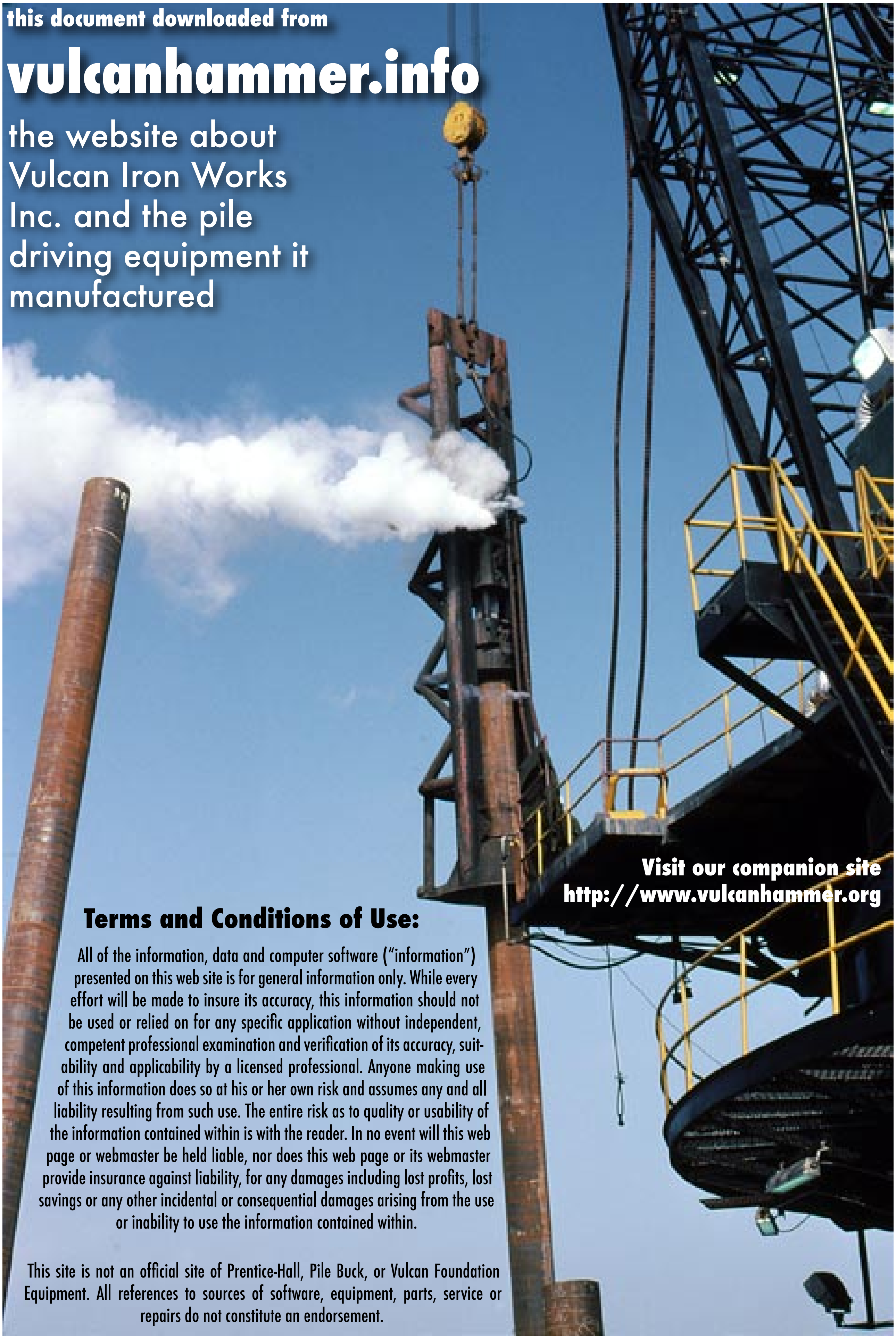

VIBRATORY PILE DRIVING PREDICTIONS

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1 INTRODUCTION

The installation and extraction of sheetpiles and foundation piles using vibratory pile driving hammers is a commonly applied technique.
In general, the choice of the size of the hammer is based on experience. In situations where experience is limited an incorrect selection may lead to premature refusal resp. non-performance situations, unexpectedly resulting in an increase in job-site costs.

Whereas in the past vibratory hammers were used mainly for temporary foundation purposes or for horizontally loaded structures only, there is a certain tendancy to use these hammers also for permanent systems as an alternative to impact hammers.
The reason for this is not only the specific advantages of the vibratory hammer such as:

- light in weight
- high rate of penetration
- low noise level
- low ground acceleration level

but also because the techniques for soil vibrations and vibratory hammers are understood much better than a decade or two ago.
In this respect the vibratory hammer lags far behind the impact hammer where for instance the computer simulation of the pile driving system started in the early sixties by E.A.L. Smith, (1).
It is approximately only 3 years ago that a similar model for vibratory hammers was initiated by TNO in The Netherlands and whose programme has been fully operational since a year ago.
This paper will describe the simulation programme and its use in the pile driving prediction calculations in more detail in the sections to follow.

2 PRINCIPLE OF OPERATION

The most common mechanical configuration used for vibratory pile driving hammers is shown on Fig. 1.
The major components of the hammer itself are:

- an (even) number of eccentric masses (total mass m_e) and rotating at radius r.
- a vibratory case incorporating the eccentric weights, and one or a set of hydraulic pile clamps, weight W_c.
- Elastomer (spring) isolated suppressor with weight W_s.

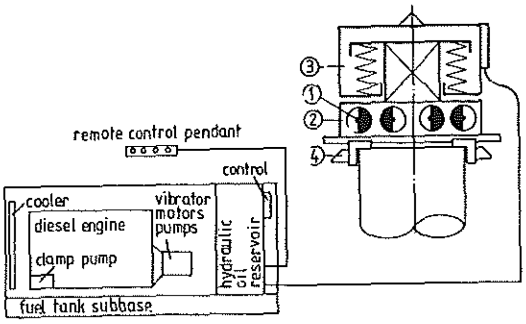

Fig. 1—Lay-out.

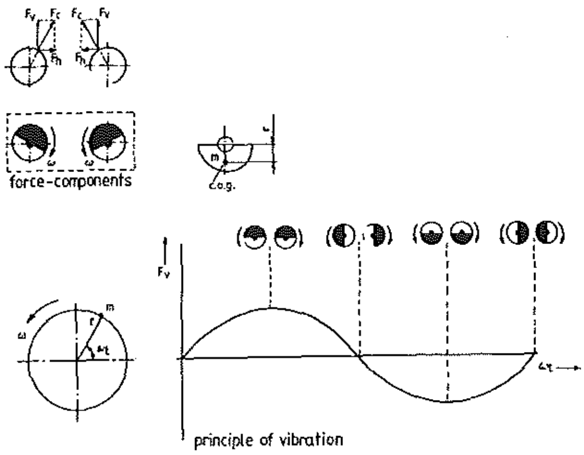

Fig. 2—Principal operation.

The pairs (one or more) of counter-rotating eccentric masses rotate usually at frequencies (f) between 20-30 Hz (1200-1800 cpm).
The generated centrifugal forces (F_c) result in oscillating pile and hammer movements, its amplitude being a function of operating frequency (f), eccentric moment (M_{ecc}), pile properties and soil response.
The eccentrics itself are phased such that horizontal components of the centrifugal forces cancel and the vertical components add, as shown in Fig. 2. They are mechanically synchronized by a usual gearing system and are driven by one or more hydraulic motors.
The driving and extracting capabilities of the vibratory hammers are generally characterized by:

- The maximum centrifugal force: $F_c = \Sigma m_e . r . (2\pi f)^2$ ... (1)
- The centrifugal force : $F = F_c . \sin(2\pi f . t)$ .. (2)
- The static eccentric Moment : $M_{ecc} = m_e . g . r.$ ... (3)
- The weight of the pile : W_p
- The total weight of the oscillating parts : $W_d = W_c + W_p$ ... (4)

3 DIFFERENCES WITH IMPACT HAMMERS

Both vibratory hammers and impact hammers are a tool to bring foundation elements to a certain prefixed penetration into the subsoil to fulfill the initial requirements and criteria which these elements were designed for.
However, the theoretical principles and therefore the practical utilities of these hammers are completely different. The basic differences are:

1) Impact hammers are High Peakforce/Low Frequency hammers, Vibratory hammers are Low Peakforce/High Frequency hammers. See Fig. 3.

2) For vibratory hammers, constant energy supply to hammer and pile due to a rigidly fixed connection between the two.
For impact hammers there is a constant energy supply to the hammer, however an intermittant energy supply to the pile. (Fig. 3).

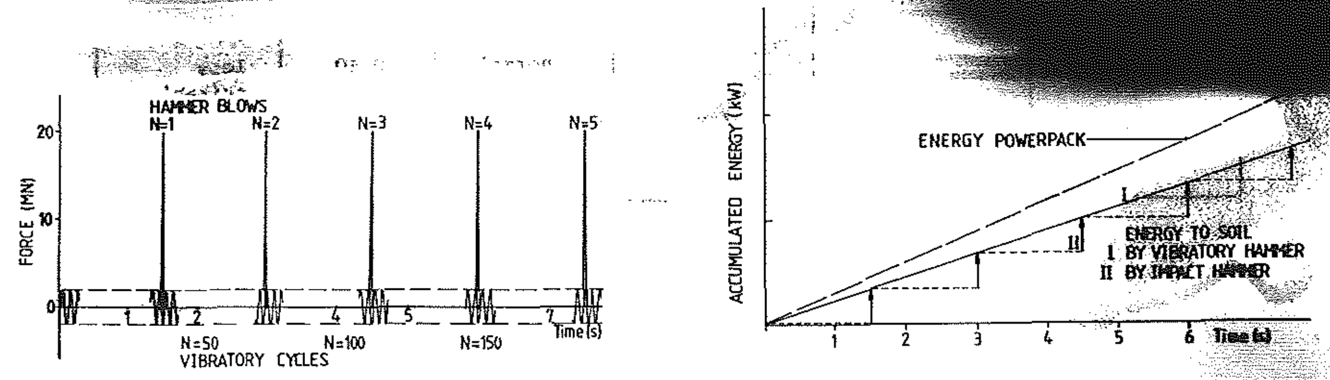

Fig. 3 : Force-time and Energy-time comparison diagrammes

3) As a result of the fixed connection between vibratory hammer and pile element energy pulses are transferred to the soil permanently and over the full length of the pile, therewith achieving pile penetrations through temporary "SOILSTRESS RELIEF".
Impact hammers transfer a high-level stresswave into the pile, propagating at a certain speed through the pile material and achieving pile penetration through temporary "SOIL OVERSTRESSING".

The discussion on mechanical and operational differences is beyond the scope of this paper and has not been further elaborated on here.

4 VIBRATORY PILE-DRIVEABILITY PREDICTION METHOD

In this paragraph a very basic concept is given on the principle method, used by the company of the author, on driveability prediction for vibratory hammers.
It is known that soils subjected to vibrations temporarily change their initial strength to a much lower level, resulting in a considerably lower resistance for a penetrating element when compared to the same element being driven into the soil statically or by impact.
The extent of the reduction in resistance will depend on the exciter frequency, the operating amplitude, soil type, water content, saturation degree, soil angularity etc.

Using the term SRV (Soil Resistance during Vibratory driving) the following simple expression can be made up, assuming that the vibratory pile will not plug during the driving process:

$$SRV_t = \beta_o F_o + \beta_i F_i + \beta_t Q_t \quad \text{. . . . . (5)}$$

where

- SRV_t = total dynamic soil resistance during vibratory driving
- β = reduction factor between static resistance and vibratory resistance
- F_o = static outer skin friction
- F_i = static inner skin friction
- Q_t = static tip resistance underneath pile wall

The formula above is in its general form. Very little is known on the indicated β values. Ref. 2 presents a list which may give indicative, and to the experience of the author, conservative values.
Experiences with this method of prediction are described in Ref. 3.
If, on the basis of above criteria the SRV value has been established, pile driveability resp. its extractability can be determined as follows:

For pile driving applications the matter is not so simple because piles cannot be considered as a single dot mass and, more difficult, the influence of soil resistances and stress-reflections can hardly be incorporated.

Proper estimations of these effects can be studied and calculated only by using a computer simulation model which incorporates time effects and allows hammer and soil modelling.

5 PRINCIPLE OF STRESSWAVE PROGRAMME TNOWAVE

The programme TNOWAVE, developed by the Dutch Institute on Applied Scientific Research (TNO), has been used for several applications in the field of pile dynamics (Ref. 4) and has recently been extended to the prediction and analyses of Vibratory Hammer performance, because stresswave propagation is the same as for Impact Pile Driving Hammers.
The difference between Impact Pile Driving and Vibratory Pile Driving is mainly caused by:

- Duration of the load. For an impact hammer the duration is expressed in milliseconds. For a vibratory hammer the oscillating forces act over a long period.
- Intensity of the load. For impact hammers expressed in Meganewtons, for vibratory hammers in Kilonewtons.
- The soil response. With impact hammers penetration is achieved by overcoming the soil resistance during each blow; with vibratory hammers the oscillating force-pulses cause a considerable soil stress relief and therewith penetration under low loads.
- Gravity. For impact pile driving the weight of the pile plays a minor role when soil-layers are penetrated. However, for vibratory pile driving the weight of the hammer and pile is the main factor contributing to the penetration of the soil layers.

The algorithm of the programme TNOWAVE is based on the method of characteristics (Ref. 5). The method is based on the principle that stress waves propagate unaltered in a frictionless pile with a characteristic velocity (Fig. 6). The method is extended to piles with friction by the introduction of discrete points along the pile shaft (Fig. 7). Between two of these points the pile remains frictionless and waves will propagate undisturbed from one point to the other. At the discrete points equilibrium and continuity conditions have to be fulfilled, and as a result waves will be reflected and transmitted. From the reflected and transmitted waves, forces, displacements, velocities and accelerations can be calculated at the location of the discrete points.

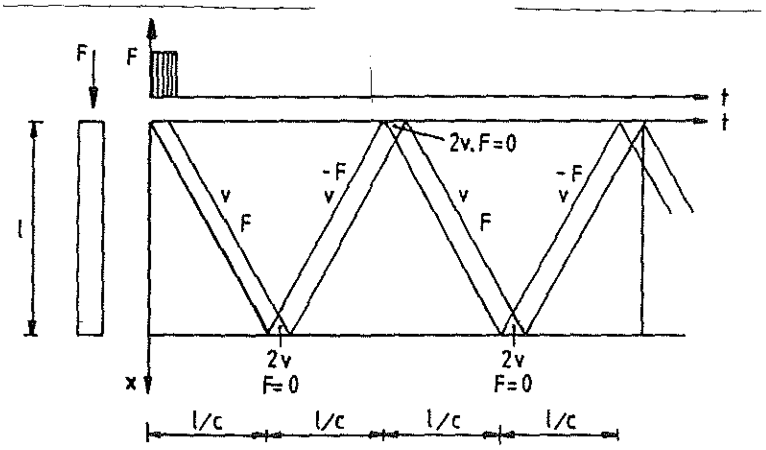

Fig. 6 : Response of a free ended prismatic bar on a pulse load at the top

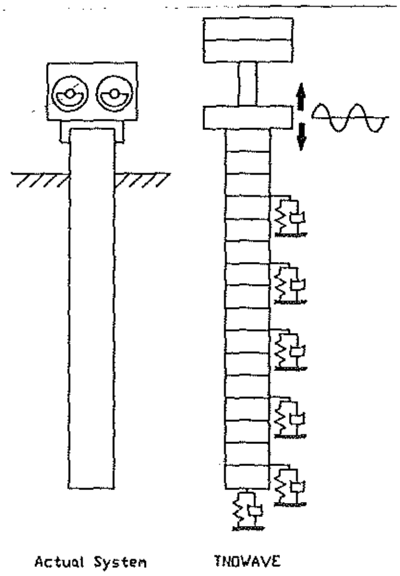

Fig 7 : Principle TNOWAVE programme

6 RESULTS OF COMPUTER RUNS

To show the capabilities of the computer a series or runs have been made for the largest available vibratory hammer the ICE-1412, having an eccentric moment of 115 kgm and a maximum centrifugal force of 2400 kN at a frequency of 22.5 Hz.
The runs simulate a free pile-tip and free pile-head system and does not include gravity.

The pile length has been varied from 15m to 150m and at various levels in the pile, the force-time, displacement-time, velocity-time and acceleration-time diagrams have been calculated.
Some of the results at a single level are presented in Fig.'s 8, 9 and 10.

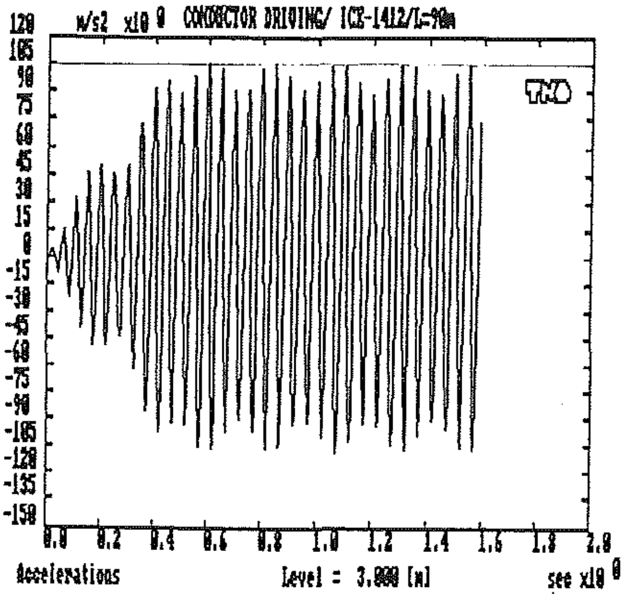

Fig. 8

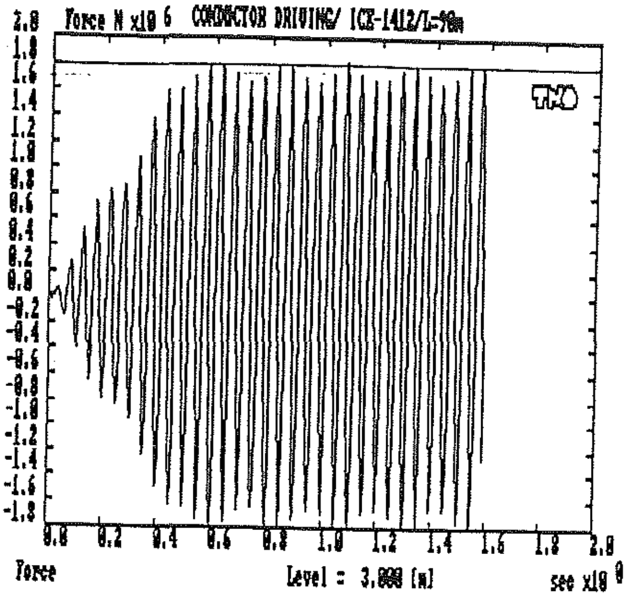

Fig. 9

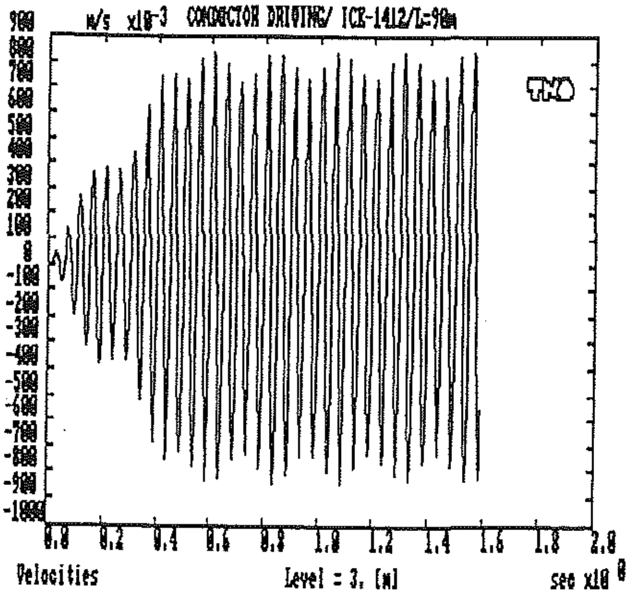

Fig. 10

The influence of the pile length on maximum peakforces, and maximum amplitudes at the pile head and 50m below pile head are given in Fig.'s 11 and 12.
These graphs show a remarkable similarity with the magnification factor diagram of Fig. 5 for a single dot-mass system.
It also shows that not for all pile lengths the maximum centrifugal force is reached in the pile head.
This is due to the fact that basically also the pile head is a free moving end with theoretically no forces and only displacements.

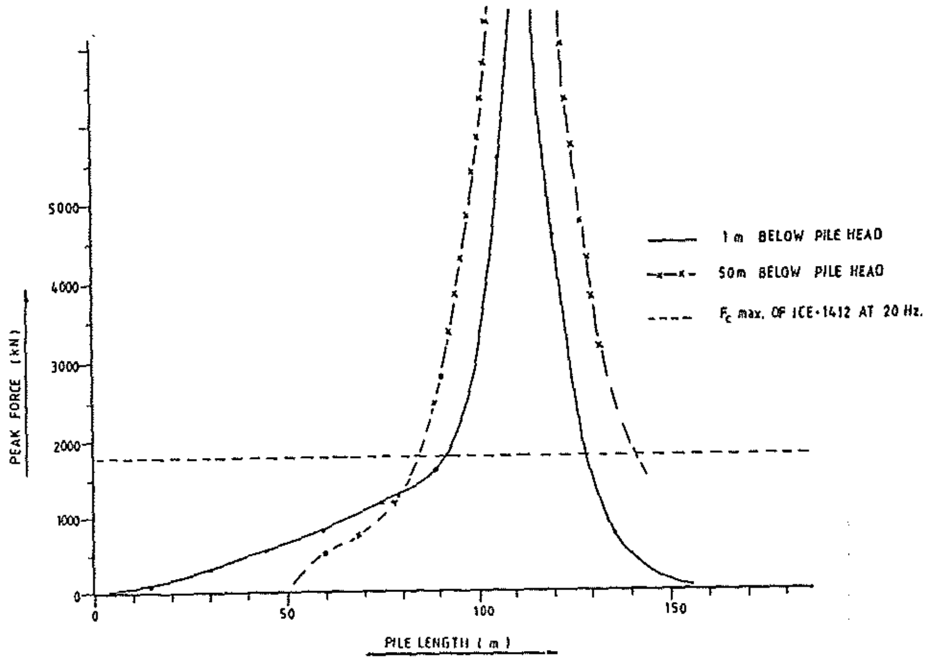

Fig. 11 : Max. Peakforce vs Pile length

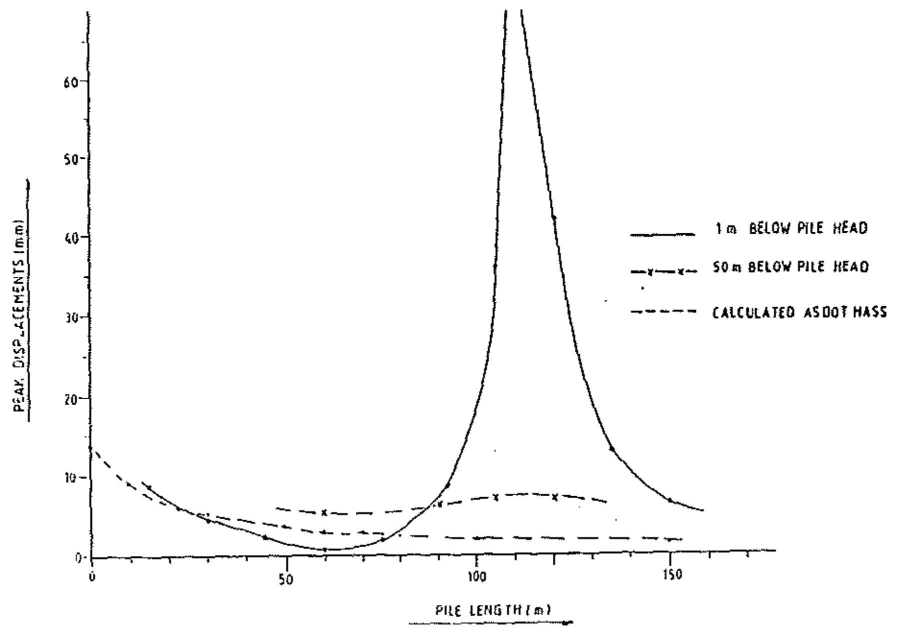

Fig. 12 : Max.

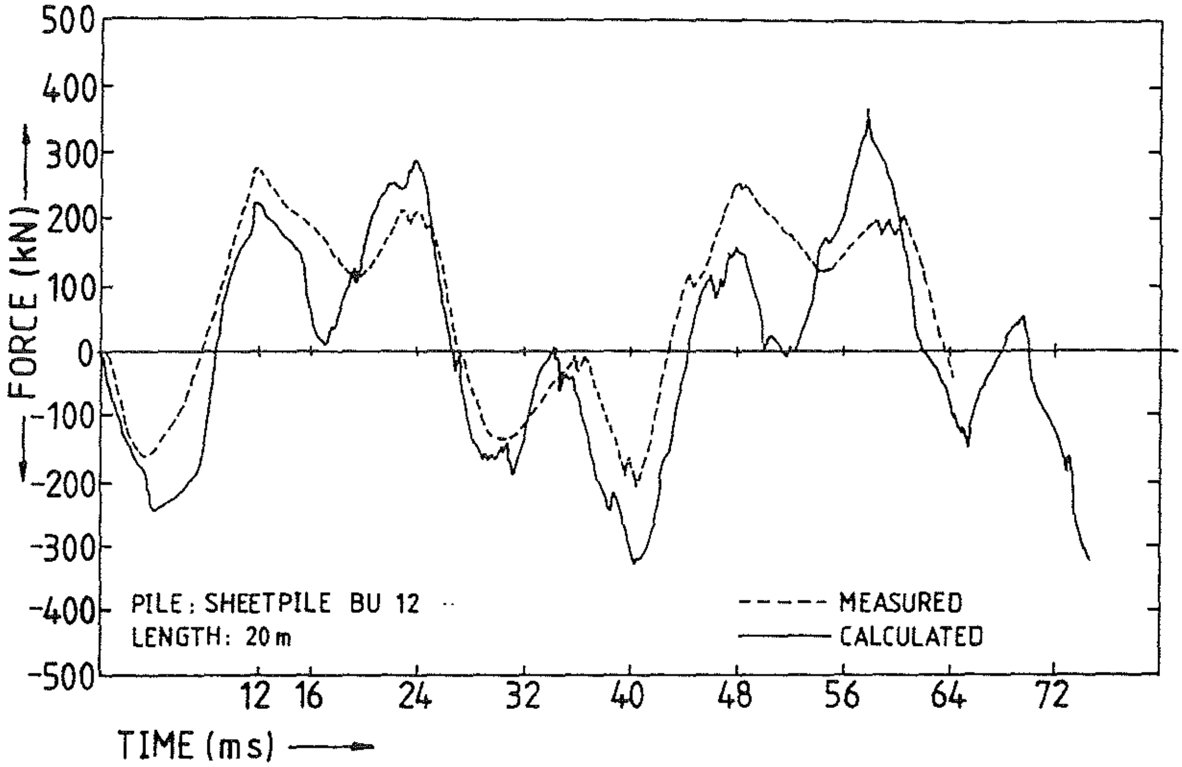

Fig. 13 : Comparison Measured and Calculated Force-time diagrammes

The above figure nevertheless shows that the first assumption on the modelling gives good results, especially where it concerns the overall shape of the diagramme and the stresswave reflections. As only limited field data were available, the actual magnitude of the measured forces might be influenced by a certain amount of soil resistance. The TNOWAVE calculations were performed for a complete free system.

7 CONCLUSIONS

The described driveability prediction method is simple and straightforward and should not be extended until further data is available from tests or pile monitoring data.
A refinement of the actual values of the β-factors is necessary as well as the influence of depth on these factors.

The TNO stresswave programme has proven to simulate the actual situation correctly and can be used as a key-tool in the final assessment of a pile's driveability.
Furthermore, it will give a tremendous impact on the basic understanding of vibratory pile driving, not only mechanically within the hammer-pile system but also on the interaction between pile and soil.

Ref. 1 E.A.L. Smith, "Pile driving analyses by the wave equation", Journal of Soil Mech. and Foundations, ASCE 86, 1960.

Ref. 2 G. Jonker, "Vibratory Pile driving hammers for Pile installations and Soil Improvement projects", OTC-5422, 1987.

Ref. 3 G. Jonker, "Subsea Installations using Vibratory hammers", OTC-5776, 1988.

Ref. 4 P. Middendorp and A.F. van Weele, "Application of Characteristic Stresswave Method in Offshore Practice", 3rd Int. Conf. on Num. Methods in Offshore Piling, Nantes, 1986.

Ref. 5 Voitus van Hamme, G.E.J.S.L., "Hydroblok and improved pile driving analyses", Magazine De Ingenieur (Dutch) no. 8, volume 86, 1974.

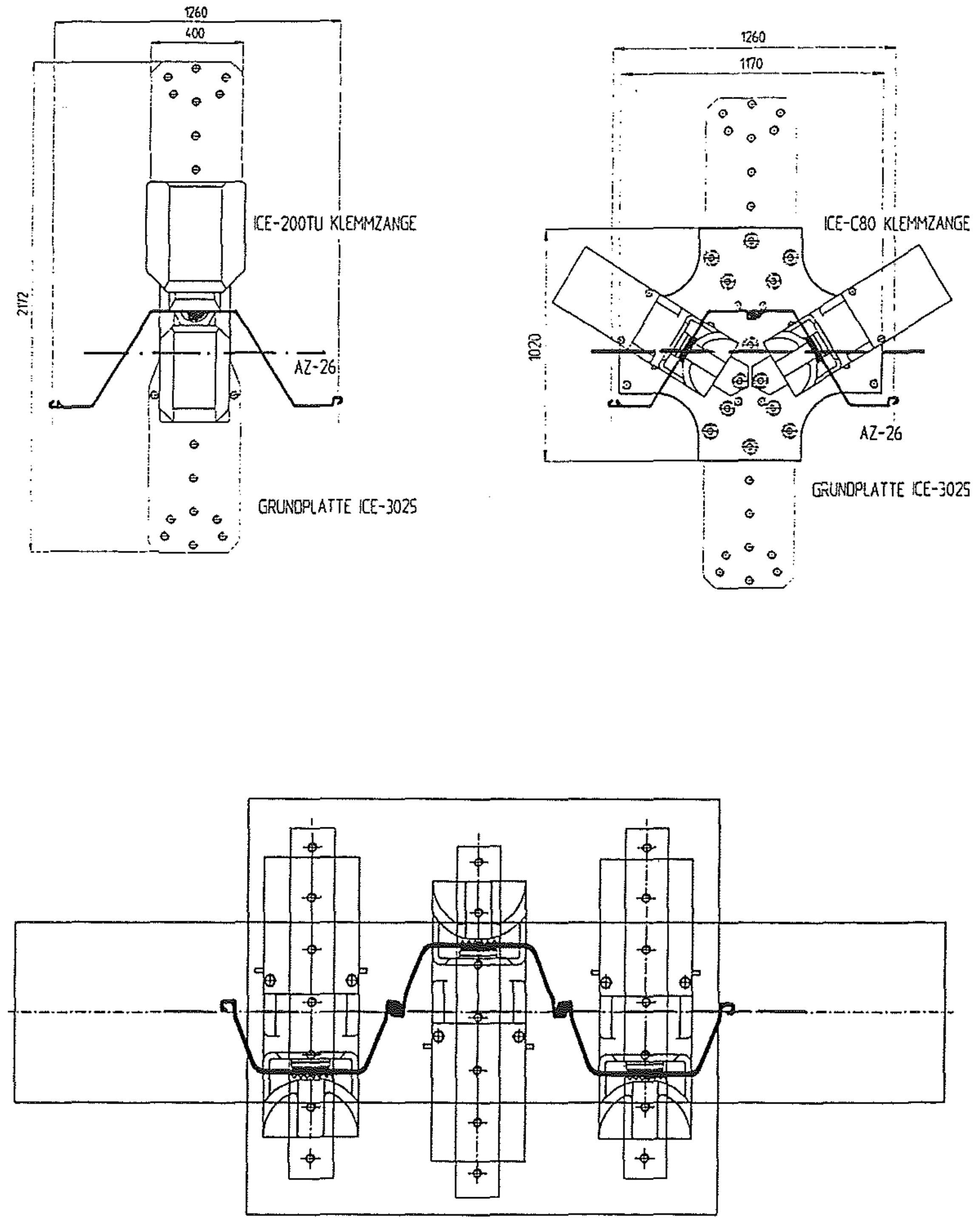

FIG. 18 CLAMP CONFIGURATIONS

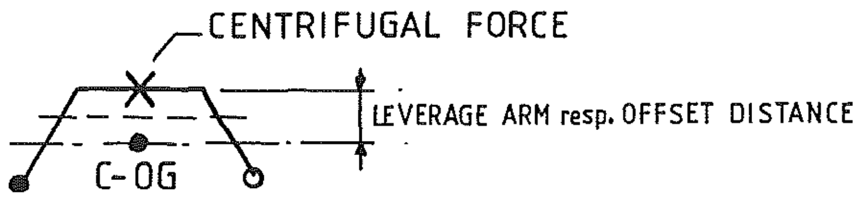

FIG.19

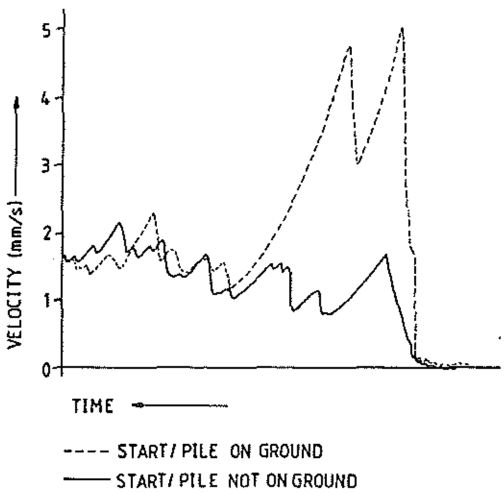

FIG. 20

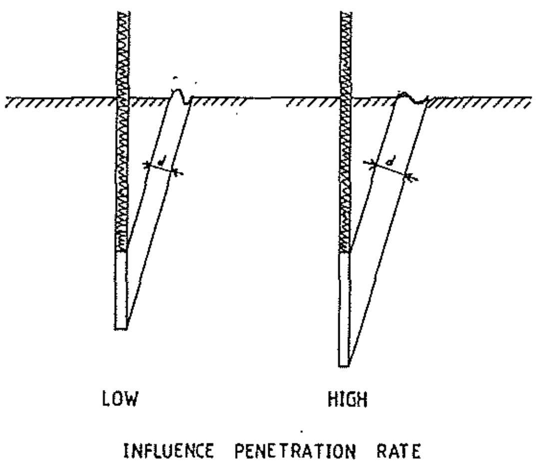

FIG. 21