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# Interpretations of Instrumented Bored Piles in Johor Bahru Old Alluvium Formation

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## ABSTRACT

In evaluating pile foundation performance, static load tests (SLT) play a critical role, as they offer a direct and reliable measure of how a pile responds under both working and ultimate load conditions. Traditionally, these tests focus on pile head load–displacement relationships. However, when piles are instrumented with vibrating-wire strain gauges (VWSG) and extensometers, the amount and quality of information obtained increase substantially. Such instrumentation allows designers and engineers to observe the mobilisation of shaft friction at different depths, distinguish the contribution of end-bearing resistance, monitor toe movement, as well as quantify elastic shortening along the pile shaft. Most importantly, it provides a clear understanding of how shaft friction and end-bearing components develop progressively with increasing pile displacement, forming a complete picture of the load transfer mechanism. Therefore, detailed interpretations of static load test results from instrumented bored piles constructed within the Johor Bahru Old Alluvium formation are carried out in this study. Through careful evaluation of strain distributions and load transfer profiles, ultimate shaft friction values of 6.35N for layers with SPT N-value ≤ 15, and 2.35N for layers with SPT N-value > 15, are established. These correlations offer meaningful insight into the behaviour of Old Alluvium materials under pile loading and provide practical parameters for use in design. The findings contribute directly to improved optimisation of pile lengths, particularly for projects with varying pile diameters and embedment depths in similar geological settings. By adopting design values grounded in instrumented test data, engineers may prevent unnecessary conservatism, reduce material usage, and achieve substantial savings in foundation construction costs while ensuring safety and performance.

**Keywords:** Instrumented bored pile, Load transfer behaviour, SPT N-value, Ultimate shaft friction, Old alluvium formation.

## INTRODUCTION

In Malaysia, bored piles are the most widely used foundation system to support heavily loaded structures such as major bridges and high-rise buildings. Their popularity arises from several key advantages including flexibility in diameter to suit varying ground conditions, minimal noise and vibration during installation, and adaptability to different loading requirements. Conventionally, the bored pile design of bored piles relies heavily on empirical correlations derived from Standard Penetration Test (SPT) data, which are generally attained during site investigations. Over time, these correlations have been refined local experience and continuous evaluation of pile load test results. However, numerous empirical and analytical methods exist for estimating both shaft friction and end bearing capacity, and the values obtained are highly dependent on both ground conditions and construction practices. Therefore, developing reliable, site-specific design parameters is crucial for the verification and optimisation of bored pile design.

Most practicing engineers in Malaysia are typically require a maintained load test (MLT) to verify bored pile capacity. However, when more detailed insights into pile–soil interaction are required, particularly for design refinement or value engineering, a full-scale instrumented test piles are adopted. These piles are equipped with multi-level strain gauges, extensometers, and Osterberg cells or polyfoam soft toes, in some cases. Quick maintained load tests are commonly used when the founding material is not prone to excessive creep or time-dependent deformation; otherwise, conventional long-duration MLT are conducted. In some projects, indirect testing methods such as high-strain dynamic tests or statnamic load tests are also implemented in verifying the capacity evaluation.

To optimise bored pile design, it is vital to accurately predict both the design parameters and pile displacement under varying load levels. The load-transfer method proposed by Coyle and Reese (1966) offers a simple yet effective means of predicting load-displacement behaviour and load distribution along the pile. However, reliable application of this method depends on having a robust database of load-transfer parameters derived from fully instrumented piles tested in comparable ground conditions, certifying improved correlation between soil properties and pile geometry.

The Old Alluvium formation, found extensively in Johor Bahru, and the surrounding offshore areas, exhibits additional challenges due to its geological complexity. Through an intense tropical weathering of Pleistocene-era mountain slopes (Gupta et al., 1987) and subsequently transported by braided river systems (Biswas, 1973), the Old Alluvium presents significant variability in deformability and strength (Orihara & Khoo, 1998). Tan et al. (1998) further mentioned that its shear strength does not correlate with depth. Therefore, this variability highlights the importance of establishing reliable load-transfer behaviour for bored piles founded in Old Alluvium.

Conventional SLT only measure load and displacement at the pile head, allowing assessment of overall pile behaviour but offering limited insight into layer-specific shaft friction or the relative contributions of shaft and base resistance. As a result, optimising pile length and evaluating performance across different diameters becomes challenging and demanding. By installing vibrating-wire strain gauges (VWSG) and extensometers at multiple depths in an instrumented test pile, engineers can measure the load distribution, shaft friction, end bearing resistance, and their development with increasing pile movement, directly. Since the cost of such instrumentation is relatively small compared to the overall testing budget, the benefits, particularly in large-scale projects are significant. Eventually, the application of detailed design parameters and load-transfer behaviour is essential in achieving value-engineered bored pile designs and ensuring reliable displacement performance in the complex Old Alluvium formation of Johor Bahru.

## LITERATURE REVIEW

### Geological Background: Old Alluvium of Johor Bahru

According to B. Alshameri (2010), alluvium is generally loose unconsolidated soil or sediments, eroded deposited and reshaped by water to make non-marine setting. In contrast, the older alluvium is semi consolidated and classified to two kinds of beds A1 overlay A2, otherwise to recognise this type of alluvium from the young one, it called older alluvium. Table 1 shows comparison between the alluvium and older alluvium in Johor state.

Table 1 Comparison between the older alluvium and alluvium at Johor state

| Name | Alluvium | Older Alluvium |
|---|---|---|
| Age | Recent to sub-recent | Pleistocene |
| Descriptions | Unconsolidated | Semi-consolidated sand and clay & boulder beds |
| Components | Gravel, sand, and clay | Type A1: Boulder beds<br>Type A2: Gravel, sand, and clay |
| Origin | Fluviatile and shallow-marine | Fluviatile and shallow-marine |

The previous geological surveyed and geological map about Old alluvium has been outline by several researchers including Mohamad *et al.*(2011); Angeles and Bali (2017); Miller and Juilleret (2020); Nikolinakou and Whittle (2021), which mentioned the following:

1. Old alluvium is located at south Johor.

2. In general, it consists of coarse feldspathic (which come from granite source) sand with occasional rounded phenoclasts also there are represented for the gravelly clay, sandy gravel, sandy clay, silty clay, clayey sand and clay. It contains phenoclasts (fragment from rocks) of vein quartz, quartzite, sandstone, siltstone, shale hornfels, granite, granite porphyry, alaskite, aplite, rhyodacite, andesite and tuff.

3. The condition of fresh older alluvium can be described as partly consolidated argillaceous members are intermediate between clay and mudstone and most the arenaceous are intermediate between sand and sandstone.

4. In general, for the structure it can organise semi-flat lying with some traces for gentle folders which have less than 15° slope. Therefore, there are some beddings steeply inclined to vertical for a few feet in small tight folds.

5. For Palaeogeography and age, the old alluvium occurred during Pleistocene period. However there some evidence direct to the shallow marine environment such as occurrence of plant remains and echinoid spines.

According to Boon K. Tan (2000), Johor Bahru has the Old Alluvium as a unique soil deposit underlying much of the city and vicinities. These Old Alluvium forms mostly low-lying hillocks and has been sourced for construction fill materials. The Old Alluvium is a highly variable material with description ranging from hard clay to gravelly silty sand. Hence, enhancing the bored pile system in Old Alluvium formations is important because this ground typically exhibits highly variable and heterogeneous soil conditions, including alternating layers of sand, silt, clay, and gravel, which high risk in leading to uncertainty in load transfer and pile performance.

During bored pile construction, stress relief and soil disturbance commonly occur, particularly in sandy and silty layers, resulting in reduced shaft resistance and increased pile settlement. In addition, achieving consistent end-bearing capacity is often challenging due to the presence of loose or partially cemented strata and fluctuating groundwater levels, which may cause base softening and borehole instability. As a result, pile behaviour in Old Alluvium is frequently governed by settlement and serviceability rather than ultimate capacity. Improving the bored pile system, through instrumentation, improved construction control or ground improvement techniques, helps to increase pile stiffness, reduce total and differential settlements, improve load mobilisation, and provide more reliable and predictable foundation performance for structures founded on this formation.

**Design of Geotechnical Capacity: Semi-empirical Method**

In tropical residual soils, bored piles are commonly adopted as deep foundations, where ground conditions are highly variable and often difficult to characterise. However, obtaining reliable undisturbed samples and conducting laboratory tests to determine strength and stiffness properties are extremely challenging. These soils exhibit significant spatial variability over short distances, while their friable and easily disturbed nature further complicates sampling and testing. As a result, theoretical design formulae become less practical, especially since many do not adequately account for soil disturbance, stress relief, and the partial reinstatement of stresses that occur during the construction of bored piles.

Hence, semi-empirical design approaches have been widely developed to address these limitations. In particular, correlations between shaft resistance, base resistance, and Standard Penetration Test (SPT) N-values have become the industry norm. These correlations are typically based on uncorrected SPT N-values obtained prior to pile installation and have been refined through extensive local experience and back-analysis of pile load tests. Despite their simplicity, such correlations remain essential for practical design in complex tropical residual soils where direct measurement of engineering properties is difficult to achieve reliably. Followings are the commonly used correlations for bored piles:

$$f_{su} = K_s \text{ x SPT N-value (kPa)} \quad (1)$$

$$f_{bu} = K_b \text{ x SPT N-value (kPa)} \quad (2)$$

Where:

$K_s$ = ultimate shaft resistance factor

$K_b$ = ultimate base resistance factor

SPT N-value = Standard Penetration Tests blow counts (blows/300 mm)

**Load Deformation Analysis**

Until relatively recently, the displacement of single pile is calculated either analytically based on many simplifying assumptions or on an empirical basis through correlations with other pile tests in similar situations. In many situations, the displacement is not calculated at all but assumed to be satisfactory if the load did not exceed one third (1/3) of the ultimate load.

However, with the advent of computers, several more sophisticated analyses are developed. These methods permit a far more realistic assessment of pile displacement because of the incorporation of the many factors that influenced pile displacement. The following are the three major categories for these various computer-based methods:

1. Elastic Analytical Methods

This method is based on elasticity techniques that employ Mindlin's equations to account for displacements within a mass of soil brought on by internal loading. Several investigators have used this approach but perhaps one of the most complete sets of solutions has been developed by Polous & Davis (1980).

The technique involves the pile discretisation into several elements. It is then necessary to obtain mathematical expressions for the vertical displacement of the pile and the soil at each element in terms of the unknown stresses on the pile. The different equations can be solved to get the displacement at any given pile head load by applying the compatibility conditions to the pile and the soil. Details of these analytical methods are discussed in some detail in Polous & Davis (1980). Design charts for a wide range of pile conditions have been developed using dimensionless parameters. The elastic approach necessitates significant idealisation and simplification.

Randolph & Wroth (1978) has developed an approximate closed form solution for the displacement of a pile in linear elastic soil under a given load.

2. Numerical Methods

Numerous researchers have developed numerical methods for the analysis of pile behaviour, such as the boundary element method and the finite element method. The methods in principle can model slip at the pile-soil interface and non-linear stress strain behaviour. However, they are relatively complex to use.

3. Load Transfer Method

The load transfer method was originally suggested by (Seed & Reese, 1957) with further refinements by (Coyle & Reese, 1966). The method is basically an iterative technique which is used to calculate load displacement characteristics at the head of the pile and thereby allow the construction of a full load displacement curve.

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The method requires the pile to be divided into several small segments which are assumed to be connected by springs, are shown in Figure 1. A small displacement is then applied to the pile base, and by calculating the forces and displacements for each segment progressively up the pile shaft, the load at the head of the pile can be determined along with its vertical displacement. This process is repeated for several base displacements until a sufficient range of pile loads and displacements are obtained to construct a complete load displacement curve.

To apply this method, it is necessary to know the load transfer characteristics of each small section of the pile shaft. These characteristics are given by the shaft resistance – shaft displacement curve that can be obtained from instrumented field tests, as shown in Figure 2.

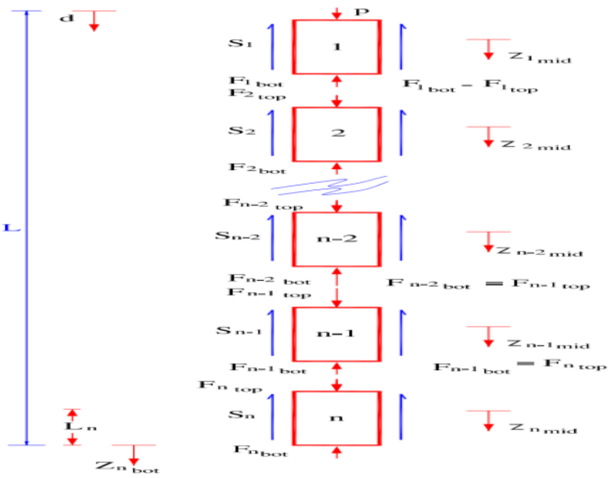

Figure 1 Load Transfer Method

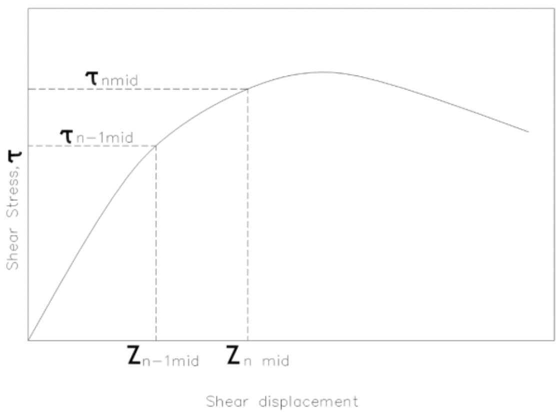


Figure 2 Shear Stress vs. Shear Displacement

# METHODOLOGY

## Data Collection

The first stage of this study involved the identification and selection of five sites within the same project area underlain by the Johor Bahru Old Alluvium formation, where SLT had been conducted on a total of 13 instrumented bored piles. All selected sites are predominantly underlain by weathered residual soils, mainly comprising silty sand, which are characteristic of the formation. A representative borehole profile together with the corresponding test pile instrumentation details is presented in Figure 3. The details of the 13 instrumented bored piles investigated in this study, obtained from the five sites within the project area, are summarised in Table 2. The collected data is comprehensive and of sufficient quality to support the objectives of this study. In addition to the instrumentation measurements obtained from vibrating wire strain gauges (VWSG) and rod extensometers, detailed subsurface and construction records are also available. These include SPT N-values, borehole logs, as well as piling, boring, and concreting records, thereby providing a robust basis for the interpretation and analysis of pile behaviour.

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**Correlation between SPT N-value and Ultimate Shaft Friction**

The SPT N-values were obtained from the nearest borehole close to the test pile. The SPT N-values were averaged between the strain gauge locations to correlate with the maximum shaft friction. It is noted that in many cases the mobilized shaft friction did not achieve the maximum value within the test load. The shaft friction values that did not reach the maximum were not included to derive the correlation. The maximum shaft resistances are determined directly from the uncorrected values of the SPT N-value obtained from Standard Penetration Test. The correlation adopted is as follows:

$$f_{su} = K_s N_s \text{ (kPa)} \quad (3)$$

Where:

$K_s$ = shaft friction factor

$N_s$ = Average SPT N-value along the pile shaft

**Generation of Load Transfer Curve**

The procedure used for generating the load transfer curves is summarised below:

i. Assuming the strain in the steel is equal to the strain in the concrete at the same level, the load distributions in the pile at the strain gauge levels are computed as follows:

$$P_s = \varepsilon A_p E_{comp} \quad (4)$$

Where:

$P_s$ = pile load along shaft

$\varepsilon$ = measured strain from strain gauges

$A_p$ = cross-sectional area of the shaft at the plane of strain gauges

$E_{comp}$ = composite modulus of concrete and steel at the strain gauge plane.

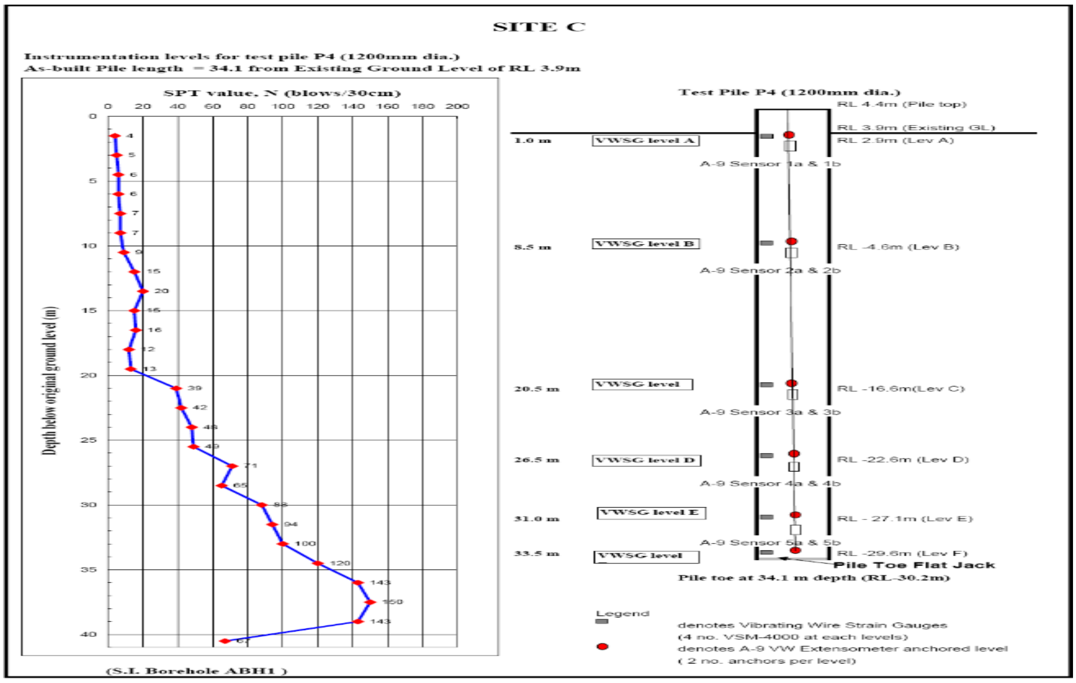


Figure 3 Borehole profile results

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Table 2 Details of the 13 instrumented bored piles

| Site | Test pile no | Pile diameter (mm) | Pile length (m) | Working load (kN) |
|---|---|---|---|---|
| A | P1 | 750 | 47.0 | 2,613 |
| | P2 | 1000 | 50.5 | 5,222 |
| | P3 | 1000 | 40.0 | 5,124 |
| | P4 | 750 | 55.7 | 3,289 |
| | P5 | 750 | 55.7 | 3,243 |
| B | P1 | 1200 | 51.2 | 8,375 |
| C | P1 | 1000 | 48.2 | 5,753 |
| | P2 | 900 | 60.5 | 4,697 |
| | P3 | 1000 | 34.3 | 5,952 |
| | P4 | 1200 | 34.1 | 8,461 |
| D | P1 | 1200 | 41.5 | 8,382 |
| E | P1 | 1500 | 50.6 | 14,900 |
| | P2 | 1500 | 45.5 | 14,838 |

ii. Using the load distributions computed at the strain gauge levels, the average shaft resistance for each of the segment is computed as:

$$f_{sm} = \frac{(P_{top\ of\ segment} - P_{bottom\ of\ segment})}{(\pi \times \text{pile diameter} \times \text{segment length})} \quad (5)$$

iii. Between the strain gauge levels, the pile is divided into segments. For each segment, the mid-segment displacement of the pile shaft is linearly interpolated between the displacement of the bottom and top of segment, that are taken using extensometers.

iv. The same process is then repeated for the subsequent head load and head displacement and the corresponding strain gauge and extensometer readings along the pile length. Therefore, for each pile, the load transfer curves for shaft are generated for each pile segment and one load transfer curve for the base.

**Generation of Normalised Load Transfer Curves**

The following procedures are used in the derivation of normalised load transfer curves:

1. After the generation of the load transfer curves, the ones with full mobilisation of the shaft frictions are selected.

2. For each of the selected curves, a critical point on the curve is located. The critical point ($f_{sc}$,$z_{sc}$) selected on the curve satisfied one of the following:

   a. Point of the maximum shaft friction, or

b. The point where the slope of the load-transfer curve starts to become noticeably smaller (showing strain hardening response).

3. The shaft displacements corresponding to these critical shaft frictions ($f_{sc}$) were denoted as critical shaft displacements ($z_{sc}$). These two parameters are known as the load transfer parameters.

4. The shaft friction and shaft displacements are normalised with the critical shaft frictions and critical shaft displacements respectively.

The same procedure used for the shaft is adopted for the normalisation of the base.

## RESULTS AND DISCUSSIONS

These sites are overlain by comparatively weak alluvial layers having depths between 8m to 30m. The SPT N-values of these weak alluvial layers are generally less than 15, with the maximum mobilised friction from the test results is observed between 15 kPa to 120 kPa. The old alluvium that underlies the weak alluvium extends to depths beyond the toe of all piles, with the maximum mobilised friction from the test results is observed between 40 kPa to 130 kPa.

At working loads, the following observations were made:

a. The head displacements are between 3.56 mm and 9.74 mm, and the base displacements are between 0.40 mm and 7.35 mm.

b. The end bearing contributed only between 0.40% and 3.34% of the total capacity. The pile lengths are between 34.1 m and 60.5 m, and the end bearing contribution was negligible at the pile working loads.

The end bearing contribution was negligible in these long piles, essentially it behaved as friction piles. Hence, no correlations between $K_b$ with SPT N-value are developed.

Figure 4 shows the correlation of ultimate shaft friction factor ($K_s$) for SPT N-value ≤ 15 (weak alluvium) and > 15 (old alluvium) respectively.

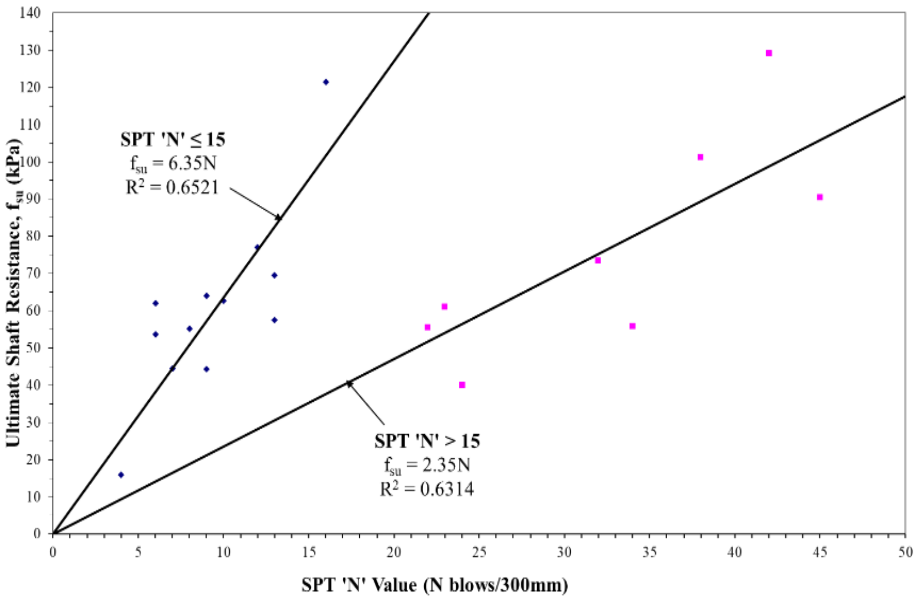


Figure 4 Correlation between Standard Penetration Test (SPT) N-values and ultimate shaft friction, $f_{su}$) in Johor Bahru Old Alluvium

The following correlations are proposed as guidelines for bored pile design:

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a. For uncorrected SPT N-value equal or less than 15,

$$f_{su} = 6.35 \text{ x SPT N-value (kPa)} \quad (6)$$

b. For uncorrected SPT N-value more than 15,

$$f_{su} = 2.35 \text{ x SPT N-value (kPa)} \quad (7)$$

The following equations are proposed for the load transfer curves for shaft friction of piles based on the normalised load transfer curves obtained, as shown in Figure 5:

For $z_s/z_{sc} \leq 1.0$, $\quad f_s/f_{sc} = 0.22Ln(z_s/z_{sc}) + 1.01 \quad (8)$

For $1.0 < z_s/z_{sc} \leq 2.0$, $\quad f_s/f_{sc} = -0.20(z_s/z_{sc}) + 1.21 \quad (9)$

For $z_s/z_c > 2.0$, $\quad f_s/f_{sc} = 0.80 \quad (10)$

The following equations are proposed for the load transfer curves for end bearing of piles based on the normalised load transfer curves obtained, as shown in Figure 6:

$$f_b/f_{bc} = 0.96(z_b/z_{bc})^{5/6} \quad (11)$$

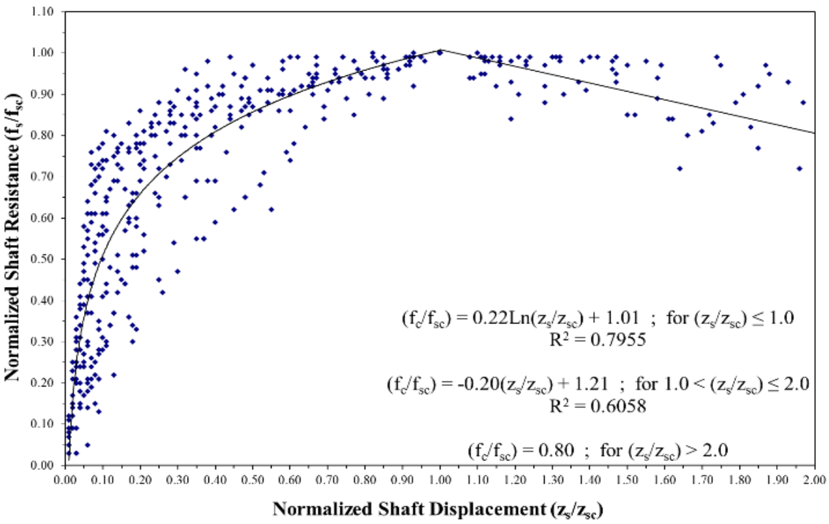


Figure 5 Normalised shaft load–transfer curve

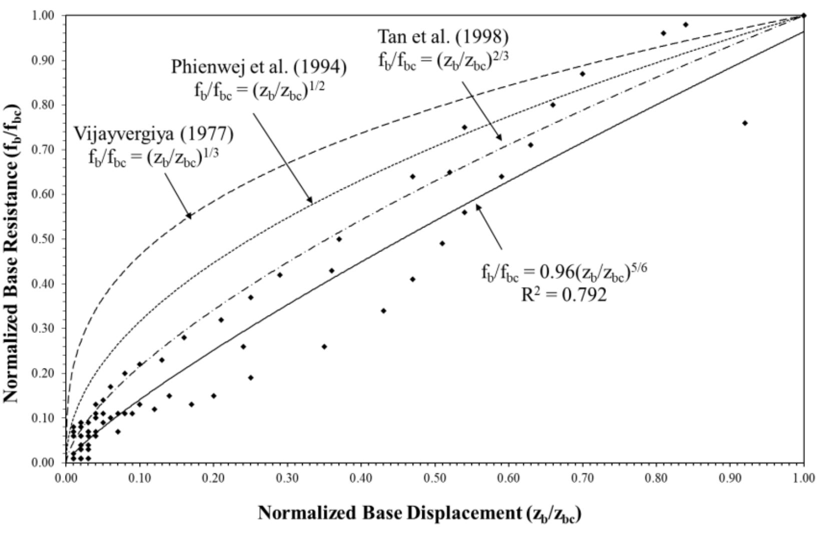


Figure 6 Normalised base load–transfer curve

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The derived $K_s$ value for old alluvium fits well within the ranges presented by most past researchers as shown in Table 3.

Table 3 Ultimate shaft factor ($K_s$) from previous researchers

| Previous Researchers | $K_s$ |
|---|---|
| Meyerhof (1976) | 1 |
| Chin et al. (1985) | 2.5 – 5.0 |
| Toh et al. (1989) | 1.5 to 5 |
| Chan (1990) | 3 |
| Chang & Broms (1991) | 2 |
| Tan (1998) | 2.6 |
| Chang (2005) | 2.0 - 3.0 |
| Angeles and Bali (2017) | 2.2 |
| Veeresh *et al.* (2017) | 2.3 - 4.4 |

## CONCLUSIONS

In achieving safe and cost-effective pile foundation designs, pile load tests play a critical role, as site-specific shaft friction and end bearing parameters can be reliably established through instrumented pile load testing. In this study, instrumented bored pile load test data from the Johor Bahru Old Alluvium formation were compiled and evaluated to assess the influence of variability in SPT N-values on the mobilised shaft friction developed during pile loading.

As illustrated in Figure 2, the mean ultimate shaft friction values are approximately 6.35 N for soils with SPT N-values ≤ 15 and 2.35 N for soils with SPT N-values > 15. Despite these representative values, a significant scatter was observed in the measured shaft friction, with ranges from 1 N to 3 N for SPT N-values ≤ 15 and from 5 N to 7 N for SPT N-values > 15, indicating substantial inherent variability in the ground conditions. Besides, analysis of the distribution of shaft friction and end bearing resistance further indicates that the installed piles behave predominantly as friction piles, with more than 97 % of the working load being resisted by shaft friction. Based on the measured load transfer behaviour, the load transfer curves presented in Figures 5 and 6 are proposed for evaluating the load–displacement response of bored piles founded in the Johor Bahru Old Alluvium formation.

In Malaysian practice, the design of bored piles in Old Alluvium formations is predominantly based on empirical correlations with SPT N-values, as adopted in Malaysia Public Work Department guidelines and common local practice. These approaches generally assume conservative mobilisation of shaft friction and end bearing and do not explicitly account for construction-induced disturbance, stress relief, or the progressive development of load transfer along the pile. By comparison, the correlations proposed in this study are developed from instrumented SLT results, allowing direct evaluation of shaft and base resistance under actual field loading conditions. Consequently, the proposed correlations provide a more representative description of pile–soil interaction in the Johor Bahru Old Alluvium formation while remaining compatible with parameters routinely obtained from standard site investigations. This offers a practical enhancement to existing design methods by improving reliability and reducing unnecessary conservatism without compromising safety.

However, to enhance practical application, it is recommended that a dedicated computational tool be developed to predict pile load–displacement behaviour using the derived load transfer curves, thereby supporting more reliable and economical pile design in this formation.

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