CONVENTIONAL AND INNOVATIVE METHODS IN PILE DRIVING AND TESTING

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ABSTRACT

Piles are columnar elements in a foundation. The pile driving of piles to support structures is one of the earliest examples of the art and science in civil engineering since centuries. Many conventional and innovative technologies had been proposed and adopted since then till today. This paper aims to elaborate the technology development and advancement of pile driving and testing from conventional to innovative solutions. Technically, pile driving and testing are two (2) important aspects in piling engineering. In pile testing, since centuries, engineers used static load test to verify the pile capacity, until innovative dynamic pile test was developed in year 1970. While in pile driving, engineers adopted conventional dynamic pile formula such as Hiley in determining pile driving criteria since 1930. This formula was derived based on Impulse-Momentum Theory and is widely used since then. In year 2000, an innovative pile driving formula based on Impact Load Theory was proposed to improve the accuracy of pile driving. As piling is a science and engineering, consistent research shall be carried out so that more innovative methods can be developed to improve the quality of piling and to fit the industry in multimedia value chain in this ICT 3G-Internet information age.

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

TRADISI DAN INOVASI DALAM PELANTAKAN DAN PENGUJIAN TIANG PANCANG

ABSTRAKSI

Tiang pancang adalah elemen utama fondasi. Pelantakan pancang sebagai pendukung struktur adalah sebuah contoh yang paling awal di bidang kejuruteraan sipil sejak berabad dahulu. Banyak cara tradisional dan solusi yang inovatif telah diajukan dan dipakai sejak dahulu hingga sekarang. Makalah ini bertujuan untuk menjelaskan perkembangan teknologi daripada pelantakan dan pengujian tiang pancang dari cara tradisional sampai ke solusi yang inovatif. Secara teknikal, pelantakan dan pengujian tiang pancang adalah dua (2) aspek penting dalam teknologi kejuruteraan pelantakan pancang. Dalam pengujian tiang pancang, sejak berabad dahulu, insinyur menggunakan ujian beban statis untuk mengesahkan daya dukung tiang pancang, sehingga ujian inovatif dinamik pancang diperkenalkan pada tahun 1970. Manakala dalam pelantakan pancang, insinyur memakai rumusan seperti Hiley dalam menentukan kriteria-kriteria pelantakan pancang semenjak tahun 1930. Rumusan ini adalah berasaskan teori 'Impulse-Momentum' dan digunakan secara meluas sampai sekarang. Pada tahun 2000, sebuah metode pelantakan pancang yang inovatif berasaskan teori 'Impact Load' telah diajukan untuk memajukan cara pelantakan pancang yang dilakukan sekarang. Oleh kerana pelantakan pancang adalah satu bidang kejuruteraan, penyelidikan yang konsisten harus dilakukan supaya lebih banyak metode yang berinovasi bisa diperkenalkan untuk memajukan kualitas pelantakan pancang dan menyesuaikan industri ini ke zaman multimedia dan informasi 3G- internet sekarang.

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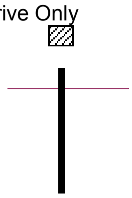
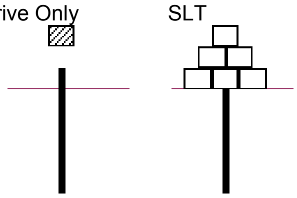
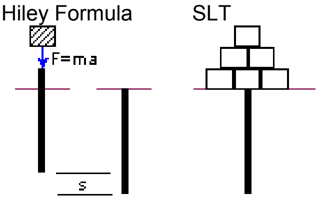
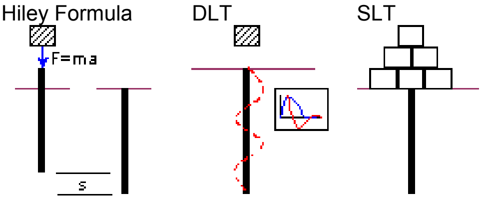
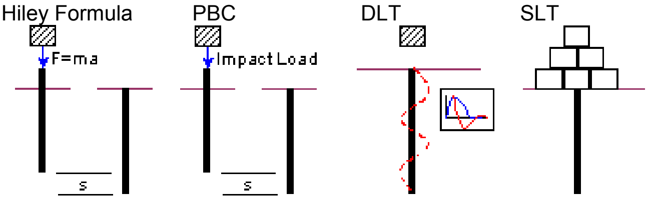
1. INTRODUCTION

In structural analysis, piles are columnar elements in a foundation. The pile driving of piles to support structures is one of the earliest examples of the art and science of the engineering since centuries. Many conventional and innovative solutions were proposed and adopted since then till today. This paper aims to elaborate the technology development and advancement of pile driving and testing from conventional to innovative solutions. Technically, pile driving and testing are two (2) important aspects in piling engineering. The summary of development and advancement of pile driving and testing since centuries till today is shown in Table 1.

Table 1: Pile Driving and Testing Technology Development and Advancement (after Wai et al., 2003)

Year (Author)	Pile Driving and Testing Technology Development and Advancement	Fundamental Theory
For Centuries	Drive Only 	Primitive
For Centuries	Drive Only; SLT 	Newtonian 3rd Law Action = Reaction *Rigid Body*
After 1930 (by Hiley)	Hiley Formula (F=ma, s); SLT 	Newtonian 2nd Law F=ma *Elastic Body* *1st Revolution*
After 1970 (by GG Goble)	Hiley Formula (F=ma, s); DLT; SLT 	Wave Mechanics *Elastic Body* *2nd Revolution*
After 2000 (by YK Wai)	Hiley Formula (F=ma, s); PBC (Impact Load, s); DLT; SLT 	Impact Load *Elastic Body* *3rd Revolution*

Note: SLT: Static Load Test; DLT: Dynamic Load Test (also well known as HSDPT or PDA); PBC: Pile Bearing Calculator

As tabulated in Table 1, the pile driving and testing industry has gone through four (4) major development and advancement in the knowledge of art and science as following since centuries:-

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 Piling
iii.) Pile as a Elastic Body based on Wave Mechanics Theory – the 2nd Revolution in Modern Piling
iv.) Pile as a Elastic Body based on Impact Load Theory – the 3rd Revolution in Modern Piling

The comprehensive description on the driving and testing of piles proposed before the end of the twentieth century is well documented by Hussein et al. (1988). The new application in pile driving using Impact Load Theory was first presented in PDA User's Day 1997 in Hong Kong (Wai, 1997) by the Authors.

2. PILE TESTING TECHNOLOGY

In pile testing, since centuries, engineers using static load test (SLT) to verify the pile capacity, until innovative dynamic load test (DLT) developed in year 1970.

2.1 Conventional Static Pile Testing since Centuries

Two principle types of tests are used for compressive loading on piles. The first is the constant rate of penetration (CRP) test, in which the compressive force is progressively increased to cause the pile to penetrate the soil at a constant rate until failure occurs. The second type of test is the maintained load test (MLT) in which the load is increased with the time-settlement curve recorded at each stage of loads (Tomlinson, 1995).

CRP and MLT tests use the same type of loading arrangements and pile preparation. Suitable loading arrangements for applying the load to the pile by a hydraulic jack using as the reaction, either kentledge, tension piles or cable anchors are shown in Figure 1(a), 1(b) and 1(c) respectively (Tomlinson, 1995). The tests have been standardized as stated in ASTM D1143: Standard Test Method for Piles Under Static Axial Compressive Load. However, in general, local code of practice may stipulate the test procedure for load increments and time sequences.

2.1.1 Advantages of Static Pile Testing

Static load testing offers several advantages as follow:-

- The result is more reliable compared to other tests because it is determine directly from the load transfer on to the pile element.
- Allow to determine long term settlement from load-settlement test results.
- Interpretation of test results is much easier than other testing methods such as dynamic tests with assumptions.

2.1.2 Disadvantages of Static Pile Testing

Although the static load test results are more reliable (provided the test has been conducted properly), however it has some significant disadvantages as follow:-

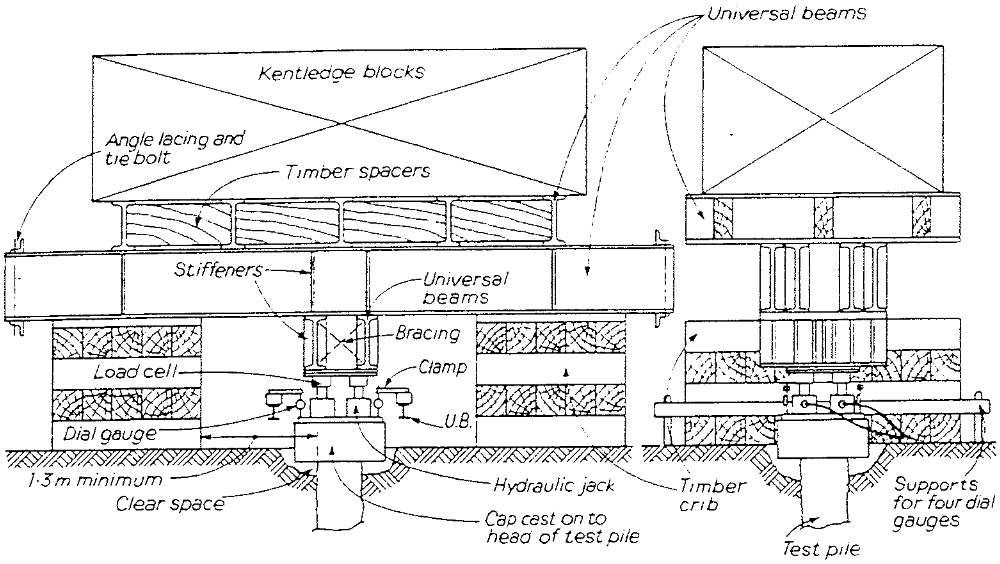
- Expensive; the cost to setup the testing system as shown in Figure 1(a), 1(b) and 1(c) is higher for a higher load test pile.
- Time consuming; the time to perform test (inclusive setup time) takes few days, sometimes even few weeks and cumbersome.
- Almost physical impossible to setup load testing for offshore pile installations.
- Require big and stable working platform to setup the testing.
- The test results are unanswerable for some failed load test piles because the pile may subject to structural integrity failure instead of geotechnical failure.

Due to the costs involved and time required, tests are only done on several selected pile points from 2% for small scale projects to as low as 0.5% for large scale projects exceeded 1000 pile points. The Engineer is supposed to decide for the whole project based on these low percentage verified piles, hence there is no way by using mathematic statistical approach to verify the foundation integrity based on such low sampling rate in testing. Therefore an innovative solution to test the pile need to be developed as described in next Section.

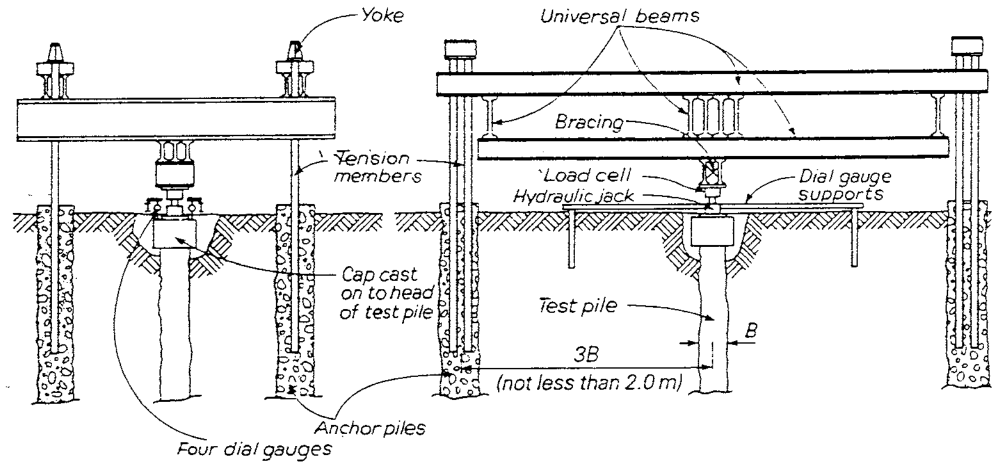
2.2 Innovative Dynamic Pile Testing since 1970

In 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-Goble Method (Goble et al., 1975, 1980, 1985).

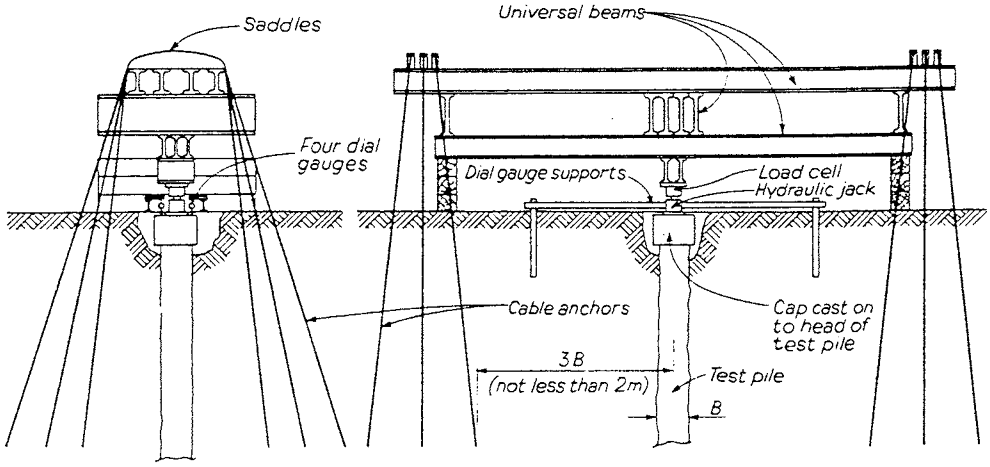
The full release of Case Method and pile driving analyzer (PDA) was in 1970s. The pile driving analyzer is a state-of-the-art testing equipment used to collect pile driving responses of force and velocity for evaluation the pile bearing capacity using the Case Method. A typical pile force and velocity traces measured in the function of time is shown in Figure 2.



(a) Testing Rig for Compressive Test on Pile using Kentledge for Reaction (conventional)



(b) Testing Rig for Compressive Test on Pile using Tension Piles for Reaction (innovative)



(c) Testing Rig for Compressive Test on Pile using Cable Anchors for Reaction (innovative)

Figure1: Static Load Testing Setup for Compressive Test on Pile (after Tomlinson, 1995)

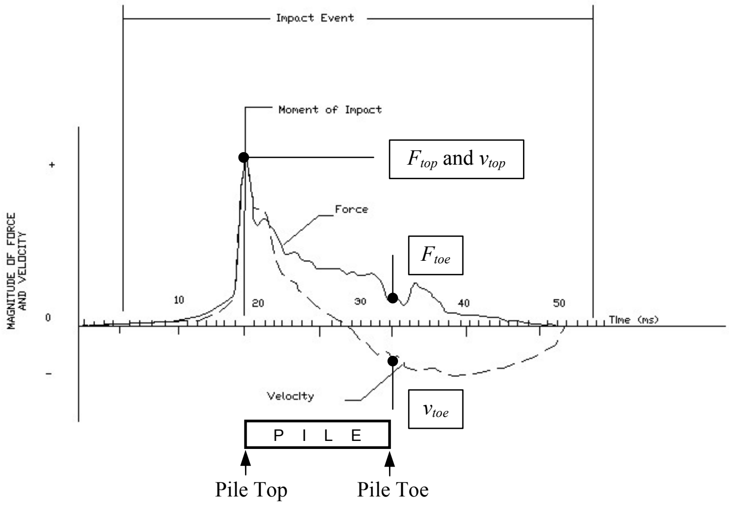


Figure 2: Typical Force and Velocity Traces, after ASTM D4945-96, and Force and Velocity at Pile Top and Pile Toe

Using Stress Wave Theory, the following Case Method is formulated to determine the static pile bearing capacity of pile (Goble et al. 1970s):-

$$R = (1 - J_c)\frac{\lfloor F_{top} + Zv_{top} \rfloor}{2} + (1 + J_c)\frac{[F_{toe} - Zv_{toe}]}{2} \qquad \text{Formula I}$$

wherein, *R*=static pile bearing; v_{top}=pile top velocity defined as the first relative maximum velocity at time *t*; F_{top}=pile top force at time *t*; v_{toe}=pile toe velocity defined as the velocity travels upward to the pile top from pile toe at time *(t+2L/c)*; F_{toe}=pile toe force at *(t+2L/c)*; J_c=dimensionless damping constant; *Z*=impedance constant; *c*=wave speed, a function of material properties of pile; *L*=pile length.

By referring to Figure 2, the pile bearing capacity, *R* can be determined based on Case Method by incorporating the values of F_{top}, v_{top}, F_{toe}, v_{toe}, determined from measurements as well as J_c constants into Formula I.

2.2.1 Advantages of Dynamic Pile Testing

There are many advantages of dynamic pile testing over the static pile testing as follow:-

- Significant less cost compared to static test with simple and fast setup.
- Provide instant results to evaluate pile bearing, integrity, driving energies and stresses.
- Flexibility and can be applied to test relatively high percentage of the piles; sometimes may as high as 100% dependent to the contract budgets.
- Allow to get more piling information in less time for decision makings.

2.2.2 Disadvantages of Dynamic Pile Testing

Technically, the significant advantages of dynamic pile testing over static pile testing are cheaper and faster. However, it has few drawbacks and disadvantages as follow:-

- Very theoretical and lengthy derivation of Case Method based on Wave Mechanics Theory.
- Require strong knowledge in mathematics to understand the method.
- The test can not predict long term pile settlements versus loads.
- Require good quality signals to assess results; garbage in garbage out (GIGO).

2.3 Innovative Automation Pile Testing Technology

As technology advances and speed of testing becomes an issue, having senior testing engineer on site may lead to undesirable time delays, scheduling problems and delays in reporting (www.pile.com, July 2005). The pile testing technology towards automation and controlled remotely will become the trend with the popularity of the engineers to adopt information-communication technology (ICT) in their operations.

2.3.1 Automation Static Load Testing

As illustrated in Figure 3, the static load test can be conducted using fully automated load control and monitoring system. The engineer can monitor the test results in a remote computer in real time and to response to the test results instantly when required.

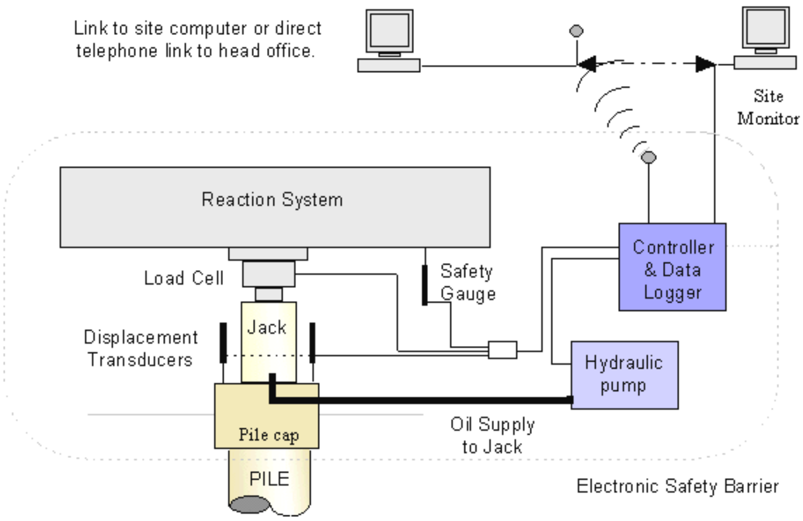


Figure 3: Automation Static Load Test Arrangement (www.skanska.co.uk, July 2005)

2.3.2 Remote Dynamic Pile Testing

To improve dynamic pile testing efficiency, Pile Dynamic, Inc. (www.pile.com, July 2005) developed the Remote Pile Driving Analyzer which collects dynamic data on site and sends data by cell phone to the office for analysis. This innovative solution as shown in Figure 4 enables the testing to be conducted by junior engineer on site and the senior engineer monitor the testing in the office.

Figure 4: Pile Driving Analyzer Model PAL-R (www.pile.com, July 2005)

3. PILE DRIVING TECHNOLOGY

In pile driving, engineers had adopted conventional dynamic pile formula such as Hiley in determining pile driving criteria since 1930. This formula was derived based on Impulse-Momentum Theory and is widely used. In year 2000, an innovative pile driving method based on Impact Load Theory was proposed to improve the accuracy of pile driving.

3.1 Conventional Pile Driving Formula since 1930

This Section aims to present the conventional Hiley Formula which is derived from Impulse-Momentum Theory and its inaccuracy in pile driving.

3.1.1 Hiley Formula

Nearly all the dynamic pile formulas currently used are derived from Impulse-Momentum Theory. The details of the formula derivations are beyond the scope of this paper and have been reported elsewhere (Hussein et al., 1988; Bolwes, 1988; Broms ,1981). The Hiley Formula is obtained as:-

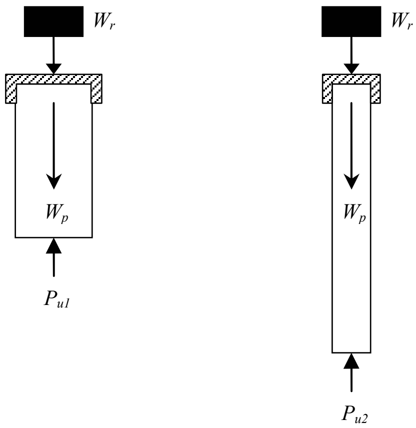
$$R = \frac{W_r h}{s + C/2} \cdot \frac{W_r + n^2 W_p}{W_r + W_p}$$ Formula II

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 Limitation of Hiley Formula and Its Inaccuracy

By referring to the Formula II, the said formula does not have physical dimensions on pile for pile length, *L*, pile size (or area), *A*, and pile material (i.e. Young's modulus), *E*. In other words, as illustrated in Figure 5, with same pile weight, *Wp* and ram weight, W_r, Hiley Formula is independent to the following conditions:

- pile length, *L*, does not affect the Hiley computation;
- pile area, *A*, does not affect the Hiley computation;
- pile modulus, *E*, concrete or steel piles will have same results with same W_p and W_r.



(a) big but short pile with W_p (b) small but long pile with W_p

Figure 5: Pile Driving Model with same Pile Weight, W_p

According to Hiley Formula which was derived from Impulse-Momentum Theory, the piles with same pile weight, W_p (or mass) regardless to their physical dimensions of *L*, *A* and *E* will have the same impulse-momentum behavior during the pile driving impacts; hence it will have same pile bearing capacities, $P_{u1}=P_{u2}$. However, this is incorrect in actual pile driving applications, because $P_{u1} \neq P_{u2}$ for different *L*, *A* and *E*.

With all the variations in *L*, *A* and *E*, Hiley Formula has greater deviations when pile become longer (*L*), bigger (*A*) with different material (*E*). Presently, it is generally accepted that Hiley Formula do not provide very reliable results (Bowles, 1988; Tomlinson, 1995).

The research carried out by the Authors revealed that the inaccurate of Hiley Formula is mainly due to nature of the formula, which is derived from Impulse-Momentum Theory that independent to length, size and material (i.e. it's only relevant to mass, *W* but not *L*, *A*, *E* in formula).

3.2 Innovative Pile Driving Formula since 2000

The new application in pile driving using Impact Load Theory was first presented in PDA User's Day 1997, Hong Kong (Wai, 1997) by the Authors. 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 2000 and 2002.

3.2.1 Y-bearing Formula

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 follow:-

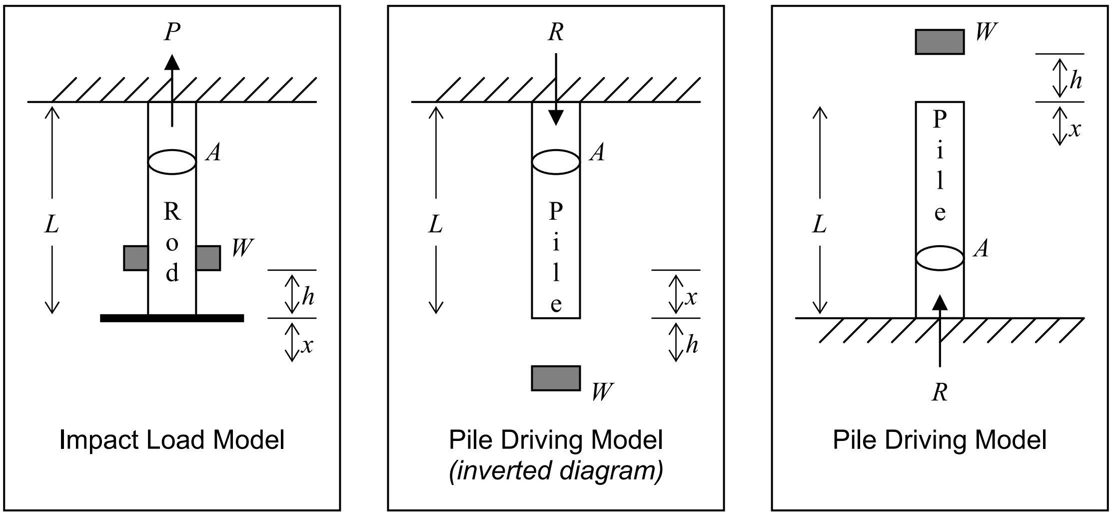
$$P = R = W\left[1 + \sqrt{1 + \frac{2hAE}{WL}}\right] \qquad \text{Formula III}$$

wherein, *P*=impact load on rod (or *R*=end bearing on pile); *W*=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).

In Figure 6(a), 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 (Formula III).

In Figure 6(b), the Impact Load Model has been applied with 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.

Figure 6(c) is the Pile Driving Model based on Impact Load Theory, and the Authors have named it the Y-bearing Method (Wai, 1997).



(a) (b) (c)

Figure 6: Y-Bearing Method derived from Pile Driving Model based on Impact Load Theory

3.2.2 Accuracy of Y-bearing Formula

Y-bearing Formula includes pile physical dimensions of *L*, *A* and *E* to solve the limitations in Hiley Formula as described in previous Section. The Y-bearing results proven have less deviations in wide spectrum of *L*, *A* and *E* compared to Hiley.

3.3 Innovative Pile Driving Technology in ICT 3G-Internet Information Age

Generally, 'site supervision' is the main factor in quality assurance/quality control (QA/QC) in piling constructions. Without proper site supervision, the Designer (or Engineer) is in no way to determine piled foundation integrity prior to the endorsement to proceed with the superstructure. Strictly speaking, we need to emphasis 'who should supervise' and 'how to supervise'.

Who should supervise? The best, of course, the Designer should supervise the piling projects because he/she will be the final person who endorses the piling eventually and liable to the client and public. However this is not an economical practice for a (senior) Designer to supervise the piling in full time.

How to supervise? In current practice of piling construction, generally site supervisors will supervise the piling works. However majority of them are not competent because not well trained and lack of experiences. In many piling works, they could not ensure the piling has been carried out according to the design specifications. Some may have financial problems and grafted. The Designer will visit the piling site time to time or when time is convenient or piling problems arising. The site visit time will reduce proportionally with the increase of traveling time as illustrated in Figure 7. Generally, when supervision is lesser, piling works will have more problems.

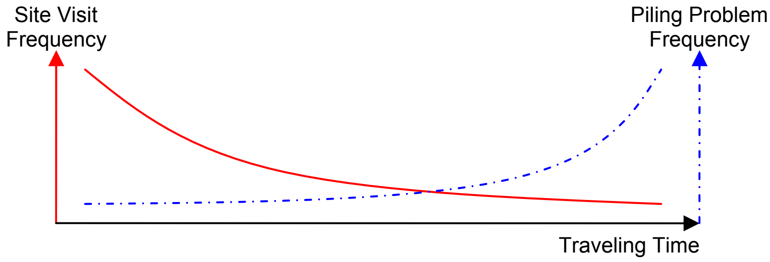


Figure 7: Site Visit and Piling Problem Frequencies versus Traveling Time to Piling Site

Some piling sites which are very remote and far from the design office, the Designer may not visit and witness the piling by his/her own eyes in the whole period of piling works. The Designer only endorses the piling works based on piling records and reports from the site supervisor(s) or junior engineer(s).

Based on the above highlighted aspects, therefore we need an appropriate means to supervise the piling project effectively. The word of 'supervision' shall be elaborated to a higher level called 'management'. Today's high foundation loads and fast track jobs require modern and advance information-communication and technology (ICT) for foundation construction control. The availability of ICT helps reduce piling costs and problems significantly with more effective and efficient piling management.

In construction management, project manager is the person to manage the project. Likewise, a piling works need a piling manager to manage. In this ICT information age with 3G-Internet info-structure, piling practitioners involved in piling projects shall be equipped by state-of-the-art piling management software (PMS) in order for them to manage and supervise the piling professionally as illustrated in Figure 8.

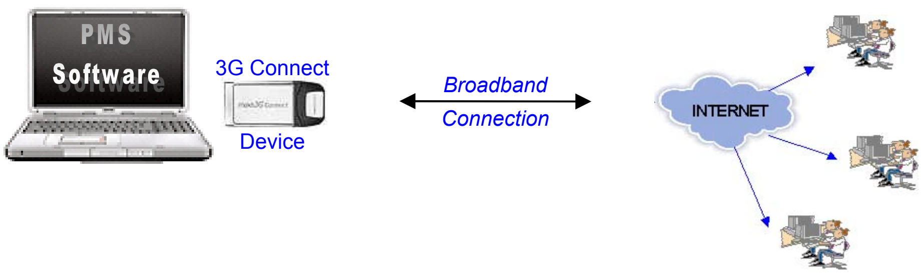


Figure 8: Piling Management Software Connectivity in 3G-Internet Info-Structure

4. CONCLUSION

The pile driving and testing industry has gone through four (4) major development and advancement since centuries till today.

In pile testing, the engineers have used conventional static load test to verify pile capacity. In primitive age, the test only been carried out by putting up the loading on top of the pile element to verify the pile capacity. This is called as static load test (SLT). With the development of technology, this SLT has been modified to innovative constant rate of penetration (CRP) and maintained load test (MLT). Also the setup for static testing also modified from conventional reaction system using kentledge to innovative reaction system using tension piles and cable anchors.

Innovative dynamic pile test (DPT) based on Case Method was developed in 1970. The major advantages of this DPT over the SLT are cost saving, easy setup and to achieve instant results. This DPT method is getting popularity in many countries worldwide presently.

As technology advances and speed of testing becomes and issue, innovative automation static load testing and remote dynamic pile testing systems are developed to minimize undesirable time delays, scheduling problems and delays in reporting process. The pile testing technology towards automation and controlled remotely will become the trend with the popularity of the engineers to adopt information-communication technology (ICT) in their daily operations.

In pile driving, engineers had adopted conventional dynamic pile formula such as Hiley in determining pile driving criteria since 1930. This formula was derived based on Impulse-Momentum Theory and is widely used. However, this formula has limitation in its application because it does not include physical dimensions on pile for pile length, *L*, pile size (or area), *A*, and pile material (i.e. Young's modulus), *E*. With all the variations in *L*, *A* and *E*, Hiley Formula has greater deviations when pile become longer (*L*), bigger (*A*) with different material (*E*).

In year 2000, an innovative pile driving method based on Impact Load Theory was proposed to improve the accuracy of pile driving. 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. This formula includes parameters of *L*, *A* and *E* to solve the limitations in Hiley Formula. The Y-bearing results proven have less deviations in wide spectrum of *L*, *A* and *E* compared to Hiley.

Today's high foundation loads and fast track jobs required modern and advance information-communication technology (ICT) for foundation construction control. In this ICT information age with 3G-Internet info-structure, the piling practitioners involved in piling projects shall be equipped by state-of-the-art piling management software (PMS) in order for them to manage and supervise the piling works professionally and to reduce piling costs significantly.

As piling is a science and engineering, consistent research shall be carried out so that more innovative methods can be developed to improve the quality of piling and to fit the industry in multimedia value chain in ICT 3G-Internet information age.

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