Pile Foundation Design and Construction – What Can Go Wrong?

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1. INTRODUCTION

The main scope of this paper is to discuss the practical aspects involved in design, construction and testing of pile foundation with particular reference to practical mitigations against what can go wrong at site.

Generally, a comprehensive scope of pile design shall include the following three fundamental parts:-

- Comprehensive analysis and calculations based on established methods and adequate SI results to show the design criteria or policy can be achieved at site;
- Adequate mitigation measures against what can go wrong at site;
- Adequate QA/QC scheme to check and to verify the important design assumptions, structural integrity and performance requirements.

Pile design is a science because pile design is based on scientific principles, but its practice is more like an art, because it invariably contains a lot of empiricism, rules of thumb and engineering judgments

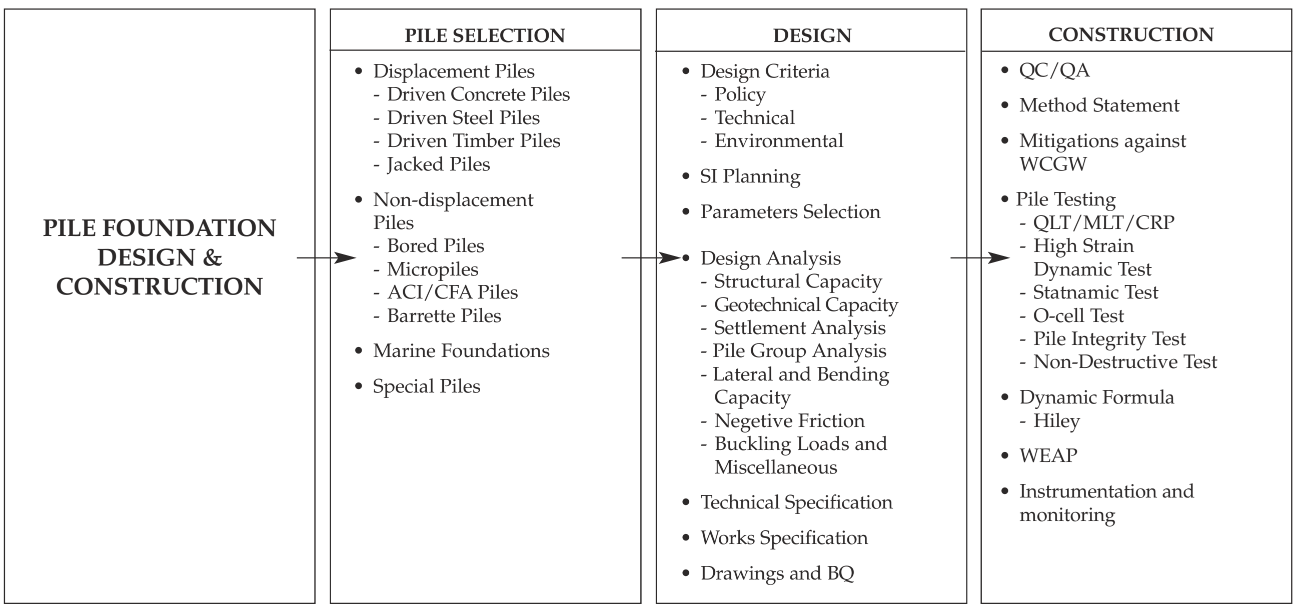

Figure 1: Pile foundation design and construction scope (after Neoh CA, 2005)

NOTES:

1. A piling system = Pile type + installation method + QC / QA scheme.
2. Structural capacity of piles (driven piles) shall be checked for handling, installation and working stresses. Refer Table 3 for the allowable stresses.
3. Method statement shall include specific details of 3M (materials, machines and manpower), sequence of works, works output rate and QC/QA scheme (type of tests / measurements / observations plus their respective frequency and acceptance criteria). Remedial measures for cases where acceptance criteria cannot be achieved shall also be indicated.

with diverging expert opinions, sometimes. Hence, pile design calculation alone is not everything until and unless it can be verified by testing. Also, testing is not everything, unless it can be convinced that the results of testing can statistically represent the untested piles on the safe side. In fact, in his Nash lecture (1987) Prof. Burland stated: *"It is both arrogant and dangerous to believe that ground engineering can be carried out solely on the basis of numbers (theoretical calculations) given from site investigation coupled with codes of practice. It is necessary to study case histories, learn about local experience, examine the soil and visit the site."* Terzaghi also stated that: "The responsibility of geotechnical engineer (pile foundation designer) *is not just to calculate accurately but more to judge soundly."* Hence, mitigation measures based on extensive experience, past case histories and practical judgment against what can go wrong at site are obviously equally, if not more important than calculation alone. This is because most of the reported pile foundations problems or failures have not been caused by erroneous calculations of pile capacity or settlement but mainly by defective pile materials or faulty workmanship or improper pile installation techniques as the result of designer's ignorance/carelessness or unawareness of what can go wrong at site, including inadequacy in subsoil characterisation due to inadequate SI or unreliable SI.

A practical and cost-effective pile design shall be the one that can be executed smoothly and successfully without encountering any big problems, i.e. no drastic pile design variations, no serious structural or durability problems that need major rectifications, negligible cost overruns and time delay.

Important scope and subjects normally covered in the Pile Foundation Design and Construction are summarised in Figure 1. This paper focuses mainly on some common problems for driven concrete piles and bored piles only.

The first task in pile design is to select a suitable pile type, size, length and installation method for a specific project, after taking into considerations of design criteria, past experience, various environmental design considerations and relevant factors, etc. The second task is to carry out analysis and calculations based on established method and adequate SI to check that the capacity and settlement, etc., as listed in Figure 1 are satisfactory with particular respect to the design criteria and policy set by the Client. The next task is to design cost-effective mitigations against what can go wrong at site. Finally, proper design of QA/QC scheme to check and to verify the important design assumptions, structural integrity and critical performance (capacity and settlement) shall be carried out. The load-settlement behaviors plus their significance and applications of end bearing piles and frictional piles are self explanatory through Figure 2.

2. WHAT CAN GO WRONG WITH DISPLACEMENT PILES?

What can go wrong at site for prefabricated steel and precast concrete displacement (or driven) piles are summarised in Table 1. In addition to checking adequacy of geotechnical capacity based on borehole results, all driven piles also shall be checked for adequacy in structural strength to undertake the anticipated handling stress, installation stress and working stress, as required by BS8004. Permissible working compressive stress for concrete and steel piles is $0.25f_{cu}$ and $0.33f_y$ respectively (f_{cu} = grade of concrete and f_y = yield stress of steel). Handling stress depends mainly on the locations of the pitching and handling points and is simple to estimate (refer Notes to Table 3) or usually not critical. Any serious mishandling for concrete piles also can be easily detected through careful inspection for cracking before driving. However, the assessment of driving stress is very complicated and is seldom carried out by the pile foundation designers, who may conveniently assume that such task should be carried out by the Resident Engineer at site. It is recommended that Prof. Broms' method should be used to assess roughly the anticipated driving stresses during the design stage and detail driving stresses by Wave Equation Analysis Program (WEAP) before commencement of piling works.

According to Prof. Broms, dynamic driving compressive stress, f_c, for concrete pile is related to effective drop of hammer (h in cm), i.e., $f_c = 3h^{1/2}$. The highest compressive stress usually occurs near the pile head, but it can also occur near the pile toe when it strikes rock. High driving tensile stress, f_t, (f_t = 10% to 30% f_c) usually happens at the instant when pile penetrates through a stratum with immediate weaker underlying layer. Bending stress can be very high when the pile is not straight or it is too slender (l/d>100) or when the pile strikes boulders/inclined bedrock or strata of different stiffness (causing it to deflect). It is recommended that the following measures shall be adopted to mitigate excessive driving stresses (f_c, f_t and f_b) and to minimise pile damages:-

a) For reinforced concrete piles, adequate reinforcement (> 1.5%) shall be provided to ensure allowable tensile stress ($0.7f_yA_s/A_c$ or 0.8 x $f_{cu}^{0.5}$ whichever is lower) is more than 5 MPa. For prestressed spun piles, the effective stress shall not be less than 5 MPa. Driven concrete piles without

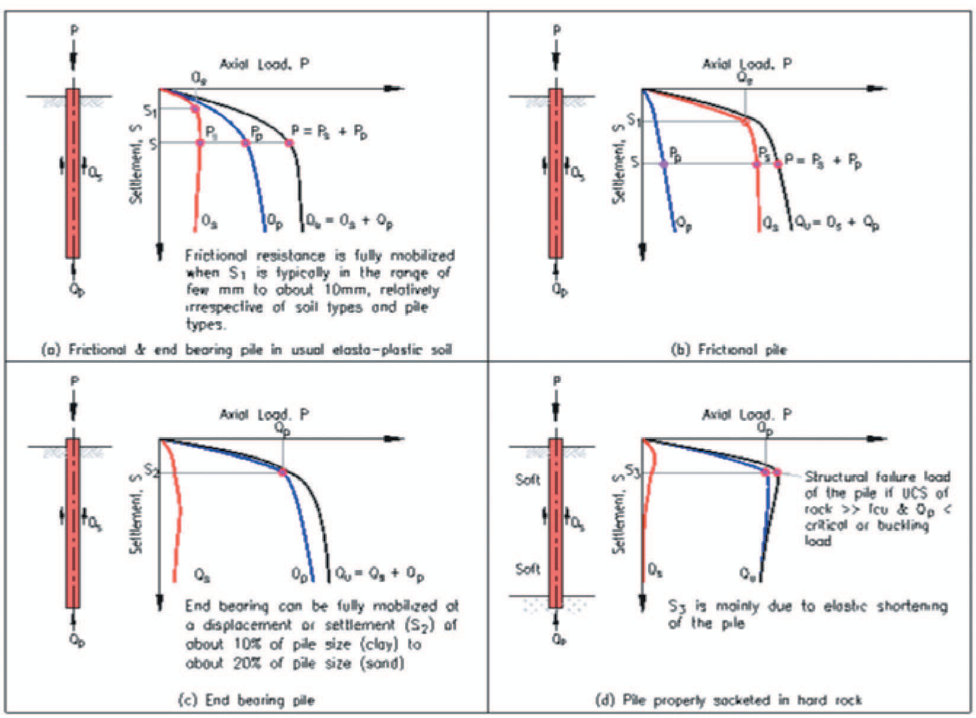

Figure 2: Characteristics of Pile-Load-Settlement behaviours

complying with these requirements are likely to be damaged by excessive tensile or bending stress except when the piles are unjointed (without any joint) or the slenderness ratio is low or well less than 100 and has been thoroughly checked by WEAP that the driving stresses are well within the permissible limits of the pile supplied (refer Table 3). When long piles are required in difficult ground such as deep deposit of soft alluvial soils or when very hard driving is required, close ended prestressed spun piles with effective stress more than 7 MPa or large precast RC piles of grade 50 with more than 1.5 % reinforcement plus inclusion of central inspection tube are recommended. These measures are necessary to mitigate against pile damages due to high driving stresses (f_c, f_t, and f_b). The closed end spun piles or central tube in RC piles are useful for inspection after driving and easy remedy in case some damages are identified.

b) Hammer drop shall be controlled and checked (by Prof. Broms' method and WEAP) to ensure that the permissible driving stresses are not exceeded (refer Tables 3).

c) The design load (Qd) for pile shall be limited in cases where high driving stresses are anticipated. The maximum structural capacity shall be discounted for slenderness ratio ($^l/_d$- 120)% and joints 5n%, where l = pile length, d = pile size and n = number of joints. Also, for very hard driving where bending stress is anticipated to be high, the design load, Q_d shall be limited to about M_c/0.15d, where M_c is the calculated cracking moment (for crack width of up to 0.3mm) and d = pile size. Calculation of M_c shall be based on crack width of 0.15mm or less if the piles are in marine or aggressive ground (pH < 4.5, resistivity < 2000 ohm.cm; sulphites / chlorides present).

d) The pile joint shall be as strong (f_b and f_t) as the pile body. For welded MS plate joint, thickness of MS plate shall be at least 12mm and in addition, welded-on-plates shall also be added if very high tensile stress or high bending stress is anticipated repeatedly. Pre-stressed spun piles with closed ends have the advantage to be inspected for structural integrity and straightness of piles after driving.

Table 1: What can go wrong for driven piles at site (after Neoh CA, 2005)

PILE TYPE	WHAT CAN GO WRONG?	POSSIBLE CAUSES
Steel piles	Pile Head Damages (e.g. buckling, longitudinal distortion, crushing, twisting)	(a) Overdriving (b) Incorrect use of dollies, helmets, packing (c) Rough cutting of pile ends (d) Eccentric hammering
	Pile Body Damages (e.g. twisting, crumpling, bending)	(a) Unsuitable hammer weight (b) Inadequate directional control of driving/ inadequate stiffness (c) Overdriving/ hard obstruction
	Collapse of tubular piles	(a) Insufficient thickness
	Pile Toe Damages (e.g. buckling, crumpling)	(a) Overdriving/ hard obstruction (b) Inadequate shoe design (c) Difficulty in toeing into rock
	Base plate rising relative to the casing, loss of plugs or shoes in cased piles	(a) Poor welding (b) Overdriving (c) Incorrect use of concrete plus
Concrete piles	Pile Head Damages (e.g. shattering, cracking, spalling of concrete) (note: Overdriving means driving stress exceeds the permissible stress. Refer Table 3)	(a) Improper reinforcement detailing and MS plate detailing for pile head (b) Insufficient reinforcement (c) Poor quality concrete (d) Inadequate concrete cover (e) Eccentric hammering (f) Incorrect use of dollies, helmets, packing/cushion (g) Overdriving
	Damages pile shaft (e.g. fracture, cracking, spalling of concrete)	(a) Excessive restraint on piles during driving (b) Improper hammer weight/cushion (c) Poor quality concrete (d) Inadequate or incorrect concrete cover (e) Hard obstructions or overdriving (f) Pile not straight/too slender/too many joints.
	Damaged pile toe (e.g. collapsing, cracking, spalling of concrete)	(a) Overdriving / hard obstruction (b) Poor quality concrete (c) Insufficient reinforcement (d) Inadequate or incorrect concrete cover (e) No rock shoe where required
	Damages due to excessive tensile stress	(a) Uncontrolled drop height of hammer (b) undersize or under strength in joints or reinforcement, etc.

How driven concrete piles can be damaged by uncontrolled driving (over-driving), and inadequate reinforcement or over-specified design load are explained in Para 4. Pile designers shall be cautioned that pile design load simply based on the structural capacity (unjointed short column capacity) recommended and published by pile manufacturers or based on sample calculations without checking the installation stresses and other design aspects mentioned in Figure 1, are bold and risky and is found to be the main cause for pile damages.

3. HILEY FORMULA AND HAMMER TYPE

Pile capacity (in end bearing) estimated by Hiley formula, if properly applied, can be better or more accurate than that estimated by some static formula, especially when SI results are inadequate or not representative or not comprehensive.

Selection of hammer type, hammer ram weight, drop height and cushion/packing material shall be such that the pile penetration per blow is about 2 mm to 60 mm for very hard to moderate driving. Weight of hammer shall be about 0.5 to 2.0 times the total pile weight. Drop height shall be 0.3m – 1.2m depending on the soil conditions and allowable compressive, tensile and bending strength of pile materials (refer Table 3). Hydraulic hammers shall be used when height of hammer needed to be controlled and varied, i.e. when driving long concrete piles in soft ground, where hammer drop shall be about 30cm to 40cm and slowly increased when in harder strata. Set used for estimating the pile capacity by Hiley formula shall be taken only when the cushion condition is in a similar reasonably good condition when taking the set, so that the estimated capacity is more comparable and realistic.

Normally, the pile cushion, aimed to provide a uniform driving compressive stress, consists of 50 mm to 100 mm of plywood which will be damaged and shall be replaced after about 1000 blows, in hard driving condition and about 2000 blows under conditions of moderate driving, especially when smoke starts coming out from the pile cushion. When the pile cushion is hardened after about 1000 blows of hard driving, it may result in a high penetration rate of say 4mm per blow. On the contrary, the 4mm set value may become 2 mm/blow if the hardened cushion material is replaced by a new one. This means that the ultimate pile capacity calculated using the Hiley formula will nearly double its value by replacing hardened cushion with a new one when taking set in similar subsoil strata where the pile capacity is actually about the same. Pile damages due to overdriving and eccentric hammering (refer Table 2) are usually caused by excessively hardened or damaged pile packing (or pile cushion), helmet being too large/long, pile deflection, etc. Hammer cushion (usually is hard wood or composite wood/ synthetic resin, etc.) shall also be replaced after about 30,000 blows or whenever the hammer starts striking eccentrically or smoke starts coming out from the hammer cushion.

4. PRECAST CONCRETE PILES

Many of the precast concrete piles available in the market do not meet the minimum requirements specified by BS 8004 and MS 1314 Part 1 (1993), e.g. the percentage of main reinforcement is less than 1% piles and low crack moment resistance, MS end plates are less than 12mm thick, centering bar smaller than 25mm in diameter and shorter than 300mm, etc. Cover for reinforcement provided by most of the pile suppliers is usually about 25mm to 35mm only. Such piles are not technically suitable for aggressive ground mentioned in Para 2(c). Structural damages to concrete piles that are substandard in respect to too low reinforcement for tensile and bending strength are very common and the consequences can be very serious especially when the pile designers simply adopt the standard structural details given by pile suppliers without carrying out the normal structural design checks illustrated below.

High reinforcement (>1.5%) to achieve tolerable driving tensile stress of 5 MPa for RC piles and high effective prestress (> 7 MPa) for spun piles are necessary to undertake high driving stresses (f_c, f_t and f_h). Why a project adopting 300mm square precast RC piles (reinforced by 4Y20, Grade 45 concrete) for a design load of 900 kN/pile (driven to set at about 50m deep by 5 Tonne hydraulic hammer at 0.6m drop through soft coastal alluvium with some

Table 2: Common piling systems (after Neoh CA, 2005)

Piling Systems	Piles Sizes (cm)	Resistance F	Resistance E	Resistance R	Capacity (kN)	Remarks
Driven Timber	10-15	√	?	X	< 200	Limited use
Driven RC (small)	15-20	√	?	?	< 300	Limited use
Driven RC	20-40	√	√	?	< 1500	Moderate capacity
Driven Spun	25-100	√	√	?	400-4000	High capacity
Driven Steel H	20-40	√	√	√	500-2000	Robust
Driven Steel Pipe	20-100	√	√	√	600-3000	Robust
Jacked RC	15-40	√	√	?	200-1500	Environment-Friendly. Low noise. No Vibration
Jacked Spun	25-60	√	√	?	300-1500	
Jacked Steel	20-40	√	√	?	400-500	
Micropile	10-35	√	√	√	< 2500	Non-displacement Piles ; Low noise. No Vibration
Bored Pile	40-200	√	√	√	Up to 25000	
Augered Pile	15-60	√	√	X	300-1200	
Special	Any	√	?	?	Any	

NOTES:

1. Abbreviations :-
   F = frictions, E = End bearing, R = Socketed in Rock
   √ = suitable, ? = doubtful, x = not suitable
2. Timber piles shall comply with MS360 (1976) and JKR Technical Directive RP3/1975. Timber piles should not be used for permanent buildings of more than 2 storeys and embedded length should not be lengthened by more than one joint. Concrete piles shall comply with MS 1314 and steel piles shall comply with BS 4360/ASTM A6.
3. Driven piles shall be designed and checked for handling, installation and working stresses (BS 8004). Make sure the recommended permissible limits (as shown in Table 3) are not exceeded (AASHTO/AS 2159/PDI):

Table 3: Permissible pile driving stresses (after Neoh, C.A., 2005)

Pile Type	Working compression stress f_{awc}	Driving compression stress f_{adc}	Driving tension stress f_{adt}	Remarks
RC	¼ f_{cu}	$0.85f_{cu}$	$0.7f_y\ ^{As}/_{Ac}$ or $0.8f_{cu}^{½}$, Whichever is lower.	To control driving bending stress, maximum structural capacity of concrete piles shall be discounted for joints (5n%) and slenderness ($^l/_d$-120)% and also the adopted design load, $Q_d > M_c/0.15d$ where n = no of joints, l = pile length, d = pile size, Mc = crack moment (BS 8110)
Prestressed	¼ $(f_{cu}-f_{pe})$	$0.85\ f_{cu}-f_{pe}$	$f_{pe} + ¼f_{cu}^{½}$	
Steel	1/3 f_y	$0.9f_y$	$0.9f_y$	
Timber	Spec	3Sa	3Sa	

NOTES:

1. Abbreviations :-
   f_{adc} = allowable driving compressive stress, MPa
   f_{adt} = allowable driving tensile stress, MPa
   f_{awc} = allowable working compressive stress, MPa
   f_{cu} = grade of concrete, MPa
   f_y = steel yield stress, MPa
   f_{pe} = effective stress, MPa
   $^{As}/_{Ac}$ = area ratio of steel rebars to concrete
   Sa = allowable timber compressive stress

2. All precast concrete piles shall be provided with adequate reinforcement to take lifting stress of 1/32WLx150% from the casting moulds and one point handling stress of 1/8 WL x 150% at site, where W = wt of pile, L = pile length.

3. For precast concrete piles designed for hard driving or driving in soft ground or driving in treacherous grounds where high tensile stress and bending stress are likely to be encountered, more reinforcement (f_{pe} >5 MPa or As/Ac >1.5%) shall be included to ensure permissible tensile stress (f_{adt}) is more than 5MPa and higher Mc is provided.
4. At least 1% of piles installed shall be subject to load tests including some high strain dynamic tests, HSDT (ASTM D4945-89) or PDA tests to ensure adequate capacity and structural integrity.

localised lenses of sand) has suffered about 20% of pile damages can be illustrated as follows :

- Driving stress by Broms' method: $f_c = 3h^{0.5} = 3 \times 60^{1/2} = 23.2$ MPa < 0.8fcu (Table3) - OK
- Possible high tensile stress when penetrating through lenses of sand, f_t = 10% - 30%f_c = 2.3 to 6.9 MPa, which is likely to exceed the permissible tensile stress of only 3.9 MPa for 4Y20 reinforcement ($f_{adt} = 0.7f_y$ As/Ac = 3.9 MPa, Table 3).
- As the pile is likely to be deflected (due to slenderness and different soil stiffness) and hard driving is required to achieve 900 kN safe geotechnical capacity (or ultimate resistance > 1800 kN), the high driving bending stress is expected. Unless continuous monitoring by PDA (or HSDT, ASTMD4945-89) is carried out, pile damages by excessive tensile and bending stress is difficult to ascertain. Based on Broms' recommendation, the design load, $Q_d < M_c/0.15d$ = 610kN only. Hence, the proposed design load, Q_d = 900 kN is too high.
- If structural capacity of pile is discounted for slenderness ratio (Table 3), adopted Q_d = 120 x 0.7 x 0.85 = 710 kN. Hence, the proposed Q_d = 900kN is still too high.
- More accurate driveability analysis by WEAP based on detail borehole results will produce more accurate driving stresses.
- Mitigations against pile damages as shown in Figure 3 for the above project is to increase permissible tensile stress (by increase % of reinforcement) and increase the pile size (reduce slenderness ratio). Of course detail geotechnical and structural analysis shall also be carried out.

5. BORED PILES

Bored piles are very cost-effective, practical and good solution for very heavy structures and in stiff overburden soil especially when ground vibration is not acceptable.

Capacity of bored piles depends very much or more on how the bored pile is installed (i.e. machine and operator dependent). Frictional resistance of bored piles can be higher than that estimated by Meyerhof formula (fs = 2N ≤100 kPa for soil and ≤ 150 kPa for highly weathered rock, RQD = 0 with SPT values >>50) if the boring and concreting are completed within 3 hours, especially in dry hole. However, frictional resistance can be well less than that estimated by Meyerhof formula if boring takes more than 6 hours to complete, especially in wet holes. The importance of using a powerful boring machine and an experienced operator plus competent supervisor to ensure boring is completed in the shortest possible time, say less than 6 hour is very obvious.

End bearing of bored pile is usually ignored in design especially in wet hole conditions because some soft debris is likely to be collected at the base, and a large settlement of up to 10% of pile size or more is necessary to mobilise the end bearing. End bearing can only be considered if effective mitigations for base cleaning and base grouting or equivalent are provided.

Guides about design of rock socket, construction method and criteria of determining the termination depth of rock socket has been explained by Engr. Neoh [reference 8.1]. Performance of rock socket depends very much on how it is specified and actually constructed. Rock socket by full coring (reverse circulation method) is very expensive while by direct chiseling method will cause serious shattering and disturbance of usual fractured bedrock resulting in low bearing capacity. The usual cost-effective and practical method is by annular coring plus subsequent chiseling and base cleaning by suitable cleanout bucket.

Common site problems of bored piling such as honeycomb and segregation of concrete, waisting, necking/cave-in, contamination of concrete with soils, soft toe, high hydraulic gradient ground, low bond strength of rock socket, etc., are mainly due to careless and poor construction practice. Effective mitigations against poor construction practice which can lead to defects or structural flaws in

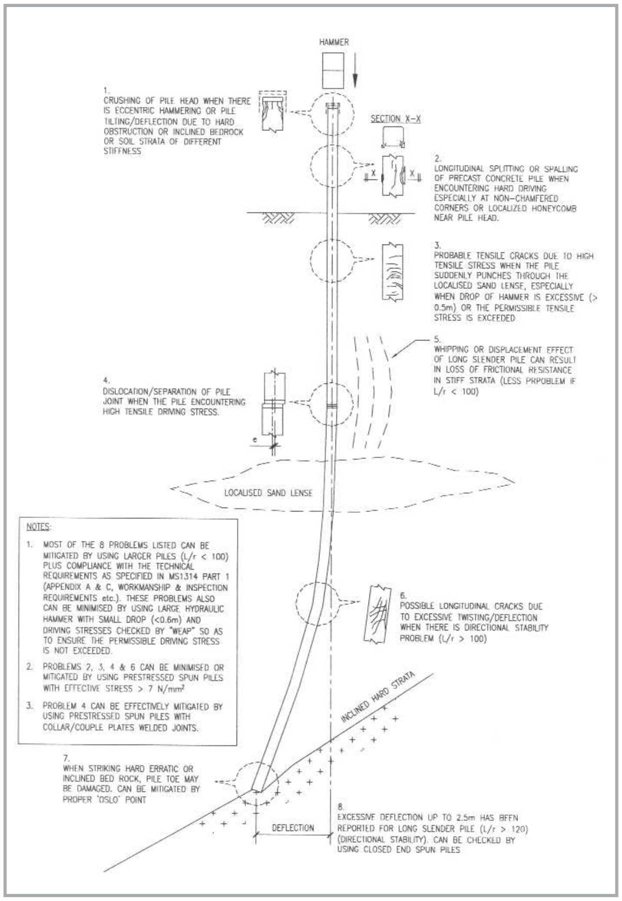

Figure 3: Problems of Long Slender Pile in Thick Soft Ground

the form of voids, degraded bond of concrete, entrapped debris, and excessive slurry coated bored shaft, etc., are effective and quality supervision. Of course a good and experienced contractor plus a proper QA/QC scheme are equally important to mitigate the risk of these common construction problems.. Suggested methods and their applications to assess and to identify the extent of these defects are excavation and visual inspection (up to a limited depth), low strain and high strain dynamic tests, cross hole ultrasonic test, coring and load test, etc.

6. MISCELLANEOUS PILING PROBLEMS

There are pros and cons of various pile testing methods such as maintained load test, constant rate penetration test, statnamic load test, high strain dynamic test (HSDT) and Osterberg load test. Standards and methods of test, the interpretation of test result and the acceptance criteria of load tests have been deliberated with some case histories by Engr. Neoh [reference 8.1].

Other piling problems such as the phenomenon of false set when driving in silty sand, the purpose and significance of re-driving test in granular and cohesive soil, ground heave, small RC piles (< 200mm), construction of pile cap in soft ground, etc., have also been also presented together with suggested proper mitigation measures by Engr. Neoh [reference 8.2].

The importance of quality supervision for piling works is also recognised by BS 8004, which recommends that a competent supervisor, properly qualified and experienced should be appointed to supervise the piling operation. An ignorant and unreliable piling upervisor/contractor can turn a sound pile design into nightmare; but an experienced and dedicated supervisor/ contractor can prevent poorly conceived pile design from disaster. In fact, most reported piling problems have not been caused by inadequacies in design and specification, but more by poor/wrong construction techniques and unawareness of what can go wrong at site by the contractor and the supervisor. The importance of checking, approving and adopting a method statement for piling works is also frequently ignored by the RE, who should not be appointed if he/she is incapable of checking the method statement. A complete and proper method statement is certainly very critical to ensure quality piling works and shall contain the following basic contents:

a) Specific machine, material and manpower (operator and supervisor) that are capable to achieve and to comply the specification shall be clearly stated.
b) Sequence of works and output of works.
c) QA/QC scheme including type of tests/measurements/observation plus their respective frequency and acceptance criteria.
d) Methods of rectification or remedy in case of non-compliance of tests are encountered.

7. CONCLUSIONS

Generally, the problem is not big in carrying out pile design based on established code of practice and adequate SI. The problems are mainly due to unawareness and ignorance of designers, supervisors and contractors about what can go wrong at site.

Mitigations against what can go wrong at site plus a proper QA/QC scheme are inseparable from proper and comprehensive pile design, which is incomplete until the design is executed and completed successfully. Awareness of what can go wrong at site and the necessary mitigations require experience, past case histories and engineering judgment. What can go wrong will go wrong unless effective mitigations are in place and there is no right way to do the wrong things! ■

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