CHAPTER 5 - PILES AND CAISSONS

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5.1 SCOPE

Monitoring of the construction of piles or caissons as the means to support road bridges is concerned with the achievement of adequate load bearing capacity and safety during construction in difficult founding conditions. Both these forms of foundation construction are subject to various degrees of financial, technical and physical risk because of the uncertainties and arising from deep foundations in ground conditions which can be highly variable and environments which often have high water tables or are subject to flooding.

Piled foundations are usually the first alternative considered when it is impractical, uneconomical or unsafe to found conventional footings at shallow or intermediate depths below ground. There is a sufficiently wide range of piling systems available from which to select appropriate foundation solutions in most types of ground conditions for road bridges which require deep founding. Piling is usually considered from depths of about 7 m and can reach depths of 50 m or more. This form of foundation is widely used in South Africa and is served by a well established industry.

Caissons provide an alternative means to achieve adequate founding at intermediate to significant depths in both land and water environments. This system has been frequently used overseas as the most practical means to found major bridges in deep water conditions and is employed in South African harbour engineering for the construction of wharves and quays. Whereas open caissons are now seldom used for bridges in South Africa because installation is comparatively slow, this form of foundation construction can be a viable option for depths of about 5 m to 9 m because of the very low establishment costs involved.

In this chapter guidance is provided about the design factors which affect the selection of particular types of piles for deep foundations and subsequently become the concern of the contractor and those monitoring the work, as well as about the issues which commonly arise during the construction of piled foundations. Similar commentary is also provided about the issues which arise during the construction of caisson foundations.

Monitoring staff who require more detailed guidance about all aspects of the design and construction of piled foundations or caissons relevant to their duties are encouraged to study the references listed at the end of this chapter.

5.2 PILES

5.2.1 Function and Form

The function of piled foundations is to transmit the applicable combinations of permanent and transient loads which are applied at the top of the piles, through weak compressible soil or fill materials onto stiff or dense soil strata or rock at lower levels, in such a manner as to prevent excessive settlement, horizontal displacement or rotation of the supported structure.

Piles are slender, 'column like' structural members, usually acting in groups, which are installed vertically or at a slope (rake) in the ground by various techniques, to sufficient depth to achieve the necessary load bearing capacity through frictional resistance along their sides, end bearing resistance at their bases, or combinations of both.

Traditionally the design of piles in Southern Africa has been based on Working Load methods, which embody a global factor of safety to accommodate uncertainties in both the load effects and the pile/ground resistance. In the future pile design is likely to follow the Limit State design methods
outlined in the relevant Eurocodes, in which the serviceability and ultimate limit states are considered with regard to the function and strength of the piling structure respectively.

Pile groups which are required to resist the combined effects of vertical and horizontal forces imposed on earth retaining structures such as bridge abutments for example, achieve the necessary resistance by the provision of raking piles installed at a slope in the opposite direction to the horizontal forces and/or the resistance to horizontal movement provided by the soil surrounding the piles and against the pile cap (subgrade reaction).

In circumstances when a pile is installed through compressible soil strata which undergo consolidation after the pile is in place, the downward movement of the consolidating soil and of any overlying soils relative to the pile will cause a downward drag on the shaft of the pile. This is termed 'negative skin friction'. These conditions sometimes arise in the case of bridge abutments, when the retained embankment causes down drag mainly on the rear piles of the supporting group.

In these instances it is necessary to determine from prior soils investigations, the depth to which consolidation will occur and thereafter to establish the magnitude of the induced down drag forces imposed on the piles. For the purposes of design, the capacities of the piles affected by such down drag are usually de-rated by the magnitude of the estimated down drag.

Whereas materials such as timber and steel are sometimes used for piles, in modern bridge engineering piles are predominantly formed from reinforced concrete and to a lesser extent from prestressed concrete, in some cases with steel tube casings depending on the method of forming and installing the piles. The principal piling systems, together with the various types of piles which have been developed by the specialist piling companies who carry out this type of work are discussed in section 5.2.5 of this chapter.

Photo 5.1: Typical installation of driven precast piles

5.2.2 Design and Construction Factors

Many of the factors which are described in Sections 3, 4 and 5 of Chapter 4: Foundations, apply equally to the design and construction of piled foundations. However, in the case of piling it must be emphasised that, unlike conventional foundations the nature of the founding strata can usually not be visually inspected and it is often necessary to verify the integrity of the piles by indirect methods. The selection of the piling system most suited to the particular circumstances and the load bearing capacity
of the system adopted are therefore highly dependent on the adequacy of the geotechnical and subsequent investigations and indeed on the skill and experience of the specialist sub-contractor appointed to carry out the work.

5.2.3 Geotechnical and Subsequent Investigations

In all cases when piles are likely to be adopted as the method of founding bridge structures, it is essential that the planning (location, extent and type) and implementation of the geotechnical investigation and the analysis of the data obtained, should be entrusted to an appropriately experienced geotechnical specialist. The geotechnical report should provide advice about the alternative piling types most suited to the particular founding conditions.

The services of the same specialist should be utilised for subsequent advice or analysis when relevant, concerning:

- Overcoming difficulties encountered during the installation of the piles.
- Interpretation of the mixed strata extracted as spoil from bored piles for example, which may be difficult to classify for the purposes of measurement and payment.
- Pile testing procedures, measurements and interpretation.

5.2.4 Factors which Influence the Selection of a Pile Type

NOTE: The permission of Messrs Franki Africa to reproduce the text contained in this section from their publication: A Guide to Practical GEOTECHNICAL ENGINEERING in Southern Africa (Reference 2) is acknowledged with thanks. It is advisable to have a copy of this publication on site for the guidance of the monitoring staff during piling operations.

"Before the design engineer can consider what type of pile is best suited to a project the following basic information is needed as a minimum requirement.

- Detailed geotechnical information
- Structural details and loadings
- Allowable total and differential settlements
- Knowledge of the site and its environs

Using this information, the engineer will need to consider the following points regarding the various piling systems so that the most suitable foundation system can be chosen for the project:

STRUCTURAL

- Range of pile sizes to suit the loading
- Founding level to meet the pile load capacity
- Founding level to meet the settlement criteria
- Spacing of piles
- The allowable rake of the piles if required
- The ability to resist tension forces if required
• The ability to resist horizontal forces if required
• The clearance from existing buildings
• The durability of the pile shafts

SOIL PROFILE

• If driven, whether driving will be easy, difficult or impossible
• If bored, whether temporary casings will be required
• If bored, the difficulty in penetrating to the required depth
• The presence of obstructions such as boulders
• The founding level to meet pile load capacity
• The founding depth to meet settlement criteria
• Very soft layers which can cause problems with cast-in-situ piles
• Rock-sockets
• Presence of groundwater, and at what level
• The presence of aggressive groundwater
• The potential for pile heave during installation

ENVIRONMENTAL

• The effects of noise pollution caused by piling equipment
• The effects of vibration caused by pile equipment installation

CONTRACTUAL

• Access to and on the site for equipment
• Headroom clearance on site for piling equipment
• The cost of the piles
• The cost of the pile-caps and ground beams
• The installation risks associated with a particular pile solution
• The remoteness of the site
• The availability of skills and plant to install the piling system
• Adequate plant and people resources for large contracts”

Whereas some of the factors listed above are the concern only of the bridge designer, many of these factors may come into play during the process of construction and therefore become the concern of the contractor, the specialist piling sub-contractor and the staff appointed to monitor the work. These factors should therefore be seen as a preliminary list of the points to watch out for during the installation and testing of piles.
Piles may be classified in various ways: the following schedule is based on the degree of displacement of the soil in which the piles are installed and which include various types related to the method of installation. Plant and equipment is available for each of the pile types listed, some of which are commonly used for bridge foundations in South Africa (marked thus *) and others are either seldom used for bridges or are comparatively new on the market.

**CLASSIFICATION RELATED TO DISPLACEMENT**

<table>
<thead>
<tr>
<th>LARGE DISPLACEMENT (Cast-in-Place)</th>
<th>SMALL DISPLACEMENT (Driven Pre-Formed)</th>
<th>NON-DISPLACEMENT (Bored Cast-in-Situ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Driven cast-in-place pile (DCIP)</td>
<td>* Precast pile</td>
<td>* Auger pile</td>
</tr>
<tr>
<td>Driven tube piles</td>
<td>Steel H-pile</td>
<td>Underslurry pile</td>
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<tr>
<td>Full displacement screw pile</td>
<td></td>
<td>* Continuous flight auger (CFA) pile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forum bored pile</td>
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<td></td>
<td></td>
<td>* Oscillator pile</td>
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<td></td>
<td>Rotapile</td>
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<td></td>
<td></td>
<td>Micropile</td>
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</tbody>
</table>

The details of the available pile types are summarised in Reference 2, in which the size range, typical working loads, maximum rake and depth range, cost indicators, use limitations, noise and vibration levels and site requirements are set out. The summary provides a convenient means of comparison to evaluate the suitable pile alternatives for a specific project. The summary is followed by detailed descriptions of the positive and negative features, standard and special installation procedures, potential problem areas and precautionary measures concerning each type of pile.
5.2.6 Selection of Piling System

5.2.6.1 Design data

The data required for the analysis and design of the proposed scheme and for future record purposes includes the following:

- Critical design-load combinations of the co-existent permanent and transient loads applied at the underside of the pile cap and the centroid of the pile group, relative to a defined system of axes, as shown in Figure 5.1. (Tabulated on the drawings for each pile group). Load tables should clearly state whether the loads are service or ultimate.

- Permissible movements which can be accommodated by the structure relative to the pile group centroid and system of axes, including: displacements in the horizontal plane, deflection vertically, rotation about any axis, as illustrated in Figure 5.1.

- Information required for the calculation of down drag forces on piles when relevant.

- Full details of the geotechnical investigation including borehole logs, test results etc.

![Figure 5.1]

Note:
The piling design data included on the drawings should not be interpreted by contractors as an invitation to offer alternative piling designs. This information and the As Built piling records are required for future reference in the event of the need to subsequently widen or double bridges which have piled foundations.

5.2.6.2 Proposed design

Following assessment of the structural, geotechnical, environmental and contractual factors listed in sub-section 5.2.4, a piling system deemed to be best suited to the specific project is selected and thereafter analysed and designed on an iterative basis, which usually involves refinement of the pile layout and adjustment of the pile sizes, rake etc. The proposed design resulting from this process is shown on the drawings and described in the project specifications.
5.2.6.3 Alternative designs

Some specifications (COLTO Subclause 6113(c) for example) provide for the submission of alternative piling designs. The engineer needs to be aware of the potential risks of alternative designs, which may arise from the unsuitability of the type of piling proposed in regard to the particular foundation or other site conditions. The applicable specifications (COLTO Subclause 121 for example) also invariably indicate that an alternative will be considered only if a tender for the proposed design has been fully priced and completed.

When alternative designs are permitted the engineer should ensure that the full details of the geotechnical investigation including borehole logs, test results, details of the groundwater regime, and all other factual geotechnical data are incorporated in the tender documents. Bearing in mind the limited time available during the tender period, contractors tendering for piling works should not be required, during the tender period, to visit an office to inspect geotechnical investigation reports and similar data; this information should be included in the tender documents for immediate access throughout the tender period.

Bona fide alternative piling designs which comply fully with specifications should be carefully reviewed, firstly in technical terms to ensure that these do not have any significant disadvantages compared with the 'proposed design', with regard to manufacture, quality of materials, ease of installation (including through boulder layers when relevant), structural capacity, testing procedures, durability and so on. Only when convinced of the technical merit and applicability of an alternative design should the engineer consider any financial implications of the alternative offer.

Even when an alternative piling system is deemed acceptable in general technical terms, the engineer should exercise caution unless it can be demonstrated that the plant and operators intended for the project are fit for the purpose and have the necessary skills respectively, in relation to the complexity of the foundation conditions and the size of the project.

Approval of the engineer’s recommendation rests finally with the employer. Following such approval the basis of payment must be finalised and the detailed information required from the contractor (method statement, corrected working drawings etc.) must be provided prior to the commencement of the piling work. Costs of drawing and design are to the contractor’s account.

5.2.7 Construction

The various construction operations required for the different types of piles are described in the specification, which provide a guide to the monitoring staff. Issues likely to arise and points to watch are described in the following sub-sections in relation to the usual sequence of the work.

5.2.7.1 Access and drainage

Except in the case of stand-alone piling contracts, access and drainage do not apply specifically to piling operations, but relate to the project as a whole, as briefly discussed in 4.8.4 of Chapter 4. However, with regard to piling operations, which often require the use of very large and heavy rigs and other equipment, particular attention must be paid to the size, strength and stability of access causeways and artificial islands, which require careful planning in order to facilitate the setting up and movement between pile positions.
In this context drainage relates to the exclusion of surface water from the work areas, which can become difficult or unsafe when muddy or waterlogged.

Photo 5.3: Installation of 1.35 m dia bored oscillator piles with temporary casings. Note temporary working platform in river environment.

5.2.8 Establishment on the site for piling

Establishment on the site for piling is usually included in the specifications as a separate payment item, over and above the main contract establishment, and provides for any additional measures required, such as piling platforms, floating barges etc. and for establishing and subsequent removal of the specialised plant and equipment required for carrying out the piling operations.

At the tender stage it is important that the engineer should verify that the plant and equipment proposed by the contractor is sufficiently powerful and otherwise suitable to carry out the piling operations efficiently, especially in difficult and very deep founding conditions.

If after enquiry the proposed equipment is deemed to be inadequate, this should be addressed in the conditions of award. Underpowered piling plant can lead to delays in the piling work, with a corresponding effect on the main contractor's programme, giving rise to claims on various grounds. Even spurious claims in this context can be difficult to fully defeat, particularly if the geotechnical information provided in the tender documents is not sufficiently comprehensive.

5.2.8.1 Setting out

The accuracy of setting out of piles is a critical initial step which must be carried out to the accuracy stipulated in the specifications. It is recommended that the same procedural steps as generally outlined in 4.8.1 of Chapter 4, should be followed with regard to the independent checking, verification and signing off of the setting out of pile groups and individual piles.

**IMPORTANT**

Monitoring staff are advised to speak to a knowledgeable geotechnical engineer with experience in piling to determine whether the equipment is adequate.

**WARNING**

Particular care is advocated with regard to the checking of all aspects of the setting out and geometry of raking piles, to ensure that due allowance is made for the offset in the plan position of these piles at the platform level relative to the underside of the pile cap.
Setting out also involves the provision of adequate pre-installation frames and equipment from the standpoint of the geometry of the piles, as these frames must be designed to ensure that the piles can be installed in their proper positions and true to line and slope. These and the other functions of the pre-installation frames are subject to the approval of the engineer.

5.2.8.2 Installation

Prior to the commencement of the piling operations the monitoring staff are advised to inform themselves about the intricacies and method of construction of the specific piles to be installed as well as about the capabilities and automatic recording devices of the plant to be deployed. Additionally, information about the difficulties commonly encountered with the specific piles will forewarn them of the possible need to seek the advice or intervention of the engineer.

Engineer's approval and decisions

It needs to be borne in mind that all piling work is subject to the approval of the engineer. The most critical input of the engineer during the process of installation relates to the approval of the length and founding depth of each pile, to ensure that adequate load bearing capacity has been attained, without the potential for excessive subsequent settlement.

This is often a difficult decision when significant resistance to driving or other methods of installation are encountered at depths which are substantially less than indicated by the geotechnical investigation. This may arise from the presence of unidentified obstructions (e.g. the presence of boulder layers) or of comparatively thin but very dense sand or stiff clay or hard rock layers. In other instances the contractor may report inadequate driving resistance or other indicators of concern at the pile depths shown on the drawings.

In either event the decision on the steps required to overcome difficulties or to continue to greater depth rest with the engineer. This will inevitably follow consultation with the contractor and in the event of disagreement, the engineer may require the contractor to undertake additional foundation investigations, core drilling or other measures to settle the matter. Such additional measures are sometimes also required in order to settle disputes about the classification of materials when significant financial sums are involved.

The initial duties of the monitoring staff include the verification of:

(a) The adequacy of the access and drainage arrangements, and of any piling platforms as depicted on the contractor's drawings or described in the method statements.
(b) The adequacy of the contractor's plant and equipment in terms of the contract.
(c) The accuracy of the setting out and any other geometry controls or requirements.
(d) The adequacy of the contractor's safety arrangements in terms of the approved safety plan.
(e) The suitability of the contractor's provisions to meet the requirements of the Environmental Approval.
(f) The approval of the proposed concrete mix design.
(g) Mix designs may however be required to be redesigned for aggressive ground conditions.

REQUIREMENT

The use of grout in place of concrete must be approved by the engineer.
Throughout the process of piling the monitoring staff are expected to verify that:

(a) The quality, sizes and type of the materials, prefabricated components etc. are in compliance with the specifications, drawings and supplementary documents provided by the contractor.

(b) The contractor’s work follows the dictates of sound practice in compliance with the drawings, specifications and method statements applicable to specific type of piles being installed and does not involve any short cuts which could impair the quality and load bearing capacity of the piles.

(c) It is important that the monitoring staff ensure that the lengths of all specified rock sockets are achieved.

For all types of cast-in-situ piles, the monitoring staff should check that the reinforcing steel:

(a) Complies with the sizes, types and fixing shown on the drawings and is sufficiently rigid to withstand handling, insertion and suspension in place during in-situ concreting operations.

(b) Cages have sufficient central space to permit the placing of concrete by tremie pipe or other approved means.

(c) Is adequately spliced in order to meet length and strength requirements and that there is sufficient splice reinforcement available on site to permit this operation without delay.

(d) Is inserted to the correct length, level and position and rigidly held in place by approved roller spacers, immediately prior to the commencement of concreting operations for most types of augered, bored, driven in-situ or screw piles. (It should be noted that the reinforcement for CFA piles is inserted only after the concreting or grouting has been completed and must be carried out prior to the initial set of these materials).

Any tubing shown on the drawings for subsequent integrity testing or core drilling of the piles should be equally spaced around the inner perimeter and firmly attached to the main reinforcing bars.

With regard to the in-situ concreting of piles:

(a) All pile holes which are not lined with permanent casings and which are not self supporting require temporary casing for the full depth of the hole. During concreting such temporary casings must be carefully extracted to ensure that the trailing end is below the advancing concrete level by not more than about 1 m.

(b) Thin walled permanent casing is advocated in the case of raking piles which are especially prone to the collapse of the soil faces. Casing will also overcome the difficulty of installing reinforcement which can snap in the faces of raked holes.

(c) On river bridges when pile excavations are invariably full of water, concrete has to be placed using standard tremie techniques with high slump concrete. Whereas best practice should always be followed in construction using tremie methods, the avoidance of difficulties and the quality of the pile are highly dependent on the skill and experience of the operator and the support team.

(d) In the case of CFA piles some contractors prefer to use a sand/cement grout instead of concrete as it is easier to pump. However, in sandy soil conditions there is a much greater tendency for the grout water to migrate into the surrounds than in the case of concrete, which results in a drop in the level at the head of the pile and the need to add extra grout to maintain the top level. Most of the problems arising with this type of pile relate to necking of the pile shafts arising from the extraction of the flight at a greater rate than the inflow of concrete or grout through the hollow stem of the flight auger. Unless the piling rig is...
modern and equipped with an on-board recording device which provides adequate control, the manufacture of this type of pile is largely in the hands of the operator.

Monitoring of precast pile fabrication requires special attention to:

(a) The position of coupling points, which should not be closer to the underside of the pile cap than permitted by the specifications or as instructed by the engineer. This point requires early discussion with the contractor about the lengths of piles to be precast in relation to the anticipated piling depth from ground and the level of the underside of the pile cap.

(b) The adequacy of the size and fixing of the reinforcement, the pile shoes and particularly to the accurate positioning and squareness of the pile coupler sockets.

(c) The lengthening of the piles by coupling. If the adjacent coupled sections are not truly axially in line, within the tolerance requirements, the faulty section or sections should be rejected and replaced.

During the driving of piles the monitoring staff are expected to pay special attention to:

(a) The alignment of the piles and casing controlled by the pre-installation frames, in order to prevent the bending of precast piles in particular and their subsequent classification as defective if installed outside the specified alignment tolerances.

(b) The measures adopted to prevent splitting or other damage to the heads of precast piles or the trailing edges of casings.

(c) The limitations imposed on water jetting or pre-drilling through hard layers such as very dense sands, with specific reference to percentage of length limitations. **Note:** Pre-drilling is aimed at preventing damage to the piles in hard driving and must be approved by the engineer. It is recommended that the cross-sectional area of the pre-drilled hole should not exceed about 80% of that of the pile and that the loosened material should largely be left in the hole to ensure that the lateral support to the installed pile is not compromised.

(d) The installation sequence of the piles adopted by the contractor, which may result in the heaving of previously installed piles. In the event of heaving, the corrective measures shall be determined by the engineer.
(c) The achievement of the final set of precast piles, at which the adequate load bearing capacity of the pile is deemed to be achieved.

**Note:** The final pile set is the depth of penetration of the pile into the ground following the impact of a hammer of a certain mass, dropped through a certain distance to impart a certain number of blows. All of these amounts or numbers are predetermined for each precast piling project and are usually determined from the well-known Hiley piling formula for short piles (about 20 m or less) or using the Wave Equation method for long piles (greater than about 20 m). An example of a trial pile load-settlement results for a pile driven to a pre-determined set is illustrated in Appendix 5D.

The final set and temporary compression diagram should be recorded as part of the pile record for each pile. It is recommended that when the piles are founded in saturated clay strata, the final set of a certain number of the piles should be rechecked after 24 hours by redriving to ensure that there is no subsequent increase in the set. Depending on the findings, it may be necessary to redrive all of the piles driven in the preceding 24 hours.

**Augered and bored pile holes are required to be:**

(a) Temporarily cased when there is a danger of collapse of the sides of the holes before or during concreting.

(b) Completed without the use of water unless permitted by the engineer.

(c) Cleaned out to obtain a firm and level surface and thereafter inspected by camera or by the engineer strictly in compliance with the applicable safety regulations.

(d) Underreamed after the initial inspection, as shown on the drawings, and thereafter again inspected and further cleaned out if necessary.

(e) Socketed into rock to the stipulated dimensions, when shown on the drawings. It is usually necessary to sink casings into the top part of the socket to prevent the ingress of saturated sand. The socket is formed within the casing by chiselling and removing the spoil by means of a suction baler.
5.2.8.3 Obstructions and difficulties

Obstructions are defined as identified if classified and described in the contract documents and included for payment in the schedule of quantities. The following materials are those classified as obstructions in the specifications (as defined in COLTO Subclause 6113(o) for example):

(a) Matrix
(b) Coarse gravel
(c) Boulders
(d) Rock formation.

These classes are defined in terms of sieve size and the latter three are usually required to be of at least R2 hardness in terms of the applicable rock classification in order to qualify. Rock must be further classified as R2, R3, R4 or R5 as applicable.

Unidentified obstructions by definition cannot be classified in terms of this Subclause and may be included in or excluded from the scheduled quantities for payment purposes. Payment for unidentified obstructions is usually related to the rates tendered for identified obstructions and determined from equivalent rates of penetration actually achieved, or alternatively in accordance with the provisions of the general conditions of contract.

Obstructions are the main cause of difficulty in the process of installation of any type of pile and in the case of driven displacement and prefabricated piles may result in the abandonment of a pile, if after the implementation of suitable alternative driving measures installation to the required depth still proves impossible. In this instance the engineer will inevitably order the installation of one or more replacement piles.

However, various other factors cause difficulties, delays and possible abandonment in the process of the manufacture and installation of piles. The best defence against these, as outlined in Section 5.2.4 is the selection of the type of pile best suited to the circumstances. Examples of these factors are:

(a) Heaving of previously installed driven piles due to upward movement of the surrounding soil caused by the driving of an adjacent pile. This occurs in saturated clayey and silty soils and can result in damage to the green concrete and reinforcement bond in newly cast piles. This can be avoided by predrilling, jetting or coring or by wider spacings between the piles, but must be addressed when found to occur.

(b) Splitting of the casings of driven steel tube piles, which can be avoided by top rather than bottom driving or by predrilling, jetting or coring in hard driving conditions through very dense or stiff soils.

(c) Necking of the concrete in CFA piles, as discussed above, and problems associated with blockages during the process of placing concrete by tremie methods, which can occur even when construction is undertaken by experienced teams and must be identified by integrity testing.

5.2.8.4 Determining pile lengths

The design of the piles and pile groups shown on the drawings of the 'proposed design' or on the approved alternative design and the quantities in the applicable schedule of quantities are based on the subsurface data shown on the drawings.
However the founding depth of the piles will be determined by the design engineer as the work proceeds, as discussed under Engineer’s approval and decisions in 5.2.7.4 above. For this purpose the monitoring staff are required to promptly inform the engineer of the contractor’s concern about the adequacy of any pile at the anticipated depth and indeed of any difficulties arising from obstructions or other problems arising during the manufacture and installation of a pile, following which the design engineer will prescribe the steps to be followed.

5.2.8.5 Piling data

For the purposes of measurement and payment and of the data required by the employer to be shown on the record (as-built) drawings, the monitoring staff are required to keep comprehensive records of the manufacture and installation of each pile and of the circumstances which give rise to delay and the possibility of a claim for extra work, including the standing time in respect of pre-installation frames when applicable.

The records are required to be in the form prescribed by the engineer for each pile and will generally include data such as set out in Appendix 5B (Piling Data Sheet). It is therefore essential that among other records the monitoring staff should record the following for the full length of each pile:

(a) The driving effort and penetration (set) for driven piles down to and including the founding level.
(b) The nature of the spoil extracted from augered and bored piles in terms of the classification of materials for anticipated obstructions. This record should also include the rate of penetration (m/h) through the different materials encountered down to founding level, including rock sockets when applicable.
(c) The length of each rock socket, when applicable.

Whereas the classification of materials as described in the specifications is clear cut and distinctive, in practice with large and deep piles which are required to penetrate through alternating layers of hard and soft materials of differing types, classification can be quite difficult and it is prudent to extract depth related samples from the spoil for the purposes of agreeing or later determining the classification and rock quality designation.

5.2.8.6 Stripping of pile heads

When it is intended to carry out load tests on piles it is preferable not to strip the pile heads as described in the specifications until such tests have been completed. Indeed it is preferable to place the concrete of those piles which are to be load tested to a level just above the top of the reinforcing steel.
When load testing is complete the stripping of pile heads can continue as described in the specifications followed by construction of the pile cap.

5.2.9 Pile Testing

In this section pile testing is deemed to include core drilling as well as static load testing and alternative methods of integrity testing. The main objectives of pile testing as part of bridge construction contracts are as follows:

(a) To check the structural integrity of the pile shaft and the quality of the pile/rock socket interface, when applicable.

(b) To verify that the pile's load/deflection performance meets the load capacity/deflection limitation requirements.

5.2.9.2 Core drilling

Core drilling through the entire shaft of a pile is usually considerably more expensive than integrity testing using sonic or cross-hole sonic testing methods and may not yield markedly better information when it is required to merely ascertain the presence of necking in the pile or cavities arising from blockages during concreting by tremie methods for example.

When core drilling is required to check the quality of the pile/rock socket interface of a large diameter oscillator pile it is recommended that three to four small diameter tubes are inserted in the pile to a level about 0.5 m above the bottom of the socket prior to concreting, as discussed above. Core drilling through the comparatively short length of concrete can be carried out on completion of the pile using one of the sleeves provided for this purpose.

If inadequate contact is found this should be rectified by pressure grouting using the cored hole and the results tested by coring through one of the other sleeves.
5.2.9.3 Load tests

Load tests carried out in terms of the requirements of the contract are required to follow the detailed procedures described in the specifications (refer to COLTO Subclause 8112(c) for example).

The ultimate test load defined in the specifications relates to the load at which the axial deformation of a pile under compression or tension suddenly increases disproportionately to the load applied or in the case of tension, the load applied produces a stipulated rise at the top of the pile, whichever is the lesser. This does not imply that the load should be applied to achieve these conditions but relates to that load at which the limits occur if this is lower than the maximum test load or allowable settlement stipulated on the drawings.

In the process of load testing a working pile, caution is advocated when loading the pile to more than one and a half times the working load as a test load of twice the working load can damage the pile if not applied in the correct manner, in which case the pile may have to be abandoned and replaced by one or more piles.

NOTE
It is often preferable to load test independent trial piles because of the difficulty of installing anchor piles or kentledge in the vicinity of a working pile which forms part of a group.

Trial piles constructed for the purpose of testing to actual failure are usually applicable only to large piling contracts because of the high costs involved. Static load testing procedures and configurations are fully described in Reference 2, as are the alternative methods of interpretation of the load test results. The most recent methods used for analysis of such results involve computer simulation of actual load test measurements in order to predict performance up to ultimate load, load sharing between shaft friction and end bearing and so on.

Piles may be found to be defective in terms of lack of compliance with specified geometric tolerances, damage caused during installation, load capacity or other deficiencies as determined by tests ordered by the engineer. Such deficiencies must be remedied at the contractor's cost by applying one of the methods specified by the engineer.
5.2.9.4 Pile integrity tests

Modern specifications usually provide for non-intrusive integrity testing of piles, which is undertaken by specialist companies experienced in this form of investigation. Pile integrity testing includes two alternative sonic methods viz: the Frequency Response (Pile Tapping) method and the Crosshole Sonic Logging (CSL) method.

The Frequency Response method is based on striking the pile top with an impulse hammer and simultaneously measuring the vibratory response, from which a response graph is drawn and analysed to indicate the depth of any defects. This method is applicable to piles with a minimum diameter of 250 mm and is typically limited to depths not exceeding 20 to 25 pile diameters.

The Crosshole Sonic Logging method requires the availability of minimum of three (preferably more) 50 mm diameter sleeves cast into and equally spaced near the outer perimeter of the pile, and lowering an ultrasonic transmitter and receiver into each pair of holes in turn, to log ultrasonic responses at sequential depths to detect defects. Depending on the findings of either method, the engineer will need to approve the piles or issue instructions regarding further investigations or remedial measures.

These methods should be applied to all bored piles and are quick and economical compared to load testing, which can be very expensive in the case of large diameter piles. It must be realised that the results of such integrity tests are merely indicators of structural defects and are subject to interpretation. Nevertheless they provide a useful and economical means of identifying materials and workmanship problems, which should be investigated further by more positive testing methods, such as core drilling.

The alternative methods of integrity testing of piles are described in References 2 and 3, which also outline the basis of operation of these methods and provide examples of the graphic representation of test results relating to sound and defective piles. Tests using these methods are required to be applied first to a calibration pile before testing working piles, which in turn must be tested prior to the construction of the pile cap for the pile group being investigated.

5.2.10 Measurement and Payment

The standard measurement and payment items for foundation piling are usually comprehensive (refer to COLTO Section 6100 Items 61.15 to 61.40 for examples) and need not be repeated in this text. However, it should be repeated that this is a facet of bridge construction which is the most susceptible to interpretation regarding the classification and quantities of excavated materials, standing times in the event of delays of the contractor's own making and arising from circumstances beyond his control etc. Piling work is therefore prone to the formulation of claims, whether justified or not.

The records made and kept by the monitoring staff must therefore be accurate and comprehensive in order to assist the engineer to make determinations which are fair and reasonable in relation to both parties to a contract involving piling.

5.3 CAISSONS

5.3.1 Function and Form

The function of caissons is essentially the same as for piles, viz to transmit the applicable combination of permanent and transient loads applied at the top of the caisson through weak compressive soil or fill materials onto stiff or dense soil strata or rock at lower levels, in such a manner as to prevent excessive settlement, horizontal displacement or rotation of the supported structure at the caisson cap level. In addition caissons are required to be founded at sufficient depth to prevent instability due to scour arising from major floods, when located in river environments.
Caissons for bridge foundations are usually cellular reinforced concrete structures, with circular, rectangular or more streamlined plan cross sections comprising one or more excavation compartments, and which are wholly or partly constructed at higher level and sunk in stages to the desired founding level, by internal excavation assisted by the application of kentledge. Caissons are invariably monolithic with the bridge substructure components which they support.

Small diameter concrete shafts comprising single open cells and constructed in the same manner as caissons are usually called cylinders. The distinction between cylinders and caissons is merely one of size and is necessarily arbitrary. Because of their smaller size (usually up to about 2.5 m diameter), cylinders lend themselves readily to precast concrete ring elements in their construction. This form of caisson construction can be very economical down to intermediate depths of about 7 to 8 metres because of the low establishment costs involved, but are not well suited to sinking through ground containing large boulders or with high water tables. Cylinders constructed with precast concrete rings are usually filled with reinforced concrete.

Kentledge refers to concrete blocks or similar heavy loads repeatedly erected on the top of the caisson walls in order to help overcome the frictional resistance of the soil surrounding the caisson during the stage by stage process of sinking the caisson into the ground.

5.3.2 Caisson Types and Applications

There are two principal types of caissons:

**Open caissons**

- Well type (top and bottom open to the air).
- Floating type (open top and closed bottom). During sinking operations, the chamber of an open caisson is exposed to atmospheric pressure.

**Pneumatic caissons**

- During sinking operations the internal air pressure of the closed chamber is maintained by compressed air at greater than atmospheric pressure in order to prevent water from entering the caisson working area.

Traditionally caissons are selected as the most practical method of founding long span bridges which impose heavy loads, in deep water environments. Even open caissons can be constructed to depths of 50 m or more depending on the soil conditions, whilst pneumatic caissons have been installed to depths well in excess of 100 m in other parts of the world.

In South Africa caissons have been successfully used in situations where the designs were best served by rigid support systems founded on dense sands or rock at depths ranging from about 20 m to 30 m in both land and water environments. However, along the KwaZulu-Natal coast there are a number of examples of scour related failures of bridges constructed in the period from about 1930 until 1960, which were supported on caissons sunk to inadequate depths and founded in alluvial deposits well above bedrock.

Caissons are generally deemed to be unsuited to ground conditions with a high incidence of boulders because of the tendency of one side of the caisson to hang up on boulders during sinking, with the danger of serious local damage to the cutting edge and the adjacent caisson wall. Nevertheless there are reported cases where single cell caissons have been sunk through dense boulder layers down to rock at depths of about 10 m, in which even oscillator piles were discarded as the possible means of founding, on the grounds of high cost and impracticality.
South African specifications (COLTO for example) generally describe the requirements for the construction of open caissons and exclude the construction of pneumatic caissons. This section therefore relates to the construction monitoring of open caissons only, but may need to be updated in the future to include guidance about the construction of pneumatic caissons, if the incidence of that type of caisson work is found to increase.

Photo 5.9: Scour failure of Illovo river bridge caissons, (Main Road R102 along the KwaZulu-Natal east coast)

5.3.3 Design and Construction Factors

Many of the factors which are described in Sections 3, 4 and 5 of Chapter 4: Foundations, apply equally to the design and construction of caissons. Likewise the design data outlined in subsection 5.2.6.1 of this chapter are required for the design of caissons.

However, the form, method of installation and structural behaviour of caissons are unlike those of piles. The designer, and subsequently the contractor and monitoring staff are therefore concerned with similar factors with respect to the foundation conditions but different issues concerning the forces to be resisted and the structural component design, construction and installation, such as:

(a) The nature and characteristics of the soil strata through which the caisson must be sunk with particular regard to the resisting skin friction and the obstacles encountered, including the level of the water table.

(b) The estimated maximum depth of scour when applicable, which should be conservatively established from recognised analytical methods or from model studies.

(c) The overall geometry of the caisson in relation to:
   • the configuration of the substructure components to be supported;
   • the mass required to facilitate sinking;
• the space required for the removal of spoil from within the caisson.

(d) The overall stability of the caisson and the supported structure for the most adverse combinations of loads and scour conditions.

(e) The bearing capacity and rigidity of the founding strata.

(f) The load combinations, including river forces when applicable, for which the caisson components must be designed during sinking and when complete in service.

(g) Durability considerations.

The basic elements of an open caisson in order of construction are:

(a) A cutting edge provided at the bottom of the outer perimeter of the caisson shaft, usually of structural steel, acting compositely with the adjacent concrete shaft wall.

(b) The shaft comprising the outer perimeter wall of the caisson.

(c) Internal walls, if applicable, which subdivide the well into different cellular compartments and stiffen the outer walls of the shaft.

(d) The bottom seal of the caisson, which is usually a thick mass concrete slab to close off the well when founding level has been reached, and locked in position by the provision of a large shear key or series of keys formed continuously around the inner perimeter of the shaft above the cutting edge.

(e) The backfill (ballast) to the caisson well, usually comprising clean river sand up to the underside of the caisson cover slab screed.

The cover slab is usually considered to be part of the substructure component supported by the caisson.

5.3.4 Geotechnical Investigation

Investigation of the foundation conditions for caissons is as important as that required for piled foundations and is required to provide detailed information about:

(a) The nature and characteristics (cohesive properties, angle of internal friction, density etc.) of the various soil horizons through which the caisson will be sunk.

(b) The depth of the water table and the presence of aggressive groundwater if any.

(c) The presence, classification and layer thicknesses of identified obstructions.

(d) The depth, safe bearing capacities and stiffnesses of potential founding layers.

5.3.5 Construction

The various requirements for the construction, sinking, sealing and filling of caissons are usually amply described in the specifications and do not warrant detailed repetition in this section. Brief additional comment is therefore provided as follows, which serve as points to be watched by the monitoring staff during the construction of caissons.
5.3.5.1 Access, drainage and establishment

Access and drainage as described in the specifications do not apply specifically to caissons, but relate to the project as a whole, as briefly discussed in 4.8.4 of Chapter 4. Establishment on the site for constructing the caissons is usually paid as a separate item over and above establishment on site for the project as a whole.

5.3.5.2 Setting out

The setting out of caissons is not measured and paid as a separate item but is of importance equal to that for any of the other substructure components and should therefore be given the same attention by the monitoring staff as outlined in 4.8.1 of Chapter 4.

5.3.5.3 Safety

The safety of personnel during the construction of caissons requires careful planning and constant vigilance because of the nature of the operations such as: working at increasing depth, often below the water table or in wet or submerged conditions, adjacent to a heavy structure which is in the process of being sunk into the ground and usually beneath buckets, grabs etc. used for the extraction of spoil. The degree of the danger which workmen face is related to the depth, rate of inflow of water, the size of the working space available within the well or its compartments and the manner and speed of their evacuation when dangers or difficulties suddenly arise.

The diligent implementation of the contractor's safety plan and the vigilance of the monitoring staff as well as the contractor's supervisors are of obvious importance in these circumstances. All cases of the emergence of dangers or difficulties during any of the construction operations require the prompt intervention of the engineer in consultation with the contractor.

5.3.5.4 Cutting edge

The quality, rigidity and strength of the caisson's leading cutting edge are of great importance to the subsequent success of the sinking operations through difficult strata and must be thoroughly checked by the monitoring staff regarding the quality of welds and connections and the embedments into the concrete to be cast subsequently. The cutting edge must be set dead level prior to the commencement of concreting.

5.3.5.5 Concrete work

It is preferable to decide on the height of the concrete lifts and the length of the vertical reinforcing bars and splices etc. only after consultation with the contractor in order to facilitate his construction operations.

In view of the significant forces and stresses to which caisson members can be subjected during sinking and when in service, the monitoring staff are expected to verify the highest quality of materials and workmanship on all facets of concrete work in compliance with the specifications. In particular they should pay attention to:

(a) The concrete mix design with particular reference to early strength.
(b) The concrete cover to reinforcement especially on the outside faces of the shaft.
(c) The quality and compliance with tolerances of the formwork on the shaft outer surfaces, which can significantly reduce or increase the skin friction resistances of the soil to sinking.
(d) The quality of the joints in the concrete which can be subject to tensile stresses at an early stage of concrete strength gain.
5.3.5.6 Sinking and excavation

Sinking

Once sinking commences three associated problems with the location and control of the caissons come into play, viz: tilt, twist and lateral shift. These are more pronounced and problematic during the early stages, for the following reasons:

(a) The caisson is not fully embedded in the ground.
(b) The caisson is often passing through soft layers which offer little lateral resistance and which may offer differential lateral or vertical resistance to sinking.
(c) In the presence of groundwater at a shallow depth, the effective weight of the caisson is reduced.

It is often worthwhile to ascertain the uniformity of the top three to five metres of the ground below top surface by dynamic cone penetrometer or other probes and to consider light but uniform recompaction of the top two metres of the soil. Estimates of the skin friction resistance of the soils at various depths should be made from the results of the geotechnical investigation in order to judge the timing of the need for kentledge in order to control and effect sinking.

The various ways of correcting the alignment of caissons during sinking are beyond the scope of this manual and are outlined in reference 1.

Excavation

It is usually recommended that caisson excavations should commence in the centre of the well and extend outwards towards the shaft and that excavations beneath the cutting edge should be effected simultaneously at geometrically opposite points. For large caissons the usual method of excavation in cohesive soils is by large clamshell grabs operated by a crawler crane or similar, whereas granular material can sometimes be more economically removed by sand pump. In either case, the excavation of material close to cutting edge can be facilitated by the use of jetting nozzles. These various methods can produce large volumes of water which must be handled by adequate pumping facilities.
5.3.5.7 Founding and sealing

The adequacy of the founding and sealing of caissons are important factors which have a significant influence on the load bearing capacity of these structures. The quality of the founding stratum and the means of achieving competent seating in the case of sloping rock foundations for example, must be verified by the engineer who should make a final inspection only after corrective measures have been implemented.

![Photo 5.11: Caisson cutting edge concealed below wall. Note continuous key to lock in bottom slab (seal)](image)

5.3.6 Measurement and Payment

The standard measurement and payment items for caissons are usually comprehensive (refer to COLTO Items 61.41 to 61.49 for example) and need not be repeated in this text.

5.4 CHECK LISTS

Check lists related to piles and caissons and a pile data sheet are included in the Appendices to this chapter and are intended to serve as aide memoires to the monitoring staff and as convenient date related records for the signing off of the completed work. If required, a caisson data sheet should be prepared by the monitoring staff, similar in form to that provided for piles.

5.5 REFERENCES

1.) British Standards Institution; **Code of Practice for FOUNDATIONS;** CP8004, Latest edition.


3.) SAICE Geotechnical Division; **PILE TESTING Specification, Methods & Interpretation;** One-day Seminar; Fourways, 22 June 2004.
INDEX TO APPENDICES

5A - PILING CHECK LIST
5B - PILING DATA SHEET
5C - CAISSONS CHECK LIST
5D - EXAMPLE OF LOAD-SETTLEMENT RESULTS OF A TRIAL PILE
## CONSTRUCTION MONITORING

### PROJECT NO. / NAME:

### INSPECTOR’S NAME(S):

### STRUCTURE: 

### ELEMENT: 

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<td><strong>1. DESIGN</strong></td>
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<td>1.1 Postulated</td>
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<td>1.2 Alternative</td>
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<td>• Pile group configuration</td>
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<td>• Alteration to pile cap</td>
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<td>• Casing required</td>
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<td>• Founding : level</td>
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<td>• Method of founding: bulbous base; underream; rock socket</td>
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<td>• Plant and equipment</td>
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<td><strong>3. PILING PLATFORM, PLANT AND EQUIPMENT</strong></td>
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<tr>
<td>3.1 Platform</td>
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<td>• Drawings and method</td>
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<td>• Installation CCP</td>
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<td>• Removal CCP</td>
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<td>3.2 Plant and equipment</td>
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<td><strong>4. INSTALLATION ACCEPTANCE CRITERIA</strong></td>
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<td>(Refer to pile data sheet)</td>
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<tr>
<td>4.1 Materials and workmanship</td>
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<tr>
<td>4.2 Geometry</td>
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<tr>
<td>4.3 Embedments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4 Founding</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>4.5 Pile testing</td>
<td></td>
<td></td>
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<td>• Core drilling</td>
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<td>• Load test</td>
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<td><strong>7. MEASUREMENT AND PAYMENT</strong></td>
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### STATUS INCLUDES

| A | Contractor's submission received |
| B | Engineer's appraisal            |
| C | Inspected / Tested              |
| D | Compliance Verified             |
| E | Approved / Rejected             |
| F | Signed Off                      |

CCP: Contractor's Competent Person

**Note:** Indicate N/A under Status if not applicable
CONSTRUCTION MONITORING

PROJECT NO. / NAME: ..........................................................................................................................................

INSPECTOR’S NAME(S): ........................................................................................................................................

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<tbody>
<tr>
<td><strong>1. PILE DETAILS</strong></td>
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<tr>
<td>1.1 Type</td>
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<td>1.2 Cross section dimensions</td>
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<td>1.3 Materials</td>
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<td>- Concrete or grout : Mix; slump</td>
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<td>- Reinforcement : Mains</td>
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<td>- Embedded tubes : No; dia.</td>
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<td>1.4 Fittings, sleeves etc. : Rock shoe</td>
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<td>1.5 Fittings, sleeves etc. : Rock shoe</td>
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<td>2. INSTALLATION; GEOMETRY &amp; FOUNDING</td>
<td>Date:</td>
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<tr>
<td>2.1 Geometry</td>
<td></td>
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<tr>
<td>- Accuracy : Position</td>
<td></td>
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<tr>
<td>- Inclination</td>
<td></td>
</tr>
<tr>
<td>2.2 Method of founding and dimensions; bulbous base; underream; rock socket</td>
<td></td>
</tr>
<tr>
<td>3. PILING EFFORT &amp; RECORDS</td>
<td></td>
</tr>
<tr>
<td>3.1 Driving effort and resistance to penetration at founding level (including compression diagram)</td>
<td>See attached record</td>
</tr>
<tr>
<td>3.2 Rate of penetration, particularly through obstructions (provide levels and strata thickness)</td>
<td>See attached record</td>
</tr>
<tr>
<td>3.3 Check for heave after 24 hours : Set after redriving</td>
<td></td>
</tr>
<tr>
<td>4. SUBSURFACE DATA</td>
<td></td>
</tr>
<tr>
<td>4.1 Depth to ground water</td>
<td>See attached record</td>
</tr>
<tr>
<td>4.2 Soil profile including thickness / depth of obstructions and rock socket</td>
<td>See attached record</td>
</tr>
<tr>
<td>5. PILE TESTING (indicate if trial pile)</td>
<td></td>
</tr>
<tr>
<td>5.1 Core drilling: Remedial action if any</td>
<td>See attached record</td>
</tr>
<tr>
<td>5.2 Load test</td>
<td>See attached record</td>
</tr>
<tr>
<td>5.3 Integrity test : Frequency Response</td>
<td>See attached record</td>
</tr>
<tr>
<td>6. STRIPPING OF PILE HEADS</td>
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<td>Recorded by:</td>
<td>Date:</td>
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<td>Agreed by:</td>
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**Note:** Indicate N/A under remarks if not applicable
**Note:** This data is required for pile acceptance, measurement and payment and As Built records
## CONSTRUCTION MONITORING CHECKLIST

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**INSPECTOR’S NAME(S):**

**STRUCTURE:**

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<tr>
<td><strong>1. CAISSON DETAILS</strong></td>
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<tr>
<td>1.1 Lift height</td>
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<td>1.2 Materials Concrete : Mix; slump</td>
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<tr>
<td><strong>2. SETTING OUT (Prior to sinking)</strong></td>
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<tr>
<td><strong>3. ESTABLISHMENT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Ground preparation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2 Plant and equipment</td>
<td></td>
<td></td>
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<tr>
<td><strong>4. CONSTRUCTION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 Cutting edge</td>
<td></td>
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<tr>
<td>4.2 Concrete work (per lift)</td>
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<td>• Formwork</td>
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<td>• Reinforcement including cover</td>
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<tr>
<td>• Concreting and curing</td>
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<tr>
<td><strong>5. SINKING (Attach records)</strong></td>
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<tr>
<td>5.1 Position controls: tilt, twist, lateral shift</td>
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<td>5.2 Log of sinking including:</td>
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<td>• Rate of penetration</td>
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<td>• Soil strata levels and thicknesses</td>
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<td>• Obstacles and method of overcoming these</td>
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<td>• Application of kentledge:</td>
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<td>- Form</td>
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<td>- Weight (Lift No)</td>
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<td>• Excavation method</td>
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<td><strong>6. FOUNDING</strong></td>
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<tr>
<td>6.1 Inspection and adequacy</td>
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<tr>
<td>6.2 Founding level</td>
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<td><strong>7. SEAL AND FILL</strong></td>
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<tr>
<td>7.1 Seal concrete and method placing</td>
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<td>7.2 Placing of sand fill</td>
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<td>7.3 Placing of concrete screed</td>
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<td><strong>8. STRIPPING TO UNDERSIDE OF CAP</strong></td>
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<td><strong>9. MEASUREMENT AND PAYMENT</strong></td>
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**STATUS INCLUDES**

A Contractor’s submission received  
B Engineer’s appraisal  
C Inspected / Tested  
D Compliance Verified  
E Approved / Rejected  
F Signed Off  

CCP: Contractor's Competent Person  

**Note:** Indicate N/A under Status if not applicable
EXAMPLE OF LOAD-SETTLEMENT RESULTS OF A TRIAL PILE

CLIENT:  
PROJECT:  

TRIAL PILE (No. 1) DATA

- 350 x 350 Precast concrete (50 MPa)
- Reinforcement : 4Y20
- Serviceability Load : 2000 kN
- Embedment depth : 23.9 mm
- Dense sand from 21.0 m

ESTIMATED FINAL SET

- 7.5 mm for final 10 blows (Determined from Hiley piling formula)
- Hammer mass : 50 kN
- Drop height : 600 mm

<table>
<thead>
<tr>
<th>Load kN</th>
<th>Settlement Acceptance Criteria</th>
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<tbody>
<tr>
<td></td>
<td>Pile Head Settlement</td>
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<tr>
<td>Nominal or Serviceability Load (2000 kN)</td>
<td>15 mm</td>
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<tr>
<td>150% of Nominal or Serviceability Load (3000 kN)</td>
<td>23 mm</td>
</tr>
<tr>
<td>200% of Nominal or Serviceability Load (4000 kN)</td>
<td>36 mm</td>
</tr>
</tbody>
</table>

RESULTS

- 6.0 mm set for final 10 blows
- 100% service load : Pile head settlement : 10 mm  
  : Residual pile head settlement : 1.6 mm
- 150% service load : Pile head Settlement : 18 mm  
  : Residual pile head settlement : 4 mm