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IMPACT LOAD THEORY – A NEW PILE DRIVING AND TESTING METHOD FOR THE NEW MILLENNIUM ON PILES

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Abstract

This paper presents a new pile driving and testing method in determining pile bearing capacities of driven piles based on Impact Load Theory. It is the third revolution in the world of modern pile driving and testing after Hiley Formula that was based on Impulse-Momentum Theory in 1930s and Wave Equation Analysis based on Wave Mechanics Theory in 1960s. Impact Load Theory applied in pile driving analysis only requires physical parameters of hammer, pile and soil to determine pile load bearing capacity. A case study is also presented in this paper to demonstrate the application of the new theory in piling.

Keywords: Impact Load, Wave Mechanics, Impulse-Momentum, Hiley Formula, Wave Equation Analysis, Case Method, Y-bearing Method, piling, pile driving, pile testing

1. Introduction

Piles are columnar elements in a foundation which have the function of transferring load from the superstructure to the soil. The driving of piles to support structures is one of the earliest examples of the art and science of the civil engineer. In mediaeval time, piles oak and alder were used in the foundations of the great monasteries constructed in the fenlands of East Anglia. In China, timber piling was used by the bridge builders of the Han Dynasty (200 BC to AD 200). Thus primitive rules must have been established in the earliest day of piling by which the allowable load on a pile was determined from its resistance to driving by a hammer of known weight and a known drop height. Knowledge was accumulated regarding the performance of pile and its load bearing capacity *(5)*.

Since then the pile driving and testing industry has gone through four (4) major development and advancement in the knowledge of art and science as following *(2)*:-.

i.) Pile as a Rigid Body – the Conventional Theory in Pile Driving and Testing
ii.) Pile as a Elastic Body based on Impulse-Momentum Theory – the 1st Revolution in Modern Pile Driving and Testing (1930s)
iii.) Pile as a Elastic Body based on Wave Mechanics Theory – the 2nd Revolution in Modern Pile Driving and Testing (1960s)
iv.) Pile as a Elastic Body based on Impact Load Theory – the 3rd Revolution in Modern Pile Driving and Testing (2000s)

The comprehensive description on the driving and testing of piles is well documented in Reference *(3)*. This paper does not attempt to discuss the pile driving and testing methods proposed before year 2000.

The new application in pile driving using Impact Load Theory was first presented in PDA User's Day 1997 in Hong Kong *(1)* by the Authors. The details of the theory will be described in the next Section.

2. New Method For The New Millennium

2.1 Background

This paper outlines a new method for the determination of load-bearing capacity of piles based on impact load analogy in pile driving analysis.

2.2 Scope

There are a 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 hammers.

Foundation engineers are engaged to design and choose pile types in accordance to the design requirements and standards. The foundation design is normally made after taking into consideration the columnar transferred load, 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 paper, the piling system is the pile driving system.

2.3 Fundamental Theory

The formula employed in the revolutionary new method is the Impact Load Formula that is commonly used in structural analysis, such as for a rod; which can be obtained from any literature on structural analysis, as follows *(1,2)*:-

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

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

2.3.1 Impact Load Formula

In Figure 1A, 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 observed 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 its normal equilibrium position. Neglecting loss of energy at impact, the above Impact Load Formula is obtained.

2.3.2 Analogy in Pile Driving

In Figure 1B, the Impact Load Model has been applied a load in the reverse direction. Mass, W, is now applied onto the rod from the bottom. This model, if inverted, will form a piling model.

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

2.3.3 Y-bearing Method

In conclusion, Figure 1C is the Pile Driving Model based on Impact Load Theory, and the Authors have named it the Y-bearing Method.

3. Industry Application

Any new method should meet the technical requirements of the industry. In this Section, a simple application example is illustrated to demonstrate that the Y-bearing Method only requires physical parameters of hammer, pile and soil to determine the pile bearing capacity. In this example, the soil is virtually assumed as zero set.

A pile design is confirmed as follows:-

what is a suitable hammer to drive the pile for achieving load bearing capacity, R of 500 T?

Pile Design:-

Pile Type	= 711mm Ø x 12mm wall thick steel pipe pile
Grade	= J355 Steel
Pile Length, L	= 25.0 m
Working Load	= 250 T
Factor of Safety	= 2.0
Ultimate Load	= 500 T

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, T	= 213 MPa

Hammer Selection – 1st Attempt

Hammer Type	= BSP HH9 single acting hydraulic hammer
Ram Weight, W	= 9.0 T
Ram Stroke, h	= 1.2m
Hammer Efficiency, eff	= 75%

Pile Load Bearing Capacity, $R = W\left[1 + \sqrt{1 + \frac{2hAE}{WL}}\right]$

$R = 9*\{1+[1+(2*(1.2*0.75)*263.52*2100)/(9*25)]^{1/2}\}$ *use h multiply efficiency*

R = 607.90 T

Checking: Driving Stresses = R/A
= 607.90 / 263.52 * 100
= 231 MPa
> Allowable Driving Stress, T = 213 MPa (Not OK!)

Hammer Selection – 2nd Attempt

Hammer Type	= BSP HH7 single acting hydraulic hammer
Ram Weight, W	= 7.0 T
Ram Stroke, h	= 1.2m
Hammer Efficiency, eff	= 75%

Pile Load Bearing Capacity, $R = W\left[1 + \sqrt{1 + \frac{2hAE}{WL}}\right]$

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

R = 535.16 T

Checking: Driving Stresses = R/A
= 535.16 / 263.52 * 100
= 203 MPa
< Allowable Driving Stress, T = 213 MPa (OK!)

Answer: **Select BSP HH7 single acting hydraulic hammer to install the piles.**

4. Case Study

A project was designed to use 450mm Ø Grade 80 spun concrete pile with a wall thickness of 85mm and to be driven by a single acting BSP HH7 hydraulic hammer with a drop height of 0.8m. Pile length is expected to set at 65m. The design of piles was based on soil investigation results as described in Section 4.1 and its subsequent Pile Driving Information and Pile Driveability Study were presented in Section 4.2 and 4.3.

4.1 Standard Penetration Test

A standard penetration test (SPT) was carried out according to BS 1377. The sampler was driven into the soil by a 65kg automatic trip hammer free-falling through a height of 760mm onto an anvil.

The number of blows required to effect 300mm penetration (test drive) below an initial penetration of 150mm (seating drive), was recorded as the penetration resistance or N-value. The SPTs were conducted at depths of 1.5-meter interval. The N-value and the length of the distributed samples recovered from the sampler were indicated in the borehole logs.

The relative density of cohesiveless soils and the consistency of cohesive soils have been defined based on the penetration resistance, N-value. The relationship between the N-value and relative density and consistency of soils is based on Terzaghi and Peck, "Soil Mechanics in Engineering Practice".

The SPT result for the site is shown in Figure 2.

4.2 Pile Driving Information

Since the soil type as shown in Figure 2 is an existing ground condition, the engineer may only advice on the variable factors of pile design and piling system. The foundation engineer has selected 450mm Ø Grade 80 spun concrete pile to bear the working load of 140 T and selected single acting hydraulic hammer for pile installation.

The piles for the completed project were installed based on the following information:

Structure	: 10 storey medium cost apartment
Pile Type & Size (mm)	: 450 Ø x 85 wall thick spun concrete pile
Grade (MPa)	: 80
Working Load (T)	: 140 (compression)
Ultimate Load (T)	: 280 (compression)
Length of Penetration (m)	: 65.0
Area (cm^2)	: 975
Density (T/m^3)	: 2.60
Modulus (T/cm^2)	: 513
Weight of Pile (T)	: 16.47
Hammer Name	: BSP HH7 (7T single acting hydraulic hammer)
Ram Weight (T)	: 7.0
Ram Stroke (mm)	: 800
Hammer Efficiency %	: 75 (assumed)

4.3 Pile Drieveability Study for Pile Driving

The objective of the case study is to compare the driveability of piles based on Impulse-Momentum, Wave Mechanics and Impact Load Theories.

The driveability study results (i.e. pile set criteria) are presented in the following Sub-Sections.

4.3.1 Impulse-Momentum Theory

There are many formulas used to determine the capacity of the piles based on this theory. Theoretical and semi-empirical formulas are derived to express this relationship between energy and work.

The British Standard, BS 8004:1986, Clause 7.5.2.1 cited the Hiley Formula as one of the reliable and probably the most commonly used *(6)*. In this Section, Hiley Formula is selected for the pile driveability study and its results were computed as below *(4)*:-

$$R_{Hilley} = \frac{e_h W_r h}{s + C/2} \frac{W_r + n^2 W_p}{W_r + W_p}$$

where by,

R = ultimate pile capacity, Pu
e_h = hammer efficiency
h = height of ram fall
W_r = weight of ram
W_p = weight of pile including pile cap, driving shoe and cap block
s = amount of point penetration per blow (i.e. pile set)
C = $k_1 + k_2 + k_3$

k_1 = elastic compression of capblock and pile cap and is a form of P_uL/AE
k_2 = elastic compression of pile and is a form of P_uL/AE
k_3 = elastic compression of soil, termed quake for wave-equation analysis
n = coefficient of restitution
L = pile length
A = pile cross-sectional area

Based on information as described in Section 4.2, rearrange the equation to get Pile Set, s, to achieve ultimate capacity of 280T:-

$$\text{Pile Set, } s_{Hiley} = \frac{e_h W_r h}{R_{Hiley}} \times \frac{W_r + n^2 W_p}{W_r + W_p} - \frac{C}{2}$$

$$= \frac{0.75 \times 7.00 \times 800}{280.00} \times \frac{7.00 + 0.50^2 \times 16.47}{7.00 + 16.47} - \frac{30}{2}$$

$$= -8.0 \text{ mm/blow}$$

4.3.2 Wave Mechanics Theory

In the beginning of the twentieth Century, it was recognized that pile driving was a phenomenon better approximated by wave theory. This theory became well recognized in 1960s.

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 wave theory *(6)*. In this Section, the well known wave equation analysis program, GRLWEAP is selected for drieveability study. The bearing graph computed by GRLWEAP program is shown in Figure 3.

Referring to Figure 3, the blow count per meter (BPM) for ultimate capacity of 280T is:-

BPM @ 280T ≈ 400

this is equivalent to:

Pile Set, $s_{GRLWEAP}$ = 2.5 mm/blow

4.3.3 Impact Load Theory

The newly proposed Y-bearing Method as described in Section 2 can be used conveniently to perform the drieveability study. The Authors have carried out intensive research and development since 1998 to enable the Impact Load Formula as shown in Section 2.3 to be applied practically in pile driving and testing industry.

In the year 2000, by incorporating the method into a computation tool, such as a programmable calculator, the method was able to be applied in the field or site at ease. A program algorithm based on the Y-Bearing Formula has been written and built in a handy Pile Bearing Calculator (PBC) for pile driving and testing. The computed pile set report for the driveability study was presented in Figure 4 with the following pile set result:

Pile Set, s_{PBC} = 2.3 mm/blow

4.4 Case Study Summary

Base on Section 4.3, the summary of driveability results are shown in the table below:

Pile Length (m)	Ram Stroke (mm)	Pile Bearing (T)	Pile Set (mm/blow)		
			Hiley (1)	WEAP (2)	Y-bearing (3)
65.0	800	280	-8.0 (4)	2.5	2.3

(1) Hiley Formula based on Impulse-Momentum Theory
(2) Wave Equation Analysis Program based on Wave Mechanics Theory
(3) Y-bearing based on Impact Load Theory
(4) –ve denotes invalid set

The drieveability study summary indicated that the proposed new method is able to produce pile driveability results very close to wave theory. In addition, the Hiley Formula has negative (-ve) pile set for long piles. This negative pile set indicated that the selected hammer weight in the drieveability study is too small.

The piling project was completed with 163 piles installed successfully using pile set criteria of 20mm per 10 blows with penetration ranging from 60 to 69m. The ultimate load of 280T was confirmed by one (1) static maintained load test and five (5) high-strain dynamic load tests.

The completed project concluded that the Y-bearing Method able to be applied successfully for piling project.

5. Conclusions

The technology in the modern pile driving and analysis took about 40 years in every cycle of major development and advancement. The proposed new method beyond 2000 is a simple and easy way in the determination of pile load bearing capacity for driven piles. Impact Load Theory applied in pile driving analysis only requires physical parameters of hammer, pile and soil to determine the pile bearing capacity. In this paper, the case study indicated that the proposed new method is able to produce pile driveability results very close to wave theory. However, in reality, the pile driving analysis becomes very complicated after taking the interactive of pile-soil into consideration during driving. More research in future is required to incorporate the soil parameters in the Impact Load Formula.

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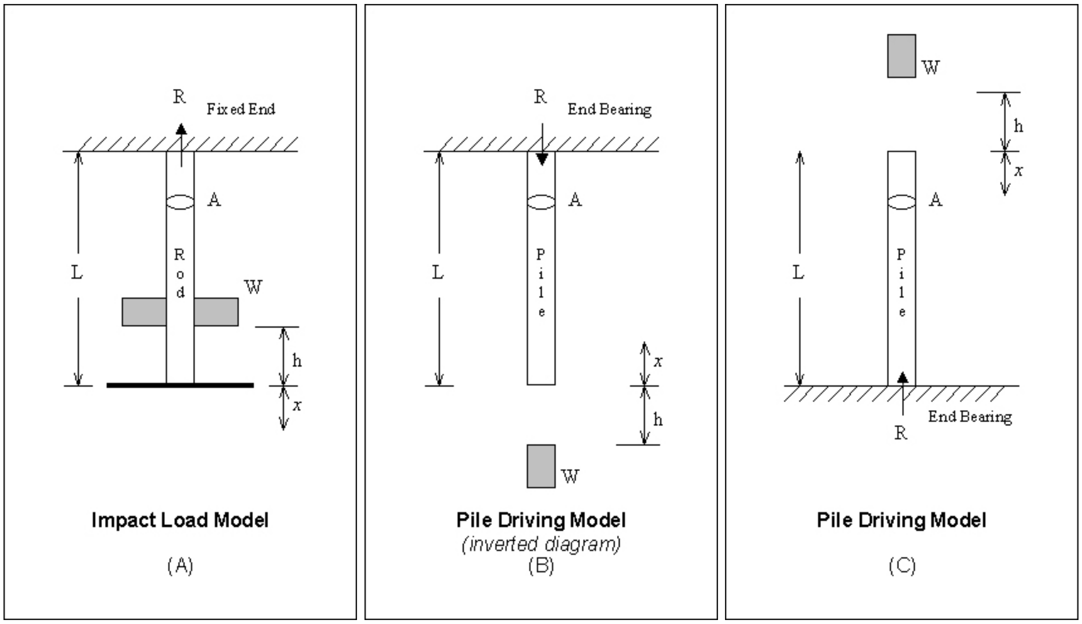

Figure 1: Y-Bearing Method derived from Pile Driving Model based on Impact Load Theory

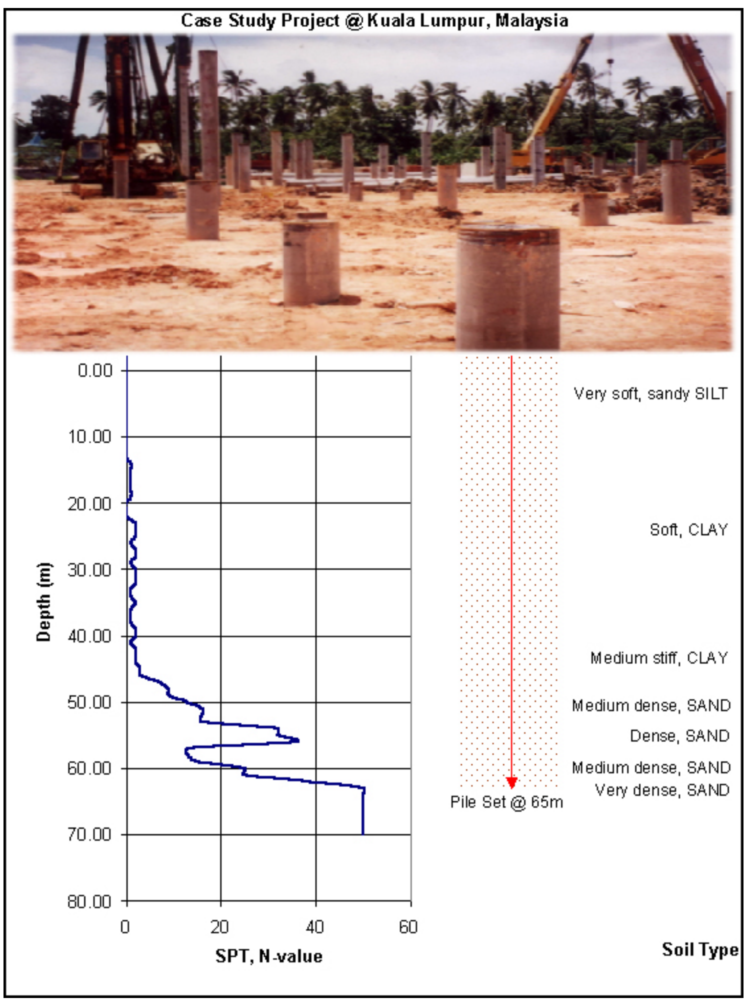

Figure 2 (top): Installed piles at site (bottom): SPT results

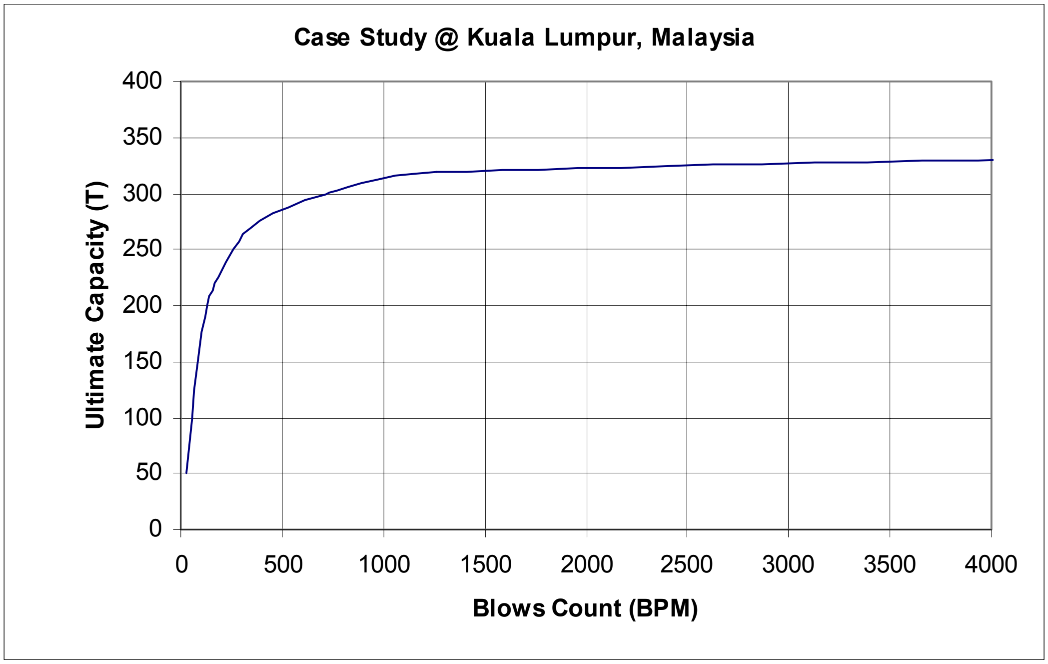

Figure 3: Bearing Graph computed by GRLWEAP program

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Computation Report For Pile Bearing Calculator (PBC) Version 1.30:
------------------------------------------------------------------
Project Name      : Case Study @ Kuala Lumpur, Malaysia
Company Name      : Traswaja Technology
User Name         : Yekong Wai
Created Date      : 24/07/2003
Updated Date      : 24/07/2003
PBC Version       : 1.30
PBC Software ID   : Traswaja Technology Sdn Bhd
------------------------------------------------------------------
Input Parameters  :
Pile Reference ID : Set-1
Ram Weight, W     : 7.00      ( t )
Ram Stroke, H     : 0.80      ( m )
Efficiency, F     : 75.00     ( % )
Pile Length, L    : 65.00     ( m )
Pile Area, A      : 975.00    ( cm2 )
Pile Modulus, E   : 513.00    ( t/cm2 )
Pile Density, N   : 2.60      ( t/m3 )
Pile Type, P      : 3         ( Spun Concrete Pile @ Gr 80 )
Pile Bearing, R   : 280.00    ( t )
------------------------------------------------------------------
Computation Result:
Pile Set, S       : 23.15     ( mm/10 blows )
```

Figure 4: Pile Set Report computed by PBC program