New Breakthrough In The History Of Pile Driving And Testing Industry On Driven Piles.

by
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Abstract: *This paper presents the history of technology advancement in the pile driving and testing industry on driven piles. Importantly it presents a new testing method in determination of pile bearing capacities of driven piles. The new method is employed from the impact load theory in pile driving analysis. There is four major technology development and advancement since centuries ago until now, i.e. pile as rigid body, pile as elastic body in impulse-momentum theory, pile as elastic body in wave mechanic theory and pile as elastic body in impact load theory.*

HISTORY OF TECHNOLOGY DEVELOPMENT AND ADVANCEMENT

Introduction

Pile driving is a rather brutal method of foundation construction. A heavy mass impact the pile until it is installed in the ground. There exist numerous ways of verifying the quality of pile foundations. Pile testing may be conducted at several stages during construction. They may be conveniently separated into pre-construction and construction control tests. A pre-construction test is performed on specially driven piles well in advance of production to guide the engineer in the selection of a proper type of pile, hammer and its load bearing capacity, or to confirm the engineer's assumptions. Static load tests or dynamic tests with measurements on the first production piles are often used to establish a pile driving criteria. During construction, some production piles may be designated as static test piles, or the engineer may stipulate that a certain percentage of piles on a work site be dynamically tested *(1)*.

The comprehensive description on the pile driving and testing on driven piles is well documented in Reference *(1)*. This paper does not attempt to discuss the test methods proposed before year 2000. However, it discusses the history of technology development and advancement in the pile testing industry on driven piles since centuries until now. Importantly it presents a new testing method in determination of pile bearing capacities of driven piles.

Table 1 is the summary of the technology development of testing methods on driven piles since centuries ago until now. In the history of pile driving and testing, the advancement of the technology can be classified into four (4) developments in terms of their fundamental theories. The brief description on each technology development is discussed in next Section.

Development I: Pile as Rigid Body – the Conventional Theory in Pile Driving and Testing

In very early days, the driven piles – the only kind of pile type at that moment, were deemed as a rigid body and hammered down into the ground. The piles were small and short and installed for low-rise structures. The piles were simply installed by using any kind of mass such as woods and stones as the hammering devices. No tests were carried out on such piles. The performances of piles were place at the hand of God. Any installations of piles were based on trial and error concepts and remedial works would be carried out on "fail" piles. The piles deemed to be failed when they could not sustain the weight of structures.

With the development of the knowledge of human kinds, some piles were tested by simply putting on some dead weight on top of the piles to verify their carrying load bearing capacity. The test was named as Static Load Test (SLT) presently. The tests were basically based on the concept of Newtonian 1st Law, i.e. "Action=Reaction".

With modernization of the society, this SLT test had been modified and developed to become the well known Maintained Load Test (MLT) and Constant Rate of Penetration Test (CRP).

Development II: Pile as Elastic Body based on Impulse-Momentum Theory – the 1st Revolution in Modern Pile Driving and Testing

For centuries, the piles had been deemed as elastic body. This was because the piles were relatively big and long for carrying medium size structures compared to very early days.

At this juncture, some means was needed in the field to determine when a pile had reached a satisfactory bearing value other than by simply driving the pile in to some predetermined depth. Driving the pile to a predetermined depth might or might not obtain the required bearing value because normal soil variations both laterally and vertically *(2)*.

There are many formulas used to determine the capacity of the piles driven into the soil. Theoretical and semi-empirical formulas are derived to express this relationship between energy and work. These equations are generally known as dynamic pile formulas, which are derived from Impulse-Momentum Theory, i.e. "F=ma". These dynamic pile formulas are also termed as rational pile formulas.

The details of the formula derivations are beyond the scope of this paper and have been reported elsewhere *(2)*.

Presently, it is generally accepted that the dynamic pile formulas do not provide very reliable results *(2,3)*. Each of the formulas has their own respective advantages. The British Standard, BS 8004:1986, Clause 7.5.2.1 cited the Hiley formula as one of the more reliable and is probably the most commonly used *(4)*.

Development III: Pile as Elastic Body based on Wave Mechanic Theory – the 2nd Revolution in Modern Pile Driving and Testing

In the beginning of 20th Century, it was recognized that pile driving was a phenomenon better approximated by wave propagation theories. Solutions to the general partial differential equation for one-dimensional propagation were developed with equations specifically representing pile driving analyses *(1)*.

In the 1950's, digital computers made a discrete solution of wave propagation practical and an algorithm and computer code were developed by Smith *(5)* for pile driving analysis. This program is deemed to be the first computer program applied in civil engineering *(1)*.

The wave equation analysis offers over the dynamic formulas is the ability to realistically consider all important parts of the hammer-pile-soil system. The details of the theory is documented in Reference *(5)*.

The British Standard, BS 8004:1986, Clause 7.5.2.2 cited that the ultimate pile bearing capacity of a pile shall be predicted by the analysis of the stress wave theory *(4)*.

In the 1960's, the advanced electronic measuring devices transformed the evaluation of pile driving from an art to a science. The techniques most widely employed today for both measurement and analysis of pile dynamics were developed under the direction of Professor G.G. Goble at Case Western Reserve University, hence, collectively referred to as the Case Method *(6)*. The full release of Case Method and pile driving analyzer was in 1970s. The pile driving analyzer is a state-of-the-art testing equipment used to collect pile driving response of force and velocity for evaluation the pile bearing capacity using the Case Method.

Development IV: Pile as Elastic Body based on Impact Load Theory – the 3rd Revolution in Modern Pile Driving and Testing

The new application in pile driving using Impact Load Theory was first presented in PDA User's Day 1997, Hong Kong *(7)* by the Author. Intensive research and development was started in year 1998 and successfully ended in 2002 with two (2) Patents accorded by the United States of Patent and Trademark Office (USPTO) in year 2001 and 2002.

The details of the theory will be fully described in the next Section.

NEW BREAKTHROUGH

Background

This paper concerns a new method for determination load bearing capacity of piles wherein the method is based on a model which has been scaled-down to a size small enough for an indoors facility measurement whereby the measurements is deployed in a mathematical formula to calculate the load bearing capacity of a pile.

It is generally accepted that the dynamic formulas do not provide very reliable predictions but are continued to be used for lack of a better method as described in previous Section.

There is therefore a need for a better method for accurately determining a pile's load bearing capacity. Due to the harsh external environment at foundation construction sites, it would be desirable if the pile capacity instrumentation and measurement could be conducted within an indoors facility such as in a geotechnical laboratory. The physical dimension limitations of an indoors facility means that the actual dimensions of the pile is preferably be scaled-down so that the pile and its requisite instrumentation or measurement means may be accommodated within the indoors facility as illustrated in Figure 1.

Such a proposed scaled-down pile model will need a mathematical relationship in order to correlate its values to the pile's values so that the model may be used as a piling application in determining the load bearing capacity of pile.

Scopes

There are few major categories of foundation piles, i.e. driven piles, cast-insitu bored piles, injected piles, etc. This new method concerns only the first category, i.e. the piles installed by pile driving hammer.

Foundation engineers are engaged to design and choose pile types as laid down by the design requirements or standards. The foundation design is normally made after taking into consideration the columnar transferred load weight, soil type and conditions, piling system and pile design. Since soil type is an existing condition and the columnar transferred load has been predetermined in the design, the engineer may only advise on the two remaining variable factors, i.e. (i) pile design and (ii) piling system. In this article, the piling system is the pile driving system.

Fundamental Theory

The formula employed in the revolutionary new method is the Impact Load Theory that is commonly used in the structural analysis, such as a rod; which may be obtained from any literature on structural analysis, as follows:-

$$P = W\left[1 + \sqrt{1 + \frac{2hAE}{WL}}\right]$$

wherein,

P	= impact load on rod
W	= weight of impact mass
h	= stroke
L	= length of rod
A	= cross sectional area of rod
E	= Young's modulus of rod

Impact Load Formula

In Figure 2A, supposing a mass W falls through a height h on to a collar attached to one end of a uniform bar, the other end being fixed. Then an extension x will be caused which is greater than that due to the application of the same load gradually applied. The mass W will subsequently oscillate about, and come to rest in, the normal equilibrium position.

Neglecting loss of energy at impact, the above Impact Load Formula is obtained.

Analogy in Pile Driving

In Figure 2B, the Impact Load Model has been given a reverse direction of the applied load. Mass W is now applied onto the rod from the bottom. This model, if inverted, will form a pile driving model.

In other words, Impact Load Formula is an analogy of impact load being applied to a pile to determine the pile bearing capacity.

Figure 2C is the Pile Driving Model based on Impact Load Theory, and the Authors have named it as Y-bearing Method.

Application

Using the above method, a scaled-down model based on the Y-bearing Method may be built to test and determine the load bearing capacity of a pile to be used in pile driving.

The model pile apparatus may be scaled-down in accordance to a certain calculated ratio. It has been found that the method herein works for a ratio of actual:model in the range of x:1 where $1 \le x \le 100$.

Using the above ratio, the pile driving model apparatus described above can be applied industrially in the foundation design for piles.

Example: Industry Application

Known properties of Grade J355 Steel:

Pile Modulus, E	=	2100 T/cm^2
Specific Weight, N	=	7.85 T/m^3
Yield Strength, y	=	355 MPa
Allowable Driving Stress, σ_{all}	=	213 MPa

Actual Pile:-

Hammer Type: 7-tonnes single acting hydraulic hammer @ ram stroke of 1.2m with efficiency of 75%

Pile Type: 711mm diameter x 12mm wall thick steel pipe pile with length of 25m

$$Rp = W\left[1+\sqrt{1+\frac{2hAE}{WL}}\right]p \qquad \textit{p: pile}$$

Rp = 7*{1+[1+(2*(1.2*0.75)*263.52*2100)/(7*25)]$^{1/2}$} *use h multiply efficiency*
= 535.17 T

Model Pile:-

$$Rm = W\left[1+\sqrt{1+\frac{2hAE}{WL}}\right]m \qquad \textit{m: model}$$

Select a model with the dimensions,

W	=	0.08 T	=	80 kg
L	=	5.00 m		
E	=	2100 T/cm^2		
N	=	7.85 T/m^3		
A	=	3.10 cm^2		

Maintaining the same driving stress for the actual and model piles,

Pile Stress, σ	=	Rm / Am	=	Rp / Ap
			=	535.17 / 263.52
			=	203 MPa < σ_{all} = 213 MPa (OK!)
=> Obtain		Rm	=	203 * 3.10
			=	6.29 T

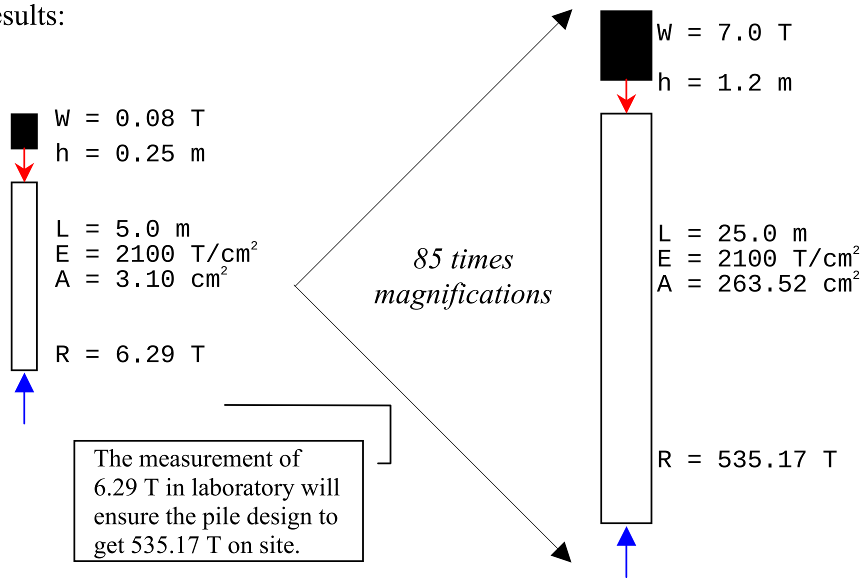
Based on this, the ratio of actual:model is,

actual : model
=> Rp : Rm
=> 535.17 : 6.29
=> 85 : 1

What is the drop height required if the above model is used?

Calculated, h = 0.247 m
≈ 0.25 m

Visualize Results:



Pile Model at Laboratory
(USPTO Patented Model)

Actual Pile at Site

Do it Yourself: The Power of Impact Load

Referring to Figure 2A, let a mass of 100 kg fall 4 cm on to a collar attached to a bar of steel 2 cm diameter, 3 m long. Find the maximum impact stress set up. Use E = 205,000 N/mm^2.

Stress at Static Load, $\sigma_s = 3.12$ N/mm^2
Stress at Impact Load, $\sigma_i = 134$ N/mm^2

i.e. even with only a 4 cm drop the impact stress is nearly 44 times the static stress.

SUMMARY

The presented new method in year 2000 is a simple and easy way in determination of pile load bearing capacity for a driven pile. Impact Load Theory applying in pile driving analysis only requires physical dimension of hammer, pile and soil to determine the pile bearing capacity. In this paper, the soil is virtually assumed as zero set. Using the Example as shown above, a scale down model based on the Impact Load Theory may be built to test and determine the load bearing capacity of a pile to be used in pile driving and installation.

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13. Goble, G.G., Rausche, F., and Likins, G.E., "The Analysis of Pile Driving A State-of-the-Art," The 1st Seminar on the Application of Stress Wave Theory on Piles, Stockholm, Sweden, 1980.
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Table 1

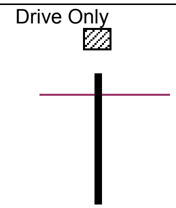
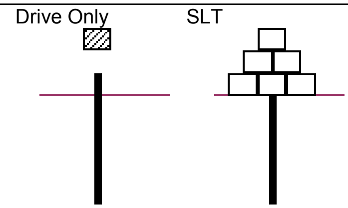
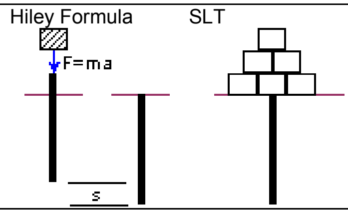
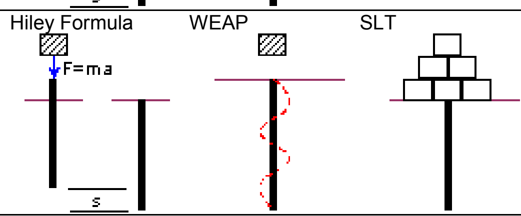
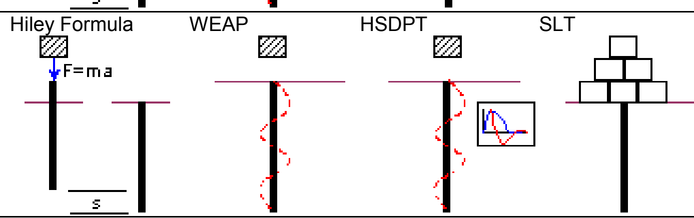
Year/Author	Technology Development & Test Precedence	Fundamental Theory	Remarks
For centuries			Rigid Body
For centuries		Newtonian 1^{st} law, Action = Reaction	Static Load Test
After 1930 by Hiley		Newtonian 2^{nd} Law F = ma	Elastic Body 1^{st} Revolution
After 1960 by Smith		Wave Mechanic (Analytical Model)	Elastic Body 2^{nd} Revolution *Wave Equation Analysis Program*
After 1970 by Goble		Wave Mechanic (Measurement Model)	*High Strain Dynamic Pile Testing*

Table 1 (con't)

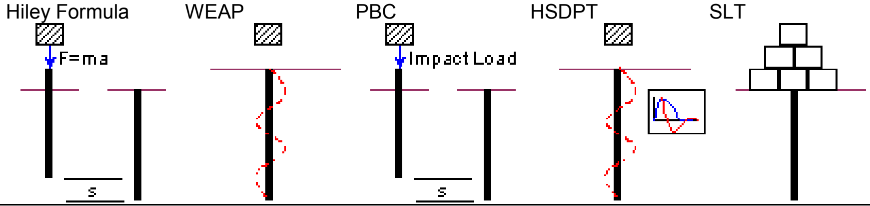
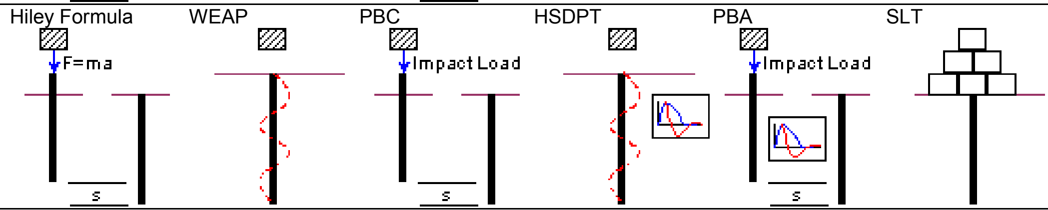
Year/Author	Technology Development & Test Precedence	Fundamental Theory	Remarks
After 1997 by Wai		Impact Load (Analytical Model)	Elastic Body 3rd Revolution *Pile Bearing Calculator*
After 2000 by Wai		Impact Load (Measurement Model)	*Pile Bearing Analyzer*

Figure 1A: Actual Pile Driving System

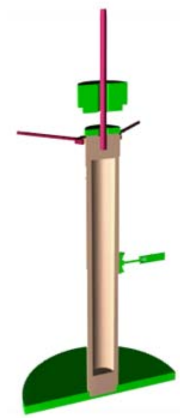


Figure 1B: Scale Down Model

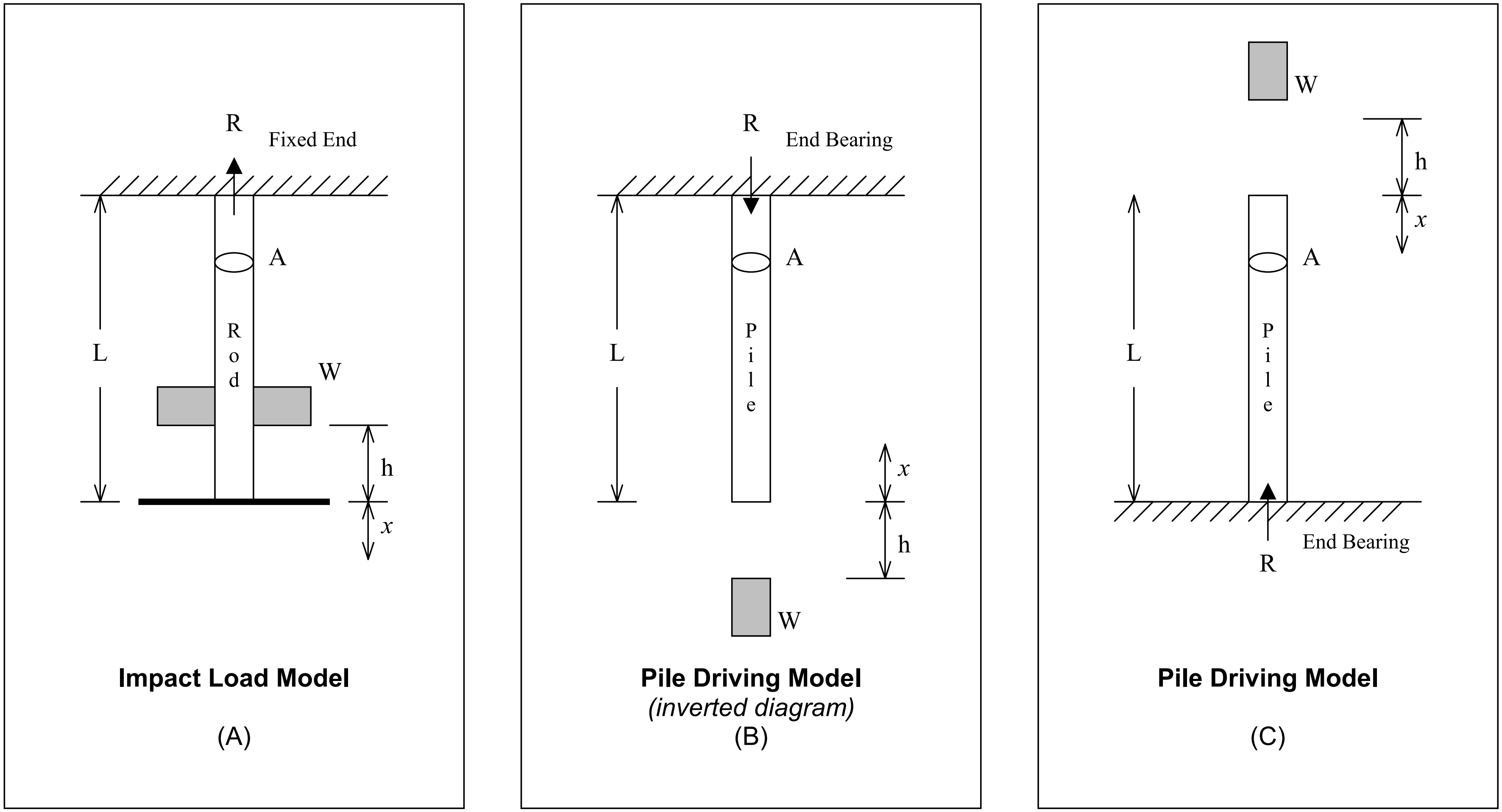


Figure 2 Y-Bearing Method Derived from Pile Driving Model based on Impact Load Theory