22 YEARS EXPERIENCES IN HIGH-STRAIN WAVE ANALYSIS AND GUIDELINES

Yekong, Wai [1]

ABSTRACT: The author of this technical paper has 22 years in dynamic pile analysis using high-strain wave analysis program (HSWAP), either well-known CAPWAP™ or ASIAWAP™. From the analysis experience and reviewed of many other analysis carried out by others worldwide, the author developed some guidelines to interpret the HSWAP analysis results easily. Some important guidelines are what is the suitable ram weight and ram stroke, proper placement of gauges, proper pile head preparation, proper pile set measurement, minimum hammer blows, minimum analysis event, velocity limit at impact, skin frictional distribution envelops, invalid analysis for those pile that is very long and velocity rebound before 0.5L/c, instability analysis, contradiction of pile integrity based on β-Value and pile modeling and etc. All these guidelines enable the analysis engineers to produce reliable analysis results and to guide engineers to interpret test results correctly.

Keywords: pile test, load test, static pile test, dynamic pile test, wave analysis, wap analysis, CAPWAP, ASIAWAP

DYNAMIC PILE TESTING INDUSTRY

For the last two (2) decades, dynamic pile testing based on high-strain method (HS) has become very popular worldwide. There are many project sites from small to medium scales have been applied HS method almost 100% to replace static pile load test (SL). Due to the popularity of HS testing, there are many testing service providers established to support the pile testing markets worldwide.

However, in reality, dynamic pile testing based on wave mechanics theory is not easy to be understood. It has two (2) significant technical drawbacks:-

- Very theoretical and lengthy derivation based on wave mechanics theory
- Require strong knowledge in mathematics to understand the theory

Both drawbacks are the main obstacles for engineers to analyze and interpret HS results professionally and correctly.

Due to the problems in understanding the HS theory and piling technology, from the courses and trainings given by the Authors and others revealed that the failure rate is very high in written examinations after the courses and trainings. It is recommended that the HS analysis shall be analyzed by analysis engineers who pass the examinations in advance level and above accredited by recognized organizations.

THE 22 YEARS EXPERIENCES AND HISTORY

The Author graduated from University of Technology, Malaysia (UTM) in 1991 with an honors degree in Civil Engineering. He choose to remain in UTM after 1991 as a research officer to conduct research in the subject of his passion, piling and dwelled into the complexities of dynamic pile testing based on high-strain and low-strain methods in determining the pile bearing capacity and pile integrity.

The Author served few pile testing firms as pile testing engineer after UTM in the year 1994. Apart from daily pile design and testing services, he also involved aggressively in R&D to develop better technology for pile driving and testing. The remarkable breakthrough in R&D was recognized in the year 2000 and 2002 with two (2) patents granted by the US Patent and Trademark Office (USPTO), a 3rd revolutionary technology in the world of pile driving and testing.

In year 2004, the Author became a certified HS analysis engineer in advance level accredited by Deep Foundations Institute (DFI), USA.

In year 2006, the Author aggressively involved in upgrading and enhancing the dynamic pile testing instruments with Rock & Soil Mechanics trademark (RSM™).

In year 2008, the Author became co-project leader to publish HS analysis software with Asia Wave Analysis Program trademark (ASIAWAP™).

[1] International Technical Chief, PT Geoindo Technostar, Jakarta, INDONESIA

In year 2012, the Author became the technical advisor to upgrade and enhance the bi-directional static pile load testing with YJack trademark (YJack^{TM}).

In year 2013, the Author visited the manufacturer who producing the radar testing instruments for checking the pile base conditions of bored piles. This is the latest technology in pile testing.

Since graduating, in 22 years, the Authors tested thousands of pile on site using the HS dynamic method and analyzed more than 25 thousand HS analysis on the following pile types:

- 125 to 550mm diameter reinforced concrete piles
- 250 to 1200mm diameter spun concrete piles
- 40 to 3000mm diameter steel or offshore piles
- 200 to 2000mm cast in-situ piles

From those 25 thousand analysis results, only less than 150 analysis results need to be reviewed or rejected.

ACCURACY OF HS METHOD

There are many technical papers published worldwide in various international seminars and conferences given high gratitude to HS method and provide many case studies to highlight its accuracy. Only few published papers indicated in-accurate of HS method.

In reality, does the HS method as accurate as many people claim? From the Author's experience, the answer is, it may or may not. There are many cases that the error range could as high as few hundred percent over-predicted the actual pile bearing capacities.

Basically, there are four (4) main key factors that contribute in-accurate of HS method:

(1) Improper analysis of test data just by using auto-matching technics. The analysis software program can perform auto-matching analysis. However, the results always not accurate. Manual analysis always required in producing accurate results.
(2) Improper analysis by junior analysis engineer by using wrong parameters and wrong engineering judgment due to their technical competency.
(3) Improper placement of the gauges at the pile head especially for cast in-situ piles with bad pile head conditions. In many cases, the gauges placements on large cast in-situ piles do not comply with ASTM D4945 and other international standards.
(4) Invalid of Case Method in some cases with damping larger than 1.0. Due to the mystery of case damping larger than 1.0, many engineers will do an analysis by matching with damping less than 1.0. In this case, the analysis results will over-predicted the pile bearing capacities extremely high.

TECHNICAL KNOW-HOW TO DO ANALYSIS

For pile driving and testing industry, it has been gone through four (4) major development (Wai, 2006), i.e.:-.

- Development 1: pile as rigid body
- Development 2: impulse-momentum theory (1930s)
- Development 3: wave mechanics theory (1960s)
- Development 4: impact load theory (2000s)

In science and engineering, there are limitations and drawbacks on any theories, methods and formulas. By fully understanding the theory in modern piling in Development 1 to 4, an engineer can become a HS analysis engineer competently.

The R&D carried out by the Author in impact load theory in pile driving and its compatibility study compared to Hiley and Case Methods (Wai 2006) enabled the Author understand the pile driving theory competently. In addition, thousands of pile testing at site enabled the Author ascertained pile driving behavior.

The technical know-how of the Author has mainly come from literature study, R&D, analysis and testing.

With the strong technical know-how, the Author developed some important guidelines to carry out HS wave analysis as described in the following sections.

DON'T AND TO REJECT HS TESTING DATA

In HS testing and data measurement, the test data for the following conditions may not appropriate and may need to be rejected.

Otherwise, the test data shall be reviewed by a HS analysis engineer with certification in advance level and above accredited by recognized organizations.

A1: Suitable Ram Weight and Ram Stroke

There are many literatures and technical papers recommended following ram weight to carry out HS testing:

- Minimum ram weight > 1% of the pile bearing capacity (in ultimate) to be tested
- No restrictions on ram weight against pile weight

From Author's various testing and analysis experiences, the above recommendation is insufficient to cover all kinds of pile testing on various pile types (from short to long and small to large piles).

The following ram weight and ram stroke conditions shall be complied to ensure correctness in HS testing and analysis:

a) For concrete piles

- Minimum ram weight > 1.5% of the pile bearing capacity (in ultimate) to be tested, or
- Minimum ram weight > 1/3 (33%) of the pile weight, and

- Maximum ram stroke < 2.0m drop height

b) For steel piles

- Minimum ram weight > 1.5% of the pile bearing capacity (in ultimate) to be tested, or
- Minimum ram weight > 1/2 (50%) of the pile weight, and
- Maximum ram stroke < 3.0m drop height

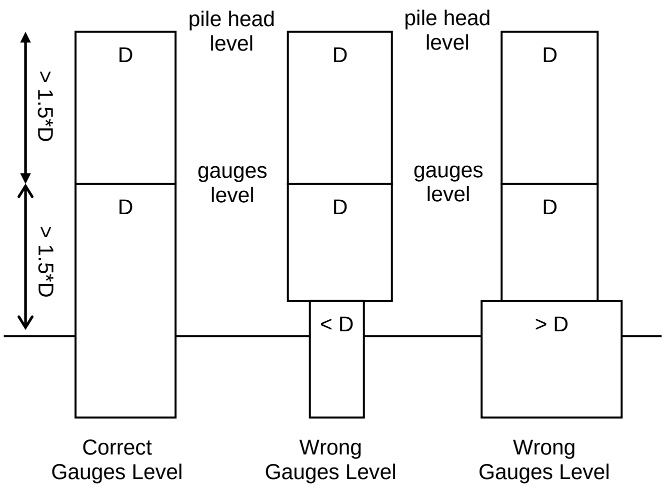
The large ram weight with small ram stroke is the best option to acquire good HS test data and tend to mobilize the pile bearing capacities. Any test data do not comply with the above condition shall be rejected.

<u>A2: Proper Placement of Gauges</u>

The ASTM D4945 (the 1st international standard to describe the HS test method) recommended the gauges shall be placed below the pile head at location minimum 1.5*D (pile diameter or pile width for square piles).

In addition to the above conditions, the pile size (i.e. pile area) from gauges level to 1.5*D below gauges level shall be uniform and the material shall be consistent to avoid early HS signal reflections due to impedance changes. For spliced pile with joint, if there is a joint reflection detected, then it is better to place gauges as far as from the joint.

The following diagram to ensure correctness to place gauges in HS testing and analysis:



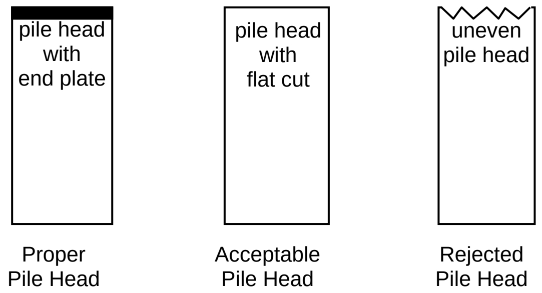
Any test data with improper gauges placement shall be rejected.

<u>A3: Proper Pile Head Preparation</u>

For driven piles, most of the piles do not require any pile head preparation. However for cast in-situ piles, pile head shall be prepared properly in order to collect acceptable and good HS data quality.

a) For driven concrete piles

For concrete or spun concrete piles, the pile head shall be flat with end plate connected. For pile without end plate, the pile head shall be prepared by using a diamond cutter to cut the pile head to get the flat head.



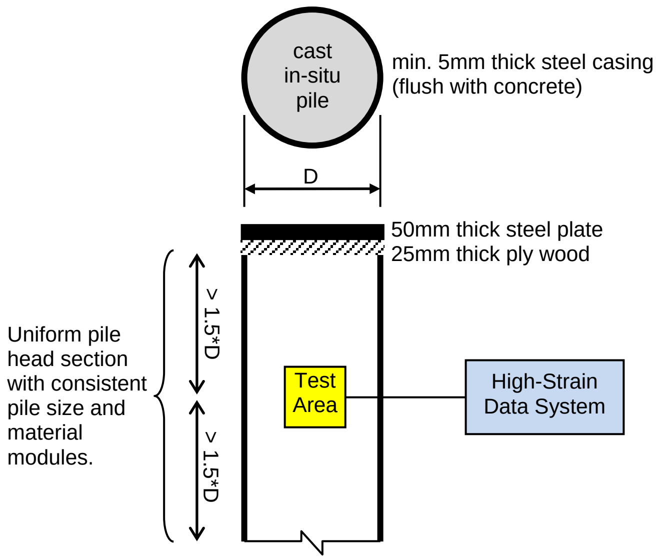
The pile head with end plate can sustain multiple blows during collecting HS data. This is the best option.

For pile head with flat cut using diamond cutter, it may sustain few blows. However, care shall be taken during hammer blows because the pile head may break anytime and data collected may be bad and sometimes even accident occur and injure the testing personnel.

For uneven pile head, from the Author's testing experience, most of the time, it may only sustain one (1) blow and break. The data quality collected is bad normally. This pile head condition shall be rejected.

b) For cast in-situ piles

For cast in-situ pile especially bored pile, the pile head shall be properly prepared with casing as illustrated below.



Test Area for cast in-situ bored pile or micropile:

200X200mm windows on the opposite sides of the pile have to be open to reach the concrete surface (solid and smooth) for gauge placement

Test Area for cast in-situ micropile with API pipe:

No window is needed but the API pipe should be exposed

Note:

The built up pile head shall be able to sustain the lateral load during impact to avoid pile head break

For cast in-situ bored pile without casing, in general, the concrete surface to be attached gauges is not smooth and contaminated with soil. Hence data collected is bad.

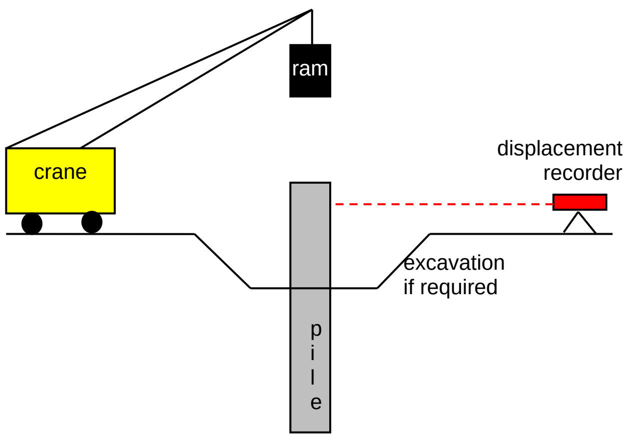
In addition, the cast in-situ bored pile without casing will not have the consistent pile size to ensure good and acceptable HS data collected. Hence cast in-situ bored pile without casing to build-up the pile head shall be rejected.

A4: Proper Pile Set Measurement

Pile permanent displacement after hammer blows (i.e. pile set) is an important parameter in determination of pile bearing capacities for driving piles. HS testing carried out on cast in-situ piles which are subjected to hammer blows will be considered as pile driving piles.

Manual pile set measurement shall be rejected for HS testing. However, the manual pile set measurement by using a pencil to draw on graph paper is good for piling record documentation and to measure temporary compression values.

The pile set measurement shall be measured by displacement recorder such as theodolite or leveling device with accuracy up to 0.5mm reading as the pile measurement setup illustrated below.



A5: Minimum Hammer Blows

In theory, only one (1) blow is required to collect HS data. But in testing, we need to comply to test repetitiveness requirement to ascertain the test data. Hence we need to collect minimum two (2) HS test data to confirm data quality. And subsequently, select one (1) blow data for analysis.

For any test, which purposely to test one (1) blow test data, the test data shall be rejected.

DON'T AND TO REJECT HS ANALYSIS RESULTS

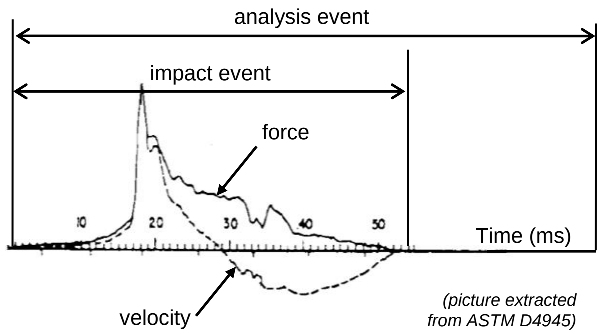
In HS analysis using any high-strain wave analysis program (HSWAP) in the market, the test results for the following conditions shall be rejected.

Otherwise, the test results shall be reviewed by a HS analysis engineer with certification in advance level and above accredited by recognized organizations.

B1: Minimum Analysis Event

In most of the signal conditions, the analysis event (i.e. analysis time frame) of 80ms is appropriate. But for extremely long piles, 80ms analysis event may be too short for analysis.

The minimum analysis event shall be 80ms, or 20*L/c (in which, L: pile length; c: wave speed) which is higher. The maximum analysis event shall be dependent to the maximum time frame for the HS data to be recorded. In general, most of the HS data system only measures HS data up to 200ms.



B2: Velocity Limit at Impact

From the Author's analysis experience, the following table for maximum velocity at impact shall not exceed the values as tabulated below if the HS testing has been carried out according to sub-sections (A1), (A2) & (A3).

Maximum velocity at impact vs. various pile types:				
Reinforced Concrete (≈35MPa)	Reinforced Concrete (≈45MPa)	Spun Concrete (≈60MPa)	Spun Concrete (≈80MPa)	Steel Piles (pipe/box)
< 1.8m/s	< 2.0m/s	< 2.2m/s	< 2.5m/s	< 3.5m/s

Any test with maximum velocity at impact larger than the above values, it means that the hammer used to test HS is relatively too small and hardly to mobilize the pile bearing capacity.

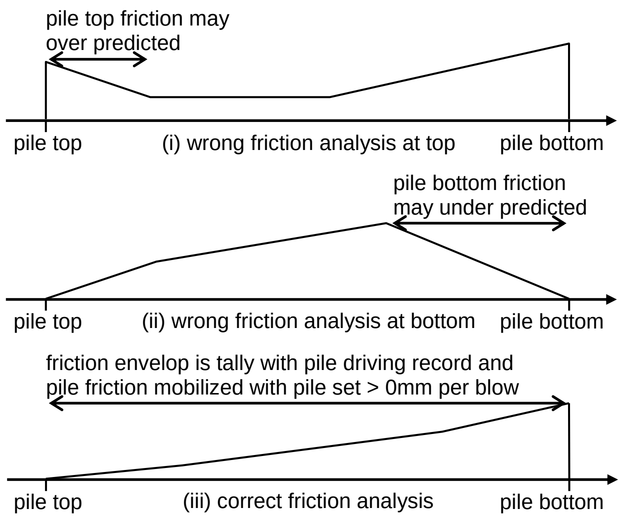
For other cases, the high velocity at impact is due to the bad data quality or data manipulations by the analysis engineer.

Hence any test results with velocity exceeds the above values shall be rejected.

B3: Skin Frictional Distribution Envelop

The skin frictional distribution is the main parameters in high-strain wave analysis. The signal can be matched perfectly with any skin friction values. However, the good match does not mean the skin friction is correct in the analysis.

The following skin friction distribution envelop shall be rejected if the friction it is not tally with pile driving records (or bore-hole records).

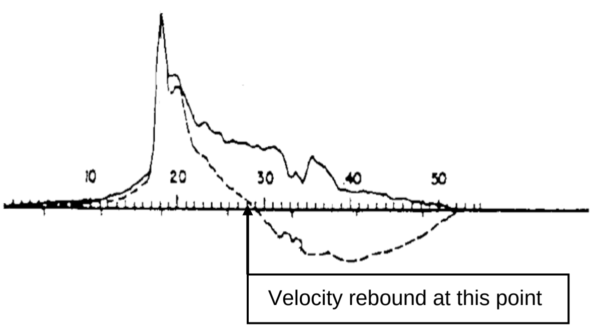


The skin friction distribution envelop type (ii) may valid if the pile is relatively long with high friction that the hammer is insufficient to mobilize the pile with pile set approximately 0mm per blow.

Any unreasonable skin frictional distribution result shall be rejected.

<u>B4: Invalid Analysis for V Rebound Before 0.5*L/c</u>

In many cases for those HS testing using relatively small hammer and the pile is relatively long that the velocity V-signal rebound too early before 0.5*L/c, the analysis is not valid (in which, L: pile length; c: wave speed).



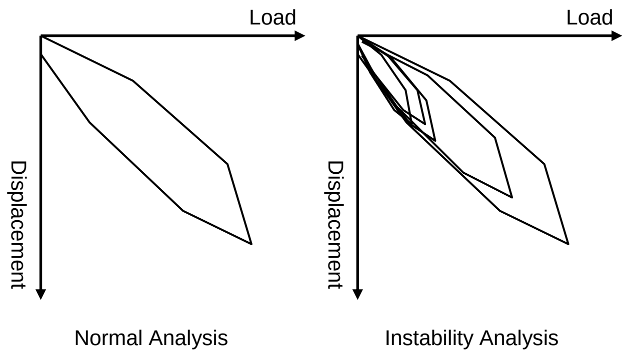
(1) If velocity rebound > 2*L/c, analysis is easy
(2) If velocity rebound > 1*L/c but < 2*L/c, analysis is difficult
(3) If velocity rebound > 0.5*L/c but < 1*L/c, analysis may wrong
(4) If velocity rebound < 0.5*L/c, analysis is invalid

For condition (1), the analysis can be carried out by an analysis engineer with junior level. For condition (2) and (3), the analysis shall be carried out by an analysis engineer with advanced level. For condition (4), the analysis shall be rejected.

<u>B5: Instability Analysis</u>

In reviewing of many analysis carried out by others, The Author's found that the analysis is carried out wrongly with wrong parameters. The obvious wrong analysis is instability analysis. In wave analysis, instability will occur if some parameters are divided by the null value (i.e. zero).

The following HS simulated load~displacement diagram illustrates the instability analysis results.



Any instability results shall be rejected.

<u>B6: Contradiction of β-Value with Pile Modeling</u>

There are many reports still adopting beta β-value in confirmation of pile integrity based on HS method. In modern HS testing and analysis, adopting of β-value in determination of pile integrity is inappropriate. This is because the formula derivation of β-value is simple with various assumptions. Furthermore, the β-value is a qualitative value. It is not a quantitative value to justify pile integrity. 90% β-value does not mean that the pile is with better integrity than a pile with 60% β-value.

In the past, due to the cost of HS analysis is relatively expensive, hence the industry adoption of β-value in determination the pile integrity. At that time, it may conduct 10*No HS tests, but only select 2*No to do HS analysis. Hence the rest of 8*No HS tests will base on β-value in determination of pile integrity.

In modern HS testing, any HS test report reported β-value less than 100% but if there is no pile modeling has been carried out in HS analysis, the report shall be rejected because the pile integrity with β-value (in Case method) and pile modeling (in WAP method) is contradiction in pile integrity results.

Therefore, in modern testing and reporting, all the analysis performed by the Author will only report pile integrity based on the HS analysis method.

The β-value is only useful as a guideline in determining of pile integrity during HS monitoring tests for blow to blow impacts. If the β-value reduces in blow to blow impacts, then there is possibility some integrity problems occurring in the pile during monitoring.

The following table is the guidelines to report pile integrity results with pile modeling using HSWAP analysis.

Integrity Class & Acceptability	HSWAP Pile modeling
Class I: Pile Integrity Intact	No modeling required; OR model with no reduction in pile area for cast-in-situ pile; OR minor joint modeling for splice-jointed driven pile.
Class II: Pile Integrity Acceptable	Minor pile modeling with reduction in pile area but does not affect the long term structural load; OR moderate joint modeling for splice-jointed driven pile.
Class III: Pile Integrity Damaged	Moderate pile modeling with reduction in pile area and may reduce long term structural load; OR use short pile intact length in analysis, but the end bearing load shall be ignored in long term design consideration; OR significant joint modeling for splice-jointed driven pile.
Class IV: Pile Integrity Broken	Significant velocity reflection prior to toe and confirmed pile integrity problem with/without modeling and the pile shall be totally rejected and replaced.

Any test results with contradiction pile integrity results shall be rejected.

CONCLUSION

There are many international and national standards published for the HS test method. Such published standards fully described the proper procedures and requirements to conduct HS testing and analysis correctly.

This technical paper does not mean to object the contents as described in the published standards. It's only elaborates some technical issues in which the published standards did not describe in the contents.

The Author only makes some guidelines for engineers to reject the HS test data and analysis results. Such guidelines are based on Author's 22 years experiences in HS testing and analysis. Those guidelines only serve as additional technical aspects other than published standards that the engineers shall be considered during applying the HS method.

The Author welcomes and encourages the worldwide researchers to comment this technical paper. And hopefully, the new standards will cover some guidelines for engineers to accept and reject the HS data and analysis results more easily and professionally.

Finally, the Author urges the engineers to prepare the bill of quantity in the tender documents to fully describe the test requirements in conducting HS testing especially for those as described in sub-sections (A1) to (A5).

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