The rebirth of traditional SITinterpretation methods to incorporate engineering judgement in present day data analysis

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ABSTRACT

The method of Sonic Integrity Testing (SIT) was developed many decades ago, at a time when the only pile testing method available was Static Load Testing. SIT was designed to test cast-in situ piles or bored deep foundations, and because of this test method cast in-situ piles (including Continuous Flight Auger (CFA) -piles) became popular in Western Europe. As the main QA method for this pile type, the application of cast in-situ piles increased the popularity of SIT and vice versa.

SIT became even more popular when digital testing equipment was developed. Easy to operate hardware and user-friendly software started to become available in the 1960s. But while the testing engineers of the first hours were used to dealing with the uncertainties associated with this test method, newer generations of engineers became increasingly just operators, relying more and more on automated interpretation algorithms. However, engineering judgement is still required from the testing engineers, as pile testing is more than simply operating a test kit and pushing the right buttons at the right moment.

This paper provides some examples of how ‘old school’ experience with this test method is still very relevant for the interpretation of ‘modern’ signals, such as the use of a site average to eliminate the soil impact (shaft friction and toe resistance) on the signals, as well as the pile signature to minimize false negative and false positive interpretations. In addition, advanced signal matching techniques for SIT data will be described as a useful method to quantify and visualize test results.

Keywords: SIT, Profiling, low strain integrity testing, site average, Signal Matching

1. INTRODUCTION

In 2014 Middendorp showed the popularity of Sonic Integrity Testing (SIT) in the Netherlands starting in the 1970s. Between then and 2022 nothing has changed: every year more than 600.000 piles are tested in The Netherlands alone and worldwide it has to be several millions. SIT (also called Pile Integrity Test or Low Strain Dynamic Testing) is still the recommended quality assurance method for testing of cast in-situ piles in The Netherlands (Middendorp and Reiding, 1988), (Middendorp and Bielefeld, 1993), (Amir, 2017) and (De Vos et al., 1992). Normally 100% of the piles are tested on a job site, thereby eliminating the option to cherry-pick the test piles and thus skew the test results. But a sound and reliable pile foundation is not only determined by a good integrity test result

(Middendorp and Bielefeld, 1993): the piles have to meet a long list of requirements. Compared to when SIT was first developed, these days much more data is available to the testing engineer to assess the pile quality, as the installation of cast in-situ piles is monitored with ever more sensors to record an increasingly wider range of parameters. However, the final proof of the quality of the pile as installed is and remains the integrity test result based on SIT.

2. BASED ON STRESS WAVES

The SIT method is using stress waves introduced by a small hand-held hammer (Middendorp and Reiding, 1988), (Reiding, 1984). Reflections are caused by distinct changes in the pile impedance and by the soil resistance. These reflections are monitored by a small handheld sensor placed on the pile top. By analyzing these reflections the pile integrity can be assessed.

Over the years, major developments in integrity testing have occurred. The sample rates have increased to 300 kHz and (although not widely used) instrumented hammers have been developed. Other development, like the use of a wireless sensor, did not really enhance the technique and some developments took the method even backwards (like the use of hammers that create a far too long blow length, which makes it impossible to detect certain defects as shown in Figure 1). But over the decades, when properly applied, SIT has proven to be a sound and reliable method to detect pile defects in piles (CUR Aanbeveling, 2013). This was also demonstrated by various research studies, whereby piles with 'hidden' defects were tested (Smits, 1992). As a result, this test method, which is really nothing more than hitting a pile with a small, hand-held hammer, became a widely used test method around the world (Tchepak, 1992), (CIRIA, 1997), (Chai et al., 2011), (Chow et al., 2003) (Verman et al., 2004) and (El-Kadi, 2009).

3. INCREASED SOFTWARE SUPPORT

Over the years major advancements have been made in the software used for SIT. Not only has it become more user friendly, it now also allows for an initial interpretation while still in the field. The software can now run on any windows touch screen tablet so no special recording device is necessary, and the screens are sizable so graphs can be clearly seen and adjusted. Some software packages can easily be controlled with touch and voice commands, but for the users, who don't want all this "fancy stuff", the "only monitoring" user level is the preferred option.

Increasingly, software also provides options to interpret the test data, and even to perform it completely automatically. This eliminates input from the testing engineer and thus the engineering judgement, which is the subject of this paper.

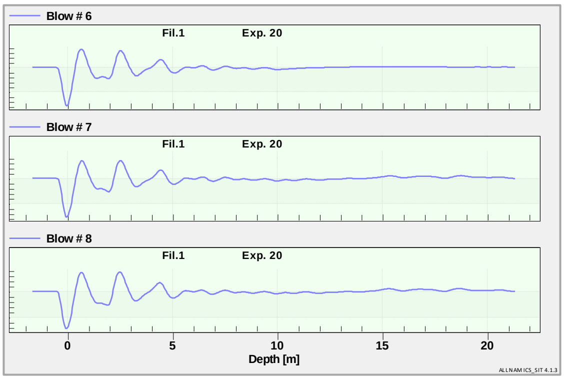

Figure 1: Quantified defect at 1-2 m below pile head pile, only to be discovered by a sharp, short hammer blow.

4. SIGNAL INTERPRETATION

From the stress wave theory it is clear that changes in the pile impedance will lead to reflections of the stress wave induced by an impact on the pile tope (Josseling the Jong, 1956), (Nanninga, 1953) and (Van Koten, 1965). These changes can be a change in the pile dimension (diameter, crack, inclusions, bulge) or in pile material quality (Youngs modulus, density, concrete quality, inclusions, etc.). This makes the sonic integrity testing such a powerful method to detect anomalies and imperfections in the pile: it detect not only changes in pile dimensions, but also potential issues with the pile material, reduced quality or voids.

However, along the pile shaft reflections are also caused by shaft friction due to the soil. A change in soil layer can therefore be seen as a change in pile impedance and thus be misinterpreted, leading to false positives and negatives.

5. BASIC INTERPRETATION RULE

To avoid that reflections caused by shaft friction are interpreted as pile impedance changes, a very basic solution was developed in the early years of SIT (Middendorp and Reiding, 1988) (Middendorp and Bielefeld 1993). The basic assumption of the solution is that all tested piles of the same size and length, or at least a group of them, are in the same soil strata. Based on that assumption these piles should show the same reflections caused by the soil, and moreover the average signal of these piles should show the soil effects only as the reflections due to changes in pile impedance are averaged out. Then, by comparing the signals for each individual pile with the average, deviations from the average signal can be classified as changes in pile impedance, indicating an anomaly in the pile. These anomalies should then be investigated further to determine whether the anomaly is detrimental and requires corrective action.

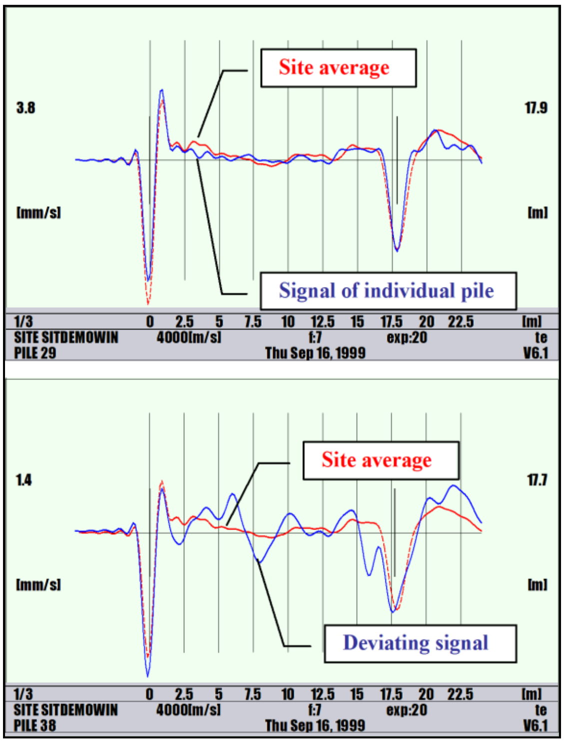

Figure 2: Example site average with an accepted corresponding signal and signals of a pile with a deviating signal.

This basic solution for analyzing and interpretating of SIT data has been lost over the years. Quite often interpretation of signals is performed by analyzing the signals for each pile separately. Not only is this very time consuming (and thus less efficient), the influences of soil and pile impedance are likely to be mixed up. Therefore the software used to analyze SIT data should be able to calculate the average signals of groups of piles as well as all piles on a particular site, the so-called site average.

Rather than using the average signal, it has been suggested to just ignore the skin friction distribution, or to assume it is known (Amir 2017). However, such approaches simply go against the stress wave theory and therefore invariably lead to incorrect conclusions.

Another consequence of not applying this basic solution is the view that this foundation test method is not suitable for complex soil profiles. This is simply a misperception: with the correct interpretation method piles in any soil profile, including complex soil strata, can be tested using SIT (Chai et al, 2011).

6. REAL-TIME SIGNAL ANALYSIS

The testing engineer should have access to all necessary tools during the testing itself. This includes, as stated before, software able to calculate the average signals of groups of piles as well as all piles on a particular site, the so-called site average. Then as soon as a particular pile has been tested the group and site average can be presented together with the measured signals of that individual pile.

The average of the signals obtained for a particular pile should not deviate substantially from the individual signals for that pile. However, there are various causes for such a deviation:

- A bad hammer blow.
- A small defect right under the sensor.
- A measurement obtained on the rebar instead of on the concrete.
- A blow whereby the hammer touches the sensor.
- A measurement with a (major) vibration source nearby.

In any event individual signals that deviate substantially from the average for that pile should be discarded and not be used any further.

7. AUTOMATED SIGNAL ANALYSIS

The complex signals of SIT are not easy to fully interpret automatically: there are simply too many unknown variables that affect the signals. Although various fully automated analysis methods have been proposed in the past (Courage and Bielefeld, 1981), (Ypey, 1984), Staalduinen et al., 1989), (Amir, 2017), the authors consider none of them suitable for routine use.

While fully automated analysis methods are not practical, automated routines can be very useful and should be available to the testing engineer:

- To detect the duration (length) of the hammer blow. As stated before and, hammer blows that are too long cover all information from defects. As a result, defects will be overseen (see Figure 3) (Middendorp and Schellingerhout, 2006)
- To generate automatically group and site averages, based on pile dimensions and lengths
- To present the average signal of individual piles on top of the group or site average
- To detect where the signal from a particular pile deviates from the average for that pile

With the assistance of those automated routines, the analysis process is quick and efficient.

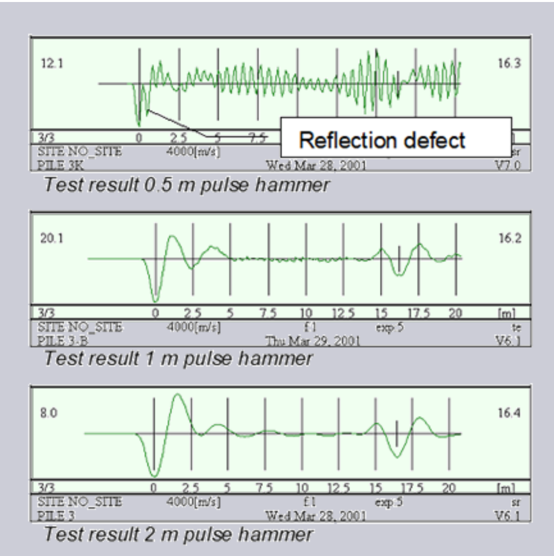

Figure 3: Integrity signals for different pulse widths

8. ENGINEERING JUDGEMENT

Unfortunately, the interpretation process seems to be less straight forward than many in the industry would like it to be. There is no reliable result that can be obtained by just pressing a button. As such pile testing is like many other areas where the computer can assist in presenting data, but cannot replace a professional (VanderBurgh, 2021), (English, 2007). To truly interpret test data the testing engineer is required to understand how piles are made and how that can affect the pile shape, as well as understand soil investigation reports from SPT or CPTs, and various other soil investigation methods, to avoid erroneous interpretation (Tchepak, 1992). Only with that knowledge the testing engineer can apply engineering judgement to assess the test data: to avoid false negatives, where serious defects are overseen, and to avoid false positives, where pile tests erroneously indicate piles with defects even though the pile is sound.

But there is another set of situations where engineering judgement is essential: those cases where interpretation of the test data is simply not possible. That determination requires courage from the testing engineer as all parties involved would like to see a definitive assessment.

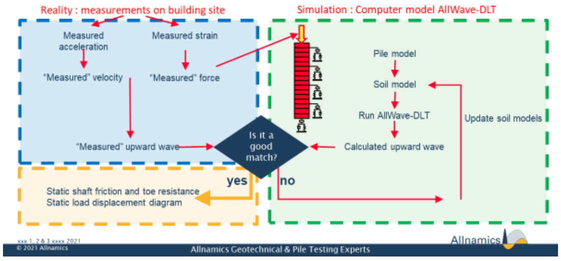

Figure 4. Schematic overview of the Signal Matching technique

9. ADVANCED SIGNAL ANALYSIS

Next to the qualitative interpretation method as described above, there is the quantitative interpretation method using Signal Matching. This technique is the standard interpretation method for high strain dynamic test data, but can be applied to SIT (a low strain dynamic test) as well (Middendorp and Reiding, 1988). For this kind of analysis the pile and soil are modeled in a Wave Equation program (like AllWave-SIT) and the stress wave propagation through pile and soil is simulated, resulting in a computed signal. The computed signal is then compared to the measured one and adjustments are made to the soil and pile model to create a better match (see Figure 4). This process is repeated until a good match between simulated and measured signals is obtained (Middendorp and Bielefeld, 1993), (Ozudogru, 2011).

In case of SIT, the Signal Matching process has two phases as shown in Figure 5. The first Signal Match is performed on the Site Average. Just as in the qualitative interpretation method described above, it is assumed that the Site (or Group) Average represents a sound pile where reflections are caused only by soil influences. Based on soil investigation, a preliminary soil model along the pile shaft is entered in the Wave

Equation software. The stress waves induced by an artificial impact on top of the pile are then calculated, and next the soil model is adjusted until there is a good match between the calculated signal and the measured signal of the group or site average.

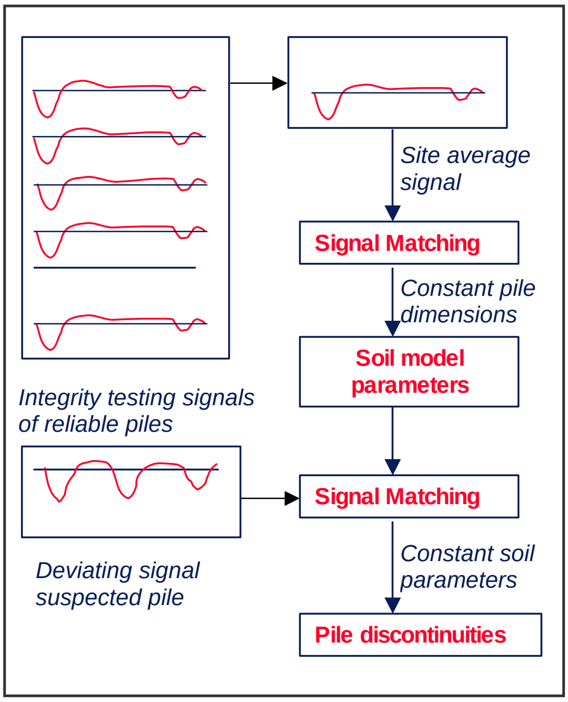

Figure 5: Signal Matching Process for SIT data

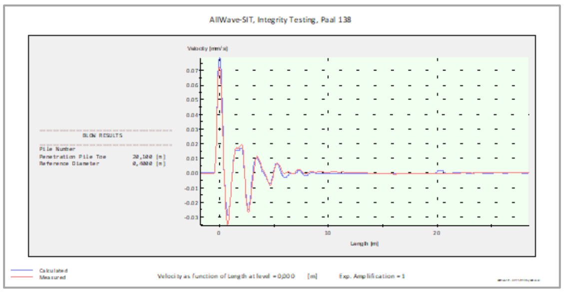

Figure 6. Result of Signal Matching technique: measured and calculated signals showing a good match

The second phase is Signal Matching on the signal of the individual pile, but now the pile model is changed until a good match is obtained. The outcome of such a process is the impedance of the pile as function of the depth:

$$Z = E.A/c \qquad \text{[eq. 1]}$$

where E is the Young Modulus and c the stress wave velocity (both representing the pile material), and A the cross-sectional area (representing the pile shape). The result of the Signal Matching process is a one-dimensional result which can be presented in 3D graphics, like in Figure 7. In this figure, a constant E and c are assumed, presenting all impedance changes as changes in cross sectional area.

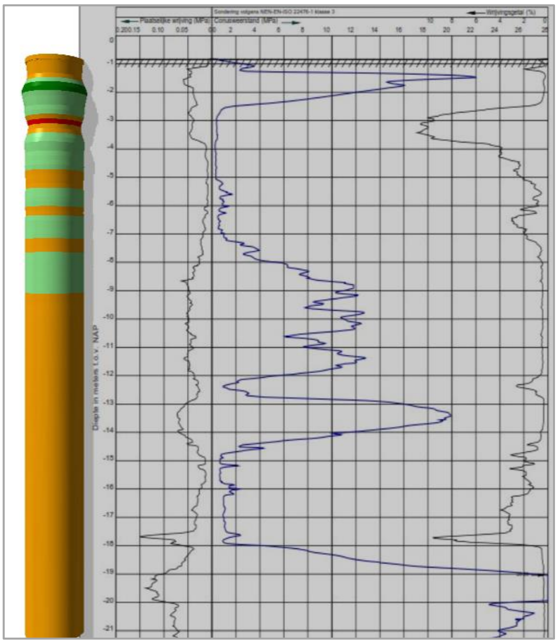

Figure 7 : Improved visualization of impedance calculations

10. ADVANTAGE OF SIGNAL MATCHING ON SIT SIGNALS

The main benefits of the advanced signal analysis are:

- Smaller anomalies can be detected than in the traditional qualitative interpretation method.
- Dimensions of the anomalies can be quantified. Therefore the decision to further investigate an anomaly has a better justification.
- Anomalies below another anomaly can be detected and quantified. Since the first anomaly ‘covers’ the reflections of deeper anomalies, those deeper defects are harder to detect and interpret in the standard qualitative interpretation method. However, reflections are in the signal, and through Signal Matching they can be properly interpreted.
- Complex or extreme complex soil profiles have no influence on the interpretation process.

11. DISCUSSION / CONCLUSION

SIT is an excellent test method to assess cast in-situ piles. However, the analysis of the test data requires engineering judgement and cannot be fully automated. Unfortunately as attempts are made in that direction, some basic principles (like the use of site and group averages) to simplify the analysis process are no longer widely applied and seem to have been forgotten. By incorporating these basic principles in the analysis software packages, SIT is not just a test method that is very easy and quick to perform, but the data analysis can be done efficiently as well. As a result it is realistic that all piles on a project are tested, eliminating the chance that the test results are skewed by selecting specific piles for testing. Moreover, using group or site averages will reduce the likelihood of false negatives (which can lead to unsafe structures), and false positives (where sound piles are rejected).

EPILOGUE

The new challenge for the construction industry in this increasingly automated world is that we must ensure that persons that are getting involved with foundation testing become good testers and automation managers simultaneously. This is no easy task. It is very likely that the student who loves the automation is not as strong in the field, and vice versa. But, whatever it takes, we must avoid creating button-pushers in the construction industry.

12. REFERENCES

1. Amir, J.M., (2017): Pile Integrity Testing: History, Present Situation and Future Agenda, Geology, 2017
2. Chai, HY., Wei, CF., Phoon, KK. et al. (2011): Some Observations on the Performance of the Signal Matching Technique in Assessment of Pile Integrity, Nondestruct Eval 30, 246–258 (2011)
3. Chow, Y.K., Phoon, K.K., Chow, W.F. and Wong, K.Y. (2003), “Low Strain Integrity Testing of Piles: Three Dimensional Effects”, Journal of Geotechnical and Geoenvironmental Engineering ASCE/November, pp 1057-1062.
4. CIRIA - R144 (1997): Integrity Testing in Piling Practice, 1997
5. Courage, W.M.G., Bielefeld M.W. (1992): TNOWave Automatic Signal Matching, Proceedings of Fourth International Conference on the Application of Stress Waves on Piles 1992, The Hague, Balkema,
6. CUR-Aanbeveling 109 (2013): Akoestisch doormeten van betonnen funderingspalen, Herziene uitgave juni 2013
7. De Vos, J., Vester, A. and Liefting, H. (1992), “Pile Integrity testing in the Netherlands”, Application of Stress-Wave Theory to Piles, F.B.J. Barends (ed.), Balkema, Rotterdam, pp 357-360.
8. DGGT (2014): Recommendations on Piling (EA-Pfähle). German Geotechnical Society, Berlin, 2014.
9. El-Kadi, A. F. (2009), "Assessment of Pile Integrity Utilizing Full-Scale Non-Destructive In-Situ Testing", Ph. D. Thesis, Geotechnical Engineering and Foundations, Ain Shams University (In Progress)
10. El-Nahhas F.M., Ali, H.A., Helmy, H.M., El-Kadi. A.F. (2008): Assessment of Pile Integrity Utilizing Non-Destructive Testing of Model Concrete Piles, Journal of the Egyptian Geotechnical Society, Vol. 18, Part 1/2, 2008
11. English, D. (2017): A Button Pusher?, Inner Art of Airmanschip Blog, September 2017
12. Glanville, W. II., Grime, G. and Davies, W. W. (1935-36): The Behaviour of Reinforced—Concrete Piles During Driving. Journ. Inst. Civ. Eng., vol. 1, p. 150, 1935
13. Josseling de Jong, G., (1956): Wat gebeurt er in de grond tijdens het heien, De Ingenieur, 22-6-1956, page 77, Edition 68-25 (jaargang 68). In Dutch (What happens in the ground during pile driving)
14. Koten, H. van, 1965, Het bepalen van de lengte en scheurvorming bij geheide palen, TNO Report BI-65-87, in Dutch (Determination of length and defects in driven piles)
15. Koten H. van, (1980): Interpretation of results from integrity tests and dynamic load tests. First International conference on the application of Stress-Wave Theory to Piles, (pp. 217-232). Stockholm.
16. Middendorp, P., Reiding, F.J. (1988): Determination of discontinuities in piles by TNO integrity testing and signal matching technique, Proceedings of the 3rd International Conference on the Application of Stress Wave Theory to Piles, Ottawa, Canada, pp. 33–43 (1988)
17. Middendorp, P., Reiding, F. J. (1988): Application of Stress-Wave Theory to Piles, 3rd International Conference on the Application of Stress Wave Theory to Piles, Ottawa, 1988

18. Middendorp P., Bielefeld M.W. (1993): Reliability of Sonic Integrity Testing, Seminar CIAS 1993, Rovinj
19. Middendorp, P., Schellingerhout J. (2006): Pile Integrity Testing in the Netherlands, 10th International Conference on Piling and Deep Foundations, 2006, Amsterdam, The Netherlands
20. Nanninga, N. (1953): The problem of Pile Driving, Le battage des pieux, Technical University, Delft, Netherlands, 1953
21. Ozudogru, Tolga. (2011). Pile Integrity Testing: Determination of Pile Quality using Low Strain Integrity Testing and Automatic Signal Matching, ISBN 978-3844331370, LAP LAMBERT Academic Publishing, April 15, 2011
22. Reiding, F. M. (1984): A digital approach to sonic pile testing. 2nd International Conference on Stress Waves (pp. 85-93). The Hague, Netherlands: Balkema.
23. Schellingerhout, A.J.G. (1992): "Quantifying pile defects by integrity testing", Proceedings of Fourth International Conference on the Application of Stress Waves on Piles 1992, The Hague, Balkema, pp 319-324.
24. Schellingerhout, A.J.G., Muller, T.K. (1996): Detection Limits of Integrity Testing, Proceeding Stress Wave Conference 1996
25. Starke, W.F., Janes, M.C. "Accuracy and Reliability of Low Strain Integrity Testing", 3rd International Conference on the Application of Stress Wave Theory to Piles, Ottawa, Canada, 1988, pp. 19-32.
26. Smits, M. Th. J. H., Pile Integrity Tests, Application of Stress Wave Theory to Piles: Test Results, Proceedings of Fourth International Conference on the Application of Stress Waves on Piles, 21-24 September 1992, page 25-54
27. Staalduinen, P.C. van, Bielefeld, M.W. and Middendorp, P. 1989. A Direct Technique for Discontinuities in Piles. The Second International Conference on Foundations and Tunnels, London.
28. Tchepak, S. (1992): Dynamic and sonic pile integrity Testing – a contractor's experience, Stress Wave Conference 1992
29. Vanderburgh, W (2021): Aviators or Button Pushers?, Thrust and Vector, March 28, 2021
30. Verman, M., Trehan, S., Anurag and Sharma, V.M. (2004), "Experience with Sonic Integrity Testing of Piles in India", The Seventh International Conference on the Applications of Stress Wave Theory to Piles, Malaysia, pp 205-211.
31. Ypey, L.P. (1984): De deconvolutie methode toegepast op het sonisch doormeten van fundatiepalen. Master's thesis. Delft University of Technology, The Netherlands (in Dutch)