

## Measurement of Strain Distribution Along Precast Driven Pile During Pile Load Test

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**ABSTRACT:** One of the basic parameters required for forecasting pile deformation under loads is the characteristics and profile of the shaft load transfer from the pile to the surrounding soil. This parameter can be obtained by measuring the strain distribution along the pile during full-scale pile load test. For cast-in situ bored pile, the strain measurement can be easily done by fixing the sensors to the reinforcement cage before pouring the concrete. For precast driven / jack-in piles, the application of instrumented full-scale static load tests is far more challenging than their bored pile counterparts due to significant difference in method of pile installation. Due to practical shortcoming of conventional instrumentation method instrumented full-scale static load tests are in fact rarely used in driven pile application in this region. For hollow precast spun concrete piles attempts have been made by geotechnical engineers to measure the strain distribution by installing either an instrumented reinforcement cage or instrumented pipe into the hollow core of spun piles followed by cement grout. However in this method, known as approximate method, the measured characteristics cannot be considered to represent the working piles because the presence of reinforcement/pipe and the grout would alter the stiffness of the test pile. In this paper a method to measure the strain distribution along the installed precast spun concrete pile during full-scale pile load test is described. The method utilizes the hollow core of the spun pile without changing the physical properties e.g. stiffness, of the pile. The main advantages of this method are: the measurement can be done at any location along the pile, the sensors can be retrieved and the measured characteristics are representative of those of the working piles.

Keywords: pile, ultimate capacity, instrumentation, spring-loaded transducer

### 1. INTRODUCTION

The high strength prestressed spun concrete piles, commonly driven with hydraulic impact hammers or preferably installed with jacked-in rigs when considering the stricter regulations with respect to noise and vibrations in more urban areas, often offer a competitive choice of foundation system for projects with medium and high loadings. They are widely used in foundations for schools, high-rise buildings, factories, ports, bridges and power plants in this region.

In early years, the main construction control for driven piles was mostly based on the measurement of set of each pile coupled with a selected small number of non-instrumented static load tests to verify the specified load-settlement requirements.

In recent years, with critical evolution in the understanding of the load transfer and bearing behaviour of piles mainly through analysis of instrumented full-scale load tests (particularly for bored cast-in-place piles), many engineers can now appreciate that the pile performance is not simply a matter of ultimate load value alone. According to Fleming [1][2] some of the basic parameters required for forecasting pile deformation under loads include (a) Ultimate shaft load and its characteristics of transformation to the ground; (b) Ultimate base load; (c) Stiffness of the soil below the pile base; (d) Pile dimensions; and (e) Stiffness of the pile material. This recent development in the understanding of the load transfer and bearing behaviour of piles in fact exerted a significant and positive influence on the evolution of codes of practice and design methods for foundations in some countries. For example, the revised Singapore

Standard on Code of Practice for Foundations CP4: 2003[3], recommends that the static load test on preliminary test pile be instrumented to measure the transfer of load from the pile shaft and pile toe to the soil. The Code also recommends that for driven piles (similar to bored cast-in-place piles), the axial load capacity can be evaluated empirically from correlation with standard penetration tests SPT N-values (which are widely used in this region) using modified Meyerhof Equation, where the ultimate bearing capacity of a pile in compression is given by:

$$Q_u = K_s * N_s * A_s + K_b * (40N_b) * A_b \quad (1)$$

where:

$Q_u$  = ultimate bearing capacity of the pile, kN,

$K_s$  = empirical design factor relating ultimate shaft load to SPT values, kN/ m<sup>2</sup> per SPT blow,

$N_s$  = SPT value for the pile shaft, blows/300mm,

$A_s$  = perimeter area of the shaft, m<sup>2</sup>,

$K_b$  = empirical design factor relating ultimate end bearing load to SPT values, kN/ m<sup>2</sup> per SPT blow,

$N_b$  = SPT value for the pile base, blows/300mm, and

$A_b$  = cross-sectional area of the pile base, m<sup>2</sup>.

For bored piles, instrumentation using sacrificial cast-in vibrating wire strain gauges and mechanical tell-tales which permit for monitoring of axial loads and movements at various levels down the pile shaft including the pile toe level had been practiced successfully within limits of accuracy posed by constraints inherent of the installation method, in this region for many decades, allowing insight evaluation of  $K_s$  and  $K_b$  factors, including well documented history of "The Design of Foundations for Suntec City, Singapore" [4][5]. Recent use of Global Strain

Extensometers (Glostrex) Method for bored piles in this region [6][7] also provides an excellent alternative means for similar purpose, but with the capability of producing a more reliable performance and accurate results. For precast driven piles, the application of instrumented full-scale static load tests is far more challenging than their bored pile counterparts due to significant difference in method of pile installation. Due to practical shortcoming of conventional instrumentation method and the lack of innovation in this area, instrumented full-scale static load tests are in fact rarely used in driven pile application in this region. Therefore, the far lacking driven pile industry is long due for a better technology to revolutionize the methodology in the acquisition of design data in a more accurate and reliable way, to catch up with the evolution in the design methods.

## 2. CURRENT METHODS OF PILE INSTRUMENTATION

### 2.1 Conventional Instrumentation Method

A conventional instrumentation scheme for spun pile static load testing is shown in Fig. 1. The method involves incorporating high temperature-resistant strain gauges into the heat-cured production process of prestressed spun concrete piles.

This method is extremely unpopular and difficult to be routinely applied in project sites due to the following constraints:

- High cost of these temperature-resistant strain gauges;
- Tremendous difficulties involved in coordinating the installation of the strain gauges into pile segments;
- Long lead-time is normally required for instrumentation works, as the instruments have to be pre-assembled and installed onto the high strength prestressing bar cage prior to heat-cured 'spin-cast' production process of the piles; and
- Great uncertainty over the ability of the delicate instruments to withstand the stresses arising from pile production and driving processes.

### 2.2 Approximate Instrumentation Method

Due to the difficulties of using the conventional method, the engineering community for spun pile industry has been using an approximate instrumentation method for the past few decades, by installing either an instrumented reinforcement cage or an instrumented pipe, into the hollow core of spun piles followed by cement grout infilling (Fig. 2(a)).

As this approximate method is comparatively more "convenient" to be implemented than the conventional method, it was widely practiced in this region for the past few decades. Some contract specifications also ask for the inclusion of conventional sleeved rod extensometers (depending on the space available) to monitor the pile shortening reading during the static load tests. Either using an instrumented reinforcement cage or an instrumented pipe, with or without the added-in sleeved rod extensometers, the end product after the cement grout infilling is more towards a solid pile, as shown in Fig. 2(b). Therefore the obvious shortcomings of this approximate method include:

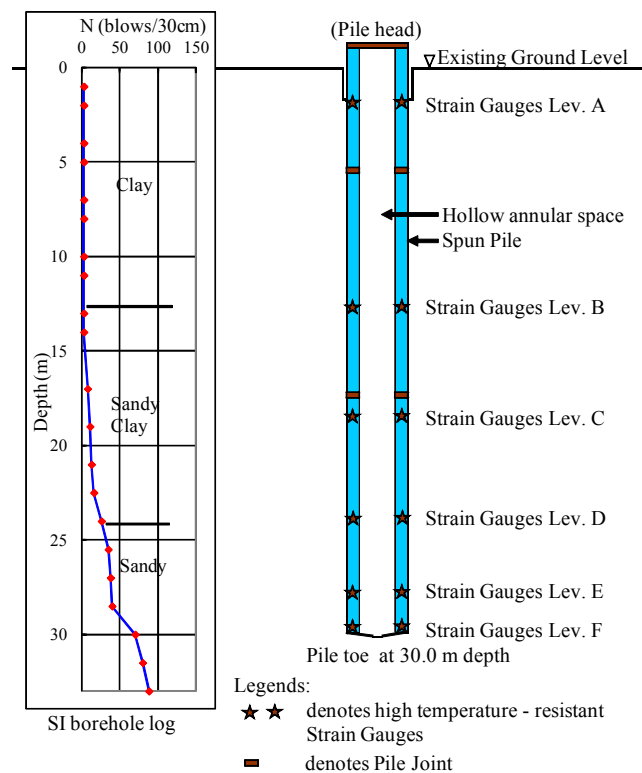


Fig.1 Diagrammatic illustration of conventional spun pile instrumentation scheme

- The infilling of cement grout substantially alters the structural properties of the piles, thus rendering them significantly different from the actual working spun piles, which are usually not grouted internally;
- The presence of the grout would change the overall stiffness of the pile and therefore the measured load distribution along the pile would be different under the applied loading.
- Structural shortening measurement of the test piles are not representative of the actual working piles;
- Structural integrity of the original pile cannot be reliably ascertained, particularly performance of pile joints, during the static load test as the stiffness of the pile has been altered; and
- Significant time loss due to grout infilling and curing process, beside the environmental unfriendly nature of this method.

## 3. RECENTLY DEVELOPED INSTRUMENTATION

To address the challenges and difficulties posed by the conventional and approximate methods, Global Strain Extensometer technology for spun piles had been developed, improved and field tested.

In order to meet the requirements for practical instrumentation application on spun piles, the desired characteristics for the retrievable pneumatically anchored extensometer system were identified as follow:

- To utilize the hollow core of spun piles (or cylinder concrete piles) as an ideal recess means for instrumentation purpose, generally the system shall be designed for clamping to internal side wall of spun piles;

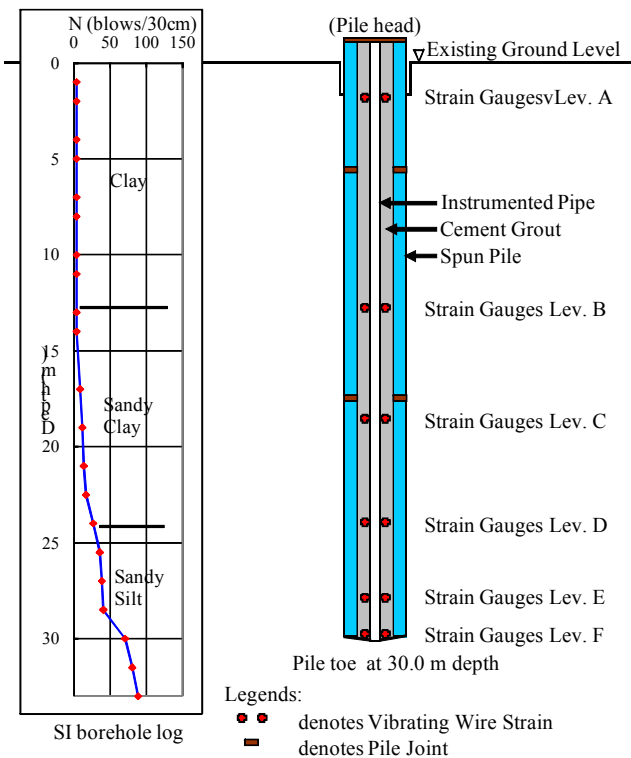


Fig.2(a) Diagrammatic illustration of approximate spun pile instrumentation method

Cement Grout Infill (Usually Grade 25)

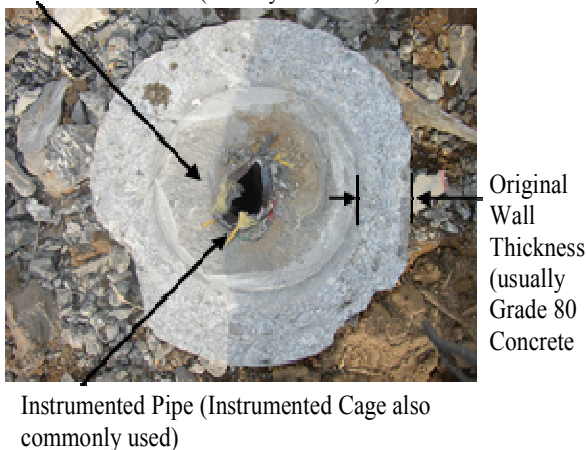


Fig. 2(b) - Section of instrumented spun pile after cement grout infilling in Approximate Method

- (ii) In use, the system shall be able to be pneumatically actuated and control remotely above the ground and the series of anchors in access hole shall be able to be connected by means of interconnecting rods.
- (iii) The system shall be designed to be retrievable from the access hole, with allowance for eight retractable pistons per anchor.
- (iv) The anchor shall be able to be clamped to the side wall by at least 300 psi pressure.
- (v) Materials : Stainless steel or copper.
- (vi) The series of anchors in access hole shall have allowance for connecting to precision transducer sensor by means of fittings that grip the interconnecting rods.

The concept of using hollow core of spun piles (or cylinder concrete piles) as recess means for retrievable instrumentation approach was then reviewed and re-examined, leading to suggested ideal arrangement of retrievable instrumentation approach as shown in Figures 3(a),(b) , (c) & (d).

### 3.1 Description of the State-of-the-Art Global Strain Extensometer technology

The technology consists of a deformation monitoring system that uses advanced pneumatically-or hydraulically-anchored extensometers coupled with high-precision spring-loaded transducers, and a novel analytical technique to monitor loads and displacements down the shaft and at the toe of foundation piles. This method is particularly useful for monitoring pile performance and optimizing pile foundation design. To appreciate the innovation contained in the technology, the basic deformation measurement in the pile by strain gauges and tell-tale extensometers are reviewed. Normally, strain gauges (typically short gauge length) are used for strain measurement at a particular level or spot, while tell-tale extensometers (typically long sleeved rod length) are used purely for shortening measurement over an interval (over a length between two levels). From a 'strain measurement' point of view, the strain gauge gives strain measurement over a very short gauge length while the tell-tale extensometer gives strain measurement over a very long gauge length! Tell-tale extensometer that measure strain over a very long gauge length may be viewed as a very large strain gauge or simply called Global Strain Extensometer. With recent advancement in the manufacturing of high-precision spring-loaded vibrating-wire sensors, it is now possible to measure strain deformation over the entire length of piles in segments with ease during static load testing.

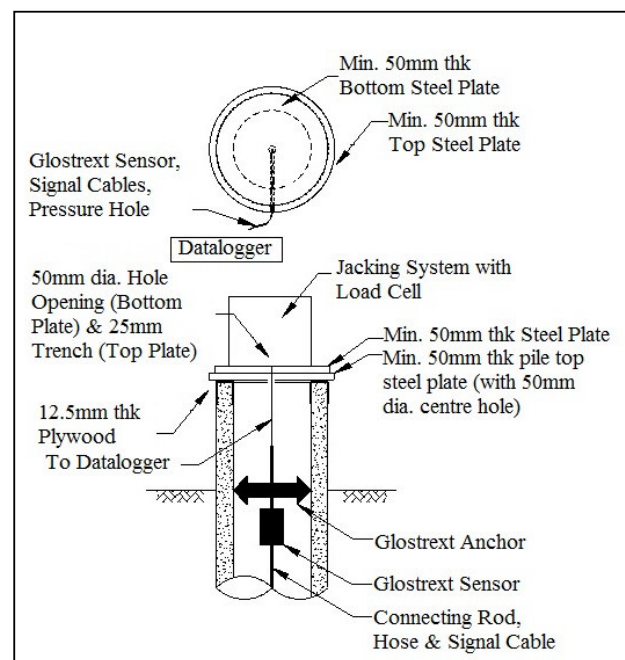


Fig.3(a) Arrangement of retrievable instrumentation approach for typical spun pile instrumentation application.

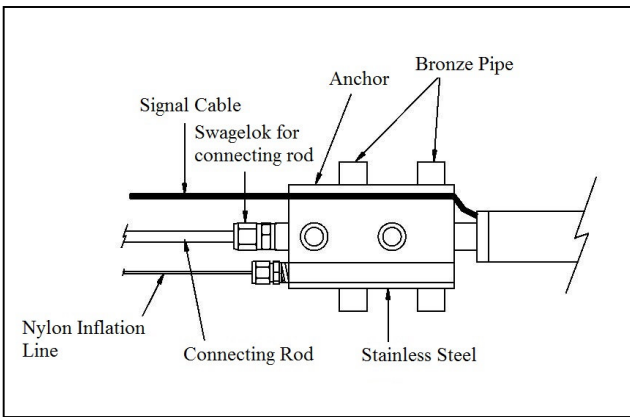


Fig.3(b) Design for retrievable pneumatic extensometer anchors and transducer system

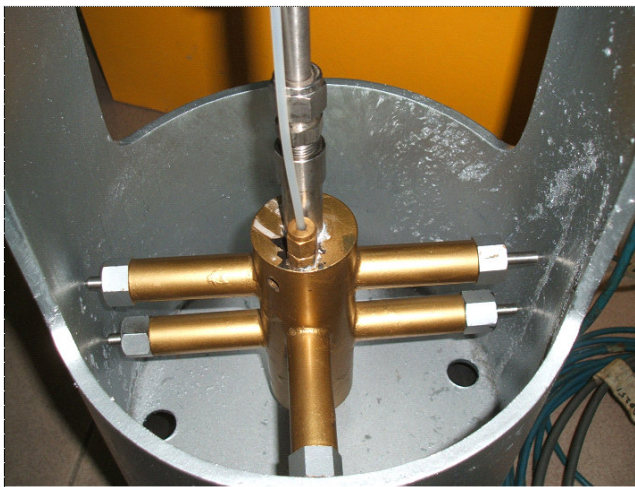


Fig.3(c) Completed improved prototype for application



Fig.3(d) Actual Global Strain Extensometer system for spun pile application

Fig. 4 shows a schematic spun pile instrumentation diagram using Global Strain Extensometer technology. This system is equivalent to the conventional method of using 24 no. strain gauges and 6 no. sleeved rod extensometers, which might not be possible to be installed satisfactorily due to congestion in the spun piles.

For the analysis of test data for spun piles using Global Strain Extensometer technology, the load distribution can be computed from the measured changes in global strain

gauge readings and pile properties (cross-section area of spun pile and concrete modulus). Load transferred ( $P_{ave}$ ) at mid-point of each anchored interval can be calculated as:

$$P_{ave} = \varepsilon(E_c A_c) \quad (2)$$

where,

$\varepsilon$  = average change in global strain gauge readings;

$A_c$  = cross-sectional area of spun pile section;

$E_c$  = concrete secant modulus in pile section.

With the instrumentation set-up as described in Fig. 4, the state-of-the-art Global Strain Extensometers system is able to measure shortening and strains over an entire section of the test pile during each loading steps of a typical static pile load test, thus it integrates the strain over a larger and more representative sample.

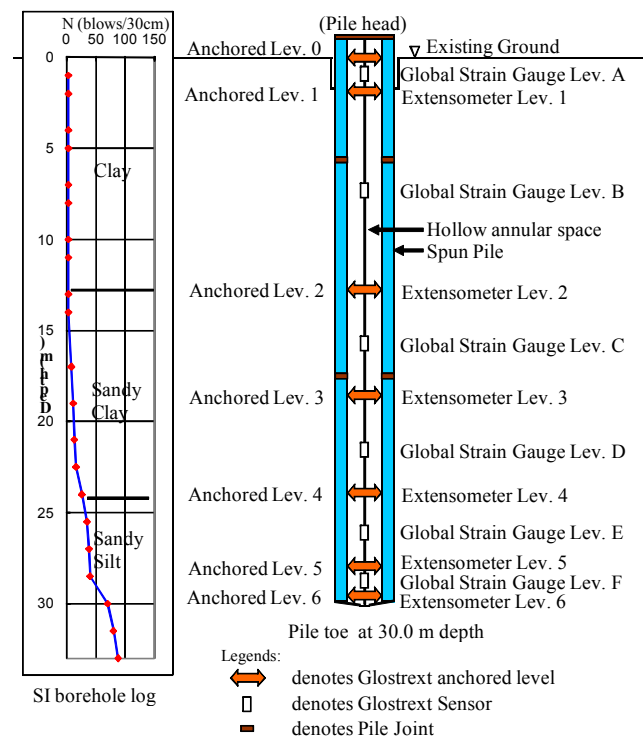


Fig.4 Schematic diagram of typical instrumented spun pile using Global Strain Extensometer technology

### 3.2 Verification of the Global Strain Extensometer System

For the purpose of verification of the Global Strain Extensometer system, a special and detailed laboratory testing programme consisting of a series of full-scale tests on spun pile sections of various sizes has been implemented. The tests were carried out and completed in the laboratory, incorporating Global Strain Extensometer instrumentation technique alongside with and against well proven vibrating wire strain gauges systems in the test sections.

The instrumented spun pile sections were tested by the normal Maintained Load (ML) Method, using hydraulic jack and high strength stress bar system. In the typical set-up used, the test loads were applied using 1 no. hydraulic jack (1,000 tonnes capacity) acting against the

main beam connected by high strength stress bar system . The jack was operated by an electric pump. The applied loads were indicated by calibrated vibrating wire load cell. To obtain good quality data, all instruments readings were logged automatic using Micro-10x datalogger, at 1 to 2 minutes interval for close monitoring during loading and unloading steps. The detailed test set-up, pile instrumentation comparison schemes adopted (using Global Strain Extensometer technique and strain gauges systems) and test data acquisition systems for verification load testing programmes are as shown in Figure 5.

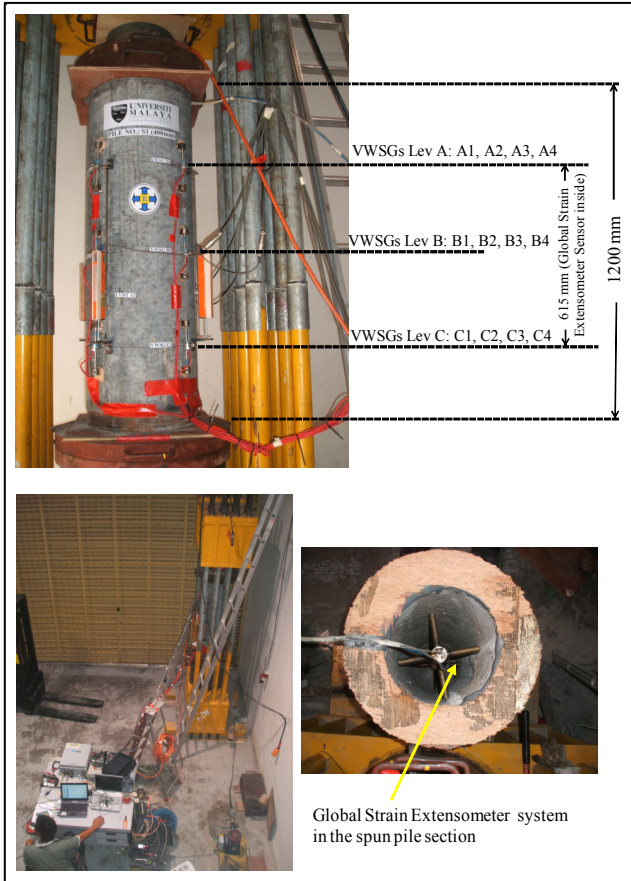


Fig.5 Instrumentation Details and Test Setup.

For a typical spun pile section, the test results for Pile Top Loads Versus Change in Strain measured by both Global Strain Extensometer Technology and Average of 12 no. Vibrating Wire Strain Gauges at Levels A, B and C are shown in Figure 6 and , plot of Pile Top Load & Change in Strain Versus Time for both Global Strain Extensometer Technology and Average of 12 no. Vibrating Wire Strain Gauges at Levels A, B and C are shown in Figure 7.

Based on the results obtained from the laboratory tests it can be concluded that the axial strains measured by the two independent systems (conventional vibrating wire strain gauges and Global Strain Extensometers technique) show very similar characteristics and therefore in good agreement.

The Global Strain Extensometers measure strains over an entire segment of the pile samples, thus it integrates the strains over a larger and more representative sample than the conventional strain gauges.

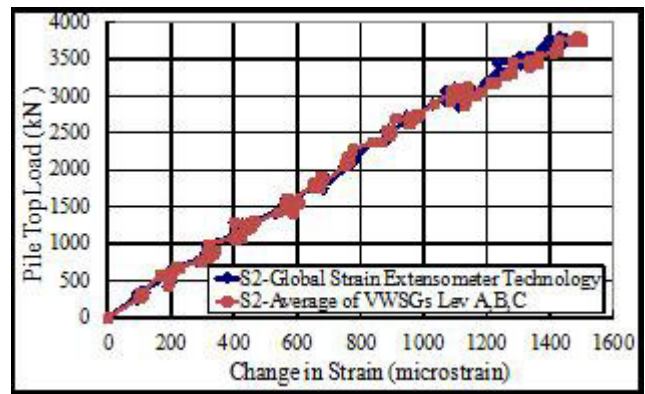


Fig.6 Plot of Pile Top Loads (kN) Vs Change in Strain ( $\mu$ s)

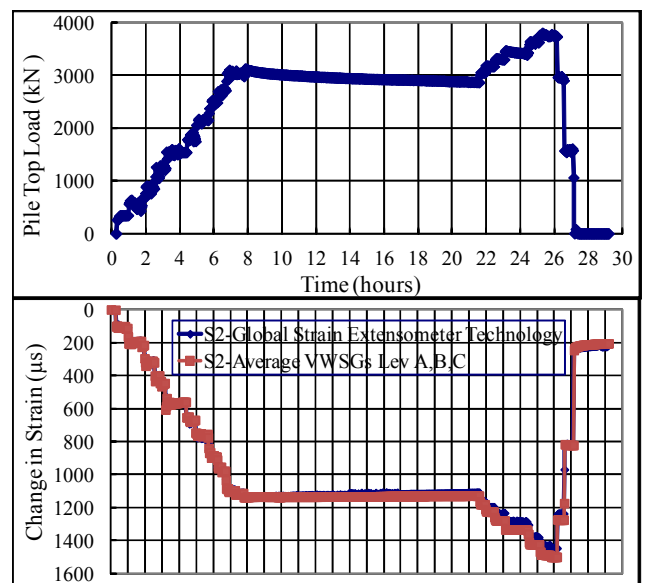


Fig.7 Plot of Pile Top Loads (kN) & Change in Strain ( $\mu$ s) Vs Time (hours) for Spun Pile Section

#### 4. FIELD TESTING ON INSTRUMENTED SPUN PILES

The unique Global Strain Extensometer technology developed has been used to fully instrument 10 nos. of static axial compression load tests on driven prestressed spun concrete pile for a project site in the state of Johor, Malaysia. The structural properties and installation details (including drop height and final set record taken) for each test pile are given in Table 1 below [8].

The high strength prestressed spun concrete piles are driven with hydraulic impact hammers at the site. The test piles STP3, STP4R and STP7 were installed with a 9-ton BSP hydraulic impact hammer, STP5, STP6, STP8R2, STP10R and STP1 were also installed with a 9-ton BSP hydraulic impact hammer, while test piles STP2 and STP9R2 were installed with a 16-ton Twinwood hydraulic impact hammer, over a period of approximately two months.

A typical pile instrumentation schemes adopted (using Global Strain Extensometer technique) for load testing programme, along with nearby borehole SPT N-values plot and subsurface exploration results from soil investigation are graphically represented in Figure 8.

Table 1. Test Piles Structural Properties and Installation Details for Driven Piles

Test Pile No.	Nominal Diameter (mm)	Wall Thickness (mm)	9mm Ø Pre-stressing Bar Reinforcement	Driven Pile Length (m)	Hydraulic Hammer Weight (tons)	Drop Height (mm)	Final Set (mm)
STP3	450	80	8 no.	47.25	9	400	3
STP4R	450	80	8 no.	38.5	9	500	10
STP7	450	80	8 no.	36.75	9	700	44
STP5	600	100	14 no.	38.0	9	900	20
STP6	600	100	14 no.	38.0	9	800	14
STP8R2	600	100	14 no.	39.75	9	800	20
STP10R	600	100	14 no.	37.75	9	600	10
STP1	700	110	20 no.	47.9	9	800	4
STP2	700	110	20 no.	36.4	16	800	36
STP9R2	700	110	20 no.	47.0	16	700	12

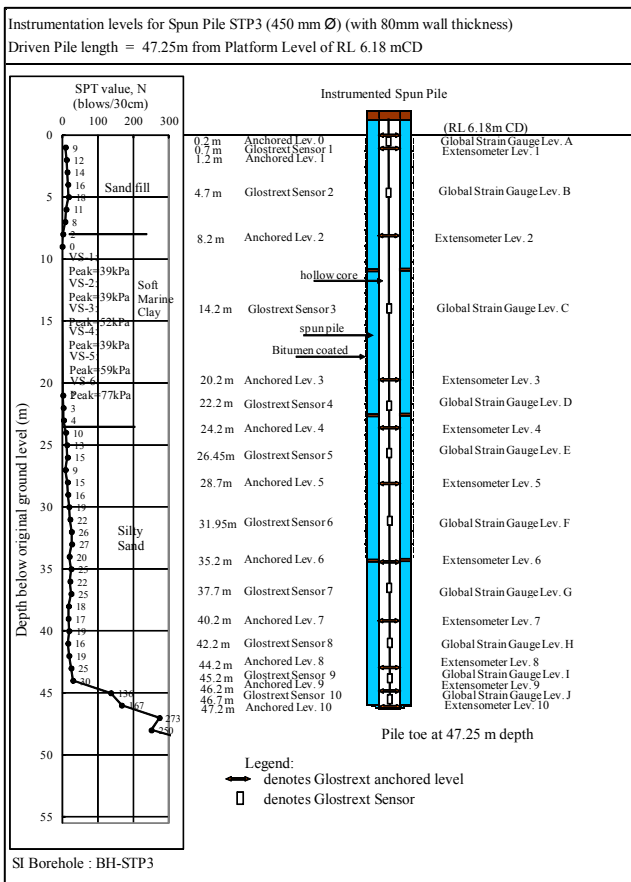


Fig.8 Pile instrumentation schemes adopted (using Global Strain Extensometer technique)

Test results acquired from Global Strain Extensometer technology on all tested piles appeared to be consistent, and the typical test results are reproduced here to highlight the capability of this technique (See Figures 9(a) to (f)). From highly consistent measurements of the structural elongation of the entire length of piles using Global Strain Extensometers the pile toe displacement behaviour can be reliably established by subtracting the structural elongation from the pile head displacement.

Similarly, Global Strain Extensometer technology also enable pile displacement under load at any depth along the shaft to be accurately derived, based on its ability to make segmental or global shortening/elongation measurement along the whole pile independent of any external reference and free of common errors associated with the conventional sleeved rod extensometers. This enables the movement and strains at various levels down the pile shaft to be accurately determined, thus permitting a significantly improved means for the acquisition of load transfer data.

The technology not only enables ease of the assessment of modulus-strain relationship and load transfer study it also significantly improves the reliability of the measurement of movement of pile between deeper soil stratum, as illustrated in the characteristic curves of mobilized unit shaft friction.

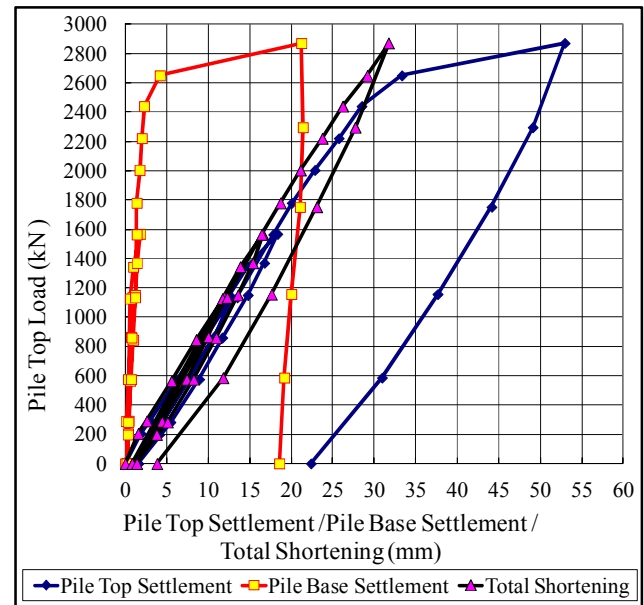


Fig.9(a) Plot of pile top load versus pile top settlement, pile base settlement and total shortening

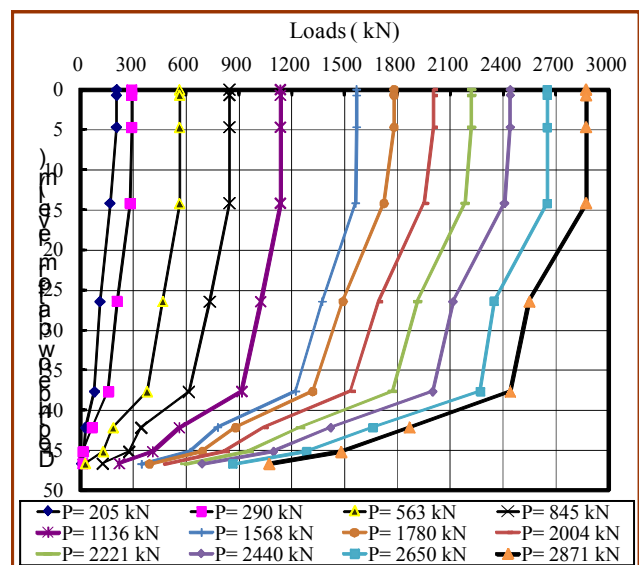


Fig.9(b) Load Distribution Curve

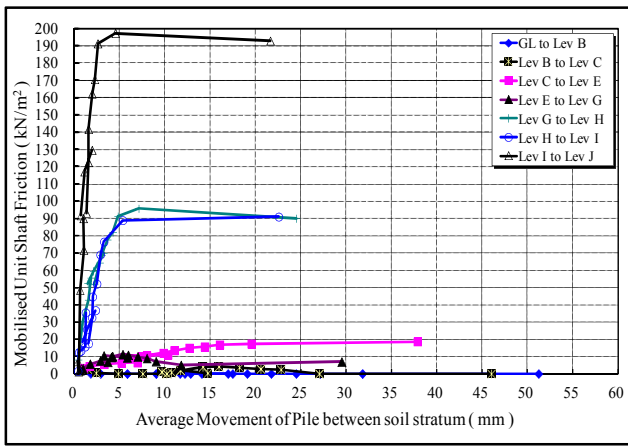


Fig.9(c) Load Transfer Characteristics during Loading Stages

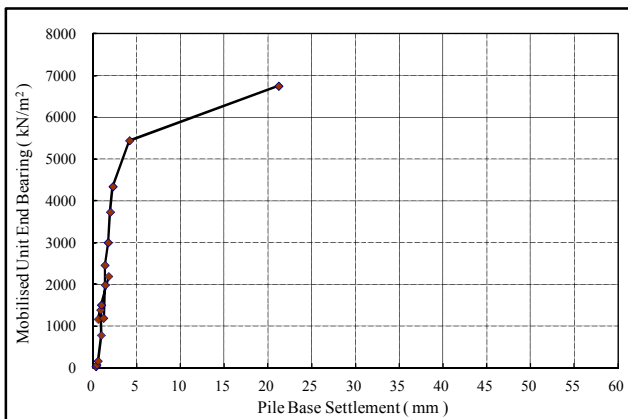


Fig.9(d) Plot of Mobilised Unit End Bearing versus Pile Base Settlement

#### 4.1 Correlation between SPT N-Value and Pile Design Parameters for Driven Spun Piles Test Results

With critical evolution in the understanding of the load transfer and bearing behaviour of piles in recent years mainly through analysis of instrumented full-scale load tests, it is common that for driven piles, the axial load capacity can be evaluated empirically from correlation with standard penetration tests SPT N-values (which are widely used in this region) using modified Meyerhof Equation, where the ultimate bearing capacity of a pile in compression is given by equation (1).

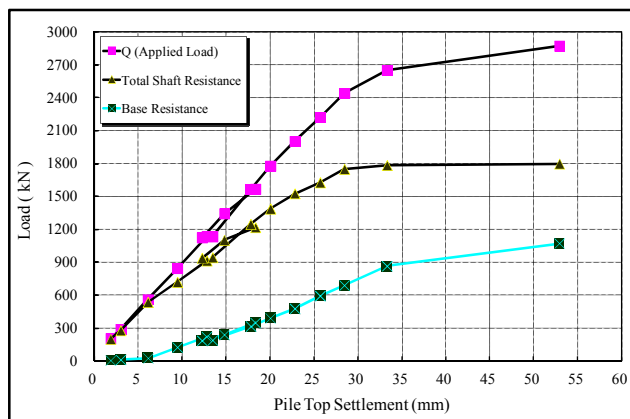


Fig. 9(e). Plot of Applied Pile Top Load, Total Shaft Resistance and Base Resistance versus Pile Top Settlement

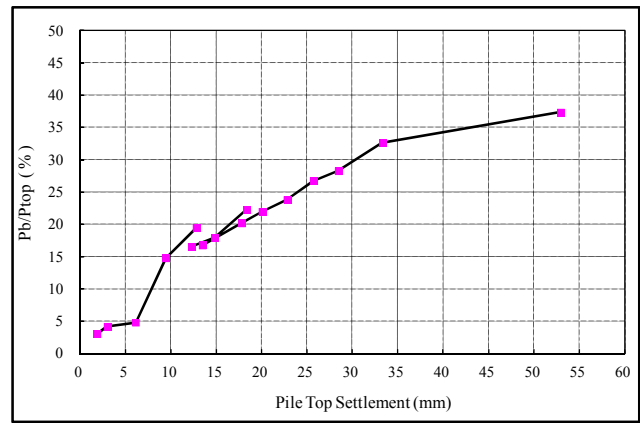


Fig.9(f) Plot of Pile Base Load over Applied Pile Top Load versus Pile Top Settlement

As the instrumented full-scale static load tests for driven piles are rarely being carried out in this region due to lack of innovation in this area, there is strong need for the evaluation of  $K_s$  and  $K_b$  factors for driven piles to be carried out more routinely for the improvement of empirical method of designing piles based on the results of full-scale instrumented load tests, to catch up with the evolution in the design methods.

For driven spun piles test results analyzed in this study, the results of the load transfer parameters for silty sand layer are summarized in the corresponding correlation of SPT-N values versus Maximum Mobilised Unit Shaft Resistance for driven spun piles under this study as shown in Figure 10. The results of the end bearing parameters for driven spun piles are summarized in the plot of SPT-N values versus Maximum Mobilised Unit End Bearing Resistance under this study as shown in Figure 11.

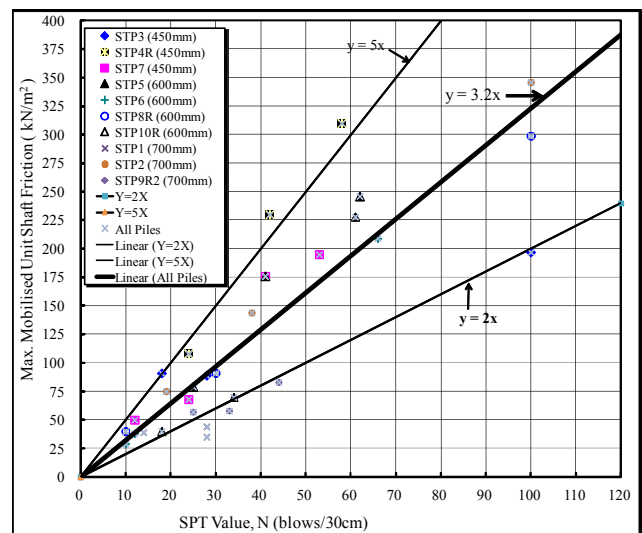


Fig. 10 Correlation of SPT value versus maximum mobilized unit shaft friction in silty sand layer for driven spun piles

The comments on correlation for driven spun piles test results are as follow:

- a) The silty sand layer for pile founding depth is generally overlain by 7m to 10m hydraulic sand fill followed by

compressible weak marine clay layer from approximately 10m to 26m depth, and the silty sand layer that underlies the sand fill and marine clay extends to depths beyond the toe of all driven spun piles;

- b) The SPT N-value in this silty sand layer generally varies between 10 and 100. The maximum mobilized unit shaft friction from the test results is generally between 29 kpa to 346 kpa;
- c) Correlation results for driven spun piles yield shaft resistance factor,  $K_s = 3.2$  in the shaft resistance empirical relationship of  $f_s = K_s \cdot N_s$ , where  $f_s$  is the ultimate unit shaft resistance,  $K_s$  is the empirical design factor relating ultimate shaft load to SPT N-value, kN/m<sup>2</sup> per SPT blow and  $N_s$  is the average SPT value for the pile shaft, blows/300mm.
- d) Correlation results for driven spun piles yield end bearing resistance factor,  $K_b = 1.3$  in the end bearing resistance empirical relationship of  $q_b = K_b \cdot (40N_b)$ , where  $q_b$  is the ultimate unit end bearing resistance,  $K_b$  is the empirical design factor relating ultimate end bearing load to SPT N-value, kN/m<sup>2</sup> per SPT blow,  $N_b$  is the SPT value for the pile base, blows/300mm.
- e) It is worth to note that Singapore Standard (SS) CP4: 2003 code of practice for foundations' recommendation for  $K_s$  is between 2 to 5 for driven piles shaft resistance factor, subject to a limit of  $f_s = 200$  kpa, and  $K_b$  is between 6 to 9 for driven piles end bearing resistance factor, subject to a limit of  $q_b = 18,000$  kpa.
- f) Normally the critical shaft displacement is relatively small to fully mobilize the shaft resistance compared to the big movement that is needed to fully mobilize the end bearing. Therefore  $K_s = 3.2$  from this study is able to serve as a useful initial design guide for shaft resistance factor in silty sand materials, while  $K_b = 1.3$  represent a conservative approach for end bearing resistance factor in silty sand materials, as the majority of the piles are not tested to full failure.

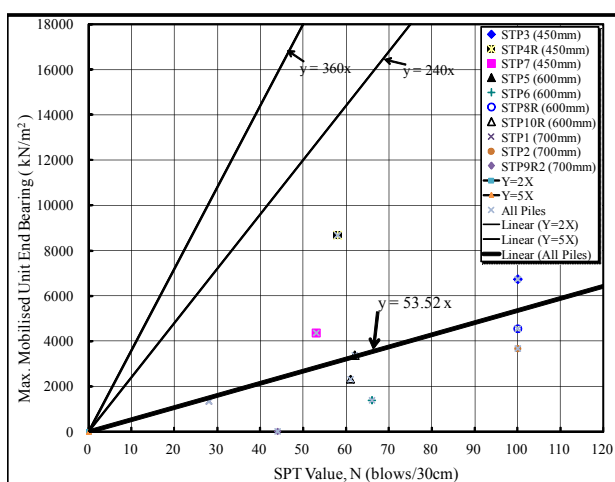


Fig.11 Correlation of SPT value versus max. mobilized unit end bearing in silty sand layer for driven spun piles

#### 4.2 Advantages of using the Global Strain Extensometer Technology

Due to the significant difference in the methodology evolution, from conventional sacrificial cast-in method to a

new retrievable post-install approach, the Global Strain Extensometer technology has been proven via full-scale load tests to be a reliable and powerful pile load testing and data interpretation tool, capable of leading the spun pile instrumentation industry to a revolutionary improvement not seen in the past.

Some of the obvious benefits of using Global Strain Extensometer technology are as follow:

- (i) The technology enables installation of instrumentation after pile-driving and thus virtually eliminates the risk of instrument damage during pile production and installation;
- (ii) The post-install nature of the method empowers engineers to select instrumentation levels along the as-built depth of foundation piles using pile driving/installation records and site investigation data as guides;
- (iii) The technology reliably measures segmental shortening/elongation and strain over an entire section of the test pile during each loading step of a typical static load test. Unlike the conventional strain gauges that make just localized strain measurements, the new technology integrates individual measurements over a larger and more representative sample;
- (iv) Significant cost and time saving, as the additional cage and cement grout infilling are not required;
- (v) The technology is extremely environmental friendly, as the sensors are retrievable, and no messing around with cement grouts; and

#### 5. CONCLUSIONS

The successful driven field testing programmes using the unique Global Strain Extensometer pile instrumentation technique have clearly demonstrated that the novel Global Strain Extensometer instrumentation technique provides high quality, reliable and consistent results. Three distinct features of this method would especially appeal to engineers:

- The method enables installation of instrumentation after pile-driving and thus virtually eliminates the risk of instrument damage during pile production and installation.
- The post-install nature of the method enables engineers to select instrumentation levels along the as-built depth of driven piles using pile driving records and site investigation data as guides.
- The method reliably measures segmental shortening and strains over an entire section of the test pile during each loading step of a typical static load test and unlike conventional strain gauges that make just localized strain measurements, integrates individual measurements over a larger and more representative sample, thus making the test results more informative.

Pile instrumentation using the Global Strain Extensometer technique developed enables acquisition of design data in a more accurate and reliable way for shaft friction and end bearing parameters to be obtained for driven piles and subsequently help to optimize pile design. It also helps to derive correlation of shaft friction and end bearing parameters with the standard penetration tests commonly used locally.

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Pertinent discussion including authors' closure, if any, will be published in the June 2014 if the discussion is received by Dec., 2013

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