

STATNAMIC SIMULATION

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Simulation of Statnamic test before the test is performed is a useful tool in determining a number of important parameters of the Statnamic test; what is the amount of propellant to be used, the height setting of the vent, the weight of the reaction mass, etc. In this paper the Statnamic simulation program, based on the TNOWAVE package, is presented. Some cases are presented. From the results it can be concluded that simulation with the TNOWAVE package is a powerful tool in preparing a Statnamic test, in interpretation and post-analysis of test results. The package can also be the basis of analytical studies to several phenomena of the Statnamic test.

1. INTRODUCTION

Statnamic load testing requires a careful preparation. The responsible test engineer must make a number of decisions. From the required load, the desired duration of the loading and the properties of the pile and soil, he estimates the weight of the reaction mass, the amount of propellant used, and the height setting of the vent. These decisions also influence the total height that the reaction mass reaches during the free flight.

Since the applied force and pile movement during a Statnamic test are the result of a complex interaction between the combustion of the propellant, the reaction mass, the Statnamic device and the properties of the pile and soil, these decisions cannot be easily made. In certain cases, experience can help to provide the answer. However, on a job site, where pile and soil properties are unfamiliar, decisions cannot be based on experience alone.

In order to facilitate decision making, the Statnamic simulation package has been developed. The package is an extension of TNOWAVE, which was originally developed to simulate the behaviour of the pile and soil during dynamic and static tests. TNOWAVE can be used for the prediction, post-analysis and research on the behaviour of foundation piles under impact loading, static loading and Statnamic loading. There are several applications, including Integrity Testing Simulation and Signal Matching (Middendorp 1988, 1993, Starke 1988), Pile Driving Prediction for Impact Hammers and Vibratory Hammers (Bielefeld 1992, 1994) and Dynamic Load Testing Signal Matching (Courage 1992, Middendorp 1985).

The simulation package is not restricted to the decision making of Statnamic tests only. The simulation package is also a powerful tool for research on several phenomena of the Statnamic tests and for the interpretation of the pseudo-Statnamic tests. As indicated by Middendorp (1995), pseudo-Statnamic tests are tests where the wave propagation in the pile has a significant influence on test results. For these tests the Signal Matching technique can be used to interpret measured signals.

2. STATNAMIC SIMULATION

A Statnamic test is a complex interaction between Statnamic device, pile and soil (Bermingham 1989, Middendorp 1992, 1993). When the soil is stiff, a Statnamic test will lead to a higher peak load than when the pile-soil system is soft. This effect is, for example, also known from pile driving with a diesel hammer. The combustion of the diesel is used to lift the ram. Little soil resistance leads to small impact heights, high resistance to high impact heights.

Statnamic simulation needs to include the combined behaviour of the pile and the soil. A one-dimensional simulation is sufficient. In principle, there are 3 methods to simulate the static and dynamic phenomena during a Statnamic test:

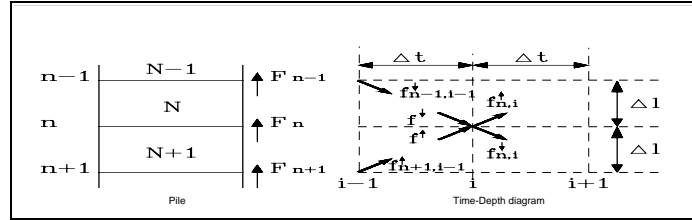
1. Finite element analysis
2. Lumped mass models (finite difference methods)
3. Method of characteristics

The finite element method allows a two dimensional modelling (Yamashita 1995). Accurate modelling with infinite elements on the boundaries and the proper time step prevents spurious reflections. The finite element method is in fact a lumped mass model. Disadvantages of lumped mass models for the simulation of dynamic effects have been described by Van Weele and Kay in 1984. They found a major influence of the time step for the integration on the results. By using a certain time step, a major error on the calculated results can be found. It can be concluded that this type of modelling is less suitable for the simulation of dynamic effects and stress wave propagation in piles. However, the method of characteristics has no numerical stability problems (Middendorp 1986). This method allows also the simulation of static phenomena, as described in section 4. For these reasons the Statnamic simulation has been based on the method of characteristics.

3. TNOWAVE STRESS WAVE ALGORITHM

The TNOWAVE program is a program to simulate the stress wave propagation in piles. The program is based on the method of characteristics, as invented by de Saint Venant in 1867. It has been Voitus (Voitus et. al. 1974) who applied this method to foundation piles with shaft friction and toe resistance.

Within the method of characteristics, it is assumed that shaft friction, which in fact acts continuously along the pile axis, is concentrated at certain discrete points along the pile. Between two of these points, also called an element, the pile remains frictionless, and the waves travel undisturbed, like in a free pile. The wave travels from one point to the other, to reach the second point. Arriving at this point, a part of the wave is reflected and the other part is transmitted. The magnitude of the transmitted and reflected parts depend on the properties of the element and the shaft friction or toe resistance. The equations for the transmitted and reflected waves are derived from two basic conditions: the equilibrium condition and the continuity condition. The obtained equations are presented below:



$$f_{n,i}^{\downarrow} = f_{n+1,i-1}^{\uparrow} * \frac{Z_n - Z_{n+1}}{Z_n + Z_{n+1}} + (2 \cdot f_{n-1,i-1}^{\downarrow} + F_{n,i-1}) * \frac{Z_n}{Z_n + Z_{n+1}}$$

$$f_{n,i}^{\uparrow} = f_{n-1,i-1}^{\downarrow} * \frac{Z_n - Z_{n+1}}{Z_n + Z_{n+1}} + (2 \cdot f_{n+1,i-1}^{\uparrow} - F_{n,i-1}) * \frac{Z_{n+1}}{Z_n + Z_{n+1}}$$

Figure 1. Waves travelling through a pile: Method of Characteristics

In which (see also

figure 1):

$f_{n,i}^{\downarrow}$ = Transmitted downward travelling wave

$f_{n,i}^{\uparrow}$ = Transmitted upward travelling wave

$f_{n+1,i-1}^{\downarrow}$ = Incident downward travelling wave

$f_{n-1,i-1}^{\downarrow}$ = Incident downward travelling wave

Z_N = Impedance of element N

Z_{N+1} = Impedance of element N+1

$F_{n,i-1}$ = Shaft friction force acting on node n

n = Discrete point or node number

N = Element number

i = Time step number

In one time step Δt the wave travels exactly the length of the element, Δl :

$$\Delta l = c \cdot \Delta t$$

The impedance, Z, of the pile can be calculated from the pile properties:

$$Z = \frac{EA}{c}$$

with:

E = Young's modulus

A = Cross sectional area

c = Stress wave velocity

ρ = Density pile material

The stress wave velocity, c , can be calculated by:

$$c = \sqrt{\frac{E}{\rho}}$$

With the equations as indicated above, waves travelling through the pile can be calculated. There are waves travelling upward and downward through the pile, reflect on changes in pile impedance, and at the top and toe of the pile. Shaft friction will result in reflections as well. To calculate the forces or the velocity at a certain level, the following basic equations can be used:

$$F = F^{\downarrow} + F^{\uparrow}$$

$$v = \frac{F^{\downarrow} - F^{\uparrow}}{Z}$$

4. STATIC AND DYNAMIC PHENOMENA MODELLED WITH TNOWAVE

The method of characteristics is a method to find a solution of the stress wave differential equation. This differential equation is based on two basic assumptions:

1. Linear relationship between stresses σ and strains ε (law of Hook): $\sigma = E \cdot \varepsilon$
2. Newton's 2nd law: sum of the forces F equals mass M times acceleration a : $F = M \cdot a$

Newton's law already indicates that the wave equation is valid for both dynamic and static effects. The static situation is only a special and theoretical situation of the dynamics: the situation that velocities approximate zero. It can be seen from the equations above that when F^+ and the F^- are equal, the velocity equals zero. Therefore any solution based on the stress wave theory is valid for both dynamic and static phenomena, including the simulation of Statnamic tests.

Depending on the length of the pile, the Statnamic test is more or less 'static'. Middendorp introduced the wave number N_w (Middendorp 1995). The wave number depends on the stress wave velocity of the pile material, c , the duration of the test load, T , and the length of the pile, L :

$$N_w = \frac{c \cdot T}{L}$$

Tests on piles with wave numbers less than 6 are considered dynamic load tests. For pile/load combinations with a wave number higher than 1000, the test is considered static. Practical values for the wave number of Statnamic load testing on piles are 12 to 50.

For the range between 6 to 12 Statnamic is considered pseudo-Statnamic, because stress wave phenomena exist. Corrections on the Unloading Point Method (UPM) interpretation method (Middendorp 1992, 1993) are required. TNOWAVE is one of the tools to make these corrections.

5.. STATNAMIC MODELLING

An important factor in the simulation of the Statnamic test is the modelling of the load on top of the pile. The typical loading characteristic of the Statnamic device depends on

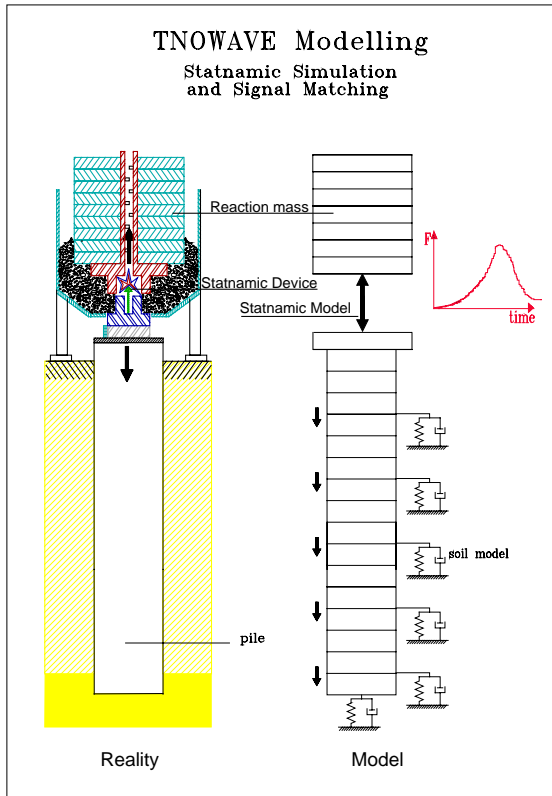


Figure 2. Simplified model of Statnamic test

many parameters; for example, the initial pressure chamber volume, type of fuel, amount of fuel, reaction mass and vent distance. All these items have been taken into account to model the Statnamic device properly. Therefore the model in the TNOWAVE program incorporates the burning of the fuel according to pyrotechniques, depending on fuel chemistry, burning coefficients and geometry of the fuel. Due to burning of the fuel, the pressure in the chamber will increase. The rise in pressure increases the rate of burn of the fuel. An important parameter is the modelling of the shape and dimensions of the vent (Fig.3). Bermingham (Bermingham 1995) presents the influence of several parameters of the Statnamic device on the load on top of the pile. These results are obtained, without taking into account the influence of the pile stiffness and the soil behaviour on the load.

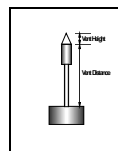
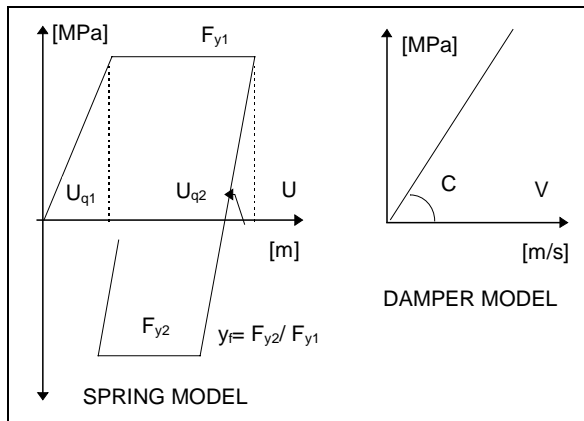


Figure 3. Vent details

6. SOIL MODELS



To model the soil behaviour accurately, several soil models are incorporated in the TNOWAVE program. The soil models consists of a static part (displacement dependent resistance) and a dynamic part (velocity or acceleration dependent resistance). As seen for example in the elasto-plastic spring model and the linear damping model in Fig. 4 below.

Figure 4. Example of soil models in TNOWAVE

7. STATNAMIC SIGNAL MATCHING

As indicated by Middendorp (Middendorp 1995), for pile tests with a wave number less than 12, stress wave effects influence the Statnamic test results. As indicated by the author, these type of tests can be indicated as pseudo-Statnamic tests. To interpret these test results properly, stress wave effects have to be taken into account. With the signal match technique, the interpretation can be performed.

Based on the pile properties and the soil conditions, a pile and soil model will be made. The TNOWAVE program applies the measured force on top of the pile and calculates the displacements of the pile. This calculated signal will be compared with the measured signal, obtained during the Statnamic test. The soil model will be adjusted until a good match between measured and calculated signals appears. Once a good match is obtained, the soil models describe the behaviour of the soil during a Statnamic load. A simulation of the static load test on this pile with these soil models can be made. This results in a static load-settlement diagram.

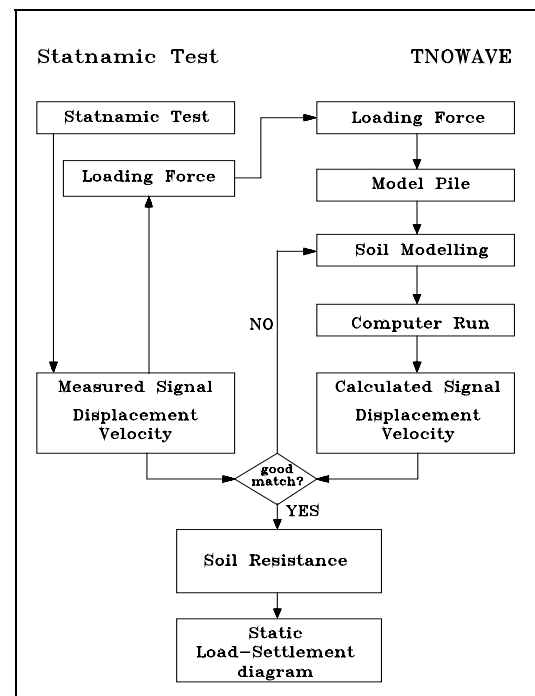


Figure 5. Statnamic Signal Match technique

This signal match technique is well known for its interpretation of dynamic load testing signals. The dynamic load test and pseudo-Statnamic test have in common the significant influence of the stress waves on the results.

8. CASE STATNAMIC PREDICTION

The Statnamic simulation package has been used in several cases and research projects. Two cases will be presented here. The first case is the simulation of a Statnamic test on a steel tubular pile. The Statnamic device is a 8 MN device. The data of this device used for the simulations is presented in table 1. The properties of the pile are presented in table 2. The applied model for the shaft friction and toe resistance are presented in figure 4. The applied model are asymmetric plastic displacement dependent and linear damping. The spring model is characterised by the yield stresses F_{y1} and F_{y2} , and the quake values u_{q1} and u_{q2} . The linear damping is characterised by the damping factor C. The values for these soil parameters for case 1 are presented in figure 6.

The time step used in the TNOWAVE calculations is $75\mu s$, corresponding to an element length of 0.375m. The simulation of the Statnamic test starts with the combustion of the fuel in the burning

Combustion chamber area	0.0968	[m ²]
Initial Chamber Volume	0.0325	[m ³]
Vent diameter	0.1077	[m]
Vent length	0.1016	[m]
Vent distance	0.1524	[m]
Plenum volume	0.6019	[m ³]
Plenum vent area	0.0219	[m ²]
Pyrotechnics data:		
Charge weight	3.8	[kg]
Mass reaction weight	39900	[kg]

Table 1. Data 8 MN Statnamic device

Pile Type	Steel pipe	
	Open ended	
Modulus of Elasticity	2.0e+11	[N/m ²]
Density pile Material	8000	[kg/m ³]
Stress wave velocity	5000	[m/s]
Pile Diameter	1.128	[m]
Wall Thickness	40	[mm]
Cross section pile head	0.137	[m ²]
Cross section pile toe	1.0	[m ²]
Perimeter	3.54	[m ¹]
Length	20	[m]
Mass	21876	[kg]

Table 2. Pile Data of case study

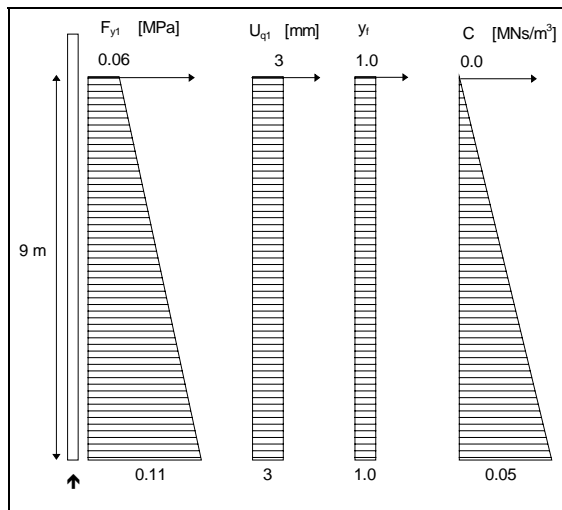


Figure 6. Soil models for simulation of case

chamber of the Statnamic device. This will lead to an increase of the pressure in the burning chamber. As a result, the mass will be accelerated and launched. The resulting reaction on top of the pile introduces forces causing stress waves to travel in the pile. Shaft friction and toe resistance will be mobilised. The displacement of the top of the pile will have its influence on the process of burning of the fuel.

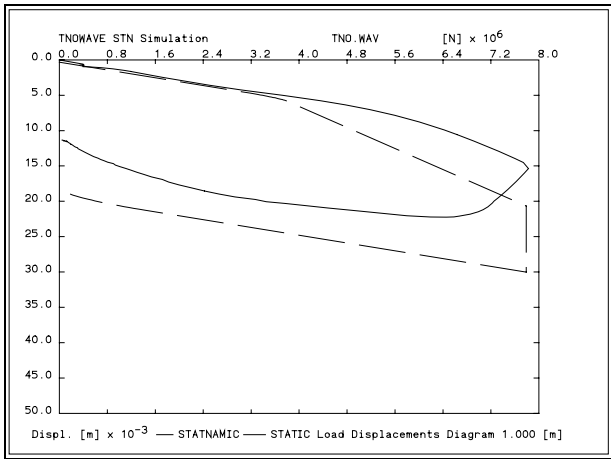


Figure 8a. Simulated Static and Statnamic load displacement diagram

As a result of the TNOWAVE calculations, graphs of forces, compression and tensile stresses, velocities, accelerations, displacements, and more can be presented as function of time, as well as function of the pile axis. Graphs as a unction of time, for the forces, displacements, velocities and accelerations at the top of the pile are presented in Fig.7. The simulated forces and displacements can be treated as if they were measured. and, thus, a load-displacement graph can be made, as indicated Fig.8. In this graph, the

simulated static load-settlement behaviour is presented as well. Interpretation methods, like the UPM method can be applied. For this case, the UPM method gives a static resistance of 7.4 MN.

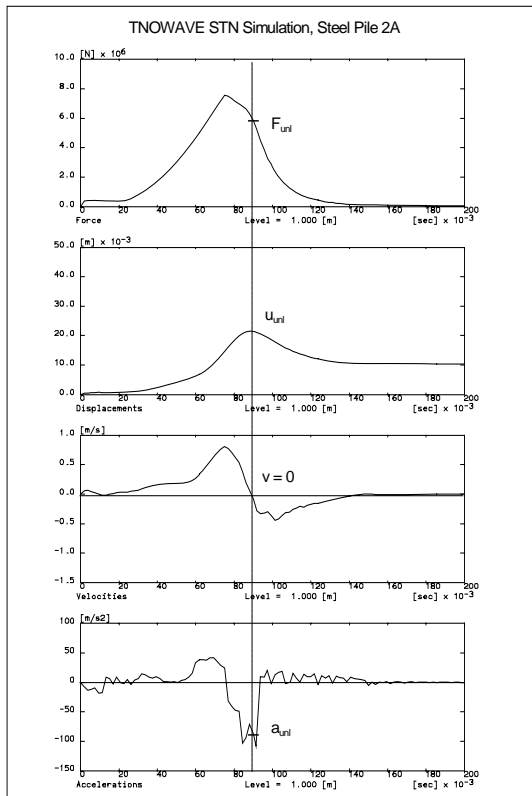


Figure 8b. Simulated Static and Statnamic load displacement diagram

Figure 7. Calculated signals as function of time, case 1

9. CONCLUSIONS

The paper has shown the possibilities of the Statnamic Simulation technique. Based on the experience gained with the TNOWAVE Statnamic simulation package, the following can be concluded:

- The Statnamic simulation package is valuable for common practice, interpretation of signals and research and studies to several phenomena of Statnamic testing
- There is a good performance of the one dimensional simulation method, based on the method of characteristics
- The method of characteristics is able to model dynamic effects, as well as static or quasi-static phenomena
- TNOWAVE Statnamic simulation can play an important role for interpretation of the Statnamic signals and add techniques for interpretation of Statnamic tests
- Examples show good correspondence between predicted and measured observed STN tests
- Signal Matching is a tool to interpret pseudo-Statnamic tests, especially when the wave number is smaller than 12

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