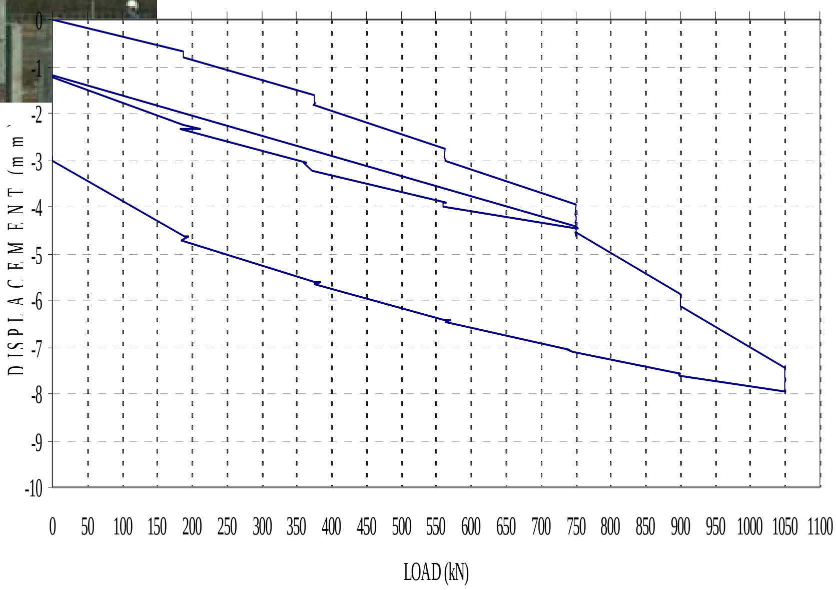
Federation of Piling Specialists

Handbook on Pile Load Testing



Foreword

This handbook was published in March 2006 by the Federation of Piling Specialists (FPS) to provide guidance on the principles and practical issues that relate to load testing of bearing piles, and thereby to assist informed decisions about testing requirements on construction projects involving piled foundations.

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The FPS anticipates that this handbook will be of particular interest to civil or structural engineers with little or no experience of piling who find themselves in the position of specifying load testing requirements on a project involving piled foundations. The target audience for this publication also includes main contractors, management contractors and young piling engineers.

The handbook was prepared for publication by a working group comprising the following representatives of FPS member companies: -

Bob Handley	Aarsleff Piling (Chair)
Jon Ball	Roger Bullivant
Andrew Bell	Expanded Piling
Tony Suckling	Stent Foundations

The Safety and Training Forum of the FPS were invited to review the final draft of the handbook, in particular the chapter on safety. Their suggestions and comments (for which the working group are most grateful) have been incorporated into the finished handbook.

The FPS acknowledges, with thanks, information and photographs contributed by the following: -

Aarsleff Piling
Dr. Michael Brown, University of Dundee
LOADTEST
Precision Monitoring & Control (PMC)
Roger Bullivant
Stent Foundations

Ken Cameron and Martyn Ellis of PMC carried out an independent review of the final draft of the handbook, for which the FPS wishes to express its thanks.

Chapter 1 Introduction

Year on year, load testing of bearing piles represents an estimated 4 to 6% of the total value of the UK piling market. The cost of load testing on individual contracts can vary from zero in many cases to as much as 10% of the value of the piling works. One aim of this handbook is to provide guidance on an overall strategy with the aim of promoting better specification, planning and execution of pile testing.

A lack of clear objectives often means that expenditure on load testing may be at best poorly allocated or at worst wasted. The testing requirements may well be set simply to comply with the relevant regulations and to follow "common practice", rather than to promote "best practice".

The ability of load testing to play an important part in value engineering and the geotechnical and structural optimisation of foundation solutions should be recognised not only in financial terms, but also with regard to sustainability.

It is important, therefore, that load testing of piles is factored into the project cost plan and programme at an early stage. The programme should allow sufficient time for an objective appraisal of the test results and subsequent design revisions/value engineering to be carried out.

A lack of clear objectives and understanding combined with poorly specified requirements can lead to problems that could have been avoided. Examples of such problems are: -

- Insufficient time to carry out tests and to evaluate the test results
- Lack of flexibility in the testing regime
- No provision for value engineering
- Unrealistic performance criteria specified
- Inappropriate test method specified
- Load test conditions are not representative of the working piles
- Piles infrequently loaded to failure

Pile load testing provides an opportunity for continuous improvement in foundation design and construction practices, while at the same time fulfilling its traditional role of design validation and routine quality control of the piling works. In order to achieve this improvement, data from pile tests has to be collected and analysed to enable the piling industry, both individually and collectively, to make the best use of resources.

To justify its cost to the industry, pile testing must have a value. The magnitude of this value will be increased through a better understanding of the process and its benefits.

In this handbook the Federation of Piling Specialists aims to provide guidance on issues that should be considered to enable better planning, specification and execution of pile tests, thereby increasing the value of the testing process.

Chapter 2 Safety

Key safety issues must always be considered in the planning and execution of pile load tests, including the following: -

2.1 Preparation and Maintenance of Test Area

- The area surrounding the test pile must be cleared of pile spoil, slurry and rubbish.

- A properly designed level platform of sufficient plan dimensions to support the testing equipment safely and with suitable access for operatives, transport vehicles and lifting plant must be provided. The working platform for lifting plant must be designed to withstand the loads applied by tracks or out-riggers.

- Construction plant that may be operating elsewhere on site must be excluded from the test area during the course of the pile test so that the test pile's performance can be accurately monitored in a safe environment.

- Electronic barriers with audible warnings can be used to keep the test area clear, and under no circumstances will any excavations be permitted within the exclusion zone.

2.2 Lighting

- Dependant upon the loading regime agreed it may be required that some operations are carried out during periods of poor natural lighting or darkness; the area must be adequately lit to enable the load test to be undertaken safely and for the test pile performance to be monitored throughout the full duration of the test.

2.3 Load application limits

- The maximum test load to be applied must be agreed in advance so that the test pile, pile cap (if required) and the load testing equipment (reaction piles/kentledge/ hydraulic ram and pump/bi-directional load cell/rapid or dynamic test energy) can all be designed or chosen so as to apply the maximum test load safely.

- When it is the intention to test a pile to geotechnical failure, due consideration must be given to the capacity of the whole test system. If geotechnical failure of the test pile has not occurred on application of the maximum test load, then this fact should be accepted. Increasing the load beyond the safe design capacity of the test system must not take place.

- All supervisory site staff must be made aware of the specification and the loading regime to be followed, and also the agreed method statements and risk assessments relating to the load test.

- During the course of the load test the whole system should be monitored for eccentricities and appropriate actions taken if this becomes excessive.

- Systems using only two reaction piles are inherently less stable than those with three or more and consequently should only be considered where test loads are light and the ground conditions permit location of the reaction piles to more stringent tolerances than normal.

- If any anomaly occurs during the load test that could give rise to an unsafe situation, such as those illustrated in Figures 2.1 and 2.2, no further loading should be applied in order to prevent these happening. The test area should be cleared immediately and advice sought from the pile testing contractor.

2.4 Site operative instructions

The issuing of correct and concise instructions to suitably experienced site personnel is essential for the safe completion of a load test on a pile.

- Where possible, standard testing equipment and loading procedures should be used. Consistency in the equipment set up and loading procedure will reduce the possibility of errors occurring, although the risk of complacency should not be overlooked. The relative plan position, vertical alignment and fit of the component parts of the set up should be checked to ensure that these are within permissible tolerances and prior to the application of load the set up should be checked for any eccentricity of loading. The equipment should be “self- stable”.

- Proper operative training and the use of written method statements for setting up/dismantling the test equipment and the application of the load are essential.

- The setting up and dismantling of kentledge tests involves operatives working at height and alternative methods of providing the reaction for the test load should be adopted wherever reasonably practicable.

- If the load test involves out of hours working, a safe system of operation should be established and agreed in advance. This may require a minimum of two people present on site during the duration of the test.

- Pile load tests harness significant amounts of energy and if this energy is not controlled in a safe manner it presents a significant safety hazard. Failures can occur rapidly with little or no warning. Site personnel must therefore be made aware that correct test procedures must always be followed.

- The use of readily available remotely operated methods of applying the load and measuring pile movement is recommended to avoid the site personnel being close to the testing equipment during the course of the test, particularly during the loading and unloading cycles of the test.

- The relative levels of the top of the test pile cap and the underside of the main reaction beam should be arranged so as to minimise the depth of any additional packing above or below the load train which might otherwise lead to some instability in this area of the test set up.

Figure 2.1 Failure of tension bar system in reaction pile

Figure 2.2 Platform bearing failure under kentledge test

Chapter 3 Testing Strategy

3.1 Strategy

This chapter concentrates on vertical load tests on piles. However, most of the recommendations in this chapter are equally valid for load tests on raking piles, tension piles and for the lateral load testing of piles. It is essential to seek expert advice for these types of pile test.

The strategy for pile testing needs to be established at the time the piles are being designed. For most projects the main purpose of pile testing is either to validate the design before construction and/or to check compliance with the specification during construction. However in some cases there are benefits in using testing for design development or research to provide the best solution. Testing strategies can therefore be divided into four main categories: -

- Design validation
- Quality control
- Design development
- Research

The scope of testing will depend on the complexity of the foundation solution, the nature of the site and the consequences if piles do not meet the specified requirements. The pile designer therefore needs to assess the risks and develop the testing regime accordingly. The main risks are: -

- insufficient site investigation
- lack of experience of similar piles in similar ground conditions
- insufficient time to verify the pile design and realise any savings
- cost and programme implications of undertaking the pile tests
- cost and programme implications of a foundation failure

For simple structures on a site where the ground conditions are well understood and there is pile test data from adjacent sites that have used similar piling solutions, then the risks are low and pile load testing can usually be restricted to routine checks for compliance or can even be omitted.

For situations where the ground conditions or structural requirements are complex, or there is little experience of similar piling work, then careful evaluation of the piling proposals is essential prior to embarking on the main piling works. Here the testing regime may need to be considered in two phases comprising preliminary pile testing before the main piling works and then proof testing of working piles.

The testing strategy for pile testing should address a project-specific set of stated objectives, which should include the following: -

- to minimise risk by investigating any uncertainties about the ground conditions, contractor's experience or new piling techniques
- to optimise the pile design in terms of size, length and factor of safety

- to confirm any pile installation criteria such as founding strata identification, pile set or pile refusal criteria
- to assess buildability, site variability, pile uplift, soil remoulding along the pile shaft or relaxation at the pile toe
- to check that the pile performance meets the required load/settlement behaviour during loading
- to assess environmental impacts of noise, vibration or pollution

In Table 3.1 below the level of risk is related to the characteristics of the piling works. The pile testing strategy varies according to this level of risk.

Characteristics of the piling works	**Risk level**	**Pile testing strategy**
Complex or unknown ground conditions. No previous pile test data. New piling technique or very limited relevant experience.	High	Both preliminary and working pile tests essential. 1 preliminary pile test per 250 piles. 1 working pile test per 100 piles.
Consistent ground conditions. No previous pile test data. Limited experience of piling in similar ground.	Medium	Pile tests essential. Either preliminary and/or working pile tests can be used. 1 preliminary pile test per 500 piles. 1 working pile test per 100 piles.
Consistent ground conditions. Previous pile test data is available. Extensive experience of piling in similar ground.	Low	Pile tests not essential. If using pile tests either preliminary and/or working tests can be used. 1 preliminary pile test per 500 piles. 1 working pile test per 100 piles.

Table 3.1

For pile tests in situations where the risk level is high, consideration should be given to using instrumentation within the pile, employing either strain gauges or fibre optics.

Where piles are required to carry very heavy loads, it may be uneconomic to carry out full scale standard load tests. In such circumstances, consideration can be given to carrying out tests on smaller diameter piles using the same method of construction (as provided for in EC7 for example), provided the results of the tests can be extrapolated with some degree of confidence to predict the load settlement characteristics of the larger piles. The test piles should be founded at the same level and in the same soil as the works piles. Alternatively, a bi-directional pile test with an O-cell cast into the pile can be used.

For rapid loading and dynamic pile tests it may be necessary to increase the applied loads to the pile in order to overcome the ground damping effects. Calibration with static load tests is preferable, depending on the prevailing ground conditions.

For preliminary pile tests it is preferable to place the test pile(s) close to a borehole so that the test results can be reliably evaluated.

Where the ground conditions are reasonably uniform over the site area, working test piles should be located in positions that will give the best possible coverage of the area to be piled.

Where ground conditions vary across the site, the number of test piles may have to be increased in order to check the pile characteristics in different areas of the site.

Care should be taken when choosing the test pile locations to ensure that there is sufficient space available for the reaction system to be installed without interference with other piles on the site. Consideration should also be given to the location of test piles in relation to the work in progress on the site while the tests are being carried out. Vibrations from other works can interfere with the test pile results and a test being carried out at an inconvenient location will disrupt other works on site.

For projects with a very large number of piles, say over 1000, the number of test piles can be reduced below that recommended in Table 3.1, once the pile designer can demonstrate confidence in the ground conditions and the pile construction method.

3.2 Acceptance criteria

The Performance Specification must state the maximum settlement permitted on an individual pile during load testing at the design verification load (DVL). It is the responsibility of the Engineer, when choosing this settlement value, to assess the effects of pile group action and the sensitivity of the structure to differential movement.

For insensitive buildings, the maximum settlement permitted at the head of an individual pile during load testing at DVL should be 10mm plus the calculated elastic shortening of the pile shaft, for piles less than 1000mm diameter. For test piles greater than 1000mm diameter a value in excess of 10mm may be appropriate.

Maximum settlement at loads greater than DVL should not be specified for insensitive buildings.

If the measured pile settlement exceeds the permitted value then the pile designer and the piling contractor should investigate the causes and undertake appropriate remedial action, if any.

Chapter 4 Testing and Specification

4.1 Types of pile test

The various available methods of testing piles are best characterised by the duration that the force is applied to the pile and the strain induced in the pile. Tests involving large forces applied for long periods of time such as static load tests are used to assess pile load capacity and small energy low strain tests are used to assess pile integrity. In high strain dynamic and rapid load tests, although the force is comparable in magnitude to a static test, it is applied over a much shorter period than in a static load test. Careful consideration is therefore needed in the interpretation of the dynamic effects in order to derive static load capacities.

The various types of test and their application are summarised below. More details of individual testing methods are included in Chapter 5 ‘Load Testing Methods’.

The static load test relies on a suitable reaction system from which to apply loading to the pile under test. Typical reaction systems are described in Chapter 5.

Instrumentation may be built into preliminary test piles to investigate the load transfer mechanism during the test. Piles may be equipped with strain gauges, push rods, load cells and other devices to enable the designer to isolate key pieces of information and improve the analysis of the test result and confirm or refine the design approach. This type of equipment is normally of a specialist kind and requires careful selection, installation and additional monitoring. It is preferable to have specialist advice on the installation, monitoring and testing of any instrumentation.

At present, the most frequently used types of static load testing are the Maintained Load Test (MLT) and the Constant Rate of Penetration Test (CRP). Both manual and automated test methods are suitable for either type of test.

For further information on the MLT or CRP load test procedure refer to the ICE Specification for Piling and Embedded Retaining Walls.

4.1.1 Maintained Load (MLT) Test

In the MLT, the load is applied to the pile in discrete increments and the resulting pile movement/settlement monitored. Subsequent load increments are only applied when the minimum specified time period has elapsed and the rates of induced settlement are below the specified criteria. The normal U.K. practice is to load the pile up to DVL, then to unload back to zero loading. Subsequent load cycles are applied, taking the loading to specified values above the DVL depending on the requirements of the test. The test will normally last between 24 and 48 hours excluding erecting and dismantling the test equipment.

The MLT method is normally the most suitable in determining the load/settlement performance of a pile under working loads and at 1.5 times working load conditions.

4.1.2 Constant Rate of Penetration (CRP) Test

In the CRP test, the load required to cause a pile to penetrate into the ground at a constant rate is monitored until either the maximum specified test load is achieved or "failure" of the pile occurs. The performance of the test takes less than 24 hours excluding erecting and dismantling the test equipment.

The measured penetration of the pile is plotted against the load applied, the purpose of the test being to determine the ultimate bearing capacity of the pile, particularly for piles constructed within predominantly cohesive material and deriving their capacity mainly in shaft friction. However, due to the high rate of loading, the measured maximum soil resistance may over-predict the ultimate capacity.

4.1.3 Bi-directional Load Cell

Another form of MLT uses a bi-directional load cell. This system is usually only applicable to conventional auger bored piles carrying high axial loads. The method is described in detail in Chapter 5, and involves a load cell or cells placed in the pile bore either at the pile base or part of the way up the pile shaft during the concreting operation. In the test the cell is hydraulically expanded so the upper part of the pile reacts against the lower part.

4.1.4 Rapid Load Test

Rapid Load Tests use a combustion chamber to provide a rapid load application to the pile head. The length of the stress wave in these tests is sufficiently long to encompass the whole pile and therefore there is no need for complex wave equation analysis when interpreting the results. However, in common with the dynamic load test, effects of creep and pore water dissipation can influence the results although to a slightly lesser extent because the rate of loading is lower.

4.1.5 Dynamic Load Test

These methods are based on monitoring the response of a pile subjected to hammer blows applied at the pile head. The measured response parameters are subsequently analysed to give predictions of the soil resistance that would be mobilised by the pile under static load conditions, based on stress wave theory.

The analytical models of the pile/soil interaction have been further developed to provide prediction of the load/settlement performance of the tested pile.

Developed initially for use with driven piles and now universally accepted, dynamic load testing of cast in place piles is now quite widely used to predict the static soil resistance and the load/settlement behaviour. The test method is similar to that used on driven piles with the monitoring of hammer blows and subsequently analysing the pile response to the stress wave propagation. A separate hammer or drop weight is usually brought to site to allow the dynamic load to be applied to a cast in place pile.

Due to the very high rate of applied loading, dynamic load testing cannot take into account time-related effects such as consolidation, relaxation or creep; consequently care should be exercised in reviewing the results of tests carried out in soils which may exhibit these features. However, the use of dynamic testing after calibration within a particular geological profile will allow more comprehensive testing at low cost in comparison to static testing. Typically a dynamic test will take about 15 minutes to perform on a precast concrete pile using the piling rig hammer to 30 minutes on a bored cast in place pile requiring the use of a separate drop weight.

4.1.6 Summary

Table 4.1 on page 12 summarises the types of pile load tests as described above.

Test Type	Reaction System	Maximum Test Load	Advantages	Disadvantages
Static Maintained Load (MLT)	Reaction piles (Rock anchors may provide an alternative reaction system for piles end bearing in rock) Kentledge	30MN (generally) 3MN (generally) In both cases higher test loads are possible.	Suits all soil conditions and pile types. Manual and automated systems available. Piles can be instrumented. Tension and lateral testing possible.	Reaction piles/kentledge and frame are required. Kentledge tests are relatively expensive. Setting up and dismantling the test equipment involves operatives working at height. Long duration.
	Bi-directional load cell	27MN per cell	Very high test loads achievable. No reaction system required.	Relies on sophisticated pile instrumentation and analysis. Suits bored piles only. Relatively expensive and long duration.
Static Constant Rate of Penetration (CRP)	As for MLT	As for MLT	Suits all pile types. Manual and automated systems available.	Reaction piles/kentledge and frame required. Kentledge tests are relatively expensive. Limited to cohesive soils. May over predict ultimate load.
Rapid Load Test	Combustion chamber	30MN	No reaction system required. Fast test.	May require calibration with static test. Caution required in cohesive soils and in chalk. Unsuitable for piles in excess of 40m deep. Suitable for testing pile groups and piles of variable or unknown pile shaft profile, e.g. CFA piles or re-used piled foundations.
Dynamic	Piling hammer or separate drop weight	3MN (generally, but can be greater) Hammer weight should be in the range 1 to 2% of load to be proved.	Fast and relatively inexpensive. Suitable for both driven and bored piles. Correlation with static tests on bored piles generally good.	May require calibration with static test. Results may be unrepresentative in soils that exhibit relaxation (reduction of end bearing in Coal Measure Mudstones for example). Correlation of dynamic and static results on piles in cohesive soils and chalk must consider time-related effects and the length of pile tested.

Table 4.1

4.2 Specification

4.2.1 Test Procedure

All load tests should be carried out in accordance with the ICE Specification for Piling and Embedded Retaining Walls.

4.2.2 Maximum Test Load

Load tests on preliminary or non-working test piles, in advance of or during the early stages of the piling works, are normally carried out to DVL plus 1.0 or 1.5 times the specified working load (SWL). DVL is the working load plus allowances for soil induced forces such as downdrag or heave, and any other particular conditions of the test such as a variation of pile head casting level.

Load tests on working piles are normally taken up to a maximum load of DVL plus 0.5 times the specified working load. This is sufficient to verify the load settlement characteristics of the piles under service conditions.

4.2.3 Concrete and Reinforcement

The strength of the concrete in the pile must be considered in all cases where a load test is to be carried out, in order to ensure that the concrete is not over-stressed during testing. This is particularly important with preliminary test piles where the stresses in the concrete may be very high. Preliminary test piles are often loaded to between two and three times their normal specified working load and this may call for higher grades of concrete than those to be used in the works. There is no evidence to suggest that this affects the bearing capacity of a pile within the limits of normal concrete strength. Enhanced reinforcement may also be required in preliminary piles to prevent structural failure under such loading conditions.

For working pile tests, the test should not proceed until compressive tests on works cubes have confirmed that the concrete strength is at least twice the concrete stress in the pile at the maximum specified test load. It is also necessary to ensure that the trimmed head of the pile is in intimate contact with the pile cap with a horizontal, clean and well formed joint.

Common examples of factors contributing to unsuccessful static load tests are: -

- Pile cap not concentric with pile shaft
- Poorly formed joint between pile head and pile cap
- Poorly designed/insufficient reinforcement in pile head or pile cap to withstand bursting stresses
- Pile cap concrete of inadequate strength or poor quality

Pile head preparation of bored/CFA piles undergoing dynamic load testing is critical. Unless the pile has a permanent liner, the pile shaft must be built up 2 to 3 pile diameters above ground level at the pile position within a thin-walled liner, suitably reinforced and finished with a smooth flat surface normal to the pile axis. A pair of diametrically opposed windows, 200mm square, must be cut into the liner to reveal smooth concrete surface to which the gauges can be attached. CFA piles subject to dynamic load tests will require the main reinforcement to extend to the pile toe. The heads of piles undergoing rapid load tests will require similar pile head preparation to that necessary for static load tests.

Chapter 5 Load Testing Methods

5.1 Maintained Load Tests in Compression

This method of testing involves the use of a reaction system to allow the application of a load to the test pile for an extended period of time. It therefore follows that when under test, there can be a very significant amount of energy contained in the system and as such they can be deceptively hazardous. It is therefore strongly recommended that only experienced, specialised personnel are employed to carry out the process.

The ground conditions will generally dictate the method of application of the reaction, which falls into three categories. Each method should be carried out using a suitably robust load transference system.

5.1.1 Reaction Piles

Ground conditions, pile type and site constraints often make the use of reaction piles economical. A number of reaction (anchor) piles can be placed surrounding the test pile and will provide the required tensile capacity and act as reaction against the compression test pile. Transfer of the forces involved is carried out by a series of beams, bars and couplers as illustrated in Figure 5.1. The beams are placed over the piles and securely connected by the couplers to high strength threaded bars cast into the anchor piles and specifically designed for the purposes of the test.

As only a relatively small amount of equipment is required, the site footprint is relatively small. The size of the testing apparatus is generally a function of the pile size and loading to be applied. Reaction piles should be placed at a sufficient distance from the test pile so as to avoid any interaction of soil resistances. In broad terms an area of at least 8m x 5m is required for the test.

Measurement

Once assembled the deflection of the pile is measured using a number of dial gauges, or electronic transducers arranged around the pile. The gauges are supported on a reference beam attached to the ground at a suitable distance. Directly above the test pile, along its axis, the load train is placed (see Figure 5.2). This consists of a jack, packer plates and load measurement device in the form of a calibrated pressure gauge, mechanical proving ring or ideally, a digital load cell.

Figure 5.1 30MN reaction pile test

Figure 5.2 Load Train

5.1.2 Kentledge

Should the ground conditions or site constraints preclude the use of reaction piles, the alternative is to use kentledge. A frame is assembled over the pile to be tested on top of which an amount of weight (a minimum 110 to 120% of maximum test load) is safely stacked. This generally takes the form of concrete blocks of regular dimensions and weight although steel ingots can be used provided that their weight can be assessed with reasonable accuracy. The size of the testing apparatus is generally a function of the pile size and loading to be applied. In broad terms an area of at least 15m x 15m is required for the test (see Figure 5.3). At the time of assembly, the presence of the additional cranes and associated transport deliveries will increase this working area. Consequently this is the most costly and disruptive method of providing a reaction for load testing of piles in compression.

Measurement

This method uses the same method as found in the reaction piles arrangement, as illustrated in Figure 5.2.

Figure 5.3 3MN kentledge test

5.1.3 Bi-directional Method

This system is usually only applicable to conventional auger bored piles, and involves a load cell or cells placed in the pile bore either at the pile base or part of the way up the pile shaft during the concreting operation (see Figure 5.4). In the test the cell is hydraulically expanded so the upper part of the pile reacts against the lower part. Schematic details of the testing system are illustrated in Figure 5.5.

Where the cell is at the base of the pile, the soil at the base provides the reaction. More than one cell can be provided to test different sections. There must however always be sufficient shaft resistance from the pile section above the load cell to provide the necessary reaction force to stop the pile being forced out of the ground.

Interpretation of the results is needed to derive a load/settlement plot and this can be complicated. The test arrangement needs to be carefully designed to make interpretation as straight forward as possible.

As there is no reaction frame assembly only a small working area is required, dictated by the independent method of measurement.

Measurement

The load is quantified by measurement of the hydraulic pressure of the jack cast into the pile. The reinforcement cage also allows the installation of extensometers to measure movement.

Figure 5.4 Load cell in reinforcement

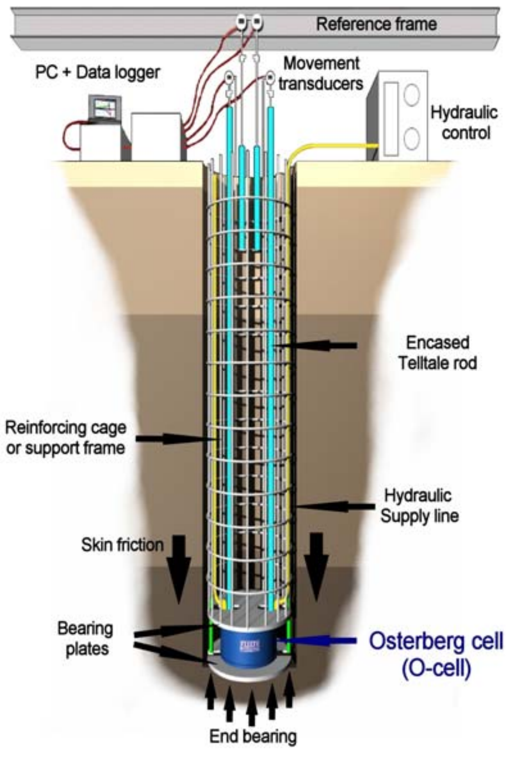

Figure 5.5 Schematic details of system

5.1.4 Rapid Load Testing

This involves the assembly of a relatively small counterweight over the top of the test pile and a controlled fast burning charge is then ignited in the mechanism. After combustion is complete a hydraulic or mechanical catching mechanism safely brings the counterweight to rest. Other methods provide extended duration of force by the use of springs and large hydraulic hammer. The method is rapid allowing a large sample of piles to be tested and the working area required is again a function of the magnitude of load required. Smaller tests can be undertaken using a crawler mounted system (see Figure 5.6), while large scale tests require an area in broad terms of at least 3m x 3m plus a working area for a large attendant crane (see Figure 5.7).

Measurement

The charge controls the force imparted to the pile, which in turn is measured by a load cell contained within the apparatus. Deflections are recorded by laser reference source and photovoltaic cell or indirectly by an accelerometer.

Figure 5.6 Crawler mounted 1MN test

Figure 5.7 3MN capacity test

5.1.5 Dynamic Load Testing

In order to carry out this method of testing an impact hammer is required. The hammer should ideally be sufficiently large to fully mobilise and therefore characterise the dynamic pile capacity without damaging the pile, and in the case of driven piling will usually be the same hammer as used to install the pile (see Figure 5.8). Dynamic load testing of bored cast-in-place or CFA piles will generally require the use of a separate hammer or drop weight (see Figure 5.9).

Dependant upon the method employed, electronic gauges are attached to the pile as illustrated in Figures 5.10 and 5.11. The gauges measure the acceleration of the pile (and therefore (indirectly) velocity with a knowledge of the pile properties) and strain within the pile just below the head as the hammer strikes the pile. The information is then recorded in the associated site computer. A variation of the method involves deflection measurement directly by laser theodolite.

In addition to access for the piling hammer/drop weight only minimal access is required to attach the gauges, provided that the pile shaft protrudes at least 2 to 3 pile widths/diameters above ground level; this safeguards the gauges and allows the propagation of a uniform stress wave.

A large number of piles can be tested in the course of one day using dynamic load testing methods.

Analysis of data

Once the data has been recorded, it can then be analysed by suitably experienced personnel using associated programs to provide the information on mobilised soil resistance, pile integrity and hammer performance.

Figure 5.8 Dynamic load testing of driven precast concrete piles

Figure 5.9 Dynamic load testing of cast-in-place pile

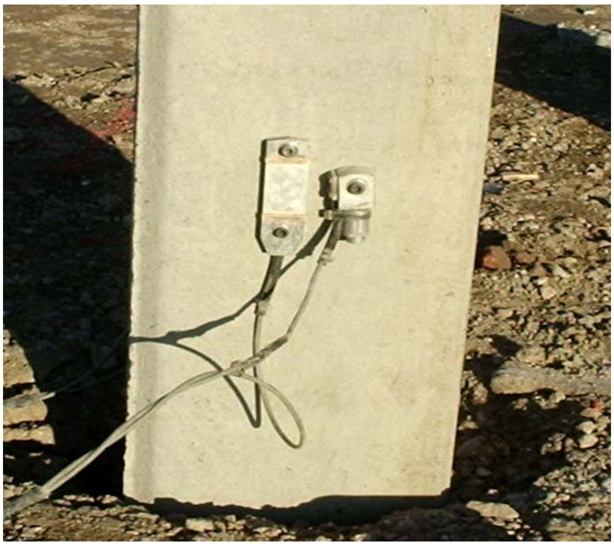

Figure 5.9 Strain gauge and accelerometer bolted to precast concrete pile
The arrangement is repeated on the opposite pile shaft face

Figure 5.10 Bored cast in place/CFA pile head preparation with window cut in liner to allow strain gauge and accelerometer to be attached to the pile

Chapter 6 Results and Interpretation

The ICE Specification for Piling and Embedded Retaining Walls sets out the requirements of reporting the results of a load test.

6.1 Maintained Load Tests

6.1.1 Results

The results of an MLT on a bearing pile will comprise records of time, load and settlement for the specified loading and unloading cycles and the periods of maintained load.

Computer controlled methods of load application and measurement in conjunction with electronic transducer systems of settlement measurement enable accurate records of the behaviour of the pile to be made and stored. Manual application of the load and the use of dial gauges to measure settlement are becoming less frequently used as the remote computer controlled methods provide a great improvement in operator safety and consistency in carrying out the test procedure.

Whichever method of settlement measurement is used in the test, the results should also include, where required by the particular specification, regular precise level measurements taken on the datum beams onto which the electronic transducers or dial gauges bear, as variations in temperature may cause some movement in these datum beams which may distort the measurements.

The load test records will normally be presented in tabular form with pile settlement recorded as the average of the displacement transducers or dial gauges at any point in time. Modern methods of data storage allow the easy calculation of cumulative settlement and increase in settlement during loading cycles (or recovery during unloading cycles), the latter being required to verify that limiting rates of movement have been achieved prior to increasing or decreasing the load on the pile. In addition to the numerical results, a graphical plot of load versus deflection and a separately plot of load and deflection versus time should also be included in the test results.

6.1.2 Interpretation of Results

Before embarking upon a detailed analysis of a set of load test results certain fundamental issues should be considered: -

- Are the results accurate and consistent, or have they been subject to distortion by some external influence such as weather effects or adjacent activities?
- Are the results in accordance with the designer's expectations?
- Does the pile performance satisfy the specification, and if not what remedial actions are required?

If a pile fully mobilises the soil resistance during a load test intentionally taken to failure or when an unexpected premature failure occurs, the ultimate bearing capacity of the pile should be as defined in the ICE Specification for Piling and Embedded Retaining Walls.

In the case of pile load tests that have not been taken to the point of failure of the pile/soil interface, estimates of the failure load can be made using methods devised by Davisson, Butler & Hoy, De Beer, Fuller & Hoy, Vander Veen, Brinsch Hansen, Mazurkiewicz or Chin, all of which were compared by Bengt Fellenius in his paper published in Ground Engineering in September 1980. It is not surprising to note a variation in predicted failure load of 30% between the lowest predicted load (Davisson) and the highest (Chin) in a comparison of the analysis of the same set of test results illustrated in the paper.

The Chin method also attempts to separate out components of shaft friction and end bearing, but is only moderately successful when one or other of these components predominates, in which case a review of the form of the load settlement plot will give a reasonable indication. Acquisition, storage and manipulation of data by computers has enabled more meaningful predictions of failure loads and proportions of the two components, provided that a reasonable amount of end bearing is mobilised during the test. Fleming (1992) is the most recent authoritative paper on this subject.

6.1.3 Recognising Problems from Test Results

In the event of a pile not performing as anticipated during an MLT, the shape of the load settlement plot may give some indication of the reason for this. Tomlinson gives examples of typical load settlement plots for a number of soil conditions and construction irregularities in his book “Pile Design & Construction Practice”.

Examples of some commonly encountered problems are outlined in Table 6.1 below: -

Problem	**Reactive measures**
Exceeding the permitted settlement specification.	Can structure accept the extra movement?
Preliminary test failing to prove required factor of safety.	Review design parameters and construction records; can the factor of safety be reduced?
Displacement pile has been lifted off its seating by ground heave and re-seated during the load test.	Re-drive preformed piles if predominantly end-bearing; if friction piles check that settlement at DVL & DVL + 50%SWL is within acceptable limits.
Soft toe results in excessive settlement or failure	Review construction records; redesign piles to increased FOS on shaft/wall friction; construct piles to deeper toe levels; consider a reduced SWL.
Structural failure in preliminary load test	Check concrete cube strengths (should be done before the test)

Table 6.1

It is important to appreciate that some margin between expected values of the load settlement characteristic and the specified values is required to allow for natural variations in ground conditions.

Equally important is an understanding that piles deriving their load bearing capacity primarily in end bearing will usually settle more than those carrying the same pile head load in shaft friction. The settlement of any pile will be influenced by pile type and length as well as founding stratum soil type.

Elastic shortening of relatively highly stressed long piles of slender cross section will contribute to greater settlements, up to as much as 25mm at working load in some cases.

6.2 Rapid Load Tests

6.2.1 Results

These test results take the form of an ‘equivalent static load test’ load deflection curve after extraction of the dynamic loading effects, and the data is very similar to that obtained in a constant rate of penetration test.

6.2.2 Analysis

Two main types of analysis of the field data may be employed, the unloading point method (UPM) and the non-linear soil dependant approach.

The UPM identifies the point where the pile has zero velocity (unloading point) and assumes that the pile resistance at this point is equivalent to the static pile resistance. By considering the pile resistance between the peak applied load and the unloading point a damping constant is found which is used to remove the rate dependent component of the rapid load test. There are other variants of UPM such as the modified unloading point method (MUPM) and the segmental unloading point method (SUPM). These methods were developed for long piles (<40m) or piles with rock sockets and rely on embedded instrumentation.

For skin friction piles in clays, ultimate capacity can be predicted using a non-linear velocity dependant relationship as proposed by Randolph (2003), which has its origins in the Smith wave equation analysis. This approach requires soil specific empirical damping factors which may be obtained from high speed laboratory testing or back analysis of rapid load tests.

6.2.3 Interpretation of Results

Rapid load testing is well suited for use in a proof load testing regime, and when used correctly provides a quick and cost-effective method of verifying that both test and working piles will meet a performance specification. However the method does have certain limitations, such as: -

- The test loads may need to be specified to mobilise the toe resistance of the pile. These loads may to be significantly greater than the loads required in a static test due to rate effects (damping).

- The UPM analysis technique performs well in granular soils but may over predict pile capacity by up to 50% in cohesive soils. However adjustment factors are available to correct UPM results in different soil types.

- Non-linear viscous parameter based analysis performs well in cohesive soils but is limited by the need for soil specific damping parameters.

- The predicted load deflection curve will not take into account creep or consolidation effects.

Notwithstanding these limitations, the rapid load testing method has been used worldwide since the late 1980's and in the UK since the mid 1990's. Although currently not so widely used in the UK as in the United States and Japan, draft codes of practice for ASTM and the Japanese Geotechnical Society have now been formulated. Guidance on its use and analysis has also been produced for the US Transportation Research Board and the Florida Department of Transportation.

6.3 Dynamic Load Tests

6.3.1 Results

The results of stress wave analysis carried out for piles that have been dynamically load tested are normally presented as graphical presentations of the matching of measured force and velocity traces against time, with a simulated load deflection curve for the pile head and the pile toe. A graphical and tabular distribution of mobilised soil resistance is also provided, together with pile stresses and hammer energy. CASE® analysis can be performed also, but provides less information.

6.3.2 Analysis

Two types of analysis of the field data are possible, CASE® and CAPWAP®/SIMBAT®.

CASE® analysis calculates the dynamic resistance of the soil and using an empirical damping factor relates this to the static resistance. The value of the damping factor can be determined from the soil type at the pile toe to provide an early indication of soil resistance on site at the time of testing, or back-analysed from the stress wave analysis to determine a site specific value for sites with a reasonably consistent soil profile. CASE® analysis is more suited to end bearing piles than friction piles.

CAPWAP®/SIMBAT® analysis involves the manipulation of a number of variables in the program to obtain the best match between the force and velocity traces of the measured and computed stress wave. These variables are static resistance, soil damping and soil elasticity or quake, each being adjusted on the shaft and the toe of the pile.

Whereas CASE® analysis will only predict total mobilised soil resistance, CAPWAP®/SIMBAT® stress wave analysis will proportion this resistance between shaft friction and end bearing, as well as providing a predicted immediate load deflection curve.

6.3.3 Interpretation of Results

Dynamic load testing is well suited for use in a proof load testing regime, and when used correctly provides an extensive and cost-effective method of verifying that piles will meet a performance specification. However the method does have certain limitations, such as: -

- The mobilised static soil resistance will not necessarily represent an "ultimate capacity" as full mobilisation of toe resistance often requires so much energy to create the necessary movement per hammer blow that the pile may be damaged during testing.

- Predicted soil resistances will generally be within plus or minus 15% when compared with the results of a static load test. However, in certain soil conditions a less satisfactory degree of correlation may be experienced.

- The predicted load deflection curve will not take into account creep or consolidation effects, nor can it accurately model the onset of failure of the pile/soil interaction.

Common reasons for apparently poor correlations between dynamic and static load test results include: -

- Comparing results from different piles

- Time related set-up/relaxation effects

- Comparing piles of differing length

- Incorrect assumptions of soil type

Notwithstanding these limitations, the dynamic load testing method has been used in the UK since the early 1980’s, during which time it has gained widespread acceptance within the industry, becoming particularly popular in off-shore construction where traditional methods of load testing piles are impractical.

Chapter 7 References

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