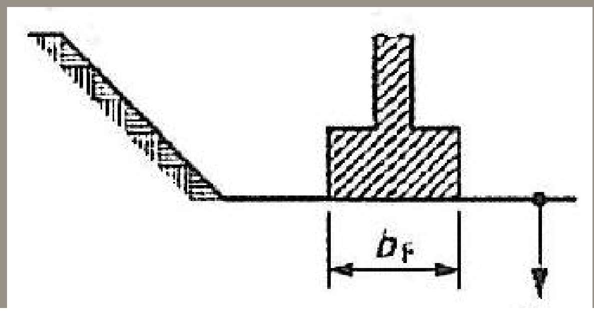
RECOMMENDATIONS FOR THE SPACING AND DEPTH OF INVESTIGATIONS BASED ON E.C. 7

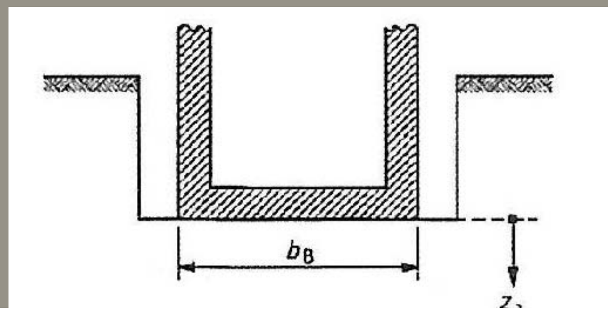
Spacing

- **For high-rise & industrial structures : grid pattern with points at 15 m to 40 m distance;**
- **For special structures (e.g. machinery foundations, etc) : 2 to 6 investigation points per foundation.**

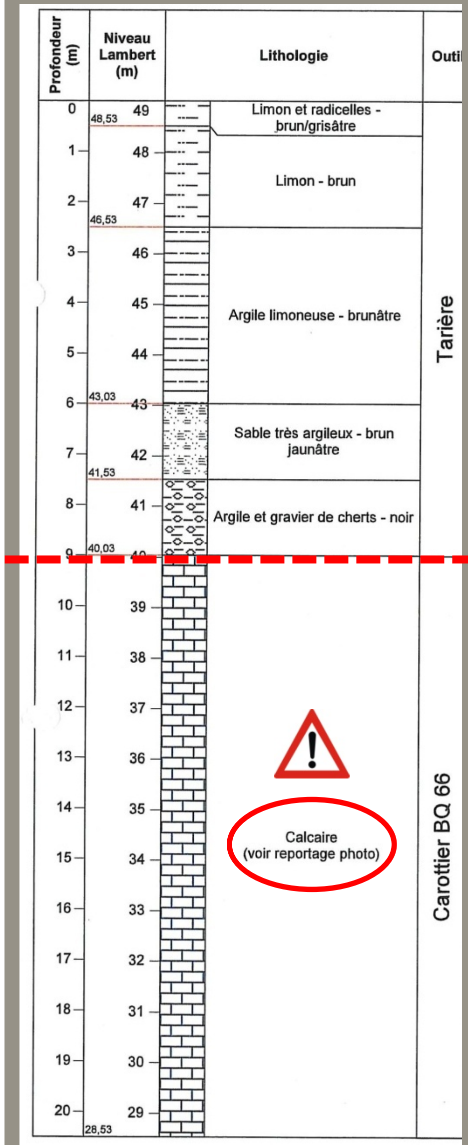
Depth

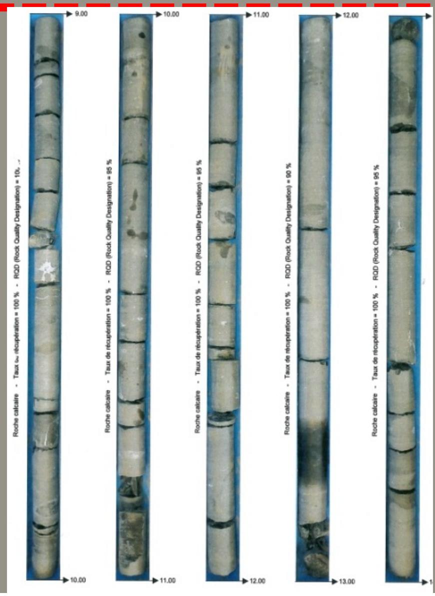
- **For high-rise structures : investigation depth ≥ 3*bf ;**
- **For raft foundations with several foundation elements whose effects in deeper strata are superimposed on each other : investigation depth ≥ 1.5*bB.**

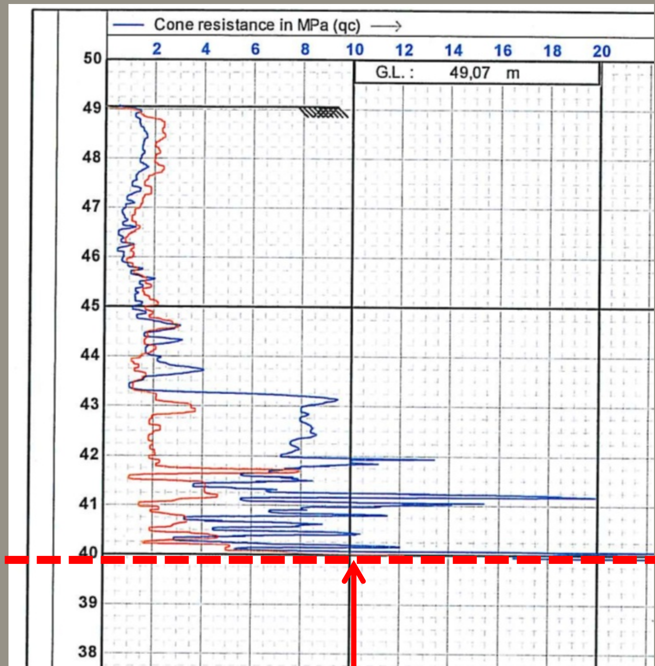


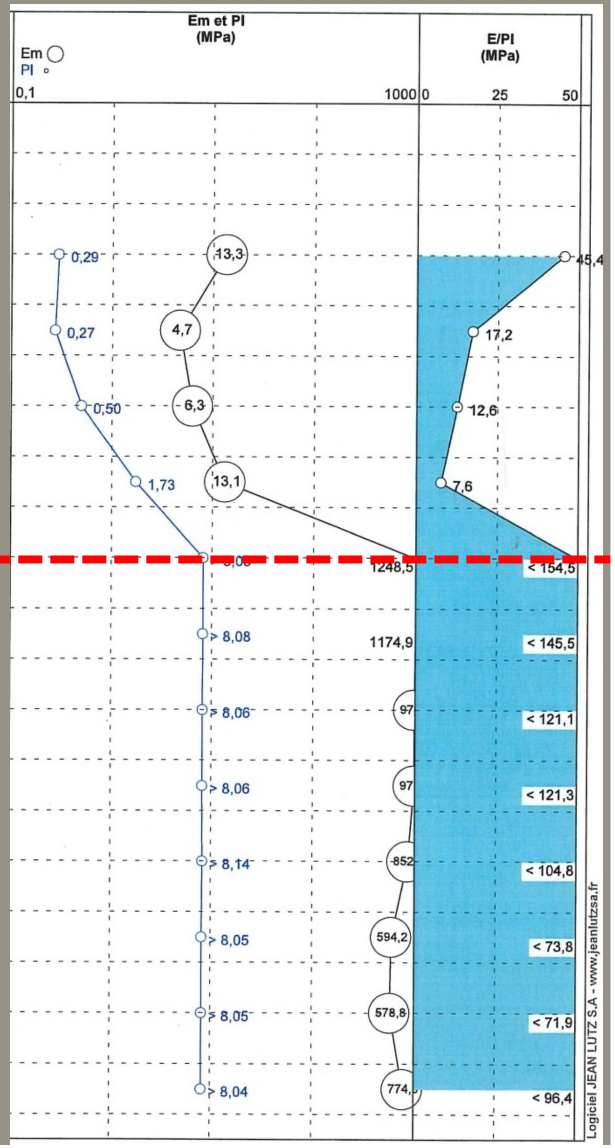


GEOTECHNICAL SOIL INVESTIGATION (WT 10)









NO DATA WITH CPT

PILE DESIGN BASED ON PRESSUREMETER (1)

The limit pile load Qu is obtained by additing the limit pile base load Q_{pu} with the limit friction load Q_{su}:

$$Q_u = Q_{pu} + Q_{su} \quad [kN]$$

Where $Q_{pu} = \rho_p . A . q_{pu} \quad [kN]$

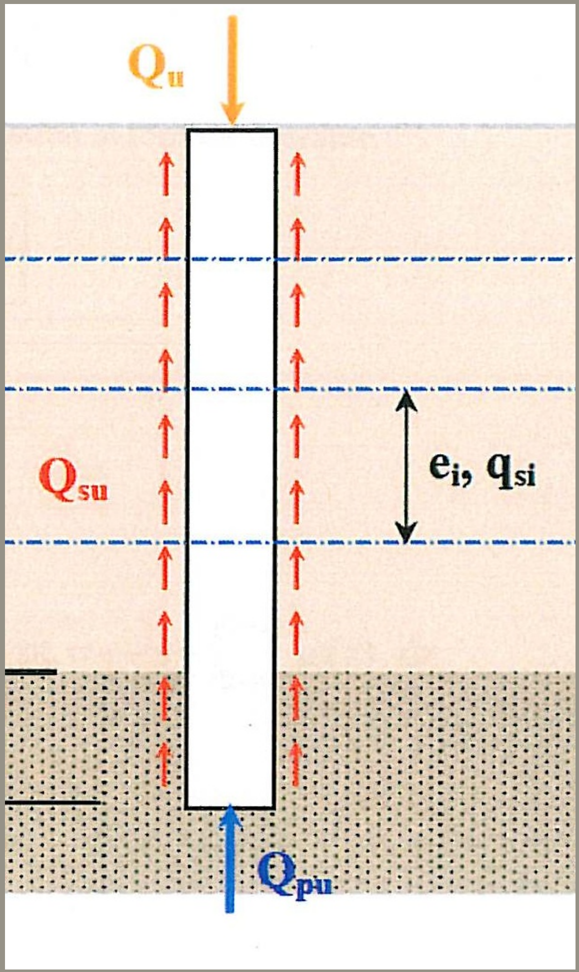
With

- ρ_p **: the reducing area factor for the pile base force;**
- **A : the pile base area;**
- q_{pu} **: the limit pile base strength.**

Where $Q_{su} = \rho_s . P . \sum q_{si} . e_i \quad [kN]$

With

- ρ_s **: the reducing area factor for the lateral friction force;**
- **P : the pile base perimeter;**
- q_{si} **: the limit unit lateral friction in the soil layer i;**
- e_i **: the soil layer i thickness.**



PILE DESIGN BASED ON PRESSUREMETER (2)

Limit base pressure q_{pu}

According to fascicule 62 – titre V, the limit base stress is provided by the formula

$$q_{pu} = k_p . p_{le}^* \quad [kN/m^2]$$

where k_p is the bearing factor depending on soil nature and pile type (see table here below)

Nature des terrains		Eléments mis en oeuvre sans refoulement du sol	Eléments mis en oeuvre avec refoulement du sol
ARGILES – LIMONS	A	1,1	1,4
	B	1,2	1,5
	C	1,3	1,6
SABLES – GRAVES	A	1,0	4,2
	B	1,1	3,7
	C	1,2	3,2
CRAIES	A	1,1	1,6
	B	1,4	2,2
	C	1,8	2,6
MARNES, MARNO–CALCAIRES		1,8	2,6
ROCHES ALTEREES (1)		1,1 à 1,8	1,8 à 3,2

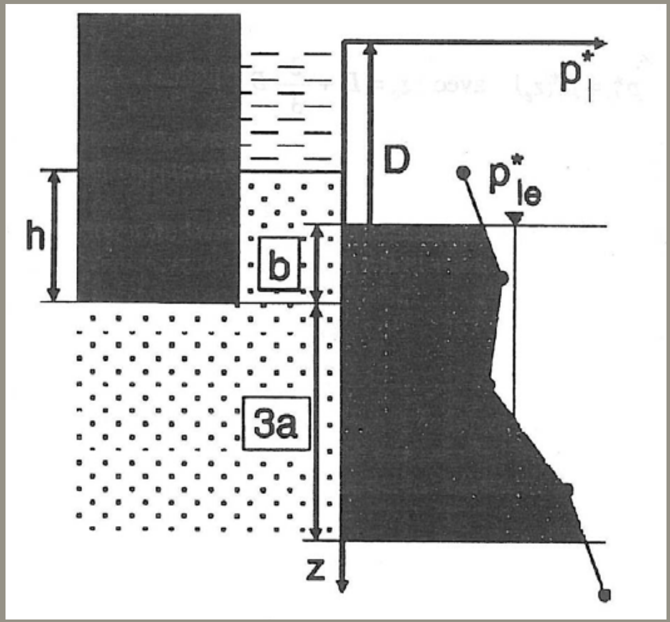
(1) La valeur de k_p pour ces formations est prise égale à celle de la formation meuble du tableau à laquelle le matériau concerné s'apparente le plus.

PILE DESIGN BASED ON PRESSUREMETER (3)

P^*_{le} is the soil equivalent net limit pressure under the pile base

$$p^*_{le} = \frac{1}{b+3a}\int_{D-b}^{D+3a} p^*_l(z).dz$$

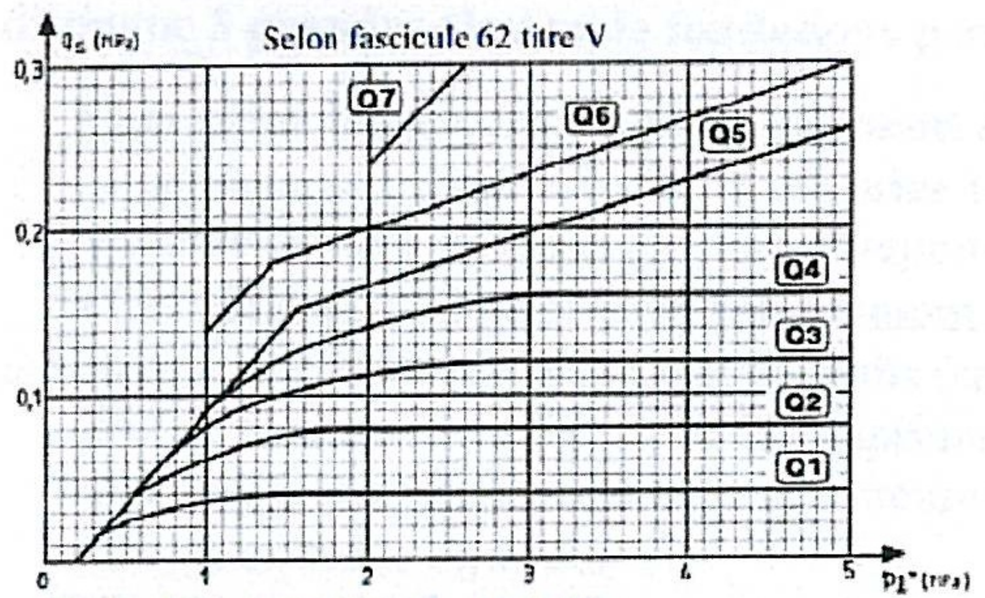
With a = max (B/2; 0.50 m)
b = min (a,h)
D = real pile anchorage depth
h = pile anchorage depth in the bearing soil layer



PILE DESIGN BASED ON PRESSUREMETER (4)

Lateral friction q_s

Based on fascicule 62 – titre V, the lateral friction q_s is a function of the limit net pressure p^*_l and the curve to consider depends on soil nature and pile type.



Courbes de frottement latéral - qs= f(pl*)

	ARGILES – LIMONS			SABLES – GRAVES			CRAIES			MARNES		ROCHES
	A	B	C	A	B	C	A	B	C	A	B	
Foré simple	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
Foré boue	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
Foré tubé (tube récupéré)	Q_1	Q_1, Q_2 (3)		Q_1	Q_2, Q_1 (2)	Q_3, Q_2 (2)	Q_1	Q_2	Q_3, Q_4 (3)	Q_3	Q_4	–
Foré tubé (tube perdu)	Q_1			Q_1		Q_2	(4)			Q_2	Q_3	–
Puits (5)	Q_1	Q_2	Q_3	–			Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
Métal battu fermé	Q_1	Q_2		Q_2		Q_3	(4)			Q_3	Q_4	Q_4
Battu préfabriqué béton	Q_1	Q_2		Q_3			(4)			Q_3	Q_4	Q_4
Battu moulé	Q_1	Q_2		Q_2		Q_3	Q_1	Q_2	Q_3	Q_3	Q_4	–
Battu enrobé	Q_1	Q_2		Q_3		Q_4	(4)			Q_3	Q_4	–
Injecté basse pression	Q_1	Q_2		Q_3			Q_2	Q_3	Q_4	Q_5		–
Injecté haute pression (6)	–	Q_4	Q_5	Q_5		Q_6	–	Q_5	Q_6	Q_6		Q_7 (7)

(1) Réalésage et rainurage en fin de forage.
(2) Pieux de grande longueur (supérieure à 30 m)
(3) Forage à sec, tube non louvoyé.
(4) Dans le cas des craies, le frottement latéral peut être très faible pour certains types de pieux. Il convient d'effectuer une étude spécifique dans chaque cas.
(5) Sans tubage ni virole foncés perdus (parois rugueuses).
(6) Injection sélective et répétitive à faible débit.
(7) Injection sélective et répétitive à faible débit et traitement préalable des massifs fissurés ou fracturés avec obturation des cavités.

Choix de la courbe de frottement latéral

PILE DESIGN BASED ON PRESSUREMETER (5)

In order to calculate the bearing capacity of a deep foundation, the limit values for the pile base strength Q_{pu} and the lateral friction Q_{su} have to be multiplied by the following reducing factors, depending on the limit state considered:

	Serviceability Limit State (SLS)	Ultimate Limit State (ULS)
Pile base strength Q_{pu}	0.33	0.3
Lateral friction Q_{su}	0.5	0.75

PILE DESIGN BASED ON PRESSUREMETER (6)

The soil horizontal stiffness K_h is provided by the following formula based on the Menard modulus E_M measured with the pressuremeter.

$$K_h = \frac{12.E_M}{\frac{4}{3}\frac{B_0}{B}\left(2{,}65.\frac{B}{B_0}\right)^{\alpha} + \alpha} \quad [T/m^3]$$ **(short term)**

With

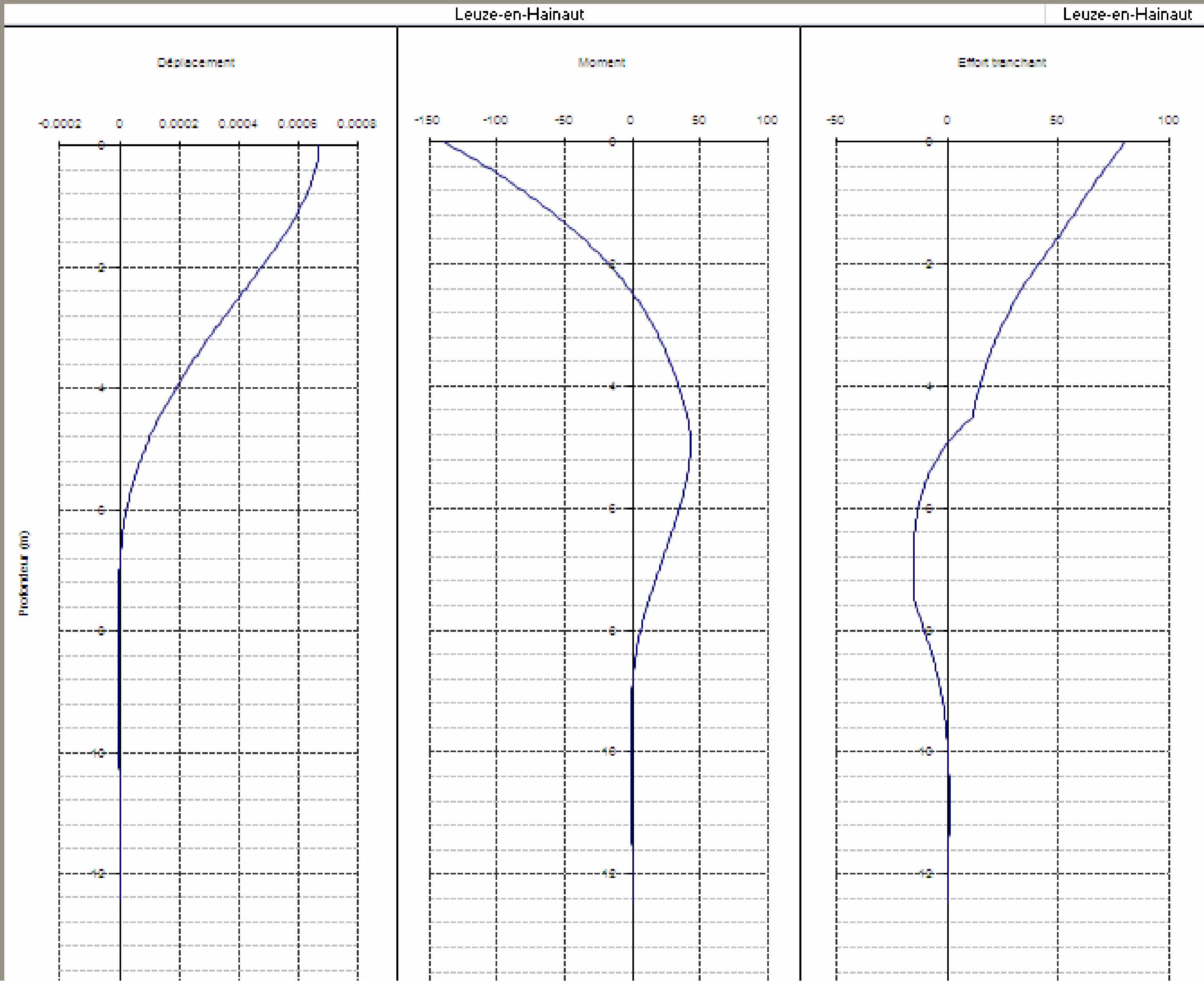
- **B_0 = 0.60 m;**
- **B : the pile base diameter [m]**
- **α: a coefficient depending on soil type.**

	Tourbe	Argile		Limon		Sable		Grave	
TYPE	α	E_M/p_l	α	E_M/p_l	α	E_M/p_l	α	E_M/p_l	α
Surconsolidé ou très serré	–	> 16	1	> 14	2/3	> 12	1/2	> 10	1/3
Normalement consolidé ou normalement serré	1	9-16	2/3	8-14	1/2	7-12	1/3	6-10	1/4
Sous-consolidé altéré et remanié ou lâche	–	7-9	1/2	5-8	1/2	5-7	1/3		–

PILE DESIGN BASED ON PRESSUREMETER (7)

The soil horizontal stiffness is calculated for different soil layers along the pile length and are introduced in the software Pilplamt in order to obtain the pile head displacement δ.

Based on this pile head displacement and on the horizontal force V applied on pile head, the pile horizontal stiffness is provided by the ratio $K_h = V/\delta$.


Leuze-en-Hainaut
Leuze-en-Hainaut
Déplacement
Moment
Effort tranchant
Profondeur (m)
-0.0002 0 0.0002 0.0004 0.0006 0.0008
-150 -100 -50 0 50 100
-50 0 50 100
0 2 4 6 8 10 12

PILE DESIGN BASED ON PRESSUREMETER (8)

The pile vertical stiffness K_v is provided by the following formula taking into account the vertical load applied on pile head N_c in SLS and the vertical pile head displacement δ_v.

$$K_v = \frac{N_c}{\delta_v} \quad [MN/m]$$

The following spring stiffness are taken into account to calculate the vertical pile head displacement:

- k_T is the lateral friction vertical stiffness [MN/m];
- k_q is the pile base vertical stiffness [MN/m];
- k_{pieu} is the pile vertical stiffness [MN/m].

The Fascicule 62 – titre V provides a method to calculate the vertical stiffness of piles based on lateral friction and cone resistance mobilization laws.

Considering bored piles and soil type at pile base, the friction and base vertical stiffness k_τ and k_q are provided by the following formula:

$$k_\tau = \frac{2E_M}{B} \quad \text{and} \quad k_q = \frac{11E_M}{B} \qquad [MN/m^3]$$

where

- E_M is the Menard's modulus [MN/m²];
- B is the pile diameter [m].

To obtain the calculated stiffness expressed in MN/m, k_T and k_q have to be respectively divided by the pile shaft area and the pile base area A.

The pile vertical stiffness k_{pieu} is obtained by the formula provided here-under:

$$k_{pieu} = \frac{EA}{L}$$

where

- E is the concrete Young's modulus = 17 000 MN/m² at long term;
- A is the pile base area [m²];
- L is the pile length [m].

THANKS FOR YOUR ATTENTION.