The foundation of the new sewage plant at le Havre
An alternative solution with a preloading embankment

F. Baguelin & Seng Y Ung (FONDASOL)
F. Gaillard & J.P. Commun (RAZEL)

Journée franco-britannique CFMS-BGA,
Paris, le 2 décembre 2011

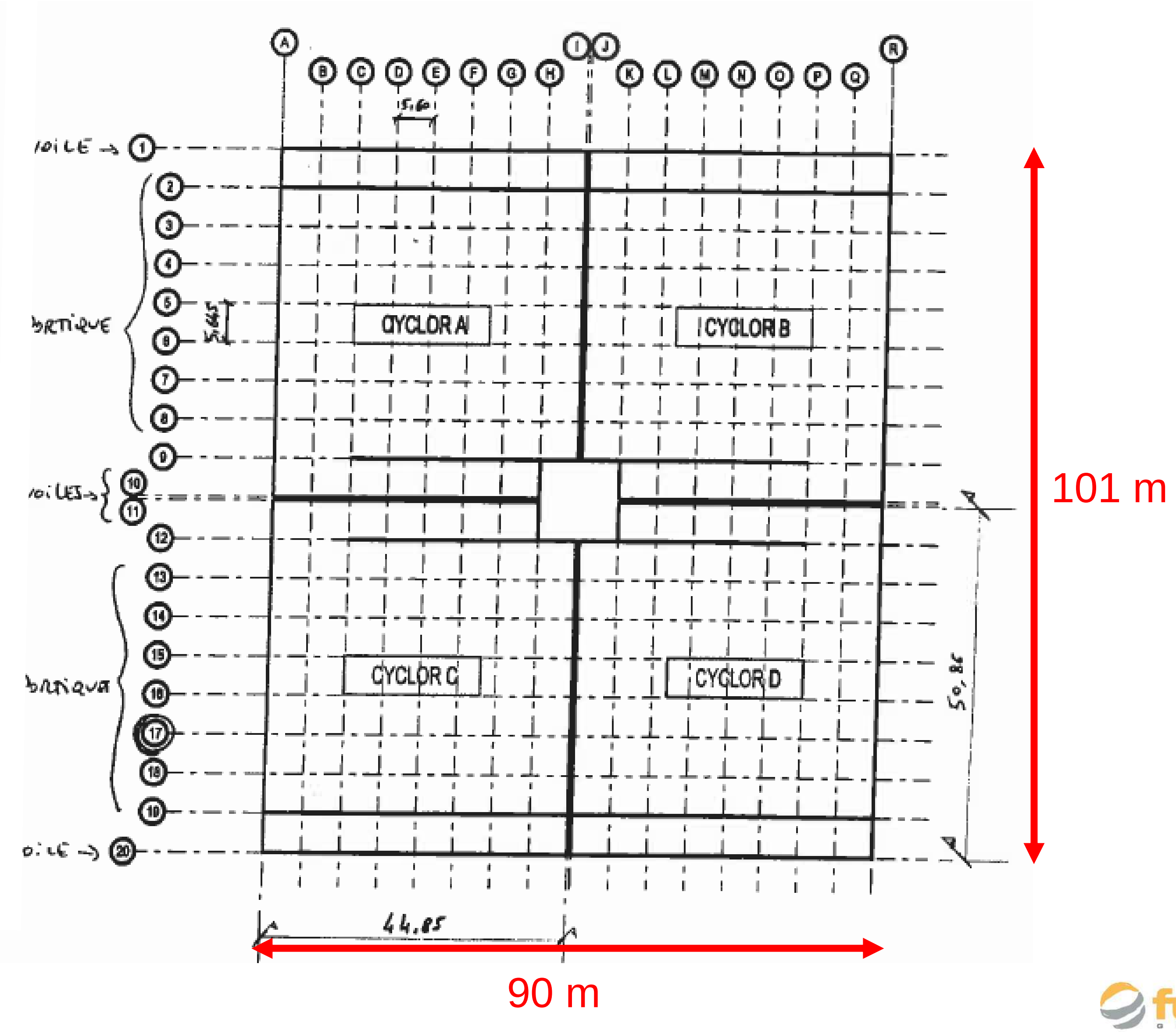
THE PLANT

2 superimposed tanks

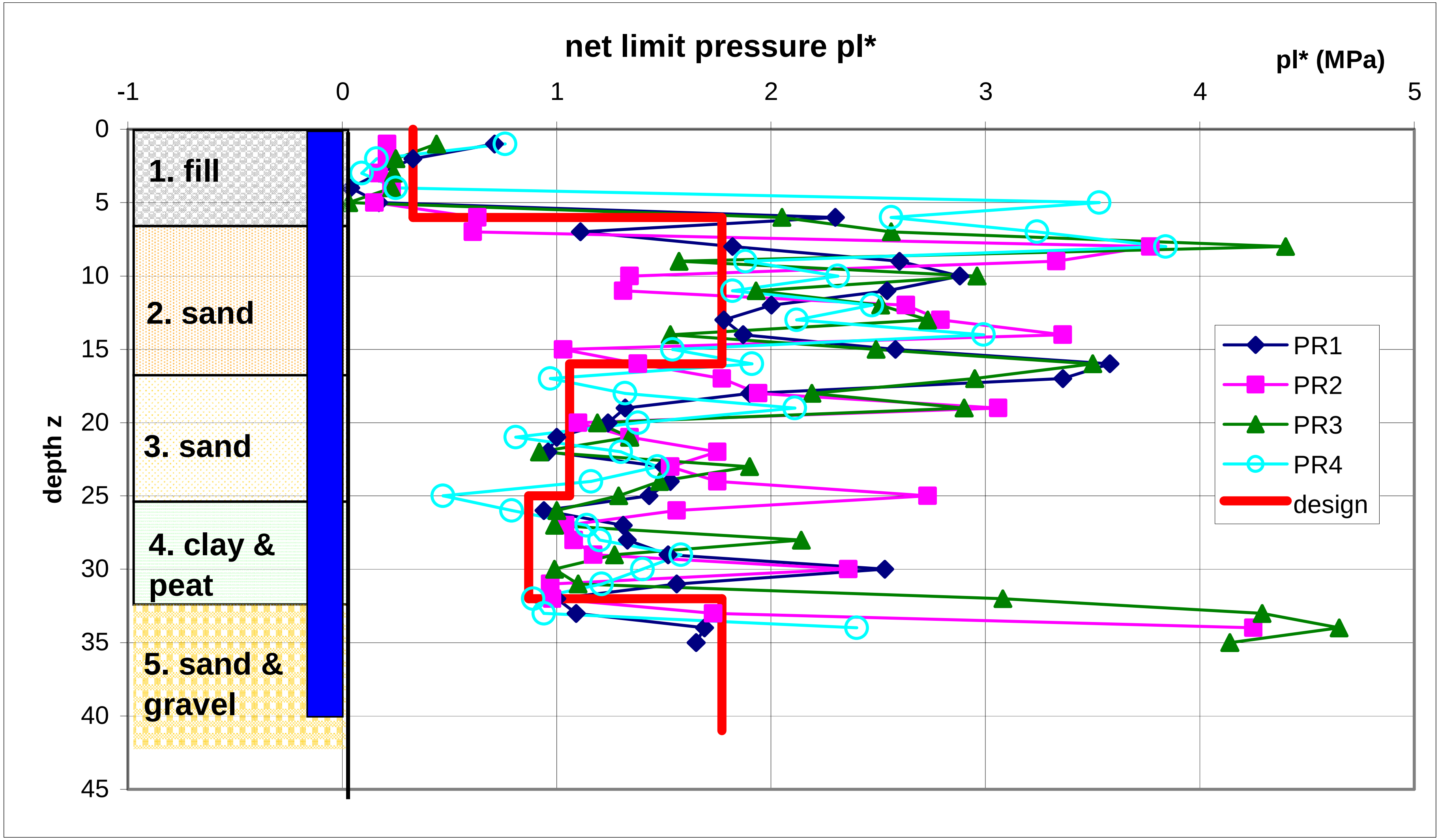
each : ~ square 100m x 100m

6,6m of water

The 4 units : cyclors A, B, C, D



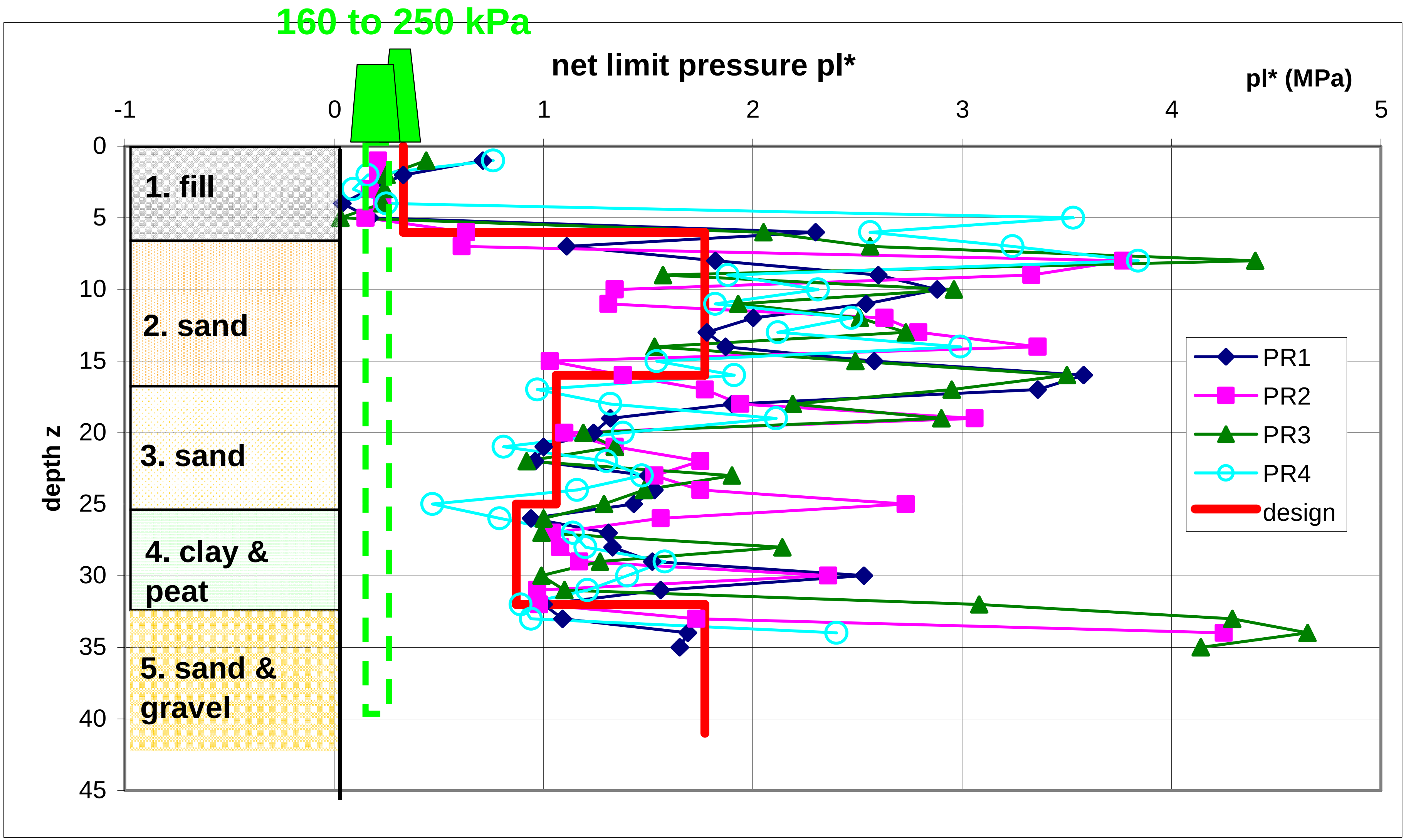
PILES = the initial foundation concept



360 piles mesh : 5,6mx5,6m

L=40m Ø=1.4m Q_{ELS} = 800 t

The alternative solution : preloading



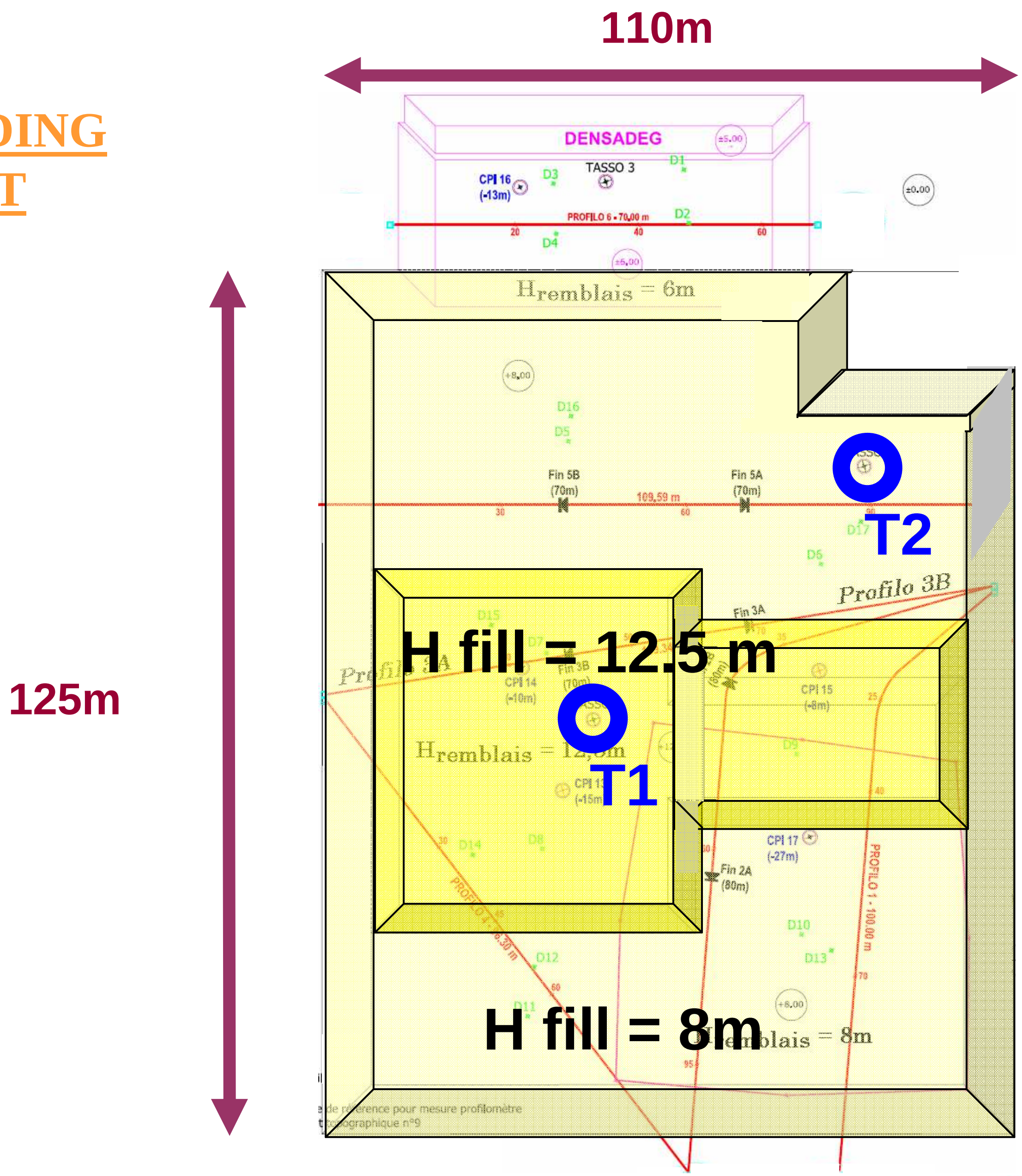
360 piles

L=40m Ø=1.4m

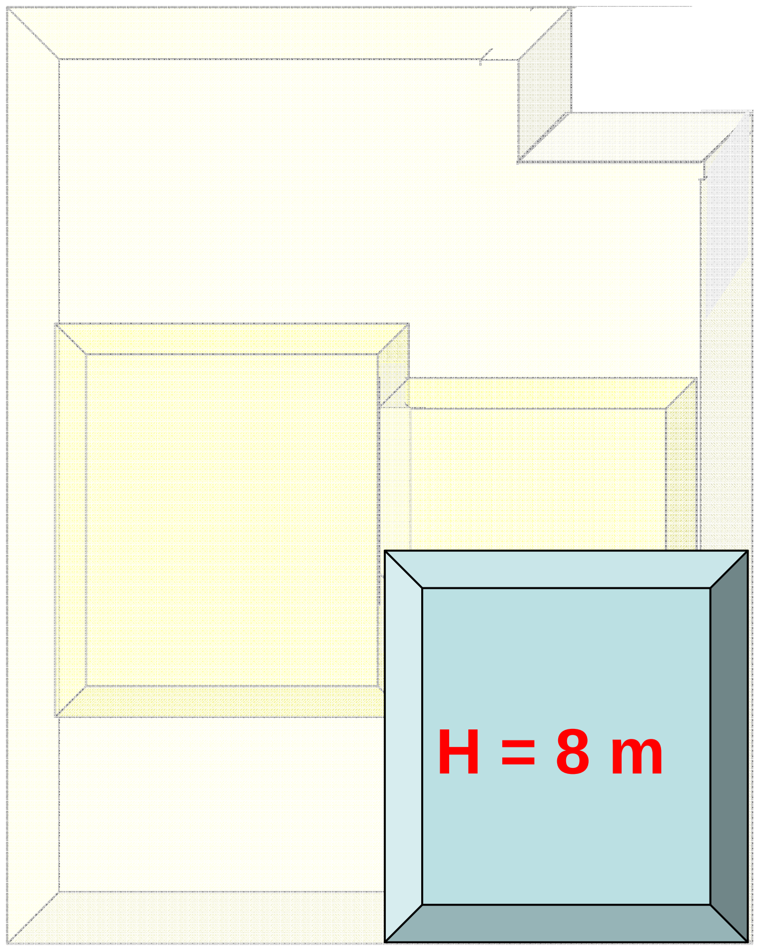
mesh : 5,6mx5,6m

Q_{ELS} = 800 t

THE PRELOADING EMBANKMENT



THE TRIAL EMBANKMENT



THE TRIAL EMBANKMENT

H= 8 m

Results

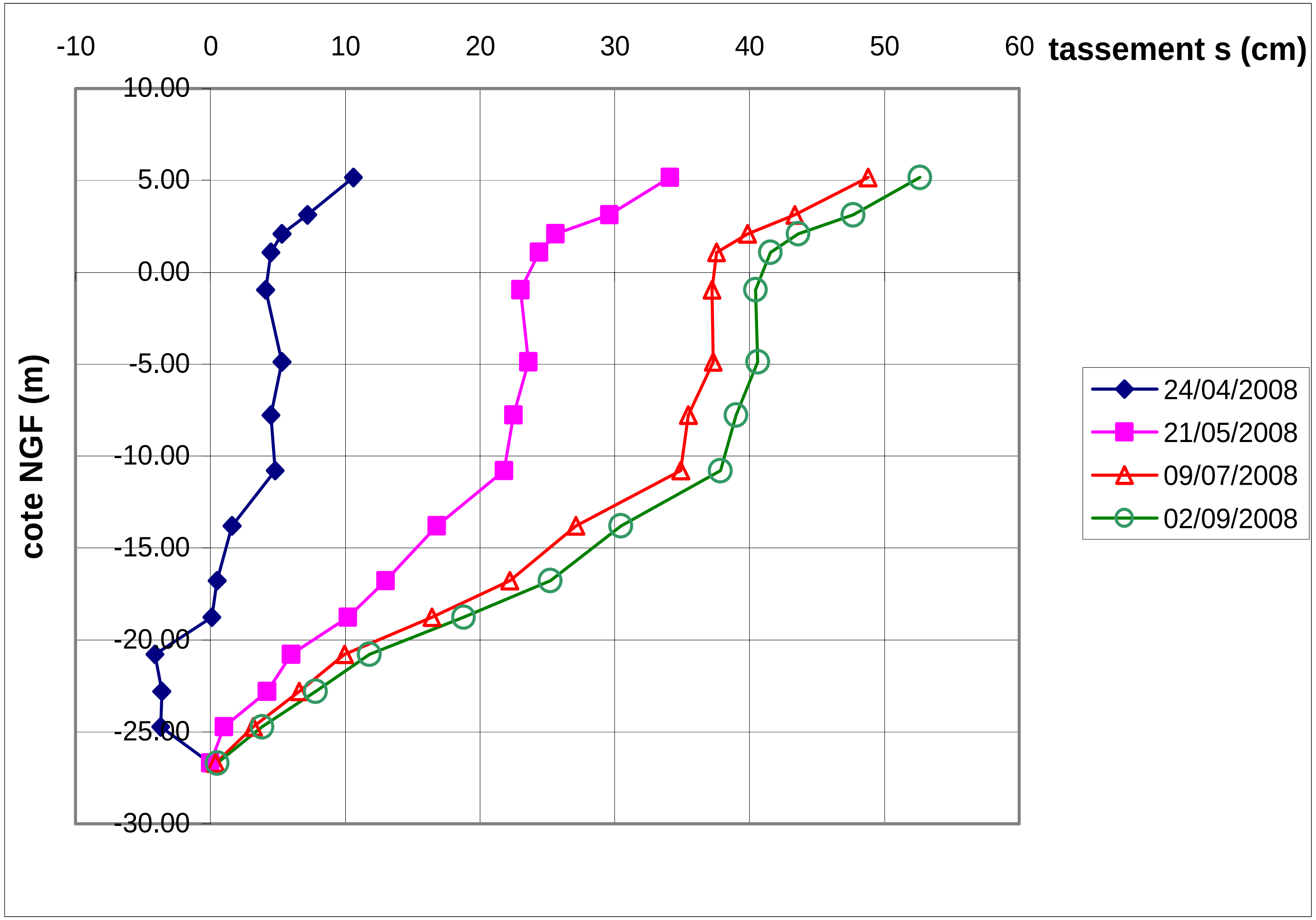
- no instability during fill construction
- in 4 months
  - pore pressures dissipated
  - settlements stabilised and magnitude as predicted

Conclusion : preloading possible without vertical drains in all alluvial deposits

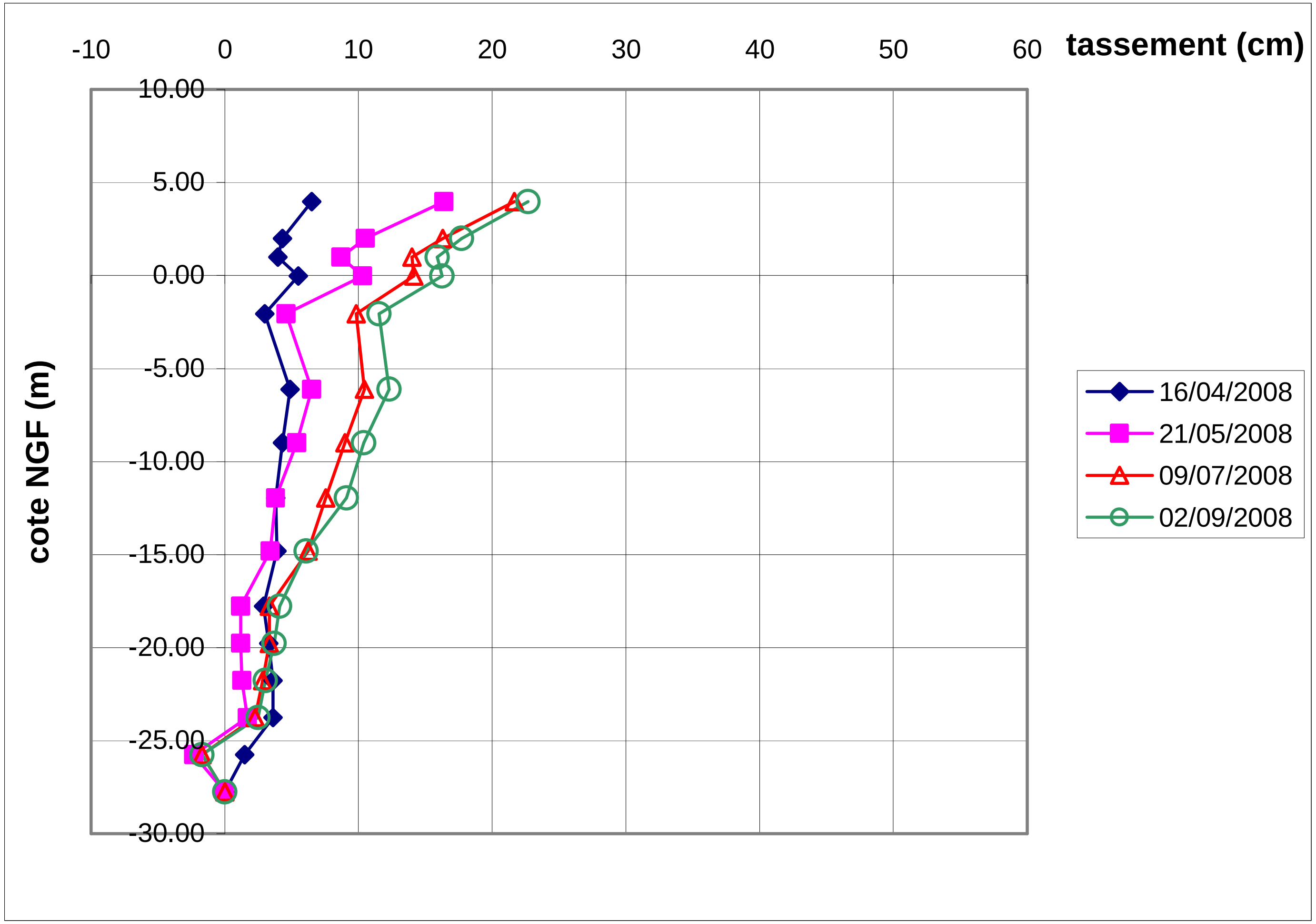
THE PRELOADING EMBANKMENT

Measurements	Results
➢ inclinometers	➢ no instability confirmed
➢ pore pressures	➢ confirms quick rate of consolidation and establishes ▪ time of fill removal ▪ degree of creep attained ▪ residual settlement at service
➢ multipoint tassometers T1 & T2	
➢ settlement profiles	➢ checks settlement model & provides settlement pattern for structural design

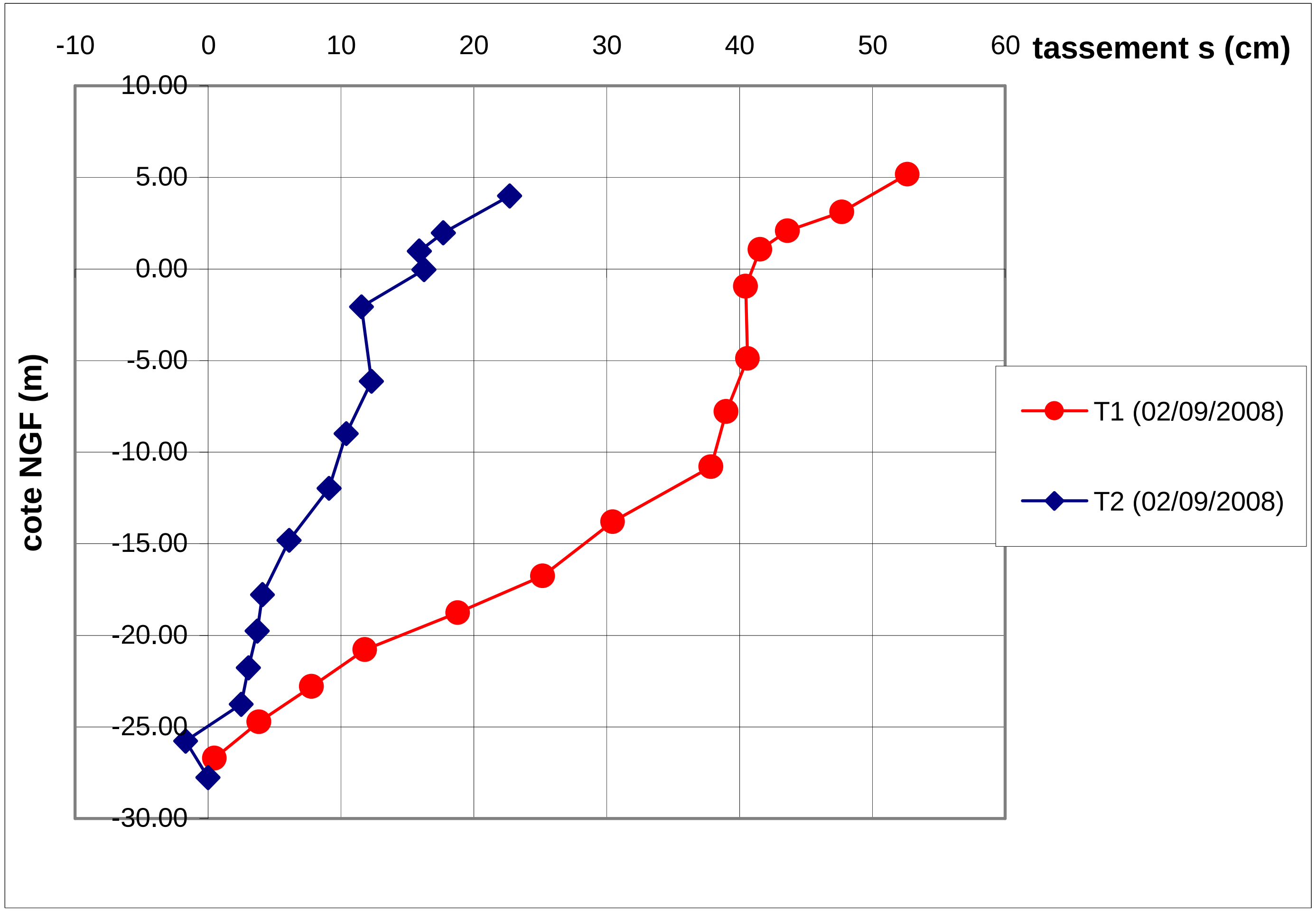
MULTIPOINT TASSOMETER T1



MULTIPOINT TASSOMETER T2

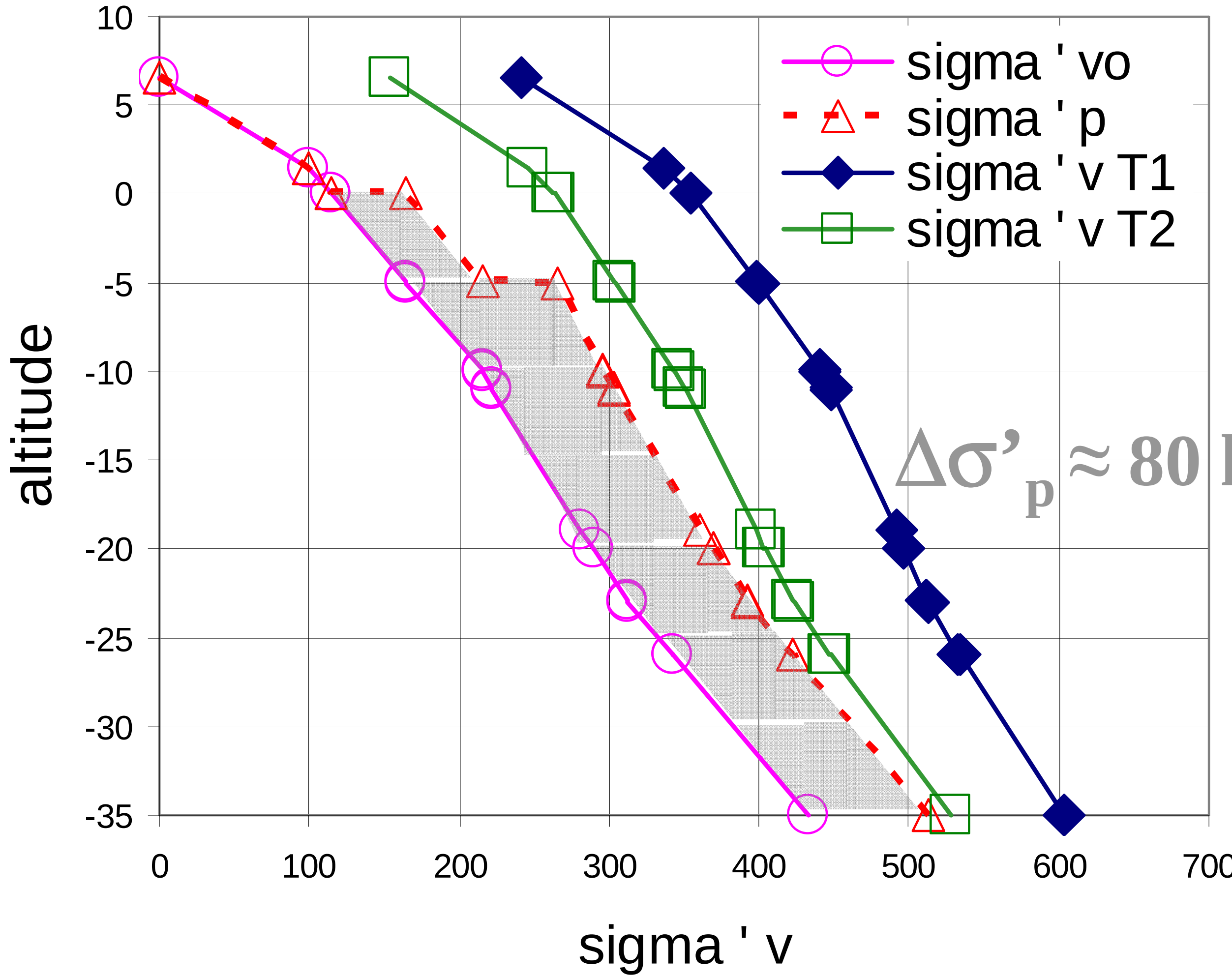


MULTIPOINT TASSOMETERS T1 & T2 – Final values



CALIBRATE OVERCONSOLIDATION MARGIN $\Delta\sigma'_p$ (POP)

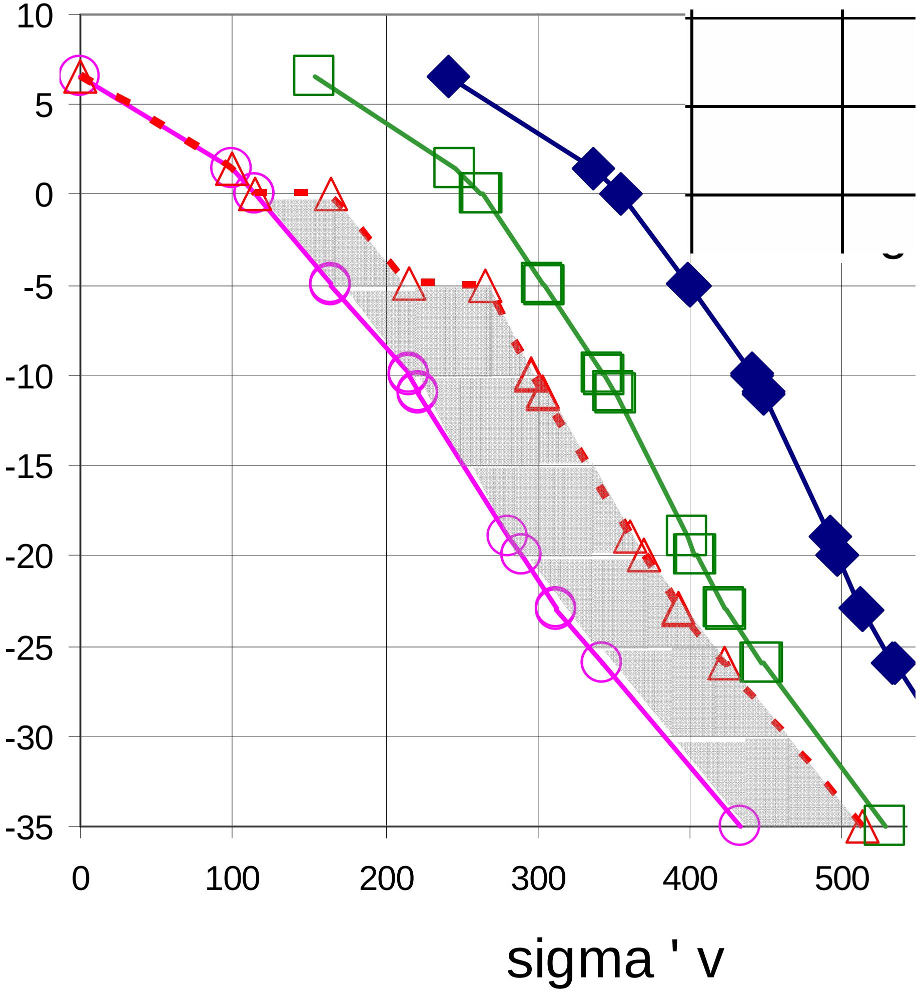
$$\Delta\sigma'_p = \sigma'_p - \sigma'_{v0}$$

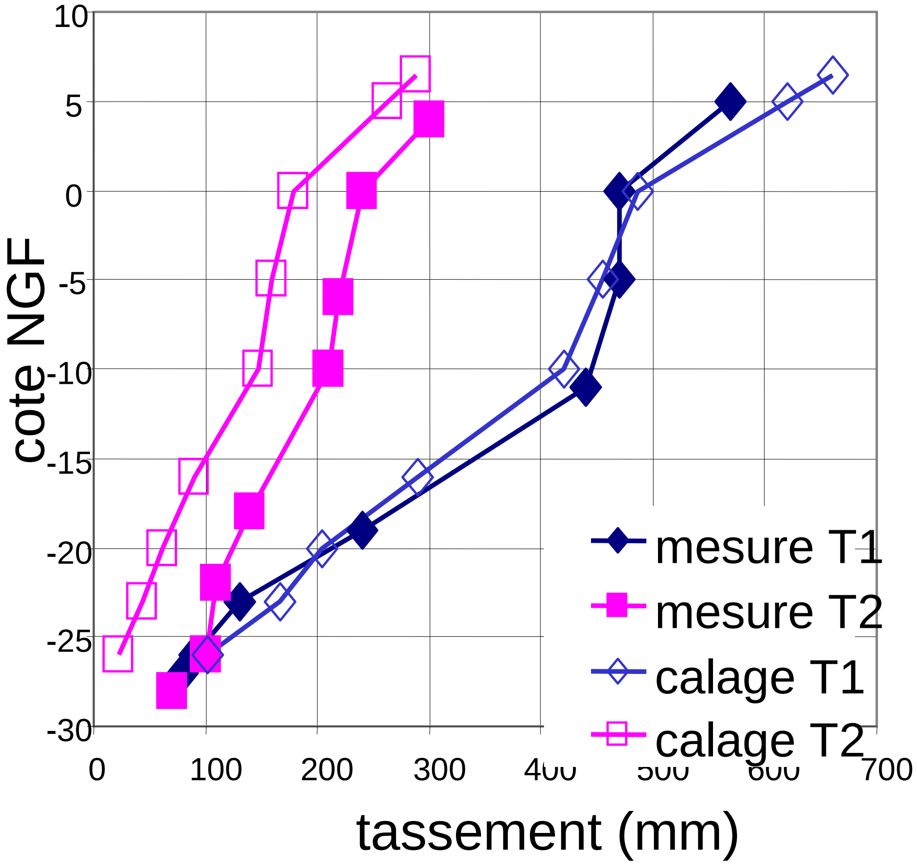


$\Delta\sigma'_p \approx 80$ kPa

MULTIPOINT TASSOMETERS T1 & T2 : measured & calculated settlements

overconsolidation margin → fit for settlements



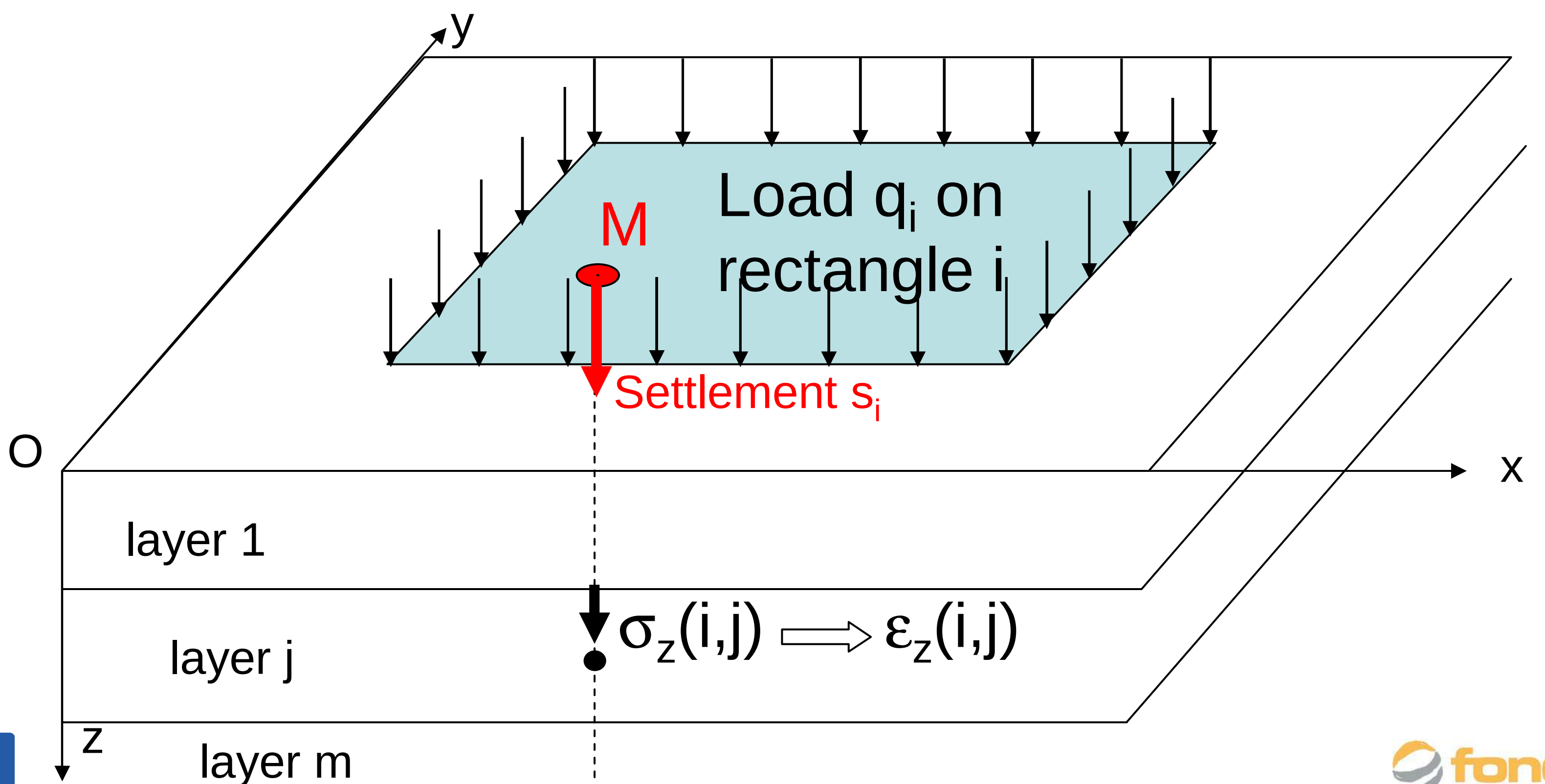


SETTLEMENT MODEL : TASSUNI (FONDASOL software)

n rectangles i with load q_i

m soil layers j with σ'_p and :

- either : moduli (E, Er)
- or : compression indexes C_C, C_S



SETTLEMENT MODEL : TASSUNI (FONDASOL software)

n rectangles i with load q_i

m soil layers j **with σ'_p**

and :

- either : moduli (E, Er)

$$\varepsilon_z = \frac{\sigma'_p - \sigma'_{v0}}{E_r} + \frac{\sigma_z + \sigma'_{v0} - \sigma'_p}{E}$$

For example : $E = E_M/\alpha$ & $E_r = 3 \text{ to } 10\ E_M/\alpha$

- or : compression indexes C_C, C_S

$$\varepsilon_Z = \frac{C_S}{1+e}\log\frac{\sigma'_p}{\sigma'_{v0}} + \frac{C_C}{1+e}\log\frac{\sigma'_{v0} + \sigma_z}{\sigma'_p}$$

TASSUNI : 13 LAYERS

DONNEE

Point courant x **33.40** Tassomètre T1
M(x,y) y **5.00**

Résultats du point courant

s(6.5) = $\boxed{0.656}$
s(5) = 0.616
s(0) = 0.482
s(-5) = 0.451
s(-10) = 0.415
s(-16) = 0.265
s(-20) = 0.180
s(-23) = 0.123
s(-26) = 0.059

DONNEES STRATIGRAPHIQUES ET MECANIQUES

cote générale du terrain NGF **6.5**
cote du plan de calcul NGF **6.5**
poids volumique γ **20**
contrainte initiale σ_{voo}' 0.0

*	Cote base	index	γ' #	σp'-σvo'	1 / 2	Cc/1+eo / E	Cs/1+eo / Er	Cc / Cs ou Er / E	Cas 2 Er tangent
précharg	6.50	1	*	*	*	*	*		
remblais	5.00	1	20	0	2	9000	90000	10	
nappe	1.50	1	20	0	2	9000	90000	10	
remblais	0.00	1	10	0	2	9000	90000	10	
graves	-5.00	1	10	50	1	0.02	0.0016	12.5	237 454
sables	-10.00	1	10	100	1	0.04	0.00308	13	160 893
sables	-11.00	1	7.5	80	1	0.15	0.01	15	51 233
"	-16.00	1	7.5	80	1	0.15	0.01	15	59 867
"	-20.00	1	7.5	80	1	0.15	0.01	15	66 775
"	-23.00	1	7.5	80	1	0.15	0.01	15	71 956
argile	-24.50	1	10	80	1	0.18	0.025	7.2	30 164
tourbeuse	-26.00	1	10	80	1	0.18	0.025	7.2	31 545
substratum	-35.00	1	10	80	2	50000	250000	5	
"	-60.00	1	10	80	2	50000	250000	5	

TASSUNI : 13 LOADS FOR PRELOADING

DONNEES DES CHARGES Pour la définition des rectangles, voir le schéma de la notice.

Cote : Entrer la cote d'assise pour les charges au contact avec le terrain (indiquées en italique gras).

Pour les autres charges, qui sont au-dessus de la charge d'assise, entrer la cote générale du terrain.

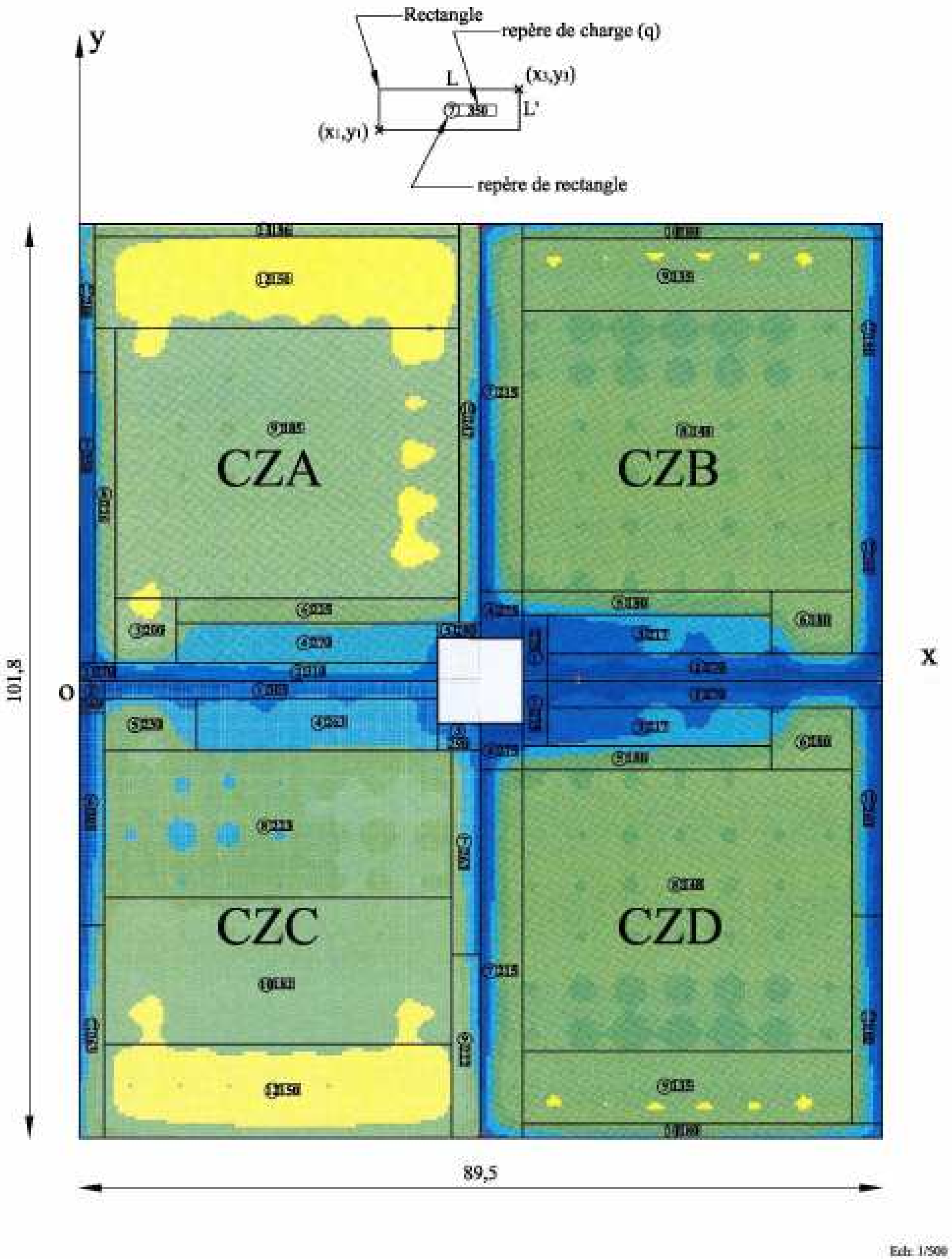
Charge nette = charge brute - γ . [cote générale du terrain - cote charge]

Charges	Nord 1	Nord 2	N° charge	1	2	3	4	5	6
			q	***51.33***	51.33	51.33	***51.33***	51.33	51.33
			x1	-7.98	-5.40	-2.82	-7.98	-5.40	-2.82
Choix			y1	59.63	57.05	54.47	0.00	0.00	0.00
n°1	n°2	n°3	n° choix	3	3	3	3	3	3
L	x2	x3	L, x2 ou x3	75.34	72.76	70.18	100.47	97.89	95.31
L'	y2	y3	L', y2 ou y3	75.41	72.83	70.24	59.63	57.05	54.47
α	L'	α	α, L' ou α	0.00	0.00	0.00	0.00	0.00	0.00
(0° à +90°)		(0° à +90°)							
			cote	6.50	6.50	6.50	6.50	6.50	6.50
Charges	Sud		N° charge	7	8	9	10	11	12
			q	***51.33***	51.33	51.33			
			x1	-7.98	-5.40	-2.82			
Choix			y1	-59.92	-57.34	-54.76			
n°1	n°2	n°3	n° choix	3	3	3	3	3	3
L	x2	x3	L, x2 ou x3	100.47	97.89	95.31			
L'	y2	y3	L', y2 ou y3	0.00	0.00	0.00	0.00	0.00	0.00
α	L'	α	α, L' ou α	0.00	0.00	0.00	0.00	0.00	0.00
(0° à +90°)		(0° à +90°)							
			cote	6.50	6.50	6.50	6.50	6.50	6.50
Charges	Ouest	Est	N° charge	13	14	15	16	17	18
			q	***44.00***	44.00	***44.00***	44.00		
			x1	-0.40	1.87	49.64	47.38		
Choix			y1	-27.79	-25.53	-10.56	-8.29		
n°1	n°2	n°3	n° choix	3	3	3	3	3	3
L	x2	x3	L, x2 ou x3	49.64	47.38	92.88	90.62		
L'	y2	y3	L', y2 ou y3	27.79	25.53	10.56	8.29		
α	L'	α	α, L' ou α	0.00	0.00	0.00	0.00	0.00	0.00
(0° à +90°)		(0° à +90°)							

TASSUNI : 62 LOADS FOR PERMANENT STATE

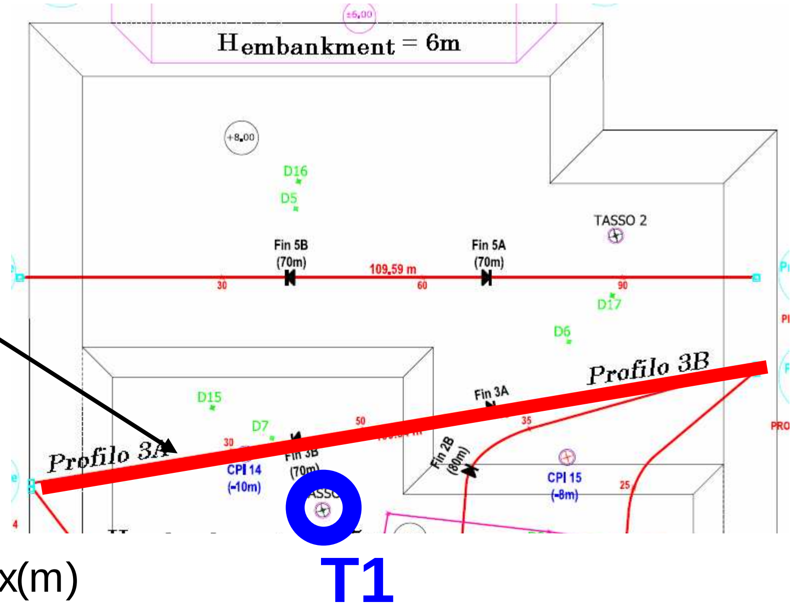
Cas 200: charges quasi-permanentes du cyclor

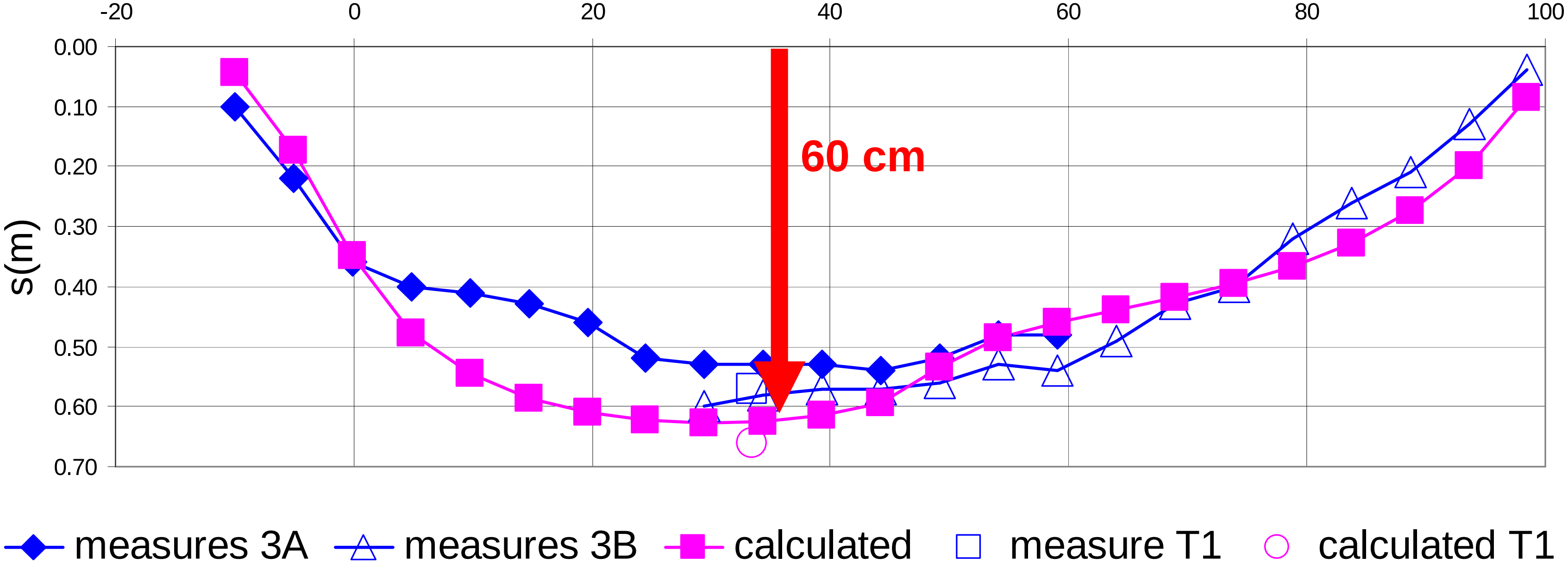
CZ	Rect	x1	y1	x3	y3	q(kPa)	L	L'	S	Q(kN)	TOT	Total théorique
A	1	0	0	4.02	2	370	4.02	2	8.04	2975		
	2	4.02	0	39.96	2	310	35.94	2	71.88	22283		
	3	4.02	2	10.82	9.07	200	6.8	7.07	48.076	9615		
	4	10.82	2	39.96	6.43	270	29.14	4.43	129.09	34854		
	5	39.96	4.74	44.7	6.43	290	4.74	1.69	8.0106	2323		
	6	10.82	6.43	42.37	9.07	225	31.55	2.64	83.292	18741		
	7	0	2	1.69	34.34	350	1.69	32.34	54.6546	19129		
	8	1.69	2	4.02	39.18	226	2.33	37.18	86.6294	19578		
	9	4.02	9.07	42.37	39.18	180	38.35	30.11	1154.72	207849		
	10	42.37	6.43	44.7	50.92	247	2.33	44.49	103.662	25604		
	11	0	34.34	1.69	50.92	288	1.69	16.58	28.0202	8070		
	12	1.69	39.18	42.37	49.57	150	40.68	10.39	422.665	63400		
	13	1.69	49.57	42.37	50.92	186	40.68	1.35	54.918	10215	444 636	444 670
B	1	49.41	0	52.23	7.23	275	2.82	7.23	20.3886	5607		
	2	52.23	0	89.5	2.98	270	37.27	2.98	111.065	29987		
	3	52.23	2.98	77.15	7.23	217	24.92	4.25	105.91	22982		
	4	44.7	4.74	49.44	9.89	275	4.74	5.15	24.411	6713		
	5	49.41	7.23	77.15	9.89	180	27.74	2.66	73.7884	13282		
	6	77.15	2.98	86.13	9.89	180	8.98	6.91	62.0518	11169		
	7	44.7	9.89	49.44	50.92	215	4.74	41.03	194.482	41814		
	8	49.41	9.89	86.13	41.27	148	36.72	31.38	1152.27	170536		
	9	49.41	41.27	86.13	49.32	135	36.72	8.05	295.596	39905		
	10	49.41	49.32	89.5	50.92	180	40.09	1.6	64.144	11546		
	11	86.13	2.98	89.5	26	260	3.37	23.02	77.5774	20170		
	12	86.13	26	89.5	49.32	180	3.37	23.32	78.5884	14146	387 859	387 120
C	1	2.76	-1.94	39.96	0	303	37.2	1.94	72.168	21867		
	2	0	-3.61	2.76	0	360	2.76	3.61	9.9636	3587		
	3	39.96	-7.71	44.7	-4.74	290	4.74	2.97	14.0778	4083		
	4	13.04	-7.71	39.96	-1.94	263	26.92	5.77	155.328	40851		
	5	2.76	-7.71	13.04	-1.94	230	10.28	5.77	59.3156	13643		
	6	0	-27.13	2.76	-3.61	303	2.76	23.52	64.9152	19669		
	7	41.56	-30.41	44.7	-7.71	263	3.14	22.7	71.278	18746		
	8	2.76	-24.07	41.56	-7.71	223	38.8	16.36	634.768	141553		
	9	41.56	-50.89	44.7	-30.41	222	3.14	20.48	64.3072	14276		
	10	2.76	-40.46	41.56	-24.07	182	38.8	16.39	635.932	115740		
	11	0	-50.92	2.76	-27.13	263	2.76	23.79	65.6604	17269		
	12	2.76	-50.92	41.56	-40.46	150	38.8	10.46	405.848	60877	472 181	472 000
D	1	49.41	-7.23	52.23	0	275	2.82	7.23	20.3886	5607		
	2	52.23	-2.98	89.5	0	270	37.27	2.98	111.065	29987		
	3	52.23	-7.23	77.15	-2.98	217	24.92	4.25	105.91	22982		
	4	44.7	-9.89	49.44	-4.74	275	4.74	5.15	24.411	6713		
	5	49.41	-9.89	77.15	-7.23	180	27.74	2.66	73.7884	13282		
	6	77.15	-9.89	86.13	-2.98	180	8.98	6.91	62.0518	11169		
	7	44.7	-50.92	49.41	-9.89	215	4.71	41.03	193.251	41549		
	8	49.41	-41.27	86.13	-9.89	148	36.72	31.38	1152.27	170536		
	9	49.41	-49.32	86.13	-41.27	135	36.72	8.05	295.596	39905		
	10	49.41	-50.92	89.5	-49.32	180	40.09	1.6	64.144	11546		
	11	86.13	-26	89.5	-2.98	260	3.37	23.02	77.5774	20170		
	12	86.13	-49.32	89.5	-26	180	3.37	23.32	78.5884	14146	387 594	387 120



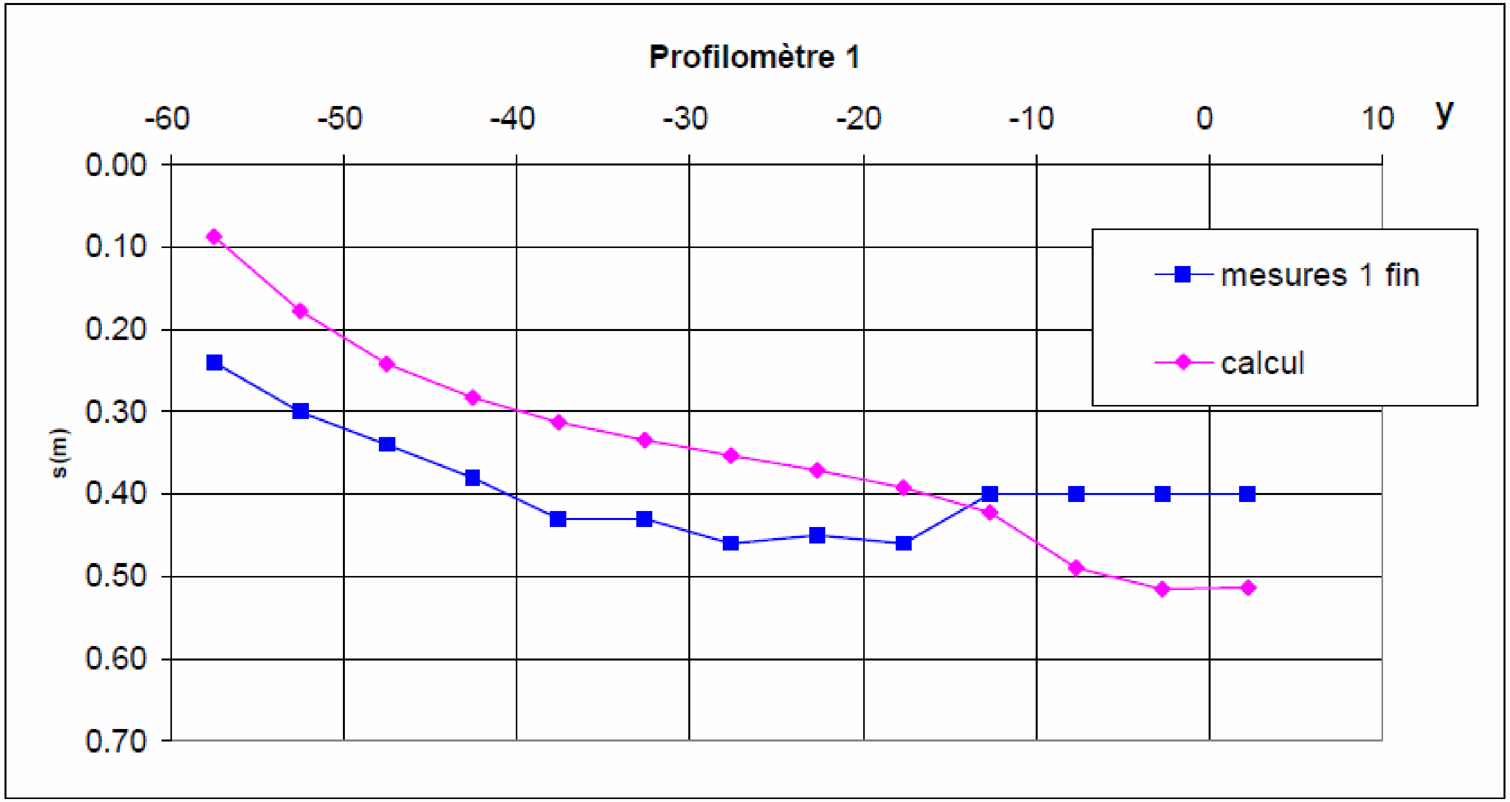
PROFILOMETER 3

Comparison between measured and calculated settlements before fill removal

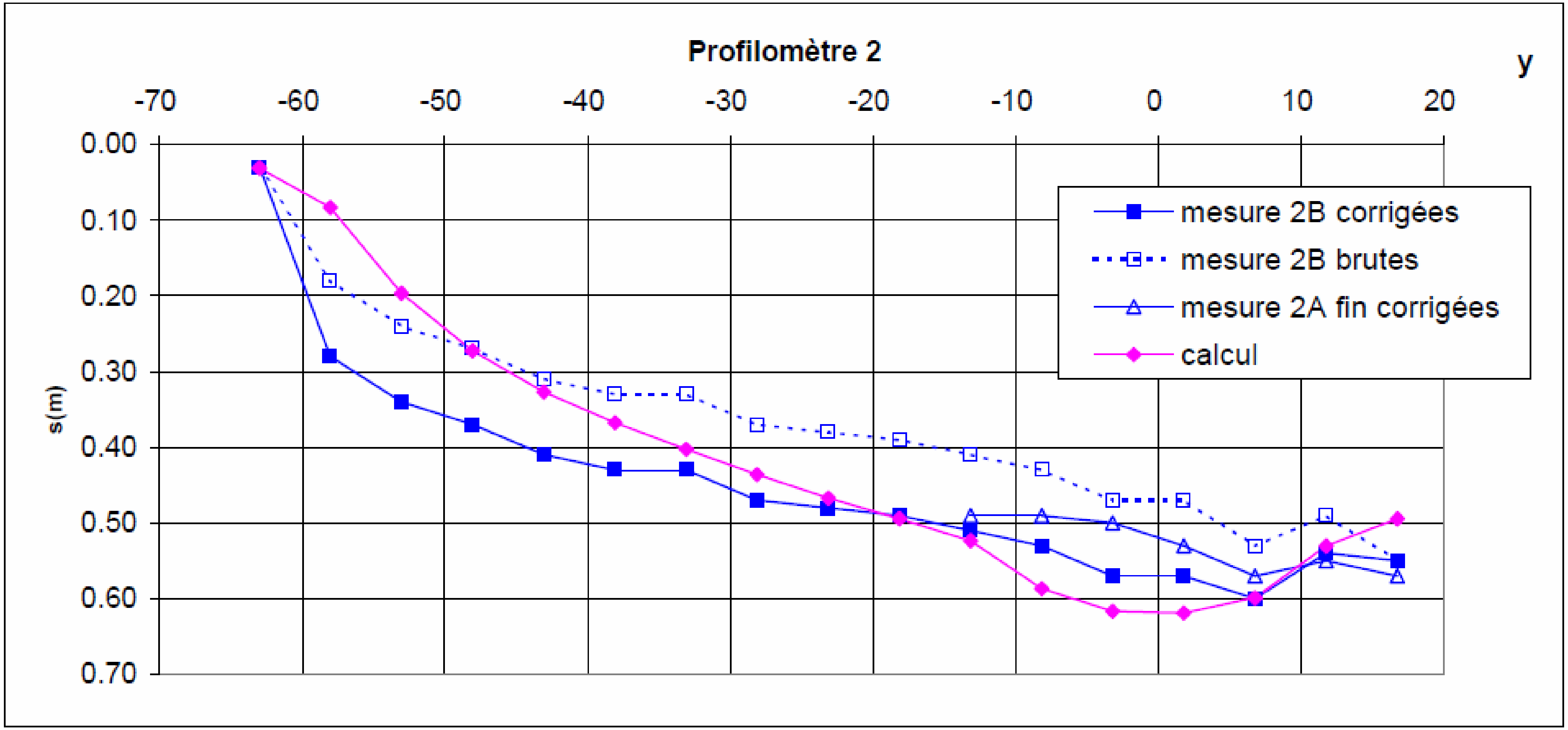




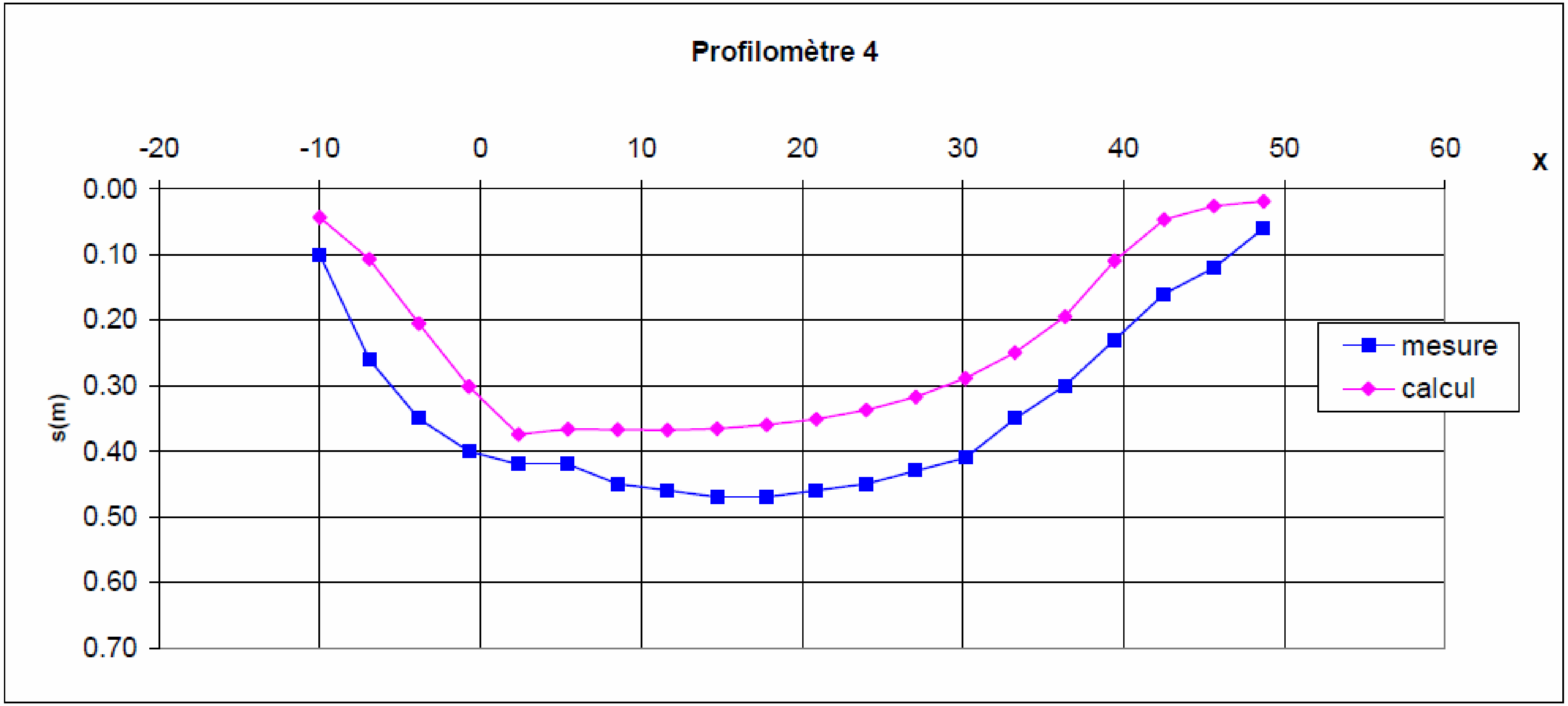
OTHER PROFILOMETERS



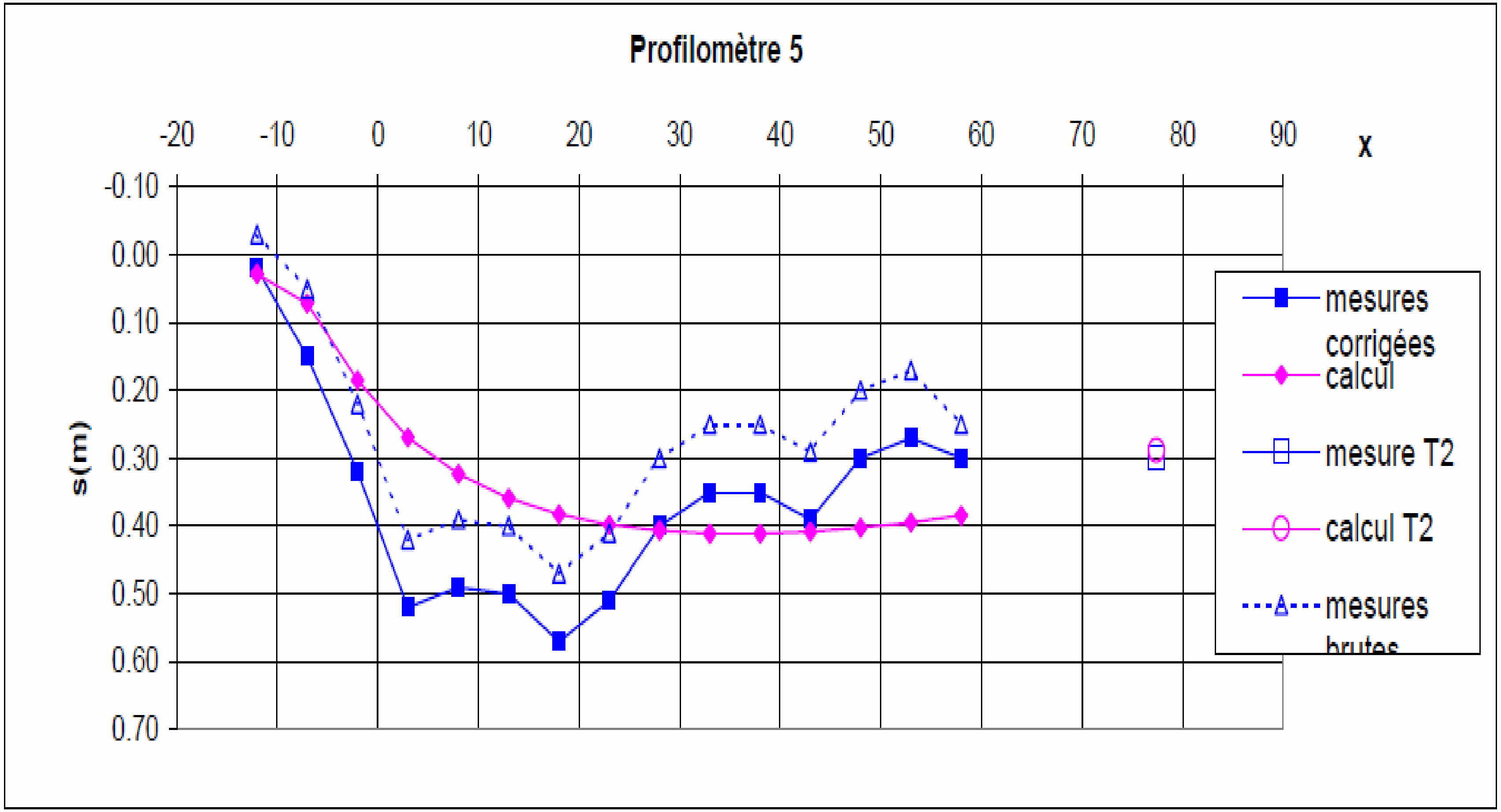
OTHER PROFILOMETERS



OTHER PROFILOMETERS



OTHER PROFILOMETERS



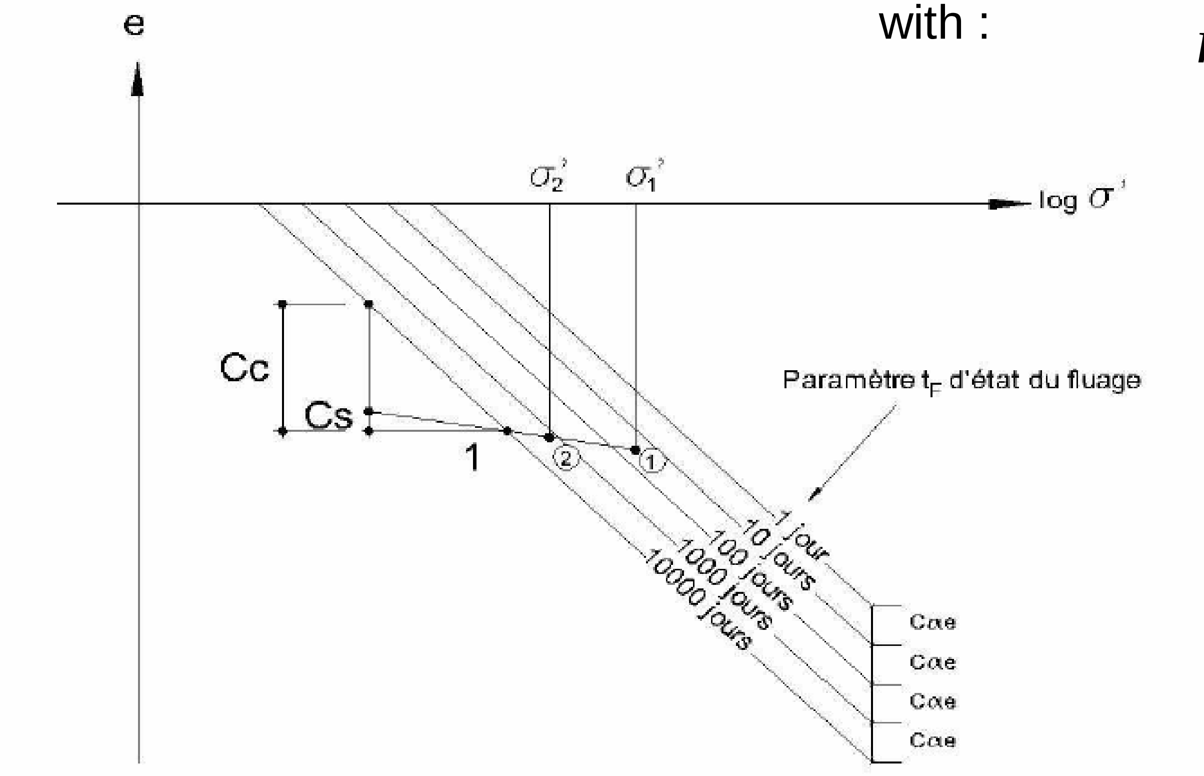
Bjerrum creep model - parameter t_F for creep lines

Unloading from 1 to 2 :

$$t_{F2} = t_{F1}\left[\frac{\sigma'_1}{\sigma'_2}\right]^m$$

with :

$$m = \frac{C_C - C_S}{(1+e)\ C_\alpha}$$



SOIL CONSOLIDATION & CREEP

Loi de consolidation

loi de Terzaghi $\boxed{s_c = a \,.\, U(T)}$

avec :

a = tassement de consolidation
h = épaisseur de la couche, drainée sur les deux faces
H = h/2 = longueur du chemin de drainage

$$T = \frac{t}{c} \qquad c = \frac{H^2}{c_v}$$

Loi de fluage

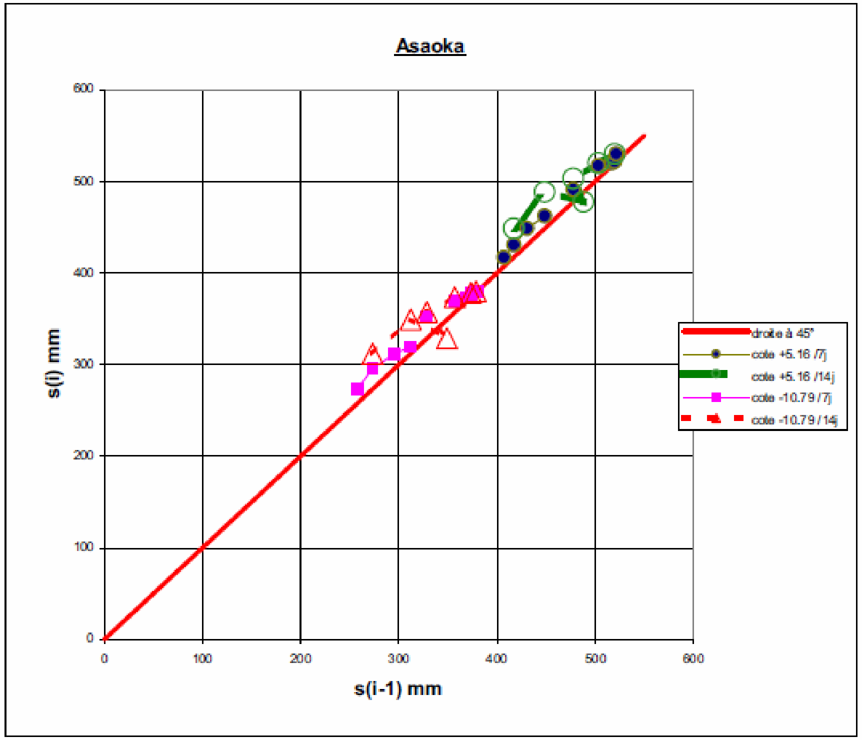
$$\boxed{s_f = s_0 + C_\alpha \,.\, h \,.\, \log\left[\frac{t - t_{00}}{t_0 - t_{00}}\right]}$$

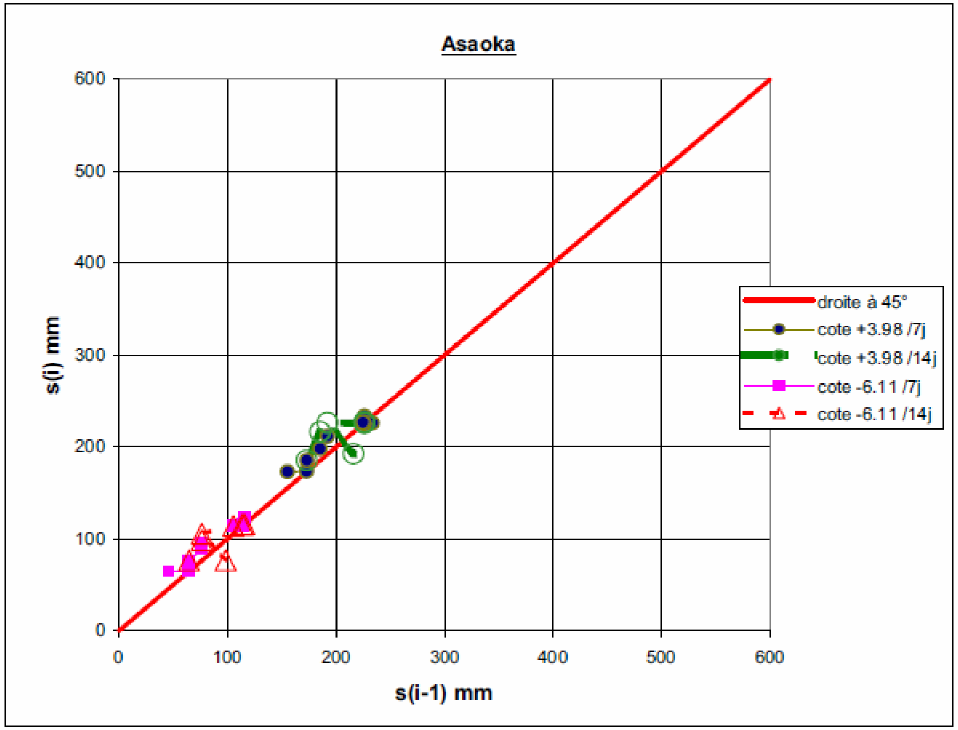
ou : $s_f = s_0 + C_F \,.\, h \,.\, \ln\left[\frac{t - t_{00}}{t_0 - t_{00}}\right]$

avec :

h = épaisseur de la couche
C_α = paramètre de fluage $C_{\alpha e}$ = (1+e). C_α
$$C_F = \frac{C_\alpha}{\ln 10} = \frac{C_\alpha}{2{,}3}$$
t = temps courant les temps sont exprimés en jours
t_{00} = temps de démarrage du fluage
t_0 = temps de raccord des courbes de consolidation et de fluage
s_0 = tassement au point de raccord des courbes de consolidation et de fluage

SOIL CONSOLIDATION : ASAOKA

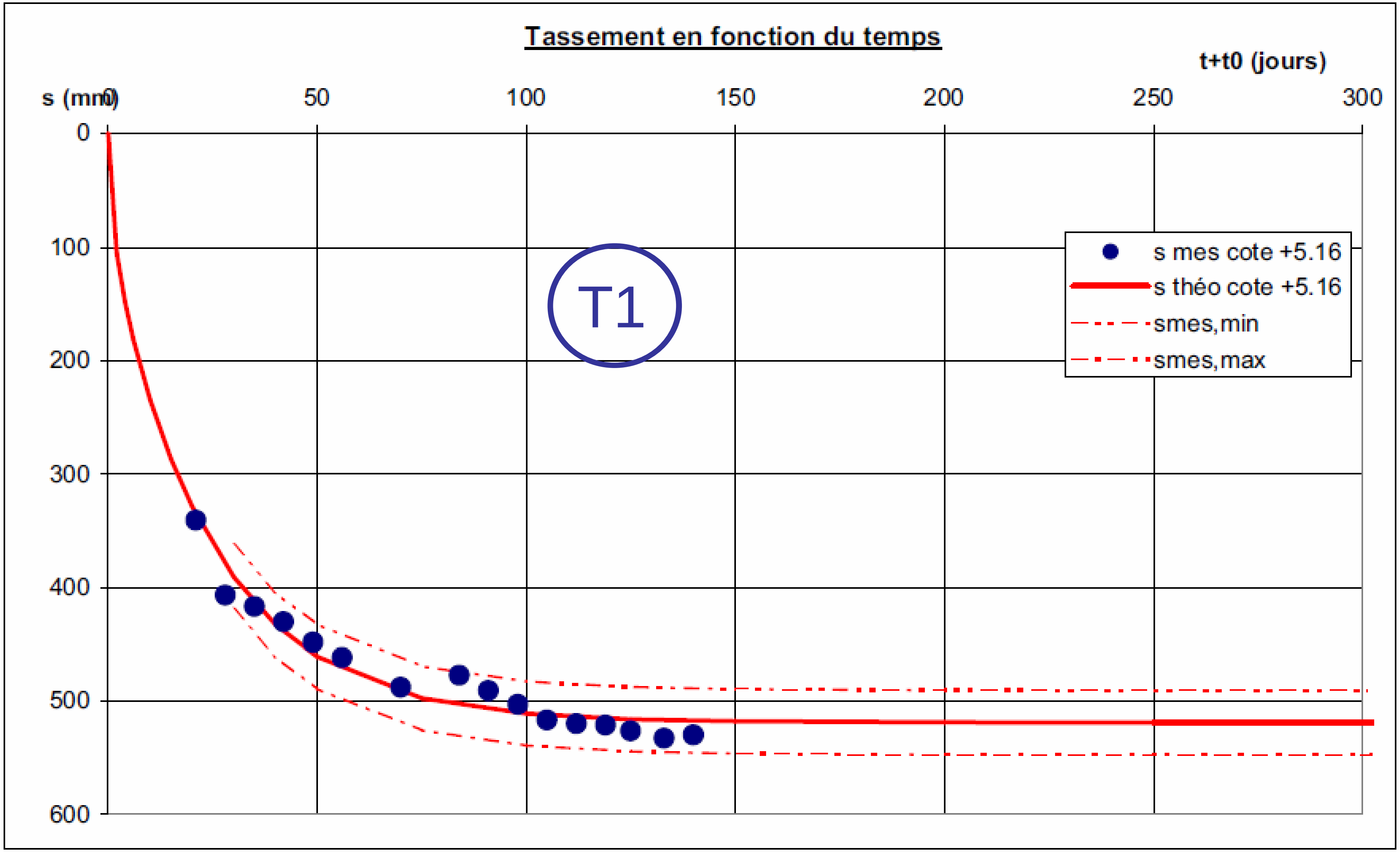




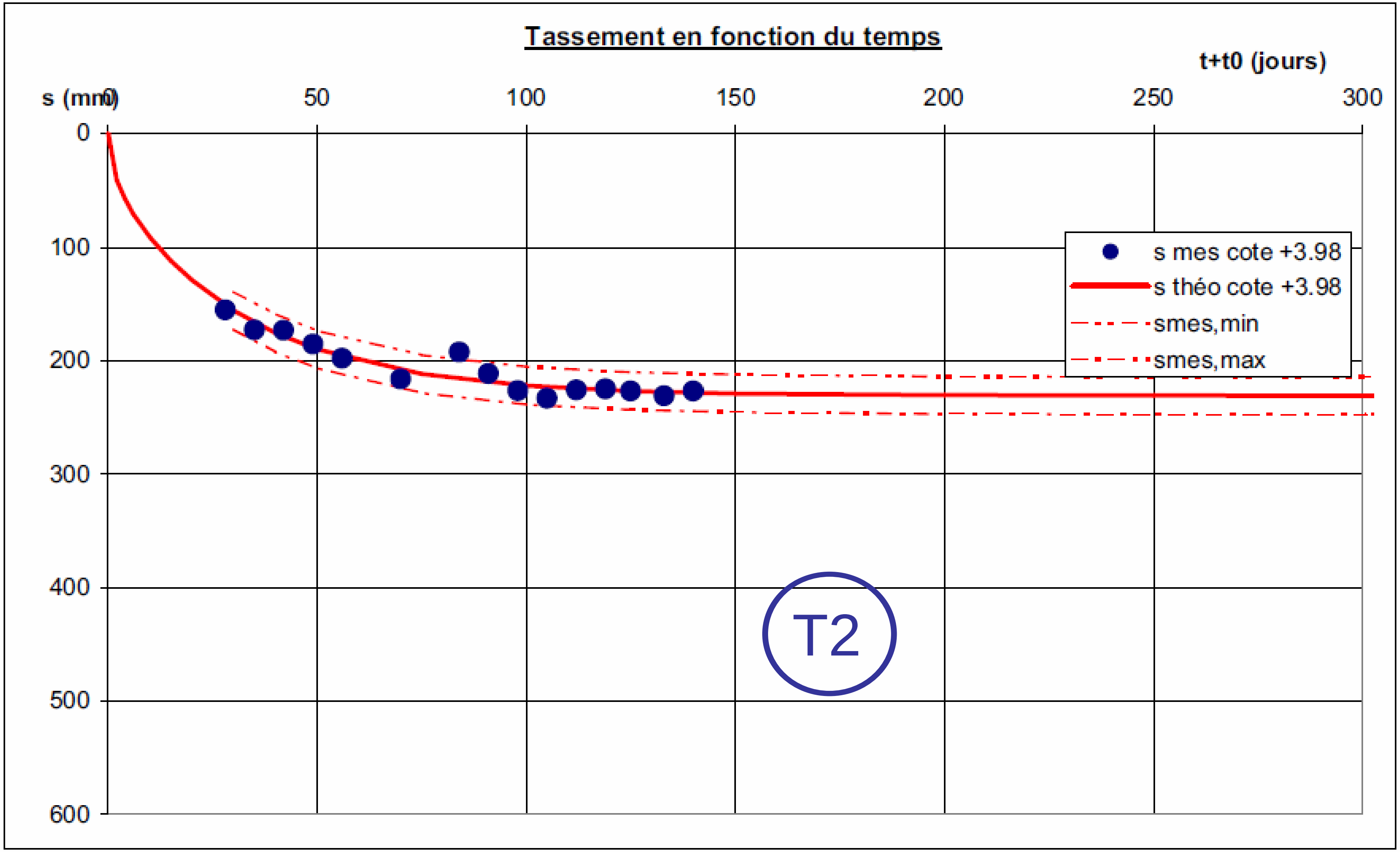
T1

T2

SOIL CONSOLIDATION : CURVE FITTING



SOIL CONSOLIDATION : CURVE FITTING



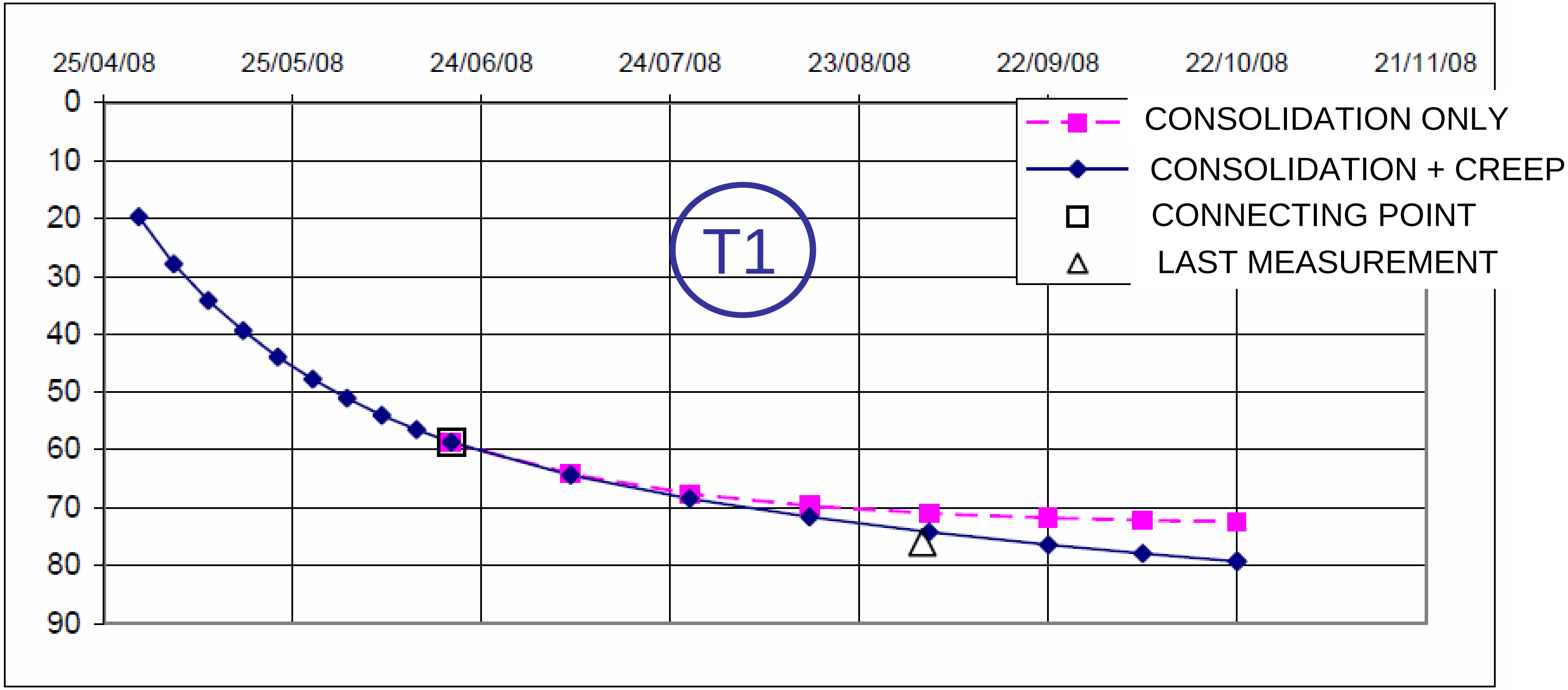
SOIL CONSOLIDATION & CREEP

layers subjected to creep at 25m depth : peaty clay , cumulated thickness = 3m

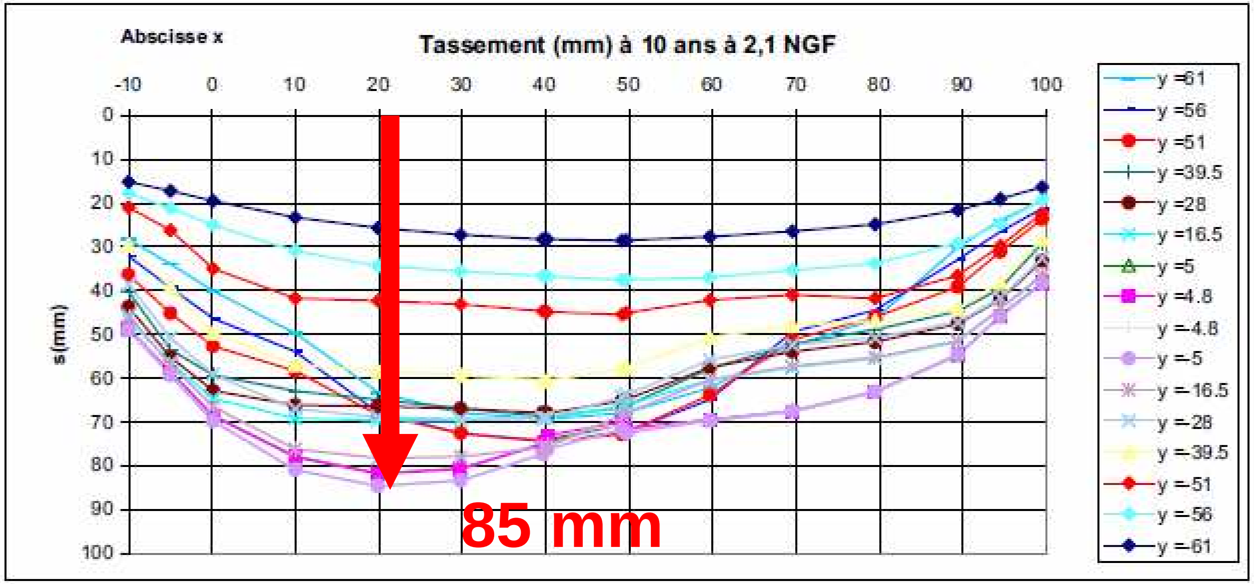
Creep parameter

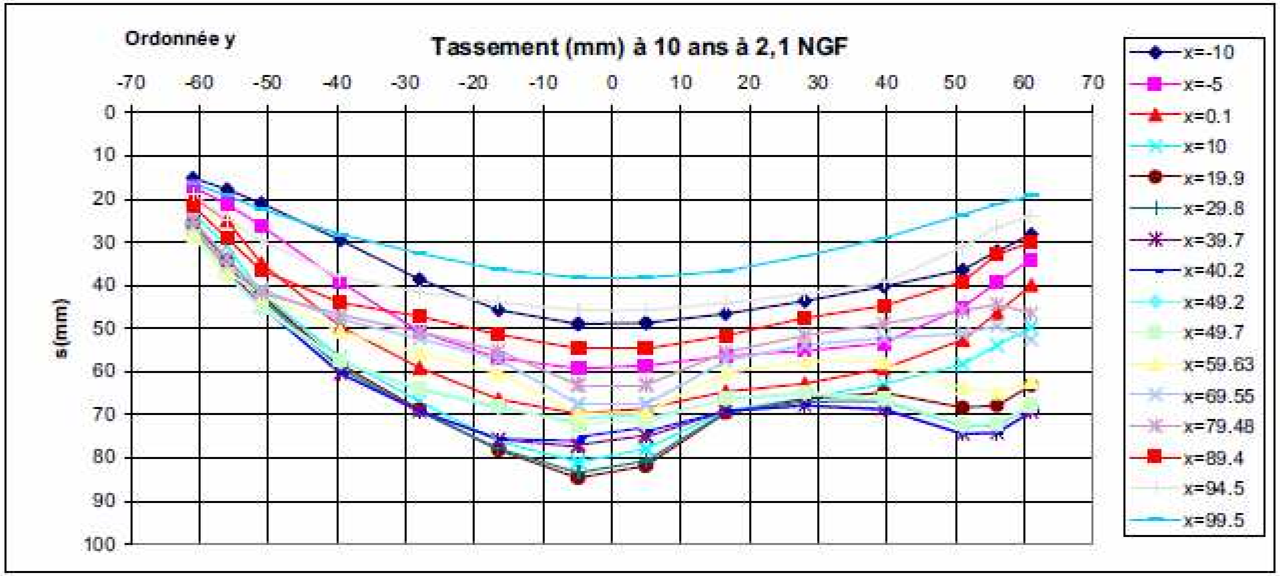
C_α	1+e	$C_{\alpha e}$	C_F
0.0110	2.2844	0.0252	**0.0048**

$C_F = C_\alpha / \ln 10 = 0{,}434\ C_\alpha$



SETTLEMENT PREDICTED at 10 years under permanent loads





fondasol
GÉOTECHNIQUE

SETTLEMENT PREDICTED at 10 years under permanent loads

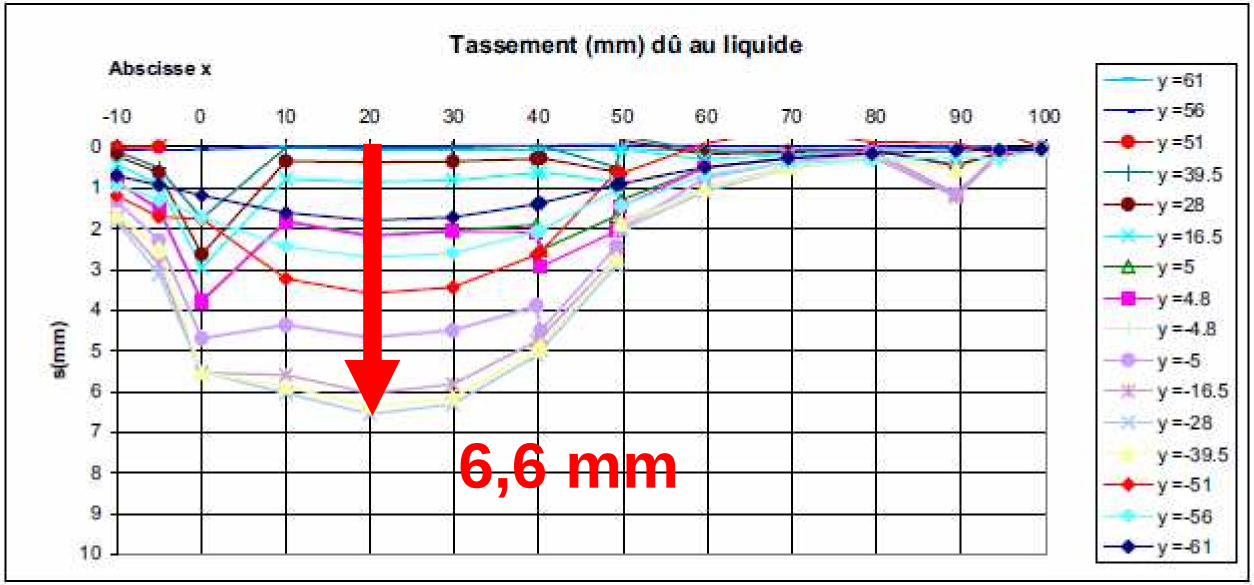
Tassement à 10 ans en mm

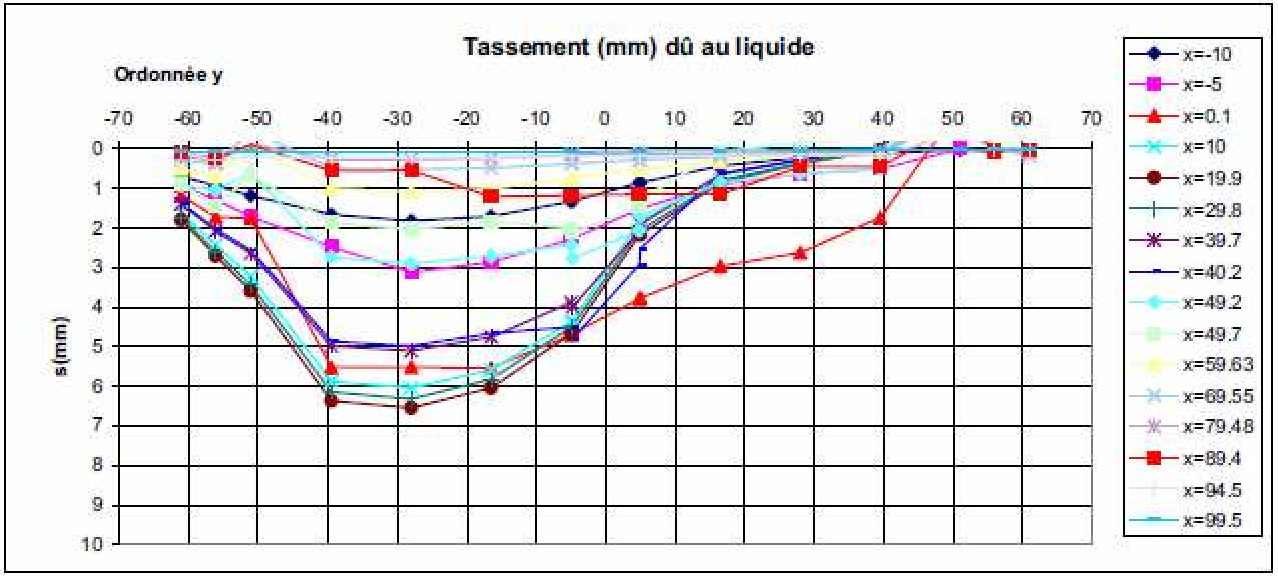
Cyclor

s(m)		x=-10	x=-5	x=0.1	x=10	x=19.9	x=29.8	x=39.7	x=40.2	x=49.2	x=49.7	x=59.63	x=69.55	x=79.48	x=89.4	x=94.5	x=99.5
		-10	-5	0.1	10	19.9	29.8	39.7	40.2	49.2	49.7	59.63	69.55	79.48	89.4	94.5	99.5
y=61	61	28	34	40	50	63	68	69	69	68	68	62	53	46	30	24	19
y=56	56	32	39	46	54	68	73	74	74	72	72	65	49	44	33	26	21
y=51	51	36	45	53	58	68	72	74	74	73	72	64	51	46	39	31	24
y=39.5	39.5	40	53	59	63	65	67	69	69	67	66	58	52	49	45	39	29
y=28	28	44	55	63	66	66	67	68	68	65	65	57	54	52	48	42	33
y=16.5	16.5	47	56	65	69	70	69	69	69	66	66	60	58	55	52	44	37
y=5	5	49	59	68	78	82	81	75	74	71	72	69	67	63	55	46	38
y=4.8	4.8	49	59	69	78	82	81	75	73	70	71	70	68	63	55	46	38
y=-4.8	-4.8	49	59	70	81	85	83	77	75	71	72	70	68	63	55	46	38
y=-5	-5	49	59	70	81	85	83	77	76	72	72	70	67	63	55	46	38
y=-16.5	-16.5	46	57	66	76	78	78	76	76	68	68	60	57	55	51	44	36
y=-28	-28	39	51	59	67	69	69	69	69	64	64	56	52	51	47	42	33
y=-39.5	-39.5	30	39	50	57	58	59	60	60	58	57	51	48	47	44	38	28
y=-51	-51	21	26	35	42	42	43	45	45	45	45	42	41	42	37	30	22
y=-56	-56	18	21	25	31	34	36	37	37	38	37	37	35	34	29	25	19
y=-61	-61	15	17	20	23	26	27	28	28	29	29	28	28	25	22	19	16

de 0 à 10
de 10 à 20
de 20 à 30
de 30 à 40
de 40 à 50
de 50 à 60
de 60 à 70
de 70 à 80

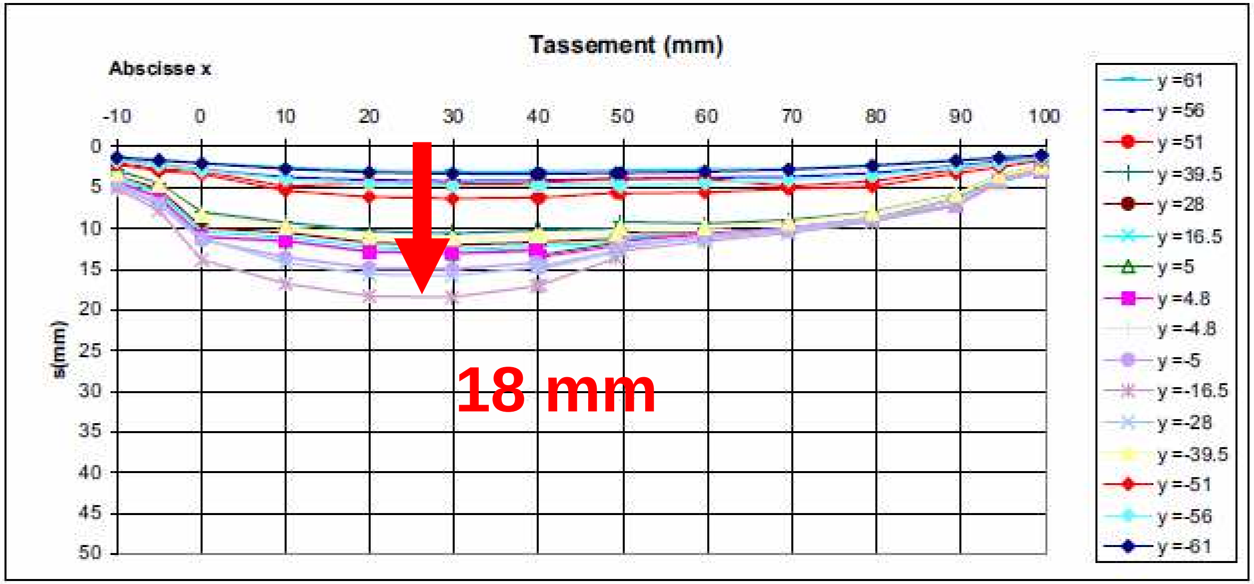
SETTLEMENT PREDICTED under water load in cell CZC

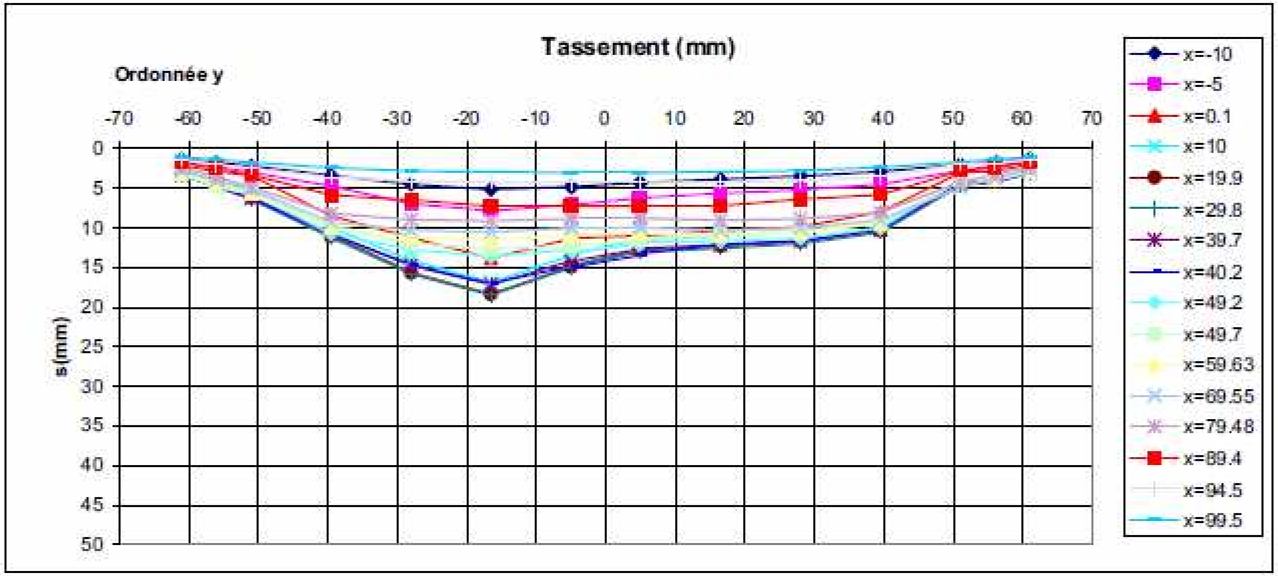




SETTLEMENT PREDICTED under maximum variable load

Tassement sous Qmax - Qqp





SOIL-STRUCTURE INTERACTION

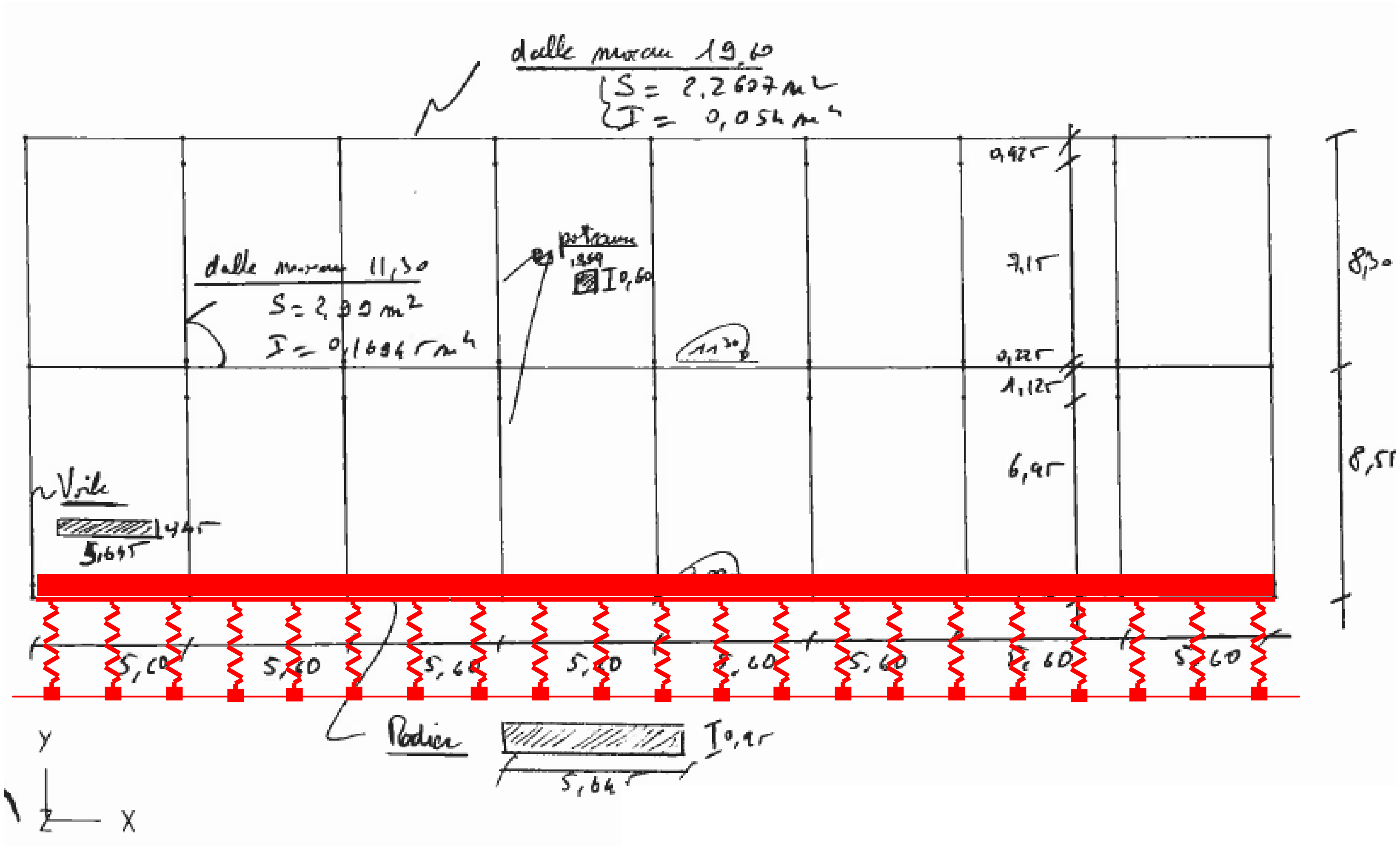
Model 1 : structure (3D) + subgrade springs for soil

=> initial reinforcement in the structure

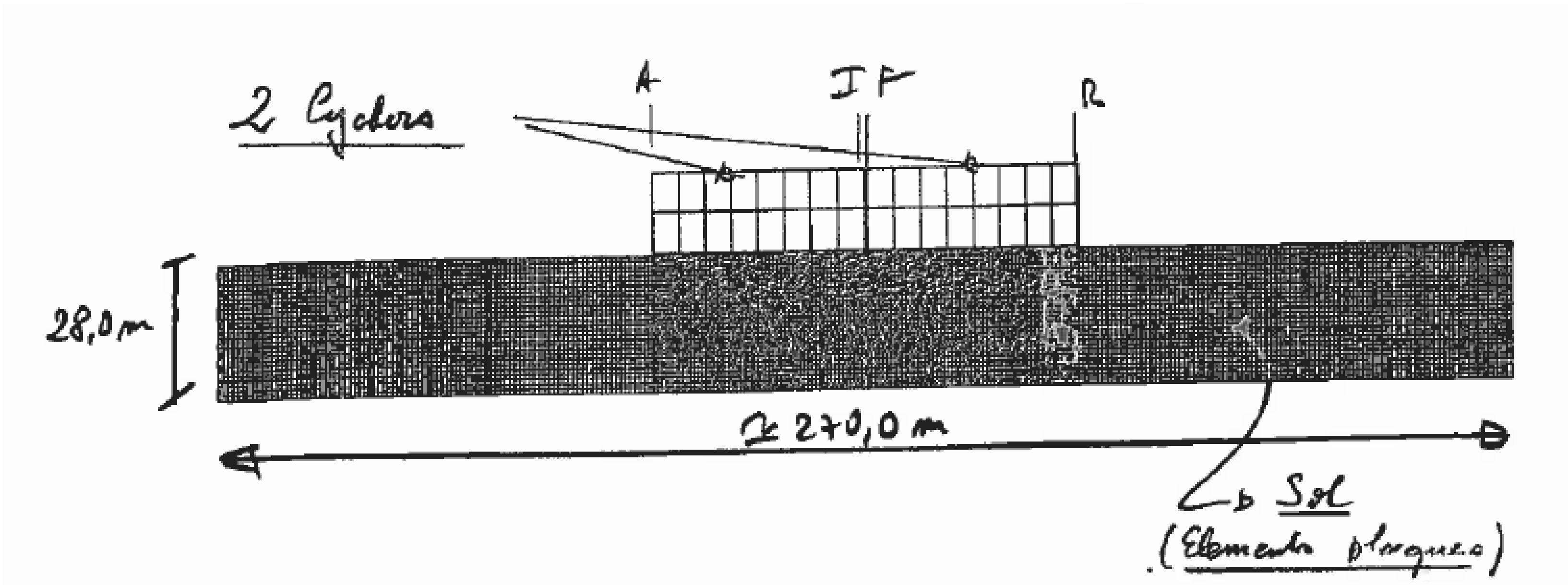
Model 2 : 2D a slice of the structure, 5.6m thick : walls or porticos
+ elastic layer (28m thick) for soil

=> additional reinforcement (+10%)

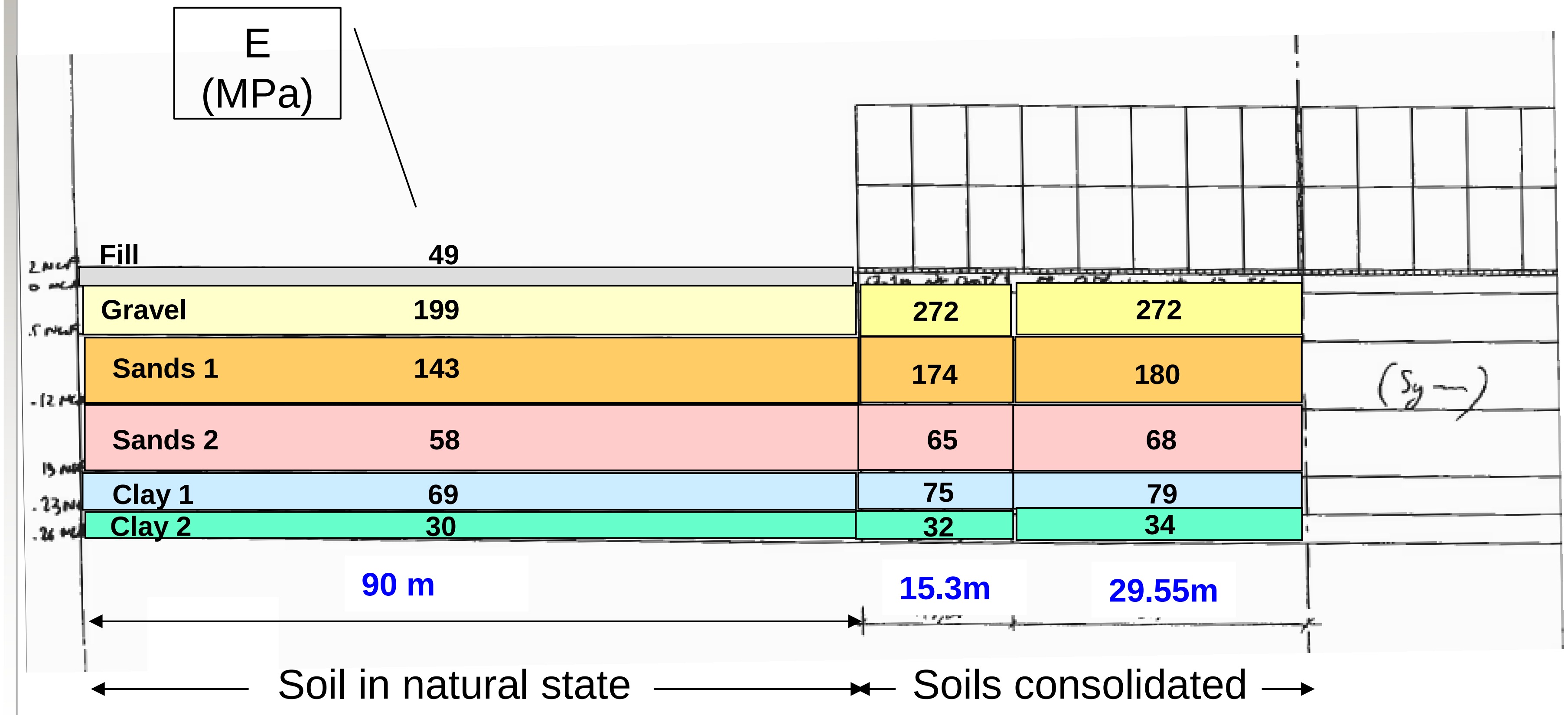
SOIL-STRUCTURE INTERACTION Model 1 : structure on springs



SOIL-STRUCTURE INTERACTION Model 2 (2D) : structure on elastic soil



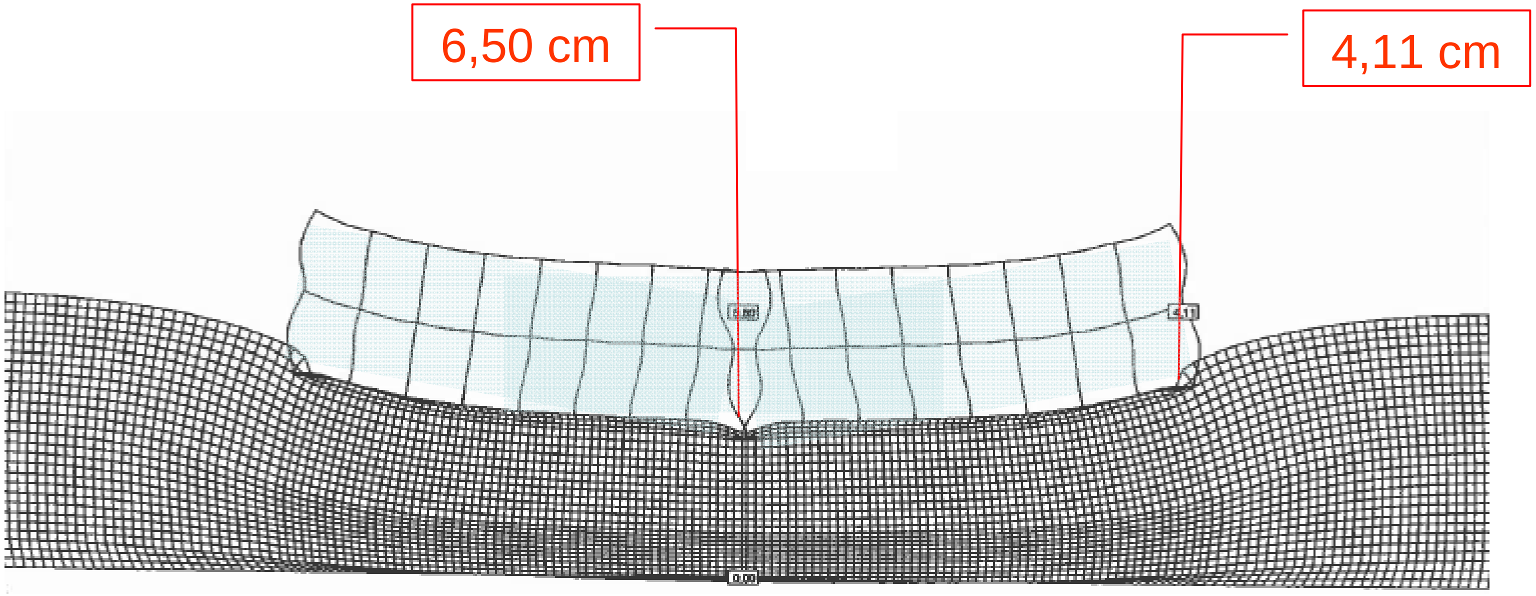
SOIL-STRUCTURE INTERACTION Model 2 (2D) : E values for soil



SOIL-STRUCTURE INTERACTION Model 2 (2D)

Settlement at row 17 (columns)

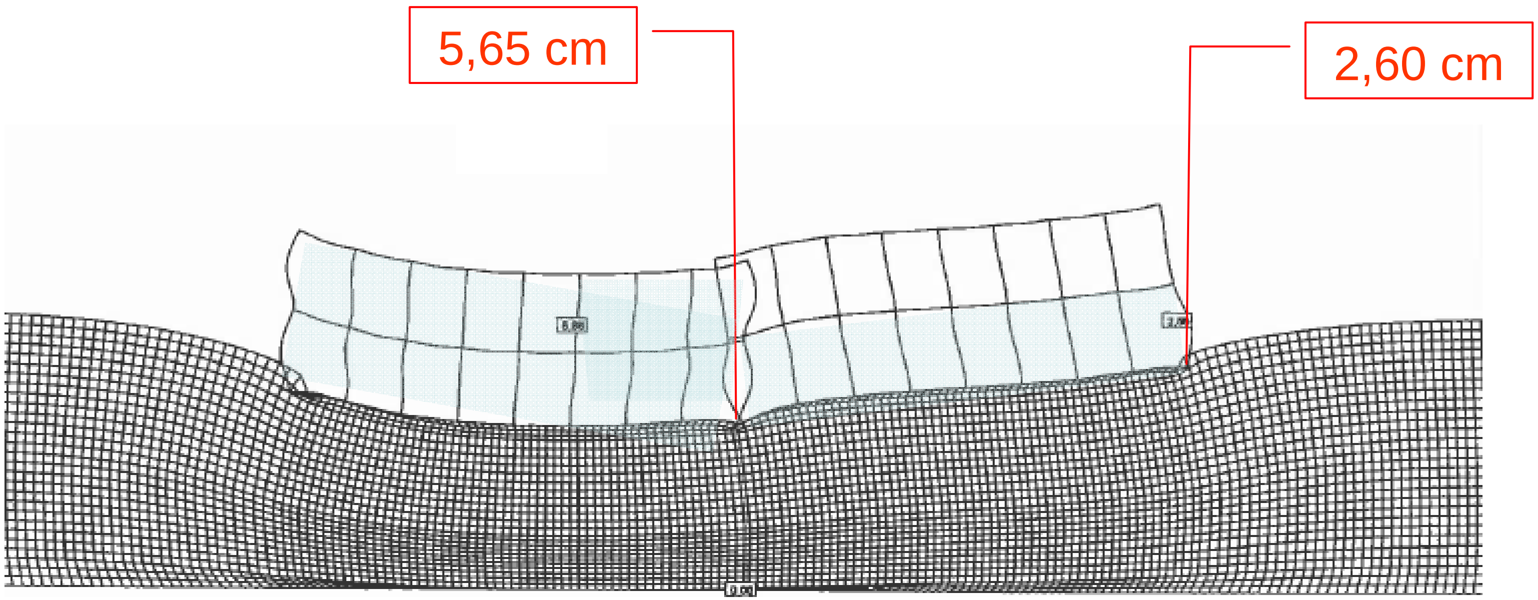
Water in the 4 tanks



SOIL-STRUCTURE INTERACTION Model 2 (2D)

Settlement at row 17 (columns)

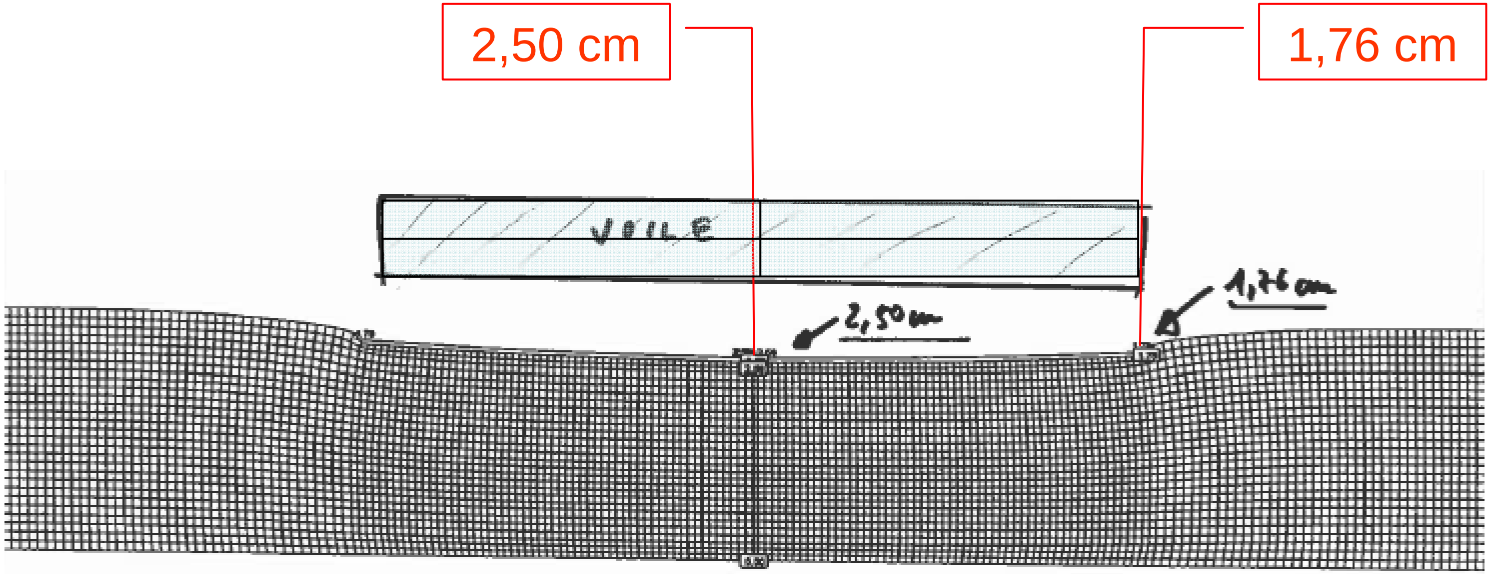
Water in 2 tanks on left, 1 on right



SOIL-STRUCTURE INTERACTION Model 2 (2D)

Settlement at rows 1 & 20 (walls)

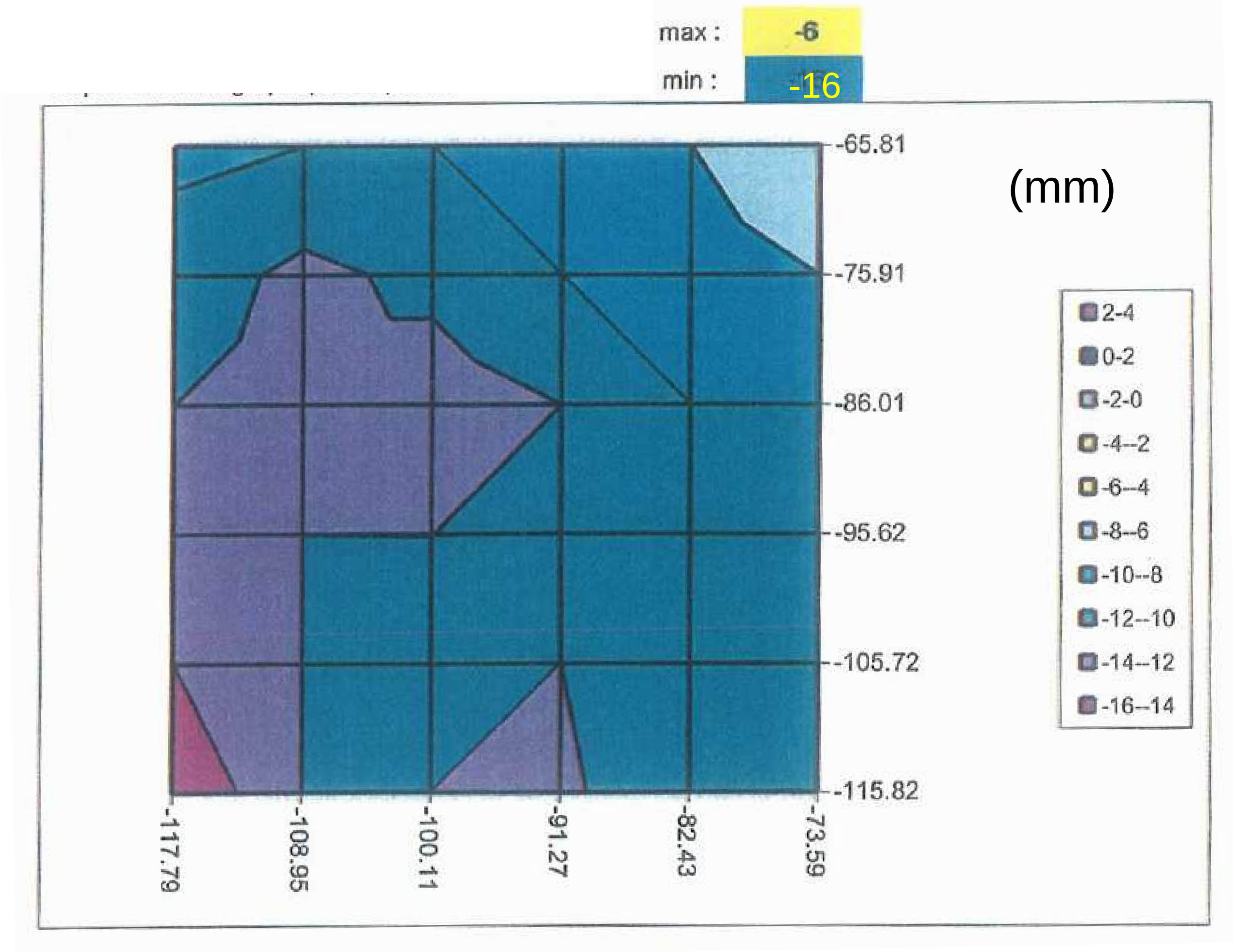
Water in the 4 tanks



SETTLEMENTS MEASURED IN SERVICE

CELL CZA

Settlements under water level fluctuation of 1,1m in one tank



THE OPINION OF THE CONSTRUCTION WORKS DIRECTOR
On the preloading solution

PROS	CONS
Lower cost	Fill material management at acceptable cost (supply, disposal)
Simple technique (standard earth works)	Impact of road transportation (400 trucks / day in the city)
hence : allows to prepare easily the structure works	Lack of schedule visibility
	Difficulty to obtain approval by the supervisor on the method and on the time for fill removal

THANK YOU FOR YOUR ATTENTION !