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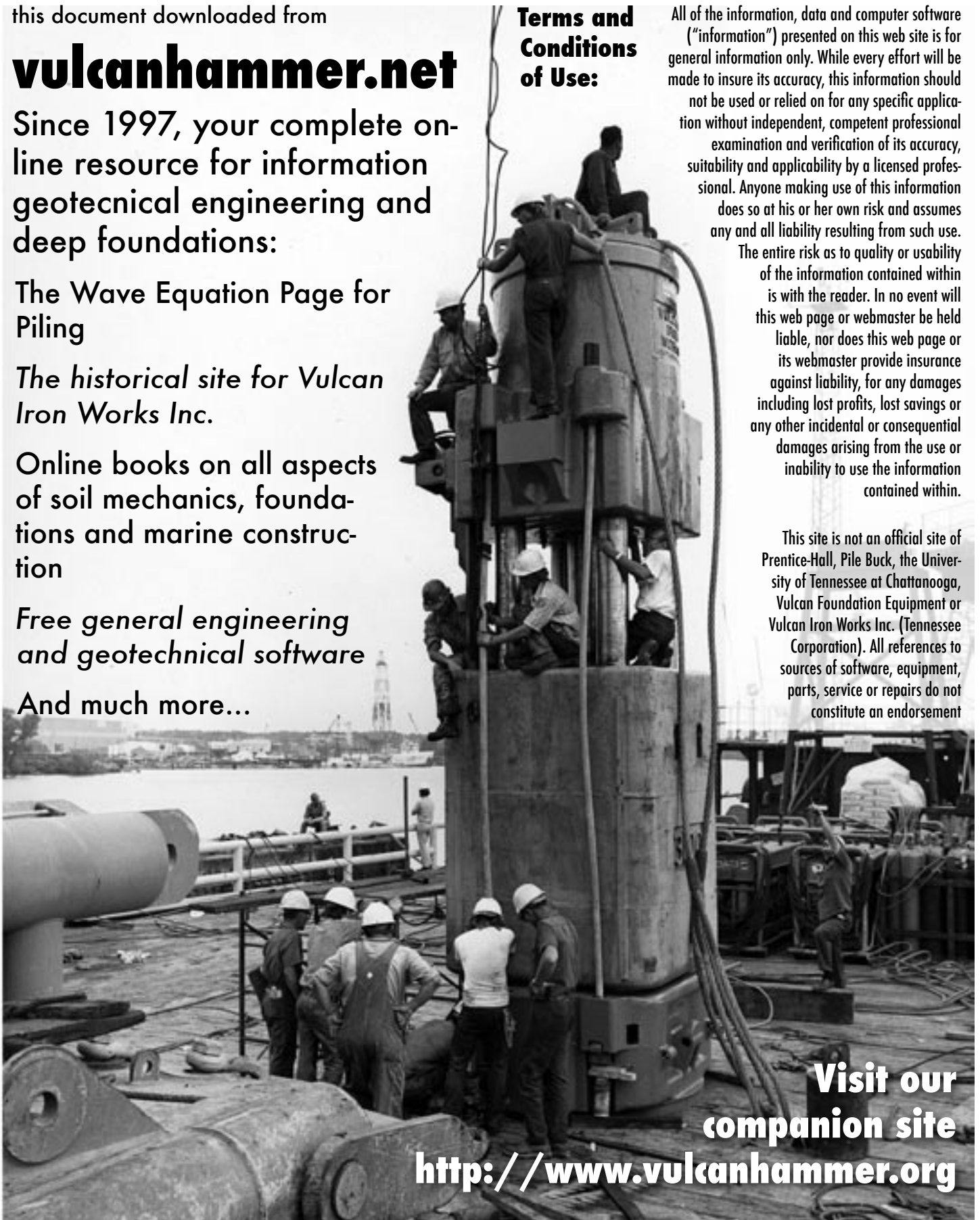
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30 YEARS OF EXPERIENCE WITH THE WAVE EQUATION SOLUTION BASED ON THE METHOD OF CHARACTERISTICS

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Abstract

This paper will describe a brief history of the method of characteristics as an accurate solution of the wave equation, and the authors' experiences with the method of characteristics over a period of 30 years.

As a result of the offshore pile driving activities associated with the development of the North Sea oil fields in the 1970's, two Dutch companies initiated extensive efforts to research the dynamic behavior of soil during driving as well as to extend the method of characteristics with a straightforward theoretical solution for the shaft friction along the pile.

The Dutch governmental research institute TNO started the development of the wave equation program TNOWAVE in the late 1970's based on this extended method of characteristics with the theoretical solution for shaft friction. Today the program has a worldwide application in the field of pile testing. This paper will describe its development and application over time and its relation to today's applications for drive-ability studies for impact hammers (PDPWAVE) and vibratory hammers (VDPWAVE), signal matching for Dynamic Load Testing (DLTWAVE), Pile Integrity Testing signal matching (SITWAVE) and Statnamic simulation (STNWAVE).

The paper will then focus on Sonic Integrity Testing signal matching, and indicate some areas where developments are required to enhance this type of testing.

Introduction

Former United States president Ronald Reagan often quoted a Russian proverb "doveray, no proveryay", which he translated as "trust, but verify", as he laid out his vision regarding nuclear arms control during the cold war era. Having spent more than 30 years dealing with the Wave Equation Solution based on the Method of Characteristics, and the application of this solution to pile foundation testing and monitoring, the author is regularly reminded how true this observation is. While it is true that over the years increased knowledge regarding the installation techniques has improved the quality of installed drilled shafts, and that many contractors around the world can be trusted with this type of work, it is nevertheless still appropriate to verify the product.

Last year, during the 7th International Conference on the Application of Stress Wave Theory to Piles in Kuala Lumpur, Malaysia a paper was presented covering some of the author's experience with the method of characteristics with the focus on the algorithm used in TNOWAVE. This paper will expand on that topic by looking at the subject of the Wave Equation Solution application in pile foundation technology by focusing on the application from a different angle: how this method can be used to assess the quality of drilled shafts through Sonic Integrity Testing (SIT).

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The Pre-History

In the 1860's a Frenchman, A.J.C Barre de Saint Venant, applied the principles of conservation of mass and momentum to the water flow in an open channel. The application resulted in two quasi-linear differential equations, for which de Saint Venant produced a theoretical solution, the so-called method of characteristics. This method was then used for a variety of hydrology related issues, such as to predict the propagation of tidal waves, based on the work of J. Massau and J.C.Schonfield.

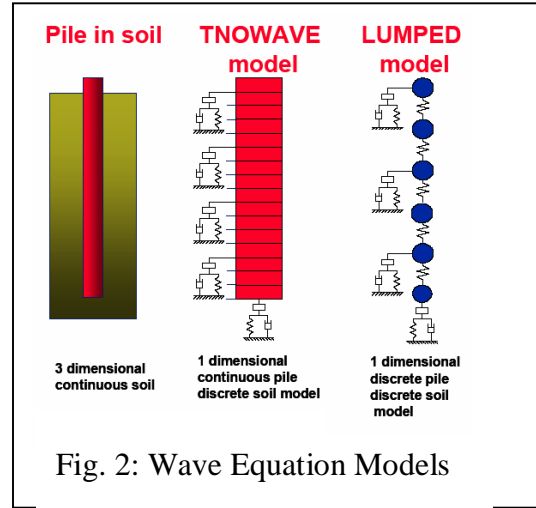
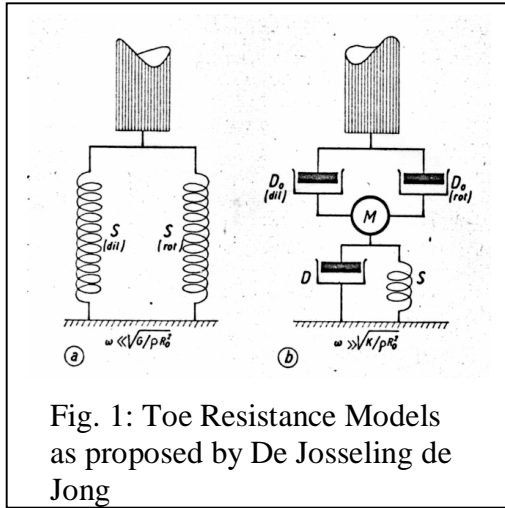
Starting in the 1930's Saint Venant's equations were applied to pile driving by several scientists around the world, such as L.H. Donnell in the United States, D.V. Isaacs in Australia, and W.H. Glanville in England. The latter directed the first comprehensive study aimed at understanding cracking in concrete piles at both the top and the bottom during pile driving. As part of this work, measurements were taken during pile driving using what was considered at that time portable equipment in a construction trailer. As such Glanville is truly the pioneer in the field of PDA, as it would take some 18 years before similar work was done in the Netherlands (by A. Verduin) and some 25 years before it was done here in the United States (by G.G. Goble).

Just as Glanville can be considered the father of PDA, Isaacs can be considered the first to ever use wave equations for modeling pile driving. But apart from that, he should also be remembered for his insights on the issue of safety factors. In an article published in 1931 in the Journal of the Institution of Engineers Australia, Isaacs wrote the following on this subject:

It should be remembered, however, that these are not true factors of safety, but include a "factor of ignorance." The author suggests that when the ultimate resistance of any pile has been determined, in fixing the factor of safety...the most unfavorable conditions possible in the supporting strata should be judged (the range of conditions possible being narrowed with better knowledge of the subsurface conditions and of the possibility of disturbance from extraneous sources) and a proportion of the factor of safety -- a "factor of ignorance" -- then allowed in respect to these possible conditions, the manner of determining the ultimate load, and the type of loading to be borne. The remaining proportion of the factor of safety -- or true margin of safety -- should be approximately constant for all classes of loading and foundation conditions involving the same value of loss in case of failure; and the overall factor of safety...will then be equal to the product of the true factor of safety with the "factor of ignorance." (p. 305)

This way of dealing with safety factors was and remains extremely insightful, and is just another example why it is important to know the past.

The original method of characteristics was valid for a free rod, not interacting with shaft friction or toe resistance. After all, the method is based on the phenomenon that stress waves propagate unaltered with a characteristic stress wave velocity. In 1956 Dutch scientist G. de Josseling de Jong proposed a model to incorporate the toe resistance into the method of characteristics (Fig. 1), and then in 1974 the Dutch company HBG extended the method by formulating the theoretical solution for piles with shaft friction. This development was part of HBG's development of the Hydroblok impact hammer, a high-tech hammer using nitrogen cushioning to improve efficiency.



Until 1974 when friction was introduced, the partial differential equation could only be solved analytically if the friction was represented as an analytical function. The solution was then found by integral transforms (such as the Laplace transform) and obtained in the form of Fourier series (Van Koten, et al. 1980). However, if the shaft friction was assumed to depend on the velocity or displacement, there was no theoretical solution and a numerical integration of the differential equation had to be used, as was done at that time in the numerical wave equation program developed by E.A.L. Smith. For this purpose the pile was modeled by a number of point masses, with the shaft friction and toe resistance introduced through a series of springs with dash-pots connected to the point masses (the so-called Lumped Model, Fig. 2).

To be able to generate a theoretical solution, the HBG took a different approach to account for the friction, which – with hindsight – was really very simple: “when the friction is concentrated at a number of points, the parts of the pile between these points are not subject to friction and the simple stress wave theory is valid for them”, and the discontinuities that occur at the points where the friction is modeled can be easily dealt with. This method formed the basis for HBG’s computer program PILEWAVE that was released in 1974, a few years before the WEAP program was released in the USA and TNOWAVE was released in The Netherlands.

TNOWAVE

Although it is a small country, The Netherlands has a huge piling market because of the poor soil conditions. Every year between 700,000 and 1,000,000 pre-cast piles are driven and a similar number of cast in situ piles are installed. It is therefore not surprising that there was a need for basic research in the area of pile foundations. Consequently in the 1960’s a group was established within the Building and Construction Research Department of the Dutch organization for Applied Scientific Research (TNO), the second largest R&D organization in Europe. The Foundation Pile Diagnostic Systems (FPDS) Group, as it was initially called before it was renamed Profound, took on a broad range of activities for its clients in foundation pile testing with state-of-the-art technology that was developed in research and development projects.

In the 1970's this group started to really focus on the field of stress wave applications when two Dutch companies (Heerema and HBG) together with TNO intensified their research in this area because of the offshore pile driving activities associated with the development of the North Sea oil fields.

In 1975 Heerema performed research at the TNO laboratories to investigate soil behavior during pile driving to develop models for pile driveability analysis, elaborating on the work done by H.M. Coyle and G.C. Gibson in the United States. At the same time HBG used the stress-wave application in their development of the Hydroblok, which led to the release of PILEWAVE in 1974.

Following the release of PILEWAVE, TNO wanted to develop its own wave equation program. While it was considered to use Smith's algorithm as the basis for such a program, it was decided to use the method of characteristics instead and the first issue of the program TNOWAVE was released in 1978. In the following years much work was done to better understand the dynamic soil model parameters, and to establish signal matching techniques, similar to CAPWAP. The first commercial version of the DLTWAVE module was released in 1982.

In the second half of the 1980's TNOWAVE was extended to vibratory pile driving prediction, again in response to developments in the offshore oil & gas industry. At that time the theories to predict the performance of a vibro-hammer were based on a single, lumped-mass pile model. This approach is valid for relatively short piles, but not for long piles (such as used offshore). A long pile is not moving as a single lumped mass, and stress wave phenomena have to be taken into account. Using the method of characteristics the VDPWAVE module was developed (and released in 1988) and with this module it was demonstrated that long offshore piles could be installed with vibro-hammers (Jonker & Middendorp, 1988).

From the above it is obvious that the early development of TNOWAVE was heavily affected by the offshore oil & gas industry (just as the United States Federal High Way Administration and the New York Department of Transportation had a strong influence on the development of the WEAP program in the United States). By the late 1980's and early 1990's there were several features added to the program to address needs in the pile foundation industry in general.

First, the Dutch pre-cast piling industry wanted to know the minimum amount of steel required to allow pile driving without loss of quality and reliability. Since the main function of the reinforcement is to prevent or at least reduce cracking during pile driving, a numerical crack model was developed and implemented into TNOWAVE in 1988. This model contains the following options:

- Simultaneous wave propagation in the concrete and the reinforcement
- Bond forces between concrete and reinforcement
- Pre-stressing
- Cracking models
- Multiple cracking
- Opening and closing of cracks

Secondly, around that same time the TNOWAVE signal matching technology was extended to pile integrity testing, and in 1988 the SITWAVE module was released. Later that year the module was successfully tested on piles with known defects.

Finally, in the early 1990's the program was expanded one more time with the release of the STNWAVE module to cover the development of Statnamic testing, which was developed by TNO and Berminghammer. It is interesting to note that this module strictly speaking doesn't

belong in TNOWAVE. Given the long duration of the Statnamic test (compared to a dynamic load test) it was first assumed and later demonstrated that the pile could be modeled as a lumped mass with springs and that stress wave phenomena did not have to be taken into account.

Sonic Integrity Testing

In 1973 TNO initiated research to determine the shape (impedance) and length of drilled shafts. The results were promising and in the late 1970's the very first "Foundation Pile Diagnostic System" (FPDS-0) was released. This equipment consisted of an analogue signal processor, an oscilloscope to collect and display the data, and a Polaroid camera to record the data.

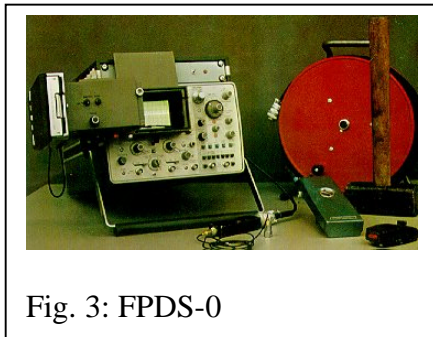


Fig. 3: FPDS-0



Fig. 4: FPDS-1

In the mid 1980's the next version of the FPDS was released, which processed the incoming data digitally. The FPDS-1 used a Unix workstation with a 16-bit MC68000 chip and with a built in keyboard, disk drive, monitor and printer/plotter. As late as 1997 FPDS-1 systems were still actively used for SIT.

In the 20 years since the release of FPDS-1 six upgrades were released, each with more powerful electronic capabilities to process the signals generated as part of the test.

Today more than 100,000 piles are tested each year in The Netherlands alone, and it is estimated that by now worldwide more than 10 million piles have undergone SIT.

Despite the large number of tests that have been performed, SIT is still seen by many as some magical act, with the handheld hammer used in the test as a sort of SIT wand. Yet the base principals of SIT are very simple and can be summarized as follows:

- A stress wave (sound wave) is introduced into the pile by means of a hammer blow on the pile head; this stress wave travels at the speed of sound to the pile toe and reflects back to the pile head.



Fig. 5: FPDS-7

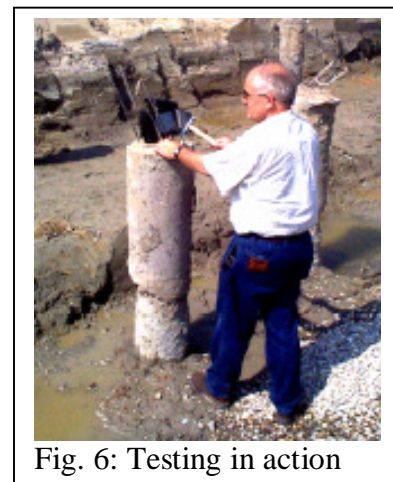


Fig. 6: Testing in action

- If on the way down impedance variations are encountered (e.g. as a result of changes in the cross sectional area, cracks, variations in soil layers, or inclusions of foreign material), then a part of the wave will reflect from this impedance variation and return to the pile top.
- The response of the pile head, as a result of the hammer blow and reflections, is measured with an acceleration transducer.
- For each pile at least 3 hammer blows are applied to the pile head and the results are presented as 3 traces in a diagram; to proof the quality of testing, the 3 traces should be similar.
- Due to shaft friction the toe reflection might be of small magnitude; to make the reflection visible, the measured signal is amplified.
- To remove noise from the signals a filter value can be applied.
- To differentiate between a change in soil resistance and a pile discontinuity, the SIT signal from a test pile should be compared to a "characteristic signal" deemed to be representative of similar piles in similar soil conditions on site (this characteristic signal can either be an average of a number of piles on site or the SIT signal of a reference pile chosen prior to testing); if the test signal is different than the characteristic signal, then any impedance changes are due to the changing pile impedance and not characteristic of the site, and such changes require further analysis to determine the cause.

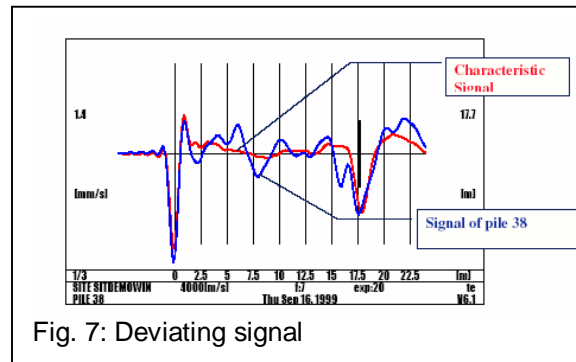


Fig. 7: Deviating signal

This simple testing method can be applied to up to 300 piles per manday, and any pile can be tested. These two aspects are important to consider, especially when comparing this testing method with Cross-hole Sonic Logging. The latter requires substantially more time and can only be performed on pre-selected piles.

SITWAVE

To analyze qualitatively the difference between the test signal from a specific drilled shaft and the characteristic signal, signal matching must be applied, which consists of three parts:

1. The first part is the generation of a computer model using the theoretical pile dimensions and available soil information. With this data the theoretically anticipated response to a hammer blow on the pile head is calculated, and this response is then compared to the characteristic signal.
2. In the second part the soil data in the computer model is modified until the computer model generates a signal that matches the characteristic signal as closely as possible.

- Using the soil data generated during the second part, the pile data is now modified until the computer model generates a signal that matches the test signal from the specific drilled shaft as closely as possible.

The outcome is a dimensional model of the specific drilled shaft using the theoretical pile dimensions as a basis.

While this description of SITWAVE is somewhat simplified (as is the description of Sonic Integrity Testing in the previous paragraph) by not addressing each and every aspect that ensures a successful test, it should be obvious that this type of testing is a simple and low cost testing method to determine major defects in drilled shafts. The best evidence of this conclusion is the widespread use of this testing procedure as mentioned earlier in this paper.

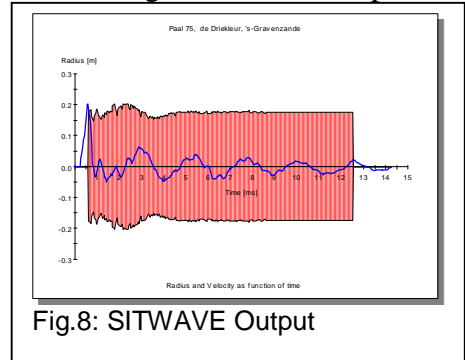


Fig.8: SITWAVE Output

The Present and the Future

It is clear that the stress-wave programs, such as TNOWAVE and WEAP, have allowed and continue to allow lowering of the costs for foundations using driven piles and drilled shafts. First, through the simulation mode it provides engineers the opportunity to optimize the design of both the pile itself and the pile foundation. Secondly, through the signal matching mode it allows the widespread use of dynamic load testing as well as Statnamic testing, which provides valuable information on the bearing capacity of the pile or drilled shaft, and therefore enables further optimization of the foundation design. In addition the signal matching also provides a simple and low cost method to test the integrity of the drilled shafts.

The remaining question is how we can further develop stress-wave programs in the area of integrity testing. One area that can never be overlooked is the soil modeling. The TNOWAVE soils investigation module handles many different types of soil investigations (e.g. CPT, SPT, DMT and PMT or bore hole results), but this part is undoubtedly the weakest link in the overall computer model. To borrow a phrase from Isaacs, the *factor of ignorance* is the greatest in the soil modeling, and therefore research efforts should be directed towards this area, making full use of the ever increasing computing capabilities. In this regard the efforts in the Netherlands surrounding the Geotechnical Exchange Format (GEF) should be noted. Soil investigation data (like CPT results) are recorded in a standardized digital format (GEF) and the TNOWAVE program can then read these GEF files, after which the soil investigation module automatically determines the soil types and then converts the soil investigation data into the fundamental static and dynamic soil parameters used in the algorithms.

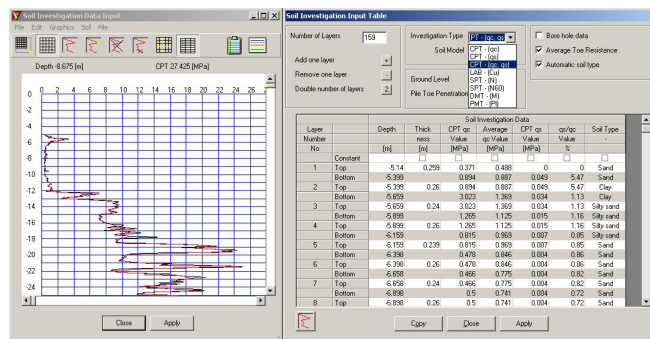


Fig. 9: Soil investigation input module

A second focus area should be the automatic pre-selection of potential problem piles. This will considerably reduce the interpretation time, especially when hundreds of piles have to be tested in one day as is common in The Netherlands. It should be noted that the final selection of potential problem piles is still to be made by a person experienced in this type of testing.

As engineers we need to keep pushing the envelope for these developments to take place, but at the same time we need to ensure that we have a clear understanding of the theoretical principles. It appears that some users of the SIT method rely entirely on the outcome of the computer program, which can easily lead to misinterpretation. As an example, defects in the top section of the shaft are sometimes missed, because the hammer pulse (which is a function of the hammer mass and material) is too long and masks the wave reflection caused by a defect in the top of the shaft. It is therefore very important that testing staff is adequately trained, not only in the practical application of SIT, but also in the theory behind this testing procedure.

Similarly we need to be aware of the limitations of SIT. While this method is able to detect many types of defects, there are others that cannot be detected, such as:

- gradually increasing and decreasing pile diameters;
- curved pile shapes;
- small soil inclusions;
- local loss of reinforcement cover;
- thickness of debris layer at pile toe.

Only if we are well aware of its limitations, can we make full use of the SIT method, a method that allows us to verify the work done by contractors we trust.

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