The first Statnamic load testing of foundation piles in Europe

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ABSTRACT:
An overview is given of the development and application of a new pile load test method, called Statnamic. Its long duration load compared to dynamic load testing allows a straightforward determination of the static load behaviour of piles. A description of the applied pile and soil model is presented. The commercial application of the method started in North America and Japan. The first testing has started recently in Europe and two case histories from the Netherlands and Germany will be presented in the paper.

1 INTRODUCTION

In building construction there is a growing demand for the verification of performance requirements. This is also valid for the foundation of a structure. A performance requirement that has to be verified for a pile foundation is the ultimate capacity or the settlement of the pile head under working load. A reliable method for verification is the static load test. However this method is too expensive and time consuming to be applied for daily practice. Until recently dynamic load testing by means of a drop hammer or a pile driving hammer was the only economic alternative for static load testing. Although economic and efficient in performance, the dynamic load test has some disadvantages compared to static load testing:

- Stress waves can introduce tension waves that can crack or break a pile.
- Eccentric loading can introduce bending stresses and cause damage to the pile.
- Elaboration of measurement results by means of signal matching requires experienced and highly educated engineers.
- Calibration with a static load test is required in many situations. For example Eurocode 7 prescribes: the results of a dynamic load test may be used for design provided an adequate site investigation has been carried out and this method has been calibrated against static load tests on the same type of pile, of similar length and cross-section, and under comparable soil conditions.

To overcome the above-mentioned disadvantages, a new pile-load test method has been developed by the companies Berminghammer (Canada) and TNO Building & Construction Research (Netherlands) (Bermingham 1989). The name of the method is Statnamic, which is a junction of the words STATic and dyNAMIC. As indicated by the name Statnamic load testing is positioned between static load testing and dynamic load testing. The duration of the load applied to the pile top is longer compared to dynamic load testing but shorter than the load duration for static load testing.

2. PRINCIPLE OF STATNAMIC LOAD TESTING

The principle of Statnamic is based on the launching of a reaction mass from the pile head (Fig 1). Launching takes place by generating high pressures in a cylinder, caused by the burning of a special fuel. As a reaction on the launching the pile is gently pushed into the soil. The load exerted on the pile head is measured by means of a load cell. The displacement of the pile head is registered by means of a special developed laser sensor. Load cell and laser sensor are integrated components of the Statnamic loading device. No instrumentation has to be installed on the pile shaft. The required reaction mass for a Statnamic load tests equals 5 to 10% of the mass required for a static load test. As an example: for a pile which to be loaded to 2 MN a reaction mass of 0.1 to 0.2 MN (10 to 20 tons) has to be launched.

The reaction masses have a simple design and can be made on site if necessary, to reduce costs of transportation. The simple modular and compact construction of the Statnamic device allows the testing of piles that are difficult to access.

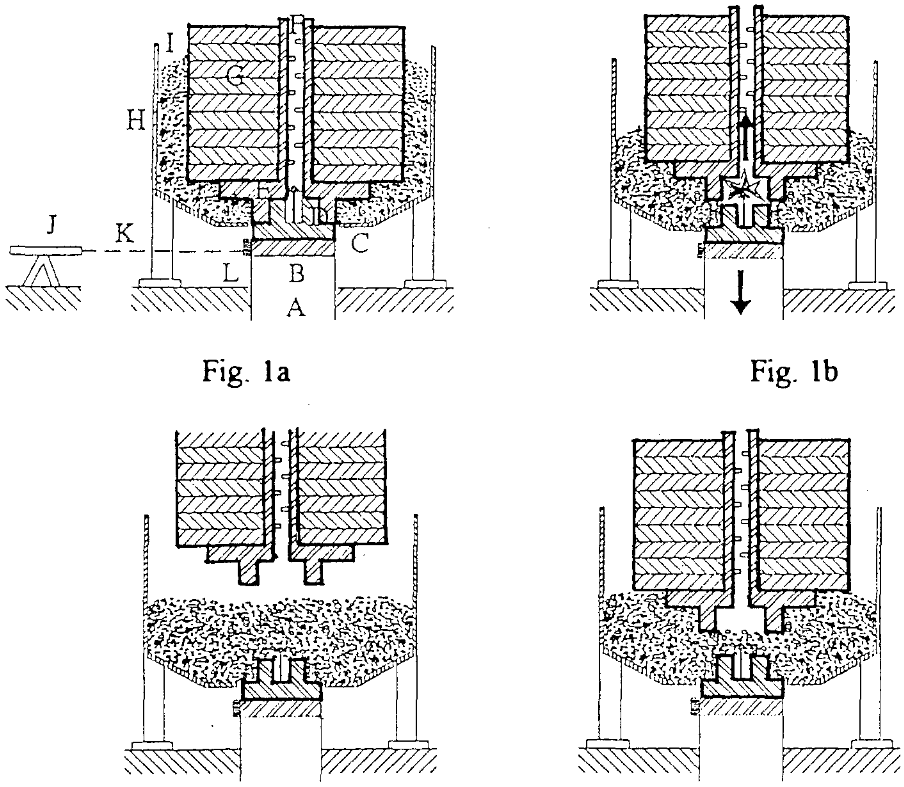


Fig. 1a Fig. 1b

Fig 1c Fig 1d

Fig. 1 Statnamic setup and succsesive stages of testing

The test set up of a Statnamic device has been presented in Fig. 1a. The characters in the graph correspond with the following components:

A = pile to be tested
B = load cell
C = cylinder with burning chamber
D = piston
E = platform
F = silencer
G = reaction mass
H = gravel container
I = gravel
J = laser
K = laser beam
L = laser sensor

The set up consists of a load cell on the pile head to measure the force and a laser sensor to measure the displacement of the pile head. On the load cell a cylinder is placed. The piston forms an integral part with a platform on which the reaction masses can be placed. Cylinder and piston form a burning chamber. The reaction masses may be shaped as blocks or disks and be fabricated from steel, concrete or lead. A silencer is placed in the centre of the platform and is connected with the burning chamber. A gravel container is placed over this set up. The space between container and reaction masses is filled with gravel. The gravel is used to catch the reaction mass when it falls back after launching and to protect the cylinder and pile head.

The figures 1a to 1d represent successive stages of a Statnamic load test. Fig 1a is the situation just before launching. In Fig. 1b the fuel has been ignited. The burning of the fuel generates high pressures and the reaction mass is accelerated. At this stage the actual loading of the pile takes place. The reaction force pushes the pile into the ground. The force signal and the displacement signal are registered by TNO's Foundation Pile Diagnostic System (FPDS). The upward movement of the reaction mass results in space, which is filled by the gravel (Fig.1c). Gravity causes the gravel to flow over the pile head as a layer. When the reactionmass falls back it is catched by the gravel and impact forces are transferred to the subsoil (Fig. 1d). The catching method with gravel is very safe because it based on the always present gravity. With the present configuration, based on the catching of the reaction masses with gravel, one or two piles can be Statnamic load tested. For the testing of piles unto 8 MN a catching mechanism is under development to be able to test more piles in one day.

The development of Statnamic started in 1988. At this moment (September 1992) Statnamic load tests have been performed in Canada, United States, Netherlands Japan and Germany. The equipment available at present can perform Statnamic load tests up to 16 MN. Design and construction of higher capacity Statnamic devices (30 MN or more) can be expected in the coming years. The high capacity Statnamic devices are not restricted to test single piles, but also allow the testing of pile groups and structural elements such as bridge piers and spread footings. Because the principle of Statnamic is based on the acceleration of masses, piles can be tested in any direction, also horizontal.

The duration and loading rate of a Statnamic test can be controlled with the volume of the burning chamber and the shape of the cylinder and piston, the amount and type of fuel and the amount of reaction mass launched. As a result, the load can be introduced more gradually and for a much longer duration compared to dynamic load testing.

As an example the force time diagrams of dynamic load test, a Statnamic load test and a static load test have been presented in Fig.2 . The long duration of the Statnamic loading keeps the pile under constant pressure and tension stresses can not develop. The central location of the Statnamic loading device on the pile top guaranties an axial introduction of the load into the pile

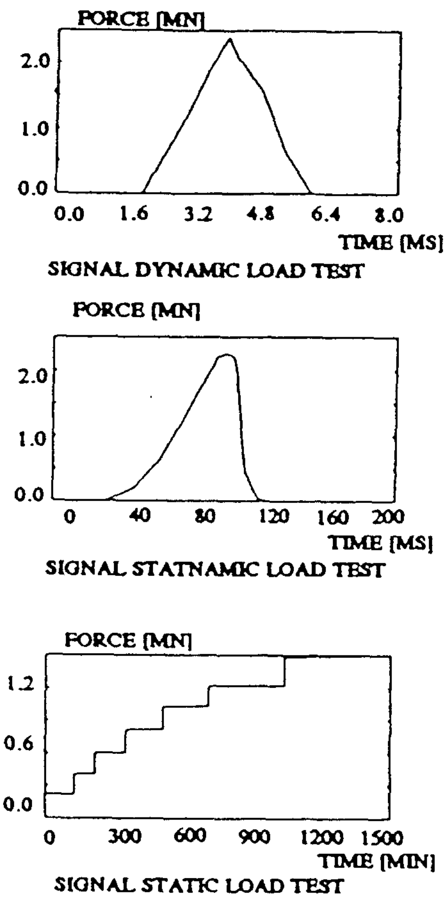


Fig. 2 Force versus time diagrams

The long duration of the Statnamic loading causes for all pile levels a similar displacement behaviour as can be observed with static load testing.(Middendorp 1992). This justifies a simple modelling of pile and soil, in which stress wave phenomena do not have to be taken into account. The pile is considered to be a mass on which the Statnamic force, the inertia force and soil resistance are acting (Fig. 3).

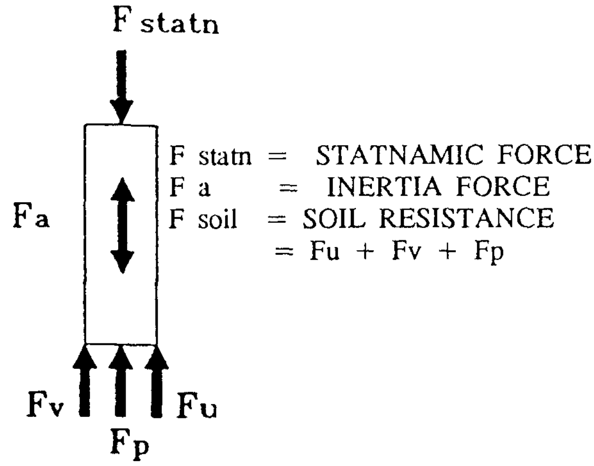


Fig 3 Forces acting on the pile during Statnamic loading

2.1.Dynamic phenomena

Although the duration of loading is several times longer than dynamic load testing and pile and soil behaviour are closer to static load testing, the Statnamic test must still be considered a dynamic test. Dynamic phenomena have to be taken into account. Testing results from Statnamic tests performed on piles in stiff soils or with the pile toe on rock (Janes 1991) show an almost one- to-one relation with static load test results. However, testing in soft soils shows that dynamic phenomena can strongly influence the load displacement behaviour. A method has been derived which takes these dynamic phenomena into account and will be illustrated in the next sections. The analysis is simple and straightforward and allows the derivation of static load displacement behaviour shortly after testing.

3. STATNAMIC PILE AND SOIL MODELLING

As already mentioned, the long duration of the loading allows the pile to be modelled as a mass on which the following forces are acting (Fig. 3):

1 - Statnamic force (F_{stn})
2 - Inertia force (F_a)
3 - Soil resistance (F_g)

The Statnamic force F_{stn} and displacement u are measured as function of time.

For equilibrium the following equation is valid:

$$F_{stn}(t) = F_{soil}(t) + F_a(t) \qquad (1)$$

in which

t	= time	
$F_{stn}(t)$	= Statnamic load (measured)	
$F_{soil}(t)$	= soil resistance	
	$= F_u(t) + F_v(t) + F_p(t)$	(2)
$F_u(t)$	$= k \cdot u(t)$	(3)
	= static resistance	(4)
$F_p(t)$	$= P \cdot v(t)$	
	= water pore pressure resistance	(5)
$F_v(t)$	$= C \cdot v(t)$	
	= damping force from soil	(6)
$F_a(t)$	$= m * a(t)$	
	= inertia force	(7)

with:

k	= spring stiffness	[N/m]
C	= damping factor	[Ns/m]
m	= pile mass	[kg]
P	= pore pressure damping	[Ns/m]

and

$u(t)$ = displacement (measured)	[m]
$v(t) = du/dt$ = velocity	[m/s]
$a(t) = d^2u/dt^2$ = acceleration	[m/s²]

A simple linear damper model represents the combined action of geometric and hysteric damping. It has been assumed for the simplicity of further analysis that the pore pressure resistance can be taken into account as a part of the damping. So we take $F_p(t)$ out of the equations.

Fig. 4 shows an example of a Statnamic load displacement diagram. It represents a worse case scenario for the Statnamic test. Strong dynamic components are present in the measurement results. Some areas can be distinguished in the diagram. In area 1, the Statnamic reaction mass is placed on the pile top. The load displacement behaviour is fully static. The measured load and displacement at the end of area 1 are called F_{stat} and u_{stat}. The spring stiffness k_1 in this are can be calculated with:

$$k_1 = F_{stat}/u_{stat} \qquad (8)$$

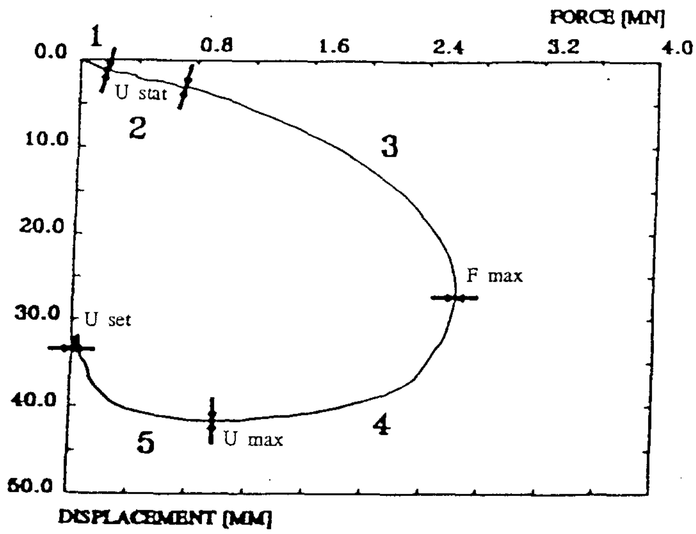


Fig 4 Important areas for analysis

In area 2 the reaction mass is launched and Statnamic loading starts. The soil resistance is elastic; inertia and damping forces are acting on the pile. In area 3 the static soil resistance reaches ultimate strength and yields at a value F_{uy}. Velocity and inertia increase more progressively. At the end of this area the maximum Statnamic load is reached. In area 4 the Statnamic load decreases. Because of the inertia of the pile, there is still an increasing displacement. The soil is yielding with value F_{uy}. Pile velocity reduces to zero and changes sign. At the end of this area, at time t_{umax}, the displacement reaches a maximum value u_{max} and the velocity becomes zero. Because of zero velocity, the damping forces become zero and the Statnamic load minus the inertia force equals the static soil resistance at this point.

$$F_u(t_{umax}) = F_{stn}(t_{umax}) - m \cdot a(t_{umax}) \qquad (9)$$

This force can be seen as an under limit of the maximum static resistance delivered by soil during loading. When the pile has been loaded to failure, the ultimate capacity F_{uy} is considered to be equal to $F_u(t_{umax})$ for Statnamic.

$$F_{uy} = F_u(t_{umax}) \qquad (10)$$

In area 5 the unloading force $F_u(t)$ of the static soil resistance overcomes the other opposing forces and pushes the pile upwards. At the end of this area the final settlement of the pile can be observed.

3.1 Construction of the static load displacement diagram.

The static load behaviour can be derived as follows.

Eq. 1 can be written as

$$F_u(t) + F_v(t) = F_{stn}(t) - F_v(t) - F_a(t) \qquad (11)$$

or

$$F_{soil}(t) = F_{stn}(t) - F_a(t) \qquad (12)$$

Fa(t) can be directly derived from the measured displacement signal.

$$F_a(t) = m \, . \, a(t) \qquad (13)$$

so the soil resistance can be calculated as:

$$F_{soil}(t) = F_{stn}(t) - m \, . \, a(t) \qquad (14)$$

Because of the rigid body assumption the displacement of the soil equals the measured displacement at the pile top. Drawing the soil resistance as function of displacement, the maximum value of Fsoil(tmax) can be seen as an upper limit for the static soil resistance F_{uy}. In cases where damping plays a minor role, the values for $F_u(t_{max})$ and $F_{soil}(t_{max})$ will have similar values.

For the calculation of $F_u(t)$ the damping force $F_v(t)$ must be known. In the following sections it will be shown that the damping C can be calculated in area 2 and area 3.

3.2 Calculation of damping in area 2.

To calculate the damping we use the data from area 1 and area 2 in the soil resistance - displacement diagram. We assume that the spring stiffness k_2 at the start of area 2 equals the spring stiffness k_1 of area 1. The difference in load settlement behaviour between the extrapolated linear behaviour from area 1 and the measured displacement behaviour must be caused by damping and equal to $F_v(t)$.

Eq. 1 can be expressed as:

$$F_v(t) = C \, . \, v(t)$$
$$= F_{stn}(t) - F_u(t) - F_a(t) \qquad (15)$$

or

$$C = F_{stn}(t) - F_u(t) - m \, . \, a(t)) / v(t) \qquad (16)$$

For a certain time t_2 corresponding with known displacement u_2, velocity v_2, acceleration a_2 and Statnamic load F_{stn2} we can write :

$$C_2 = (F_{stn2} - k_1 \cdot u_2 - m \cdot a_2) / v_2 \qquad (17)$$

Knowing C_2, the static resistance can be calculated by rewriting Eq. 1:

$$Fu(t) = F_{stn}(t) - C_2 \cdot v(t) - m. a(t) \qquad (18)$$

With $F_u(t)$ and u(t) a load displacement diagram can be drawn representing the static soil resistance as function of displacement.

3.3 Calculation of damping in area 3

Assuming that the ultimate static soil resistance F_{uy} has been mobilised in area 4, the damping at a time t_4 can be calculated with Eq.15 :

$$C_4 = (F_{stn4} - F_{uy} - m \cdot a_4) / v_4 \qquad (19)$$

Knowing C_4, the static resistance can be calculated by rewriting Eq. 1:

$$F_u(t) = F_{stn}(t) - C_4 \cdot v(t) - m.a(t) \qquad (20)$$

With $F_u(t)$ and u(t) a load displacement diagram can be drawn representing the static soil resistance as function of displacement. Examples of diagrams calculated this way have been presented in Fig 7. Because the load displacement diagram can have an irregular shape they are approximated by a best fit hyperbolic curve, which has also have been presented in Fig 7.

4 CASE STUDY STATNAMIC LOAD TEST IN THE NETHERLANDS

On a site of the Dutch Railways at Utrecht the Netherlands a new type of prefabricated concrete pile (Europile) was applied. The pile has thread on the outside side and is screwed into the ground. To check the performance of this type of piles a static load test was performed on one pile (# 6). To check the performance of 3 other piles (# 7, #39 and #40) Statnamic load testing has been applied. A Statnamic load test has also been performed on pile #6 for verification.

4.1 Description of the pile and installation

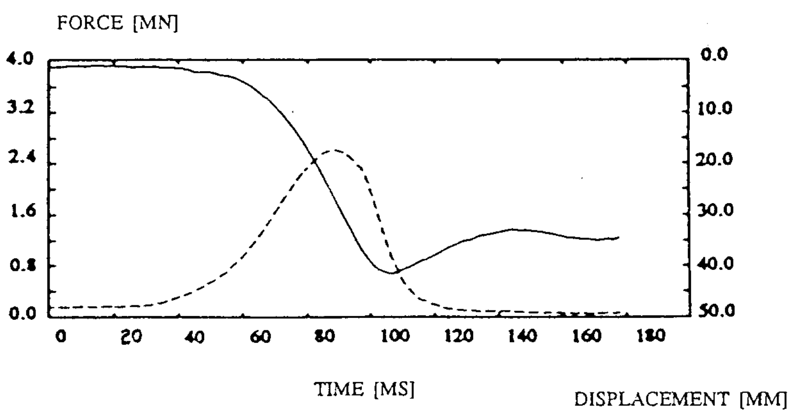
The Europile is a hollow tubular closed ended concrete pile which has screw-thread on the outside over the last 6 m. It is made of a high quality concrete B80 - B100. The outside diameter of the shaft is 0.5 m and the wall-thickness 700 mm. The outside diameter of the screw-thread is 0.64 m. Installation takes place by means of screwing the pile into the ground. The screwing unit applied was a Hitachi KH 180 GLS with a maximum rotation moment of 250 kNm.

4.2 Soil Description

On the site several Dutch Cone Penetration Tests have been performed. The first soil layer of 5.9 m can be characterised as silty sand with small clay layers with a mean cone resistance of 2.6 MPa. The second layer of 0.6 m consist of clayey peat with a mean cone resistance of 0.4 MPa. The third layer of 8.8 m consist of sand with a varying cone resistance of 10 MPa at the start of the layer and 21 MPa at the end of the layer.

4.1 Description of the static load test

The static load was applied to the pile with steps of 0.2 MN. The duration of loading for each step was a minimum of one and a maximum of four hours. At the end of the constant loading, five loading cycles were performed, each loading and unloading cycle was performed in five minutes. An extra loading cycle with a duration of 15 minutes was performed at the final stage of testing. The results of the static load test are presented in Fig 8 .



------ FORCE SIGNAL

——— DISPLACEMENT SIGNAL

Fig.5 Statnamic signals pile #7

4.3 Statnamic results

The load-time and displacement-time diagrams of pile #7 have been presented in Fig. 5. The Statnamic load Displacement diagram of all four piles have been presented in Fig. 6. The calculated static behaviour of all four piles has been presented in Fig. 7. The damping has been calculated in area 4.

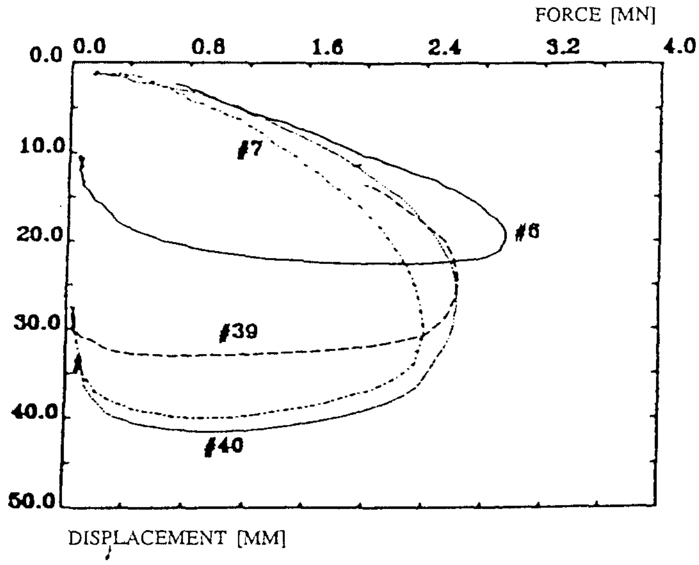


Fig. 6 Statnamic load displacement diagrams of 4 piles

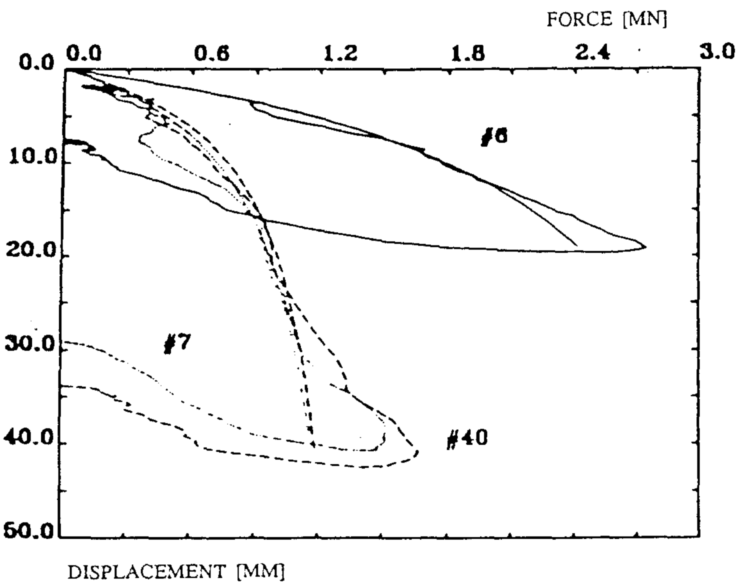


Fig.7 Calculated static load displacements diagrams from Statnamic

4.2 Comparison of Statnamic and static load test results

When comparing the results of Statnamic with static load test results, the load history must be taken into account. Pile #6 is preloaded by the static load test and the Statnamic load test must be considered as the next loading cycle. The other piles are virgin piles and Statnamic must be compared with the first loading cycle.

The results of the static load test on pile #6 together with the calculated static results with Statnamic of piles #6 and #7 have been presented in Fig 8.

The similarity between the static load test results and calculated static load test results from Statnamic is obvious. All tested piles were accepted by the client.

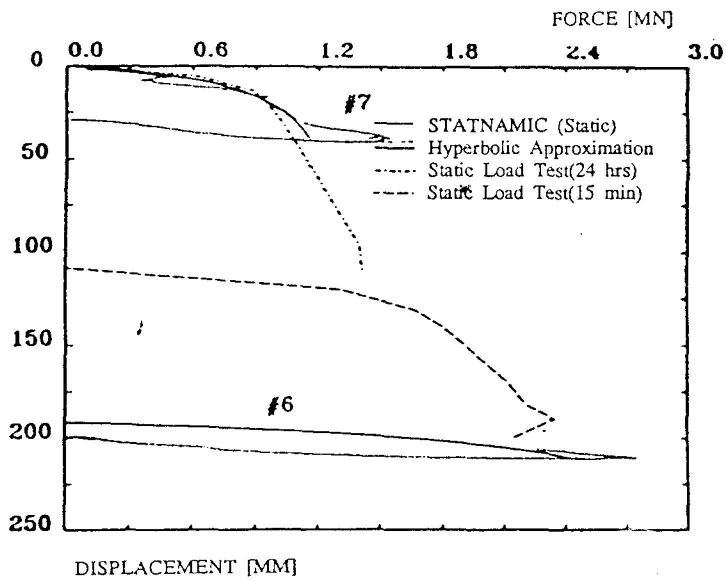


Fig .8 Comparison static load test results and Statnamic load.test results

5 CASE STUDY STATNAMIC LOAD TEST IN GERMANY

On a site of Franki Grundbau at Emden, Germany a test program has been performed to determine the load displacement behaviour of Franki cast in situ piles with different type of pile toe dimensions. On two piles (#5 and #6) Statnamic load testing has been performed before the execution of the static load tests. The predicted static load behaviour derived from the Statnamic load tests was supplied to the client before the excecution of static load test.

5.1 Description of the pile and installation

Both piles were constructed with a length of 15 meter and a diameter of 0.8 m. The last 4m near the pile toe have been manufactured inside gravel. The gravel was installed and densified by driving before concreting. The wide toe of pile #5 had a concrete volume of 0.4 m^3. The wide toe of pile # 6 consisted of 0.2 m^3. concrete

5.2 Soil Description

On the site several Dutch Cone Penetration Tests have been performed. The first soil layer of 10 m consists of clay with a mean cone resistance of 1.5 MPa. The next layer of 7.5 m consists of Holocene sand with a cone resistance's ranging among 16 and 4 MPa.

5.4 Statnamic and static load test results

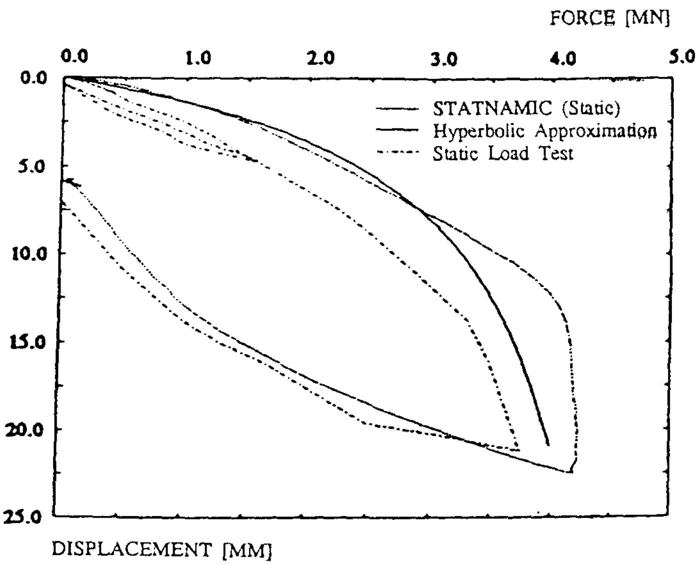


Fig. 9 Comparison static load test results and predicted static load test results from Statnamic of pile #5

Fig 9 represents the calculated static load results from Statnamic and the static load test results from pile #5. Fig 10 represents the result of pile #6. Pile #5 has a higher capacity and shows a stiffer behaviour than pile #6; as can be expected from the difference in toe dimensions. This can be observed in the Statnamic load testing results and static load test results.

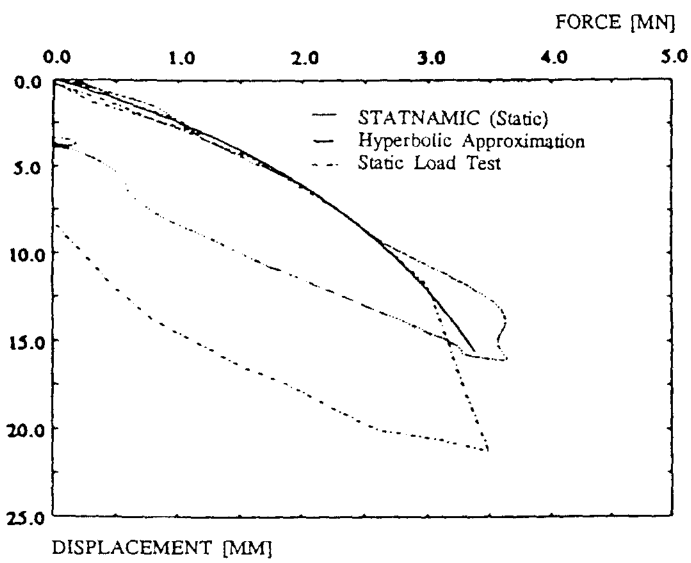


Fig. 10 Comparison static load test results and predicted static load test results from Statnamic of pile #6

The Statnamic results of pile #5 show a stiffer behaviour compared with the static load test. The agreement between the predicted static behaviour from Statnamic load testing and static load testing for pile #5 is satisfactory. The agreement between the predicted static behaviour from Statnamic results and the static load test results for pile #6 is good.

6 CONCLUSIONS

- During Statnamic load testing, pile behaviour can be modelled as a mass on which inertia forces and soil resistance are acting. This allows the simple calculation of the static load behaviour.
- Statnamic load testing can be performed on piles situated in soils with a strong dynamic response.
- The point of unloading (maximum displacement) in the Statnamic load displacement diagram allows the direct calculation of the maximum static soil resistance during testing.
- Two case histories in the Netherlands and Germany showed satisfactory and good agreement between static load behaviour from Statnamic results and static load test results.

7. REFERENCES

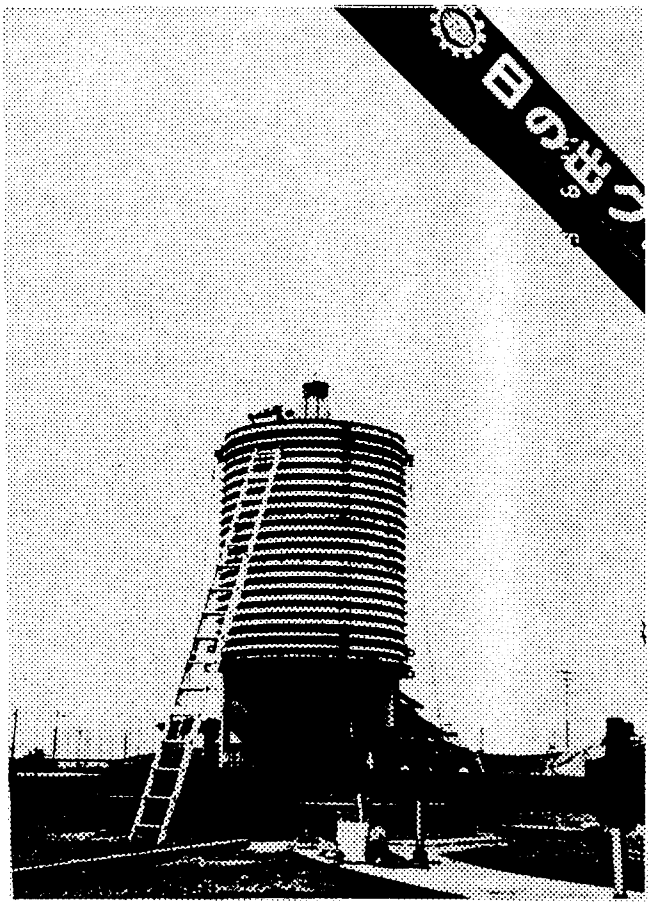
Bermingham P., Janes M., 1989, An innovative approach to load testing of high capacity piles, Proceedings of the International Conference on Piling and Deep Foundations, London, p.409-413.

Janes, M., Horvath, B., 1991, Pile load test results using the Statnamic method. 4th International DFI Conference at Stresa, Piling and Deep Foundations, Balkema

Horvath, R.G., 1990, Statnamic, an accurate and innovative load test method for high capacity deep foundations. Foundation Drilling, Volume. XXVIII, No. 11.

Middendorp, P., Reiding, F.J., 1991, Statnamic, a cost effective alternative for test loading of piles and caissons. Bangkok, 9 ARC.

Middendorp, P, Bermingham P., Kuiper B, 1992, Statnamic load testing of foundation piles. 4th International Conference on Stress Waves, The Hague, Balkema

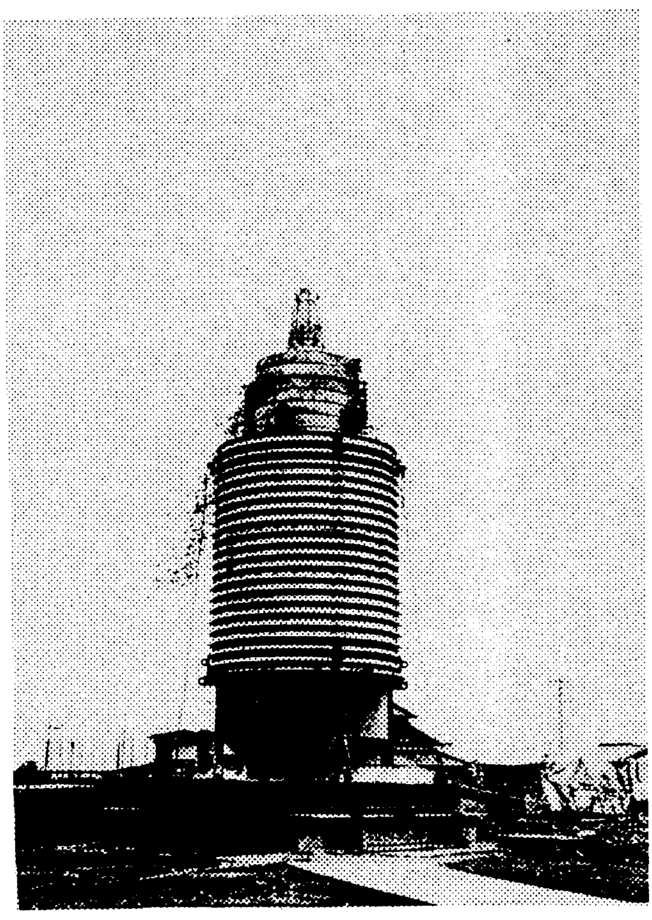


Fuel chared in

Chamber and gravel

filled in the container.

Ready for pile load test.



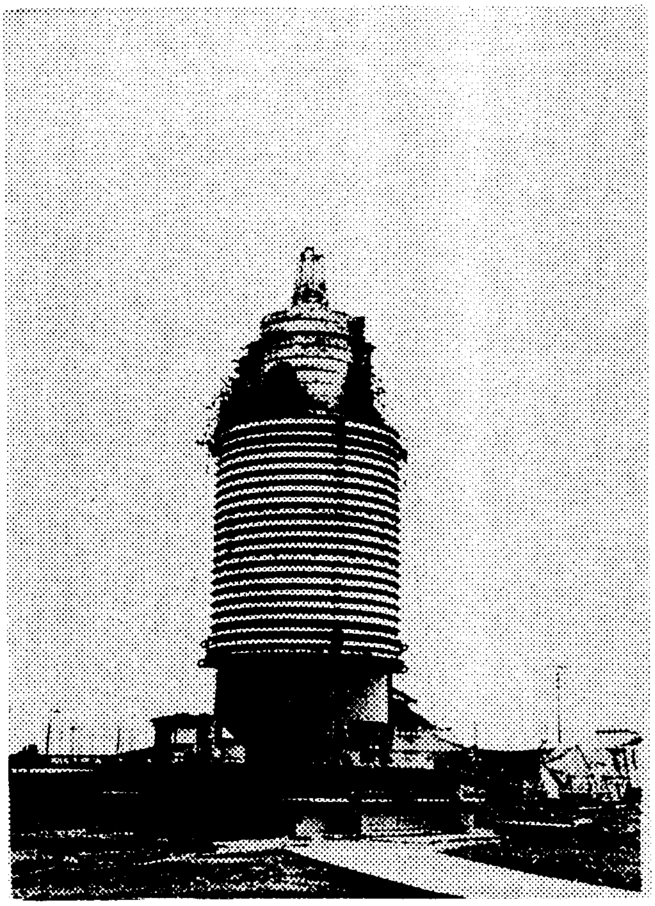
Launching by burning of

a special fuel in the chamber.

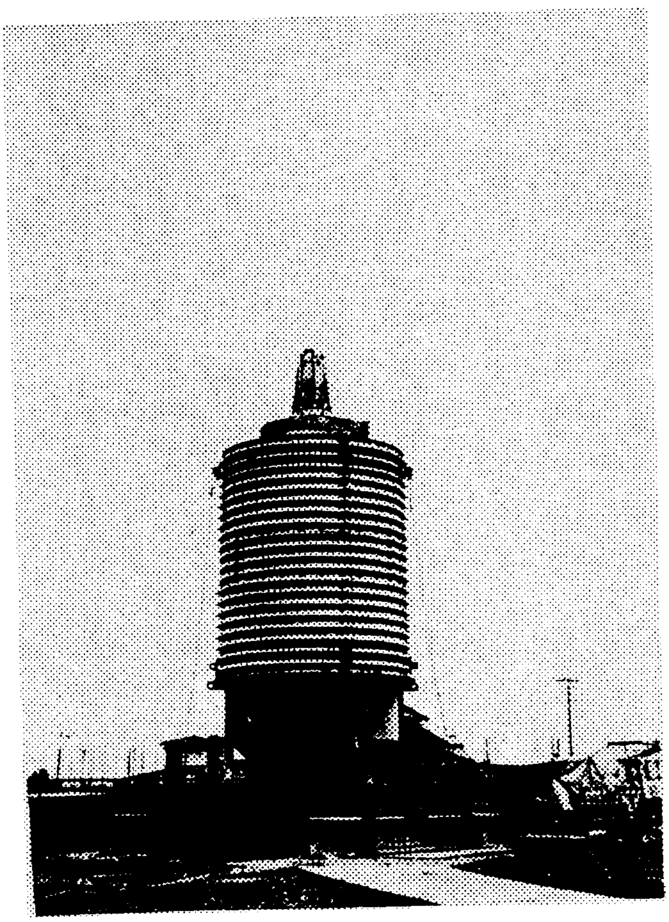
As a reaction on the launching

the pile is gently pushed into the

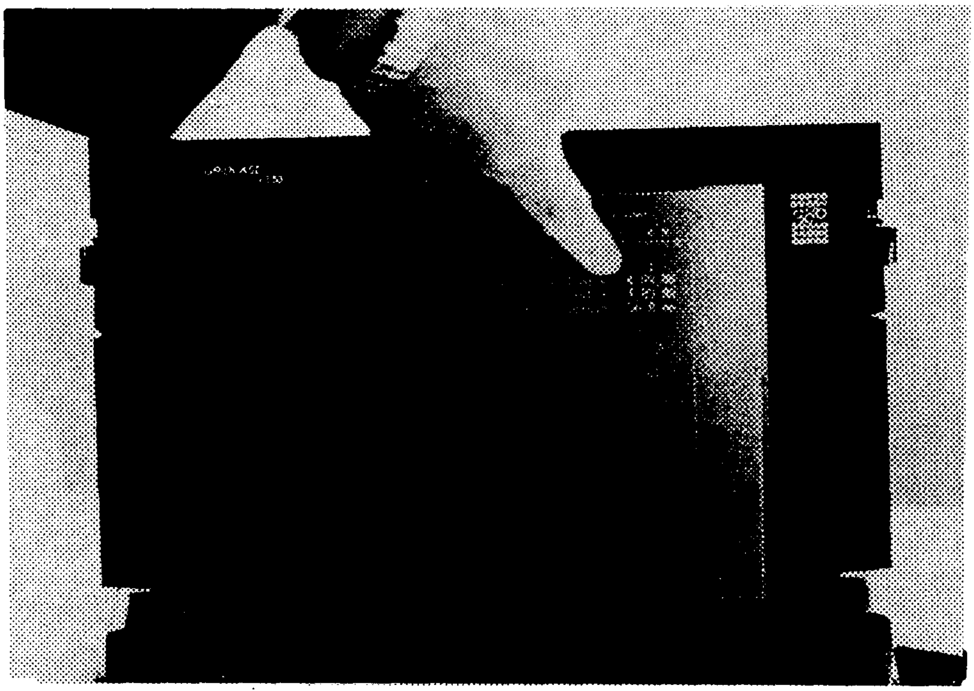
Soil.



Peak upward movement of reaction mass.



Completion of STATNAMIC Pile Load Test (Average testing time duration is app. 120 ms)



An immediate view to the result of STATNAMIC pile load test on the screen (FPDS), at the jobsite