

The Influence of Stress Wave Phenomena during Statnamic Load Testing

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Abstract

Because of its advantages compared to static and dynamic load testing, especially for bored piles, the application of Statnamic load testing has increased considerably. The Unloading Point Method (UPM) has become a standard tool for the analysis of Statnamic (STN) load testing signals. The method is based on the assumption that the pile can be modelled as a concentrated mass and springs. Modelling is only valid when stress waves phenomena are minimal. In case of long piles or short duration STN testing, stress wave phenomena are not negligible. The sensitivity of STN to stress wave phenomena can be characterised by the wave number which is determined by the duration of the STN load, the stress wave velocity and the pile length. With the stress wave program TNOWAVE simulations have been made for piles with the same ultimate capacity but different wave numbers. Conclusions are drawn from these results as to what wave number UPM can be applied reliably to predict ultimate load capacity. Some measures to correct for stress wave phenomena, when they occur, are discussed.

Introduction

The Statnamic pile load testing method has several advantages compared to static and dynamic load tests, especially in the case of bored piles. Since its start in 1988 and first publication (Bermingham et. al. 1989) the application of Statnamic (STN) load testing has increased continuously and is applied on several continents. The Unloading Point Method (UPM) (Middendorp et. al., 1992, 1993) has become a standard tool for the analysis of STN signals. UPM has proven to be successful in many cases. However cases have occurred in which prediction deviations were more than 20% compared with the results of static load tests (SLT) (Brown, 1994). The UPM method is based on the assumption that the pile can be modelled as a concentrated mass and springs. Modelling is only valid when stress waves phenomena are minimal. In case

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of long piles or short duration STN testing stress wave phenomena will not be minimal any more and result in prediction errors when not taken into account. The paper deals with UPM prediction deviations caused by stress wave phenomena. Measures to correct for stress wave phenomena are discussed.

Comparison of Pile Load Tests

A first impression of the influence of stress waves on different types of load testing can be obtained when the stresses, velocities and displacements along the pile shaft are compared. This is presented in Fig. 1 for dynamic load testing (DLT), Statnamic load testing (STN) and static load testing (SLT).

In DLT, a short duration impact is introduced to the pile head by a drop hammer or a pile driving hammer. A stress wave travels along the pile resulting in large differences in stresses from pile level to pile level. Some pile levels can be under compression while others are under tension. This pattern fluctuates strongly with time. The same is true for the velocities along the pile shaft. The displacements along the pile vary strongly from pile level to pile level and with time.

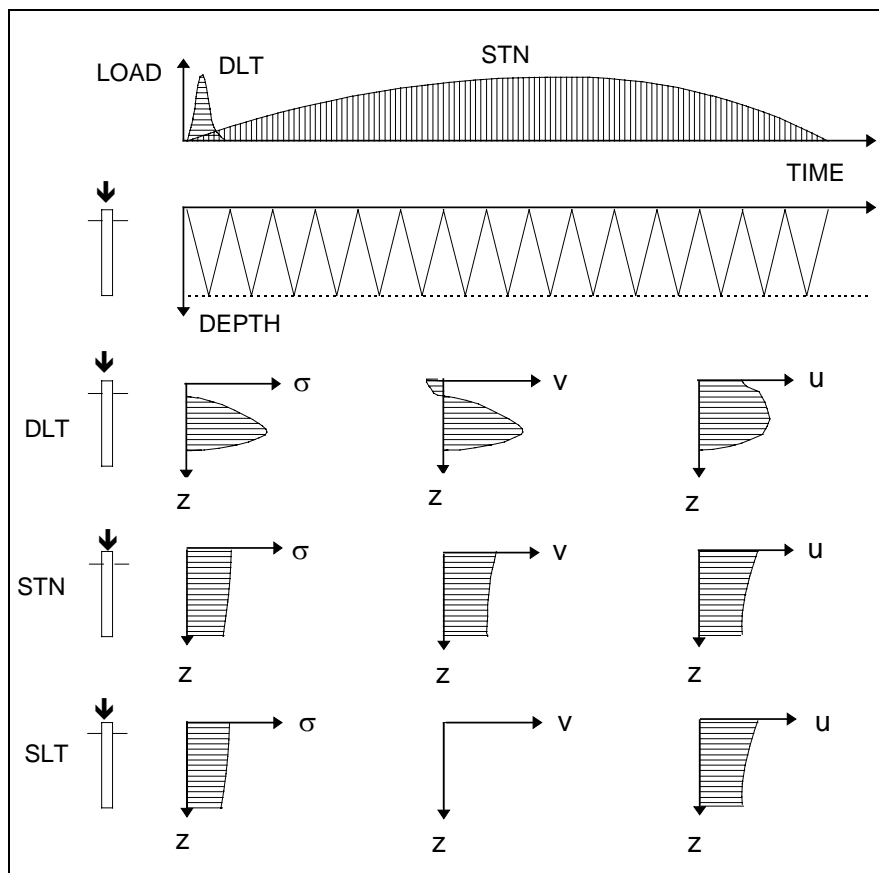


Figure 1. Comparison of stresses, velocities and displacements for DLT, STN and SLT

In STN, the load is gradually introduced to the pile. Compression stresses show a gradual change along the shaft. All pile parts remain under compression. Along the pile the compression stresses are reduced by shaft friction. Pile levels move with similar velocities and displacement along the pile show gradual changes.

In SLT, the load is introduced to the pile in successive steps. Each step is maintained over a period from minutes to hours. Compression stresses show a gradual change along the shaft. All pile parts remain under compression. Along the pile, compression stresses are reduced by shaft friction. The pile levels move with almost zero velocity. Displacements along the shaft show gradual changes.

This comparison shows that STN is closer to SLT than DLT. The major difference between STN and SLT is caused by the velocities along the pile shaft. For SLT, the velocities can be considered close to be nil while for STN they can be in the range of 0.1 to 2 m/s. The long duration of STN loading results in a pile behaviour close to SLT (Middendorp, 1992, Matsumoto, 1994). The fact that pile levels move in the same velocity range allows the modelling of the pile as a concentrated mass combined with springs (Fig. 2). In this pile model STN load (F_{stn}), inertia force (F_a) and soil resistance (F_{soil}) are acting. The soil resistance is composed of a static resistance F_u and a damping force F_v .

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

$$F_{soil} = F_u + F_v \quad (2)$$

$$F_{stn} = F_u + F_v + F_a \quad (3)$$

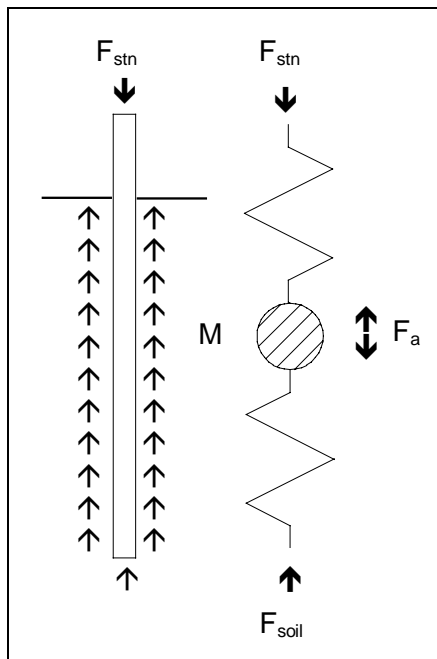


Figure 2. Pile and soil modelling with Unloading Point Method

Stress wave phenomena play a minor role. An important point with the analysis is the point where the pile top reaches maximum displacement, also called unloading point. The UPM method states that at the time of maximum displacement ($t=t_{umax}$, $v=0$) the damping force becomes zero ($F_v=0$) and the static soil resistance F_u can be calculated directly. This because the displacement u , acceleration a , and STN load F_{stn} are measured signals and fully known (see also Fig. 6):

$$F_u = F_{unl} - F_a = F_{unl} - M \cdot a_{unl} \quad (4)$$

In which

F_{unl} = STN load at $t=t_{umax}$

M = pile mass

a_{unl} = acceleration at $t=t_{umax}$

When the duration of STN loading decreases,

one can imagine that the pattern of stresses, velocities and displacements will be closer to DLT and stress wave phenomena can not be neglected.

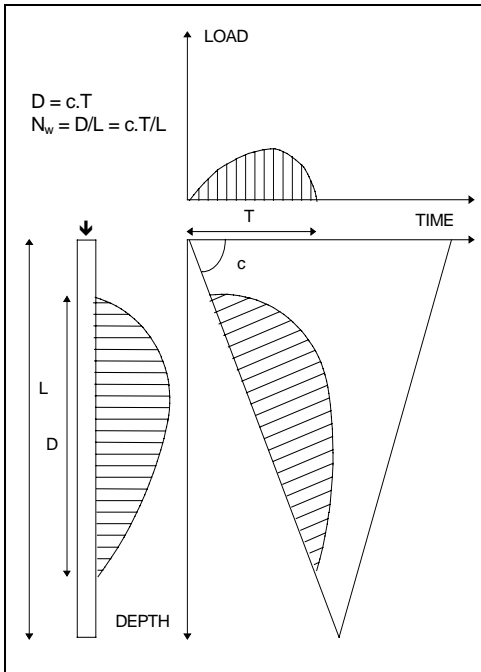


Figure 3. Relation between wave number N_w , duration load T and wave length D

Stress Wave Number

The significance of stress wave phenomena can be characterised by a parameter that is introduced by the authors and called wave number (N_w). As soon as load is applied to the pile head, stress waves will travel in the pile with a velocity c . Fig. 3 shows the load time diagram on the pile head and a depth time diagram with the load propagating in the pile. The duration of the load is T seconds. In T seconds, the stress waves travels a distance D along the pile.

$$D = c.T \quad (5)$$

This distance, corresponding to the load duration, is called wave length. The wave number N_w is obtained by division of the wave length D with the pile length L .

$$N_w = D / L \quad (6)$$

For the example in Fig. 1 the wave number N_w is less than one for DLT while $N_w = 30$ for STN. To investigate the influence of stress wave phenomena for varying wave numbers, STN computer simulations have been made with the stress wave program TNOWAVE (Bielefeld et.al., 1995).

STN Simulations

The stress wave program TNO-WAVE has an option to simulate STN load testing (TNOSTN). To investigate the influence of stress wave phenomena, simulations have been made for a 8 MN Statnamic loading device on 5 steel tubular piles (A) and 5 concrete piles (B). The data of the 8 MN loading device used for the simulations is presented in table 1.

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	3.810 [kg]
Mass reaction weight	39900 [kg]:

Table 1. 8 MN STN Device data

Steel tubular piles A (closed toe)			Solid concrete piles B		
Modulus of elasticity	= 2.0e+11	[N/m ²]	Modulus of elasticity	= 4.0e+10	[N/m ²]
Density pile material	= 8000	[kg/m ³]	Density pile material	= 2500	[kg/m ³]
Stress wave velocity	= 5000	[m/s]	Stress wave velocity	= 4000	[m/s]
Cross section pile head	= 0.137	[m ²]	Cross section pile head	= 1.0	[m ²]
Cross section pile toe	= 1.0	[m ²]	Cross section pile toe	= 1.0	[m ²]
Perimeter	= 2.215	[m]	Perimeter	= 2.215	[m]
Pile no	Length [m]	Mass [kg]	Pile no	Length [m]	Mass [kg]
1A	10	10938	1B	10	24983
2A	20	21876	2B	20	49966
4A	40	43751	4B	40	99933
6A	60	65627	6B	60	149900
8A	80	87502	8B	80	199866

Table 2 . Pile properties

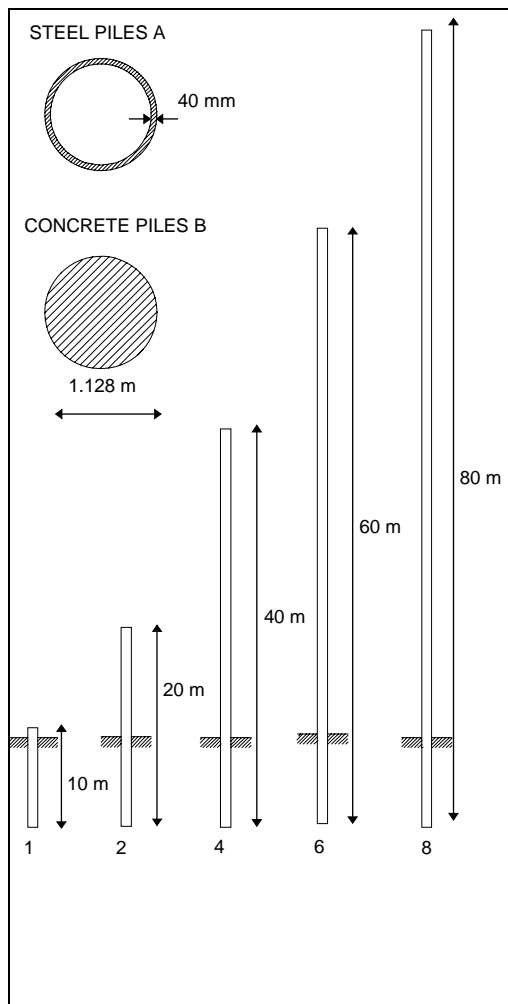


Figure 3. Pile modelling data

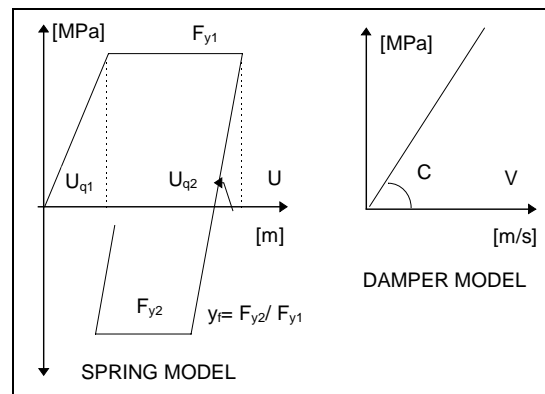


Figure 4. Spring and damper models for STN simulation

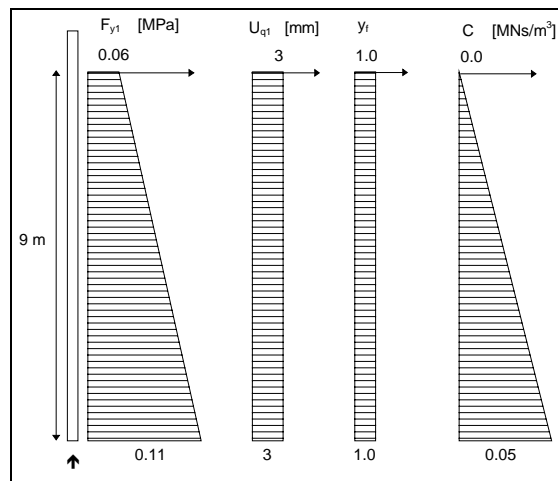


Figure 5. Shaft friction layer modelling

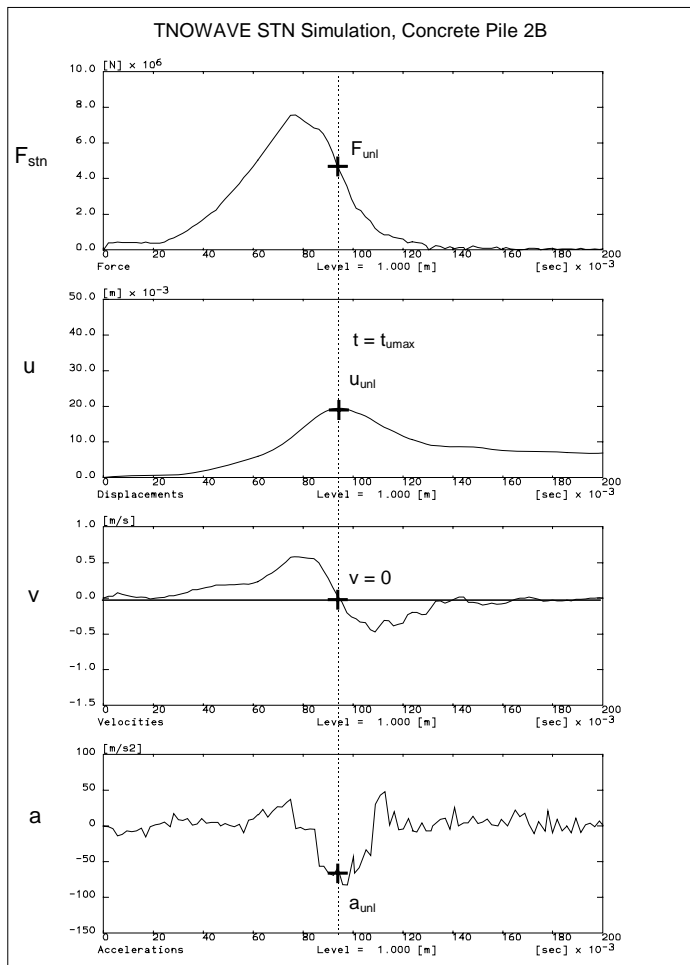


Figure 6. STN Response signals at pile head for pile 2B

with different lengths to introduce the effect of stress waves. To be able to compare the prediction of static capacities, all piles have the same soil modelling and penetration into the soil (9m). This modelling will not always meet structural and geotechnical criteria, but is applied to show differences in stress wave phenomena. The time step used in the TNOWAVE calculations was 75 μ s, which corresponds with pile element lengths of 0.375 m for the steel tubular piles and 0.300 m for the concrete piles.

The properties of the steel and concrete piles are presented in table 2 and Fig. 3. The variations in lengths (factor 8) and mass (factor 20) allow the study of stress wave phenomena and resulting inertia effects.

The applied soil models for the shaft friction and toe resistance are presented in Fig. 4. The spring model is asymmetric plastic and the damper model is linear. 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 damper is characterised by the damping factor C . The modelling of soil layers and associated parameters are presented in Figure 5.

The piles are modelled

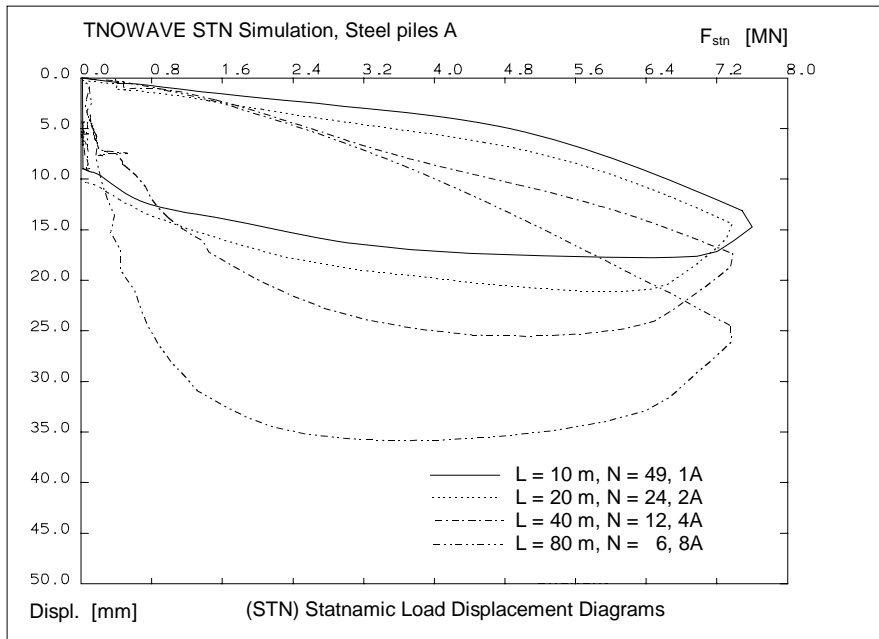


Figure 7. STN load-displacement diagrams for steel piles

For each modelled pile, STN simulations and SLT simulations have been made. The STN simulations start with the combustion of the fuel in the burning chamber of the STN device and the launching and acceleration of the reaction masses. The resulting reaction on the pile head introduces compressive forces and stress waves will travel in the pile. Stresses, displacement, velocities and acceleration are generated along the

pile axis and shaft friction and toe resistance act on the pile. With the SLT simulations static load is introduced to the pile head in steps. No dynamic effects are present and the results represent the pure static loading behaviour of the pile.

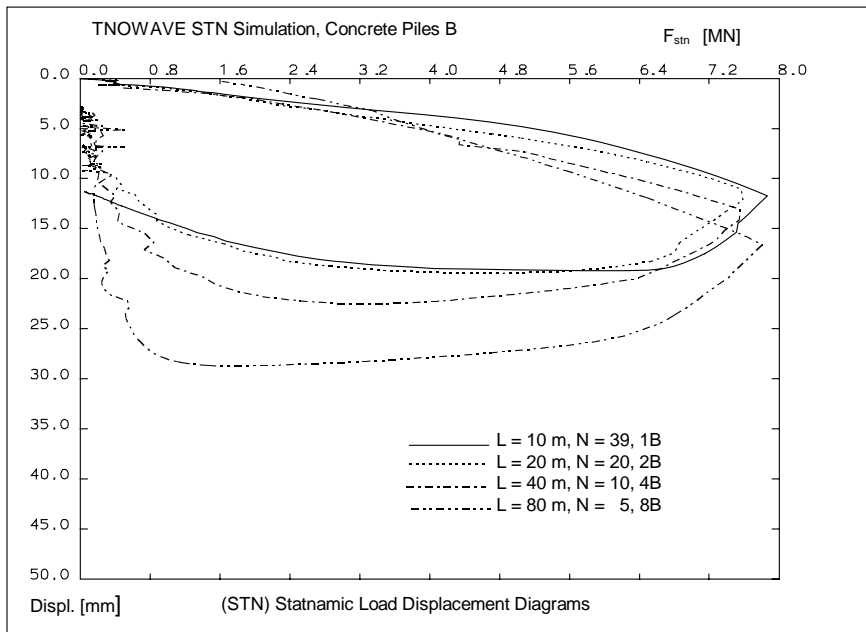


Figure 8. STN load-displacement diagrams for concrete piles

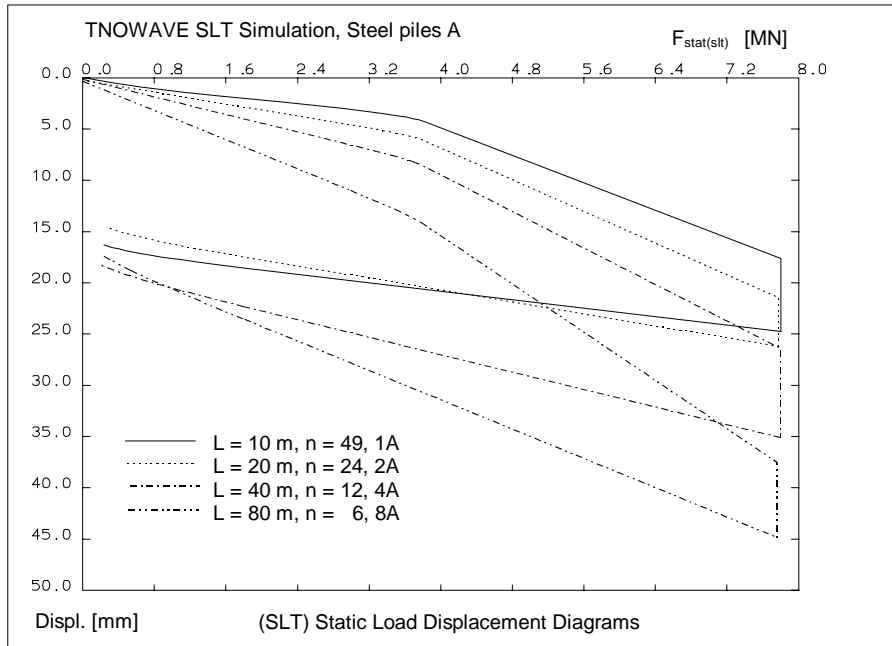


Figure 9. SLT Static load-displacement diagrams

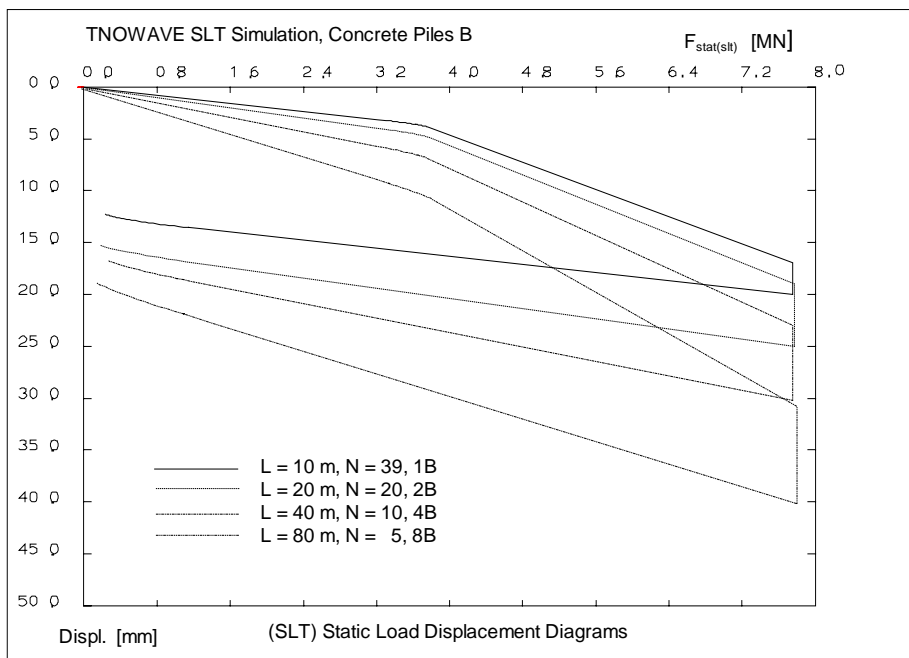


Fig. 10. SLT Static load-displacement diagrams

STN Simulation Results

With TNOWAVE the response of the pile at any level can be calculated. Pile head response to STN loading has been presented in Fig. 6 for the concrete pile 2B. An example of response signals on pile top as load, displacements, velocities and accelerations are presented in this figure and UPM values can be derived directly. From the calculated load and displacement signals STN load-displacement diagrams can be drawn. For the steel tubular piles the STN load-displacement diagrams have been drawn in Fig. 7 and for the concrete piles in Fig. 8. These diagrams include damping and inertia forces.

From the SLT simulation static load-displacement diagrams are obtained. For the steel tubular piles, the SLT load-displacement diagrams have been drawn in Fig. 9 and for the concrete piles in Fig. 10. The STN signals from the simulations can be analysed with UPM and compared with the SLT results. Table 3 and table 4 summarise the results of the analysis. The listed parameters are defined as follows.

- F_{stn} = STN load on pile head
- $F_{stn(max)}$ = maximum STN load on pile head
- u_{stn} = displacement of pile head under STN load
- u_{unl} = maximum displacement during STN, corresponding with zero velocity
- t_{umax} = time of occurrence of maximum displacement u_{unl}
- F_{unl} = STN load at moment of maximum displacement t_{umax}
- a_{unl} = acceleration at t_{umax}
- M = total pile mass
- F_a = inertia force = $M \cdot a_{unl}$ (7)

- $F_{stat(stn)}$ = $F_{unl} - F_a$ (8)
mobilised static resistance obtained with STN at displacement u_{unl}
- $F_{stat(slt)}$ = real static resistance obtained with SLT at a similar displacement as u_{unl}
- f_{sc} = stress wave capacity factor, defined as $F_{stat(stn)} / F_{stat(slt)}$

The wave numbers have been calculated from wave length of the STN load and the pile length. The wave length is determined by the duration of the STN load (appr. 0.098 s) and the stress wave velocity. The stress wave velocities taken into the calcu-

Pile	Wave number	u_{unl}	F_{unl}	a_{unl}	F_a	$F_{stat(stn)}$	$F_{stat(slt)}$	f_{sc}
no		[mm]	[MN]	[m/s ²]	[MN]	[MN]	[MN]	
1A	49	18	6.97	-58	-0.62	7.58	7.58	1.00
2A	24	26	5.66	-152	-1.68	7.34	7.58	0.96
4A	12	31	4.72	-74	-3.26	7.97	7.58	1.05
6A	8	33	4.62	-119	-5.18	9.81	7.58	1.29
8A	6	41	3.61	-105	-5.67	9.29	7.58	1.22

Table 3

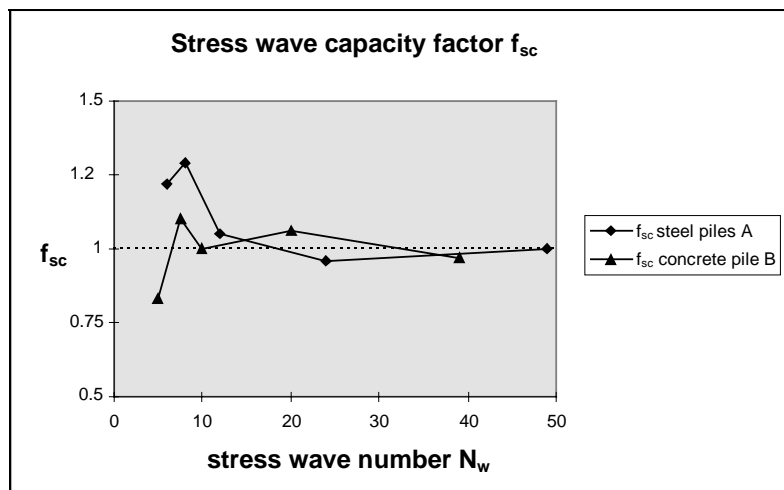
lations were 5000 m/s for the steel tubular piles and 4000 m/s for the concrete piles. The corresponding wave lengths are 490 m and 392 m.

Pile	Wave number	u_{unl}	F_{unl}	a_{unl}	F_a	$F_{stat(stn)}$	$F_{stat(slt)}$	f_{sc}
no		[mm]	[MN]	[m/s ²]	[MN]	[MN]	[MN]	
1B	39	19	6.21	-116	1.16	7.37	7.58	0.97
2B	20	25	4.24	-76	3.77	8.01	7.58	1.06
4B	10	28	2.57	-50	4.96	7.53	7.58	1.00
6B	7.5	26	2.84	-36	5.43	8.27	7.58	1.09
8B	5	30	1.42	-24	4.83	6.25	7.58	0.82

Table 4

Figures 7 and 8 show slight variations for the maximum load ($F_{stn(max)}$) although there is a large difference in pile length and pile stiffness. The acceleration at time of unloading has negative sign, meaning that the inertia force becomes negative and the pile is decelerated by the soil. The soil has to withstand the sum of F_{stn} and deceleration force F_a . For longer piles, the unloading force (F_{unl}) decreases while the deceleration force (F_a) increases. For smaller wave numbers, larger deviations between predicted static resistance ($F_{stat(stn)}$) and real static resistance ($F_{stat(slt)}$) occur.

In Fig. 11 the relation between wave number (N_w) and stress wave capacity factor (f_{sc}) has been presented. A f_{sc} factor of 1.0 corresponds with a good agreement between static resistance predicted $F_{stat(stn)}$ and real static resistance $F_{stat(slt)}$. It can be seen that for $N_w > 10$, good agreement is obtained between $F_{stat(stn)}$ and $F_{stat(slt)}$ with errors less than 6%. For $N_w < 10$ errors up to 17% occur. It will be clear that UPM needs correction for lower N_w values.



It has been discussed with UPM whether F_{unl} should be taken as static resistance, neglecting inertia forces F_a . Totally neglecting inertia forces is not acceptable because Newton's law is applicable during deceleration of the pile.

Fig. 11 Relation stress wave capacity factor and wave number

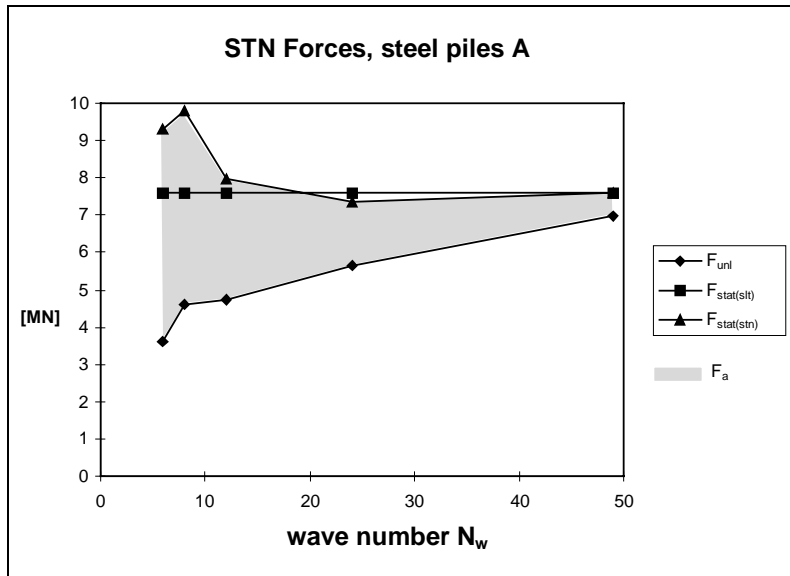


Fig. 12 Influence of F_a on prediction of real static capacity $F_{stat(stl)}$

forces for UPM, the force F_{unl} , $F_{stat(stn)}$ and the real static capacity $F_{stat(stl)}$ are presented in Fig. 12 for the steel piles A and in Fig. 13 for the concrete piles B. The following can be seen from Fig. 12. When F_{unl} is considered to be the static resistance and inertia force F_a is not taken into account, there is an increasing underprediction error with decreasing N_w , compared to $F_{stat(stl)}$. For $N_w < 12$ the prediction error can increase up to 29% when the inertia force is taken into account. When inertia force is taken into

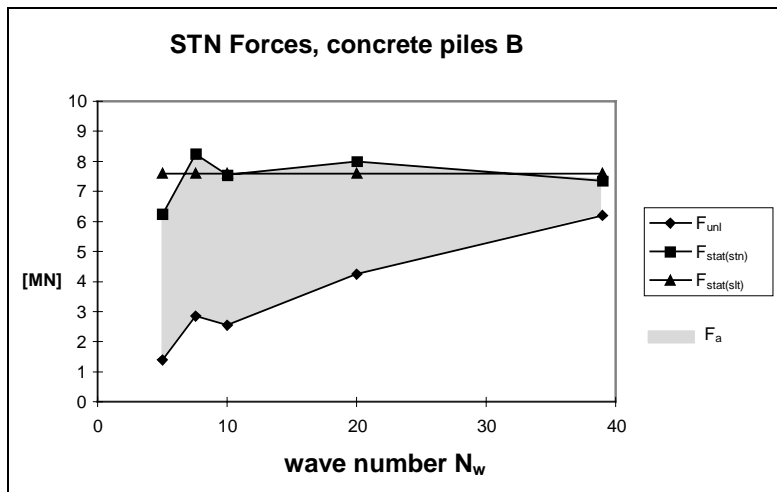


Figure 13 Influence of F_a on prediction real static capacity $F_{stat(stl)}$

account there is an increasing underprediction error with decreasing N_w . compared to $F_{stat(stl)}$. For $N_w < 10$, the prediction error varies when the inertia force is taken into account. When inertia force is taken into account, prediction errors are less than 5% for $N_w > 10$.

However, when stress wave phenomena get more dominant, the decelerated mass is not necessarily equal to the total mass of the pile. In this case, only part of the pile mass is decelerated by the soil at the time of unloading t_{umax} and results in a reduction of the inertia force.

To show the influence of inertia forces for UPM, the force F_{unl} , $F_{stat(stn)}$ and the real static capacity $F_{stat(stl)}$ are presented in Fig. 12 for the steel piles A and in Fig. 13 for the concrete piles B. The following can be seen from Fig. 12. When F_{unl} is considered to be the static resistance and inertia force F_a is not taken into account, there is an increasing underprediction error with decreasing N_w , compared to $F_{stat(stl)}$. For $N_w < 12$ the prediction error can increase up to 29% when the inertia force is taken into account. When inertia force is taken into account there is a prediction error of less than 10% for $N_w > 12$.

In Fig. 13 the same phenomena can be seen. When F_{unl} is considered to be the static resistance and inertia force F_a is not taken into account there is an increasing underprediction error with de-

Thus for approximate N_w values, it can be concluded that for $N_w > 12$, UPM can be applied straight forward while for $N_w < 12$ stress wave phenomena corrections are required.

The basic design philosophy of STN is to apply a load duration such that stress wave phenomena are negligible. Thus for wave numbers $N_w < 12$, the testing does not satisfy the STN philosophy and becomes pseudo STN. One can imagine that for very large N_w , loading becomes close to static load testing, while for small N_w analysis methods used for DLT can be applied (Fig.14).

The strategy is presented as a flow diagram in Fig. 14. The listed values for N_w are arbitrary.

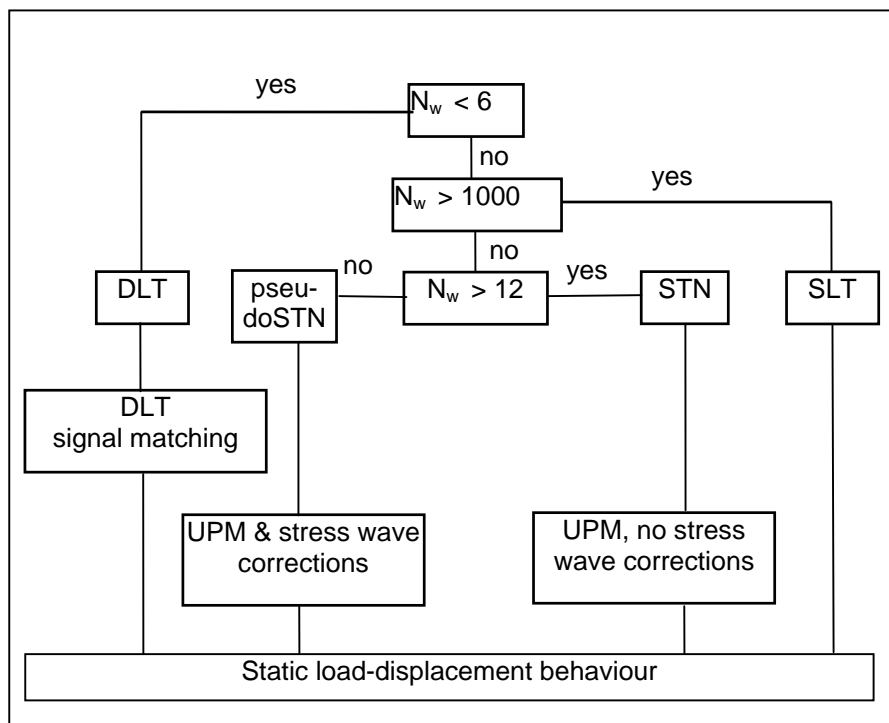


Figure 14 Load test as function of N_w

A value of $N_w < 6$ for DLT is chosen because signal matching is performed in practice over a time $6L/c$ while a load duration of L/c has been assumed. A value of $N_w > 1000$ for SLT is chosen because loading will take more than several seconds and inertia forces and damping forces become negligible.

Measures to Correct for Stress Wave Phenomena

For $N_w < 12$, correction for stress wave phenomena is required. The following measures to correct for stress wave phenomena are available and will be discussed:

- * Increase of STN loading duration
- * Stress wave analysis
- * Stress wave capacity factor

Increase of STN load duration.

Increase in STN load duration will lead to higher N_w values. An increase of load duration can be obtained by increasing the reaction mass or vent distance (Birmingham et al., 1995). However, there are physical limitations. An increase of the reaction mass will make STN less attractive compared to SLT. More fuel and later venting will result in larger acceleration duration and higher launching heights of the reaction masses. With higher launching heights, an increasing amount of kinetic energy has to be absorbed during the landing of the reaction masses. The amount of energy that can be absorbed is limited and too much landing energy can damage the catching structure.

Stress wave analysis

Some pile types, like offshore piles penetrate partly into the soil (Fig. 15). The wave number N_w can be increased by stress wave analysis in these cases. No friction is acting over the free standing length

$$H = L - P \quad (9)$$

Stress waves travel undisturbed over distance H when the pile is of uniform cross-section. We can write for force F_H , velocity v_H and displacement u_H at level H and at time t :

$$F_H(t) = F_0^\downarrow(t-H/c) + F_0^\uparrow(t+H/c) \quad (10)$$

$$v_H(t) = (F_0^\downarrow(t-H/c) - F_0^\uparrow(t+H/c))/Z \quad (11)$$

$$u_H(t) = \int v_H(t).dt$$

with

$$F_0^\downarrow(t-H/c) = (F_0(t-H/c) + Z.v_0(t-H/c))/2 \quad (12)$$

$$F_0^\uparrow(t+H/c) = (F_0(t+H/c) - Z.v_0(t+H/c))/2 \quad (13)$$

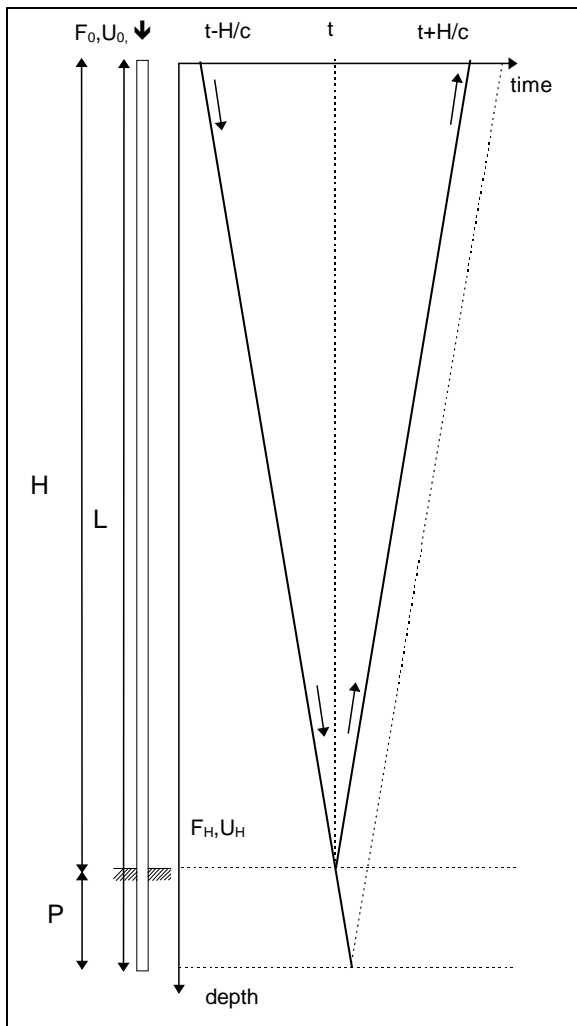


Fig. 15. Load and displacement calculation at depth H, by means of stress wave analysis

$F_0 = F_{stn}$, Statnamic force measured at pile head

u_0 = measured displacement at pile head

$v_0 = du_0/dt$

$Z = A\sqrt{E}\rho$ = pile impedance

A = cross-section pile

E = Modulus of elasticity pile material

ρ = density pile material

With $F_H(t)$ and $u_H(t)$, an alternative STN load-displacement diagram can be derived for a pile with length P and pile head at level H . The corresponding wave number N_w is determined by the pile length P , instead of the total pile length L . So N_w increases considerably and stress wave phenomena are less influential. For pile 8A, N_w increases from a value 6 with a factor L/P (80/9) to 53.

Fig 16. represents for pile 8A the STN load diagram at the pile head (F_{stn}, u_{stn}) and the STN load diagram at 71 m from the pile head ($F_{stn,H}, u_{stn,H}$).

The displacement and load at the unloading point for pile length P will correspond with values $u_{unl,H}$ and $F_{unl,H}$. The corresponding static load-

displacement diagram is defined by $F_{stat(stn),H}$ and $u_{stat(stn),H}$. The static load-displacement diagram at the pile head ($F_{stat(stn)}, u_{stat(stn)}$), can be obtained by adding the deformation of the pile part H under load $F_{stat(stn)}$

$$F_{stat(stn)} = F_{stat(stn),H} \quad (14)$$

$$u_{stat(stn)} = u_{stat(stn),H} + F_{stat(stn)} H/(E.A) \quad (15)$$

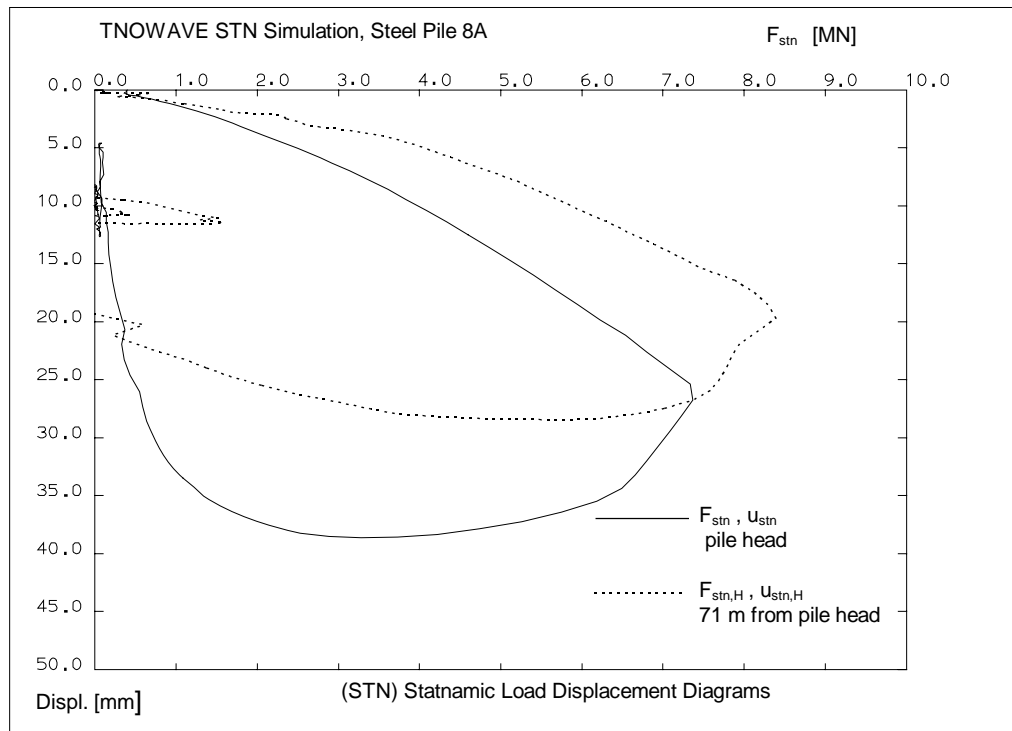


Fig. 16. STN load-displacement diagrams at pile head and depth H

Stress wave capacity factor

Before the performance of a STN test, the stress capacity factor can be estimated by performing a stress wave simulation with modelling of the pile and soil. This value can be used directly after the STN test to compensate for stress wave phenomena.

Conclusions

The sensitivity of STN load tests to stress wave phenomena can be characterised by the wave number N_w .

For $N_w > 12$, the Unloading Point Method can be straightforwardly applied. The inertia force calculated from the total pile mass has to be taken into account to predict the proper static resistance.

For $N_w < 12$, the Unloading Point Method needs correction for stress wave phenomena and only part of the pile mass will contribute to the inertia force.

The basic design philosophy of STN is to apply a load duration such that stress wave phenomena are negligible. So for wave numbers $N_w < 12$ the testing does not satisfy the STN philosophy and becomes pseudo STN. However, with correction methods predictions of static load behaviour can be made.

When large prediction deviations between STN and SLT occur and $N_w > 12$, the deviations are not caused by stress wave phenomena. The deviations must be caused by pore water pressure phenomena or strain rate dependency of the soil. (The condition of $N_w > 12$ is arbitrary and can change slightly from case to case.)

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