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Some dynamic parameters of drilled piles under low- and high-energy tests. Correlation with the static pattern.

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SYNOPSIS

The aim of this article is to present and discuss some parameters and experimental results obtained by both kinds of dynamic testing (low- and high-energy tests) on drilled piles in different sites, and some correlation between some specific dynamic and static parameters, when static tests have been carried out on the same piles.

The dynamic tests are the following:

- In the field of *Low-energy testing* (integrity tests): the "Mobility" (or Admittance, or Vibration) method;
- In the field of *High-energy testing* (Capacity tests): the "Case" method.

The parameters which are examined are connected with the dynamic behaviour of piles: the first one *(Dynamic Stiffness)* is obtained by low-energized piles, the other (the *"Dumping Factor"*) by high-energized piles. They have an equivalent in the static pattern of behaviour.

Some experimental data - obtained in different sites - are published.

Correlation concern: *"Dynamic Stiffness"* versus *"Case Capacity"* - *"Case Capacity"* versus *"Static Capacity"*, and they are shown graphically.

INTRODUCTION

The dynamic behaviour of drilled piles under low-energy testing (such as obtained by "Mobility" or "Admittance" methods) and under high-energy testing (such as obtained by CASE, or SIMBAT or CAPWAP tests) is more and more frequently analysed in order to derive information concerning the Integrity of the structure (by the low-energy tests) and its Capacity (by the high-energy tests), respectively.

The aim of this article is to present and discuss some parameters and experimental results obtained by both kinds of dynamic testing (low- and high-energy tests) on drilled and cast-in-place piles in different sites, and some correlation between some specific dynamic and static parameters, when static tests have been carried out on the same piles.

The dynamic tests that have been carried out on drilled and cast-in-place piles in different sites are the following:

- Low-energy tests (Integrity tests): the "Mobility" (or Admittance, or Vibration) method;
- High-energy (or High-Strain) tests (Capacity tests): the "CASE" method (the standard CASE method modified).

A good knowledge of the above methods is helpful for a better understanding of the following paragraphs. Theoretical basis and experimental results about the said methods can be found mainly in [3] in French, [10], [33], [34] in English and [5] in Italian.

Sites where tests have been carried out, dimensions of the tested piles (in m) and soil conditions are listed in Table 1 (next page). Dynamic testing has been carried out before the static ones, except on T.P.2 in site n. 11 (*). Results of low-energy tests are plotted in Figure 7, while results of high-energy tests are plotted in Figures from 9 to 18.

The parameters that we are going to examine are:

- The *"Dynamic Stiffness"*, in the low-energy "Mobility" testing
- The *"Dumping Factor"* in the "CASE" method testing with the involved parameter of the "Impedance Profile".

The correlation that we are going to examine are:

- *"Dynamic Stiffness"* versus *"Dynamic capacity"*;
- *"Dynamic bearing capacity"* versus *"Static Bearing Capacity"* (we mean capacity determined by dynamic and static testing procedures).

SOME PARAMETERS FROM THE "MOBILITY" AND "CASE" METHODS

The two parameters which we are going to examine hereunder are connected with the dynamic behaviour of piles: the first one *(Dynamic Stiffness)* is obtained by low-energized piles, the second one (the *"Dumping Factor"*) by high-energized piles. They have an equivalent in the static pattern of behaviour.

"Mobility" method: the "Dynamic Stiffness"

In a pile dynamically exited at low frequencies, the inertia effects are insignificant and the pile-soil unit, behaving like a spring, gives a straight line response at the start of the Vo/Fo curve. The slope of this straight line is "Elasticity", and the reciprocal is "Stiffness".

Formula of Stiffness (S) is:

$$S = \int \left|\frac{V}{F}\right|_{(\omega)}^{\alpha} = \frac{1}{\Omega M} \left|\frac{V}{F}\right|_{(M)}$$

According to A.G.Davis and C.S.Dunn [9] [10] *"E' corresponds to the slope of the initial tangent modulus to a load-displacement graph obtained from a static load on the pile. Although it cannot be pretended that the measurement of E' can be precise, it does give a good indication of the ability of a pile to carry load"* (page 679).

The same Authors enumerate the factors affecting the stiffness measured at the head of the pile, as follows:

(a) the stiffness of the concrete constituting the pile Eo;
(b) the stiffness of soil surrounding the pile as indicated by the attenuation of the oscillations of the V(M)/F(M) response curve and measured by the *damping factor*;
(c) the stiffness of the soil supporting the base of the pile.

N.	Sites	Pile l. (m)	Pile Φ (m)	Soils
1	Columbia A	22	0,6	Clays with gravel - silty and sandy clay
2	Columbia B	13	0,3	Silty clays with gravel - soft clay w.peat-greyclays.
3	Fiumicino	35-40	0,8	Silt, from loose to plastic, with peat.
	(Rome)	26-28	0,6	Clayey silt, sandy silt, fine sand
4	Marghera (Venezia)	12	0,6	Sandy silt, medium to fine sand
5	Roma	35	0,8-1	Silts, silty clay, sands
6	Abruzzi	20	1	Clays
7	Lazio	-	1,2	Gravels, silty clays, clay.
8	Lazio	-	0,6	Sandy silts and clayey silts
9	Mostacciano (Lazio)	22,5 22,5 22,5 17,0	0,5 0,5 0,5 0,5	Silty and sandy clays Silty sands Sandy silts. Sandy silts.
10	Lazio (Vitil.)	6,5	0,5	Sandy and clayey silts
11	Turkey T.P. 2 (*)	26	1,2	Fragm. of claystone, limest., sandst. in clay matrix.
	T.P.4	16	1,2	Silty clay w. sand + gravel; clayey sand w. granite fragments.
	T.P.5	24	1,2	Silty clay, weathered granite in clayey matrix.
	T.P.6	34	1,2	Silty sand, sandy clay, clayey sand w. rock fragm.
	T.P.7	23	1,2	Silty clay w. claystone + limestone fragments.
12	Nocera inf.	35	1,2	Sands with gravel - gravel with sand - mediium sands - vulcanic tuff
13	Bergamo	18	1	Sandy gravel with coarse gravel
14	Contarina	24	0,6	Silty and medium sands with organic matter
15	Castelmassa			
	TP1	24	0,6	Clay and silty clay
	TP2	24	0,6	Fine to medium sands
16	Luzem (CH)	25,5	0,9	Silty Sands
17	Belgium	14,5	1	Clays, medium to fine sands
18	Milano E116	26	0,8	Gravels and medium to fine sands
	D13	16	1	Gravels and medium to fine sands
	E232	16	0,8	Gravels and medium to fine sands

Table 1

At the base of the pile, the anchoring soil has a Stiffness which can be calculated from Boussinesque theories in semi-infinite pattern. Let us consider:
a) Embedding conditions in soil at the base: the effect on top of the pile (stiffness measured at the head of the pile E') of this deep stiffness will be higher as much as such embedding is important; on the contrary, E' will be attenuated in a long pile and in a stiff soil.
b) Lateral soil conditions: E' will increase with the length of the pile, up to an asymptotic value equal to: $\sqrt{RI/SI}$, where: $RI = \pi v^1$ is the value of stiffness from lateral soil, (and v^1 is the module of elasticity of soil); $SI = 1/SE$ is the Elasticity of a free pile (S=section of the pile, E = Young's modulus of concrete).
The stiffness measured at the head of the pile will be the sum of the two terms whose variations in function of the length of the pile can be represented as shown in Fig. 1 (from [3]; on the left the case of a short pile, on the right the case of a very long pile).

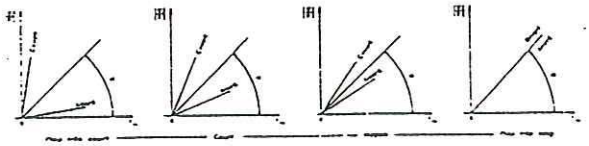


Figure 1

At very low frequencies, Admittance has the following expression: $j\omega/E'$; such an expression increases with the frequency of excitation

The starting part of Admittance curves can be represented as follows in Figure 2, where $tg\alpha = \sqrt{SI/RSI}$. The Admittance curves allow an estimation of the embedding conditions of a (not too long) pile: in the case of a strong anchoring the curve will show the first resonant peak at a frequency equal to Co/4l, and in general the slope of the curve will be as flat as the embedding conditions are good [9].

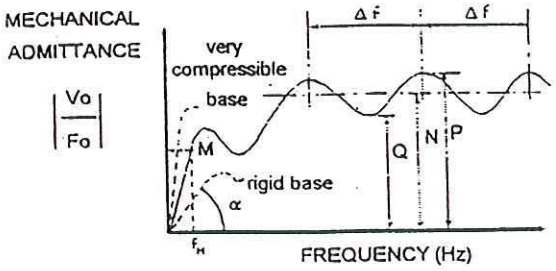


Figure 2

It is worth noticing that the calculation of E' from the Mobility curve is often difficult owing to the "noise" disturbances which generally occur in the first part of the curve (low frequencies). This is the reason why a new procedure has been developed allowing a very accurate calculation of E'.

The principle is that if a level of force unit is applied to a structure, its displacement will have the elastic elasticity as its limit. The displacement of the pile under the impact of the instrumented hammer is calculated by the integration of the velocity signal, with some corrections

that take into account the non-linearity of the geophones.

The reply of the pile to the level of unit force is obtained by integration both of force and displacement. The two calculations are represented in the Figure 3.

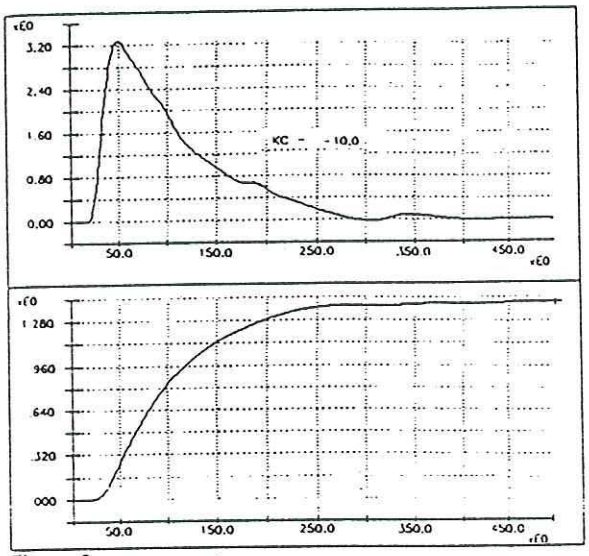


Figure 3

Some interesting comments about dynamic and static stiffness, and their connection with the "quake" (the displacement needed to mobilise the maximum soil resistance locally under dynamic conditions) can be found in [38].

The "Case" method : the Dumping Factor

In the "General Report" n. 2 of the *"Proceedings of the Fourth International Conference on the Application of Stress-Wawe Theory to Piles"*, held in The Hague (Holland) in 1992, Prof. M. W. Bielfeld and F. Rausche write (page 217): *"With proper care, static testing is the best, but also the most expensive way to be certain about the bearing capacity of a pile. More efficient and economical is to load the pile dynamically"*. This explains why, from 25 years, dynamic load tests for driven and drilled piles have been available and are in quite common use throughout the world.

Pile and soil behaviour can be modelled with different criteria, and signals can be processed in different ways: so a certain number of procedures have been developed: CAPWAP (Rausche et al., 1972), TNOWAVE (Middendorp, 1987), SIMBAT (Paquet, 1988), and others.

The CASE Method (Goble et al., 1975) was developed to evaluate the total resistance Q (shaft and toe) based on the assumption of a rigid-plastic behaviour of all factors contributing to the resistance. See the Formula of Q in [16].

The static resistance Q_s is obtained by formula :

$$Q_s = Q_0 - J\,[F(t^*) + I \cdot v\,(t^*) - Q]$$

in which t* is the time corresponding to the maximum of velocity.

According to Paquet [36] and [37] the simplified formula of Q_0 is: $Q_0 = F\uparrow - F\uparrow_{free}$, that is to say the difference between the actual upward force (measured at the pile top) and the same force calculated for a free pile.

It is now clear that in order to obtain the maximum of reliability when the classic CASE method is applied for the calculation of the Capacity, the actual values of the Damping Factor and of Impedance along the pile shaft should be carefully assumed.

It can be easily seen that the only unknown parameter is the Factor "J", while the others are measured on top of pile (for factor I see next §). J is the "Case Factor" or the "Damping Factor", a nondimensional empirical Factor which is commonly assumed on the basis of soil conditions. Suggested values can be found in literature, as many Authors have studied this parameter in different kinds of soil: see Ref. [16], [39], reconsidered by [45] page 176, suggesting new values at page 178, and [38] page 263). Figure 4 shows the load/displacement curve of a static load test on a drilled pile and the different bearing static capacity estimations obtained by the Case Dynamic test on the same pile, when assuming different values of the "Case Factor".

PROJECT: Warehouse
PILE TYPE: DRILLED
DIAMETER = 800 mm LENGTH = 35 m
COEFF CASE = 0 3 ESTIMATE STATIC CAPACITY = 185.2 +/- 14.2 t

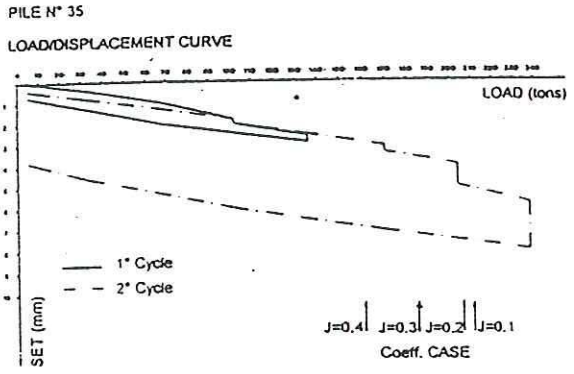


Figure 4

It can be easily seen that the choice of the right value of J is important in order to obtain a realistic estimate of the static capacity.

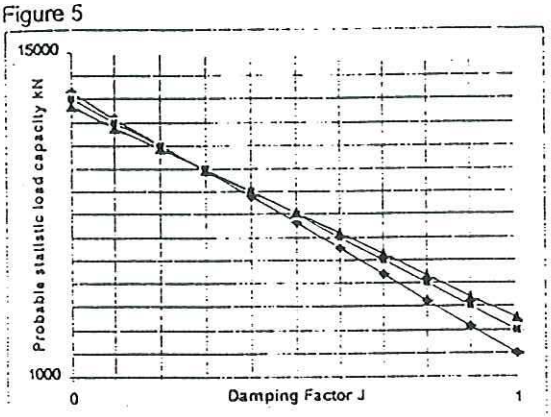
The most reliable way to be sure that we are choosing the right value of J is to calculate it on the basis of the results obtained by carrying out both dynamic and static load tests on the same pile (the so called "Trial Piles" or T.P.): an experimental correlation can thus be obtained.

Another way for an appropriate choice of the value of the J Factor is to assume the value that corresponds to the intersection of the curves (generally three) obtained experimentally by dropping the mass on the pile from different heights (for instance 0.3 - 0.6 - 0.9 m), measuring on the pile the dynamic reaction for each one of them, and then calculating the corresponding (bearing) capacities assuming different values of J (see Fig. 5).

Owing to the time-dependent visco-elastic nature of the soil, the faster is the strain rate, the highter will be the

soil reaction. In other terms, the shaft resistance is not a constant but velocity dependent. As T. P. are seldom available on sites, this procedure becomes very interesting.
Note that a similar procedure is applied in other testing methods such as SIMBAT (see Ref. [8] page 551 and the "K Method" [48] page 345). See also Ref.[24] page 421.

Figure 5



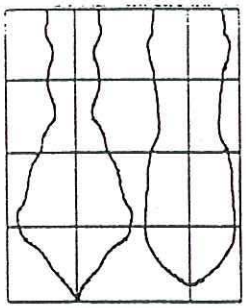


Figure 6

The Impedance log. As a matter of fact, in any simulation of the dynamic behaviour, the pile is represented by a dashpot with a dumping factor equal to the pile impedance: $I\ (Z) = \rho\ c\ A$, where A is the cross - section of the pile.
Generally, the Z value is introduced into calculation as the result of the theoretical dimensions of the pile section, concrete density and velocity of the compression waves into the pile. Such values are considered as a constant along the whole length of the shaft. Recently developed procedures for interpreting low - strain tests.
in terms of an "Impedance Profile" [37] can now be adopted for a better assumption of the real pile impedance.
Fig 6 shows how much the impedance profile can be different from the theoretical one.

The shaft resistance mobilisation. One of the major objections to the Dynamic Load tests is that the skin friction of the soil is not always fully mobilised. A diagram of shaft resistance versus time and depth has been suggested by Paquet [36] to verify the extent of mobilisation during the impact.

With reference to Table 1, on the Site n. 11, an Impact Force of 12700 kN has allowed to excite strain-gauges situated at - 23 m (TP5) and -17 m (TP6); the dumping was 10 dB and 8 dB respectively.
By installing strain-gauges at different levels inside the pile shaft, the distribution of strain along the shaft under dynamic loading can be obtained, as we are used to getting from the static loads.

CORRELATION

Correlation between static capacities and the estimates obtained by different dynamic tests have been examined in [22] over 46 cast-in-place piles selected among one hundred groups of tests. Dynamic methods which have been considered are: P.D.A. (Pile Driving Analysis), W.E. (Wave Equation) i.e. the CASE method, and F.S. (Frequency - Stiffness) method. Within the range from 0,9 and 1,1 the Error Distribution of the comparison of Static and Dynamic Tests have been 82,4% by the PDA method, 66,7 % by the WE method and 23,5% by the F.S. method.
The Authors underline: a) that the main factor of error in the F.S. Method is essentially due to the difficulties in determining the exact shape of the shaft, and the quality of the concrete of the piles (i.e. the "Impedance"); b) that specific criteria should be adopted for single regional areas, adapting the dynamic approach to the specific soil conditions and piles characteristics.

"Dynamic Stiffness" (E' dyn) vs "Case" Capacity.

The graph of Figure 7 shows the correlation between Dynamic Stiffness (by Mobility or Admittance method) and Dynamic Capacity (by the "Case" method), plotting the data obtained in11 of the sites listed in Table 1. The value of the Dynamic Capacity is assumed as the maximum load that the pile can bear without permanent settlement. It is therefore the limiting value of load between elastic and plastic behaviour of the pile (see more details in next §).

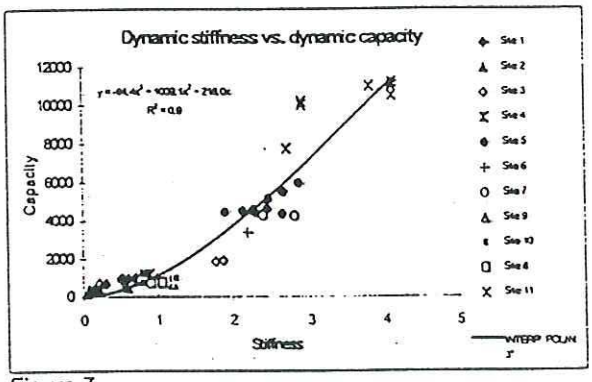


Figure 7

"Case" Capacity vs Static Capacity

In literature, statements of good correlation between static and dynamic (bearing) capacities are more and more frequent. We will limit our comments to drilled and cast-in-place piles and to tests carried out by CASE or similar dynamic methods, where static tests have been carried out as well. Historic cases of Dynamic Load Tests on driven piles are numberless.

In [7] such correlation concerns 2 piles (0,8 m in diam., 30 m long), drilled in silty clays and sands, embedded in medium dense saturated sands. On test n. 1 the Static Capacity was 2750 kN and Dynamic (by CAPWAPC) was 2822 (ratio 1,026). On pile n. 2 the Static Capacity was 4000 kN and Dynamic was 3290 (ratio 0,823). Static tests have been performed after the Dynamic tests.

In [12] correlation concerns 20 bored piles (0,8 m in diam., from 22 to 46 m length) embedded in weathered rocks: ultimate resistance varies between 1700 and 6600 kN, and the relative deviation Static/Dynamic (by CASE Method) varies between about -9% and + 6%.
In [47] a large review of tests on different kinds of piles is provided: Franki, Atlas and "grout-injected" piles have been tested by CAPWAPC and TNO methods, and results show good agreement with static behaviour.
In [48] the dynamic behaviour of 4 drilled and cast-in-place piles is observed by a measurement of strain and displacement at the top of the pile (similar to the CASE Method with displacements measurements added: it is called the "K Method"). Capacity is estimated from a change of a rigid motion in the soil spring constant, caused by the non-linearity of the soil under different impact forces. Static tests have been carried out after the Dynamic tests. The very good correlation in the calculation of the Capacity with Static and Dynamic tests is shown in Table 3.
Numberless examples of good correlation in large diameter drilled piles have been presented in the Proceedings of the Fifth Int. Conference on Application of Stress-Wave theory to Piles, Orlando, September 1996.
We present (Annexe) the results of 10 tests carried out on drilled and cast-in-place piles, in 6 different sites (listed in Table 1). The results are shown in a graphic way (Fig from 9 to 18).

CONCLUSIONS

Concerning "Dynamic Stiffness"

a) The value of the "Dynamic Stiffness" *E'*, if calculated as mentioned, *"provides an evaluation of the pile stiffness under static loads"* (Ref.[19] page 213). Authors Ref. [43] have suggested a correlation between static (bearing) capacity and head stiffness of piles, by a so called "layered integral load transfer method". Even if we have no elements enough to share completely this opinion, we estimate that such a value shows very good correlation with the behaviour of a pile under a static load in the elastic field (which is generally the case of the working loads). This means that such a parameter can be used also to select - rationally - the pile (or piles) to undergo static tests inside a pile population, which is generally chosen without any geotecnical criteria.
b) The value of the *E'* and the position of the first resonant peak on the Frequency (x) axes of the Mobility curve allows to establish if a pile is embedded or not.
c) A simple statistical treatment of the *E'* values of a pile population - in similar soil conditions - allows a judgement on the "quality" of the whole foundation. Quality is higher if the distribution of the "stiffness" values has a sharp gaussian curve shape. Fig.8 shows (sites 1 and 2) the typical distribution of *E'* in a "good quality" foundation (upper) and in a "bad quality" foundation.
A similar approach to the *"quality assurance"* of a pile population has been suggested by Klingmuller in [25], where wave velocity in the piles is statistically evaluated. We rather suggest to take into account the Stiffness, as it seems to be a more sophisticated and interesting parameter then wave velocity, as it deals not only with the concrete quality but also with the pile behaviour under load in the elastic field.

See also Ref. [9] Fig. 18.
d) Figure 7 suggests that a good correlation between Dynamic Stiffness and Dynamic Capacity can be assumed, when the Stiffness value is carefully measured as described, and the high-energy tests are carried out with the described procedures.

The correlation curve is a third order polinomial, with a coefficient equal to 0.9.

Such correlation can be better defined within a single site.

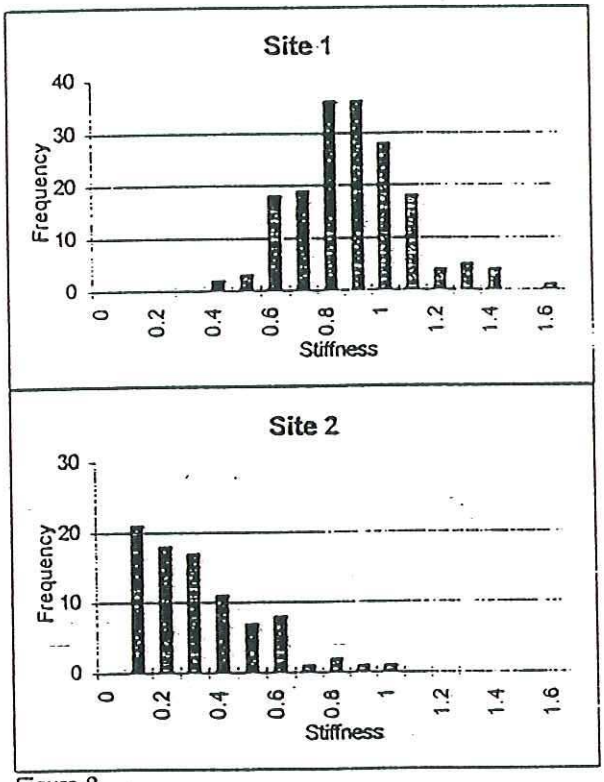


Figure 8

e) Inside the Chineese school, some Authors estestimate that a good correlation (0,9 - 1,1) between Dynamic Stiffness and Static Capacity in drilled and cast-in-place piles can be obtained, provided that great accuracy is observed in the tests and in calculations [22]. In particular, the shape of the pile (i.e. Impedance Profile), the difference between shear wave velocity inside the pile and in the soil, should be carefully taken into account.

Concerning Capacity by "Case" method.

Two different kinds of Static load tests are generally prescribed and executed on sites: the "Design Tests" (with the aim of verifying the calculations, carried out on the so called "Trial Piles"), and the "Control Tests" on some "working piles" of the whole population (whose aim is to verify that the behaviour of thje pile corresponds to design). "EUROCODE 7" Part. 1 "Geotechnical Design, General Rules" states that: *"The design shall be based on one of the following approaches": (a) The results of Static Load Tests...; (b) empirical or analytical calculation methods...; (c) "the*

results of dynamic load tests whose validity has been demonstrated by static load tests in comparable situations" (Art. 7.4.1).
Authors who deal with the Dynamic Capacity are reluctant to define the actual meaning of such a parameter in the static pattern. Some of them speak of "ultimate " bearing capacity. The Chinese School has a familiarity with the term "Yield load", which is the load corresponding to maximum curvature of the load/settlement curve. We share the opinion of A.E. Holeyman in Ref. [19] page 213: *"..the confidence in soil resistance prediction will be limited to the ultimate shaft resistance distribution and the beginning of the loading curve at the pile toe"*. Experimental results shown in Figures from 9 to 18 authorise us to understand the value obtained from the suggested "CASE" method (the classic CASE method improved by more accurate determinations of *J* and by variables values of *Z* derived by the "Impedance Profile") as the value of the load that the pile can bear with a minimum elastic settlement. Such a value is therefore situated at the end of the elastic phase or the beginning of the plastic phase of the load/settlement curve.

We estimate that the best procedure is that of carrying out both Dynamic and Static load tests on the Trial Piles, and then to check the Capacity of a significant number of working piles of the whole population by the sole Dynamic tests. If Trial Piles are not available, we believe that Dynamic tests can be performed as a valid substitute of the Static Tests: they have reached enough reliability and, thanks to their low cost and rapid execution, they can be extended to a high number of piles, offering a better knowledge of the actual quality of a population of piles. We underline that traditional habit (according to usual prescriptions and some standards) of carrying out Static Tests on 1 or 2% of the population of a pile foundation gives no significant information from a statistic point of view. Last but not least, EUROCODES (Table 7.1) introduce a Factor ξ in deriving the *"ultimate characteristic bearing resistance Rck from values Rc measured in one or several pile load tests": Rck = Rc/ ξ.*
Such a Factor decreases as the number of load tests increases: it means that one can assume a higher value of the"ultimate characteristic bearing resistance Rck" as many load tests have been carried out.

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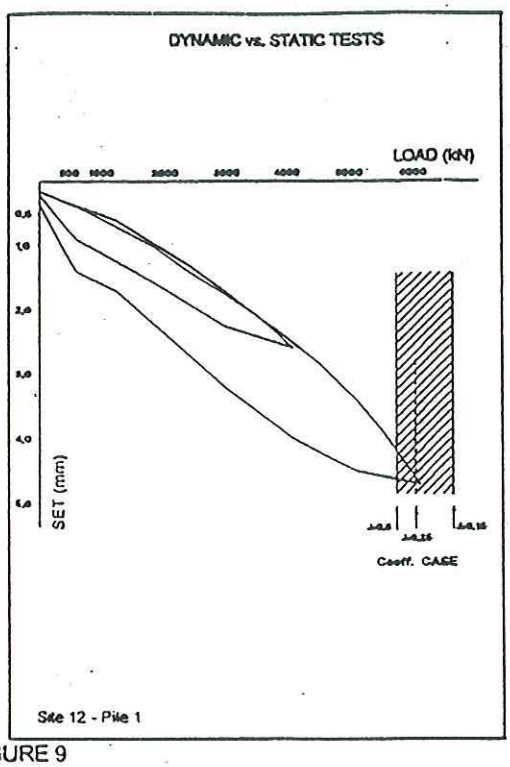


FIGURE 9

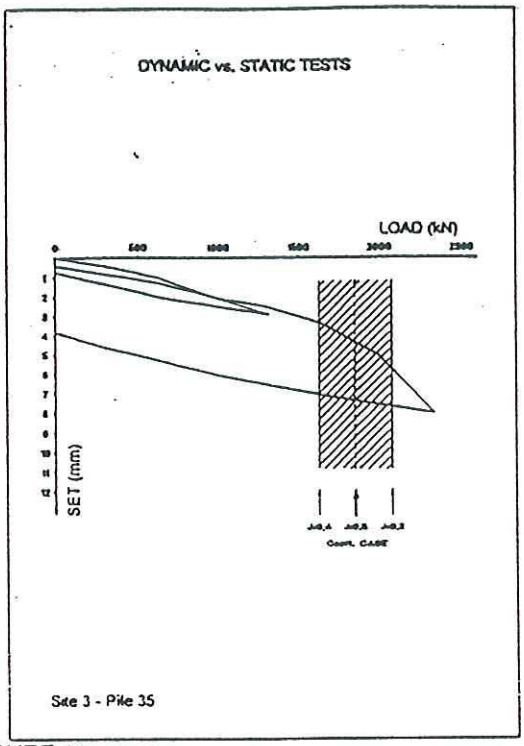
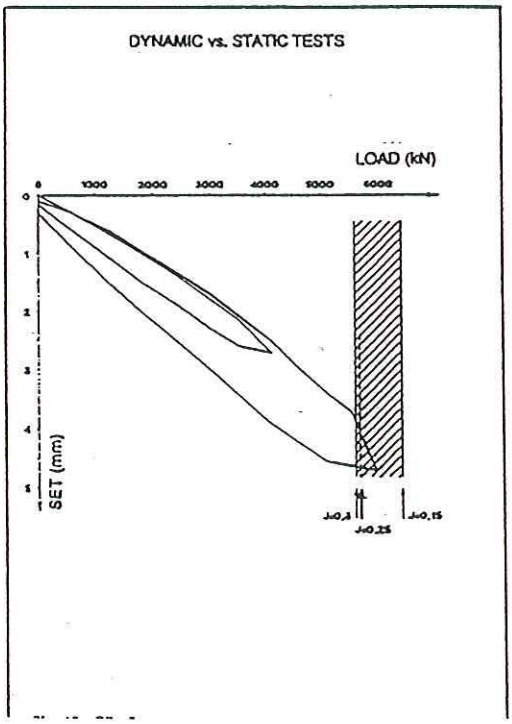
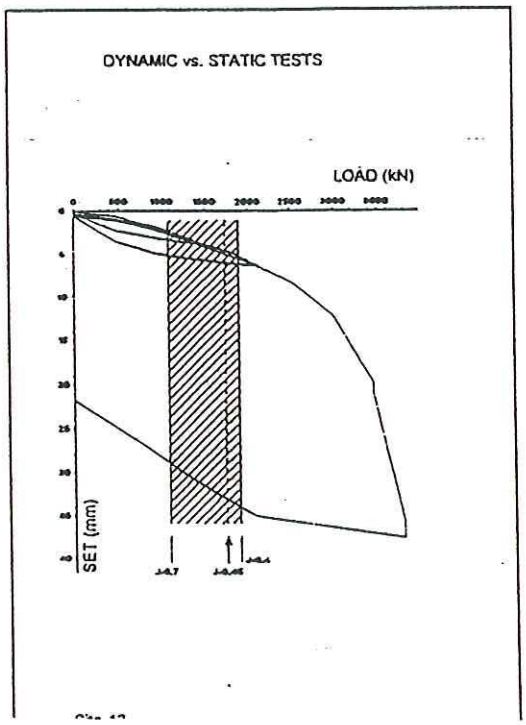


FIGURE 11





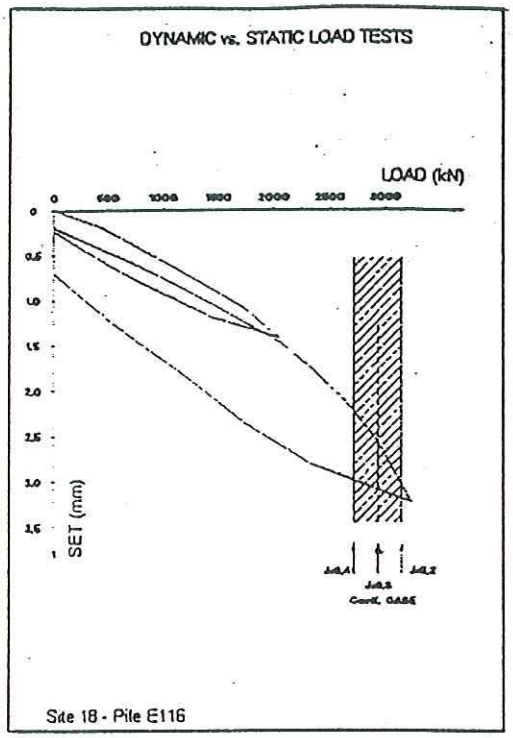


FIGURE 13

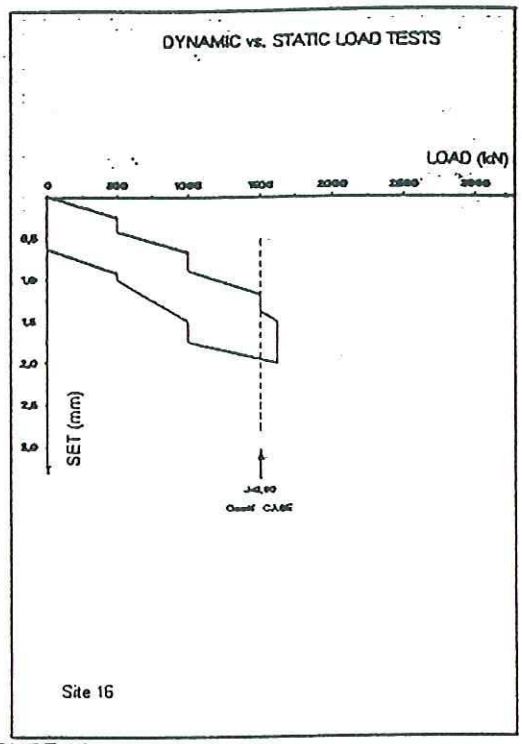


FIGURE 15

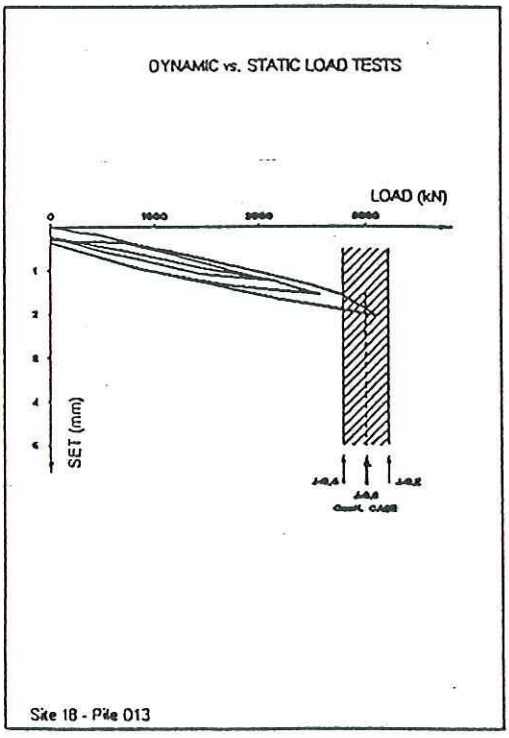


FIGURE 14

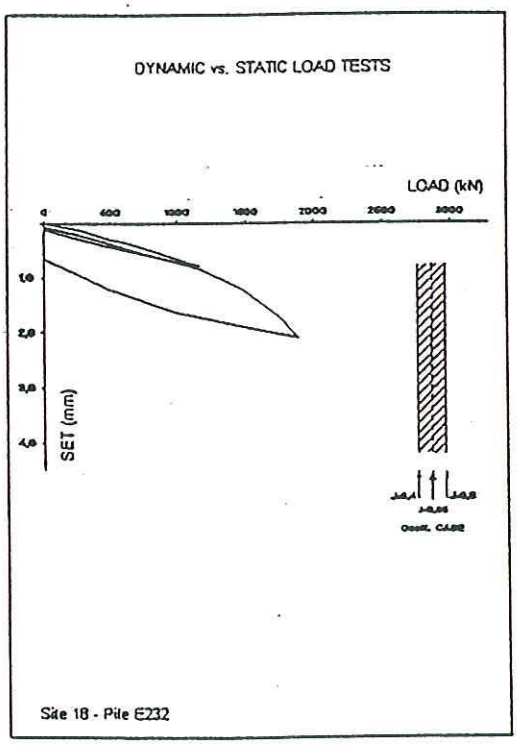


FIGURE 16

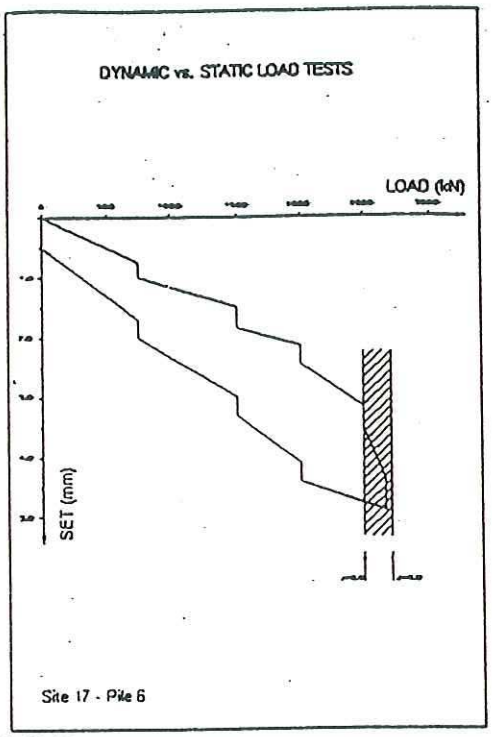


FIGURE 17

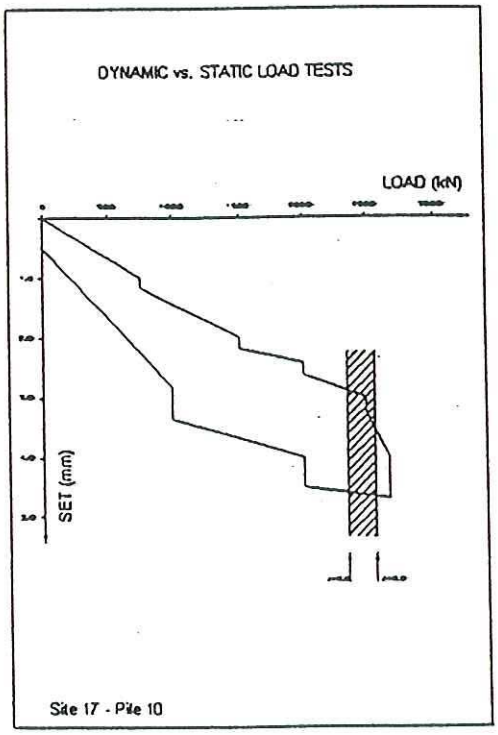


FIGURE 18