IMPACT LOAD THEORY – A NEW THEORY IN PILE DRIVING AND ITS COMPATIBILITY STUDY COMPARED TO HILEY AND CASE METHODS

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ABSTRACT: Modern pile driving and testing methods presently involved two fundamental theories, i.e. Impulse-Momentum Theory and Wave Mechanics Theory which have been popular and widely accepted since 1930s and 1960s. At 2000s, a new theory, Impact Load Theory was proposed as an advancement of technology to both the existing theories in modern pile driving and testing. This paper presents the compatibility study of the new theory to both the existing theories. This new theory has led to the development of Y-Bearing Method in analytical and measurement models. Technically, analytical model of Y-Bearing is compatible to the well known Hiley Method (based on impulse-momentum theory). In addition, measurement model of Y-Bearing is compatible to Case Method (based on wave mechanics theory). This new technology enables the engineers to implement Y-Bearing Method during the pre-piling stage using its analytical model to complement the results based on Hiley Method and subsequently apply its measurement model during piling stage to compliment the results based on Case Method.

Keywords: piling, driving, Hiley Method, Case Method, Y-Bearing Method

1 INTRODUCTION

Since mediaeval time, piles oak and alder were used in the foundations. 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.

Since then the pile driving and testing industry has gone through four (Wai, 2003) major development and advancement in the knowledge of art and science as following:-.
  i.) Development 1: Pile as a Rigid Body – the Conventional Theory in Pile Driving and Testing
  ii.) Development 2: Pile as a Elastic Body based on Impulse-Momentum Theory – Modern Pile Driving and Testing (popular wide acceptance since 1930s)
  iii.) Development 3: Pile as a Elastic Body based on Wave Mechanics Theory – Modern Pile Driving and Testing (popular wide acceptance since 1960s)
  iv.) Development 4: Pile as a Elastic Body based on Impact Load Theory – Modern Pile Driving and Testing (2000s)

The comprehensive description on the driving and testing of piles proposed before the end of the twentieth century is well documented by Mohamed Hussien (1988); whilst the details of Impact Load Theory and its applications are comprehensively described by Wai (1997, 2003).

2 IMPACT LOAD THEORY

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

2.1 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 (Ryder, 1969), as follows:-

$$F = R = W_r \left[1 + \sqrt{1 + \frac{2hAE}{W_r L}} \right] \qquad \text{Formula 1}$$

wherein,

F : impact load on rod (or R : end bearing on pile)
W_r : weight of impact mass (or ram)
h : stroke;
L : length of rod (or pile)
A : cross sectional area of rod (or pile)
E : Young's modulus of rod (or pile).

2.2 Y-Bearing Method

In Figure 1a, supposing a mass, W_r, 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_r, 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 (Formula 1).

In Figure 1b, the Impact Load Model has been applied with a load in the reverse direction. Mass, W_r, 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.

Figure 1c is the Pile Driving Model based on Impact Load Theory, and the Author has named it the Y-Bearing Method (Wai, 1997).

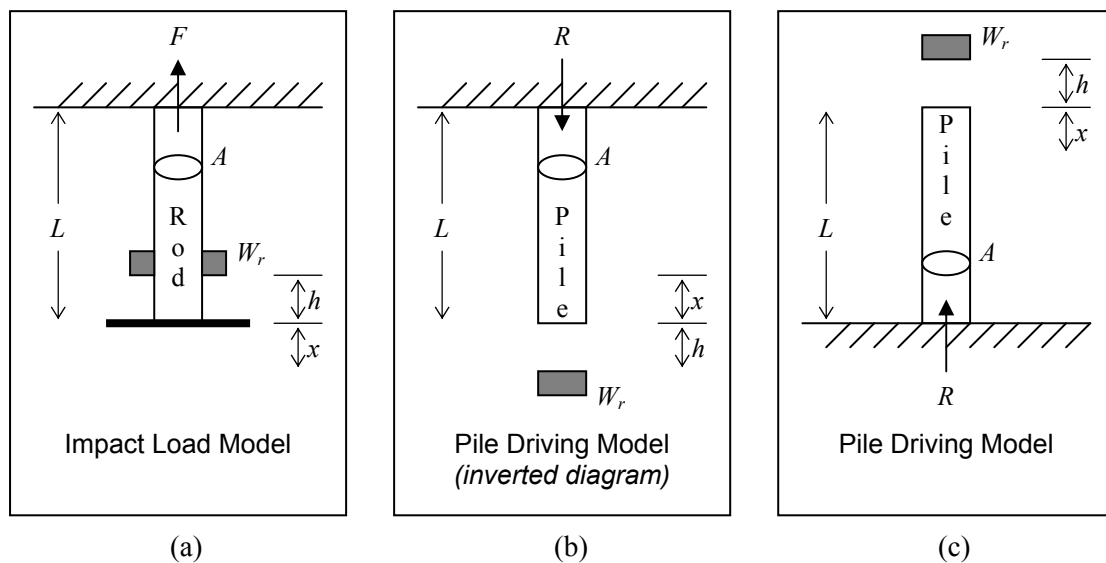(a)   (b)   (c)

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

2.3 Y-Bearing Method in Pile Driving and Testing Applications

Any new method shall meet the technical and engineering requirements of the industry. An industry application example and a case study of Y-Bearing Method are presented and described by Wai (2003).

This Section will describe the formula derivation of Y-Bearing Method in two models in order for them to be applied as industry applications in pile driving and testing. The first model to be presented is the analytical model of Y-Bearing (also regarded as prediction model); whilst the second model is the extension of the first model to become a measurement model. Importantly, both formulated models will be used to analyze their compatibilities with Hiley Method and Case Method in the next Sections.

2.3.1 Y-Bearing Analytical Model

The Formula 1 as described in Section 2.1, can be simplified and then apply as an analytical model in pile driving and testing. The derivation is illustrated as follows.

In the pile driving analysis, 1 to 2% of ram weight (i.e. weight of impact mass) is sufficient to drive the pile to achieve the desired bearing capacity (Tatsunori Matsumoto, 1997), hence, end bearing, $R \cong 100W_r$, therefore Formula 1 becomes, $100W_r \Leftrightarrow W_r\left[1 + \sqrt{1 + 2hAE/W_rL}\right]$; and in this relationship, $2hAE/W_rL$ portion is the dominant factor, then, $100W_r \Leftrightarrow W_r\left[\sqrt{2hAE/W_rL}\right]$. Substitute back $100W_r$ as end bearing, R, then to become, $R = W_r\left[\sqrt{2hAE/W_rL}\right]$; and rewrite as, $R = \sqrt{2AEW_rh/L}$; and by incorporating the energy losses, η, due to impact, represented by an hammer efficiency factor, thus, become Y-Bearing Analytical Model:-

$$R = \sqrt{\frac{2AE\eta W_r h}{L}}$$
Formula 2a

2.3.2 Y-Bearing Measurement Model

The Y-Bearing Analytical Model, Formula 2a, as described in Section 2.2.1 can be further developed to become a Measurement Model. The derivation is illustrated as follows.

In Hooke's Law, within the elastic limits, the displacement, $x = FL/AE$, wherein F is the impact load; and substitute into the Formula 2a, to become, $R = \sqrt{(F/x).(\eta W_r h)}$. If the potential hammer energy, $W_r h$, represented by e, thus get Y-Bearing Measurement Model:-

$$R = \sqrt{\frac{2\eta eF}{x}}$$
Formula 2b

In measurement terminology, R is the measured pile end bearing, computed from, hammer energy, e; imparted force from ram, F; and displacement, x. All these e, F, x are determined from measurement signals by a data acquisition system.

3   COMPATIBILITY STUDY

The Clause 7.5.2.1, BS 8004 (1986), cited the Hiley Method, based on Impulse-Momentum Theory, as one of the more reliable and is probably the most commonly used; whilst Clause 7.5.2.2 cited that the ultimate pile bearing capacity of a pile shall be determined by the analysis of the stress wave, based Wave Mechanics Theory, resulting from the hammer blow (BS8004, 1986). Although Hiley Method and Case Method have their popularities and have been widely used, however both do not have compatibility in engineering science either in terms of fundamental theory or measurement technology.

This paper presents the compatibility study of the new theory (i.e. Impact Load Theory) to both the existing theories. The new theory has led to the development of Y-Bearing Method as described in Section 2.1.3.

Next section will comprehensively describe:
-    the compatibility of Y-Bearing Method against Hiley Method in fundamental theory, and
-    the compatibility of Y-Bearing Method against Case Method in measurement technology

3.1   Compatibility of Y-Bearing Method against Hiley Method in Fundamental Theory

This Section aims to present the compatibility of Y-Bearing Method against Hiley Method in terms of their fundamental theories. In addition, explains the breakpoint value of "2" in the Hiley Method.

3.1.1 Fundamental Theory of Impulse-Momentum Theory

Nearly all the dynamic pile formulas currently used are based on Impulse-Momentum Theory. The details of the formula derivations are beyond the scope of this paper and have been reported elsewhere (Joseph E. Bowles, 1988):-

$$R = \frac{W_r h}{s + C} \cdot \frac{W_r + n^2 W_p}{W_r + W_p}$$
                                                                                                    Formula 3a

wherein,

W_r : weight of ram
W_p : weight of pile
s : amount of point penetration (i.e. pile set) per blow
C : pile top displacement (i.e. elastic compression)
n : coefficient of restitution.

3.1.2 Hiley Method

In 1930, rewriting Formula 3a, and factoring out ½ the term C, then Formula 3a, subsequently regarded as Hiley Method (Joseph E. Bowles, 1988):

$$R = \frac{W_r h}{s + C/2} \cdot \frac{W_r + n^2 W_p}{W_r + W_p}$$
                                                                                                    Formula 3b

If we combine the impact term, $(W_r + n^2 W_p)/(W_r + W_p)$, in the Hiley Method as hammer efficiency together with all the losses after impact, $\eta = (W_r + n^2 W_p)/(W_r + W_p)$, then, Formula 3b becomes a simplified Hiley Method as:-

$$R = \frac{\eta W_r h}{s + C/2}$$
                                                                                                    Formula 3c

3.1.3 Compatibility study

By matching the simplified Hiley Method as shown in Formula 3c into the piling model as illustrated in Figure 1 (i.e. the ideal case in pile driving), thus the 100% end bearing pile will have zero displacement, i.e. $s = 0$, and the extension, x, can be determined by Hooke's Law, as $x = FL/AE$. This x equivalents to C as described in Section 3.1.1, and replace into Formula 3c to become, $R = (\eta W_r h)/[(1/2)(PL/AE)]$; and for pile driven to s ≈ 0 (i.e. driven to refusal), then $F \approx R$, subsequently rewrite as:-

$$R = \sqrt{\frac{2AE\eta W_r h}{L}}$$
                                                                                                    Formula 3d

This modified Hiley, Formula 3d exactly same as Formula 2a in Y-Bearing Analytical Model. This reveals that both formulas have the compatibility in their fundamental theory and explains the breakpoint value of "2" in the Hiley Method which did not explain and elaborate in most of the piling literatures.

3.2   Compatibility of Y-Bearing Method against Case Method in Measurement Technology

This Section aims to present the compatibility of Y-Bearing Method against Case Method in terms of their measurement technology. Furthermore, to introduce the deployment of Y-Bearing Measurement Model as a pile top measurement technology based on data acquisition system proposed by Goble (1975).

3.2.1 Measurement Technology of Wave Mechanics Theory

In the 1960's, advanced electronic measuring devices transformed the evaluation of pile bearing from an art to a science (Goble, 1975). The technique most widely employed for measurement in pile dynamics is Case Method. The Case Method requires the measurement of force and velocity of the pile during driving. A typical pile force and velocity signals measured in the function of time is shown in Figure 2.
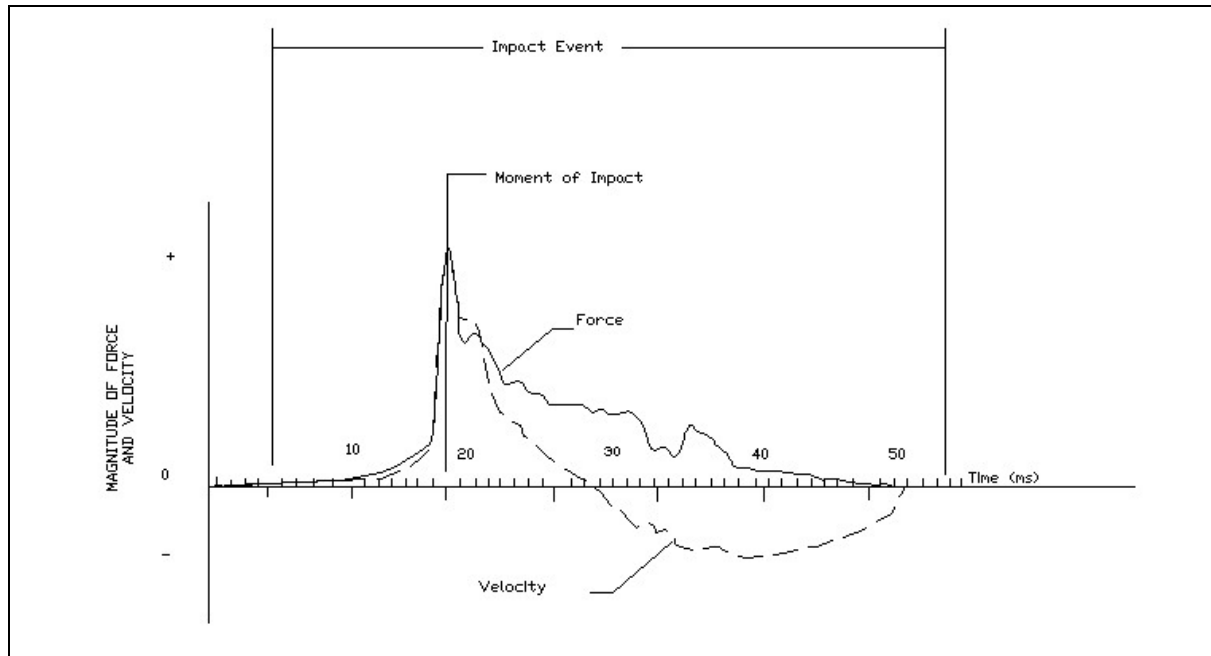

Figure 2: Typical Force and Velocity Signals, after ASTM D4945-96

3.2.2 Case Method

Using Stress Wave Theory, the following Case Method is formulated to determine the static pile bearing capacity of pile (Goble, 1975):-

$$R = (1 - J_c)\frac{[F_{t1} + Zv_{t1}]}{2} + (1 + J_c)\frac{[F_{t2} - Zv_{t2}]}{2} \qquad \text{Formula 4}$$

wherein,

R : static pile bearing capacity
F : measured force by strain transducer
v : measured velocity by velocity transducer or accelerometer
$t1$: time at initial impact or moment of impact
$t2$: time of reflection of initial impact from pile toe (t1 + 2L/c)
Z : pile impedance = EA/c
E : pile modulus of elasticity
A : pile area at gauges location
c : wave speed of pile material
L : pile length below gauges location
J_c : dimensionless damping factor of soil

By referring to Figure 2, the pile bearing capacity can be determined based on Case Method by incorporating the values of F_{t1}, v_{t1}, F_{t2}, v_{t2}, as well as J_c and Z constants into Formula 4. In define as a mathematical function, Case Method is a function of:-

$$R_{case} = f\{F(dt), v(dt), J_c, Z\} \qquad \text{Function I}$$

3.2.3 Compatibility Study

In Formula 2b, the actual value of hammer energy (after losses), e, can be obtained by integrating the product of force and velocity signals (as shown in Figure 2) over time domain, $e(dt) = \int F(dt).v(dt)$; and x is the displacement obtained by integrating the velocity signal, $x(dt) = \int v(dt)$. The pile bearing capacity of Y-Bearing can be determined by incorporating the corresponding values of $e(dt)$, $F(dt)$, and $x(dt)$, when the pile subjected to maximum displacement after impact, i.e. $x(dt)_{max}$, into Formula 2b. In define as a mathematical function, Y-Bearing Measurement Model is a function of:-

$$R_{y-bearing} = f\{F(dt), v(dt)\}$$ Function II

By comparing both mathematical functions in Function I and II, this reveals that Y-Bearing Measurement Model and Case Method have the compatibility in terms of their measurement technologies. In application, Function II comply all the measurement requirements of Case Method in Function I. In other words, Y-Bearing pile bearing capacity, $R_{y-bearing}$, can be computed based on the Case Method measurement technology without any modification onto the data acquisition system.

3.2.4 Case Study

Figure 3 is a measured force and velocity signals by a pile driving analyzer (PDA) on a spun concrete pile driven to refusal with the following information:-

Pile Length,	*LE*	*= 32.0 m*
Pile Area,	*AR*	*= 1885 cm²*
Pile Modulus,	*EM*	*= 490 tn/cm³*
Pile Density,	*SP*	*= 2.60 tn/m³*
Wave Speed,	*WS*	*= 4300 m/s*
Impedance,	*EA/C*	*= 214.9 tn-s/m*
Soil Damping,	*JC*	*= 0.6*

The PDA analyzer computes the Case Method pile bearing capacity based on the measured force and velocity signals based on Formula 4. From the information shown above, the computed Case Pile Bearing Capacity:-

$$R_{case} = 424\ tn$$

From Figure 3, the Y-Bearing Method requires the following information to compute the Y-Bearing Capacity:-

Measured Force when Max. Displacement occurred, F(dt) at $x(dt)_{max}$	*= 200 tn*
Measured Energy when Max. Displacement occurred, e(dt) at $x(dt)_{max}$	*= 6.45 tn-m*
Measured Max. Displacement, $x(dt)_{max}$	*= 15 mm*

Based on Formula (2b) as discussed in Section 2.3.2, Y-Bearing Capacity can be computed as follows:-

$$R_{y-bearing} = \sqrt{\frac{2*6.45*200}{15}} = 415\ tn \quad (\eta e: measured\ energy)$$

In summary, R_{case} and $R_{y-bearing}$ have *424* and *415 tn* respectively. This case study indicated that new Y-Bearing Method is an alternative to determine the pile bearing capacity measured by a pile driving analyzer to complements the results based on Case Method without any modification onto the data acquisition system.
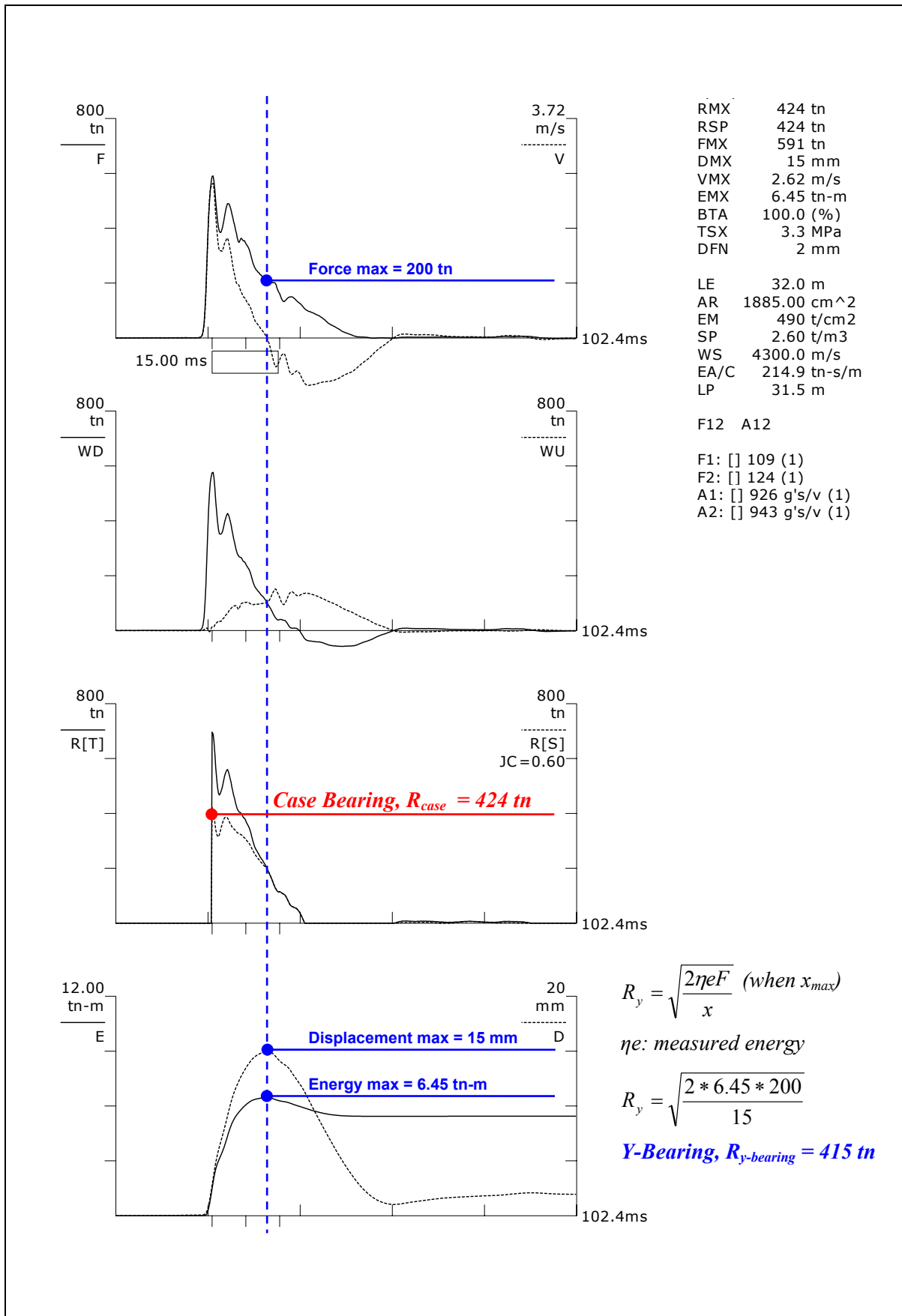
RMX	424 tn
RSP	424 tn
FMX	591 tn
DMX	15 mm
VMX	2.62 m/s
EMX	6.45 tn-m
BTA	100.0 (%)
TSX	3.3 MPa
DFN	2 mm
LE	32.0 m
AR	1885.00 cm^2
EM	490 t/cm2
SP	2.60 t/m3
WS	4300.0 m/s
EA/C	214.9 tn-s/m
LP	31.5 m

F12   A12

F1: [] 109 (1)
F2: [] 124 (1)
A1: [] 926 g's/v (1)
A2: [] 943 g's/v (1)

Force max = 200 tn

Case Bearing, R_{case} = 424 tn

Displacement max = 15 mm

Energy max = 6.45 tn-m

$$R_y = \sqrt{\frac{2\eta e F}{x}} \ \textit{(when } x_{max})$$

ηe: measured energy

$$R_y = \sqrt{\frac{2*6.45*200}{15}}$$

Y-Bearing, $R_{y\text{-}bearing}$ = 415 tn

Figure 3: Measured Force and Velocity Signals by a Pile Driving Analyzer

4   CONCLUSIONS

Technically, Y-Bearing is compatible to the well known Hiley Method (based on Impulse-Momentum Theory) in terms of fundamental theory and explains the breakpoint value of "2" in the Hiley Method in its prediction model.

In addition, it is compatible to Case Method (based on Wave Mechanics Theory) in terms of measurement technology in its measurement model.

This new technology enables the engineers to implement Y-Bearing Method during the pre-piling stage using its Prediction Model to complement the results based on Hiley Method and then apply its Measurement Model during piling stage to compliment the results based on Case Method.

5   REFERENCES

Yekong Wai, 1997, *Impact Load Analogy in Pile Driving Analysis*, PDA User's Day, Hong Kong.

Yekong Wai and Md Nuri Salimin, 2003, *Impact Load Theory - A New Pile Driving And Testing Method For The New Millennium On Piles*, 5th Asia-Pacific Conference on Shock & Impact Loads on Structures, Changsha, Hunan, China.

Mohamad Hussein, Garland Likins, and Frank Rausche, 1988, *Testing Methods of Driven Piles*, Handbook/Directory of the Pile Driving, Foundation and Marine Construction Techniques, Engineers, Contractors, Manufacturers, Distributors and Supplies.

Joseph E. Bowles, 1988, *Foundation Analysis and Design*, 4th Edition, McGraw-Hill Company, pp191-803.

British Standard, BS8004, 1986, *Foundations*, British Standard Institution, pp103-104

Smith, E.A.L., 1960, *Pile Driving Analysis by the Wave Equation*, Journal of Soil Mechanics and Foundations, ASCE, pp36-61.

Goble, G.G., Likins, G.E., and Rausche, F., 1975, Bea*ring Capacity of Piles From Dynamic Measurements - Final Report*, Dept. of Civil Engineering, Case Western Reserve University, Cleveland, Ohio.

Tatsunori Matsumoto, 1997, *Different Methods of Vertical Pile Load Tests and Applications*, Department of Civil Engineering, Kanazawa University, Japan.

Fox, E.N., 1932, *Stress Phenomena Occurring in Pile Driving, Engineering*, pp263-265.

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

Rausche, F., Goble, G.G., and Likins, G.E., 1985, *Dynamic Determination of Pile Capacity*, Journal of Geotechnical Engineering, ASCE.

H.H. Ryder, 1969, *Strength of Materials*, 3rd Edition, ELBS, pp3,9-10.

ASTM D4945, 1996, *Standard Test Method for High-Strain Dynamic Testing of Piles*, American Society For Testing And Materials.