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Predicting the bearing capacity of sheet piles under vertical load

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Predicting the bearing capacity of sheet piles under vertical load

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ABSTRACT: In connection with joint research on the behaviour and bearing capacity of vertically loaded sheet piling, Unimétal and the Foundations Section of the LCPC have carried out a series of full-scale tests on box pile and wall elements, driven in the dense sands of the Dunkirk area and in the plastic clays of the North of France. The tests were on wall elements made up of 4 sheet piles of the Larssen IIs and IIn types, embedded 7.5 m and 12 m deep in the soils. The box piles were made of welded Larssen IIs elements. The sheet piles were fitted with removable extensometers or bonded gauges to determine the load distribution along the sheet piles and so be able to estimate the unit skin friction and point resistance. Based on the measurements made, an original method of estimating the bearing capacities of sheet pile walls and open box piles based on pressuremeter, CPT, and SPT tests has been imagined. Generally, the tests have shown that sheet piles can carry large vertical loads, suggesting that they can be used more often as foundations for civil engineering works or buildings.

1. GENERAL INFORMATION ABOUT SHEET PILES AND THEIR APPLICATIONS

Metallic sheet piles have been in long use in public works and civil engineering. The technique has evolved significantly since its origins and is still widely used. The annual output of the western hemisphere is currently between 1.5 and 2 million tons, about 12,000,000 m^2 of sheet piles, clear proof that sheet piles can still compete with more recent techniques.

Hot-rolled sheet piles are made in large rolling mills with several stands, known as "reversible two-high mills". Their production requires powerful installations of which there are very few in the world - about ten altogether, only one of them in France.

The successive improvements made to existing installations have made it possible to produce larger profiles than in the past. The profiles have become wider and wider: first 400 mm, then 450, 500, and now 600 mm of effective width.

As for the overall geometry of the profiles, partisans of U and Z profiles used to debate their respective merits, sometimes heatedly. These quarrels are now a thing of the past, and in most cases users prefer the U profiles, for reasons of ease of placement, to the Z profiles, which in theory have a better geometrical efficiency (ratio of modulus to weight).

In France, the mostly widely used sheet piles are the Larssen type, with an overall U shape and triangular interlock.

As for the steels, a broad range of grades is proposed to users, with yield strengths ranging from 240 to 430 N/mm2 and more.

High-yield-strength grades are increasingly used, both because their allowable moment/cost ratio is higher and because they stand up much better to driving.

Furthermore, the new steels for sheet piles are prepared with pure oxygen and have limited carbon contents, and so can be welded like standard building steels.

2. EVOLUTION OF DOMAINS OF USE

Concurrently with the technical evolution of the product, described briefly above, there has been steady growth of the domains of use of the sheet pile.

It was originally primarily a site material, used temporarily by contractors for cofferdams and sheeting, i.e. to make it possible to build conventional masonry or concrete foundations under dry conditions.

It was then used extensively in the maritime sector (including rivers and canals), a field in which it is still the material of choice for the construction of quay walls, locks, dikes, dry docks, and similar structures.

But is only recently that it has won recognition on dry land, where it is now in common use for such permanent and visible works as bridge abutments and piers, retaining walls for roads and rail lines, walls of underground parking facilities, normal and undersized cuttings and underpasses, noise barriers, and so on.

To win its place in these structures, remote from its traditional domain of use, the sheet pile had to overcome two further difficulties that were an obstacle to wider use:

- it had to be accepted as an attractive construction material in its own right, just like stone, brick, concrete, wood, etc.;
- it had to be recognized capable of carry large vertical loads to load- bearing strata.

There was much foot-dragging on the first score, because to many people the sheet pile called up images of rusting docks or, at best, walls with a summary coating of tar. But a few bold projects demonstrated that the sheet pile had a number of advantages over other materials: flexibility in adaptation to alignments, corrugations doing away with the monotony of large smooth surfaces, painted steel offering the possibility of countless colour schemes, etc. Because of this, many architects now accept the sheet pile as a construction material with undeniable aesthetic qualities in structures of all kinds.

The second point was more technical: it had to be shown that sheet piling could carry large vertical loads in addition to the customary bending loads, and ways had to be devised of predicting the bearing capacities of sheet piles in different types of soil.

This highly interesting subject led to experimental research, directed and implemented by the LCPC with help from Unimétal, the French producer of hot-rolled sheet piles.

3. RESEARCH OBJECTIVES AND MEANS

With a view to developing a representative design method applicable to all actual cases, it was decided:

1. to carry out full-scale static loading and pull-out tests on sheet piles installed by specialized contractors with the usual driving equipment;
2. to perform these tests on elements of sheet-pile walls and also on isolated box piles so as to make it possible to design mixed walls, often an advantageous variant in practice;
3. to work on instrumented profiles so as to ascertain the force distribution and laws of mobilization, i.e., distinguish between point resistance and skin friction [Ref.1];
4. and finally, so as to be able to deal with the commonest geotechnical situations, to conduct the research in compact and dense sands and in firm to very stiff plastic clays.

At the two locations chosen for this research, the same arrangements were used for:

a) the types of sheet pile and their embedment length in the soil;
b) the test procedure [Ref.2];
c) the preliminary soil surveys;
d) the load application and reaction devices;
e) the instrumentation of the profiles and measurement systems;
f) the recording of characteristic parameters during driving.

It was, for example, decided to use wall elements consisting of four Larssen IIn or IIs sheet piles, previously welded together in pairs in the workshop. The isolated box piles, with open or closed points, were also assembled in the workshop, from LP IIs sheet piles. Tables 1 and 2 summarize the characteristics of the profiles used, which are shown in Fig. 1 and 2, respectively.

Table 1

Sheet type	B	H	E (mm)	S	Perimeter (cm)	Weight (kg/m)	Sa (cm^2)
Box pile LPIIs	533	385	12.3	342	164	139	177

Table 2

Sheet pile type	B	H	E (mm)	R	Perimeter (cm/ml)	Weight (kg/m)	Sa (cm^2/m)
IIs	500	340	12.3	280	282	139	177
IIn	400	270	9.5	250	293	122	156

There was a survey of each of the test sites, including, as appropriate:

- 1 sounding with the taking of intact cores for laboratory tests;
- 4 static cone penetration tests (CPT);
- 2 Ménard pressuremeter tests (PM);
- 2 standard penetration tests (SPT);
- 1 self-boring pressuremeter test (PAF);
- 1 dynamic cone penetration test (CPD).

The load application and reaction devices were the same at both sites. The reaction device consisted of a metal beam connected to two reaction sheet piles. A 3 MN jack supplied by an electric pump was used to apply the test loads.

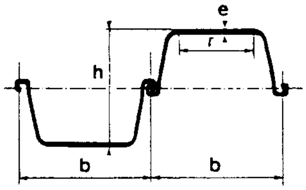

Figure 1. Section and caracteristics of the sheet pile wall element.

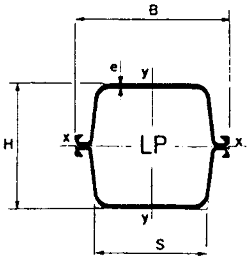

Figure 2. Section and caracteristics of the box-pile.

In addition to surface displacement measurements by 0.01 mm dial gauges, LPC removable extensometers (Fig. 3) were used for subsequent determination of the load distribution along the profiles. These latter measurements were accompanied, near the pile point, by measurements made using glued strain gauges. In the case of isolated box piles with open points, movements of the soil column (or "plug") inside the shaft were observed by a special set-up including an 0.01-mm dial gauge. All of the measuring and monitoring instruments were calibrated.

Figure 3. Removable extensometer being inserted into the sheet pile wall element of Merville.

Both the sheet pile wall elements and the isolated box piles are tested in accordance with the LPC procedure, i.e. in successive loads maintained for from 15 to 60 minutes, with no unloading between load levels.

When the profiles were driven on site, care was taken to record the characteristic driving parameters.

As for the procedures for calculating the bearing capacities of the various profiles, it was considered justified to use the formulae for piles. The well- known ultimate load formula was therefore used [Ref.3] :

$$Q_L = Q_L^P + Q_L^S$$

where:

Q_L is the total ultimate load at the pile head;

Q_L^P is the ultimate point resistance term;

Q_L^S is the total ultimate skin friction term along the shaft;

and, for each of the terms Q_L^P and Q_L^S:

$$Q_L^P = k.s_p.\alpha$$

$$Q_L^S = s_{lat}.q_s$$

where:

k is a point bearing capacity factor, designated k_p, k_c, or k_n according to the type of in situ test performed;

s_p is the point cross section;

α is the soil strength parameter measured at the point, designated p_l, q_c, or N according to the type of in situ test performed;

s_{lat} is the lateral area of the shaft;

q_s - unit skin friction.

In the specific case of the sheet piles, the research consisted of defining s_p and s_{lat} and quantifying the values of factor k and of unit friction q_s.

4. TESTS IN SANDS [Ref.4]

These tests were carried out in connection with a precise project. The opportunity was provided by the need to build several overpasses on mixed walls (sheet and box piles) in the Dunkirk area. The test section was located next to the right-bank abutment of bridge PI 54. The grain size distributions of Fig. 4 and the pressuremeter and penetrometer profiles of Fig. 5 and 6 give an idea of the sands encountered.

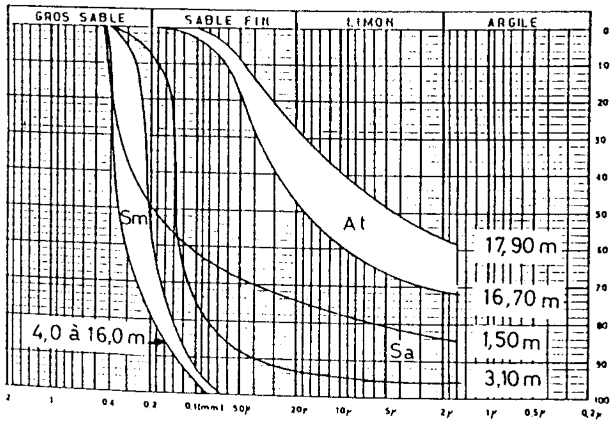

Figure 4. Grain size distributions for the sands of Dunkirk.

The timetable for work on the approaches to PI 54 made it possible to carry out a series of ten tests over a period extending from 1 April 1983 to 9 August 1984. Table 3 summarizes all of the tests.

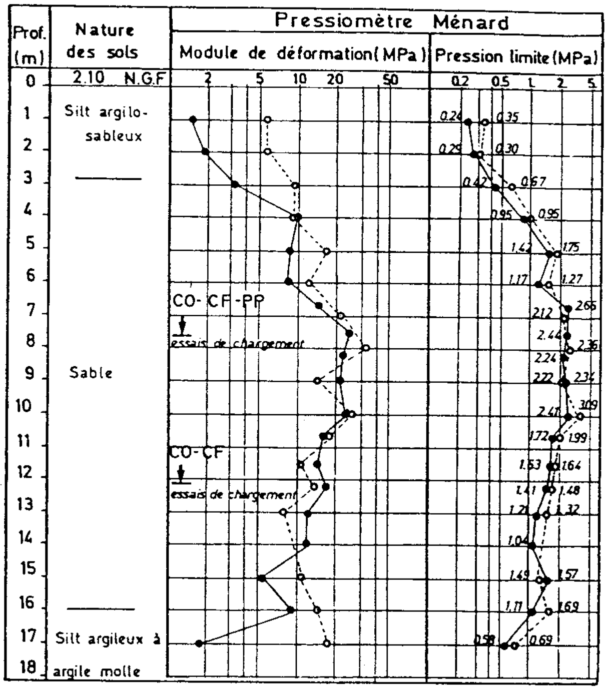

Figure 5. Pressuremeter profiles. Dunkirk.

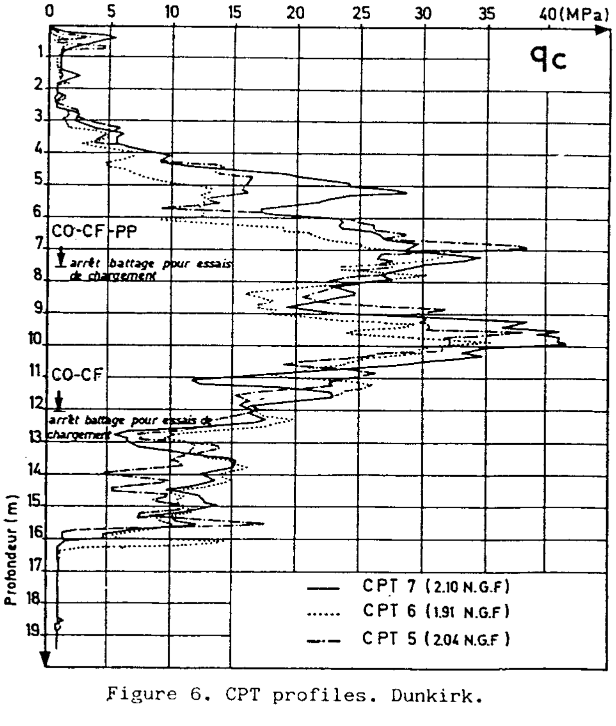

Figure 6. CPT profiles. Dunkirk.

It should be noted in connection with table 3 that test 4 on the open-point box pile was of a special type. It was performed to ascertain the actual behaviour under load of a box pile that had an open point but the top of which was filled after driving. The purpose of this arrangement was to simulate concreting of the top, customary at construction sites and also used subsequently to connect the pile to the structure.

Interpretation of all measurements yielded the following characteristic relations:

- settlement s_o/head load Q_o;
- settlement s_o/logarithm of time t;

Tableau 3

Sheet Pile	Test n°	Embedment (m)	Compression test	Pulling out	Observations
Closed end box-pile	1	7.76	1/04/83	----	none
	2	12.26	3/05/83	----	
	3	12.26	----	4/05/83	
	4	12.26	26/01/84	----	stopped test
Open end box-pile	1	7.72	31/03/83	----	open head
	2	12.22	28/04/83	----	
	3	12.22	----	29/04/83	
	4	12.22	19/04/84	----	closed head
	5	12.22	9/08/84	----	excavated up to 10.50 m
Sheet pile wall	1	7.42	26/04/83	----	none

Table 4

Sheet pile	Test n°	Depth (m)	Load (kN)				Factor k		
			Q_L	Q_L^P	Q_L^S	Q_C	k_p	k_c	k_N
PP	1	7.42	2400	520	1880	1800	1.07	0.10	0.59
CO	1	7.72	1140	480	660	900	1.25	0.10	1.11
	2	12.22	1500	467	1033	1200	2.04	0.17	1.08
	3	12.22	700	-	700	600	0	0	0
	4	12.22	1650	500	1150	1200	2.18	0.18	1.15
	5	12.22	1200	315	885	indet.	0.44	0.04	0.23
CF	1	7.76	2000	1280	720	1600	3.34	0.27	1.84
	2	12.26	2250	840	1410	1900	3.67	0.30	1.94
	3	12.26	1060	-	1060	800	0	0	0
	4	12.26	>1950	>690	>1260	≥1900	3.01	0.25	1.59

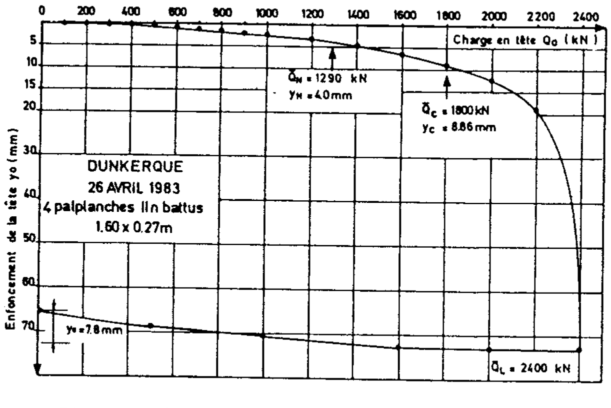

Figure 7a). Measured head load-settlement curve. Dunkirk.

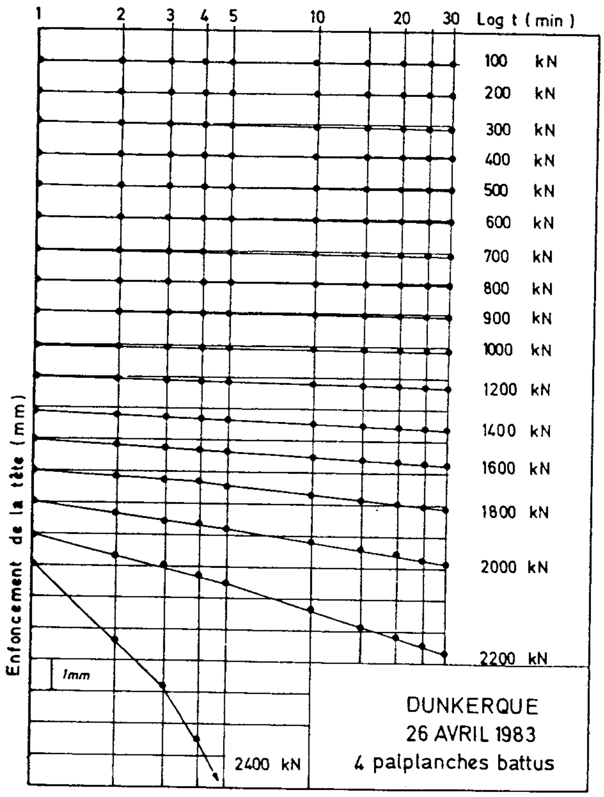

Figure 7b). Settlement variation versus time for each load step. Dunkirk.

- load distribution along shaft for each load level;
- curves of mobilization of unit skin friction.

As an example, some of these relations are given, in Fig. 7 and 8, for the 12.22 m open box pile (CO) and for the wall element consisting of 4 sheet piles (PP) (7.42 m long). All of the main results obtained in the ten tests are summarized in table 4. It is to be noted that the values of factor k are given for a settlement of the point equal to 10% of the equivalent diameter of the box pile or of the breadth of the wall element.

5. TESTS IN CLAYS [Ref. 5 & 6]

All of the tests, five in this case, were carried out on a special site at Merville, at the request of Unimétal. Below the clayey silt covering, about 2 to 3 m thick, overlies Flanders clay, very similar to London clay. Its main properties as measured in the laboratory are:

W = from 30 to 41;

W_L = from 72 to 92;

I_p = from 38 to 58;

γ = from 18.2 to 19.1 kN/m^3.

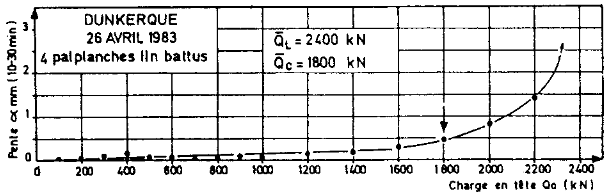

Figure 7c. Determination of the creep load. Dunkirk.

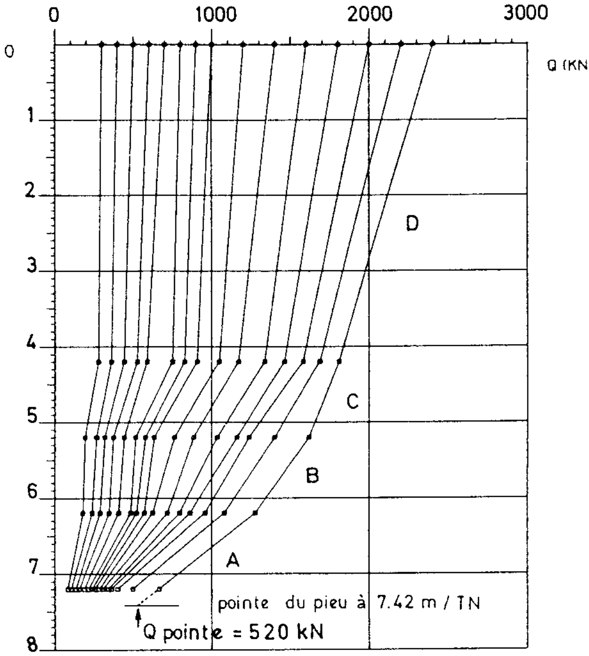

Fig. 7d). Load distribution along the sheet pile wall element. Dunkirk.

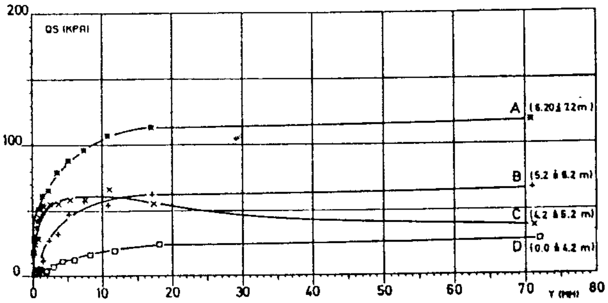

Figure 7e). Measured skin friction mobilization curves for the sheet pile wall element. Dunkirk.

Tableau 5

Sheet pile	Test n°	Embedment (m)	Compression
Closed end box pile CF	1 2	7.5 12.0	01/07/85 14/10/86
Sheet pile wall element 4PPIIs	1 2	7.5 12.0	02/07/85 15/10/86
Sheet pile wall element 4PPIIn	1	7.5	03/07/85

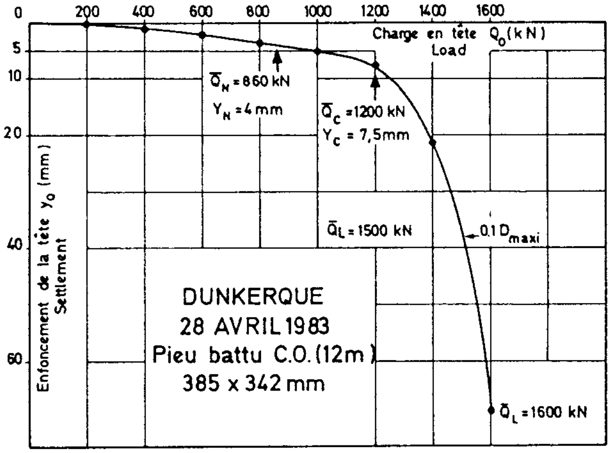

Figure 8a). S_o/Q_o curve for the box pile. Dunkirk.

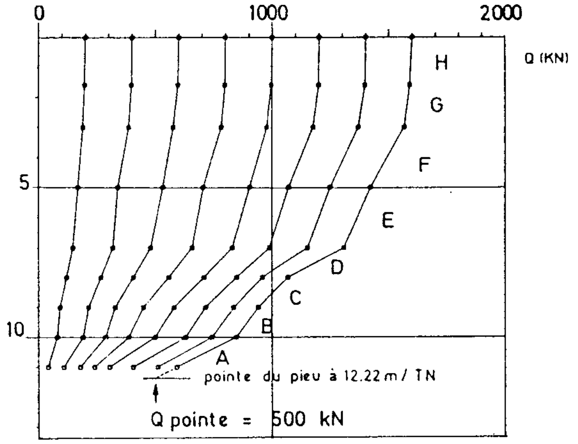

Figure 8b). Load distribution along the open end box pile. Dunkirk.

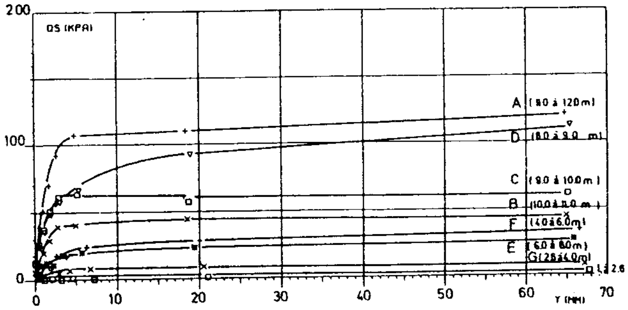

Figure 8c). Skin friction mobilization curves for the open end box pile. Merville.

Tableau 6

Sheet pile	Test n°	Depth (m)	Load (kN)				Factor k		
			Q_L	Q_L^P	Q_L^S	Q_C	k_p	k_c	k_N
CF	1	7.50	625	150	475	450	1.00	0.45	0.43
	2	12.00	1300	243	1057	950	1.20	0.49	0.54
PPIIs	1	7.50	1750	285	1465	1375	0.97	0.44	0.42
	2	12.00	3000	509	2491	2625	1.30	0.53	0.59
PPIIn	1	7.50	1300	275	1025	1000	1.37	0.62	0.59

The pressuremeter, penetrometer, and SPT tests carried out on the test site yielded the profiles shown in Fig. 9 and 10.

Table 5 sums up all of the tests, carried out from 1 July 1985 to 15 October 1986.

Fig. 11 and 12 give the characteristic relations obtained by interpretation of the measurements on the 12 m closed box-pile (CF) and the wall element made of four 12 m IIs sheet piles.

The main results deduced from the five tests are given in table 6. The values of factor k in this table are for a point settlement equal to 10 % of the equivalent diameter of the box pile or of the breadth h of the wall.

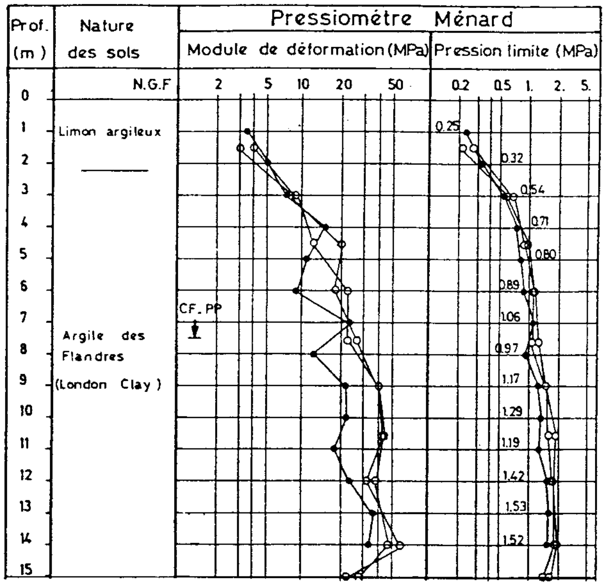

Figure 9. Pressuremeter profiles. Merville.

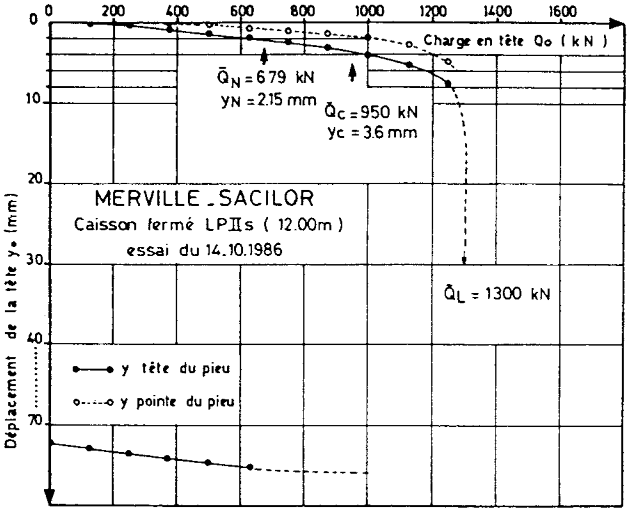

Figure 11a). S_o/Q_o curve for the end closed box-pile. Merville.

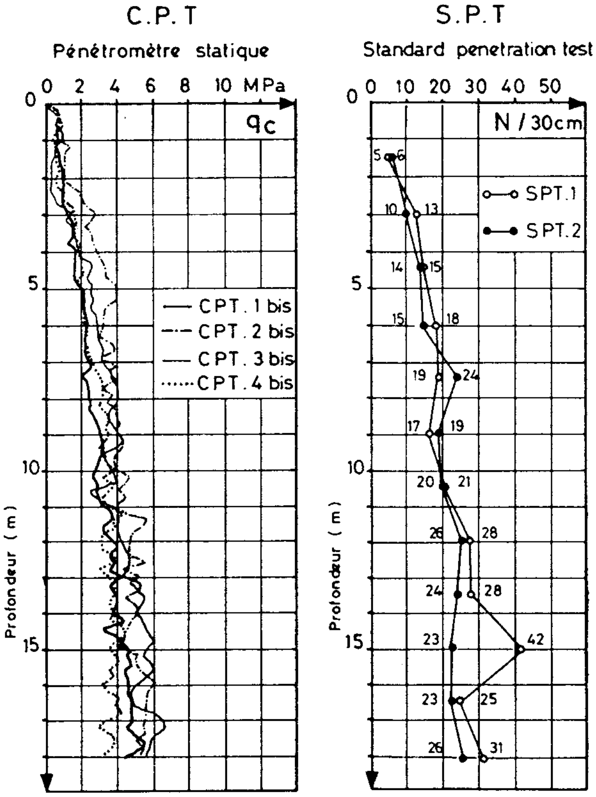

Figure 10. CPT and SPT profiles. Merville.

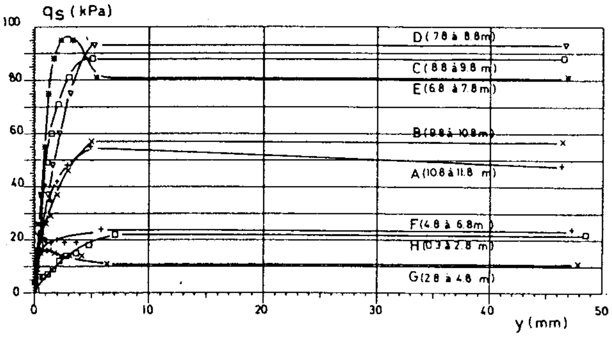

Figure 11b). Skin friction mobilization curves for the end closed box-pile. Merville.

Tableau 7

Sheet pile	Sands			Clays		
	k_p	k_c	k_N	k_p	k_c	k_N
PP	1.1 à 1.5	0.1 à 0.15	0.55 à 0.75	0.9 à 1.3	0.45 à 0.6	0.45 à 0.75
CO	1.3 à 2.1	0.15 à 0.2	0.8 à 1.1	0.8 à 1.1	0.4 à 0.5	0.4 à 0.6
CF	3.2 à 4.2	0.25 à 0.35	1.6 à 2.1	1.0 à 1.3	0.4 à 0.6	0.45 à 0.65

6. PROPOSED DESIGN METHOD

As stated earlier in section 2, this method is based on the usual formula for the ultimate load:

$$Q_L = Q_L^P + Q_L^S$$

As for the values s_p and s_{lat} used in the calculation of the terms Q_L^P and Q_L^S, they are defined as equal:

a) in the case of sheet-pile walls, to:

s_p - the inside area bounded by the flanges of the profiles;

s_{lat} - the developed area of the wall;

b) in the case of closed or open box piles, to:

s_p - the full point cross section of the box pile;

s_{lat} - the outside area of the box pile.

Fig. 13 shows all of these conventions schematically.

The values of bearing capacity factors k to be used according to the type of shape, type of soil, and type of in situ test are those given in table 7.

In the case of the open box pile, the values of k above can be applied only if the height of the soil column inside the shaft is equal to at least 15 diameters. This condition is based on the findings from the tests at the Dunkirk and Merville sites.

For the calculation of the total ultimate skin friction Q_L^S, the values of the unit ultimate skin frictions q_s are given by the charts of Fig. 14 and Table 8.

In the case of mixed walls with alternating sheet-pile wall elements and box piles, the bearing capacity calculations are performed by adding together the bearing capacities of the separate elements.

The allowable loads Q_A are calculated by applying the usual safety factors stipulated by regulations to the ultimate loads Q_L calculated as indicated above [Ref.7].

Tableau 8

Profile	Sand	Clay
Sheet pile walll element	Q_1 Q_2 if p_1 > 1MPa	Q_1 Q_2 if p_1 > 1MPa
Open end box-pile	Q_2	Q_1 Q_2 if p_1 > 1MPa
Closed end box-pile	Q_2 Q_3 if p_1 > 1,5MPa	Q_1 Q_2 if p_1 > 1MPa

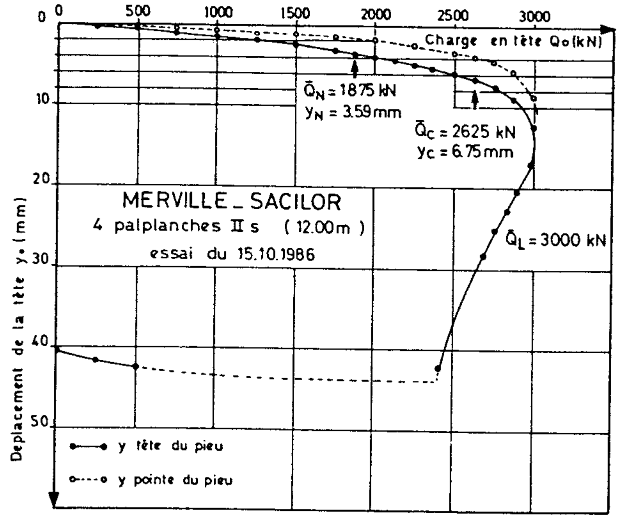

Figure 12a). S_o/Q_o curve for the sheet pile wall element. Merville.

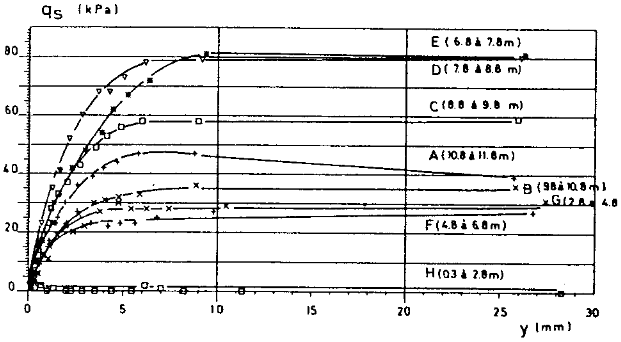

Figure 12b). Skin friction mobilization curves for the sheet pile wall element. Merville.

7. CONCLUSIONS

The main conclusions that can be drawn from these tests are as follows:

A. Sands :

1) the bearing capacity of a wall element made of four sheet piles is high; at the same embedment length the ultimate load QL reached is about 210 % of that of the open box pile (CO) and 120 % of that of the closed box pile (CF) (for a two sheet pile wall element only, divide these figures by two);

2) the total bearing capacity of the closed box pile (CF) is on average 75 to 50 % greater than that of the open box pile (CO), depending on embedment and soil compacity;

3) the ultimate point resistance Q_L^P of a closed box pile is 260 to 180 % greater than that of an open box pile in which the soil column (or "plug") inside the shaft adheres to the shaft walls;

4) concreting the top of an open box pile after driving, does not give it the bearing capacity of a closed box pile.

B. Clays :

1) the bearing capacity of a four sheet pile wall element is extremely high in comparison with a box pile; for the same embedment the Q_L is about 280 to 230 % of that of the closed box pile (CF), depending of the soil stiffness.

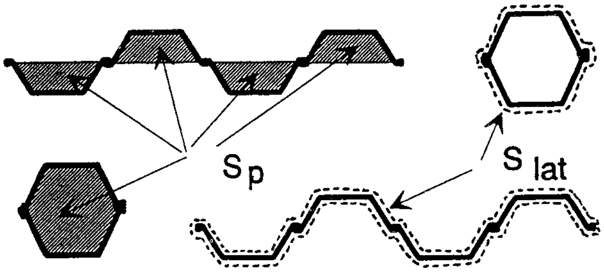

Figure 13. S_p and S_{lat} definitions S_p correspond to the shaded area.

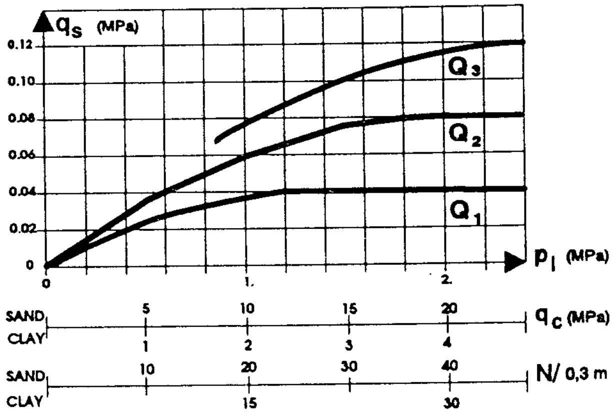

Figure 14. Chart for the assessment of unit friction q_s as a function of p_l, q_c and N.

8. REFERENCES

[1] Bustamante M., Gianeselli L. & Jézéquel J.F.. La mesure des déformations à l'aide des extensomètres amovibles LCPC, Méthode d'essai LPC 34, (à paraître).

[2] Bustamante M. & Jézéquel J.F.. Essai statique de pieu isolé sous charge axiale. Méthode d'essai LPC 31, févr. 1989.

[3] Règles de justification des fondations sur pieux à partir des résultats des essais pressiométriques, document SETRA-LCPC, otc. 1985.

[4] Bustamante M., Gianeselli L. & De Coninck J. Etude de la portance de profilés métalliques battus dans les sables de Dunkerque. Rapport interne LCPC, janv. 1986.

[5] Bustamante M. & Gianeselli L. Compte rendu d'essais de chargement Merville-Sacilor 1, Rapport interne LCPC, nov. 1985.

[6] Bustamante M. & Gianeselli L. Compte rendu d'essais de chargement de profilés battus Merville-Sacilor 2, Rapport interne LCPC, déc. 1986.

[7] Bustamante M., & Gianeselli L. Coefficients de sécurité liés au calcul des pieux. Compte rendu du XIème CIMSTF, San Francisco, août 1985.