# Design & Construction of Bored Pile Foundation

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**ABSTRACT: This paper presents some aspect of design and construction of bored pile foundation in Malaysia. Empirical equations correlating the value of the ultimate shaft resistance ($f_{su}$) and the ultimate base resistance ($f_{bu}$) to SPT'N' values are suggested as design of bored piles under axial compression in Malaysia is usually based on the Standard Penetration Tests (SPT), which is extensively carried out at site. Some aspects of design and construction in difficult ground conditions such as limestone areas and soft ground are presented together with some suggestions on quality control for bored pile construction.**

## 1.0 Introduction

Bored piles are commonly used in Malaysia as foundation to support heavily loaded structures such as high-rise buildings and bridges in view of its low noise, low vibration, and flexibility of sizes to suit different loading conditions and subsoil conditions. Such attributes are especially favoured in urban areas where strict restrictions with regards to noise and vibration are imposed by relevant authorities which restricted the use of other conventional piling system, e.g. driven piles. This paper presents a summary of design methodologies commonly adopted in Malaysia for bored piles under axial compression together with a brief discussion on the construction aspects of bored piles.

## 2.0 Geotechnical Capacity of Bored Piles

### 2.1 Factor of Safety

The Factors of Safety (FOS) normally used in static evaluation of bored pile geotechnical capacity are partial FOS on shaft ($F_s$) and base ($F_b$) respectively; and global FOS ($F_g$) on total capacity. The lower geotechnical capacity obtained from both methods is adopted as allowable geotechnical capacity

$$Q_{ag} = \frac{Q_{su}}{F_s} + \frac{Q_{bu}}{F_b} \qquad \text{(eq.1)}$$

$$Q_{ag} = \frac{Q_{su} + Q_{bu}}{F_g} \qquad \text{(eq.2)}$$

Note: Use the lower of $Q_{ag}$ obtained from eq. 1 and eq. 2 above.

Where:

| | | |
|---|---|---|
| $Q_{ag}$ | = | Allowable geotechnical capacity (have not included down-drag force, if any) |
| $Q_{su}$ | = | Ultimate shaft capacity = $\sum_i (f_{su} \times A_S)$ |
| $i$ | = | Number of soil layers |
| $Q_{bu}$ | = | Ultimate base capacity = $f_{bu}\ A_b$ |
| $f_s$ | = | Unit shaft resistance for each layer of embedded soil |
| $f_b$ | = | Unit base resistance for the bearing layer of soil |
| $A_s$ | = | Pile shaft area |

$A_b$ = Pile base area
$F_s$ = Partial Factor of Safety for Shaft Resistance = 1.5
$F_b$ = Partial Factor of Safety for Base Resistance > 3.0
$F_g$ = Global Factor of Safety for Total Resistance (Base + Shaft) = 2.0

In general, the contribution of base resistance in bored piles shall be ignored due to difficulty of proper base cleaning especially in wet hole (with drilling fluid). The contribution of base resistance can only be used if it is constructed in dry hole, proper inspection of the base can be carried out or base grouting is implemented.

### 2.2 Design of Geotechnical Capacity in Soil

The design of bored pile geotechnical capacity commonly used can be divided into two major categories namely:

a) Semi-empirical Method
b) Simplified Soil Mechanics Method

#### 2.2.1 Semi-empirical Method

Bored piles are constructed in tropical residual soils that generally have complex soil characteristics. The complexity of these founding medium with significant changes in ground properties over short distance and friable nature of the materials make undisturbed sampling and laboratory strength and stiffness testing of the material difficult. Furthermore current theoretically based formulae also do not consider the effects of soil disturbance, stress relief and partial reestablishment of ground stresses that occur during the construction of bored piles; therefore, the sophistication involved in using such formulae may not be necessary.

Semi-empirical correlations have been extensively developed relating both shaft resistance and base resistance of bored piles to N-values from Standard Penetration Tests (SPT'N' values). In the correlations established, the SPT'N' values generally refer to uncorrected values before pile installation.

The commonly used correlations for bored piles are as follows:

$$f_{su} = K_{su} \times SPT'N' \text{ (in kPa)}$$

$$f_{bu} = K_{bu} \times SPT'N' \text{ (in kPa)}$$

Where:
$K_{su}$ = Ultimate shaft resistance factor
$K_{bu}$ = Ultimate base resistance factor
SPT'N' = Standard Penetration Tests blow counts (blows/300mm)

For shaft resistance, Tan *et al*. (1998), from the results of 13 nos. of fully instrumented bored piles in residual soils, presents $K_{su}$ of 2.6 but limiting the $f_{su}$ values to 200kPa. Toh *et al*. (1989) also reported that the average $K_{su}$ obtained varies from 5 at SPT'N' 20 to as low as 1.5 at SPT'N'=220. Chang & Broms (1991) suggests that $K_{su}$ of 2 for bored piles in residual soils of Singapore with SPT'N'<150.

For base resistance, $K_{bu}$ values reported by many researchers varies significantly indicating difficulty in obtaining proper and consistent base cleaning during construction of bored piles. It is very dangerous if the base resistance is relied upon when the proper cleaning of the base cannot be assured. From back-analyses of test piles, Chang & Broms (1991) shows that $K_{bu}$ equals to 30 to 45 and Toh *et al*. (1989) reports that $K_{bu}$ falls between 27 and 60 as obtained from the two piles that were tested to failure.

Lower values of $K_{bu}$ between 7 and 10 were reported by Tan *et al*. (1998). The relatively low $K_{bu}$ values are most probably due to soft toe effect which is very much dependent on the workmanship and pile geometry. This is even more pronouncing in long pile. Furthermore, a relatively larger base movement is required to mobilise the maximum base resistance as compared to the displacement needed to fully mobilise shaft resistance. The base displacement of approximately 5% to 10% of the pile diameter is generally required to mobilise the ultimate base resistance provided that the base is properly cleaned and checked.

In view of the large movement required to mobilise the base resistance of bored piles and difficulty in base cleaning, the authors strongly recommend to ignore the base contribution in the bored pile design unless proper base cleaning can be assured and verified.

### 2.2.2 Simplified Soil Mechanics Methods

Generally the simplified soil mechanics methods for bored pile design can be classified into fine grained soils (e.g. clays, silts) and coarse grained soils (e.g. sands and gravels).

**Fine Grained Soils**

The ultimate shaft resistance ($f_{su}$) of bored piles in fine grained soils can be estimated based on the semi-empirical undrained method as follows:

$$f_{su} = \alpha \times s_u$$

Where :
$\alpha$ = adhesion factor
$s_u$ = undrained shear strength (kPa)

Whitaker & Cooke (1966) reports that the $\alpha$ value lies in the range of 0.3 to 0.6 for stiff over-consolidated clays, while Tomlinson (1994) and Reese & O'Neill (1988) report $\alpha$ values in the range of 0.4 to 0.9. The $\alpha$ values for residual soils of Malaysia are also within this range. Where soft clay is encountered, a preliminary $\alpha$ value of 0.8 to 1.0 is usually adopted together with the corrected undrained shear strength from the vane shear test. This method is useful if the bored piles are to be constructed on soft clay near river or at coastal area. The value of $\alpha$ to be used shall be verified by preliminary pile load test.

In the case where bored piles are subjected to significant variations in stress levels after installation (e.g. excavation for basement, rise in groundwater table) the use of the effective stress method is more representative as compared to undrained method. This is because the effective stress can take account of the effects of effective stress change on the $K_{se}$ values to be used. The value of ultimate shaft resistance may be estimated from the following expression:

$$f_{su} = K_{se} \times \sigma_v' \times \tan \phi'$$

Where :
$K_{se}$ = Effective Stress Shaft Resistance Factor = [can be assumed as $K_o$]
$\sigma_v'$ = Vertical Effective Stress (kPa)
$\phi'$ = Effective Angle of Friction (degree) of fined grained soils.

However, this method is not popular in Malaysia and limited case histories of back-analysed $K_{se}$ values are available for practical usage of the design engineer.

Although the theoretical ultimate base resistance for bored pile in fine grained soil can be related to undrained shear strength as follows;

$$f_{bu} = N_c \times s_u$$

Where:
$N_c$ = bearing capacity factor

it is not recommended to include base resistance in the calculation of the bored pile geotechnical capacity due to difficulty and uncertainty in base cleaning.

**Coarse Grained Soils**

The ultimate shaft resistance ($f_{su}$) of bored piles in coarse grained soils can be expressed in terms of effective stresses as follows:

$$f_{su} = \beta \times \sigma_v'$$

Where:
$\beta$ = shaft resistance factor for coarse grained soils.

The $\beta$ values can be obtained from back-analyses of pile load tests. The typical $\beta$ values of bored piles in loose sand and dense sand are 0.15 to 0.3 and 0.25 to 0.6 respectively based on Davies & Chan (1981).

Although the theoretical ultimate base resistance for bored pile in coarse grained soil can be related to plasticity theories, it is not recommended to be included in the calculation of the bored pile geotechnical capacity due to difficulty and uncertainty in base cleaning.

## 2.3 Design of Geotechnical Capacity in Rock

The three major rock formations, namely sedimentary, igneous and metamorphic rocks, are commonly encountered in Malaysia. When designing structures over these formations using bored pile, the design approaches could vary significantly depending on the formations and the local experience established on a particular formation.

In Malaysia, bored pile design in rocks is heavily based on semi-empirical method. Generally, the design rock socket friction is the function of surface roughness of rock socket, unconfined compressive strength of intact rock, confining stiffness around the socket in relation to fractures of rock mass and socket diameter, and the geometry ratio of socket length-to-diameter. Roughness is important factor in rock socket pile design as it has significant effect on the normal contact stress at the socket interface during shearing. The normal contact stress increases due to dilation resulting increase of socket friction. The level of dilation is mostly governed by the socket roughness. The second factor on the intact rock strength governs the ability of the irregular asperity of the socket interface transferring the shear force, otherwise shearing through the irregular asperity will occur due to highly concentrated shear forces from the socket. The third factor will govern the overall performance of strength and stiffness of the rock socket in jointed or fractured rock mass and the last factor is controlled by the profile of socket friction distribution. It is very complicated to quantify all these aspects in the rock socket pile design. Therefore, based on the conservative approach and local experience, some semi-empirical methods have evolved to facilitate the quick socket design with considerations to all these aspects. In most cases, roughness of socket is qualitatively considered as a result of lacking of systematic assessing method. Whereas the other three factors can be quantified through strength tests on the rock cores and point load tests on the recovered fragments, the RQD values of the core samples and some analytical method on assessing the socket friction distribution. It is

also customary to perform working load test to verify the rock socket design using such semi-empirical method. Safety factor of two is the common requirements for rock socket pile design. Table 1 summarises the typical design socket friction values for various rock formations in Malaysia.

Table 1 Summary of Rock Socket Friction Design Values

| Rock Formation | Working Rock Socket Friction* | Source |
|---|---|---|
| Limestone | 300kPa for RQD <25%<br>600kPa for RQD =25 – 70%<br>1000kPa for RQD >70%<br><br>The above design values are subject to 0.05x minimum of {$q_{uc}$, $f_{cu}$} whichever is smaller. | Neoh (1998) |
| Sandstone | $0.10 \times q_{uc}$ | Thorne (1977) |
| Shale | $0.05 \times q_{uc}$ | Thorne (1977) |
| Granite | 1000 – 1500kPa for $q_{uc}$ > 30N/mm$^2$ | - |

* Note: Lower range to Grade III and higher range for Grade II or better

Another more systematic approach developed by Rosenberg & Journeaux (1976), Horvath (1978) and Williams & Pells (1981) is also used in Malaysia. The following simple expression is used to compute the rock socket friction with consideration of the strength of intact rock and the rock mass effect due to discontinuities.

$$f_s = \alpha \times \beta \times q_{uc}'$$

Where:
$q_{uc}$ is the unconfined compressive strength of intact rock
$\alpha$ is the reduction factor with respect to $q_{uc}$ (Figure 1)
$\beta$ is the reduction factor with respect to the rock mass effect (Figure 2)

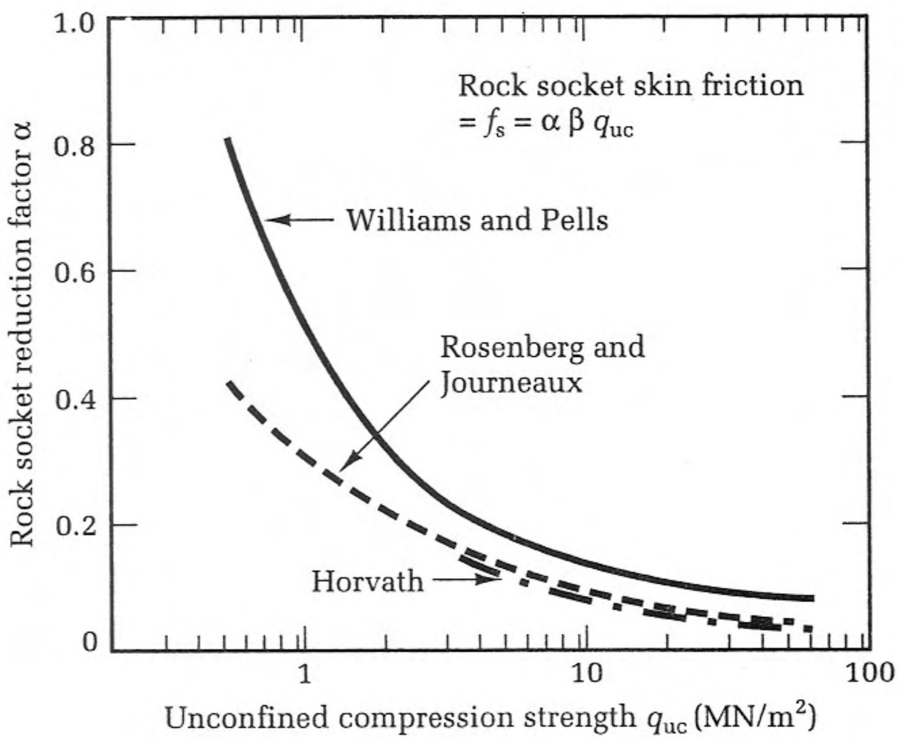



Figure 1 Rock Socket Reduction Factor, $\alpha$, w.r.t. Unconfined Compressive Strength (after Tomlinson, 1995)

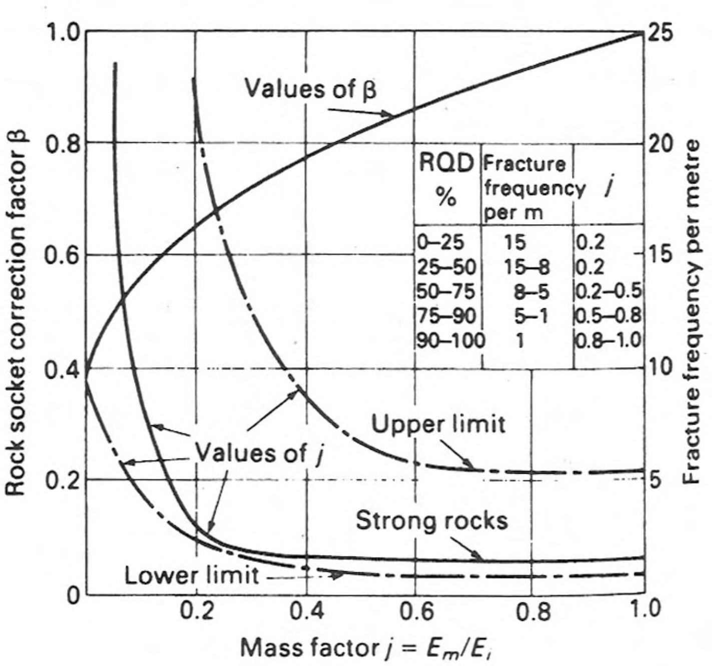



Figure 2 Rock Socket Reduction Factor, β, w.r.t. Rock Mass Discontinuity (after Tomlinson, 1995)

During borehole exploration, statistics of $q_{uc}$ can be established for different weathering grade of bedrock and the rock fracture can be assessed through the Rock Quality Designation on the rock core recovered or by interpretation of pressuremeter modulus in the rock mass against the elastic modulus of intact rock, which is equivalent to mass factor j, which is the ratio of elastic modulus of rock mass to that of intact rock, as in Figure 2. Alternatively, Figure 3 can provide some indications of the modulus ratio of the rock mass. In the some cases, at very small cost, point load test equipment is used to assess and verify the rock strength on the recovered rock fragment during bored pile drilling after proper calibration with borehole results.

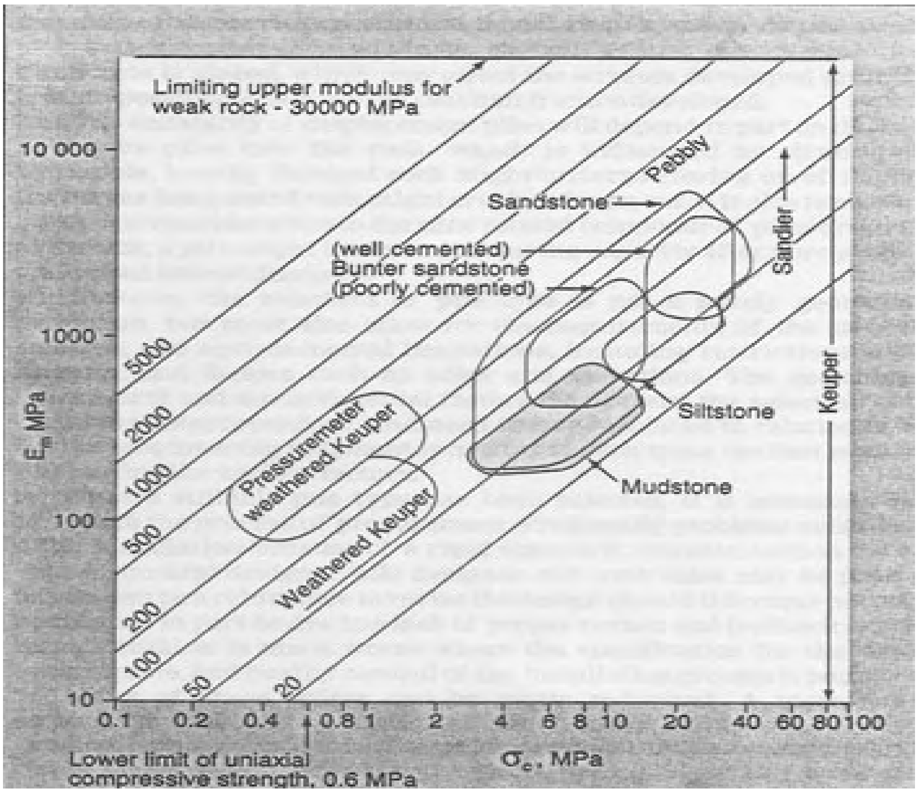



Figure 3 Modulus Ratio Ranges
(after Hobbs,1974)

Due to difficulties on quantification of socket roughness, the effect of roughness has not been explicitly addressed in the above approach, but rather implicitly included in the $\alpha$ factor with certain socket construction method. Based on the works by Kulhawy & Phoon (1993), in which is an extension of the above mentioned model by modifying the friction reduction factor with respect to different socket roughness as shown in the following expression and Figure 4, Seidel & Haberfield (1995) have further developed the theoretical methodology and a computer program, "Rocket" for rock socket design. However, it has not gained wide acceptance in Malaysia as a result of requiring special measuring equipment for the socket roughness for the input of the said computer program. Nevertheless, Figure 4 does provide useful reference on limestone, sandstone, shale, mudstone and clay to account for the socket roughness. The parameter, $\psi$, is used to represent the socket roughness.

$$\alpha = \psi \times (q_{uc}/2p_a)^{-1/2}$$

Where:

$\psi$ : Indicator of socket roughness

$p_a$ : Atmospheric pressure for normalisation

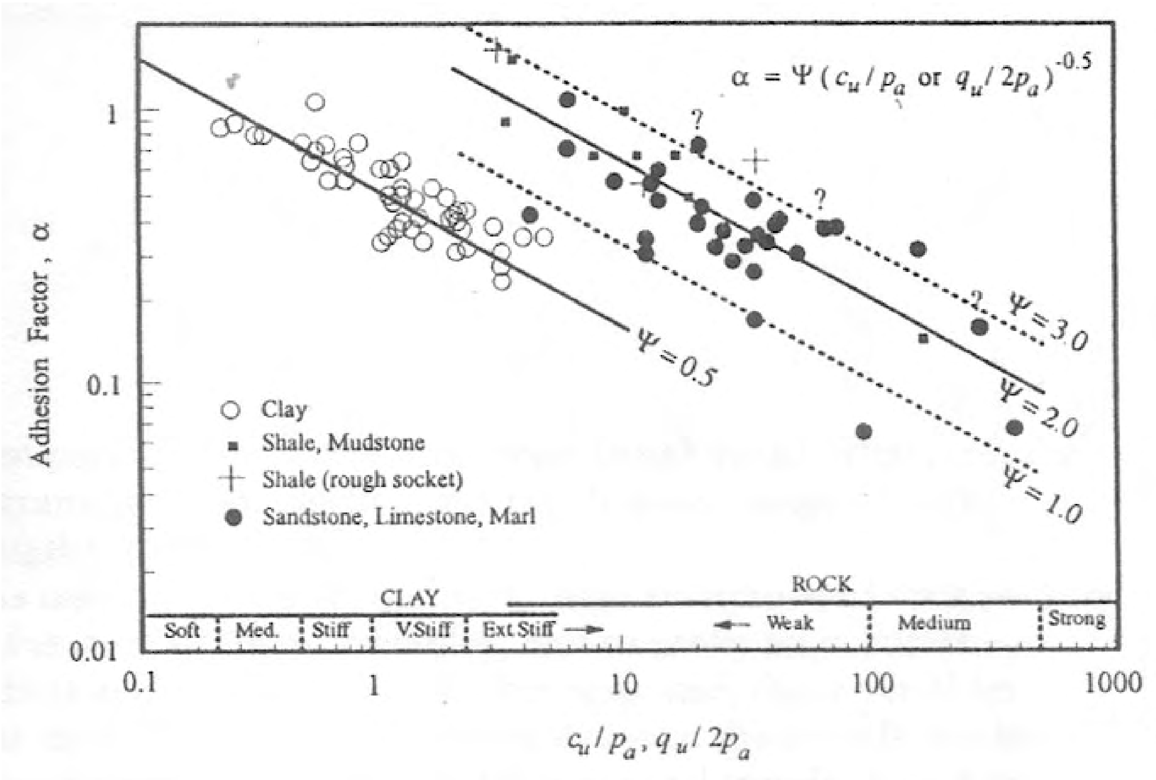



Figure 4 Relation between Socket Roughness, Socket Reduction Factor and Normalised Rock Strength (after Kulhawy & Phoon,1993)

It is also important to optimise rock socket design with due consideration of the load transfer behaviour of the socket. Figure 5 shows the analytical results of the socket load transfer behaviour for modulus ratio, $E_p/E_r$ ranging from 0.25 to 1000. As shown in the figure, it is obvious that there is really no reason to extend the socket beyond 5 times the pile diameter for $E_p/E_r$ =0.25 (very competent intact rock) as no load will be transferred below this socket length.

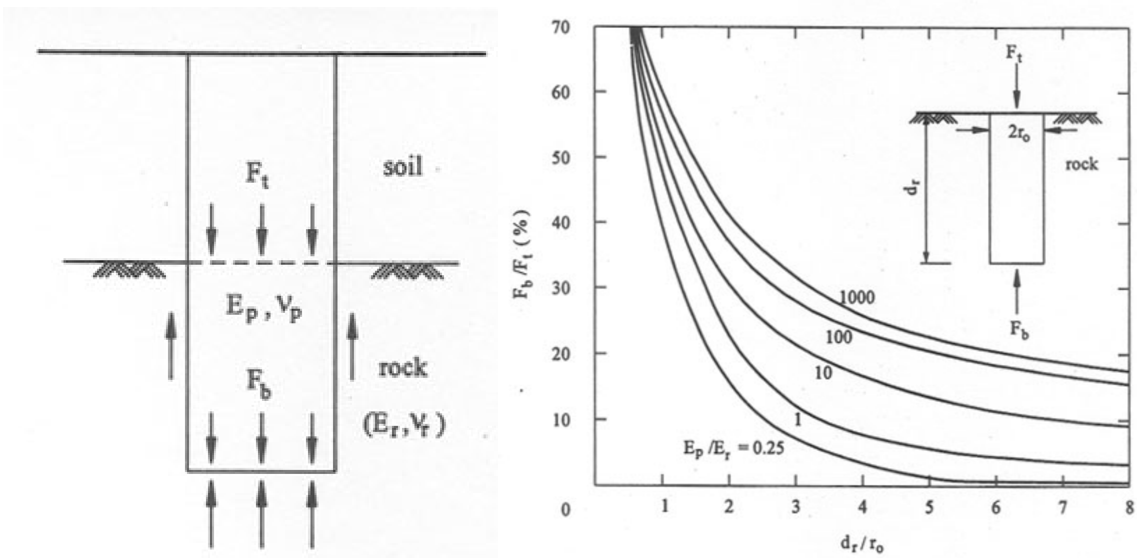



Figure 5 Distribution of Socket Resistance w.r.t. Socket Length and Modulus Ratio (after Pells & Tuner, 1979)

Sometimes, the borehole is a dry hole and at shallow depth, then base resistance will be considered if the base cleaning and inspection of the base condition can be carried out.

Very often, the movement to mobilise the base resistance is few folds higher than that to mobilise the socket friction despite the ultimate base resistance could be very high. As such, with consideration of compatibility of the pile movement in mobilising both the socket and base, appropriate mobilising factors to both the socket and base shall be applied to the foundation design after verification from the fully instrumented pile load test. Such mobilising factor shall be at least 3, but finally subjected to verification by instrumented load test prior to production of working piles if there is large number of piles for value engineering. The assessment of ultimate end bearing capacity of bored pile in rock can be carried using the following expression.

$$Q_{ub} = cN_c + \gamma BN_\gamma/2 + \gamma DN_q$$

Where:

| | |
|---|---|
| c : | Cohesion |
| B : | Pile diameter |
| D : | Depth of pile base below rock surface |
| $\gamma$ : | Effective density of rock mass |
| $N_c$, $N_\gamma$ & $N_q$ : | Bearing capacity factors related to friction angle, $\phi$ (Table 2, for circular case, multipliers of 1.2 & 0.7 shall be applied to $N_c$ & $N_\gamma$ respectively) |
| $N_c$ : | $2N_\phi^{1/2}(N_\phi+1)$ |
| $N_\gamma$ : | $N_\phi^{1/2}(N_\phi^2-1)$ |
| $N_q$ : | $N_\phi^2$ |
| $N_\phi$ : | $\tan^2(45°+\phi/2)$ |

Table 2 Typical Friction Angle for Intact Rock (Wyllie, 1991)

| Classification | Type | Friction Angle |
|---|---|---|
| Low Friction | Schist (with high mica content), Shale | 20° - 27° |
| Medium Friction | Sandstone, Siltstone, Gneiss | 27° - 34° |
| High Friction | Granite | 34° - 40° |

If the pile length is significant, the contribution of the shaft resistance in the soil embedment above the rock socket shall also be considered in the overall pile resistance assessment. In most cases for rock socket pile, the settlement performance is usually governed by the elastic shortening of the pile shaft. The socket displacement is usually insignificant. However, load transfer analyses would provide the overall settlement performance.
Construction method is another important aspect to be considered in the bored pile design on rock. In Malaysia, there are two most common methods in forming the rock socket, namely rock coring with rock cutting bits and chiselling by mechanical impact. Both methods have their own merits and need skilful operator to form a proper rock socket. In general, rock coring method will form a smoother, but intact, socket surface. Whereas chiselling method will form relatively rougher socket, but could be more fracture due to disturbance to the inherent discontinuities in bedrock. Chiselling is usually used as a supplementary technique in drilling through hard rock.

There are also other inherent problems associated with some of the aforementioned rock formations such as:

a. Limestone: Existence of erratic karst features will need further consideration in the foundation pile design. Downgrading of pile capacity for piles founded on these karst features or install the pile at deeper depth to penetrate these features or treatment to strengthen them can be considered depending on the cost-benefit analyses of the viable options. Another problem in limestone formation is the existence of slime made of very loose sand or soft silty clay immediately above the bedrock, which can cause frequent cave-in and pose difficulties in cleaning up the rock socket. Chan &

Hong (1985) presented the problems of pile construction over limestone. European Foundations (1998) presented the problems encountered in pile construction in Kuala Lumpur limestone. Gue (1999) presented some solutions to overcome the abovementioned problems and the construction controls.

b. Degradable sedimentary formations: These formations easily subject to rapid degradation in terms of strength and stiffness as a result of stress relief and ingression of drilling fluid. Slow progress in drilling operation due to inefficient coring method or inter-layered hard and soft rocks and delay in concreting the piles are the usual causes of such softening. The solutions to these problems are to use powerful drilling equipments and avoid delay in concreting.

c. Granite: Core boulders are common features in this formation. This feature can be easily observed from the outcrops or along river. Therefore, it is important to identify proper founding stratum for the foundation piles during the subsurface investigation. This can be overcome by careful assessment of the weathering profile interpreted from the deep boring exploratory holes.

## 2.4 Verification of Bored Piles Capacity

For the verification of bored pile capacity, maintained load test is the normal mean specified by most practicing engineers. In certain cases where detailed interaction behaviours between the pile and the foundation formations are of interest to the designer for design refinement and value engineering, full scale instrumented test pile equipped with multi-level strain gauges, extensometers and occasionally Osterberg load cell and polyfoam soft toe are constructed and tested depending the objective of the verification. Conventional static maintained load test is the most common verification pile test adopted by the design engineers in Malaysia. Quick maintain load test has also gained wide acceptance for the test piles in Malaysia. Other indirect tests, such as high strain dynamic pile and statnamic pile tests, have been occasionally used to verify the design.

## 3.0 Structural Requirements of Bored Pile

Following are some brief guidelines for structural design of bored piles:

a) Allowable structural capacity of bored piles (BS8004, Clause 7.4.4.3.1)

Allowable structural capacity of bored piles = 0.25 x $f_{cu}$ x $A_c$

Where:

$f_{cu}$ = concrete cube strength at 28 days (Grade 30 to 35 is most common)

$A_c$ = cross-sectional area of the pile

b) Cover for reinforcement (BS8004, Clause 2.4.5)

Cover for reinforcement = (40mm + values in Table 3.4, BS8110: Part 1)

For example, bored piles (concrete G35) in non-aggressive soil shall required minimum cover of (40mm + 35mm) = 75mm

c) Reinforcement (BS8110: Part 1)

For bored piles in compression only, the structural capacity is derived from the concrete strength alone and some nominal reinforcement is sometimes provided to prevent damage during construction. However, for bored piles supporting bridges where there will be bending moment and shear force acting on the piles, then the bored piles can be designed like beam. Length of the reinforcement can be curtailed until the influence depth of the flexural effect. Hanging the steel cage without the lower supporting steel reinforcements has been successfully carried out. However, for ease of construction, minimum steels are sometimes provided right to the bottom of the bored pile to support the upper steel cage during concrete casting.

## 3.1 Verification of Concrete Quality for Bored Pile (Integrity Tests)

Besides verification of capacity, concrete quality of bored piles is also an important aspect of design and construction of bored piles. Concreting for bored piles is usually carried out using tremie (self-compacting) concrete. Some general recommendations on tremie concrete as given by BS8004: 1986 are summarised below:

a) The concrete should be cohesive, rich in cement (i.e. not less than 400 kg/$m^3$) and of slump not less than 150 mm.
b) The sides of the borehole have to be stable. This may be achieved by maintaining an adequate head of fluid or by the provision of a temporary casing of the necessary length.
c) The tremie pipe should be watertight throughout its length and have a hopper attached at its head by a watertight connection.
d) The tremie pipe should be large enough in relation to the size of aggregate. For 20 mm aggregate the tremie pipe should be of diameter not less than 150 mm, and for larger aggregate tremie pipes of larger diameter are required.
e) The tremie pipe should be lowered to the bottom of the boreholes allowing ground water to rise inside it. It is essential to prevent the tremie concrete from mixing with water in the tremie pipe and to this end a plug or other devise should be used.
f) The tremie pipe should always be kept full of concrete and should penetrate well into the concrete in the borehole with an adequate margin of safety against accidental withdrawal if the pipe is surged to discharge the concrete.

g) The pile should be concreted wholly by tremie and the method of deposition should not be changed part way up the pile, to prevent the laitance from being entrapped within the pile.
h) If the time taken to form large piles is likely to be excessive, the use of set retarding admixtures should be considered, particularly in the case of high ambient temperatures.
i) All tremie pipe should be scrupulously cleaned before use.
j) When drilling muds such as bentonite suspension are used, the fluid at the pile base should be checked for contamination before concreting to ensure that it will be readily displaced by the rising concrete.

BS8004: 1986 also recommends the following slump details for concrete used in bored pile construction:

Table 3 Slump details for concrete used in bored pile construction

| **Typical conditions of use** | **Slump Range** | |
|---|---|---|
| | **mm** | **in** |
| Poured into water-free unlined bore. Widely spaced reinforcement leaving ample room for free movement between bars. | 75 to 125 | 3 to 5 |
| Where reinforcement is not spaced widely enough to give free movement between bars. Where cut-off level of concrete is within casing. Where pile diameter is less than 600 mm. | 100 to 175 | 4 to 7 |
| Where concrete as placed by tremie under water or bentonite suspension. | 150 to collapse | 6 to collapse |

Tests normally specified as a mean of quality control for concrete during construction include low strain dynamic load test (e.g. Pile Integrity Test, PIT) and Sonic Logging Test. This test is primarily used to detect any concrete defects such as honey-combing, cold joints, cracks, etc. which may affect the overall performance of the bored pile. Some typical results of integrity tests are shown in Figure 6 and Figure 7:

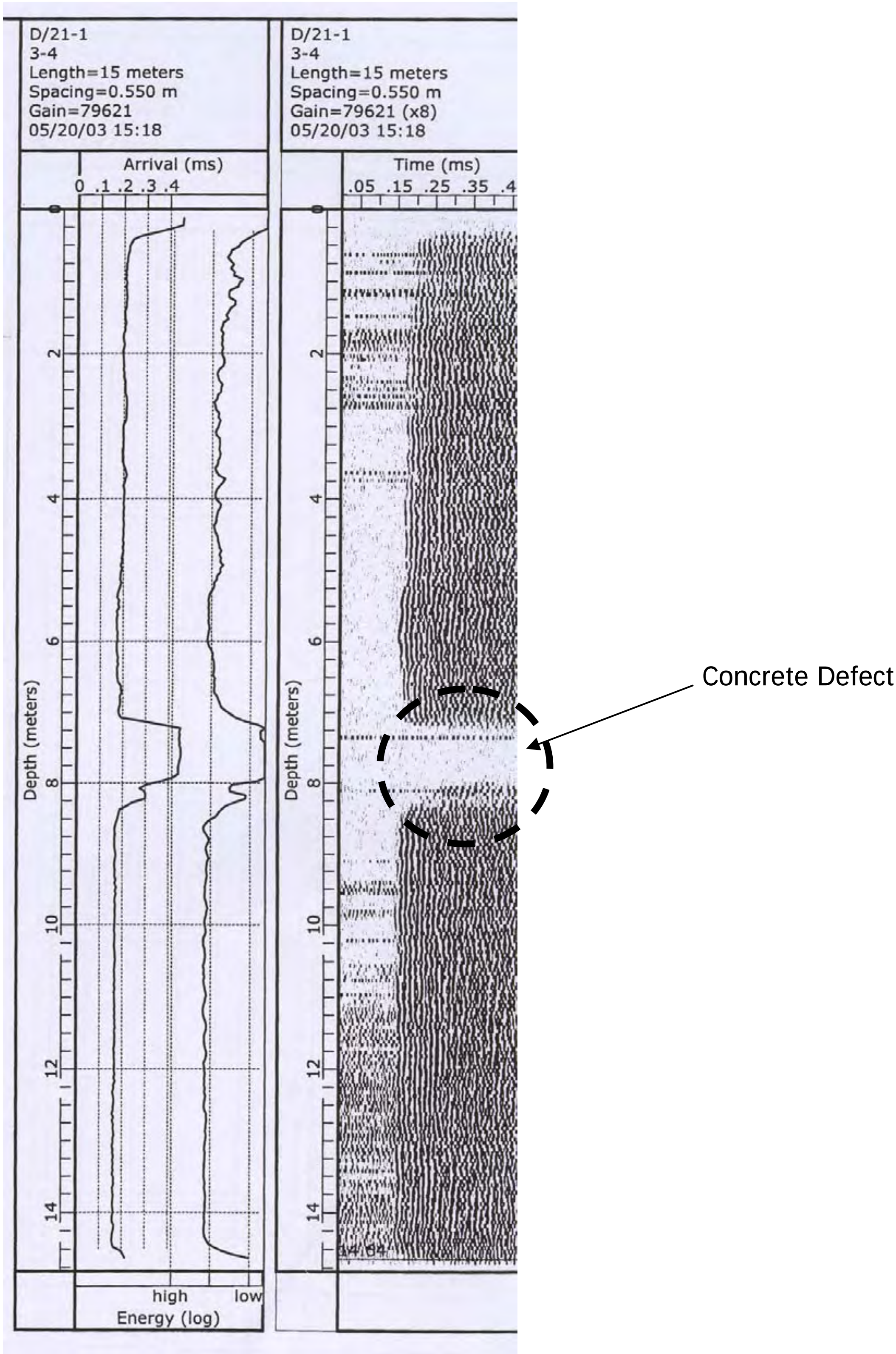



Figure 6 Typical Results for Sonic Logging Test Showing Defect in Concrete

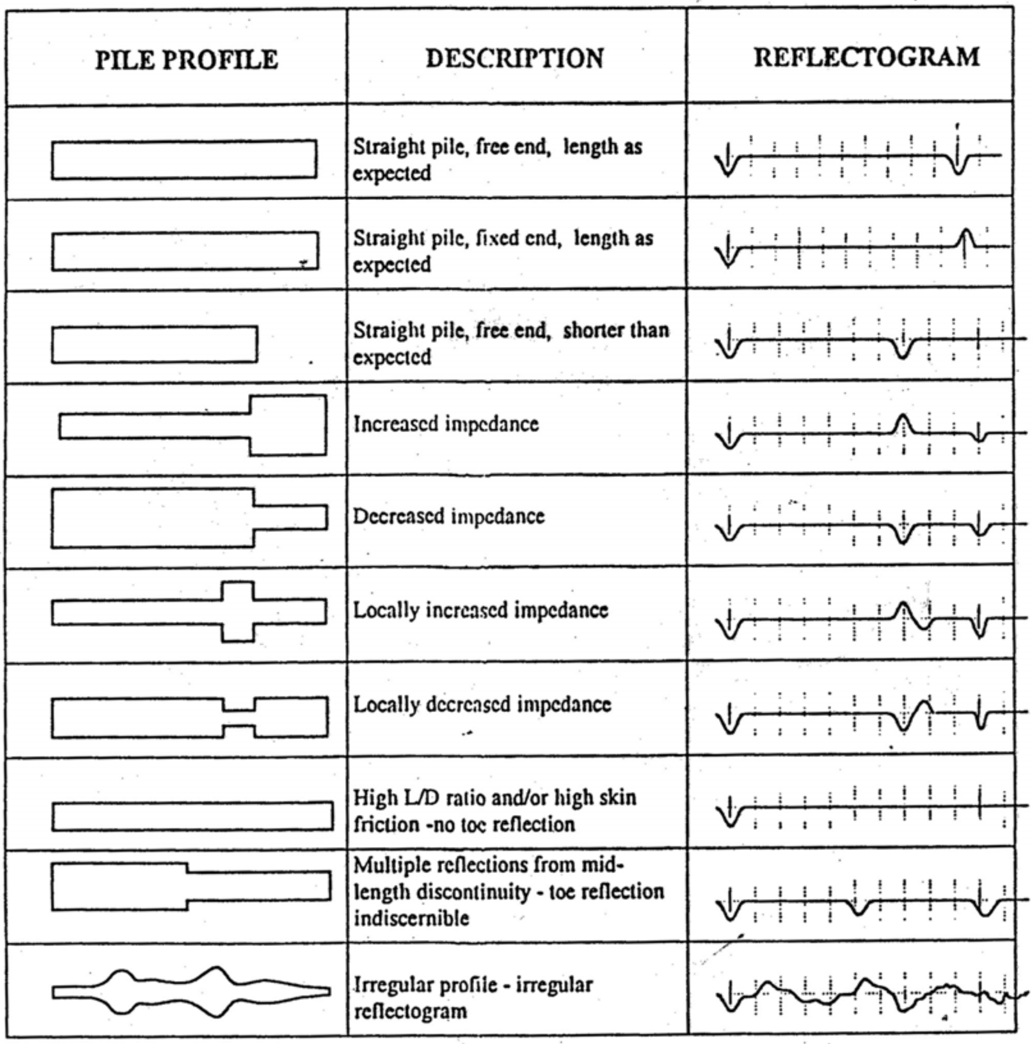



Figure 7 Typical Reflectograms from PIT Test

## 4.0 Design and Construction of Bored Piles in Difficult Ground Conditions

Design and construction of bored piles in difficult ground conditions such as limestone areas and soft ground requires careful understanding on the pile performance, geological conditions and soil mechanics. Design aspects for bored piles in such ground conditions require careful assessment of geotechnical parameters such as rock skin friction (limestone area) and soil strength parameters (soft ground). The evaluation of rock skin friction can be carried out using the methods highlighted in Section 2.2 with due consideration in determining the true bedrock level. It is important that karstic features such as overhangs, solution cavities and floaters are not mistaken as bedrock and it is usually required to specify a more stringent termination criteria of 10m of solid coring into rock in limestone areas during subsurface investigation using borehole.

Construction of bored piles in limestone areas often requires good collaboration between the design engineer and the contractor. This is due to the highly variable ground conditions which require significant input from site personnel and in addition to good geotechnical design, it is recommended that the “observational approach” to be adopted for bored piles construction in limestone areas. Such arrangement will enable any unexpected geological formation and uncertainties to be detected and changes to the design can be made immediately to ensure a safe and cost effective design. Usually some forms of ground treatments are carried out prior to the piling works (e.g. compaction grouting) or modifications are made to the method of construction.

Figure 8 Modified Rock Coring Tool for Bored Pile Construction in Limestone Area

Figure 8 shows a modified rock coring tool used for bored pile construction in limestone area. Such tool enables the casing to penetrate (reamed into) to the required rock socket length and thus prevents problems such as collapse of loose soil (slime) surrounding the bored hole normally associated with construction of rock-socketed piles as illustrated in Figure 8 below:

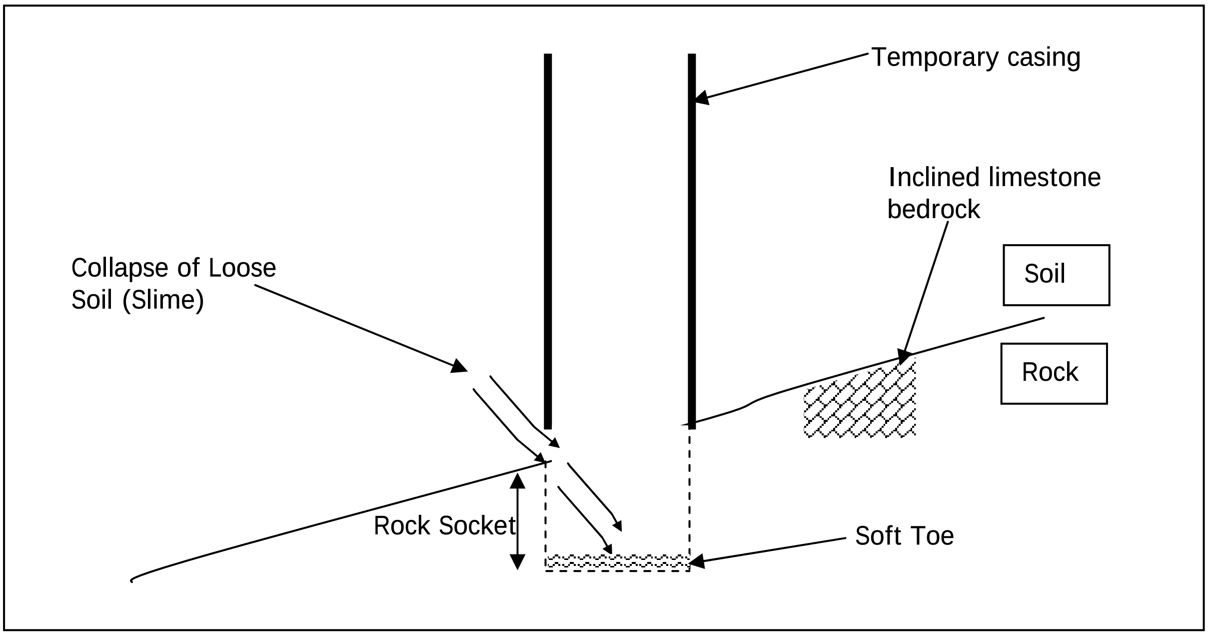



Figure 9 Collapse of Loose Soil (Slime) Surrounding the Bored Hole

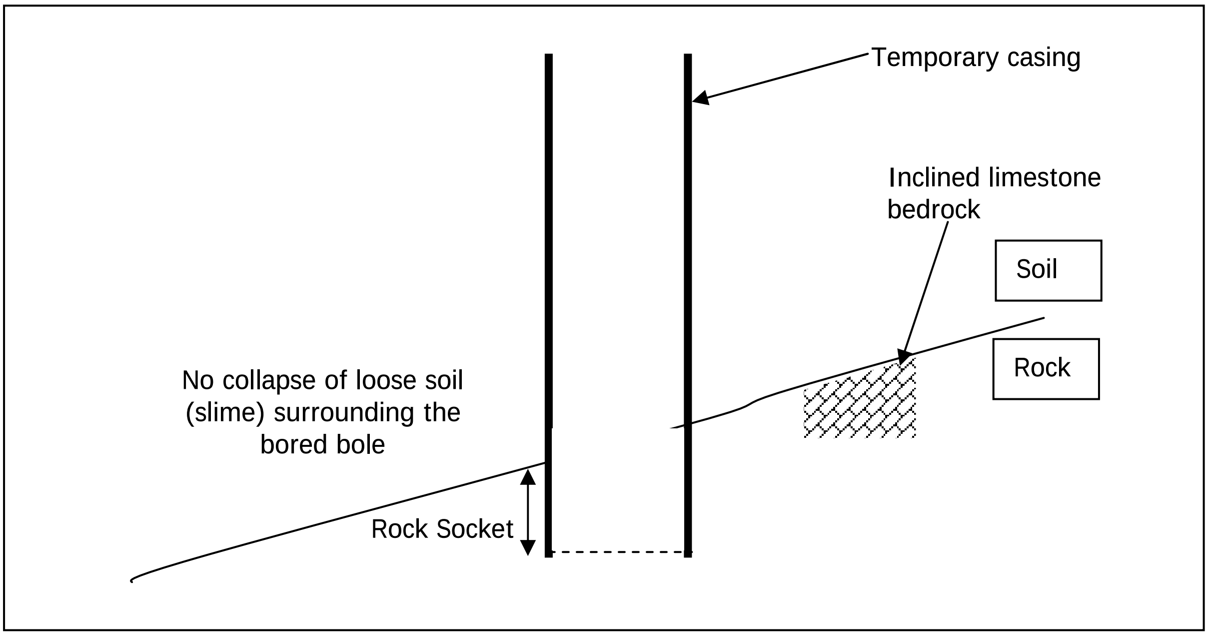



Figure 10 Performance of Modified Coring Tool

Figure 10 illustrates the performance of the modified coring tool in preventing the above problem at the interface between rock and soil by coring through to the required socket depth together with the casing. Conventional method of construction where the temporary casing is installed using vibro-hammer is unable to penetrate into the rock layer and thus causes situation such as those shown in Figure 9.

Design of bored piles in soft ground also presents difficulties in the ability of the excavated hole to remain open prior to formation of the pile (concreting). For very large bored piles, base failure of the excavated base may be a problem in soft ground, preventing the piles from achieving the design toe level or length. Two forms of base failure can manifest, i.e.:

a) Basal heave failure

   Such failure is prone to occur in very soft and soft clays and silty clays. This failure mechanism is analogous to a bearing capacity failure, only in reverse being that stresses in the ground are relieved instead of increased. There are many methods to examine the basal heave failure and two of the more popular and simple methods enabling a quick assessment are the methods given by Bjerrum & Eide, 1956 and Terzaghi, 1943 as shown in Figure 11. This failure can be prevented by using suitable drilling fluid to stabilise the hole.

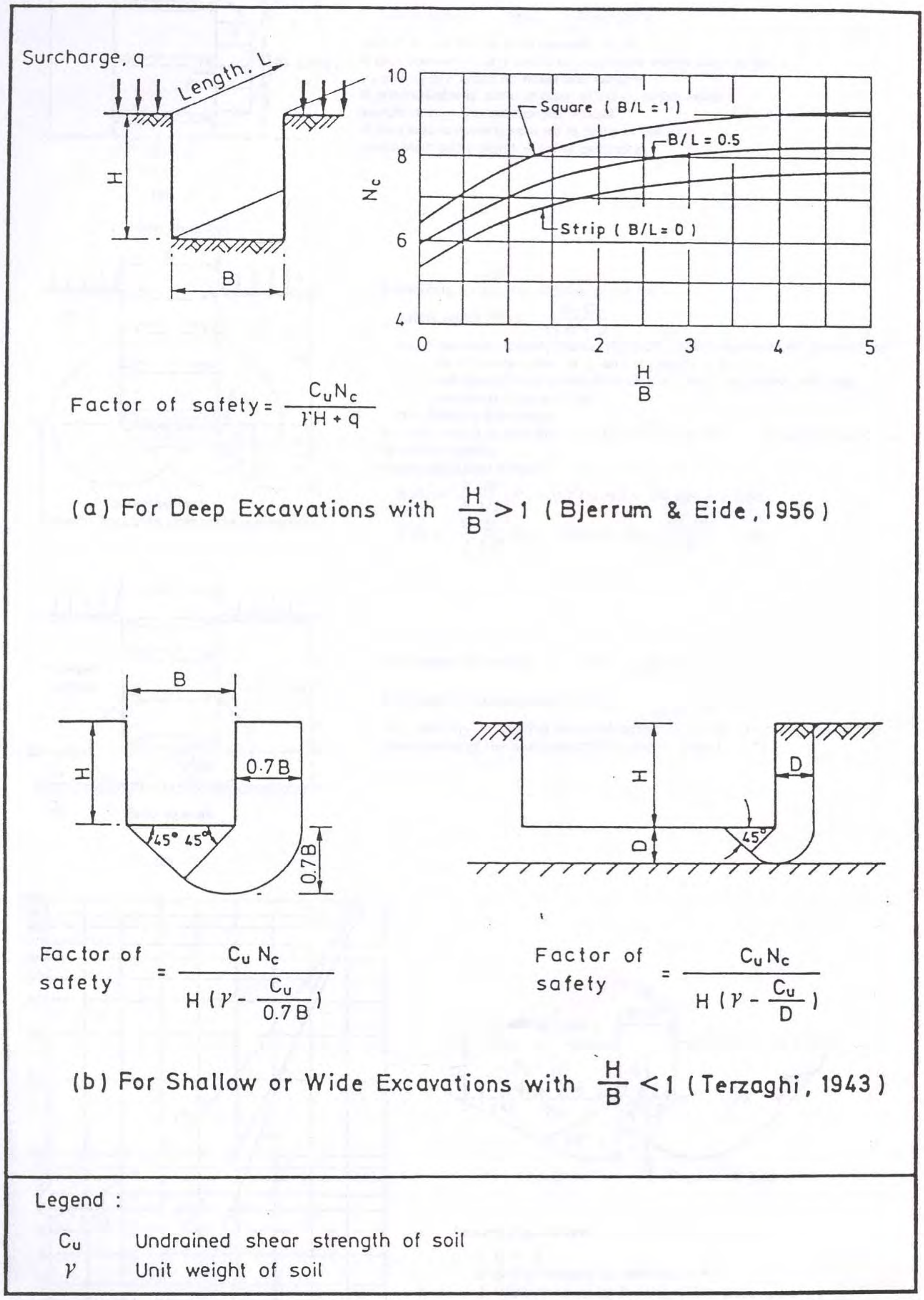



Figure 11 Basal Heave Failure Analysis

b) Hydraulic failure (Boiling)

For site with high groundwater level in sandy subsoil, a simple check against hydraulic failure can also be carried out to assess the constructability of the piles in such conditions. This problem can also be easily solved by using suitable drilling fluid to balance the hydrostatic pressure. The simple Terzaghi's method can be used in this respect as shown below:

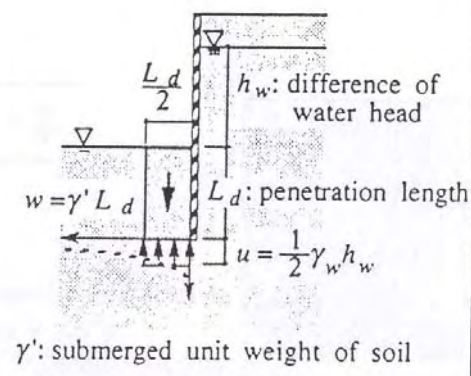
| | (1) Terzaghi's method |
|---|---|
| Diagram |  |
| Formula | $F_s = w / u = \frac{2\gamma' L_d}{\gamma_w h_w}$ |
| Remarks | * Failure width by boiling is equivalent to half of penetration length of wall.<br>* Neglecting head loss in the retained ground above excavation bottom.<br>* Groundwater level in the retained ground is unchanged. |

Figure 12 Hydraulic Failure Analysis

## 5.0 Prediction of Bored Pile Settlement

In order to optimise the design of bored pile, it is important to be able to correctly predict both bearing capacity and settlement of pile under different loading. In view of this, a simple load-transfer method (Coyle & Reese, 1966) can be utilised to predict the load-settlement and load distribution of a pile. However, to obtain reasonably reliable prediction of load-settlement characteristics of pile using this method will require sufficient good quality database of load-transfer curves and parameters from fully instrumented test piles tested in similar ground condition to be available for a better correlation with soil properties and pile geometry. Tan et al. (1998) suggests load-transfer parameters obtained from the testing of full-scale instrumented bored piles in residual soil of Malaysia. The necessary correlations to SPT'N' values are also reported.

### 5.1 Load Transfer Curves for Shaft

The development of shaft resistance is dependent on the relative settlement between the subsoil and the pile shaft and can be expressed as follows:

$$Q_s = \sum_i [f_s(z_s).\ A_s]$$

Where:

| | | |
|---|---|---|
| $Q_s$ | = | Total Shaft Capacity of the Pile (kN) |
| $f_s(z_s)$ | = | Unit shaft resistance for each layer of soil with relative displacement of $z_s$. (kPa) |
| $i$ | = | Number of soil layer. |
| $z_s$ | = | Shaft displacement (mm) |
| $A_s$ | = | Pile shaft area at each soil layer |

Figure 13 shows a typical load transfer curve for shaft. Shaft displacement, $z_s$ is the relative displacement between the pile/soil interface at the mid-depth of each soil stratum.

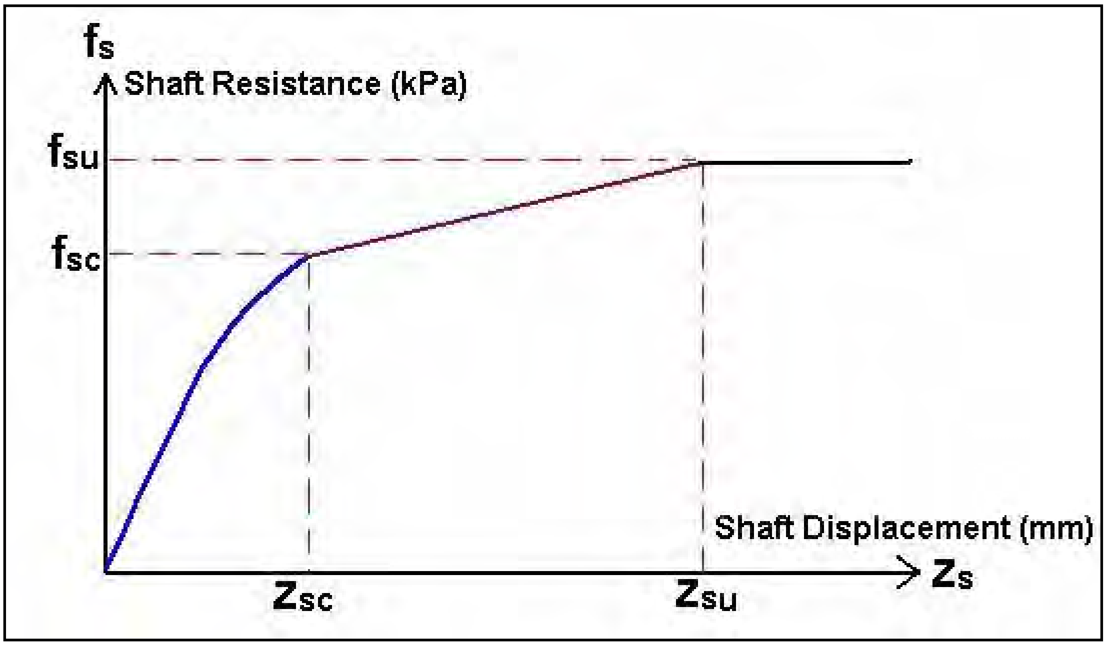



Figure 13 Typical Load Transfer Curve for Shaft

Where:

| | | |
|---|---|---|
| $f_{sc}$ | = | Critical shaft resistance corresponding to critical shaft displacement (kPa) |
| $z_{sc}$ | = | Critical shaft displacement (mm) |
| $f_{su}$ | = | Ultimate shaft resistance corresponding to ultimate shaft displacement (kPa) |
| $z_{su}$ | = | Ultimate shaft displacement (mm) |

The measured load transfer curves obtained from 13 nos. of instrumented test piles are normalised against critical shaft resistance ($f_{sc}$) and critical shaft displacement ($z_{sc}$). The normalised load transfer curve is shown in Figure 14.

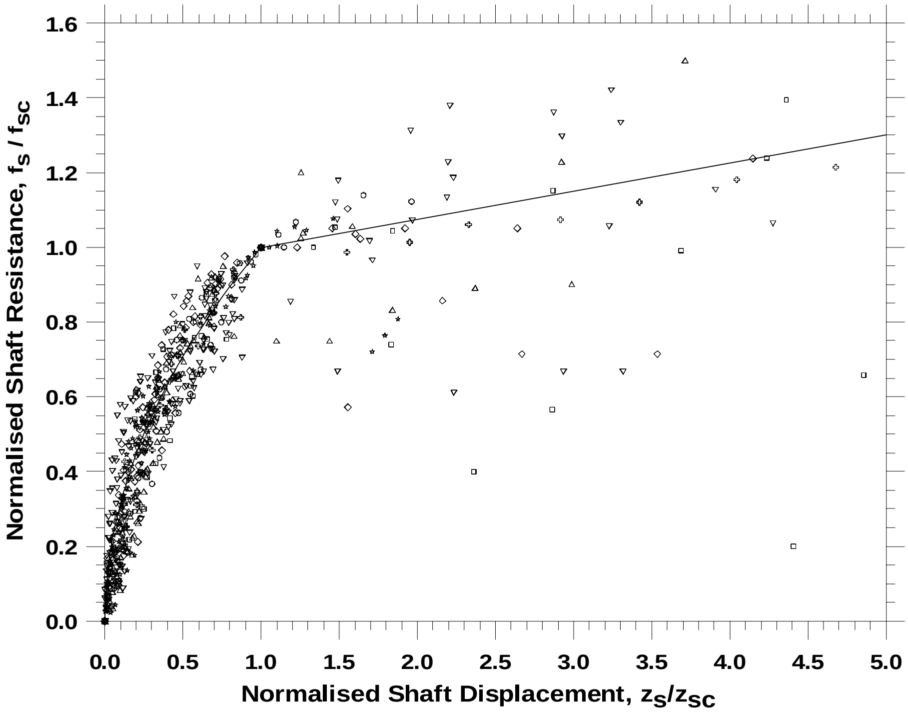



Figure 14 Normalised Load Transfer Curves for Shaft (after Tan et al., 1998)

The best-fit curve obtained to model the load-displacement characteristic of the shaft resistance is as follows:

$$(f_s/f_{sc}) = (z_s/z_{sc})^{1/2} \;\; ; \text{for } (z_s/z_{sc}) < 1.0$$

$$(f_s/f_{sc}) = 1 + \frac{3}{50}(z_s/z_{sc}) \; ; \text{for } 1.0 < (z_s/z_{sc}) < 5.0 \text{ ; and}$$

$$(f_s/f_{sc}) = 1.3 \;\; ; \text{for } (z_s/z_{sc}) > 5.0$$

and

$$f_{sc} = 2 \times \text{SPT'N' (kPa)} \leq 150 \text{ kPa}$$

$$z_{sc} = \text{can be obtained from Figure 8.}$$

There are many factors that have influence on the value of critical shaft displacement ($z_{sc}$) of bored pile and they are drilling method (dry or wet), type of drilling fluid, type of soil, spatial variation of soil properties (stiffness and strength), drilling and concreting duration, drilling tools and also diameter of piles. Tan et al. (1998) selected two key factors, namely the pile diameter and soil strength (via SPT'N' values), that can be easily quantified to evaluate their relationship with $z_{sc}$ and are presented in Figure 15. In general, the critical shaft displacement increases with the increase of pile diameter or decrease in SPT'N' values.

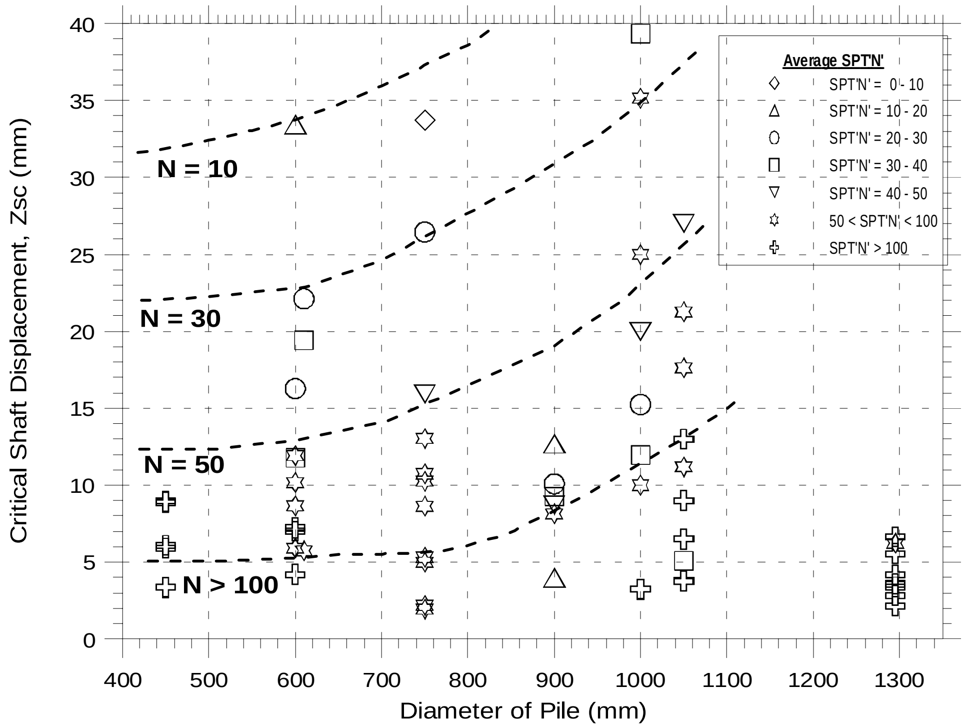



Figure 15 Relationship of $z_{sc}$ with pile diameter & SPT'N' (after Tan et al., 1998)

## 5.2 Load Transfer Curves for Base

Similar to shaft resistance, the load transfer curves for base can be normalised and presented in Figure 16.

The best-fit curve obtained to model the load-displacement characteristic of the base resistance is as follows:

$$(f_b/f_{bc}) = (z_b/z_{bc})^{2/3}$$

Where:

$f_{bc}$ = Critical base resistance corresponding to critical base displacement (kPa)

$z_{bc}$ = Critical base displacement (mm)

Note: From the field tests, the $f_{bc}=f_{bu.}$

$$f_{bc} = (7 \text{ to } 10) \times SPT'N' \text{ (kPa)}$$
$$z_{bc} = 5\% \text{ of pile diameter.}$$

Note: When using the value above, proper base cleaning using cleaning bucket shall be carried out at site.

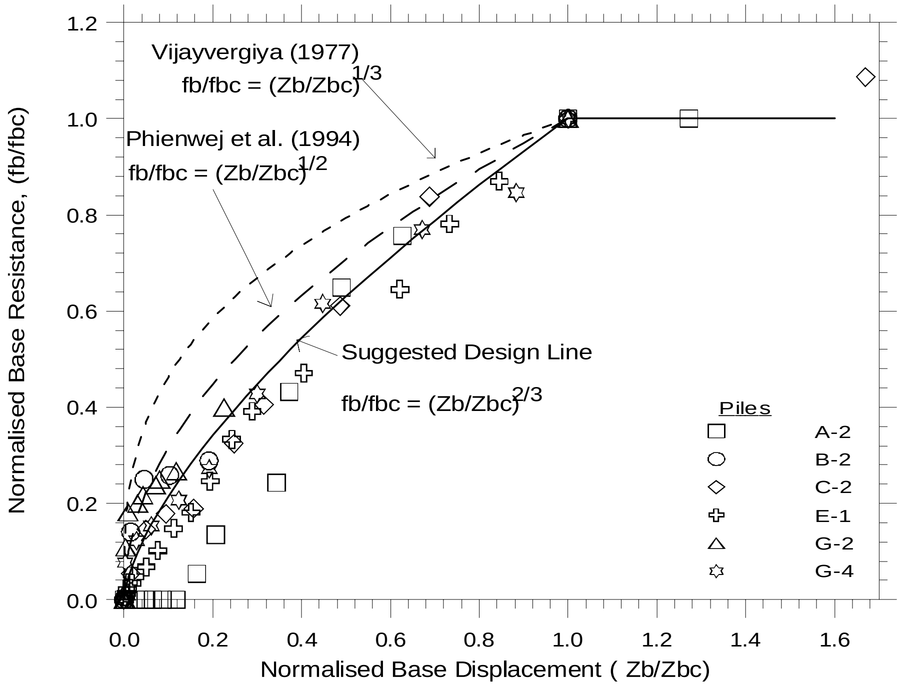



Figure 16 Normalised Base Resistance and Displacement (after Tan et al., 1998)

## 6.0 Conclusions

From the above elaborations, the following conclusions can be drawn for the design and construction of bored pile in Malaysia:

1. For the design of bored piles in soil, the two common methods, namely semi-empirical and simplified soil mechanics methods are commonly used to determine the ultimate pile capacity.
2. For the safety margin of pile capacity, partial safety factor of 1.5 and 3.0 for shaft and base resistances respectively and global safety factor of 2.0 applied to overall ultimate pile capacity (sum of ultimate shaft and base resistances) are used.
3. The use of load transfer method is important to optimise the pile design for value engineering and also provide settlement performance.
4. For rock socket pile design, design approach and charts with consideration of socket roughness, rock strength, rock mass stiffness and socket geometry are presented and discussed.
5. In most scenarios, base resistance of bored pile is usually ignored due to uncertainties in cleaning. Unless for the case of dry hole and inspection of the base is possible, then base resistance can be considered with appropriate mobilising factor.
6. Instrumentation test pile is used for design optimisation and value engineering if there are sufficient pile points for the project to justify the testing cost.

Note: The sample specifications for bored piling, testing of bored piling and checklist for construction of bored pile are attached in Appendix for further reference. Many other specifications, checklists and technical papers prepared by Gue & Partners Sdn Bhd can be downloaded from our website at ***www.gueandpartners.com.my***.

## REFERENCES

Aurora,R.R. & Reese, L.C. (1976), Field Tests of Drilled Shafts in Clay-Shales. *Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering*, Tokyo, Vol.2, pp.371-376.

British Standard Institution, BS8004 : Code of Practice for Foundations

British Standard Institution, BS8110 : The Structural Use of Concrete

Coyle, H.M. & O'Neill, M.W. (1989), New Design Method for Drilled Shafts from Common Soil and Rock Tests, *Proceedings of the Congress on Foundation Engineering : Current Principles & Practices*, Evanston, Illinois.

Coyle, H.M. & Reese, L.C. (1966), Load Transfer for Axially Loaded Piles in Clay, *ASCE Journal of the Soil Mechanics and Foundation Division*, 92(SM2), pp.1-26.

Chan, S.F. & Hong, L.P. (1985), Pile Foundations in Limestone Areas of Malaysia. *Proc. 8th Southeast Asian Geo. Conf*, Kuala Lumpur.

Chang, M.F. & Broms, B.B. (1991), Design of Bored Piles in Residual Soils based on Field-Performance Data, *Canadian Geotechnical Journal*, Vol.28, pp.200-209.

Davies, R.V. & Chan, A.K.C. (1981). Pile Design in Hong Kong. *Hong Kong Engineer.* Vol. 9, no. 3, pp 21-28.

European Foundations (1998), Looking for the Hard Rock, *European Foundations Spring*, pp.22-23.

Fleming, W.G.K., Weltman, A.J., Randolph, M.F. & Elson, W.K. (1992), "Piling Engineering", *2nd Edition, Blackie Academic & Professional, Glasgow, UK.*

Gue, S. S. and Tan, Y. C. (1998) "Design and Construction Considerations for Deep Basement", Special Lecture, *Lecture on Design and Construction Considerations for Deep Basement, The Institution of Engineers, Malaysia, Northern Branch (Penang), Penang, Malaysia.*

Gue, S.S. (1999), Foundations in Limestone Areas of Peninsular Malaysia, *Civil and Environmental Engineering Conference – New Frontiers & Challenges*, Bangkok, Thailand.

Gue, S. S., Tan Y.C. and Liew, S. S. (2003) " A Brief Guide to Design of Bored Piles under Axial Compression – A Malaysian Approach", *Seminar and Exhibition on Bridge Engineering*, *Bridge Engineering for Practising Engineers: A Practical Approach*, *Association of Consulting Engineers Malaysia, Kuala Lumpur, Malaysia.*

Hobbs, N.B. (1974), Factors affecting the Prediction of Settlement of Structures on Rock, *Proc. of the Conf. on Settlement of Structures, Cambridge: Pentech Press*, pp. 579-610.

Horvath, R.G. (1978), Field Load Test Dataon Concrete to Rock Bond Strength, *University of Toronto, Publication No. 78-07*.

Kulhawy, F.H. & Phoon, K.K. (1993), Drilled Shaft Side Resistance in Clay Soil to Rock. *Proc. On Conf. on Design and Performance of Deep Foundations : Piles and Piers in Soil and Soft Rock. Geotechnical Special Publication No. 38. ASCE*, pp. 172-183.

Neoh, C. A. (1998), Design & Construction of Pile Foundation in Limestone Formation, *Journal of Institution of Engineers, Malaysia*, Vol. 59, No. 1, pp.23-29.

Pells, P.J.N. & Tuner, R.M. (1979), Elastic Solutions for Design and Analysis of Rock Socketed Piles, *Canadian Geotechnical Journal, Vol. 16*, pp. 481-487.

Phienwej, N., Balakrisnan, E.G. & Balasubramaniam, A.S. (1994), Performance of Bored Piles in Weathered Meta-Sedimentary Rocks in Kuala Lumpur, Malaysia, *Proceedings Symposia on Geotextiles, Geomembranes and other Geosynthetics in Ground Improvement/ on Deep Foundations and Ground Improvement Schemes*, Bangkok, Thailand.

Reese, L.C. & O'Neill, M.W. (1988), Drilled Shafts : Construction Procedures and Design Methods, *U.S. Department of Transportation - Federal Highway Administration (Office of Implementation,* Washington, 564p.

Rosenberg, P. & Journeaux, N.L. (1976), Friction and End Bearing Tests on Bedrockfor High Capacity Socket Design, *Canadian Geotechnical Journal, 13*, pp. 324-333.

Rowe, R.K. & Armitage, H.H. (1987), A Design Method for Drilled Piers in Soft Rock, *Canadian Geotechnical Journal*, 24. pp. 126-142.

Seidel, J.P. & Haberfield, C.M. (1995), The Axial Capacity of Pile Sockets in Rock and Hard Soil, *Ground Engineering*, March, pp. 33-38.

Tan, Y.C., Chen, C.S. & Liew, S.S. (1998) Load Transfer Behaviour of Cast-in-place Bored Piles in Tropical Residuals Soils, *Proceedings of the 13th Southeast Asian Geotechnical Conferences*, Taipei, pp. 563-571.

Toh, C.T., Ooi, T.A., Chiu, H.K., Chee, S.K. & Ting, W.H. (1989), Design Parameters for Bored Piles in a Weathered Sedimentary Formation, *Proceedings of 12th International Conference on Soil Mechanics and Foundation Engineering*, Rio de Janeiro, Vol.2, pp.1073-1078.

Thorne, C.P. (1977), The Allowable Loadings of Foundations on Shale and Sandstone in the Sidney Region. *Part 3. Field Test Results. Paper presented to Sydney Group of Australia Geomechanics Society, Institute Engineers Australia*.

Tomlinson, M.J. (1994). *Pile Design and Construction Practice. 4th edn*. Spon.

Tomlinson, M.J. (1995). *Foundation Design and Construction. 6th edn*. Longman.

Vijayvergiya, V.N. (1977), Load-Settlement Characteristics of Piles. *Proceedings of Port'77 Conference*, Long Beach, California, pp.269-284.

Whitaker, T. & Cooke, R.W. (1966). An Investigation of the Shaft and Base Resistance of Large Bored Piles on London Clay. *Proceedings of the Symposium on Large Bored Piles,* London, pp 7-49.

Williams, A.F. & Pells, P.J.N. (1981), Side Resistance Rock Sockets in Sandstone, Mudstone, and Shale. *Canadian Geotechnical Journal*, 18, pp. 502-513.

Wyllie, D.C. (1991), Foundation on Rock. *1st edn, E&FN Spon.*

# APPENDIX A

Sample Specification for Bored Piling

# SPECIFICATION FOR BORED PILING

## 1.0 GENERAL

### 1.1 Works in accordance with Specifications

Piling shall conform in all respects with the principles contained in BS 8004.

Unless otherwise stated, concrete, reinforcement and formwork shall be in accordance with the requirements in Specification on Concrete for Structures.

In the event that the provisions of other specification clauses cause ambiguity or conflict with the requirement of this Specification clauses, the latter shall take precedence unless otherwise approved by the Engineer.

### 1.2 Setting Out

The Contractor shall be required to employ an approved Licensed Surveyor who will set up the positions of the piles as shown in the pile layout plans of the detailed design. The Contractor will be responsible for the accuracy of location and positioning of each pile. Any errors in setting out and any consequential loss to the Employer will be made good by the Contractor to the satisfaction of the Engineer.

The Contractor shall preserve the pegs set out by the Surveyor. Should any peg be displaced or lost it must be replaced by a Licensed Surveyor to the approval of the Engineer. Upon completion of all piling works, the Contractor shall produce as-built Drawings showing the positions of all piles as installed. The positions of piles shall be verified by a Licensed Surveyor.

### 1.3 Tolerances

(a) Position
The pile heads shall be positioned as shown on the Drawings within a maximum deviation of 75mm in either direction from its design position.

(b) Verticality
For bored cast-in-situ piles, the maximum permitted deviation of the finished pile from the vertical at any level is 1 in 150. The contractor shall demonstrate to the satisfaction of Engineer the pile verticality is within the allowable tolerance.

(c) Correction
Should piles be installed outside these tolerances affecting the design of the structure, the Contractor shall propose remedial design and carry out immediate remedial measure to the approval of the Engineer.

### 1.4 Person in Charge

The piling work is to be carried out by full time operators and supervisory staff who must be experienced in the installation of the proposed type of piles.

The Contractor shall submit to the Engineer for approval, written evidence to show that the persons who will be engaged in the works have had such experience.

### 1.5 Piling Equipment and Accessories

The equipment and accessories must be capable of safely, speedily and efficiently installing piles to the design requirements at the project site.

Sufficient units of equipment and accessories must be provided to keep to the agreed construction schedule.

### 1.6 Sequence of Installation of Working Piles

The Engineer reserves the absolute right and the Contractor shall recognise such right to direct the installation of working piles in any sequence the Engineer deems necessary for the satisfactory completion of the works.

### 1.7 Forcible Correction Not Permitted

Where piles have not been positioned within the specified limits no method of forcible correction will be permitted.

### 1.8 Rejected Piles

Any piling work rejected by the Engineer not truly constructed and installed in accordance with this Specification shall be replaced or rectified by the Contractor to the approval of the Engineer and this include reinstallation of piles, and the design and construction of a modified foundation and also constructing of additional compensation piles.

### 1.9 Records

A record of all piles installed shall be kept by the Contractor and a copy of the record of the work done each day shall be given to the Engineer within 24 hours. The form of record shall first be approved by the Engineer before piling works commence. Any comment by the Engineer shall be incorporated into the record form.

All unexpected boring or installation conditions shall be noted in the records.

Two (2) bound sets of collated and certified (by the Contractor's P.E.) piling records of all piles shall be submitted by the Contractor to the Engineer after the completion of the piling works.

## 2.0 BORED CAST IN-PLACE PILES

### 2.1 General

The Contractor shall carry out the works in accordance with a method statement which has been approved by the Engineer. This method statement shall include inter alia length of temporary casing, details of the constituent materials of any drilling fluid used for stabilisation, the method of inspection, details of the concrete design mix, concreting method, the minimum time between the completion of one pile and the commencement of the next, and the pattern of construction.
Unless otherwise described in the Specifications, reinforcement and concrete shall comply with the requirements in Specification on Concrete for Structures. The Contractor shall ensure that damage does not occur to completed piles through his method of working. The Contractor shall submit to the Engineer a pile installation programme. The proposed sequence and timing of pile installation shall be such that the installation works shall not cause any damage to adjacent piles. Piling works shall not commence until approval of the Engineer has been obtained. No bored pile excavation shall commence within 8m of any concreted pile which has not attained the age of 24 hours.

## 2.2 Tolerances

Tolerances shall be in accordance with the requirements in Clause 1.3 herein.

## 2.3 Concrete

(a) Trial Mix

The Contractor shall arrange to have a trial mix in the presence of the Engineer prior to the commencement of field work. The trial mix shall be carried out in accordance to the design mix submitted to the Engineer.

(b) Concrete for Piles

Unless otherwise stated, concrete used shall comply with Specification on Concrete for Structures and as approved by the Engineer. The grade of concrete shall be 35 (characteristic strength of 35 N/mm$^2$ at 28 days) with minimum cement content of 400kg per cubic meter of concrete. Concrete admixture shall only be used with the permission of the Engineer, and shall be used strictly in accordance with Specification on Concrete for Structures.

The Engineer may permit the use of ready mixed concrete provided complete details of the mix proportions and workability have been submitted to him for prior approval. Such permission shall only be given for as long as the Engineer is satisfied that the concrete complies with Specification on Concrete for Structures and the recommendations of M.S. 523. The Contractor shall ensure that the Engineer shall have access to the supplier's mixing plant at all times for inspection and checks on quality of concrete supplied. Each load shall be accompanied by a delivery note stamped with the time of mixing and stating the consignee and quantities of each material in the mix including water and additives.

(c) Concrete Testing

Close control of the mixing of the concrete shall be exercised and cube strength tests shall be carried out in accordance with M.S. 26. Unless the Engineer otherwise directs, a set of at least three 6" cubes shall be taken for every 10 cubic metres or every group of 10 batches of concrete used for the piling works. For the latter, the samples shall be taken from one single batch randomly selected from the group of batches. One cube of each set shall be tested at seven days and the remaining two at 28 days after casting. The test cubes shall be made from a representative batch of concrete as that used for the piling works and each cube shall be properly marked and identified with details relating the specimen to the borehole in which the concrete is used.

Test shall be carried out by approved lab. Test results shall be submitted to the Engineer within 48 hours after testing.

The Contractor shall not carry out the specified cube strength tests without prior notice to the Engineer. The tests must be witness by the Engineer or his representative. The contractor shall provide sufficient quantity of all necessary equipment at site to carry out these tests.

(d) Workability

Slump test shall be undertaken for every truck load of concrete. Slump measured at the time of discharge into pile shaft or at the time of discharge into the concrete pump hopper shall be in accordance with the standards shown below unless otherwise approved. A concrete pump shall not be used to place tremie concrete directly into the pile shaft.

| Class of Workability | Slump (mm) | Typical Conditions of Use |
|---|---|---|
| A | 100 ± 25 | Where concrete is to be placed in water-free shaft. |
| B | 175 ± 25 | Where concrete is to be placed by tremie method under drilling fluid. |

The concrete for piles shall be as specified in the design requirement with suitably enriched cement content to permit a high slump mix. Alternatively, the Contractor may incorporate an approved set retarding additive into the mix to ensure extended workability of the concrete after placement. It is held that the Contractor has included these provisions in the unit rate for the pile.

(e) Failure of Concrete Cube Tests

If the concrete cubes as tested failed to satisfy the criteria as prescribed in Specification, the Contractor shall undertake all necessary additional and consequential remedial/compensatory Work to the approval of the Engineer. The piles shall be rejected as in Clause 1.8 "Rejected Piles".

## 2.4 Pile Excavation

(a) Pile size and length

The Contractor shall carry out own tests along the proposed wall alignment to determine the bedrock level. Probing of bedrock shall be carried out along the proposed wall line at intervals to be agreed by the Engineer.

(b) Boring near recently Cast Piles

Piles shall not be bored next to other piles which have recently been cast less than 24 hours or contain unset concrete, whichever longer to avoid damage to any of these piles.

(c) Stability of Boreholes

It is held that the Contractor has allowed in the unit rate of the pile for the implementation of all necessary measures, including the provision of all materials, labour and plant, for maintaining the stability of the sides of boreholes during bored pile installation and successful completion of the piles. The Contractor shall submit his proposed methods for agreement prior to commencement of boring operations.

Irrespective of the presence of ground water, the sides of all borehole shall be kept intact and no loose material shall be permitted to fall into the bottom of the boreholes. The Contractor's boring equipment shall be able to sink a steel casing to support the sides of all boring.

If the sides of boreholes are found to be not stable, temporary steel casing shall be driven into stable stratum. The borehole shall be filled with drilling fluid to a level sufficiently to stabilise the boreholes.

If ground water is found in any hole in sufficient quantity or gushing out as to affect boring operations or excavations and removal of soil from the boreholes, or the sides of boreholes collapse, then a steel casing of appropriate size and length in conjunction with stabilising fluid or other alternatives of sufficient strength shall be used to support the sides of the borehole and permit boring operations to proceed smoothly and safely. The proposed drilling fluid mix must be submitted to the Engineer for approval.

Excavations shall not be exposed to the atmosphere longer than is necessary and shall be covered at all times when work is not in progress. Pile excavated shall be casted within 24 hours unless otherwise agreed by the Engineer.

In the event of a rapid loss of drilling fluid from the borehole excavation and caused instability of bore, the excavation shall be backfilled without delay or other appropriate and approved remedial measures taken by the Contractor like installing temporary casing prior to resuming boring at that location.

(d) Stability of bore by temporary casing method

Where the use of a temporary casing is required to maintain the stability of a bore, the bottom of casing shall be kept a minimum of 1 metre or more below the unstable strata to prevent the inflow of soil and the formation of cavities in the surrounding ground.

Temporary casings shall be thin walled mild steel cylindrical casing, spirally welded or other similar construction. The dimensions and quality of the casing shall be adequate to withstand without damage or distortion all handling, construction and ground stresses to which they will be subjected, including preventing concrete from within the pile from displacing soft soil or soil squeezing in and displacing fresh concrete. The casings shall have an internal diameter not less than the specified pile diameter. They shall be free of significant distortion, of uniform cross-section throughout each continuous length and free from internal projections and encrusted concrete which might prevent the proper formation of piles. The joints of casings shall be reasonably watertight.

If temporary casings are damaged during installation in a manner which prevents the proper formation of the pile, such casings shall be withdrawn from the bore before concrete is placed, repaired if necessary, or other action taken as may be approved to continue the construction of the pile.

(e) Rock Coring

Rock coring shall means coring of sound bedrock using a coring bucket or approved method. The used of chisel shall not be permitted. Coring of rock other than two items specified below shall not be considered as coring in rock, and will only be considered as boring in soil.

(i) Rock socket length
(ii) Cavity roof (in limestone formation)

Coring of inclined rock surface, limestone pinnacles, cavities and soil below boulder/floater shall be considered as boring in soils.

Socket length shall be measured from the flattened horizontal bedrock surface. This flat horizontal surface shall be probed using kelly bar or steel bar at a minimum of five positions over the borehole to confirm sound bedrock for socketing.

(f) Spillage and Disposal

All reasonable steps shall be taken to prevent the spillage of drilling fluid on the site in areas outside the immediate vicinity of boring. Discarded drilling fluid shall be removed from the site without delay. In disposal of unwanted drilling fluid, the Contractor shall comply with government regulations and shall propose a proper disposal method to be approved by the Engineer.

(g) Inspection of Pile Excavation

Where practicable, all pile excavations shall be inspected for their full length before concreting. The Contractor shall provide all the apparatus necessary for the inspection.

Inspection shall be carried out either from the ground level or below ground level at the sole discretion of the Engineer prior to concrete being placed in the borehole. For such

inspection to be carried out safely, the Contractor shall provide all facilities and assistance to enable the said inspection to be done. In the course of inspection any loose or soft material in the borehole which is likely to affect the performance of the pile shall be removed to the satisfaction of the Engineer.

In the case of inspection from ground level, the base of the boring shall be inspected by approved method for wet hole and means of a light for dry hole to ensure that all loose, disturbed and/or remoulded soil is removed and that the sides of the boring will remain stable during the subsequent concreting operations. The verticality and position of the boring shall be checked to ensure that they meet the specified tolerances.

Inspection below ground level shall be carried out for piles with shafts of 760mm (2'6") diameter and above. For this purpose the Contractor shall, apart from providing other safety measures, also provide the required facilities such as an approved type of a steel safety cage with an air-line, lifting cable and hoist, gas detector, lights, etc. to enable descent into and ascent from the borehole to be carried out safely without any danger to life. In this regard the safety precautions described in CP 2011:1969 "Safety Precautions in the Construction of Large Diameter Boreholes for Piling and Other Purposes" shall generally be followed, unless otherwise directed by the Engineer.

(h) Pumping from Bored Hole

Pumping from boreholes may be carried out from time to time on a number of piles designated by the Engineer to verify the suitability of dry hole construction, or to investigate and rectify a cold joint in a pile shaft where concreting has been interrupted.

No pumping from a borehole shall be permitted unless a casing has been placed into the stable stratum which prevents further ingress of water of significant quantity from other strata into the borehole, or unless it can be shown that pumping will not have a detrimental effect on the surrounding soil or hamper the piling operation in any way.

(i) Cleaning Out

Upon completion of boring the excavation shall be cleaned of all loose, disturbed and or remoulded soil and sediment soil to expose a firm base of undisturbed material using a suitable and effective method to be approved by the Engineer.

(j) Continuity of Construction

A pile constructed in a stable soil without the use of temporary casing or other support shall be bored and concreted without prolonged delay to ensure that the soil characteristics are not significantly altered.

(k) Surface Water

All boreholes shall be protected from the possibility of any surface water entering the hole from time to time and until the hole is completed and ready to be concreted.

(l) Excavation Materials

Surplus earth resulting from piling operations shall be used where required or removed from site as directed by the Engineer.

## 2.5 Placement of Reinforcement

Reinforcement shall be free from rust and mud and not be placed until inspected and accepted.

Reinforcement cages shall be sufficiently rigid to ensure that they remain at their correct level during the lifting and placing of the concrete and the extraction of temporary lining tubes.

Reinforcement shall be maintained in its correct position during concreting of the pile. The minimum cover to all reinforcement shall not be less than 75mm.

Concrete spacer shall be provided at every 3m interval, size and minimum yield strength of reinforcement shall be as specified in the Drawing. Details by which the Contractor plans to ensure the correct cover to and position of the reinforcement shall be approved by the Engineer.

The main longitudinal reinforcing bars in piles not exceeding 12 metres in length shall be in one continuous length unless otherwise specified. In piles longer than 12 metres and required to be reinforced throughout their full lengths when specified, joints with staggered laps of alternate bars will be permitted in main longitudinal bars at 12- metre nominal intervals unless otherwise specified in the Drawings. Joints in reinforcement shall comply with the specific requirements of BS8110 clause 3.12.8.

The Contractor shall submit for approval a method statement on the manner by which he intends to lower reinforcement cages into pile shafts. Where tack welding is carried out on pile reinforcement for the purpose of hoisting, such welding shall be located only within the top 100mm of each reinforcement cage. Where the top of a reinforcement cage being lowered is to be lapped to the next cage, as in the case of tension piles exceeding 12 metres in length, the Contractor shall provide adequate sacrificial steel to compensate any lapped reinforcement which has been tack welded, where such tack welding is the requirement of the Contractor for his hoisting operation. Sacrificial steel shall be of the same grade and size as that of the compensated bar.

If required by the Engineer, reinforcement cages shall be flushed with fresh water to remove accumulated salts or other deposits immediately prior to lowering into the pile shaft.

## 2.6 Concreting in Wet Hole

Immediately after the boring for the pile has been completed, approval to commence concreting shall be sought and, when this has been obtained, concreting shall start forthwith and continue without interruption. All concrete for cast-in-place piles shall be compacted to produce a dense homogeneous mass by a method agreed by the Engineer.

Concrete to be placed under drilling fluid shall placed using a tremie concrete pipe in accordance with BS 8004, Clauses 7.4.5.4.2 and 8.2.2.3.4. Where discrepancies arise, the provisions of this specification shall take precedence.

Alternative methods of placing concrete such as the use of a drop bottom bucket or hose from a concrete pump will not be accepted by the Engineer. At no stage concrete be permitted to discharge freely into drilling fluid.

Before placing concrete, agreed measures shall be taken by the Contractor to ensure that there is no accumulation of contaminated drilling fluid, silt or other deleterious material at the base of the bore. Contaminated drilling fluid could impair the free flow of concrete from the tremie pipe and affecting the performance of the pile.

A sample of the drilling fluid shall be taken from the base of bore using an accepted sampling device. If the drilling fluid does not comply to the specification, concrete placement shall not proceed and the Contractor shall modify or replace the drilling fluid to meet the requirements of this specification.

The tremie concrete pipe shall consist of a series of metal pipes with internal diameter not less than 250mm. The receiving hopper shall have a capacity at least equal to that of the pipe it feeds. At all times, a sufficient quantity of concrete shall be maintained within the pipe to ensure that the pressure from concrete exceeds that from the water or drilling fluid.

The hopper and pipe of the tremie shall be clean and watertight throughout. The pipe shall extend to the base of the bore and a sliding plug or barrier placed at the discharge outlet of the pipe to prevent direct contact between the first charge of concrete in the tremie pipe and drilling fluid. If the plug or barrier is sacrificial, it shall not be retained in the mass of the concrete.

The tremie pipe outlet shall be kept at least 1.5 metres below the surface of the concrete at all stages in the pour. The Contractor shall develop a system of level checks for the concrete and pipe outlet to ensure that this requirement is met. The tremie pipe shall be withdrawn upward gently behind the concrete level, and shall not be given any violent movement either in dislodging the concrete within the pipe or for any other reason.

Concrete placement shall be halted should a delay or breakdown occur during the concreting operation which in the opinion of the Engineer, could cause a cold joint, entrapment of latency in the tremie concrete, or otherwise lead to defective concrete. Before the remainder of the pile shaft can be concreted, the pile shall be dewatered and the top surface of the tremie concrete cut back to sound concrete and cleaned of all laitance and weak concrete. The remainder of the pile shall either be cast by tremie or in the dry, as directed by the Engineer. If this remedial work can not be carried out due to construction difficulty, the Contractor will need to construct a replacement pile.

The concrete for each pile shall be from the same source. The Contractor is to ensure that the supply from whatever source (whether site-mixed or ready-mixed) is of sufficient quantity so that concrete for each pile shall be placed without such interruption.

All holes bored shall be concreted within the same day. In the event of rain, the Contractor is to provide adequate shelter to keep the hole dry and to concrete under cover.

The method of placing and the workability of concrete shall be such that a continuous monolithic concrete shaft of the full cross-section is formed. The method of placing shall be approved by the Engineer. The Contractor shall take all precautions in the design of the mix and the placement of concrete to avoid arching of the concrete in the pile shaft. No spoil, liquid or other deleterious matter shall be allowed to contaminate the concrete.

Temporary casings shall be extracted while the concrete within remains sufficiently workable to ensure that the concrete is not lifted and that the resultant pile is continuous and of full section. Temporary casings shall be extracted in not more than 2 hours after concreting has completed.

When casings and linings are withdrawn as concreting proceeds, a sufficient head of concrete shall be maintained to prevent the entry of ground water which may cause reduction of cross-section of the pile. No concrete shall be placed after the bottom of the casing or lining has been lifted above the top of the concrete. Concrete shall be placed continuously as the casing is extracted until the desire head of concrete is obtained.

Adequate precautions shall be taken in all cases where the withdrawal of casing could result in excess heads of water or drilling fluid. Excess pressure heads are caused by the displacement of water or fluid by concrete as the concrete flows into its final position against the wall of the shaft. Precautions such as the use of two or more discontinuous lengths of casing (double casing) shall be deemed an acceptable method of construction in this case.

In the event of the ground water level being higher than the required pile head cut-off level shown in the contract drawings, the Contractor shall submit his proposals for agreement prior to placing concrete. The pile head shall not be let below the ground water level unless adequate and agreed precautions are taken.

The top of the pile shall be brought above the required cut-off level by an amount sufficient to ensure a sound concrete at cut-off level and the surplus removed to ensure satisfactory bonding of the pile head to the structure.

The actual volume of concrete used for each pile must be measured with the calculated volume required. If the difference between these two volumes indicates a possible necking, the Contractor shall propose and carry out appropriate tests and measures to the approval of the Engineer to ensure the adequacy of the pile.

Backfilling of Empty Bore - On completion of concreting, the remaining empty bore shall be backfilled with sand or lean concrete unless otherwise agreed by the Engineer.

Any consequences causing the pile rejected by the Engineer due to supply of concrete shall be on contractor's own risk.

### 2.7 Stripping Pile Heads and Bonding

The piles shall be constructed to a sufficient height above the required cut-off levels (‘overcast’) to ensure that all concrete at and below cut-off level is homogeneous and free of laitance and deleterious matter. The Contractor shall be required to provide adequate reinforcement with sufficient length to project above cut-off levels so that the reinforcement can be properly bonded in the capping beam. After completion of piling, the Contractor shall excavate and cut back the piles as necessary to verify the cut-off levels and to give accurate details of the pile positions as compared with the positions indicated on the pile layout plans of the detailed design. Defective concrete in pile heads shall be cut away and made good with new concrete well bonded to the pile head. If the pile is undercast, it shall be built-up with new concrete and a permanent casing.

### 2.8 Drilling Fluid and Soil Tests

Minimum frequency of testing are as follows:
1) fresh drilling fluid
2) drilling fluid taken from the bottom of the pile before concreting
3) recycle drilling fluid taken from desanding machine
4) drilling fluid left in the bored hole for more than 12 hours

The frequency of testing drilling fluid and the method and procedure of sampling shall be proposed by the Contractor and agreed by the Engineer before the commencement of the work. The frequency may subsequently be varied with the approval of the Engineer. Control tests for density shall be carried out daily on the drilling fluid using suitable apparatus. The measuring device shall be calibrated to read within 0.01 g/ml. The results shall be within the ranges stated in Table 2.1.

All reasonable steps shall be taken to prevent the spillage of drilling fluid on the site. Discarded drilling fluid shall be removed from the site without delay and such removal shall comply with the regulations of the relevant Authorities.

If sand content more than 5%, Contractor shall carried out desanding to screen out sand from drilling fluid before concreting.

TABLE 2.1 - TESTS FOR BENTONITE DRILLING FLUIDS

| Property to be measured | Compliance values measured at 20°C | Test Method/Apparatus |
|---|---|---|
| Density | Less than 1.10g/ml | Mud Density Balance |
| Fluid Loss | Less than 40ml | 30 minutes test |
| Viscosity | 30-90 seconds<br>or<br>less than 20cP | Marsh Cone method<br><br>Fann Viscometer |
| Shear Strength (10 minutes gel strength) | 1.4 - 10N/m$^2$<br>or<br>4 - 40N/m$^2$ | Shearometer<br><br>Fann Viscometer |
| Sand Content | Less than 5% | Screen |
| pH | 9.5 – 12 | pH indicator paper Strips or electrical pH meter |

Note : Where the Fann Viscometer is used, the fluid sample should be screened by 300μm sieve before testing.

Tests for drilling fluid other than bentonite have to be approved before use.

### 2.9 Dry Hole Construction (If directed by the Engineer Only)

For the purpose of the tender, the boreholes for pile construction shall be assumed to be wet holes, where the tremie method of concreting shall be adopted.

However, during pile installation as directed by the Engineer, the Contractor shall be required to determine for a number of designated piles whether dry hole construction could be implemented. The accepted method for dry hole verification shall be to pump out all water in the hole, and observe the rate of water intrusion and to be decided by the Engineer.

Whenever practicable, concrete for bored piles may be placed into a clean, dry hole. All dry holes shall be inspected and approved by the Engineer prior to placing of concrete. All facilities, labour and material required for the inspection shall be provided by the Contractor.

Agreed measures shall be taken to avoid segregation and bleeding, and that the concrete at the bottom of the pile is not deficient in grout. The concrete shall be placed by tremie. The free fall of the concrete from the bottom of the tube shall not exceed 1.5 times the diameter of the pile. The concrete shall be placed as quickly as possible where the ground is liable to deteriorate on exposure.

### 2.10 Pile Acceptance Criteria

The target termination depth, required socket length, concrete strength and the required working pile capacities are as shown in the drawings. The actual termination depths and socket lengths shall be agreed with the Engineer based on review of the conditions encountered during boring and prior to commencement of concreting. Piles shall meet tolerance requirements as specified in Clause 1.3 and satisfying integrity tests as specified in Clause 3.0.

### 2.11 Casting Level

Concrete shall be finished not less than 300mm above the cut-off level (‘overcast’) to ensure that all concrete at and below cut-off level is homogeneous and free of laitance and deleterious matter. A thicker overcast may be required by the Engineer depending on site condition, and this shall be carried out. The overcast shall be chipped off to cut-off level later by the Contractor.

### 2.12 Defective Concrete

Defective concrete in the pile heads shall be cut away and made good with new concrete well bonded into the old concrete.

### 2.13 Piling Records

Submission of the record shall be in accordance with Clause 1.9 herein.

The record shall contain all information required by the Engineer including the following:

- Name of Supervisor
- Pile forming equipment including Rig No.
- Length, diameter and reference number of the borehole
- Existing ground level

- Cut-off level, rock level, pile toe level
- Length of pile
- Log of material encountered and level of change in strata and where boring stops
- Speed of boring through soil or rock shall be recorded for every metre of drilling
- Depth bored and details of inclination or displacement of the pile during boring and date of inspection
- Length of reinforcement cage, reinforcement details
- Water table below ground level
- Levels where seepage occurs
- Results of tests on soils
- Results of tests on concrete cubes (slump test)
- Length of temporary casing if used
- Date and actual volume of concrete placed in piles, time start and complete
- Concrete level after each truck of concrete
- Details of all inspections
- Details of all obstructions, delays and other interruption
- Signature of the Resident Engineer or his representative
- Weather condition
- Method of casting (wet/dry tremie)
- Date and time boring start and complete and speed of drilling
- Type of stabilising fluid
- Collapse of bore or loss of drilling fluid
- Cavities or slump zones encountered

### 2.14 Treatment of Cavities and Slump Zones

The specification for treatment of cavities and slump zones should be followed unless otherwise instructed by the Engineer.

## 3.0 INTEGRITY TESTING OF PILES

### 3.1 General

Piles shall be selected by the Engineer for testing and detection of major faults, necking, discontinuities, and cross sectional areas of the piles. Integrity testing of piles shall be carried out by an independent testing organisation approved by the Engineer.

If the results of the tests show that the pile or piles are defective, the pile or piles shall be treated as faulty and shall be rejected unless the Contractor can demonstrate to the approval of the Engineer effective remedial measures that will be carried out.

The results of tests shall be printed out immediately during tests with printer facility at site and submit to Engineer at site. The Engineer's interpretations and conclusions arrived at on the test results shall be final.

Working piles shall be subjected to shock method and sonic logging tests.

### 3.2 Shock Method

(a) Preparation of the Pile Head

The pile head shall be clearly exposed, free from debris, etc. and not more than 1.0 metre above or below ground level, otherwise the surrounding soil shall be built up or excavated to meet this condition. The pile head shall be smooth over its complete cross-section, free from irregularities and perpendicular to the vertical axis of the pile.

The pile head shall consist of sound concrete. This shall be achieved during the concreting of the pile by flushing out all weak mortar, etc. from the top of the pile head and carefully screeding off to provide a smooth level surface in sound concrete.

Alternatively, if the pile head is prepared after concreting, all weak mortar, broken concrete, etc. shall be removed from the pile head to expose sound concrete over its complete cross-section. After cleaning it off to ensure a sound bond, a very thin screed (maximum 1cm) of strong sand/cement mortar, rapid hardening compound, shall be spread to provide a smooth working surface for the shock test equipment. The mortar shall be allowed to harden before testing.

Any reinforcement or other inclusions protruding from the pile head shall not prevent the testing team from giving the pile the required impact force over the centre of the pile and the placing of a 5cm diameter (approx.) electronic pick-up at about 10cm from the periphery of the pile. Access shall be provided for the service van within 30 metres of the pile.

(b) Shock Test Equipment

The shock which is to be imparted onto the pile head shall be carried out using a suitable hammer or any approved method which is capable of transmitting vibration to the base of the pile shaft. The electronic pick-ups located on the pile head shall be approved velocity transducers or accelerometers connected through an approved frequency analyser to a X-Y plotter. The mechanical admittance shall be plotted on a vertical scale and the frequency on the horizontal scale. Both the horizontal and vertical scales shall be varied as required. The equipment shall have an independent power supply.

(c) Shock Test

The Contractor shall provide the qualified and experienced testing team with a site plan showing the pile layout and a list of the piles to be tested.

Before testing, the heads of the piles shall be inspected by the testing team for regularity and soundness and any unsatisfactory pile heads shall be reported to the Engineer. They shall be made good to the satisfaction of the Engineer and smoothed off using a suitable epoxy mortar if necessary. Preliminary tests shall be carried out to establish the appropriate scales and to check the electronic circuit.

## 3.3 Sonic Logging Method

For the purpose of carrying out sonic logging, the Contractor shall be required to install the necessary tubing for the tests at all pile locations or as directed by the Engineer.

The tubes shall be of internal diameter not less than 50mm with no internal projections or couplings. They can be of mild steel pipes. Four (4) nos. of tubes are required for each pile greater than 700mm diameter while two (2) nos. are required for each smaller diameter pile.

The tubes shall be fixed to the longitudinal bars with equal spacing on the inside perimeter of the links. The tubes shall be watertight with the bottom of the tube sealed and suitably weighted to prevent floating. The tubes shall be secured to the internal face of the reinforcement cage at equal distance from each other on the circumference.

The tubes shall extend the full depth of the pile and project 300mm above the top of the concrete and not lower than 300mm below the surface of the ground. All joints shall be made watertight. The tubes shall be filled with water to provide the necessary acoustic coupling, and then plugged or capped before concreting. The type of tube and condition of sealing shall be checked and approved by the Engineer before installation.

The rate of logging for increments of depth shall be approved by the Engineer.

After conducting the tests, all tubes shall be grouted with approved strength and water in the tubes displaced. The grout shall be dense cement grout with an approved expanding agent.

Prior to testing, the necessary equipment shall be thoroughly checked to ensure that all parts are functioning satisfactorily. During sonic logging testing, where any irregularities are detected, the tests shall be repeated at a smaller scale to allow a 'close-up view' of the irregularities.

Presentation of Test Results

The time required to carry out the test for each pile must be recorded along with records of starting time and finishing time.

The results of the tests shall be presented in report by the testing firm and must be signed by a professional engineer. The report shall include comprehensive engineering analysis of the test results for each pile taking into consideration the soil condition and any other relevant factors. Interim reports of each pile or group of piles tested in one day shall be submitted to the Engineer within 2 days of the completion of the test or tests. A final comprehensive report shall be submitted to the Engineer within 7 days of the completion of the last test or tests.

### 3.4 Proof Coring of Pile Shafts

The Contractor shall check the quality of the concrete in the shafts of working piles as directed by the Engineer. This shall be achieved by a vertical diamond core hole drilled through the centre region of the pile from pile head to required depth. The location of the drill hole and depth shall be approved by the Engineer. Full core recovery shall be attempted. The core so produced shall not be less than 50mm in diameter. The minimum number of piles for proof coring test shall not be less than 1% of the total number of working piles or as specified in the Bill of Quantities.

For each pile to be cored, the coring work shall be completed before the concrete in the pile has reached an age of 28 days to allow the cores to be tested for unconfined compression tests at 28 days. The Engineer shall mark the sections of the core to be tested and the Contractor shall arrange for testing in an approved laboratory. A minimum of six(6) unconfined compression tests shall be conducted on cores obtained from a pile. Additional number of the unconfined compression tests may be requested by the Engineer if in the opinion of the Engineer the quality of the concrete of the pile is doubtful.

The cored hole in the pile shall be grouted after testing. The grout shall be an approved dense cement grout with a minimum 28 days strength of equal or higher than the strength of the concrete of the bored pile. If the pile is found to be faulty in the opinion of the Engineer because of defects such as cracks, overbreaks, necking, cavity, inclusion of foreign deleterious materials, poor quality concrete, etc., the pile shall be rejected and the Contractor shall undertake all necessary remedial measures to the approval of the Engineer.

In conjunction to core testing, the Engineer may request sonic logging test to be conducted in the cored holes or pre-installed tubings to determine the in-situ density of the pile and their integrity continuously along the pile length in correlation with core samples.

# APPENDIX B

Sample Specification for Testing of Bored Piling

# SPECIFICATION FOR TESTING OF BORED PILE

## 1.0 GENERAL

This specification deals with the testing of bored piles by the application of an axial load or force. It covers vertical piles tested in compression (i.e. subjected to loads or forces in a direction such as would cause the pile to penetrate further into the ground) and vertical piles tested in tension (i.e. subjected to forces in a direction such as would cause the piles to be extracted from the ground).

This specification also covers high strain dynamic testing of installed piles.

## 2.0 DEFINITIONS

Compression pile: a pile which is designed to resist an axial force such as would cause it to penetrate further into the ground.

Tension pile: a pile which is designed to resist an axial force such as would cause it to be extracted from the ground.

Preliminary pile (for failure load test): a pile installed before the commencement of the main piling works or specific part of the Works for the purpose of establishing the suitability of the chosen type of pile and for confirming its design, dimension and bearing capacity as well as value engineering.

Kentledge: the dead weight used in a loading test.

Reaction system: the arrangement of kentledge, piles, anchors or rafts that provides a resistance against which the pile is tested.

Maintained load test: a loading test in which each increment of load is held constant either for a defined period of time or until the rate of movement (settlement or uplift) falls to a specified value.

Failure load test: a load test applied to a preliminary pile. Maximum test load for this test should not normally be less than 250% of the estimated working load, but the possibility of failure load test carried well beyond 300% of the predicted working load should not be ruled out. This test serves as a design check and refinement for soil parameters used to determine the lengths of subsequent working piles.

Ultimate bearing capacity: the load at which the resistance of the soil becomes fully mobilized.

Allowable load: the load which may be safely applied to a pile after taking into account its ultimate bearing capacity, negative skin friction, pile spacing, overall bearing capacity of the ground below and allowable settlement.

Working load: the load which the pile is designed to carry without exceeding the allowable settlement requirement.

## 3.0 SAFETY PRECAUTIONS

### 3.1 General

When preparing for, conducting and dismantling a pile test, the Contractor shall carry out the requirements of the various Acts, orders, regulations and other statutory instruments that are applicable to the work for the provision and maintenance of safe working conditions, and shall in addition make such other provision as may be necessary to safeguard against any hazards that are involved in the testing or preparations for testing.

The Contractor shall be responsible for the design of the reaction system (e.g. kentledge or reaction piles/ground anchor, etc). The design of the reaction system shall be endorsed by the Professional Engineers registered with The Board of Engineers, Malaysia (BEM).

### 3.2 Personnel

All tests shall be carried out only under the direction of an experienced and competent supervisor conversant with the equipment and test procedure. All personnel operating the test equipment shall have been trained in its use.

### 3.3 Kentledge

Where kentledge is used, the Contractor shall construct the foundations for the kentledge and any cribwork, beams or other supporting structures in such a manner that there will not be any differential settlement, bending or deflection of an amount that constitutes a hazard to safety or impairs the efficiency of the operation. The kentledge shall be adequately bonded, tied or otherwise held together to prevent it from falling apart, or becoming unstable because of defection of the supports.

The weight of kentledge shall be at least 1.2 times than the maximum test load and if the weight is estimated from the density and volume of the constituent materials, an adequate factor of safety against error shall be allowed. The Contractor shall take all reasonable steps to ensure that sufficient excess load capacity is at all times available for the uninterrupted execution of a load test.

### 3.4 Reaction Piles And Ground Anchors

Where tension piles or ground anchors are used (only if specified by the Engineer), the Contractor shall ensure that the load is correctly transmitted to all the tie rods or bolts. The extension of rods by welding shall not be permitted unless it is known that the steel will not be reduced in strength by welding. The bond stresses of the rods in tension shall not exceed normal permissible bond stresses for the type of steel and grade of concrete used.

The reaction piles or ground anchorages shall be so designed that they will resist the forces applied to them safely and without excessive deformation which could cause a safety hazard during the work. Such piles or anchorages shall be placed in the specified positions, and bars, tendons or links shall be aligned to give a stable reaction in the direction required.

### 3.5 Testing Equipment

In all cases the Contractor shall ensure that when the hydraulic jack and load measuring device are mounted on the pile head, the whole system will be stable up to the maximum test load to be applied. Means shall be provided to enable dial gauges to be read from a position clear of the kentledge stack or test frame in conditions where failure in any part of the system due to overloading, buckling, loss of hydraulic pressure or any other cause might constitute a hazard to personnel.
The hydraulic jack, pump, hoses, pipes, couplings and other apparatus to be operated under hydraulic pressure shall be capable of withstanding a test pressure of 1.5 times the maximum working pressure without possible leaking.

The maximum test load or test pressure expressed as a reading on the gauge in use shall be displayed and all operators shall be made aware of this limit.

If in the course of carrying out a test any unforeseen occurrence should take place, further loading shall not be applied until proper engineering assessment of the condition has been made and steps have been taken to rectify any fault. Reading of gauges should, however, be continued where possible and if it is safe to do so.

## 4.0 MATERIALS AND LABOUR

The Contractor shall supply all labour, materials and other equipment necessary for the performance, recording and measurements of the test loads and settlement including the supply and placing in position of kentledge used in the tests. The Contractor shall subsequently dismantle and remove all the material and equipment used.

Throughout the duration and operation of the test loading the Contractor shall place competent men to operate, watch and record the test.

## 5.0 PRELIMINARY PILES

In order to determine the required length of piles at each location, the Contractor shall install and test preliminary piles in advance of the main piling operation for working piles. The locations, sizes, lengths, test loads and instrumentation required for the preliminary piles are as shown in the drawings.

Preliminary piles shall be installed with the same plant and in a similar manner as that to be used in the construction of the contract working piles.

All preliminary piles shall be instrumented in accordance with that indicated in the drawings and specification. After testing, the Contractor shall be responsible to hack away the preliminary test pile if it is obstructing the construction of the basement or other foundation works.

## 6.0 MEASURING DEVICES

Load measuring devices shall be calibrated before and after each series of tests, whenever adjustments or replacements are made to the devices or at the intervals recommended by the manufacturer of the equipment. All measuring equipment and gauges shall be calibrated together. Certificates of calibration from an approved laboratory shall be supplied to the Engineer for acceptance.

The Contractor’s proposed method of measuring the movement of pile heads and load shall be submitted to the Engineer for approval.

## 7.0 SUPERVISION

All tests shall be carried out under the direction of an experienced and competent supervisor conversant with the test equipment and test procedure. All personnel operating the test equipment shall have been trained in its use. Load testing shall be carried out in the presence of the Engineer or Engineer’s Representative.

## 8.0 LOADING TEST PILES

The rate of application and removal of the load may be altered or modified solely by the Engineer. Unless otherwise decided by the Engineer the load steps and duration are as indicated in item Test Procedure.

## 9.0 READINGS

Take readings of time, load and settlement and record immediately before and after the application of each load increment or decrement, or as directed by the Engineer. A minimum of another two readings shall be recorded at intermediate intervals.

## 10.0 INSTALLATION OF A TEST PILE

### 10.1 Inclusive Works

The works for the load tests shall include the construction and subsequent demolition of all necessary pile caps built in rapid hardening cement to the contractor's design which shall be subjected to the Engineer's approval.

### 10.2 Notice Of Construction

The Contractor shall give the Engineer at least 48 hours notice of commencement of construction of any preliminary pile.

### 10.3 Method Of Construction

Each preliminary test pile shall be constructed in a manner similar to that to be used for the construction of the working piles, and by the use of similar equipment and materials. Any variation will only be permitted with prior agreement.

Extra reinforcement and concrete of increased strength will be permitted in the shafts or preliminary piles provided prior notification is made.

### 10.4 Boring Record

For each preliminary pile which is to be tested a detailed record of the conditions experienced during boring shall be made and submitted daily, not later than noon on the next working day. Where the Engineer requires soil samples to be taken or in-situ tests to be made, the Contractor shall present the results without delay.

### 10.5 Concrete test cubes

At least four test cubes shall be made from the concrete used in the preliminary test pile and from the concrete used for building up a working pile. If a concrete pile is extended or capped for the purpose of testing, a further four cubes shall be made from the corresponding batch of concrete. The cubes shall be made and tested in accordance with BS1881.

The pile test shall not start until the strength of the cubes taken from the pile exceeds twice the average direct stress in any pile section under the maximum required test load, and the strength of the cubes taken from the cap exceeds twice the average stress at any point in the cap under same load.

### 10.6 Preparation of Working Test Pile

If a test is required on a working pile the Contractor shall cut down or otherwise prepare the pile for testing as required by the Engineer in accordance with the Specifications.

### 10.7 Cut-Off Level of Test Pile

The cut-off level for preliminary test pile shall be as specified.

Where the cut-off level of working piles is below the ground level at the time of pile installation and where it is required to carry out a load test from that installation level, either allowance shall be made in determination of the design verification load for friction which may be developed between the cut-off level and the existing ground level, or the pile may be sleeved

appropriately or otherwise protected to eliminate friction which develops over the extended length.

The Contractor shall be responsible for the selection of the piling platform level and also the platform level which the working piles are to be tested. The cost for the necessary sleeve or bond length or pile length above the cut-off level of working piles shall be born by the Contractor.

### 10.8 Pile Head For Compression Test

For a pile that is tested in compression, the pile head or cap shall be formed to give a plane surface which is normal to the axis of the pile, sufficiently large to accommodate the loading and settlement-measuring equipment and adequately reinforced or protected to prevent damage from the concentrated application of load from the loading equipment.

The pilecap shall be concentric with the test pile. The joint between the cap and the pile shall have strength equivalent to that of the pile.

Sufficient clear space shall be made under any part of the cap projecting beyond the section of the pile so that, at maximum expected settlement, load is not transmitted to the ground except through the pile.

### 10.9 Pile Connection For Tension Pile

For a pile that is tested in tension, means shall be provided for transmitting the test load axially to the pile.

The connection between the pile and the loading equipment shall be constructed in such a manner as to provide a strength equal to the maximum load which is to be applied to the pile during the test with an appropriated factor of safety on the structural design.

## 11.0 REACTION SYSTEMS

### 11.1 Compression Tests

Compression tests shall be carried out using kentledge only. Unless instructed, approved or specified by the Engineer, tension piles, ground anchors or otherwise specially constructed anchorage shall be not be used*.*

Where kentledge is to be used, it shall be supported on cribwork, disposed around the pile head so that its center of gravity is on the axis of the pile. The bearing pressure under supporting cribs shall be such as to ensure stability of the kentledge stack. Kentledge shall not be carried directly on the pile head, except when directed by the Engineer.
The kentledge may consist of concrete blocks, steel piles etc, but must be of uniform size so that weight of the kentledge can be easily calculated.

### 11.2 Tension Tests

Tension tests shall be carried out using compression piles or rafts constructed on the ground. The use of inclined reaction piles, anchors or rafts is not precluded, subject to agreement. In all cases the resultant force of the reaction system shall be co-axial with the test pile.

### 11.3 Spacing

Where kentledge is used for loading vertical piles in compression, the distance from the edge of the test pile to the nearest part of the crib supporting the kentledge stack in contact with the ground shall be not less than 1.3m

The center-to-centre spacing of vertical reaction piles, including working piles used as reaction piles, from a test pile shall be not less than three times the diameter of the test pile or the reaction piles or 2m whichever is the greatest.

Where a pile to be tested has an enlarged base, the same criterion shall be apply with regard to the pile shaft, with the additional requirement that no surface of a reaction pile shall be closer to the base of the test pile than one haft of the enlarged base diameter.

Where vertical reaction piles penetrate deeper than the test pile, the center-to-centre spacing of the reaction piles from the test pile shall be not less than five times the diameter of the test pile or the reaction piles whichever is the greatest unless the base capacity of the test pile is less than 20% of the total ultimate capacity.

Where ground anchorages are used to provide a test reaction for loading in compression, no section of fixed anchor length transferring load to the ground shall be closer to the test pile than three times the diameter of the test pile. Where the pile to be tested has an enlarged base the same criterion shall apply with regard to the pile shaft, with the additional requirement that no section of the fixed anchor transferring load to the ground shall be closer to the pile base than a distance equal to the base diameter.

### 11.4 Adequate Reaction

The size, length and number of reaction piles or the area of the rafts, shall be adequate to transmit the maximum test load to the ground in a safe manner without excessive movement or influence on the test pile.

### 11.5 Care Of Piles

The method employed in the installation of any reaction piles or rafts shall be such as to prevent damage to any test pile or working pile.

### 11.6 Working Piles as Reaction Piles

The Contractor shall no use working piles a reaction piles.

### 11.7 Loading Arrangement

The loading arrangement used shall be designed to transfer safely to the test pile the maximum load required in testing. Full details shall be submitted to the Engineer prior to any work related to the testing process being carried out on the Site.

### 11.8 Pilecaps and Structural Elements

Temporary pilecaps and other structural elements forming part of the reaction system proposed by the Contractor shall be designed and built by the Contractor, and to the approval of the Engineer. The cost of building and demolishing such pilecaps and structural elements shall be borne by the Contractor.

## 12.0 EQUIPMENT FOR APPLYING LOAD

### 12.1 General

The equipment used for applying load shall consist of one or more hydraulic rams or jacks. The rams or jacks shall be arranged in conjunction with the reaction system to deliver an axial load to the test pile. The complete system shall be capable of transferring the maximum load required for the test.

### 12.2 Jack Capacity

The total capacity of the jacks shall exceed by 20% or more the required maximum test load, thereby avoiding heavy manual pumping effort when nearing maximum load and minimizing the risks of any leakage of oil through the seals.

The loading equipment shall be capable of adjustment throughout the test to obtain a smooth increase of load or to maintain each load constant at the required stages of a maintained load test.

The length of stroke of a ram shall be sufficient to cater for deflection of the reaction system under load plus a deflection of a pile head up to 15% of the pile shaft diameter unless otherwise specified.

## 13.0 MEASUREMENT OF LOAD

### 13.1 Load Measurement Procedure

The load shall be measured by a load measuring device and by a calibrated pressure gauge included in the hydraulic system. Reading of both the load measuring device and the pressure gauge shall be recorded. In interpreting the test data, the values given by the load measuring device shall normally be used. The pressure gauge readings are required as a check for gross error. The pressure gauge shall have been recently calibrated.

The load measuring device may consist of a proving ring, load measuring column, pressure cell, vibrating wire load cell or other appropriate system. The load cells or proving ring shall be calibrated immediately prior to the test and a certificate shall be submitted to the Engineer.

A spherical seating shall be used in conjunction with any devices that are sensitive to eccentric loadings; care must be taken to avoid any risk of buckling. Load measuring devices and jacks shall be short in axial length in order to achieve the best possible stability. The Contractor shall pay attention to details in order to ensure that axial loading is maintained.

Any increments of load shall not be allowed to fall below 1% of the specified load.

The Engineer’s agreement shall be obtained in writing prior to any modification of this procedure.

### 13.2 Calibration of Load Measuring Devices

The load measuring device shall be calibrated before and after each series of tests, whenever adjustments are made to the device or at intervals appropriate to the type of equipment. The pressure gauge and hydraulic jack shall be calibrated together.

Certificates of calibration performed by an approved testing laboratory shall be supplied to the Engineer prior to carrying out the load test.

### 13.3 Measurement Of Settlement

Settlement shall be measured by use of a reference beam or wire supported independently of the test pile, reaction pile or piles supporting reaction loads. Settlements shall be measured to the nearest 0.1mm for reference beams or 0.5mm of reference wires. A precise optical level shall be used to check movements of the reference frame against an independent datum. The reference beam supports shall be located at least 3m from the test pile, reaction pile or piles supporting reaction loads. The reference beams or wires shall be protected from the effects of temperature changes. Construction equipment and persons not involved in the

test shall be kept well clear to avoid disturbance of the measuring system. Pile driving or similar operations will not be permitted in the vicinity of the test unless the Engineer is satisfied that the measuring system will not be affected.

Deflections shall be precisely measured by four dial gauges equally spaced around the pile head to accuracy of 0.01mm to give useful information on pile bending as well as axial movement. These dial gauges shall be firmly attached to the reference beams, so that the plungers are parallel to the pile axis. The plunger points shall bear onto reference plates by means of machined plates or glass slides attached to the pile head. The reference plates shall be equidistant from the centre of the pile, diametrically opposed, and carefully aligned so that they are perpendicular to the pile axis in order that sideways movements do not produce any axial components.

Before stacking up of the kentledge or construction of the reaction piles / ground anchors, the preparation of the pile head shall be carried out and the reduced level of the pile head surveyed and recorded.

### 13.4 Initial Zero Load Readings

Before the first increment of test load is applied, all gauges shall be read at 30 minutes intervals over a period of 24 hours under zero load to determine the effect of variable site conditions on the test pile. Air temperature shall be recorded with each set of readings. The test set-up shall be exactly as during the test proper, with the loading jack in position but clear of the loading frame.

## 14.0 MEASURING MOVEMENT OF PILE HEADS

### 14.1 Maintained Load Test

In a maintained load test, movement of the pile head shall be measured by one of the primary systems and one of the secondary systems described in this section.

### 14.2 Primary System

An optical or any other leveling method by reference to an external datum may be used.

Where a level and staff are used, the level and scale of the staff shall be chosen to enable readings to be made within an accuracy of 0.5mm. A scale attached to the pile or pilecap may be used instead of a leveling staff. At least two datum points shall be established on permanent objects or other well-founded structures, or deep datum points shall be installed, so that any one datum point can be re-established in case it is inadvertently demolished. Each datum point shall be situated so that only one setting of the level is needed.

No datum point shall be affected by the test loading or other operations on the Site.

Where another method of leveling is proposed, this shall be agreed in writing.

### 14.3 Independent Reference Frame

An independent reference frame may be set up to permit measurement of the movement of the pile. The supports for the frame shall be founded in such a manner and at such a distance from the test pile, kentledge support cribs, reaction piles, anchorages and rafts that movements of the ground in vicinity of the equipment do not cause movement of the reference frame during the test which will effect the required accuracy of the test.

Observations of any movements of the reference frame shall be made and a check shall be made of the movement of the pile head relative to an external datum during the progress of the test. Supports for the reference frame shall be placed not less than three test pile

diameters or 2 metres, whichever is the greater, from the center of the test pile, and not less than 1 metres from the nearest corner of the kentledge support crib.

The measurement of pile movement shall be made by 4 dial gauges equally spaced around the pile and equidistant from the pile axis. Dial gauges shall be rigidly mounted on the reference frame and bear on surfaces which are normal to the pile axis and fixed to the pilecap or head.

Alternatively the gauges may be fixed to the pile and bear on surfaces on the reference frame. The dial gauges shall have a travel of 50mm and shall be accurate to 0.01mm.

The reference frame shall be protected from direct sunlight, wind and rain.

### 14.4 Secondary Systems

### 14.5 Reference Wire

A reference wire shall be held under constant tension between two rigid supports founded as in the method used for the primary Reference Frame system. The wire shall be positioned against a scale fixed to the pile and the movement of the scale relative to the wire shall be measured.

Observations of any movements of the supports of the wire shall be made or a check shall be made of the movement of the pile head as in the method used for primary Reference Frame systems. Readings shall be taken to within an accuracy of 0.5mm.

The reference wire shall be protected from direct sunlight, wind and rain.

### 14.6 Other Methods

The Contractor may propose and implement any other suitable and adequate method of measuring the movement of pile heads subject to the prior agreement of the Engineer.

### 14.7 Instrument Calibration

Prior to carrying out the load test, the Contractor shall submit to the Engineer the calibration certificates of dial gauges performed by an approved testing laboratory.

### 14.8 Night Readings

The entire test area shall be adequately lighted up during the night to facilitate taking readings.

## 15.0 PROTECTION OF TESTING EQUIPMENT

### 15.1 Protection From Weather

Throughout the test period, all equipment for measuring load and movement shall be protected from direct exposure to sunlight, wind and rain.

### 15.2 Prevention Of Disturbance

Construction equipment and persons who are involved in the testing process shall be kept at a sufficient distance from the test to avoid disturbance to the measurement apparatus.

## 16.0 SUPERVISION

### 16.1 Notice Of Test

The Contractor shall give the Engineer at least 24 hours notice of the commencement of the test.

### 16.2 Records

During the progress of a test, the testing equipment and all records of the test as required under the section headed 'Presentation Of Results' in this specification shall be available for inspection by the Engineer.

## 17.0 TEST PROCEDURE

### 17.1 Failure Load Tests (Preliminary Test Pile)

Failure Load Tests shall be performed on preliminary piles designated by the Engineer at the commencement of the contract to verify the design parameters used and to determine the lengths of subsequent working piles. The preliminary piles shall be the only ones made in the first instance, and the load tests carried out prior to the installation of any other piles. Piling works shall not commence until after the failure load test results have been analysed, and upon instruction by the Engineer.

The provisional number of Failure Load Test shall be as specified in the Bills of Quantities. However, the Engineer reserves the right to alter the number of tests subject to the nature of subsoil conditions encountered and the pile system adopted vis-à-vis the method of installation, material and plant usage.

The test procedure shall be as follows, with the percentage for loading and unloading operations given in terms of the working load taken as 100%:

**LOADING CYCLES FOR PRELIMINARY PILES**

| Load Percentage Of Working Load | Time Of Holding Load (minutes) |
|---|---|
| 0 | 10 |
| 10 | 10 |
| 20 | 10 |
| 30 | 10 |
| 40 | 10 |
| 50 | 10 |
| 60 | 10 |
| 70 | 10 |
| 80 | 10 |
| 90 | 10 |
| 100 | 60 min or settlement rate less than 0.25 mm/hr (whichever is longer) |
| 75 | 10 |
| 50 | 10 |
| 25 | 10 |
| 0 | 30 |
| 25 | 10 |
| 50 | 10 |
| 75 | 10 |
| 100 | 10 |
| 110 | 10 |
| 120 | 10 |
| 130 | 10 |
| 140 | 10 |
| 150 | 10 |
| 160 | 10 |

| | |
|---|---|
| 170 | 10 |
| 180 | 10 |
| 190 | 10 |
| 200 | 60 min or longer as instructed by the Engineer |
| 150 | 10 |
| 100 | 10 |
| 50 | 10 |
| 0 | 30 |
| 50 | 10 |
| 100 | 10 |
| 150 | 10 |
| 200 | 10 |
| 210 | 10 |
| 220 | 10 |
| 230 | 10 |
| 240 | 10 |
| 250 | 10 |
| 260 | 10 |
| 270 | 10 |
| 280 | 10 |
| 300 | 60 min or longer as instructed by the Engineer |
| 200 | 10 |
| 100 | 10 |
| 0 | 30 |

The test schedule for compression test is for guidance only. It is subject to variation by the Engineer to meet site conditions.

The procedure for tension pile tests shall be exactly as described in this section for compression pile test; for tension test, the words “settlement” and “rebound” should be read “displacement” in the column “action to be taken after Load Stage.”

For failure load tension pile test, the Contractor shall provide adequate reinforcement in the test pile to carry the ultimate tension load. It is held that the cost of each reinforcement is included in unit rate for test pile.

All loading and unloading operations shall take place during the day. Pressure gauge readings shall be recorded at each load increment or at each decrease in load. During waiting periods at various loading stages, all readings shall be recorded after the load has been applied and before the commencement of next loading stage. Take readings at 15 minute intervals at 100%, 200% and 300% of working load.

If large discrepancies occur between different measurement systems, the test shall be halted and the cause for the discrepancy corrected. The test shall be restarted from the beginning in this instance.

### 19.1 Working Load Test on Working Piles

A number of working load tests on 2.0 times the working capacity of the pile shall be carried out on working piles to be designated by the Engineer, and in accordance with BS 8004: 1986 Clause 7.5.5. In case of discrepancies the provision of this specification shall take precedence. The Contractor shall submit a detailed proposal of load tests to the Engineer, and shall obtain his approval in writing before carrying them out. On completion of the test, the Contractor shall submit to the Engineer the test results, including graphs showing load and settlement versus time and settlement versus load.

The provisional number of working load tests to be carried out shall be specified. The Engineer may reduce the number of tests if a consistent high quality of workmanship and pile material is well established and if the nature of soil conditions encountered does not vary substantially, Conversely, the Engineer reserves the right to increase the number of tests

either to verify the quality of workmanship and pile material or in response to variable subsoil conditions.

Unless otherwise specified by the Engineer, the test procedure shall be as follows, with the percentage for loading and unloading operations given in terms of the working load, taken as 100%:

**TABLE 1: LOADING CYCLES FOR WORKING PILES**

| Load. Percentage Of Working Load | Time Of Holding Load (minutes) |
|---|---|
| 0 | 10 |
| 10 | 10 |
| 20 | 10 |
| 30 | 10 |
| 40 | 10 |
| 50 | 10 |
| 60 | 10 |
| 70 | 10 |
| 80 | 10 |
| 90 | 10 |
| 100 | 60 min or settlement rate less than 0.25min/hr (whichever is longer) |
| 75 | 10 |
| 50 | 10 |
| 25 | 10 |
| 0 | 30 |
| 25 | 10 |
| 50 | 10 |
| 75 | 10 |
| 100 | 10 |
| 110 | 10 |
| 120 | 10 |
| 130 | 10 |
| 140 | 10 |
| 150 | 10 |
| 160 | 10 |
| 170 | 10 |
| 180 | 10 |
| 190 | 10 |
| 200 | 60 min or longer as instructed by the Engineer |
| 150 | 10 |
| 150 | 10 |
| 50 | 10 |
| 0 | 30 |

The test schedule for compression test is for guidance only. It is subject to variation by the Engineer to meet site conditions.

The procedure for working load tension pile tests shall be exactly as described in this section for compression pile tests; for tension test, the words "settlement" and "rebound" should be read "displacement" in the column "action to be taken after Load Stage".

All loading and unloading operations shall take place during the day. Minimum three (3) sets of readings shall be taken in each loading stage: one set each at the beginning, middle and end of each loading or unloading stage. When a test load is maintained for more than 30 minutes, readings shall be taken at maximum half-hourly intervals thereafter unless otherwise specified by the Engineer.

If large discrepancies occur between different measurement systems, the test shall be halted and the cause for the discrepancy corrected. The test shall be restarted from the beginning in this instance.

## 18.0 ABANDONMENT OF PILE TEST

Test shall have to be discontinued if any of the following occurs:

- faulty jack or gauge,
- instability of kentledge,
- improper setting of datum, or
- unstable Bench Marks or Scales,
- measuring instruments used are found to have been tampered with by anyone,
- pre-jacking or pre-loading before commencement of the test.

Should any test be abandoned due to any of the above causes, the Contractor shall carry out further tests to the Engineer instructions after rectification of the errors.

## 19.0 PRESENTATION OF RESULTS

### 19.1 Results To Be Submitted

A written summary to the Engineer within 24 hours (or unless otherwise directed) of the test, which shall give:

(i) For each stage of loading, the period for which the load was held, the load and the maximum settlement or uplift recorded.

(ii) Load vs. Settlement curve.

The completed schedule of recorded data as described hereunder in this section shall be submitted to the Engineer within seven days of completion of the test.

### 19.2 Schedule Of Recorded Data

The Contractor shall provide information about the tested pile in accordance with the following schedule where applicable.

### 19.3 General

* Site location
* Contract identification
* Proposed structure
* Main Contractor
* Piling Contractor
* Engineer
* Client
* Data of test

### 19.4 Pile Details

All piles
* Identification (no. and location)
* Position relative to adjacent piles
* Brief description of location (e.g. in cofferdam, in cutting, over water)
* Ground level at pile location
* Head level at which test load is applied
* Type of pile (e.g. precast reinforced concrete, steel H, bored in place, driven in place, composite type)
* Vertical or raking, compression or tension

* Shape and size of cross-section of pile, position of change in cross-section
* Shoe or base details
* Head details
* Length in ground
* Level of toe

**19.5 Installation Details**

To follow the Bored Piling Specification.

**19.6 Test Procedure**

* Weight of kentledge.
* Tension pile, ground anchor or compression pile details
* Plan of test arrangement showing position and distances of kentledge support, rafts, tension or compression piles and reference frame to test pile
* Jack capacity
* Calibration certificates of pressure gauges and dial gauges
* Method of load measurement
* Method(s) of penetration or uplift measurement
* Proof test by maintained loading
* Relevant dates and times

**19.7 Test Results**

* In tabular form
* In graphical form: log P plotted against log S (only for Failure Load Tests), load plotted against settlement (or uplift load and settlement or uplift) plotted against time, load distribution with depth (if strain gauges are available), settlement of pile shaft at different depth (if extensometers are available), load settlement (load transfer) for shaft at different depths (if strain gauges and extensometers are available).
* Ground heave

**19.8 Site Investigation**

* Site Investigation report reference number and coordinate or grid reference
* Borehole reference

**20.0 COMPLETION OF A TEST**

**20.1 Measuring Equipment**

On completion of a test, all equipment and measuring devices shall be dismantled, checked and either stored so that they are available for use in future tests or removed from the Site.

**20.2 Kentledge**

Kentledge and its supporting structure shall be removed from the test pile and stored so that they are available for use in future tests or removed from the Site.

**20.3 Ground Anchors And Temporary Piles**

On completion of a Failure Load Test, temporary pile and ground anchors shall be cut off below ground level, removed from the Site and the ground made good with approved material.

The pilecap, if formed in concrete, shall be broken up and removed from the Site. If the pilecap is made of steel, it shall be cut off and either stored so that it is available for use in further tests or removed from the Site.

### 20.4 Preliminary Test Pile

Preliminary test piles which are not to be incorporated into the permanent works shall be broken down to 2m below ground level or as required, and the ground backfilled to the original level with approved material. For preliminary test piles which are to be incorporated into the permanent works, the pile head shall be made good or extended to the cut off level in the manner described in the section headed "Installation of a Test Pile" in this specification.

## 21.0 DETERMINATION OF ULTIMATE LOAD FROM THE FAILURE LOAD TEST RESULT

As general guide for test completion, failure load test shall terminate when the test pile settles by an amount equal to 10% of the effective pile diameter, but for a pile effective diameter not exceeding 250mm the corresponding pile head settlement shall be 25mm maximum. The foregoing guideline is given subject always to the condition that all failure load test shall be taken beyond the ultimate load of the pile. The load test may be terminated earlier at lower total settlement provided the Contractor can adequately demonstrate to the satisfaction of the Engineer, by load-settlement curve method or otherwise, that the ultimate load for the test pile has been exceeded at that settlement.

The ultimate bearing capacity of the test pile, if well defined in the load versus settlement curve plotted from the load test data, shall be taken as the ultimate load which is the load with a corresponding pile head settlement of not more than the lesser of 10% of the effective pile diameter or 25mm. In this case, the working load of the pile shall be taken as ultimate load divided by a factor of safety.

If the ultimate bearing capacity of the test pile is not well defined in the load versus settlement curve plotted from the load test data, the yielding load shall be taken as the lesser of either:

a. the load where the load (P) versus settlement (S) curve becomes steep and straight, or
b. the load where the log P versus log S curve shows a change in slope.

Subject to the agreement of the Engineer and provided always that the corresponding pile head settlement does not exceed an amount equal to the lesser of 10% of the effective pile diameter or 25mm. In this case, the working load of the pile shall be taken as yielding load divided a factor of safety.

The effective pile diameter shall be considered as the diameter of the circle inscribed in the section of the pile.

## 22.0 HIGH STRAIN DYNAMIC TESTING OF PILES

### 22.1 General

High Strain Dynamic testing of piles shall be carried out by an independent testing organisation approved by the Engineer.

If the results of the tests show that the pile or piles are defective, the pile or piles shall be treated as faulty and shall be rejected unless the Contractor can demonstrate to the approval of the Engineer effective remedial measures that will be carried out.

The Engineer's interpretations and conclusions arrived at on the test results shall be final.

All preliminary pile shall be subject to high strain dynamic test before and after the static load test.

## 22.2 High Strain Dynamic Test

High Strain Dynamic Test shall be conducted on working piles to be selected by the Engineer as the work progresses.

Dynamic Pile Testing is carried out for any of the following: -

- Determination of pile bearing capacity
- Determination of pile integrity
- Determination of pile stress during driving
- Determination of hammer efficiency

All tasks require measurement of both axial pile forces and accelerations under at least one hammer blow. A permanent pile set of more than 1.2mm per blow is recommended for activation of soil resistance. Smaller sets may under-predict static capacity. For integrity, permanent set is not required, but the blow should cause motion of the pile toe.

### i) Apparatus For Applying Impact Force

The apparatus for applying the impact force shall be either a conventional pile driving hammer or a similar device acceptable for applying the impact force provided it is capable of generating a net measurable pile penetration, or an estimated mobilised static resistance in the bearing strata which, for a minimum period of 3 milliseconds, exceeds the working load assigned to the pile. The driving apparatus shall be positioned so that the impact is applied axially to the head of the pile and concentric with the pile.

### ii) Apparatus For Obtaining Dynamic Measurements

The apparatus shall include transducers, which are capable of independently measuring strain and acceleration versus time at a specific location along the pile axis from the moment of impact until the pile comes to a rest. The transducers shall be placed at the same location diametrically opposed, and on equal distances from the longitudinal axis of the pile so that the measurements are not affected by bending of the pile. At the upper end of the pile they shall be attached at least one and one-half to three pile diameters from the pile head. Care shall be taken to ensure that the apparatus is securely attached to the pile so that slippage is prevented. The apparatus shall be calibrated to an accuracy of 2 percent throughout the applicable measurement range. If damaged is suspected during use, the transducers shall be recalibrated or replaced.

Force measurements shall be made by strain transducers. A minimum of two of these devices shall be securely attached to the pile on opposite sides of the pile so that they do not slip. Bolt-on, glue-on or weld-on transducers are acceptable. The strain transducers shall have a linear output over entire range of possible pile strains.

Velocity data shall be obtained with accelerometers. A minimum of two accelerometers with a resonant frequency above 10,000 Hertz shall be attached to the pile securely on diametrically opposite sides of the pile so that they do not slip and at equal distances from the pile axis. Bolt-on, glue-on and weld-on transducers are acceptable. The accelerometers shall be linear to at least 1,000g and 10,000 Hertz for satisfactory result on concrete piles. Either a.c. or d.c. accelerometers shall be used. If a.c. devices are used, the time constant shall be a least one second.

### iii) Apparatus For Recording, Reducing And Displaying Data

The signals from the transducers during the impact event shall be transmitted to an apparatus for recording, reducing and displaying data to allow determination of the

force and velocity versus time. The acceleration and displacement of the pile head, and the energy transferred to the pile shall be determined. The apparatus shall include an oscilloscope or screen for displaying the force and velocity, a tape recorder for obtaining a record for future analysis, and a means to reduce the data. The apparatus for recording, reducing and displaying data shall have the capability of making an internal calibration check of force, velocity and time scales. No error shall exceed 2 percent of the maximum signal expected.

Signals from the transducers by means of an apparatus on which the force and velocity versus time can be observed for each hammer blow such as an oscilloscope or oscillograph. Both the force and velocity data shall be reproduced for each blow and the apparatus shall be capable of holding and displaying the signal from each selected blow for a minimum period of 30 seconds.

**iv) Dynamic Measurements**

Dynamic properties shall be determined from a minimum of ten impact records during initial driving. Soil resistance computations shall be determined from one or two representative blows at the beginning of restriking. The force and velocity versus time signals shall be reduced by computer or manually to calculate the developed force, velocity, acceleration, displacement, and energy over the impact event. The number of impact for a specific penetration ram travel length, and the number of blows per minute delivered by the hammer shall be recorded. The testing shall be performed by an experienced engineer in the field of dynamic testing.

**v) Submission Of Test Records**

The Contractor shall submit all records of results and any other information to the Engineer within three (3) days from the completion of the test.

The results shall consist of the stresses in piles, pile integrity, hammer performance, pile bearing capacity, and whatever information deemed necessary for the report.

For preliminary test and complicated cases, CAPWAP laboratory analysis shall be carried out.

The Engineer's interpretation and conclusion arrived at on the test result shall be final.

**vi) CAPWAP Computer Analysis Program**

The outputs shall consist of matches of forces and velocities, resistance distribution, static simulation and complete tables of numeric values.

The specialist Contractor shall complete and provide the following: -

- Static capacity of pile including the toe resistance and shaft friction
- Hammer Efficiency
- Integrity of Pile
- Case Damping Factor Jc
- Predicted Load Vs Settlement Plots

CAPWAP computer analysis report shall be submitted to the Engineer within seven (7) days from the issuance of instruction.

The report shall contain complete analysis, result and their interpretation.

## 23.0 SHOCK METHOD

### 23.1 Preparation of the Pile Head

The pile head shall be clearly exposed, free from debris, etc. and not more than 1.0 metre above or below ground level, otherwise the surrounding soil shall be built up or excavated to meet this condition. The pile head shall be smooth over its complete cross-section, free from irregularities and perpendicular to the vertical axis of the pile.

The pile head shall consist of sound concrete. This shall be achieved during the concreting of the pile by flushing out all weak mortar, etc. from the top of the pile head and carefully screeding off to provide a smooth level surface in sound concrete. Alternatively, if the pile head is prepared after concreting, all weak mortar, broken concrete, etc. shall be removed form the pile head to expose sound concrete over its complete cross-section. After cleaning it off to ensure a sound bond, a very thin screed (maximum 1cm) of strong sand/cement mortar, rapid hardening compound, shall be spread to provide a smooth working surface for the shock test equipment. The mortar shall be allowed to harden before testing. The soundness shall be tested by means of light blows from a small hammer.

Any reinforcement or other inclusions protruding from the pile head shall not prevent the testing team from giving the pile the required impact force over the centre of the pile and the placing of a 5cm diameter (approx.) electronic pick-up at about 10cm from the periphery of the pile. Access shall be provided for the service van within 30 metres of the pile.

### 23.2 Shock Test Equipment

The shock which is to be imparted onto the pile head shall be carried out using a suitable hammer or any approved method which is capable of transmitting vibration to the base of the pile shaft. The electronic pick-ups located on the pile head shall be approved velocity transducers or accelerometers connected through an approved frequency analysed to any X-Y plotter. The mechanical admittance shall be plotted on a vertical scale and the frequency on the horizontal scale. Both the horizontal and vertical scales shall be varied as required. The equipment shall have an independent power supply.

### 23.3 Shock Test

The Contractor shall provide the testing team with a site plan showing the pile layout and a list of the piles to be tested.

Before testing, the heads of the piles shall be inspected by the testing team for regularity and soundness and any unsatisfactory pile heads reported to the Engineer. They shall be made good to the satisfaction of the Engineer and smoothed off using a suitable epoxy mortar if necessary. Preliminary tests shall be carried out to establish the appropriate scales and to check the electronic circuit.

## 24.0 SONIC LOGGING METHOD

For the purpose of carrying out sonic logging, the Contractor shall be required to install the necessary tubing for the tests at all pier location or as directed by the Engineer.

The tubes shall be of internal diameter not less than 50mm with no internal projections or couplings. They can be of mild steel pipes or PVC pipes. Four (4) nos. of tubes are required for each pile greater than 700mm diameter while three (3) nos. are required for each smaller diameter pile.

The tubes shall be fixed to the longitudinal bars with equal spacing on the inside perimeter of the links. The tubes shall be watertight with the bottom of the tube sealed and suitably weighted to prevent floating. The tubes shall be secured to the internal face of the reinforcement cage at equal distance from each other on the circumference.

The tubes shall extend the full depth of the pile and project 300mm above the top of the concrete and not lower than 300mm below the surface of the ground. All joints shall be made watertight. The tubes shall be filled with water to provide the necessary acoustic coupling, and then plugged or capped before concreting. The type of tube and condition of sealing shall be checked and approved by the Engineer before installation.

The rate of logging for increments of depth shall be approved by the Engineer.

After conducting the tests, all metal tubes shall be grouted and water in the tubes displaced. The grout shall be dense cement grout with an approved expanding agent.

Prior to testing, the necessary equipment shall be thoroughly checked to ensure that all parts are functioning satisfactorily. During sonic logging testing, where any irregularities are detected, the tests shall be repeated at a smaller scale to allow a "close-up view" of the irregularities.

## 25.0 PRESENTATION OF TEST RESULTS

The time required to carry out the test for each pile must be recorded along with records of starting time and finishing time.

The results of the tests shall be presented in report form by the testing firm and must be signed by a professional engineer. The report shall include comprehensive engineering analysis of the test results for each pile taking into consideration the soil condition and any other relevant factors. Interim reports of each pile or group of piles tested in one day shall be submitted to the Engineer within 3 days of the completion of the test or tests. A final comprehensive report shall be submitted to the Engineer within 10 days of the completion of the last test or tests.

## 26.0 PROOF CORING OF PILE SHAFTS

The Contractor shall check the quality of the concrete in the shafts of working piles as directed by the Engineer. This shall be achieved by a vertical diamond core hole drilled through the centre region of the pile from pile head to required depth. The location of the drill hole and depth shall be approved by the Engineer. Full core recovery shall be attempted. The core so produced shall not be less than 50mm in diameter. The minimum number of piles for proof coring test shall not be less than 1% of the total number of working piles.

For each pile to be cored, the coring work shall be completed before the concrete in the pile has reached an age of 28 days to allow the cores to be tested for unconfined compression tests at 28 days. The Engineer shall mark the sections of the core to be tested and the Contractor shall arrange for testing in an approved laboratory. A minimum of six (6) unconfined compression tests shall be conducted on cores obtained from a pile. Additional number of the unconfined compression tests may be requested by the Engineer if in the opinion of the Engineer the quality of the concrete of the pile is suspicious.

The cored hole in the pile shall be grouted after testing. The grout shall be an approved dense cement grout with a minimum 28 days strength of 30N/mm2. If the pile is found to be faulty in the opinion of the Engineer because of defects such as cracks, overbreaks, necking, cavity, inclusion of foreign deleterious materials, poor quality concrete, etc., the pile shall be rejected and the Contractor shall undertake all necessary remedial measures to the approval of the Engineer.

In conjunction to core testing, the Engineer may request sonic logging test to be conducted in the cored holes or pre-installed tubings to determine the in-situ density of the pile and their integrity continuously along the pile length in correlation with core samples.

## 27.0 INSTRUMENTATION FOR TEST PILES

### 27.1 Strain Gauges

Vibrating wire type strain gauges shall be installed in preliminary pile. The following vibrating wire strain gauges and equipment or equivalent to the approval of the Engineer shall be used:

i) Vibrating wire type weldable strain gauge. Steel wire of length of about 60mm (e.g. 62mm), and frequency range 0.8 to 2.4 kHz and associated connections, cables and read out device.
ii) 3M Scotchcast Insulating Resin 4.
iii) Miscellaneous small tools and materials for making concrete.

All strain gauges shall be mounted on major longitudinal steel bars of the steel cage of the preliminary pile. The strain gauges shall be installed in sets of four and equally spaced on the steel cage at levels directed by the Engineer. A total of 6 sets of strain gauges shall be installed.

The steel bars shall be polished using a hand held electrical grinder to obtain a flat surface for the strain gauges to be placed on. Polishing shall be completed by hand using silicon carbide paper. The surfaces of the polished bars shall be cleaned using acetone.

The weldable strain gauges shall then be bonded to the steel bars using a microbond welder. Next, the strain gauge sensors shall be placed on the strain gauges and tied firmly to the steel bars with wires. Short lengths of PVC protective pipe shall be placed over the strain gauge locations, and filled with insulating resin.

The electrical lead wires from the sensors shall be brought to the top of the pile through PVC pipes tied to the steel cage.

The gauges shall be checked before and after microwelding, after installation, after placement of the steel cage in the borehole, and after concreting.

### 27.2 Rod Extensometers

A system of sleeved rods to the approval of the Engineer shall be installed in each preliminary pile to determine the movement under testing loads. A minimum of three (3) levels within the pile shaft shall be measured as shown in the drawings. The rod extensometers shall have the capability of measuring movements both mechanically and electronically.

### 27.3 Instrumentation Installation

The Contractor shall follow the manufacturer recommended procedures for instruments installations and shall provide a method statement for approval prior to installation. The work shall be carried out by persons experienced in this type of work. A data logging system shall be provided for all automatic recording instruments.

### 27.4 Instruments Identification and Recording

The leads of various instruments shall be probably identified to facilitate easy hook-up and recording. All instrument readings shall be recorded as directed by the Engineer in approved forms. Any sort of calibration or conversion charts shall be available on site at all times.

### 27.5 Monitoring

The nominated testing agency shall submit a method statement on pile instrumentation for the Engineer's agreement before the conduct of the tests. The method statement shall give full details of the proposed methods, equipments, specifications and precautions to be taken for

the proper installation and monitoring of pile instrumentation, and the criterion and procedure for interpretation of results obtained, including any other relevant information required by the Engineer. Prior to the tests, the instruments and necessary monitoring equipment shall be checked to ensure all parts are functioning satisfactorily.

The results of the pile instrumentation and monitoring programme shall be presented in a report prepared by the testing agency and signed by a qualified engineer. The report shall include a comprehensive engineering analysis of the test data, taking into consideration the soil condition and any other relevant factors. An interim report shall be submitted to the Engineer within 3 working days after the completion of each Failure Load Test, and a final comprehensive report shall follow 7 days later. The testing agency shall be required to correlate the results of pile instrumentation with that of the Failure Load Test and against the soil information available in the soil report from exploratory boreholes located in the vicinity of preliminary test piles.

The Contractor shall make every necessary allowance for the proper execution of the instrumentation programme. Full cooperation shall be given to the nominated agency carrying out the tests. The Contractor shall not be allowed to claim for extra time to the contract on all matter arising from the execution of pile instrumentation, and on any consequences arising out of such instrumentation.

Both soft and hard copy of the report shall be submitted to the Engineer in the format approved by the Engineer.

# APPENDIX C

Sample Checklist for Construction of Bored Pile

## CHECKLIST FOR BORED CAST-IN-PLACE PILE

| | CHECKLIST ITEMS | Checked By Engineer | Remarks |
|---|---|---|---|
| | **Project Name** : ______________________________<br><br>**Piling Contractor** : ______________________________ | | |
| **1.0** | **CONSTRUCTION METHOD AND TECHNIQUES** | | |
| | • Pile Diameter ________________________________<br>• Concrete Grade ________________________________<br>• Pile Raked Gradient ______ Vertical : ______ Horizontal | | |
| | • Grab Construction (Using Crawler Crane, Casing Oscillator, etc)<br>• Rotary Drilling (Contiguous Flight Auger, Twin Head Rotary Drive)<br>• Rock Coring (Chisel, Core Barrel, Cross Head Cutter, Reamer, etc.) | ❑<br>❑<br>❑ | |
| | • Direct Circulation Drill<br>• Indirect Circulation Drill | ❑<br>❑ | |
| | Concreting Method<br>• Poured (With Tremie for Wet Hole Construction)<br>• Injected | <br>❑<br>❑ | |
| | Reinforcement<br>• Reinforcement Cage : Main _______ Link _____________<br>(eg. 32T20) (eg. T12 @ 150 Spiral)<br>[Note: T = 460 N/mm2 , Y = 410 N/mm2 , R = 250 N/mm2 ]<br>• Lapping Length : _____________________________<br>• Concrete Cover/ Spacer : _______________________ | | |
| **2.0** | **PILING EQUIPMENT AND ACCESSORIES** | | |
| | Excavator:<br>• Crawler Crane (Grab method)<br>• Rotary Drive (Continuous Flight Auger, Twin Rotary Head) | | |
| | • Temporary Casing | | |
| | • Drilling Fluid (Bentonite or other Slurry Stabilisation) | | |
| | • Concrete Tremie Pipe (for concreting under water or wet hole)<br>• Hover with short length of chute (direct discharge method for dry hole) | ❑<br>❑ | |
| **3.0** | **PILE POSITION SETTING UP** | | |
| | • Three reference points to be setup with respect to the proposed pile point. | | |
| **4.0** | **BORED PILE CONSTRUCTION** | | |
| | **Predrilling** | | |

| | | | |
|---|---|---|---|
| | • To determine the bored pile length<br>• To check verticality of borehole<br>• To check any deviation in the distance of pile point to the reference points after soil boring. | | |
| | **Stability Of Borehole**<br>• Temporary steel casing with appropriate size and length (minimum 1m or below the unstable strata) should be applied to prevent loose materials falling into the bottom of borehole.<br>• Borehole to be filled with drilling fluid to stabilise the borehole [See note ##] unless stiff clayey soils are encountered. | | |
| | **Verification Of Bedrock (If Required)**<br>• Inspection of the excavated rock fragments<br>• The depth achieved (rock encountered / total length) to be compared with the borehole data and checked by a measurement tape.<br>• The bottom soundness is checked with a weight on a tape tamped on the founding strata.<br>• In-situ rock strength test (e.g. Point Load Test) to be conducted [See note ##] | | |
| | **Airlifting (Base Cleaning)**<br>• Use cleaning bucket to clean the base before carrying out air lifting.<br>• To ensure the cleanliness of the loose and caving-in soil at base.<br>• Make sure the hose is at the base of the pile (not suspended half-way). | | |
| | **Reinforcement Cage**<br>• The length of the cages should match with the excavated depth.<br>• Insert fabricated reinforcement cage into the cased borehole | | |
| | Check Lap length (if any) | ❑ | |
| **5.0** | **CONCRETING** | | |
| | • Concrete overbreak after each batch of concreting<br>• Pour in concrete (by tremie concrete method or direct discharge method), simultaneously displacing slurry.<br>• Check the density of fluid as in the specification.<br>• The bottom end of the tremie pipe should be always about one to two metres submerged below the level of the concrete. (Not to pull up too abrupt)<br>• Concreting could only be stopped at about 1m above the cut-off level<br>• Record any interruption on concreting (record the duration)<br>• Test Cube :<br>o at least 6 Nos.<br>o achieve design strength (within 28 days)<br>• Concrete Slump Test<br>• Record :<br>o Number of trucks<br>o Discharge amount per trucks | | |

| | | | |
|---|---|---|---|
| **6.0** | **PROOF DRILLING** | | |
| | Core drilling to be carried out through piles to check the qualities of<br>• Concrete<br>• Contact between the rock and concrete<br>• Quality of the rock beneath the toe | | |
| **7.0** | **CHECK BORED PILE SHAFT INTEGRITY** | | |
| | • Use High Strain Dynamic Load Test (HSDLT)<br>• Pile Integrity Test (PIT).<br>• Sonic Logging | ❑<br>❑<br>❑ | |
| **8.0** | **POST-INSTALLATION** | | |
| | Penetration length<br>• Piling Platform level : ____________<br>• Borehole Drilling Record : _________<br>• Predicted Length at site : _________ ( from HSDLT or PIT ) | | |
| | Compared penetration lengths with Borehole or Proof Drilling from Subsurface Investigation. | | |
| | Check As-built position of the bored pile group<br>(Typically eccentricity < 75mm) | | |
| **9.0** | **COMPUTATION**<br>Estimate the amount of concrete and materials for each piles. | | |
| | Signature by Engineer | | |

Note : [##] represents the items that will be followed if only necessary.

# APPENDIX D

Design of Piles with Lateral Loadings

# DESIGN OF PILES WITH LATERAL LOADINGS

Pile foundations for structures such as bridge abutments and piers for bridges are subjected to lateral loadings that need to be assessed carefully. The design of piles subjected to lateral loadings are often governed by lateral deflections. However, ultimate resistance may be important for:

a) Short piers
b) Long slender piles
c) Non-linear analysis of deflections

Design of pile foundations with lateral loadings requires the assessment of failure modes and head conditions as follow:

*Failure modes:*

a) Short pile mode: Failure of the supporting soil
b) Long pile mode: Structural failure or yielding of the pile itself

Both modes need to be analysed, and the more critical mode established.

*Head conditions:*

a) Free or unrestrained head – no head restraint
b) Fixed head or restrained head – no rotation of head

In this short note, Broms' theory on the estimation of ultimate lateral load and Randolph's elastic continuum approach for the estimation lateral deflections which are two of the most widely used method will be presented.

## Broms' theory (Ultimate lateral load)

Useful and simple to use design charts for eight different categories are available:

a) Cohesive soils
    i. Short and long pile failure – unrestrained head
    ii. Short and long pile failure – restrained head

b) Cohesionless soils
    i. Short and long pile failure – unrestrained head
    ii. Short and long pile failure – restrained head

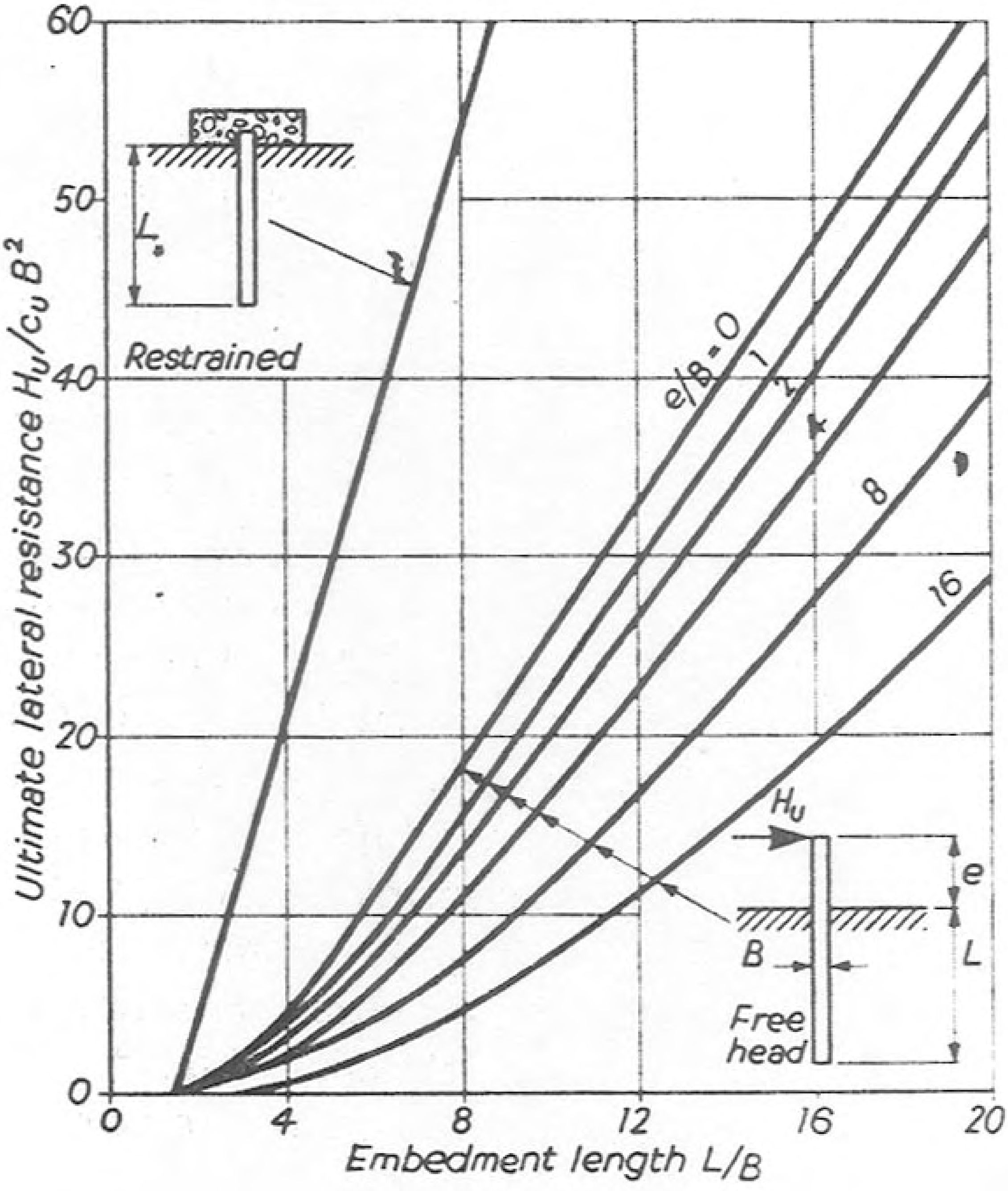



**Figure 1: Short Pile in Cohesive Soil**

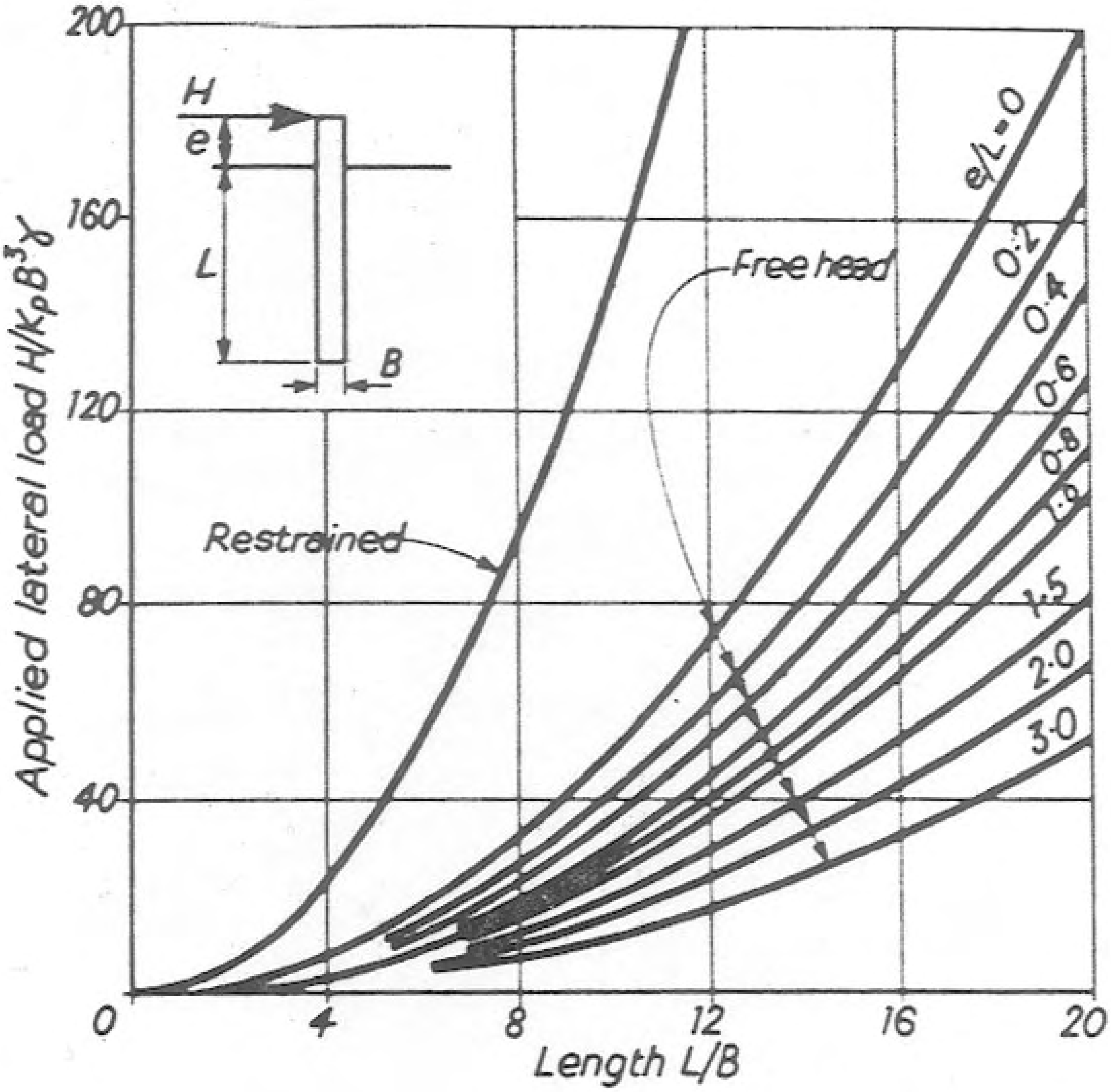



**Figure 2: Short Pile in Cohesionless Soil**

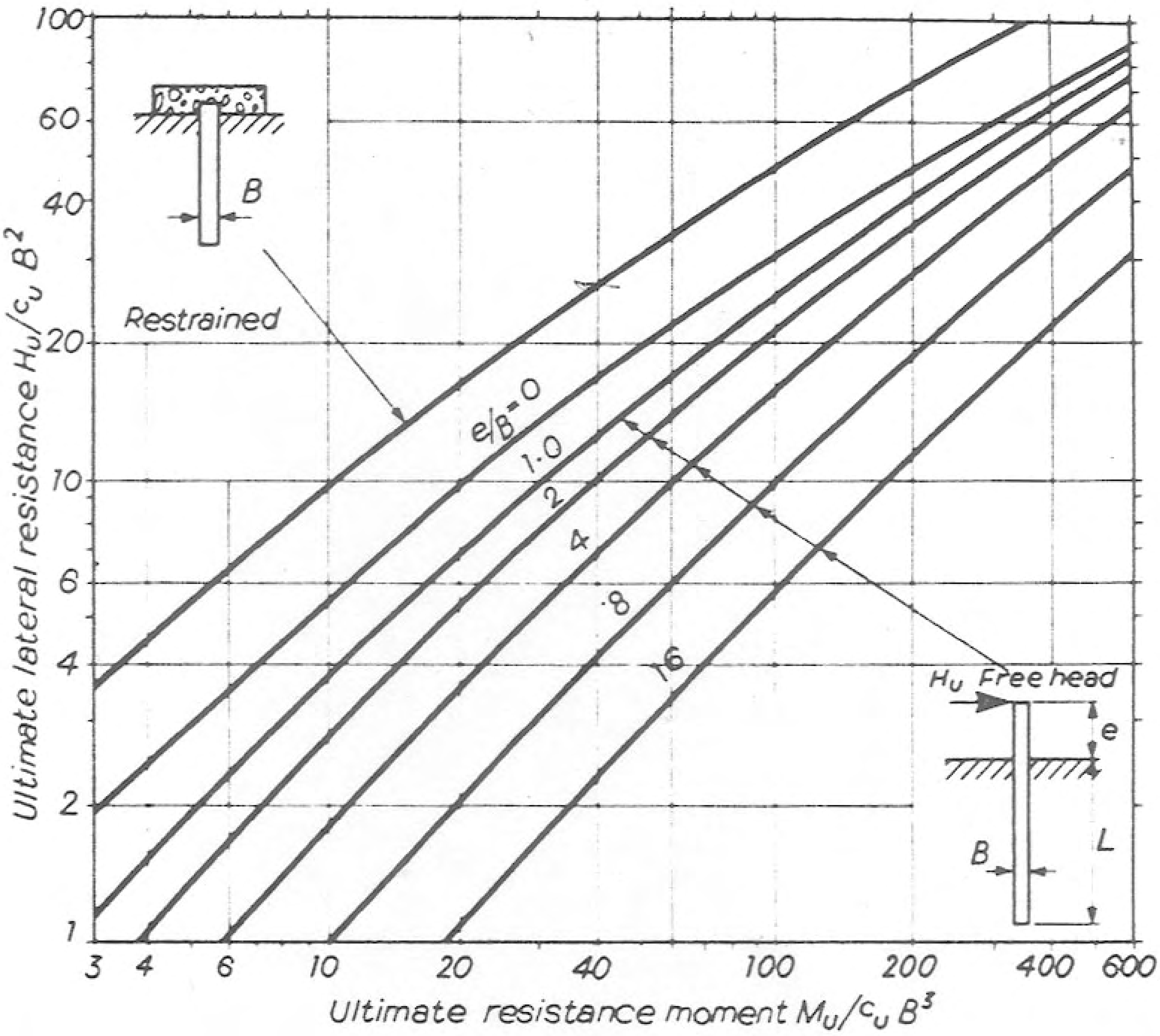



**Figure 3: Long Pile in Cohesive Soil**

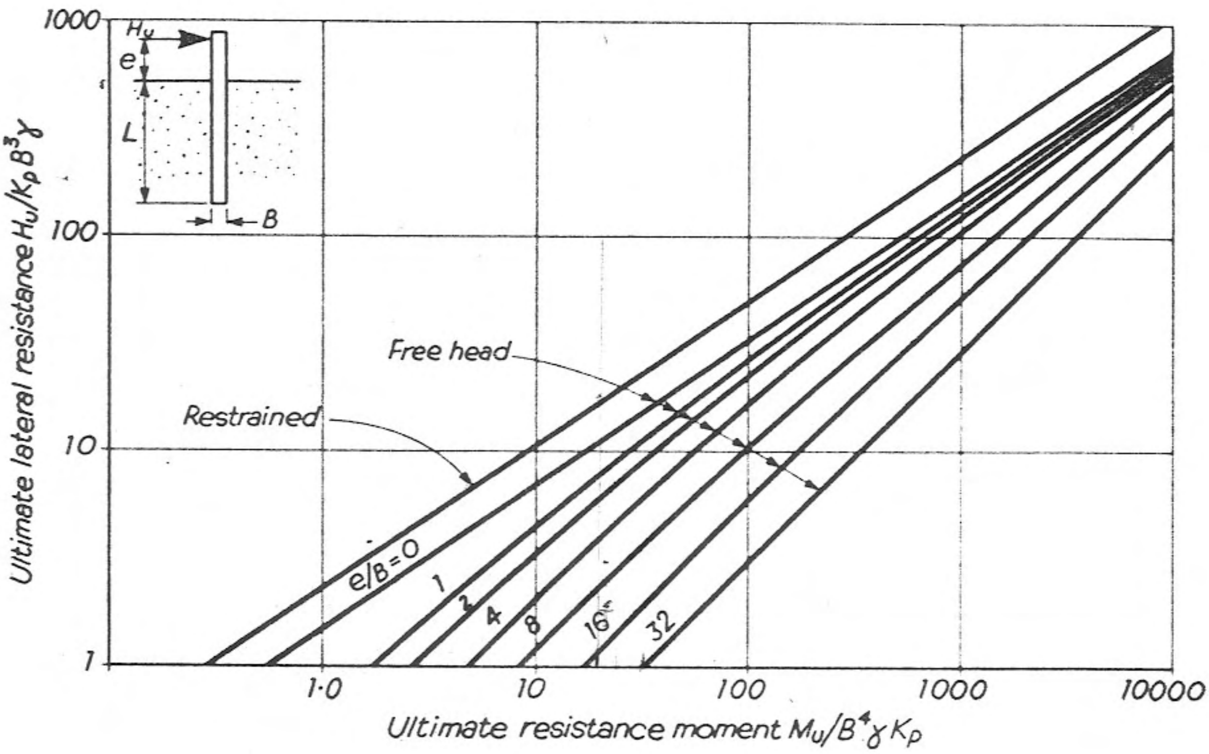



**Figure 4: Long Pile in Cohesionless Soil**

The above charts are simple and easy to use. The required information for the determination of ultimate lateral resistance is:

a) Undrained shear strength, $\mathbf{c_u}$ (for cohesive soil)
b) Coefficient of passive earth pressure, $\mathbf{K_p}$ and density of soil, $\gamma$ (for cohesionless soil)
c) Yielding moment for pile, $\mathbf{M_u}$
d) Embedded pile length, **L**
e) Pile diameter / width, **B**
f) Height from the ground surface to the point of application of the load (free head pile), **e**

For design, both short pile and long pile mode of failures need to be considered and the most critical value adopted.

<u>Example:</u>
Determine the required embedment depth of a $\phi$800mm bored pile sustaining a horizontal load of 960 kN (restrained head). Undrained shear strength of soil = 75 kPa.

For short pile failure mechanism, $H_u / c_uB^2 = 20$, from Figure 1: L/B = 4

Therefore, required L = 4 x 0.8 = 3.2m x 2.5 (FOS) = **8.0m**

In addition, adequate reinforcement should also be provided for the bored pile to sustain bending moment given by:

For long pile failure mechanism, from Figure 3: $M_u / c_uB^3 = 30$,

Therefore, $M_u = 30 \times 75 \times 0.8^3 = 1152$ kNm

## Randolph's elastic continuum approach (Lateral deflections)

For the application of this approach, Randolph has introduced the following parameters:

a) Shear modulus, $G^* = G\,(1 + 3\nu/4)$

b) Variation of shear modulus, $\rho_c = G^*_{lc/4} / G^*_{lc/2}$

c) For an equivalent pile of radius $r_o$, Young's modulus, $E_p = (EI)_p / (\pi r_o^4/4)$

Definition of the above parameters are as shown in Figure 5.

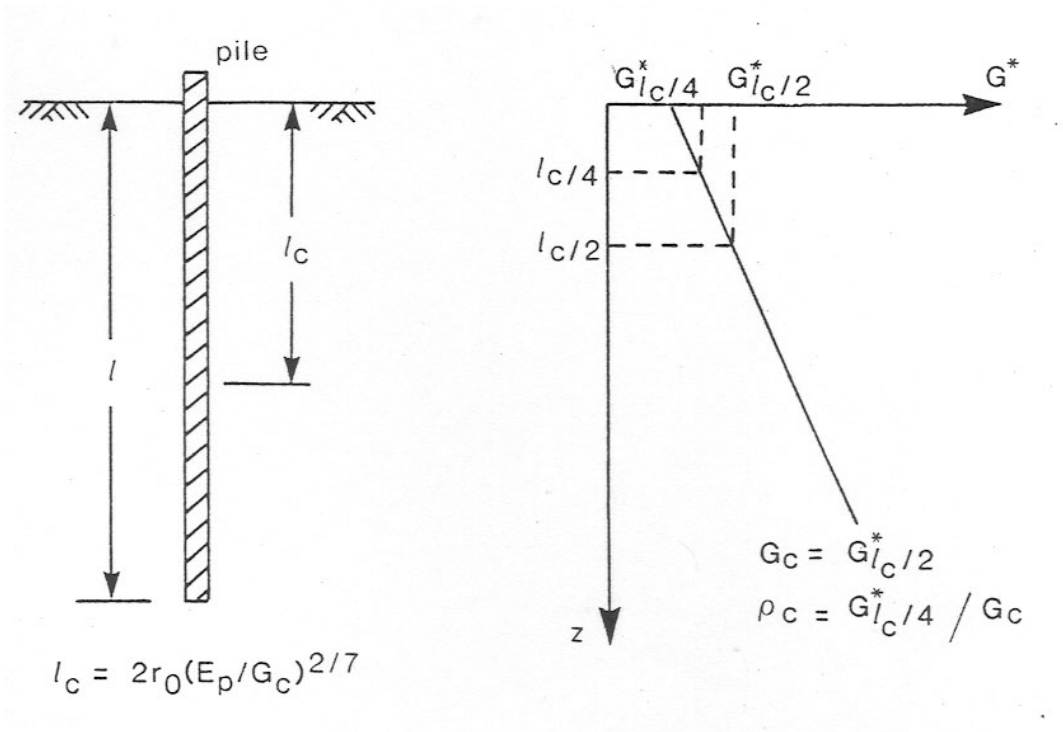



**Figure 5: Definition of $\rho_c$ and $G_c$**

The critical pile length is defined by Randolph as:

$$\mathbf{l_c = 2r_o\,(E_p/G_c)^{2/7}} \qquad (1)$$

It may be seen from Figure 5 that the definition of $G_c$ requires the knowledge of the critical length which is in turn defined in terms of $G_c$. Thus some iteration is required except for the extreme cases of homogeneous soil ($\rho_c$ = 1) and soil where G is proportional to depth ($\rho_c$ = 0.5), where the critical length reduces to:

$$\mathbf{l_c = 2r_o\,(E_p/m^*r_o)^{2/9}} \qquad (2)$$

where m* is the rate of increase of $G^*$ with depth.

With the concept of a characteristic shear modulus, $G_c$ and a critical pile length, $l_c$ introduced, the lateral deflection, u and rotation, $\theta$ are given by:

$$\mathbf{u = [\ (E_p/G_c)^{1/7} / \rho_c G_c\ ]\ [0.27\ H\ (l_c/2)^{-1} + 0.30\ M\ (l_c/2)^{-2}]} \qquad (3)$$

$$\mathbf{\theta = [\ (E_p/G_c)^{1/7} / \rho_c G_c\ ]\ [0.30\ H\ (l_c/2)^{-2} + 0.80\ (\rho_c)^{1/2}\ M\ (l_c/4)^{-3}]} \qquad (4)$$

where H = lateral load and M = moment

According to Randolph, the maximum moment for a pile under a lateral load of H, occurs at a depth between $l_c/4$ (for homogeneous soil) and $l_c/3$ (for soil with stiffness proportional to depth). The value of the maximum moment may then be estimated as:

$$\mathbf{M_{max} = (0.1/\rho_c)\ H\ l_c} \qquad (5)$$

For piles within a group, the pilecap may prevent rotation of the head of the pile. For such "fixed-headed" piles, Equations (3) and (4) may be used to find the fixing moment, $M_f$. Setting $\theta = 0$, the fixing moment is given by:

$$\mathbf{M_f = -\ [0.375 / (\rho_c)^{1/2}]\ H\ l_c/2} \qquad (6)$$

The resulting deflection of the pile head may then be calculated from Equation (3):

$$\mathbf{u_f = [\ (E_p/G_c)^{1/7} / \rho_c G_c\ ]\ [0.27 - 0.11 / (\rho_c)^{1/2}]\ H\ (l_c/2)^{-1}} \qquad (7)$$

It is important to take note that the above equations are for piles longer than their critical length. For piles shorter than their critical length, the head deformation will be larger especially when the pile length falls below about 0.8 $l_c$. Solutions for short piles will not be discussed here and interested readers may refer to works by Carter & Kulhawy (1988) and Poulos & Davis (1980).

<u>Example (after Fleming et. al, 1994):</u>
Consider the response of a steel pipe pile, 1.5m in diameter, with 50mm wall thickness, embedded in soft, normally-consolidated clay with a shear strength which increases at a rate of 2.5 kN/m$^2$ per metre of depth. The equivalent modulus of the pile is calculated as:

$$E_p = E_{steel}\ [1 - (r_i/r_o)^4] = 50600\ MN/m^2$$

where

$r_i$ = inner radius of the pile
$E_{steel}$ = 210 GN/m$^2$

Taking a shear modulus for the soil of $G = 100c_u = 0.25z$ MN/m$^2$ and Poisson's ratio, $\nu = 0.3$, the critical pile length may be calculated as:

$$l_c = 2r_o\,(E_p/m^*r_o)^{2/9} = 2(0.75)[50600/(0.306 \times 0.75)]^{2/9} = 23.1 \text{ m}$$

where $m^* = 0.25\,(1 + 0.75 \times 0.3) = 0.306$ MN/m$^3$. The value of $G_c$ is then given as:

$$G_c = G^*_{lc} / 2 = 23.1 \times 0.306 / 2 = 3.53 \text{ MN/m}^2$$
$$\rho_c = 0.5$$

Therefore, under a lateral load of 1 MN, with no rotation allowed at ground level, the maximum bending moment and ground level deflection may be calculated from Equations (6) and (7):

$$M_f = -\,[0.375 / (0.5)^{1/2}]\,(1)\,(23.1)/2 = -6.1 \text{ MNm}$$
$$u_f = [\,(50600/3.53)^{1/7} / (0.5 \times 3.53)\,]\,[0.27 - 0.11 / (0.5)^{1/2}]\,(1)\,(23.1/2)^{-1} = 22.0 \text{ mm}$$