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More than 80 Years of Experience with the Method of Characteristics - from Graphical Analyses to Advanced Driveability Analyses by Scripts.

Peter Middendorp

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SW22

11th International Stress Wave Conference Rotterdam, The Netherlands September 20-23, 2022

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Presentation Scope

The Museum of Pile Drivers
GIKEN, Kochi Japan

Creating the Future
by
Learning from the Past
and
Knowing the Present

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11th International Stress Wave Conference Rotterdam, The Netherlands September 20-23, 2022

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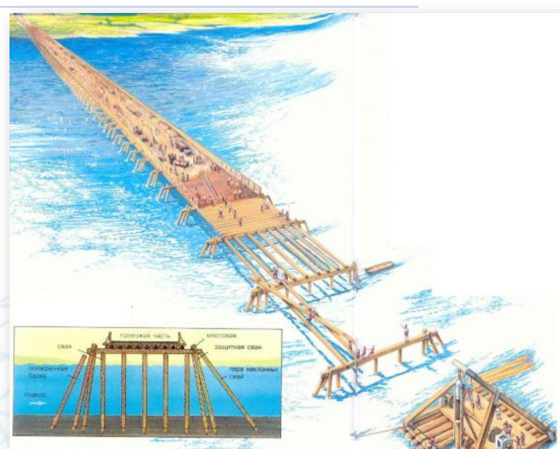
Introduction -The Past - Europe

- Bronze Age, houses on piles to prevent flooding
- Romans who were the first to use piles as the foundation for bridge abutments. An impressive example is Caesar's Rhine Bridge 55 B.C.

Introduction – The Present, still the same questions

Caesar's engineers had to answer the same questions that are posed today:

- what equipment is needed to drive a pile to a required penetration,
- how many piles are needed and
- how much penetration is required to obtain the necessary capacity to support the superstructure safely.

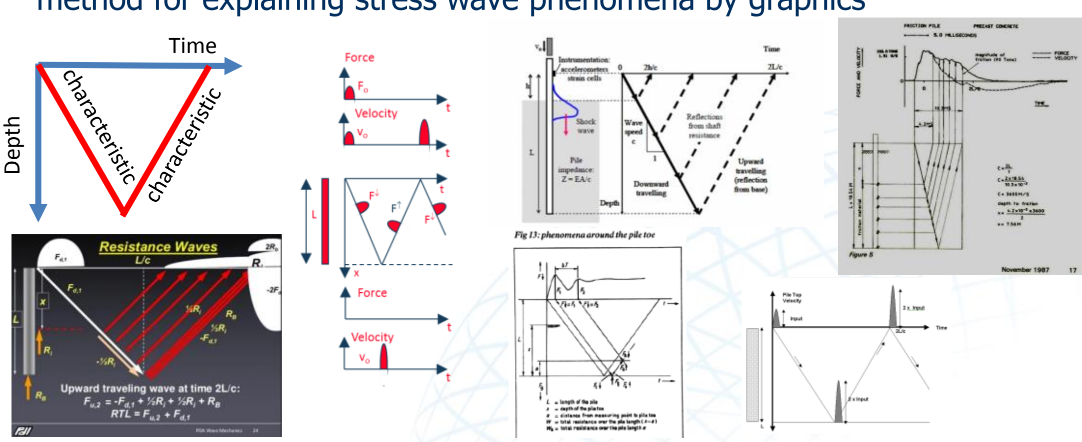


Introduction- Answers

- Still often today a learning loop of trial and error – research follows pratice
- Learning starts with local experience, performing tests, the use of rule of thumbs and in the past pile driving formula's
- The introduction of the wave equation theory (WEQ) gave a deeper understanding of the stress wave phenomena.
- Before computers became available, wave propagation, stresses, velocities and displacement could be quantified by means of graphical tools.
- these graphical tools were the basis for the present-day computer algorithm using the Method of Characteristics (MOC).

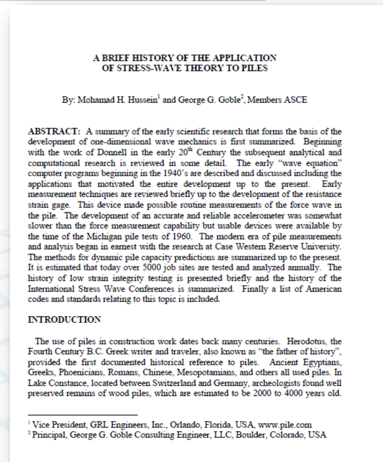
Introduction – MOC most applied for explaining SW

- The Method of Characteristics (MOC) is almost certainly the most applied method for explaining stress wave phenomena by graphics



FROM ESTIMATE TO PREDICTION HISTORY

- Several publications about SW history and it contributors with brief descriptions
- Some contributors will be highlighted and some added that deserve more attention
- It starts with capacity estimates and Pile Driving Formula's
- Rondelet (1802): capacity is a function of pile cross section with a fixed value of 30 kgf/cm2 (2.94 MPa)



A BRIEF HISTORY OF THE APPLICATION
OF STRESS-WAVE THEORY TO PILES

By: Mohamad H. Hussein[1] and George G. Goble[2], Members ASCE

ABSTRACT: A summary of the early scientific research that forms the basis of the development of one-dimensional wave mechanics is first summarized. Beginning with the work of Donnell in the early 20th Century the subsequent analytical and computational research is reviewed in some detail. The early "wave equation" computer programs beginning in the 1940's are described and discussed including the applications that motivated the entire development up to the present. Early measurement techniques are reviewed briefly up to the development of the resistance strain gage. This device made possible routine measurements of the force wave in the pile. The development of an accurate and reliable accelerometer was somewhat slower than the force measurement capability but usable devices were available by the time of the Michigan pile tests of 1960. The modern era of pile measurements and analysis began in earnest with the research at Case Western Reserve University. The methods for dynamic pile capacity predictions are summarized up to the present. It is estimated that today over 5000 job sites are tested and analyzed annually. The history of low strain integrity testing is presented briefly and the history of the International Stress Wave Conferences is summarized. Finally a list of American codes and standards relating to this topic is included.

INTRODUCTION

The use of piles in construction work dates back many centuries. Herodotus, the Fourth Century B.C. Greek writer and traveler, also known as "the father of history", provided the first documented historical reference to piles. Ancient Egyptians, Greeks, Phoenicians, Romans, Chinese, Mesopotamians, and others all used piles. In Lake Constance, located between Switzerland and Germany, archeologists found well preserved remains of wood piles, which are estimated to be 2000 to 4000 years old.

[1] Vice President, GRL Engineers, Inc., Orlando, Florida, USA, www.pile.com
[2] Principal, George G. Goble Consulting Engineer, LLC, Boulder, Colorado, USA

Hussein. M H., and Goble. GG, (2004).

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FROM ESTIMATE TO PREDICTION - EYTELWEIN

- Pile driving formula Eytelwein (1808)
- Seems intuitively correct, became very popular

Bearing capacity R_u could be found with the formula:

$$R_u = \frac{e_h . E_h}{n . s \left[1 + \frac{w}{W}\right]}$$

with E_h = Rated Energy, e_h = Efficiency, s = permanent set after a blow, w = weight pile, W = weight ram, n = safety factor

- Proved to be notoriously unreliable, but is still used
- Misconceptions: rigid pile, ignoring soil type and energy transfer in hammer components

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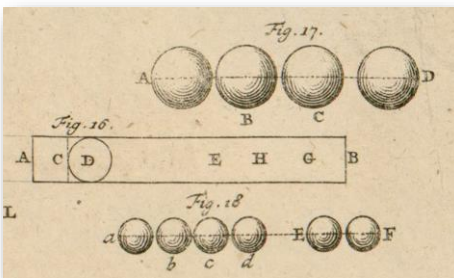
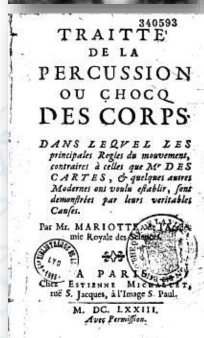
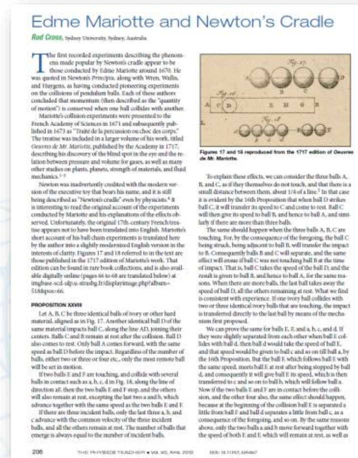
FROM ESTIMATE TO PREDICTION - MARIOTTE

- The dawn of stresswave (energy) propagation awareness
- Marriotte – experiments with a row of impacting ivory balls (1673)




340593
TRAITTÉ
DE LA
PERCUSSION
OU CHOCQ
DES CORPS.
DANS LEQUEL LES principales Regles du mouvement, contraires à celles que Mr DES CARTES, & quelques autres Modernes ont voulu établir, sont demonstrées par leurs veritables Causes.
Par Mr. MARIOTTE, ... mie Royale des Sciences.
A PARIS,
Chez ESTIENNE MICHALLET, ruë S. Jacques, à l'Image S. Paul.
M. DC. LXXIII.
Avec Permission.


Edme Mariotte and Newton's Cradle
Rod Cross, Sydney University, Sydney, Australia

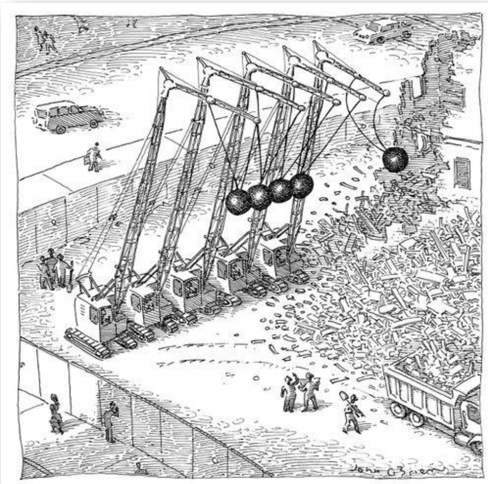
Cross, R., (2012)

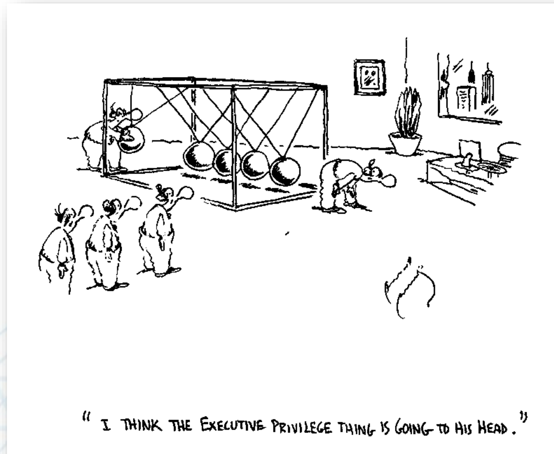
FROM ESTIMATE TO PREDICTION - MARIOTTE

Marriotte on BBC-2

https://www.youtube.com/watch?v=Gz_3-x6lUzE

Craddle Cartoons





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Flexible Impulse Transfer using a Newton's Cradle Inspired Catheter: A Feasibility Study

Sakes *et al.* / Elsevier Medical Engineering and Physics

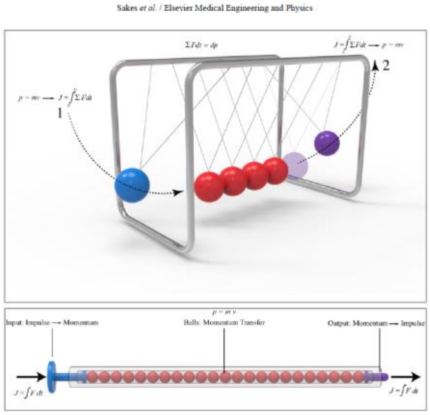

Fig. 1. *Newton's Cradle* mechanisms. Top: *Newton's Cradle*. Bottom: Schematic representation of the *Newton's Cradle's* inspired catheter. Color indications: blue = input ball, purple = output ball, and red = intermediate balls.

A major challenge encountered during minimal invasive surgery is transferring high forces through small and flexible instruments, such as needles and catheters, due to their low buckling resistance. In this study we have determined the feasibility of using a Newton's Cradle inspired catheter (patented) to transfer high force impulses

Sakes *et al.* / Elsevier Medical Engineering and Physics

Flexible Impulse Transfer using a Newton's Cradle Inspired Catheter: A Feasibility Study

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Abstract

A major challenge encountered during minimal invasive surgery is transferring high forces through small and flexible instruments, such as needles and catheters, due to their low buckling resistance. In this study we have determined the feasibility of using a Newton's Cradle-inspired catheter (patented) to transfer high force impulses. Exerting a high-force impulse on the tissue increases the critical buckling load and as such can prevent buckling. The system consisted of an input plunger onto which the impulse is given, a (flexible) shaft filled with Ø2 mm stainless steel balls, and an output plunger to transfer the impulse to the target tissue. In the proof-of-principle experiment, the effect of clearance (0.1, 0.2, and 0.3 mm), length (100, 200, and 300 mm), shaft type (rigid vs. flexible), curve angle (0, 45, 90, 135, and 180°), and curve radius (20, 40, 60, and 100 mm) on the efficiency was determined. The catheter was able to deliver forces of 6 N without buckling. The average impulse efficiency of the system was 35%, which can be further increased by optimizing the design. As such, this technology is promising for high force delivery in miniature medical devices during minimal invasive surgery in future.

Keywords: Buckling, Catheter, Feasibility, Force, Guidewires, Impulse, Medical Device Design, Momentum, Minimal Invasive Surgery, Newton's Cradle.

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PRESENT FOR SW2022 PARTICIPANTS

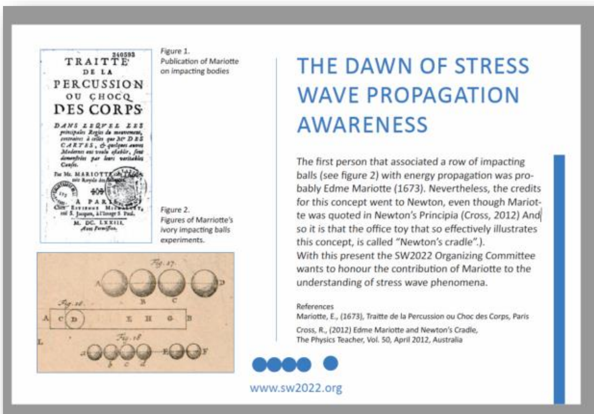
Figure 1.
Publication of Mariotte on impacting bodies

Figure 2.
Figures of Marriotte's ivory impacting balls experiments.

THE DAWN OF STRESS WAVE PROPAGATION AWARENESS

The first person that associated a row of impacting balls (see figure 2) with energy propagation was probably Edme Mariotte (1673). Nevertheless, the credits for this concept went to Newton, even though Mariotte was quoted in Newton's Principia (Cross, 2012) And so it is that the office toy that so effectively illustrates this concept, is called "Newton's cradle".).
With this present the SW2022 Organizing Committee wants to honour the contribution of Mariotte to the understanding of stress wave phenomena.

References
Mariotte, E., (1673), Traitte de la Percussion ou Choc des Corps, Paris
Cross, R., (2012) Edme Mariotte and Newton's Cradle, The Physics Teacher, Vol. 50, April 2012, Australia

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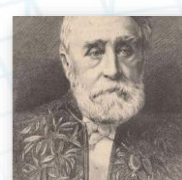
FROM ESTIMATE TO PREDICTION - HISTORY

- Stress wave phenomena were understood for a long time but not applied to pile driving
- d'Alembert (1747) discovered the wave equation and Saint Venant's (1867) found the wave equation solution for impacting rods
- The first observation of stress waves in piles is by Isaacs (1931), who created an integration technique best described as a semi graphical one.
- Isaacs developed a mathematical model based on the successive transmission and reflection of waves, like the **Method of Characteristics (MOC)**.


d'Alembert


Saint Venant

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GRAPHICAL TOOLS- - ISAACS

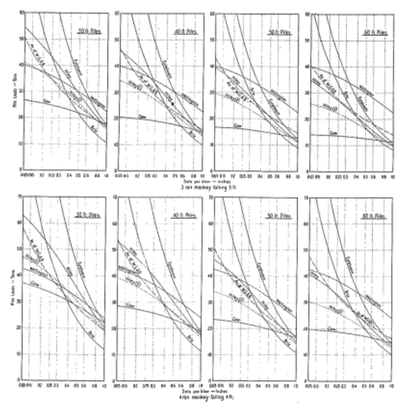
Fig. 4.—Comparative Graphs for 18 in. x 18 in. Piles.

Pile Driving Formula's

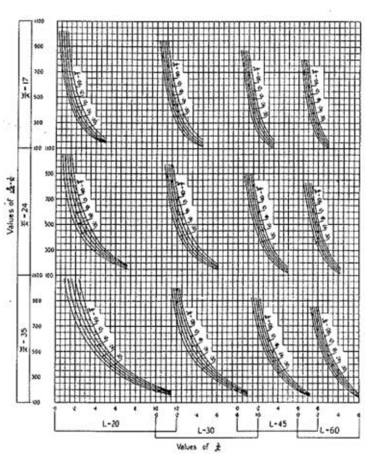
Fig. 17.—Graphs giving Driving Resistances for given Sets per Blow.

Results from Isaacs MOC analysis

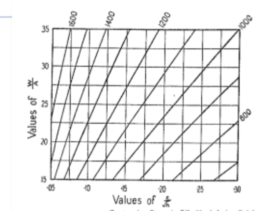
Fig. 18.—Graph giving Compressive Stress in Pile Head during Driving / √h

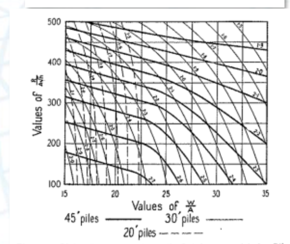
Fig. 19.—Giving Percentage of Tensile Reinforcement (p) for Piles of 3,000 lb. per sq. in. Concrete.
(For other Strengths of Concrete the Percentages are proportional to the Strengths. For Piles longer than 45 ft., use Percentages as for 45 ft. Piles.)

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MECHANICAL/GRAPHICAL TOOLS - ISAACS (1931)

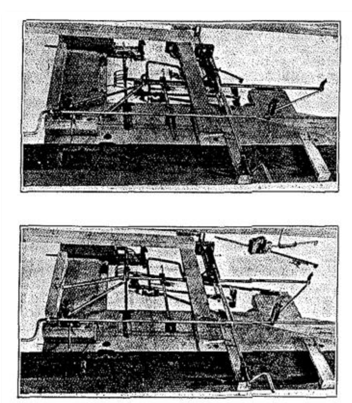


Fig. 15.—Curve Drawing Machine Completely Assembled.
Fig. 16.—Showing Curve Drawing Unit Separate from Machine.

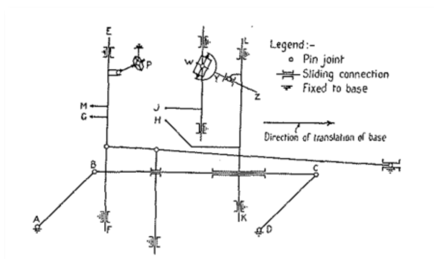


Fig. 14.—Diagram illustrating Principle of Curve Drawing Machine

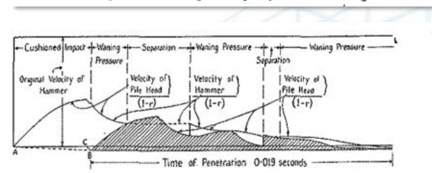


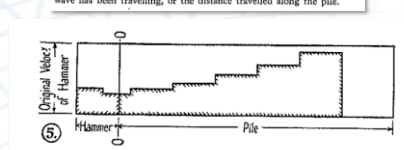
Fig. 11.—Wave Diagram for L = 20, r = 0.13, k = 20, l = 3¾, q = 0.1; i.e., a 20 ft. Pile, well cushioned, a light hammer, and medium Driving.

(ii) *Ideal uncushioned impact of a short hammer on a long pile.*

When the impulsive relative velocity **vr** in the hammer reaches the top end, it is reflected as a tension impulse **vr**, so that, for portions of the hammer near to the top where both impulses now overlap, the relative velocity is **2vr**, and the stress is zero. By the time the reflected wave has reached the bottom of the hammer the whole hammer has been given a relative velocity of **2vr** and all stress in the hammer has been eliminated, so that the hammer now has the same relationship to the pile as a hammer possessed of velocity (v — 2vr), *and just beginning an impact.* A new cycle thus starts, and the process is repeated. If l be the length of the hammer, the time required for a complete cycle will be

$$2t = \frac{2l}{\varrho V} \text{ seconds.}$$

The velocity of the base of the hammer and the head of the pile at the beginning of the impact is thus v(1 — r) feet per second; 2t seconds later it is v(1 — r) (1 — 2r); 4t seconds later it is v(1 — r) (1 — 2r)²; 6t seconds later it is v(1 — r) (1 — 2r)³, and so on. The compression wave propagated along the pile is thus of stepped form as shown in Fig. 5, where the ordinates represent velocities or intensities of compression, and abscissae, measured from the line OO to any portions of the wave, represent the time during which the wave has been travelling, or the distance travelled along the pile.



Case that will be simulated by AllWave-PDP

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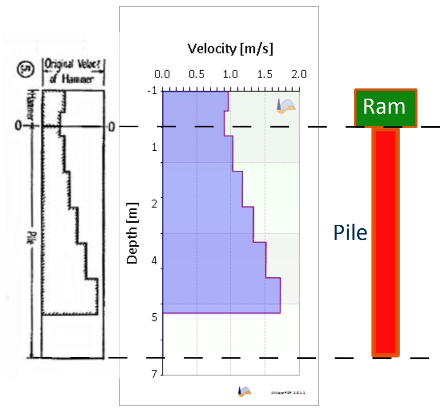
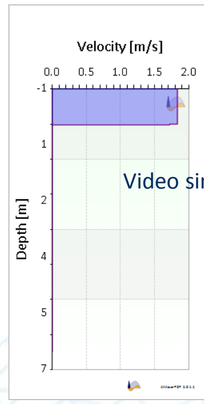
MECHANICAL/GRAPHICAL TOOLS - ISAACS (1931)

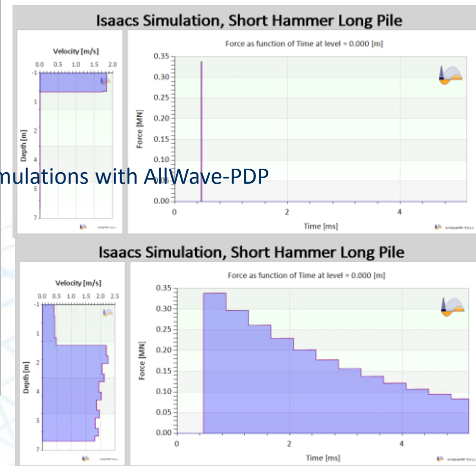


Snapshot of a travelling wave according to Isaacs (1931) and AllWave (2022) for "Ideal uncushioned impact of a short hammer on a long pile."



Negative depth is along the ram, positive values along the pile

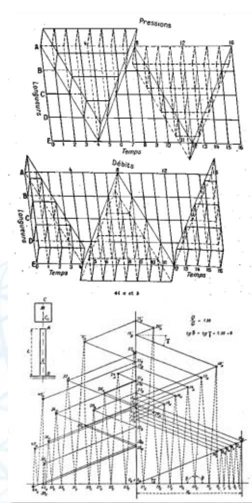
Video simulations with AllWave-PDP



Results at end of simulation

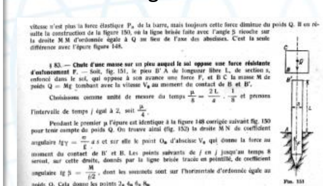
HYDR./MECH. ENGINEERING – BERGERON (1937)

- Bergeron (1937) proposed a graphical MOC based method to predict the propagation of waves in water channels and piles .
- In principle Bergeron already described how to incorporate phenomena like friction (sudden jumps) for the propagating of waves with discrete points along a pile:



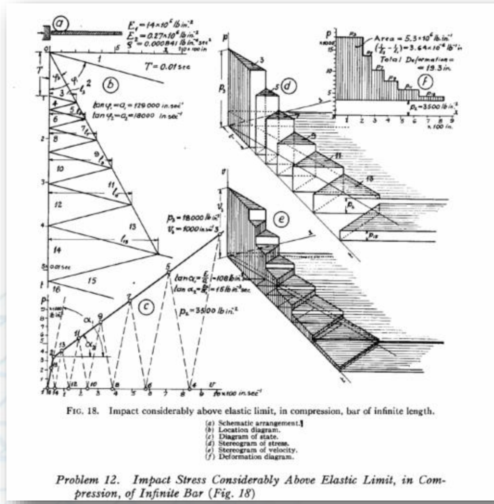
Hydraulics and mechanics graphical MOC analysis examples by Bergeron

Bergeron



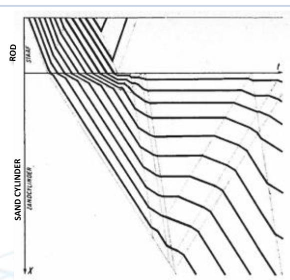
MECHANICAL ENGINEERING – DE JUHASZ (1949)

- In mechanical engineering one was interested in the stresses generated by impacting rods, and similar graphical tools as described by Bergeron were used to study the subject
- An excellent example is the work of *De Juhasz* (1949) with impressive graphics of stress wave propagation for cases exceeding the elastic limit of the rod material.

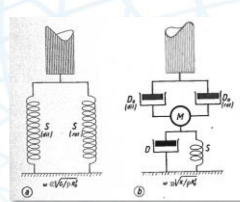


SOIL MECHANICS – JOSSELIN DE JONG (1956)

- De Josselin de Jong (1956) applied the MOC to pile driving and proposed a model for the toe resistance including porewater pressure phenomena
- His paper in Dutch from 1956 has been translated by SW2022 organizing committee members into English
- De Josselin De Jong, G. (1956, 2022), What happens in the soil during pile driving*, English Translated Version, 11th International Stress Wave Conference, Rotterdam, The Netherlands,* 2022.



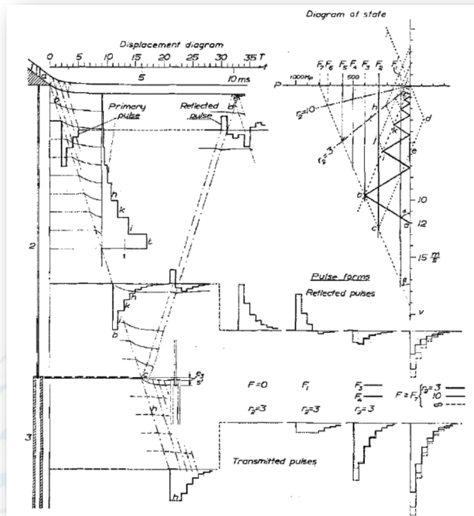
Lines representing the energy transmission in the sand



Schematic of the impedance experienced by the pile toe from the soil at (a) low and (b) high frequencies.

ROCK MECHANICS – FISCHER (1960)

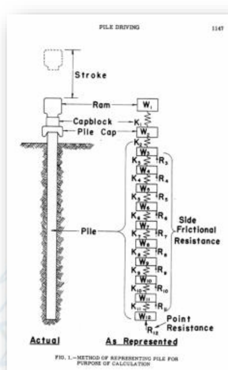
- Fischer (1960) applied MOC with his grapho-dynamical method and performed extensive research on the influence of ram and anvil dimensions for rods penetration into soil.



WEQ COMPUTER APPLICATIONS – SMITH (1954)

- Another approach with series of springs and masses, with a finite difference solution of the WEQ
- It seems that Smith was not aware of the work of Bergeron, de Juhasz and Fischer (mathematically exact results with MOC - 0%)
- No surfing (manual analysis) of the MOC waves anymore

PILE-DRIVING ANALYSIS BY THE WAVE EQUATION
By E. A. L. Smith (1960)



So far as the writer is aware, D. V. Isaacs, in 1931, was the first to point out[4] that wave action occurred during the driving of piles. In 1938, E. N. Fox published[5] a solution of the wave equation applied to pile driving, but, as no electronic computers were available at that time, he was forced to use a number of simplifying assumptions that lessened the value of his solution. At the present time (1960), by using the conceptions of the wave equation and resorting to numerical integration and electronic computers, a solution of the pile-driving problem can be obtained that produces mathematical accuracy within about 5%. This degree of accuracy is more than sufficient in view of our present imperfect knowledge of the physical conditions involved.

The mathematical method described herein may, with slight modification, be applied to other impact problems such as the design of a foundation for a forging hammer, or a fendering system for a dock.

WEQ COMPUTER APPLICATIONS – VOITUS (1974)

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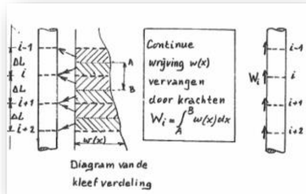
- Voitus van Hamme adopted the MOC approach similar to that formulated by Bergeron and programmed it for the computer application for hammer design and pile driving prediction PILEWAVE.
- His method assumes that the continuous skin-friction can be replaced by a great number of concentrated frictional forces.



Until 1976 there was not any computer program based on MOC available and Voitus van Hamme (1980) stated at the Numerical Methods in Offshore Piling conference:

It is, however, astonishing that none of the programs known to the writer is based on a solution of the wave equation with the exception of the HBG pile driving program PILEWAVE designed by the writer.

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Inspiring MOC paper

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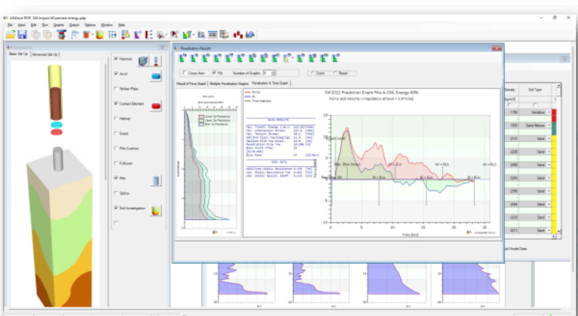
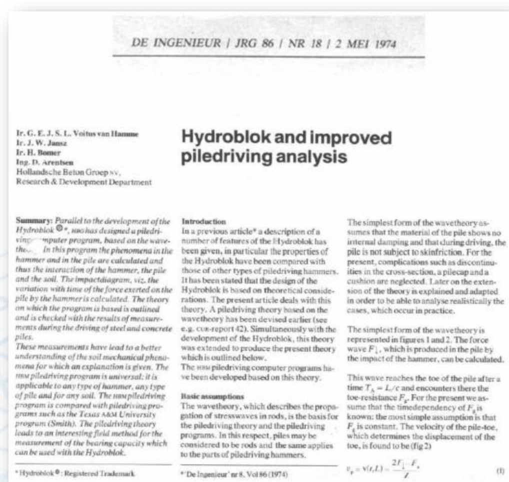
- This paper inspired the presenter to apply MOC for developing the wave equation program TNOWAVE (AllWave nowadays)



AllWave-PDP Screenshot



DE INGENIEUR / JRG 86 / NR 18 / 2 MEI 1974

Ir. G. E. J. S. L. Voitus van Hamme
Ir. J. W. Jansz
Ir. H. Bomer
Ing. D. Arentsen
Hollandsche Beton Groep NV,
Research & Development Department

Hydroblok and improved piledriving analysis

Summary: *Parallel to the development of the Hydroblok®*, HBG has designed a piledriving computer program, based on the wave-theory. In this program the phenomena in the hammer and in the pile are calculated and thus the interaction of the hammer, the pile and the soil. The impactdiagram, viz. the variation with time of the force exerted on the pile by the hammer is calculated. The theory on which the program is based is outlined and is checked with the results of measurements during the driving of steel and concrete piles.*
These measurements have lead to a better understanding of the soil mechanical phenomena for which an explanation is given. The HBM piledriving program is universal: it is applicable to any type of hammer, any type of pile and for any soil. The HBM piledriving program is compared with piledriving programs such as the Texas A&M University program (Smith). The piledriving theory leads to an interesting field method for the measurement of the bearing capacity which can be used with the Hydroblok.

Introduction
In a previous article* a description of a number of features of the Hydroblok has been given, in particular the properties of the Hydroblok have been compared with those of other types of piledriving hammers. It has been stated that the design of the Hydroblok is based on theoretical considerations. The present article deals with this theory. A piledriving theory based on the wavetheory has been devised earlier (see e.g. CUR-report 42). Simultaneously with the development of the Hydroblok, this theory was extended to produce the present theory which is outlined below.
The HBM piledriving computer programs have been developed based on this theory.

Basic assumptions
The wavetheory, which describes the propagation of stresswaves in rods, is the basis for the piledriving theory and the piledriving programs. In this respect, piles may be considered to be rods and the same applies to the parts of piledriving hammers.

The simplest form of the wavetheory assumes that the material of the pile shows no internal damping and that during driving, the pile is not subject to skinfriction. For the present, complications such as discontinuities in the cross-section, a pilecap and a cushion are neglected. Later on the extension of the theory is explained and adapted in order to be able to analyse realistically the cases, which occur in practice.

The simplest form of the wavetheory is represented in figures 1 and 2. The force wave $F_\downarrow$, which is produced in the pile by the impact of the hammer, can be calculated.

This wave reaches the toe of the pile after a time $T_A = L/c$ and encounters there the toe-resistance F_g. For the present we assume that the timedependency of F_g is known: the most simple assumption is that F_g is constant. The velocity of the pile-toe, which determines the displacement of the toe, is found to be (fig 2)

$$v_p = v(t,L) = \frac{2F_\downarrow - F_g}{Z} \quad (1)$$

* Hydroblok®: Registered Trademark

* 'De Ingenieur' nr 8, Vol 86 (1974)

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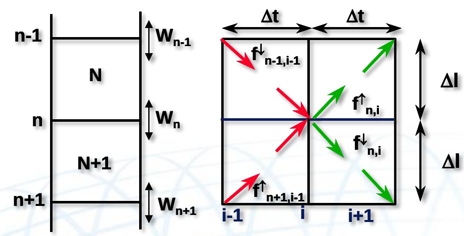
WEQ COMPUTER APPLICATIONS TNOWAVE - ALLWAVE

- The presenter has a hydrodynamics background, and his thesis was based on the Long Wave Theory in channels, which is based on the MOC
- While working for the research organization TNO and reading the work of Voitus van Hamme the presenter decided to use this straightforward and elegant MOC approach for the development of the driveability prediction program TNOWAVE
- The successor of TNOWAVE is ALLWAVE



See keynote paper for additional formula's

MISCONCEPTIONS ABOUT MOC

- There are still misconceptions about the MOC, one of which can be found in Hussein et. Al. (2004). That publication discusses the lump mass approach by Smith and the MOC and the authors state:

Thus, two approaches developed for the analysis of a pile under impact: the more flexible lumped mass method of Smith and the Donnell-de Juhasz method of characteristics. The latter method is more exact for ideally elastic, continuous systems. However, it is more difficult to apply to the pile capacity problem due to the difficulty of including a realistic soil, hammer and driving system model.

- The statement that MOC is more exact is true, but the limiting statements are not correct as proven by numerous publications for MOC based programs like TNOWAVE, ALLWAVE, CAPWAP and IMPACT

ADVANTAGES OF MOC

There are several authors mentioning the advantages of MOC compared to the Smith lump mass approach, among which

- Voitus van Hamme
- Frank Rausche
- Mark Randolph

- Frank Rausche (1983) stated as MOC advantages when CAPWAP was converted from Smith to MOC

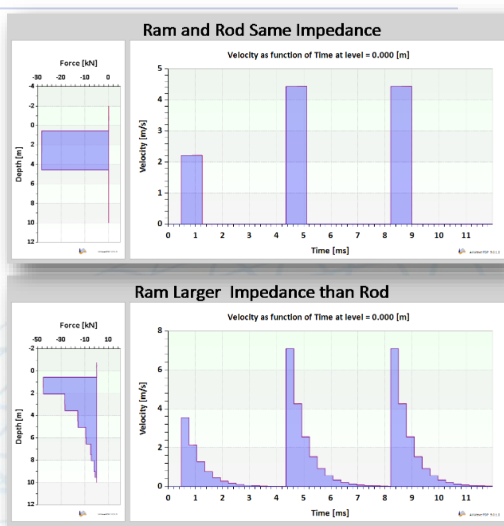
High viscous damping forces do not lead to unstability, as the Smith model does. If soil segments are chosen at every third pile element and at a 6000 sps frequency, then the CAPWAP/C analysis is approximately 20% faster than CAPWAP. Further time savings can be obtained in cases with little or no skin friction over substantial pile portions (offshore). The response at time 2L/c is much more accurate than that of the lumped mass analysis, in particular on long piles. Thus model changes to avoid phase shifts are unnecessary.

See keynote paper for additional statements

MOC - Check on Algorithm Performance

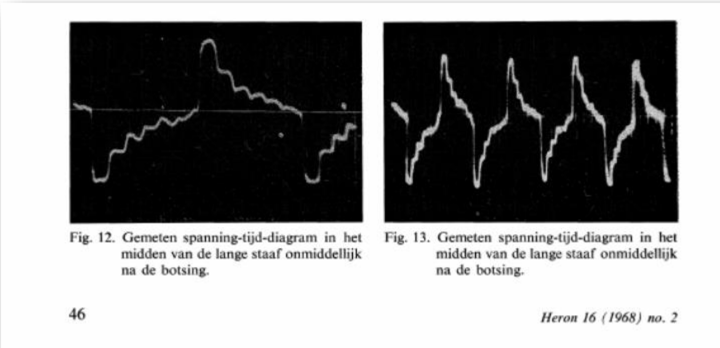
A check on algorithm performance and/or programming can be done by comparing the outcome with theoretical solutions:

- a ram with the same impedance as the pile (which should result in a rectangular pulse wave)
- a ram with a larger impedance than the pile (which should result in a step wise decreasing block shaped pulse).
- check the driveability software you are using with these basic cases to check their possibilities and limitations



AllWave-PDP Simulation Results

Real Measurements with Oscilloscope (1968)



Strain meaurements for case impedance ram larger than impedance rod

Fig. 12, Measured strain time diagram in the middle of the long rod immediately after impact

Fig. 13, Measured strain time diagram in the middle of the long rod immediately after impact (longer time duration)

Koten van, H., SPANNINGSGOLVEN IN EEN AXIAAL AANGESTOTEN PRISMATISCHE STAAF (Dutch), "Stress Waves in an axial impacted prismatic rod", Heron, Jaargang 16 no. 2, Delft 1968

Measurements performed by Fokke Reiding (TNO), present at the conference

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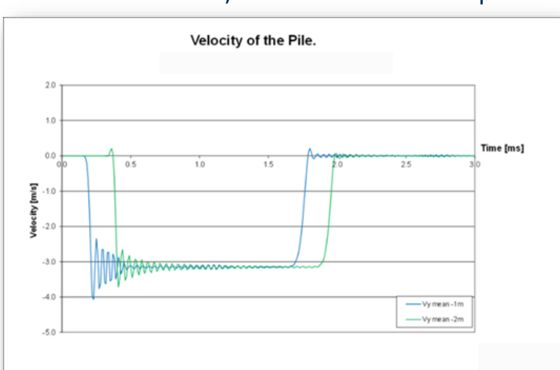
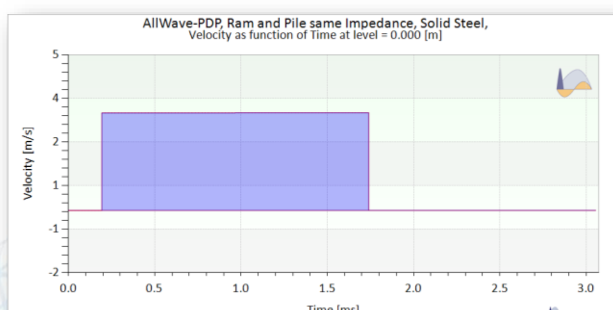
3D FEM Finite Element - 1D MOC Comparison

Basic Case, Ram and Pile same Impedance, Solid Steel D= 0.2m, Ram = 2m, Pile = 10m





1D MOC Result, agrees with theory and measurements

3D Finite Element Result, with spurious reflections

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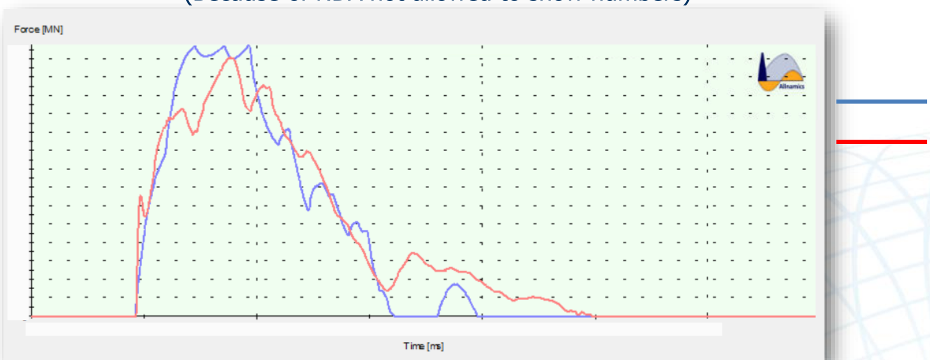
IMPACT BLOW COMPARISON 1D-MOC AND 3D-FEM

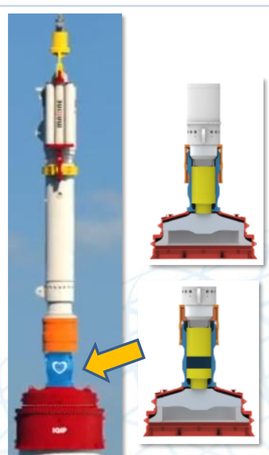
Blow on pile top, case of large monopile, large hammer, large anvil.
(Because of NDA not allowed to show numbers)



Flexibility of anvil seems to be of minor influence on impact blow.
For design and detailing hammer components 3D – FEM is required, but for driveability studies 1D - MOC AllWave-PDP does an excellent job.

MOC - IMPACT HAMMER NOISE REDUCTION MODELLING

- Nowadays a long list of hammer types (e.g., steam hammers, diesel hammers, hydraulic hammers, rapid load testing devices and vibratory drivers) have been modelled with MOC.
- Also advanced impact noise reduction systems like PULSE (IQIP), MNRU (Menck), Blue Piling water vessel ram can be modelled.

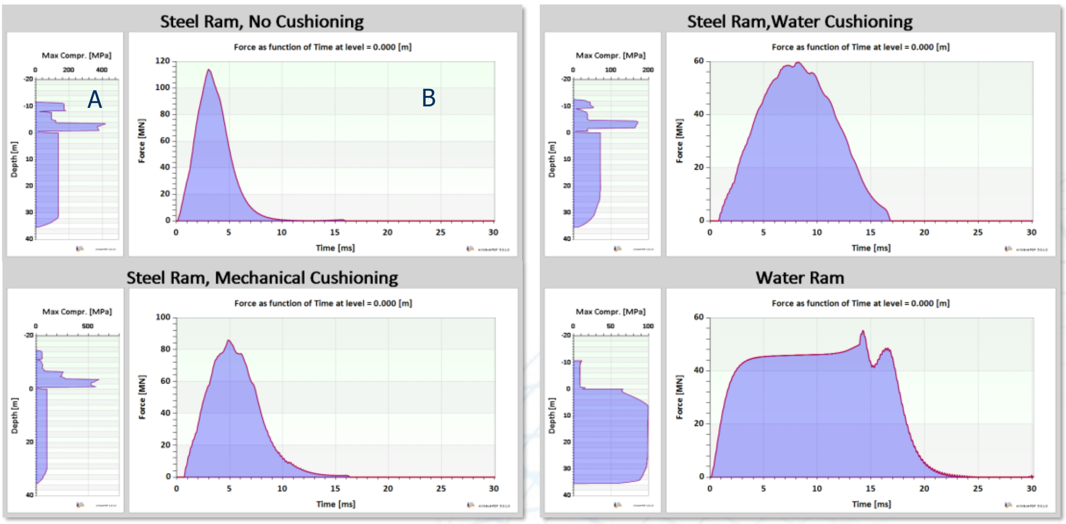


PULSE (IQIP)

MNRU (MENCK)

BLUE PILING (IQIP)

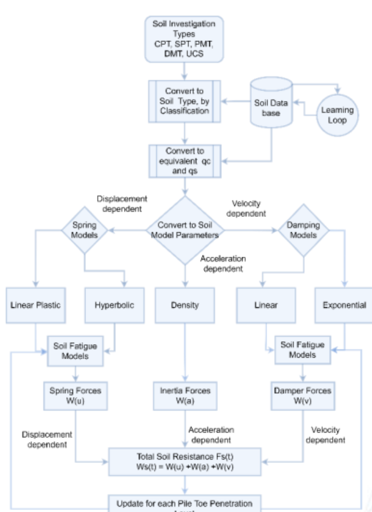
MOC - IMPACT HAMMER NOISE REDUCTION MODELLING

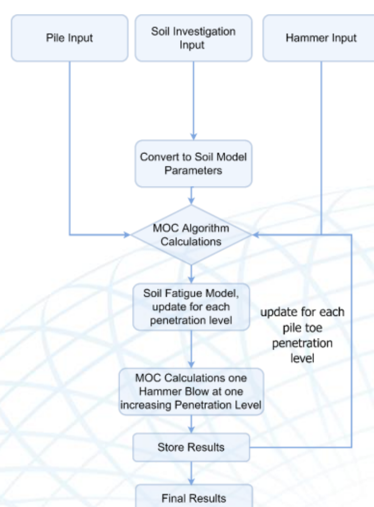


A - stresses in the ram and pile as function of depth (negative depth is in the ram, positive in the pile

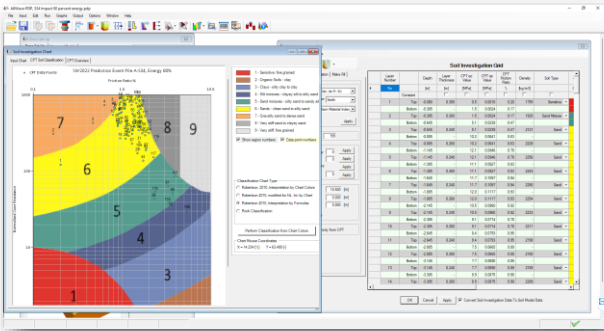
B - Impact force on pile top as function of time

FROM SOIL INVESTIGATION TO STATIC AND DYNAMIC SOIL PARAMETERS – ALLWAVE-PDP APPROACH



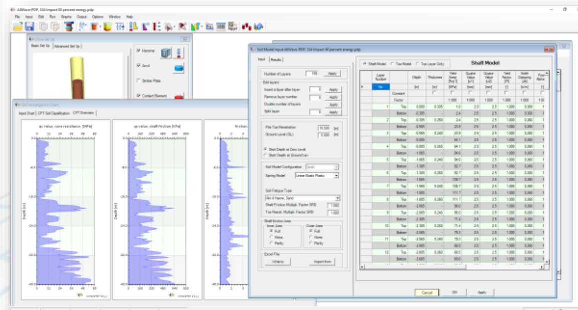


FROM SOIL INVESTIGATION TO STATIC AND DYNAMIC SOIL PARAMETERS – ALLWAVE-PDP APPROACH



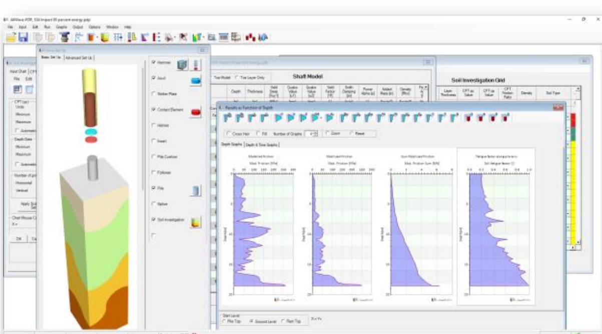
CPT – Soilinvestigation Input Example

Screen Shots



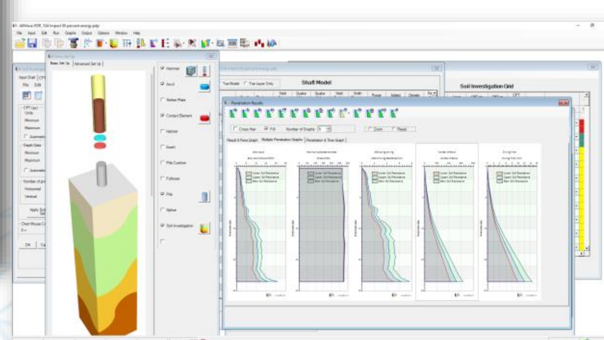
Derived Soil Model Parameters

FROM SOIL INVESTIGATION TO STATIC AND DYNAMIC SOIL PARAMETERS – ALLWAVE-PDP APPROACH



SRD and Soil Fatigue at end of driving
The soil fatigue is update at each intermediate pile toe penetration level

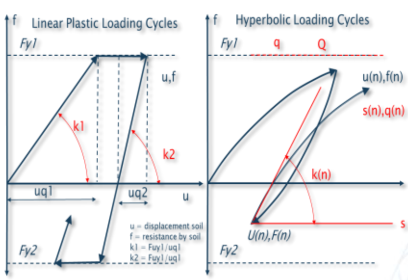
Screen Shots



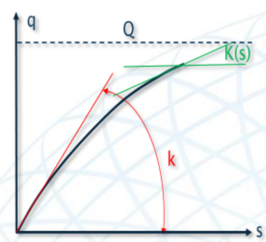
Predicted values

MOC – STATIC SOIL RESISTANCE MODELLING

- The most applied static resistance model is the linear plastic behaviour, based on quake values (uq1, uq2) and yield values (Fy1, Fy2). However, a hyperbolic loading cycle approach based on yield strength Q and shear modulus k is closer to the real cyclic soil loading behaviour of soil.



Static soil resistance models



Hyperbola definition

$$q = \frac{s}{(bs+a)}$$

$$a = 1/k$$

$$b = 1/Q$$

$$K(s) = \frac{dq}{ds} = \frac{a}{(a+bs)^2}$$

s = displacement, q = load, k= initial spring stiffness, Q = asymptote hyperbola

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SOIL FATIGUE MODELLING

- There are various fatigue models published in the literature (e.g., Toolan & Fox (1977), Stevens (1982), Alm & Hamre (1998), Alm & Hamre (2001)).

- To the presenter's opinion the model presented by Fischer et al. 2015 should be considered as it emphasizes mixed fatigue modelling per soil layer designating each soil layer with a different fatigue model.

- An interesting development is the Unified CPT-based method (Lehane et al. 2020).

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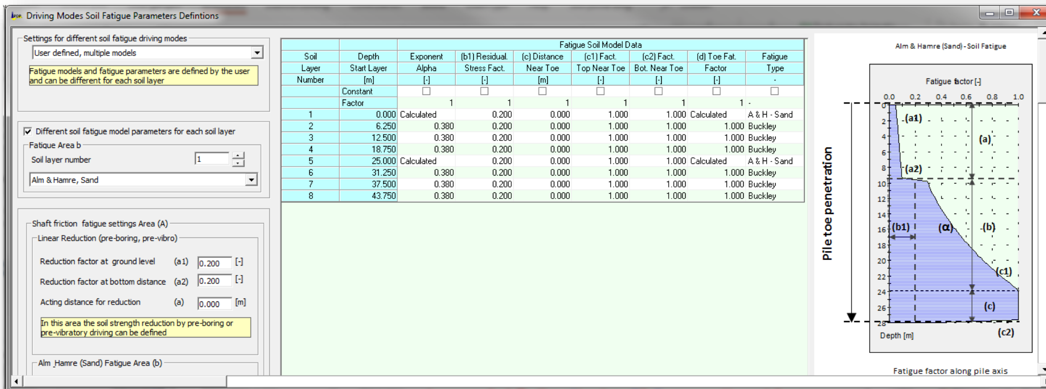
ALLWAVE-PDP MIXED FATIGUE MODELLING PER SOIL LAYER

KIVI The Royal Netherlands Society of Engineers



AllWave-PDP Mixed Soil Fatigue Modelling per Layer Example

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MOC -VIBRATORY DRIVING PREDICTION

KIVI The Royal Netherlands Society of Engineers

- The first MOC based publications for vibratory driving of offshore piles was by Jonker et al. (1988) and Middendorp et al. (1988)
- For longer piles a wave equation approach is required to correctly model the shift in strain state along the pile

To behave like a rigid body, it was required that the driving frequency was chosen to be equal or less than 10% of the natural frequency of the full-sized pile as a freely vibrating rod, expressed as:

$$f_d \le 0.1 f_n = 0.1\, c_b/2L$$

Or

$$L \le c_b\,/20 f_n$$

with f_d = driving frequency [Hz], f_n = longitudinal natural frequency of a free slender bar/pile [Hz], c_b = pile stress wave velocity [m/s], L = length of the pile [m].

For steel piles and a typical vibratory driving frequency of 23Hz this means that the rigid body assumption is only valid for pile with a length smaller than:

$$L \le \frac{5172}{400} \approx 11\ [m]$$

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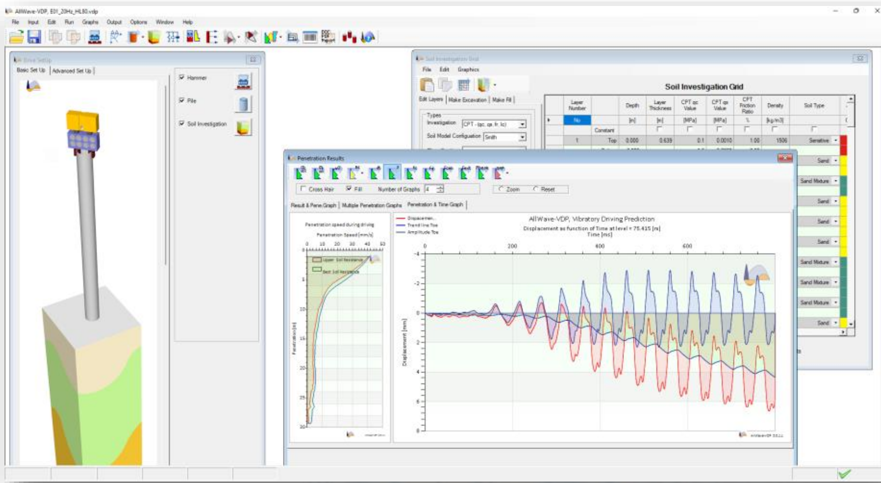
MOC -VIBRATORY DRIVING PREDICTION ALLWAVE-VDP



AllWave-VDP Screenshot

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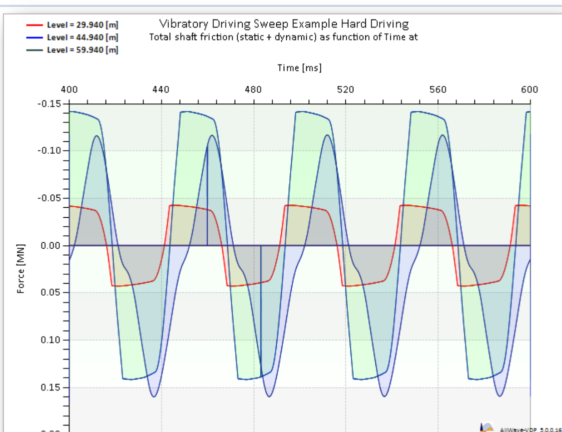
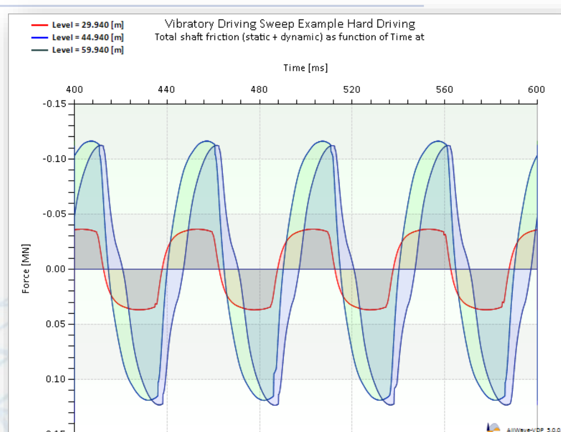
MOC - SOIL RESISTANCE MODELLING





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Snapshot of a Vibratory Driving simulation based on an elastoplastic soil resistance model.

Snapshot of a Vibratory Driving simulation based on an hyperbolic soil resistance model.

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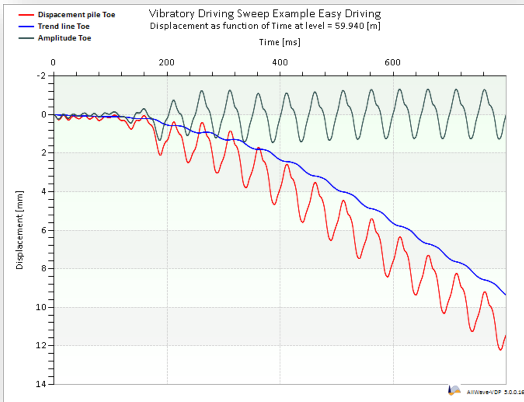
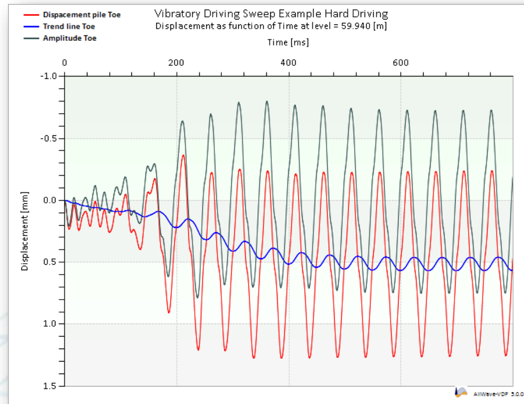
MOC - VIBRATORY DRIVING PREDICTION

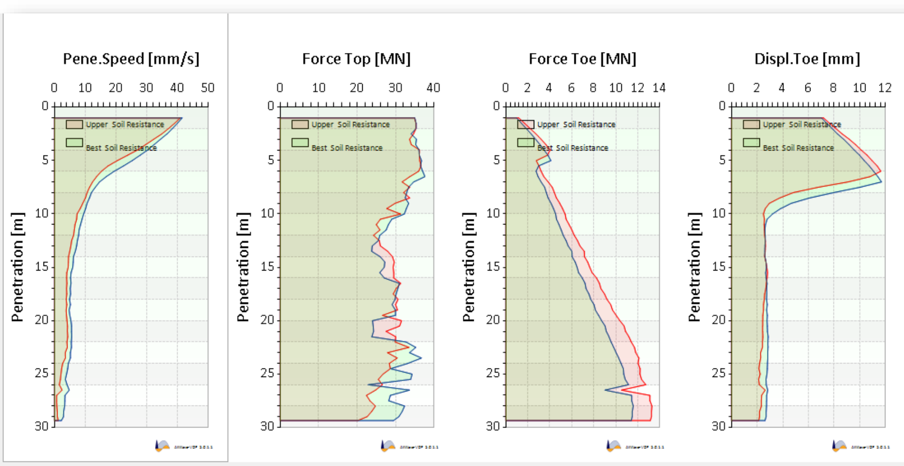


Pile displacement for easy driving with trend line for penetration speed determination



Pile displacement for hard driving with trend line for penetration speed determination

MOC - VIBRATORY DRIVING PREDICTION



Soil fatigue has been updated for each pile penetration level

Some AllWave-VDP results: pile penetration speed, force and displacement amplitudes toe

RIFFGAT PROJECT

FIRST VIBRATORY DRIVEN MONOPILES Made Possible by

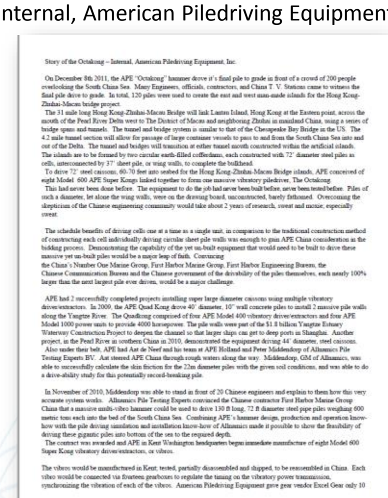
STORY OF THE OCTAKONG

STORY OF THE OCTAKONG

In 2010 the companies APE, CAPE-Holland, APE-China and Allnamics teamed up to convince the Chinese contractor First Harbor Marine Group China that a massive multi-unit vibrohammer could be used to drive 49 m long, 22 m diameter steel caisson pipe piles weighing 600 tonnes each 25 m into the bed of the South China Sea, where the soil consists of silty clay, clay and sand with SPT N-values ranging from 8 to 40.

The driveability studies were performed with AllWave-VDP, which showed the feasibility of driving these gigantic piles into the bottom of the sea to the required depth.

Internal, American Piledriving Equipment, Inc.



Story of the Octakong – Internal, American Piledriving Equipment, Inc.

On December 8th 2011, the APE "Octakong" hammer drove it's final pile to grade in front of a crowd of 200 people overlooking the South China Sea. Many Engineers, officials, contractors, and China T. V. Stations came to witness the final pile drive to grade. In total, 120 piles were used to create the east and west man-made islands for the Hong Kong-Zhuhai-Macau bridge project.

The 31 mile long Hong Kong-Zhuhai-Macau Bridge will link Lantau Island, Hong Kong at the Eastern point, across the mouth of the Pearl River Delta west to The District of Macau and neighboring Zhuhai in mainland China, using a series of bridge spans and tunnels. The tunnel and bridge system is similar to that of the Chesapeake Bay Bridge in the US. The 4.2 mile tunnel section will allow for passage of large container vessels to pass to and from the South China Sea into and out of the Delta. The tunnel and bridges will transition at either tunnel mouth constructed within the artificial islands. The islands are to be formed by two circular earth-filled cofferdams, each constructed with 72' diameter steel piles as cells, interconnected by 37' sheet pile, or wing walls, to complete the bulkhead.

To drive 72' steel caissons, 60-70 feet into seabed for the Hong Kong-Zhuhai-Macau Bridge islands, APE conceived of eight Model 600 APE Super Kongs linked together to form one massive vibratory piledriver, The Octakong.

This had never been done before. The equipment to do the job had never been built before, never been tested before. Piles of such a diameter, let alone the wing walls, were on the drawing board, unconstructed, barely fathomed. Overcoming the skepticism of the Chinese engineering community would take about 2 years of research, sweat and monie; especially sweat.

The schedule benefits of driving cells one at a time as a single unit, in comparison to the traditional construction method of constructing each cell individually driving circular sheet pile walls was enough to gain APE China consideration in the bidding process. Demonstrating the capability of the yet un-built equipment that would need to be built to drive these massive yet un-built piles would be a major leap of faith. Convincing the China's Number One Marine Group, First Harbor Marine Group, First Harbor Engineering Bureau, the Chinese Communication Bureau and the Chinese government of the drivability of the piles themselves, each nearly 100% larger than the next largest pile ever driven, would be a major challenge.

APE had 2 successfully completed projects installing super large diameter caissons using multiple vibratory driver/extractors. In 2009, the APE Quad Kong drove 40' diameter, 10" wall concrete piles to install 2 massive pile walls along the Yangtze River. The Quadkong comprised of four APE Model 400 vibratory driver/extractors and four APE Model 1000 power units to provide 4000 horsepower. The pile walls were part of the $1.8 billion Yangtze Estuary Waterway Construction Project to deepen the channel so that larger ships can get to deep ports in Shanghai. Another project, in the Pearl River in southern China in 2010, demonstrated the equipment driving 44' diameter, steel caissons.

Also under their belt, APE had Aat de Neef and his team at APE Holland and Peter Middendorp of Allnamics Pile Testing Experts BV. Aat steered APE China through rough waters along the way. Middendorp, GM of Allnamics, was able to successfully calculate the skin friction for the 22m diameter piles with the given soil conditions, and was able to do a drive-ability study for this potentially record-breaking pile.

In November of 2010, Middendorp was able to stand in front of 20 Chinese engineers and explain to them how this very accurate system works. Allnamics Pile Testing Experts convinced the Chinese contractor First Harbor Marine Group China that a massive multi-vibro hammer could be used to drive 130 ft long, 72 ft diameter steel pipe piles weighing 600 metric tons each into the bed of the South China Sea. Combining APE's hammer design, production and operation know-how with the pile driving simulation and installation know-how of Allnamics made it possible to show the feasibility of driving these gigantic piles into bottom of the sea to the required depth.

The contract was awarded and APE in Kent Washington headquarters began immediate manufacture of eight Model 600 Super Kong vibratory driver/extractors, or vibros.

The vibros would be manufactured in Kent; tested, partially disassembled and shipped, to be reassembled in China. Each vibro would be connected via fourteen gearboxes to regulate the timing on the vibratory power transmission, synchronizing the vibration of each of the vibros. American Piledriving Equipment gave gear vendor Excel Gear only 10

STORY OF THE OCTAKONG

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STORY OF THE OCTAKONG

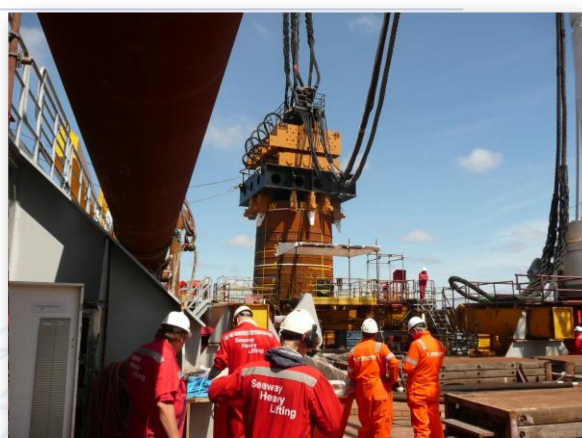
STORY OF THE OCTAKONG

Completed caisson installation

MOC - VIBRATORY DRIVING PREDICTION

Following the successful vibratory driving at the Hong Kong-Zhuhai-Macau Bridge project the contractor Seaway Heavy Lifting opted for the use of a vibratory hammer for the installation of the monopiles for the Riffgat project. (de Neef at al. 2013).

By choosing this innovative way of pile installation they could adhere to the strict environmental rules, which apply in Germany, and keep the environmental impact due to noise and vibrations within acceptable limits.



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MOC - VIBRATORY DRIVING PREDICTION

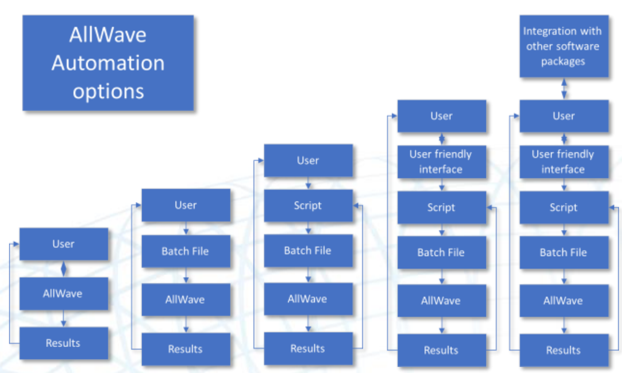
In the view of the author, vibratory driving and impact driving are complimentary, and as a minimum vibratory driving can be used for stabbing the piles.

If final penetration levels cannot be achieved by vibratory driving, the impact hammer can finish the job.

This approach, i.e., performing vibratory driving predictions with MOC and the installation of monopiles by vibratory hammers, are common practice in the design and construction of offshore wind energy farms nowadays.

DRIVEABILITY PREDICTIONS WITH SCRIPTING

- The current development of offshore wind energy farms may require the installation of hundreds of piles.
- To perform the design in an efficient way driveability studies must be automated, much like many other processes are automated.
- This requires that the MOC simulation programs allow the option to be operated externally by scripting methods.
- In this case scripting refers to a program or a sequence of instructions that is carried out by another program rather than by the computer processor.
- AllWave can be operated by scripts, run on desktops, company servers and from the cloud.



DRIVEABILITY PREDICTIONS WITH SCRIPTING AND ARTIFICIAL INTELLIGENCE

- The next logical development is the merger of driveability prediction programs with Artificial Intelligence to make full use of all the data that has been collected in the 80 years that the Method of Characteristics has been used for pile driving simulation, modelling and signal matching

- This collected data will surely include all the data that will become available from the SW2022 Demonstration Day/Testing Program.

Conclusions

- The presenter is impressed with the ingenuity of our forefathers to solve and apply the WEQ solution without the assistance of computers
- The MOC graphics method is widely used to explain and understand stress wave propagation phenomena.
- The MOC algorithm has many advantages over the Smith finite difference method (lumped masses and springs).
- AllWave 1D_MOC yields similar impact blow results as 3D-FEM.
- Soil fatigue model parameters should be updated for each pile toe penetration level.
- Operating prediction software by scripts and from the cloud and assisted by AI is already taking place and will be increasingly applied.
- The presenter hopes that Mariotte, Bergeron, Josselin de Jong and Voitus van Hamme get their deserved place in the Stress Wave Community history.

Creating the Future
by
Learning from the Past
and
Knowing the Present

SURF THE WAVES WITH THE METHOD OF CHARACTERISTICS

Thank you for your attention

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