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Compliance Testing and Instrumentation of Piles

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Compliance Testing and Instrumentation of Piles

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1. Introduction

This paper is intended to provide an overview of the issue of foundation pile instrumentation, and to help the practitioner understand some of the options that are available, and some of the issues which are pertinent to the choice, specification and interpretation of piling instrumentation.

The paper takes a wide view of what constitutes piling instrumentation. In some, this may be generic devices which are utilized in piling instrumentation - for instance to measure strain or displacement. In other cases, the paper looks at piling-specific technology or measurement systems which have been developed to collect particular information.

In general, piling instrumentation is used to ensure construction works compliance testing. It is used as part of a testing regime, or a quality assurance system in order to ensure that the completed pile, as a representation of the whole foundation, will perform satisfactorily for the life of the structure which is to be supported.

Although this is by no means a unique problem in geotechnical engineering, the fundamental problem that we face with ensuring compliance with foundations is that the entire system is buried. The quality and fitness of the foundation is dependent on a large number of issues :

- the type of foundation element (see Figure 1);
- the quality of the construction process;
- the experience of the supervisory and construction personnel;
- the quality of the site investigation;
- the variability and sensitivity of the ground conditions discovered in that investigation;
- the designer's awareness of and response to those conditions;

Our confidence in the foundation also depends on :

- the type of verification testing which is undertaken
- the frequency of that verification testing

The Australian Standard, AS2159-1995 : Piling – design and installation, accounts for these issues in Section 4 – Geotechnical Design. In particular, Table 4.1 and Table 4.2 provide guidance to the designer on the selection of the geotechnical strength reduction factor. These tables are reproduced in Figure 2 and Figure 3.

The primary function of these tables is to draw the designer's attention to the risk factors and issues which affect foundation construction. The use of a range of ϕ_g values instead of a single value is intended to highlight and encourage the benefits that accrue from good practice – in site investigation, in design, in construction and in verification. Ideally, the additional costs of good practice should be more than compensated by the lower foundation cost which results from the higher ϕ_g values which can be justified.

Pile loads – particularly in Australia – are becoming ever higher for a given section. Reinforced concrete piles which 20 years ago may have been good for a 40 tonne working load are now expected to carry working loads of 200 tonne or more in some instances. Part of this may be the result of improvements in material technology, but it is more due to economic imperatives which have forced us to exploit piles to their limit in a need for design efficiency, and hence cost efficiency. Increased loads and stresses are typically associated with reduced redundancy and higher risk. It is important that the increased risk is compensated by increased monitoring and verification.

As intimated above, at a basic level, there are two approaches to ensuring compliance of foundations. These will hopefully be applied in combination rather than isolation. The first is to ensure compliance of the completed foundation with the performance specification. The second is to ensure the compliance of the construction process with good practice. We will deal with these matters separately.

2. Compliance with the Performance Specification - General

2.1 Testing programs

We can attempt to verify compliance with a performance specification by undertaking some form of instrumented testing before the construction contract, or during or after completion of the construction. The purpose of testing prior to commencement would be confirm the validity of the design and the construction process, and give maximum opportunity to modification of either with minimum cost and disruption prior to commencement of the contract. There are, of course, balancing time and cost issues related to pre-contract test programs which often make them economically unattractive. In the absence of a pre-contract program, the project partners should strive for some tests at the earliest possible time to maximize the benefit of testing. In a large contract, the testing program should be developed to give both temporal and geographical distribution of testing across the site. Critically loaded piles, or critical geotechnical conditions should be given greater emphasis.

2.2 Representativeness

It should be remembered that the costs associated with 100% compliance testing will be prohibitive in most (but not all) cases. There is a requirement, therefore, that the piles tested are either chosen on the basis of their having the likely worst performance, or alternatively that they are statistically representative of the whole foundation. Due to high costs, it is unlikely that static load testing, for instance, will ever be justified in sufficient numbers to be statistically significant. Therefore, the designer should generally target the worst likely pile for static load testing. This may be possible if the designer has an experienced representative on site, and if good construction records are available with which to make an informed decision. Nominating test piles in advance is an almost certain way of ensuring compliance of the test pile. It may, however, say nothing about the representativeness of the pile. Alternative methods such as dynamic load testing which are rapid and relatively low cost, may allow a statistically representative sample of piles, with good geographical distribution to be evaluated. A different philosophy could be used for their selection.

2.3 Proof or failure testing

In practice, most foundation testing is undertaken only as a contractual requirement, and to satisfy the nominated performance specification – i.e. a nominated 'factor of safety' above working load or in limit state reaching S^*/ϕ_g , or meeting a maximum deflection criterion at working load or equivalent. Such proof testing is usually adequate for the purposes of the contract, however, testing to 'geotechnical failure' is of tremendously more value to the designer, and should always be encouraged. The feedback available to the designer may have direct benefits to the contract in either optimising the foundations, or extrapolating to other areas or depths. In the longer term design predictions on subsequent projects in the same geology will be more realistic. It is noted that testing to geotechnical failure does not render a foundation element useless. In fact, work hardening often improves the performance of the geotechnically failed pile relative to untested piles. Of course, pile tests should not in general be taken to structural failure, and structurally failed elements must not be incorporated into the structure.

2.4 Standards

Pile testing is covered in Section 8 of AS2159. Section 8.3 covers the particular requirements for static compression, tension and lateral load testing. Section 8.4 covers the particular requirements for dynamic compression testing. Section 8.5 provides some brief clauses on integrity testing methods.

It is pertinent to emphasize that AS2159 does not preclude the use of new or different testing technologies, but notes (in 8.2) that these may be used at the discretion of the designer.

AS2159 specifies a standard incremental static load test procedure, and default acceptance criteria for static load tests. Similar standard procedures and acceptance are nominated for dynamic pile tests. However, it is important to note that variations to both the standard load schedules and the acceptance criteria are allowed. Designers are encouraged to develop load schedules and acceptance criteria which are relevant to the particular structures being supported.

2.5 Why test?

It follows from the previous section that we may wish to instrument and test a pile to determine :

1. capacity – axial compression or tension, lateral. This is a test which relates to verification of the ultimate limit state design;
2. load-deflection response – axial compression or tension, lateral. This is a test which relates to verification of the serviceability limit state design, and the structure-foundation compatibility;
3. pile integrity – this is for construction verification, especially for cast-in-situ piles, but also for driven preformed piles;
4. construction control – this will mainly be dealt with in respect of monitoring of installation. However, it is necessary to relate the outcomes of foundation verification tests to foundation installation parameters to ensure that reliable installation criteria are developed (e.g. the pile driving "set").
5. foundation system verification – as noted before, the greater purpose of pile testing is to ensure the suitability of the complete foundation system.

The following sections will discuss the available test methods which address these requirements.

3. Evaluation of Capacity and Load-deflection response – Test options and Instrumentation

The determination of capacity, load-deflection response and integrity are undertaken subsequent to construction, as a check on compliance with the performance specification. Static test methods, and quasi-static test methods (e.g. Statnamic®) can provide an assessment of both capacity and load-deflection response. Dynamic methods are separated into high-strain and low-strain methods. High-strain methods can provide assessments of capacity, load-deflection response <u>and</u> pile integrity. Low-strain methods provide information only on pile integrity. These techniques will be discussed further in this section.

3.1 Routine Static Load Testing

Routine Static Load Testing - General

The following discussion relates primarily to the most common compression load testing, however, the requirements for tension and lateral load testing are equivalent.

Static load tests are typically monitored only at the pile-head for the purpose of establishing the pile-head load-deflection response. It is extremely important that both load and deflection are measured accurately. AS2159-1995 has an absolute requirement that load is measured using a load cell. Measurement of the jack pressure using a manometer is no longer considered acceptable – studies have shown that such readings can be 20% or more in error due to very small system eccentricities.

Deflection must be measured by dial gauges or electrical transducers to an accuracy of the lesser of 1% of pile diameter or 0.5mm. Displacement measurements can often be made to much greater accuracy. AS2159 requires four dial gauges or electrical transducers to be employed at equal distances around the pile head.

The accuracy of displacement measurements depends on shielding the devices from sunlight or other environmental influences. Furthermore, a critical issue is that the deflection is relative to a stable reference, or that the reference movement is measured and that appropriate corrections are applied. The reference beam should be founded outside the footprint of the test to minimize the influence of the pile and any reaction systems on the reference beam. Pile-head movements may be measured or supplemented with precise levelling measurements from well outside the zone of influence of the test. Reference beam movements are typically monitored at each load stage using the precise level.

Depending on the reaction system used, reaction piles, anchors or kentledge supports should be monitored regularly for deflection to ensure stability and warn of any imminent failure. Anchors or reaction piles may also be monitored with load cells. Examples of static load test arrangements are shown in Figure 4.

All these measurements may be taken and recorded manually, however, it is preferable, both from the aspect of objective reliability, and for reasons of safety that measurements be made electronically and logged automatically. Access to the pile head during the progress of the test should be discouraged or disallowed. Use of dataloggers is now very common, and systems are available for total automation of static load tests including both control and monitoring by feedback control.

The interpretation of ultimate pile capacity – even if taken to "failure" is often not clear and unequivocal. As summarized by Fellenius (1980), there are many alternative proposals and constructions for interpretation of pile load tests which may result in a wide range of capacity estimates. There are a number of analytical or graphical methods which attempt to assist with interpretation of the comparative base and shaft contributions, however, these are at best only approximate. In some cases, the separation can be deduced intuitively.

Routine Static Load Testing – summary of issues

Features	**Requirements**
Generally accepted as the reference test	Reaction system and jack
Typically 7-10 days after installation	Sufficient distance between pile and reaction system
Require 100% of test load as reaction	Load cell for measurement of applied load to 2%
Compression, tension or lateral	4 dial gauges, or transducers with at least 0.5mm accuracy, or precise level
	Comply with loading regime in AS2159
Advantages	**Disadvantages**
Direct (requires no interpretation)	Expensive
Easy to understand	Time consuming
Gives most engineers confidence	Possible errors due to interaction with reaction system
	Errors from manometer (up to 20%)
	Not statistically significant
	Difficult to extrapolate logically to other piles on site
	Can't assess time effects
	No resistance distribution unless instrumented

Routine Static Load Testing – Concluding remarks

Static load testing has been in decline for many years since the advent of rapid and cheaper alternative test methods. However, despite these new tests being particularly suitable for driven piles, the philosophy which has developed of reducing the number of static load tests has been applied as a blanket approach to all piles types.

Static load testing should be reintroduced as a standard requirement for all piling contracts, as is done in most other countries. In particular, more static load testing should be demanded for piles where there is either no direct feedback during the installation process, or where the feedback (e.g. torque) is not a reliable measure of capacity, i.e. bored piles, CFA and screw piles.

As an industry we need to establish a reliable database of test results for the new pile types that we are installing and for the higher loads that we are applying.

3.2 Instrumented Static Load Testing

AS2159-1995 does not provide any guidance on instrumentation of the pile shaft, which is the preferred method of evaluating shaft and toe resistance distributions. In Australia, instrumentation of the pile shaft is uncommon, and would essentially be used only in research applications, or in cases where the potential for indirect determination of resistance distribution by measurement of the variation of strain along the pile length has the potential for significant cost savings. In other countries (e.g. Hong Kong), multi-level instrumented pile load tests are routine.

Pile instrumentation depends on measurement of strain in the pile shaft. Measured strains at each level are multiplied by assumed section modulus and shaft area to infer the shaft load. The average mobilized shaft resistance at each level are computed from the successive load differences and the intervening pile surface area. There are a number of fundamental difficulties with interpretation of this data.

1. For concrete piles, the modulus must be assumed. It is normal to calibrate the system with a set of measurements just below the pile head. Given the measured pile cross-sectional area, and the known load, the effective modulus near the pile head can be determined. The modulus may vary along the pile length, but this cannot be determined or accounted for.
2. Concrete has a highly non-linear stress-strain behaviour, with initial tangent modulus being many times higher than the secant modulus at high strain levels. The relevant modulus will therefore vary with load level, and the strain at any location in the pile.
3. For cast-in-situ piles, the cross-sectional area may also vary, and this will also remain unknown and may influence the accuracy of the results.
4. Interpretation is normally based on an assumption of a strain-free pile at the commencement of the test. This is unlikely to be true for driven piles, and may be untrue for drilled shafts. Residual stresses in the pile will lead to an overestimate of shaft resistance and an underestimate of end bearing. Special procedures are required to more accurately determine the resistance distribution.

Given the difficulties of installing strain measurement devices in harsh construction environments, measurement redundancy is highly recommended. This is particularly important near the pile head, where any bending effects coupled with inactive instruments, could result in a significant misinterpretation of the section modulus. The available devices for instrumenting static load tests are well summarized by Sellers (1995).

Instrumented Static Load Testing - Strain measurement devices

Two types of sensors are typically used for measurement of strain in instrumented static load tests – electrical resistances strain gauges, and vibrating wire strain gauges.

<u>Vibrating wire strain gauges</u> are generally preferred, as they are less susceptible to the effects of moisture and the length of cables, have significantly superior long-term stability, and require less datalogger channels for monitoring. For steel piles, either weldable, or boltable types are available (see Figure 5). Consideration must be given to physical protection of the gauges during driving, and the cables must be secured to avoid inertial effects. For cast-in-place concrete piles, either embedment strain gauges, or so-called sister bars are used.

<u>Sister bars</u> are based on vibrating wire strain gauge technology, and are constructed from 150mm of debonded high-strength steel containing an axially mounted vibrating wire strain gauge. The instrumented section is attached at either end to reinforcing bar extensions which act as the bond length, and ensure strain compatibility of the debonded section with the surrounding pile. A schematic of a sister bar is shown in Figure 6.

Embedment strain gauges are also based on vibrating wire strain gauge technology, and comprise a tube with two closing end flanges or blocks to which the internal wire is attached (see Figure 7). The gauge is embedded in concrete – the end flanges ensuring strain compatibility.

Electrical resistance strain gauges are the only suitable alternative in cases where dynamic events are being recorded (e.g. Statnamic or dynamic load tests).

In lateral load tests, it may be of interest to monitor pile bending strains to compute bending stresses and moments. Strain gauges must be suitably located in the plane of bending about the neutral axis. Gauges will generally be located particularly in the upper part of the pile and at low embedments, where bending stresses will be maximum.

Instrumented Static Load Testing - Displacement measurement devices

In order to fully analyze the pile base stress-strain response, it is necessary to determine both the base load and the base movement. The base movement may be only approximately inferred from the known pile-top movement, and the strain measurements along the pile shaft. However, a direct measurement of base movement will be much more accurate. Typically, this is determined using so-called 'telltales', however, retrievable extensometers and fibre-optic measurement systems are now also available to measure displacements with great accuracy.

Telltales are used in both cast-in-situ piles and preformed driven piles. They comprise an anchor which is embedded in the pile base (or at some other depth of interest). An open steel or plastic pipe is attached to the anchor, and houses a stainless steel or fibreglass rod which can be clipped to (and unclipped from) the pipe base. The top of the rod moves in sympathy with the anchor, and can be monitored using a dial gauge, an LVDT or other displacement measurement device. An example application is shown in Figure 10.

Retrievable extensometer systems are available to provide multiple displacement measurements along the pile length. A special steel or plastic tube is cast into the pile, and a string of vibrating wire strain gauges with associated anchors is lowered into the pipe. The anchors are locked within the tube and the distance between the anchors can be progressively monitored with the vibrating wire strain gauges. The string can be removed on completion of the test, and reused on successive tests. The system components are shown in Figure 8, and a schematic of the system is shown in Figure 9.

Fibre optic sensors are a new displacement measurement technology with many great features, but currently provided at relatively high cost. These transducers can be provided in single lengths of between 200mm and 50m, and have a measurement accuracy of 2μm, regardless of sensor length. They are insensitive to temperature, electromagnetic fields, humidity, vibrations and corrosion, require no calibration and have excellent long-term stability. There are different specific fibre-optic technologies, each with different specific features and advantages. The cost of these systems probably precludes use on small and routine projects. A fibre optic sensor placed within a reinforcing cage is shown in Figure 11.

Instrumented Static Load Testing - Load measurement devices

Load cells which rely on calibrated strain measurement are typically use to measure pile head load. As for strain measurements in the pile, vibrating wire strain gauge or electrical resistance technology can be used for load cells. However, dynamic load cells must use electrical resistance strain gauges. Load cells must be matched in size to the pile head and the jack which is used to apply the load. Sellers (1994) notes that mismatches of jack and load cell size may cause load errors of up to 10%.

Manometers attached to the loading jack measure hydraulic pressure, which can be converted to equivalent load, depending on laboratory calibration. However, under field (as opposed to laboratory) conditions, the calibrations may be invalid and load overestimation in excess of 20% are reported (Fellenius, 1980). AS2159-1995 does not allow the use of manometers for load measurement.

Instrumented Static Load Testing - Measurement of inclination

Inclinometers may be embedded in piles in order to measure the deflected shape of piles under lateral test loads. Inclinometer probes track along proprietary grooved casings which maintain the orient the probe. The probe contains accelerometers which measure the inclination of the probe in two directions. Inclination measurements can be converted to lateral displacement by integration.

3.3 Bi-directional Load Testing

Bi-directional load testing is also known by the name of the device, the Osterberg cell or O-cell. This is a form of static load test which applies the load from the bottom of the pile, rather than from the pile head. The technique is particularly designed for testing of drilled cast-in-situ piles, such as rock-socketed piles, as well as non-circular elements such as barettes. However, some tests have been performed even on driven concrete piles.

In order to perform this test, a proprietary hydraulic pressure cell, or flat jack must be placed and bedded at the pile base. The cell is connected to the pile head with hydraulic lines to allow cell inflation, and instrumentation lines and conduits to permit measurement of the response.

The particular benefits of bi-directional load testing are that :

1. a cell with a given capacity can test piles to loads of up to twice that capacity, as the shaft is loaded in an upward direction at the same time as the base is loaded in a downward direction;.
2. the base response can be loaded and measured directly
3. the shaft resistance provides the reaction, and it may not be necessary to provide any further kentledge or reaction system;

Bi-directional load testing depends on there being sufficient shaft resistance available to provide the required reaction. It may therefore not be suitable for predominantly end-bearing piles. Conventional kentledge may be used in association with the test to increase the available reaction. In addition, care should be taken in the acceptance and interpretation of the results, as the shaft resistance is being mobilized in an upward direction and the cell expansion actually generates tensile stresses at the cell level. The stress regime around the pile base may therefore not be representative of normal service loading, but should provide a conservative assessment.

The following table shows the diameters and nominal capacities of one manufacturer's bi-directional load cells.

Nominal Diameter		Nominal Capacity *	
(in)	(mm)	(kips)	(MN)
9	230	400	1.80
13	330	800	3.60
21	540	2000	8.90
26	670	3600	16.0
34	870	6000	27.0
Note : The total test capacity is twice the nominal O-cell capacity			

Bi-directional load cells may also be located at locations other than the pile base. The shaft resistance in particular sections of the pile (e.g. a rock socket) can be determined by having cells located at preselected locations. Cells may also be combined in groups of two or more at the same depth, and inflated simultaneously in order to increase the available test load. By combination, test loads of up to 133MN have been achieved.

The test instrumentation includes :

- two telltales to measure movement of the lower surface of the cell on opposite sides
- an internal LVWDT (linear vibrating wire displacement transducer) or extensometer to measure the cell expansion
- a manometer to measure cell pressure, from which the applied load is derived
- pile-top movement measurements
- reference beam movements

A schematic showing a typical instrumentation arrangement for an O-cell test, including telltales, is shown in Figure 10.

Bi-directional load testing has not been undertaken in Australia to date. It must be performed by a specialist contractor who manufactures, supplies and installs the cells in conjunction with the foundation contractor. The same firm then performs and monitors the load test. The installation is extremely important, and must be undertaken to a tight specification by experienced personnel to ensure both the success of the test, as well as the integrity of the pile. Excessive delays in installation, or poor concreting using inappropriate mixes could compromise pile capacity. On completion of a test, the hydraulic oil in all cells is displaced by grout, so that the pile can be incorporated into the foundation as a structural element.

Bi-directional Load Testing – Summary of Issues

Features	**Requirements**
Pile loaded by flat-jack from base	No reaction system (generally)
Requires 50% of test load as reaction	Specialist contractor to supply and install (U.S., Singapore and Malaysia)
Loads up on shaft and down on base.	No reaction system (generally)
Cells available from 230mm (4.0MN test load) to 870mm (55MN test load)	
Advantages	**Disadvantages**
Direct (requires minimal interpretation)	Some of the disadvantages of static load tests
Separates load-deflection response of base and shaft	Generally only for bored piles
Can be installed at multiple levels	Test pile must be nominated in advance
Sometimes implemented with strain gauges	Installation of cell may affect construction
Uses shaft resistance as reaction	Fails at 2 x minimum of shaft resistance or end bearing
No interaction with reaction	Cell expansion produces tensile zone near base

3.4 Rapid Load Testing

Rapid load testing is more commonly known by its proprietary name – Statnamic® load testing. Statnamic derives its name from a combination of the words "static" and "dynamic". This is because it is a dynamic test of longer duration than PDA tests (see later). This tends to reduce the relative importance of dynamic effects, and make the pile move more (but not exactly) like a rigid body.

The test does not give a direct value of static capacity, or load-displacement response and some interpretation is necessary. Simplistic analysis techniques are available (e.g. the unloading point method), however, wave equation analysis is the author's preferred method of evaluation.

The dynamic event in a Rapid Load Testing is generated by launching a constructed mass above the pile using slow-burning explosive in a combustion chamber between the pile and the mass. The inertial force of the launched mass generates an equal and opposite reaction from the pile. A schematic of the Statnamic test, and some views of the test set-up are shown in Figures 12 and 13.

There are several distinct advantages of Statnamic testing, and interesting applications have emerged. The test is somewhat less expensive than static load testing, however, the test can be performed in a much shorter time (perhaps 1/3 of the time for an equivalent static test). The tests can be performed in both vertical and lateral directions, and tests have been conducted on whole pile groups. Offshore testing is another good application, as the seawater can be used as a reaction. Test rigs for loads up to 50MN are available, although the limit in Australia is currently 15MN. A relatively small number of tests have been conducted in Australia.

The technique requires specialized skill, both in the design of the explosive charge to be used, and in the construction and execution of the test. If the explosive charge is excessive, then large dynamic effects will be generated, and the unloading point method will not satisfactorily account for these effects. However, for more 'balanced' charges, when the pile-soil system either remains in the elastic range, or the imposed force does not exceed the ultimate geotechnical capacity, the dynamic effects will be suitably small, and simplistic analysis may be sufficient. Long piles will usually require a more rigorous wave-equation analysis.

Rapid Load Testing – Instrumentation

The applied load is measured directly by a load cell placed between the device and the pile head. This obviates the need for any assumption of pile modulus or area.

The pile-head movement is measured using a laser-activated photo-voltaic displacement transducer. Sometimes accelerometers are used as a back-up to the laser displacement transducer for direct determination of acceleration, which is relevant to the inertial component of the response.

Rapid Load Testing – Summary of Issues

Features	**Requirements**
Pile loaded by long duration combustion	Reaction system is launched by combustion
Requires 5-10% of test load as reaction	Requires special solid fuel, required charge is estimated
Device available in Australia to 15MN, overseas to 50MN	Specialist contractor to supply and install (Franki-Keller is the agent in Australia)
Slow dynamic test, usually with reduced dynamic effects (c.f. PDA), hence resistance more similar to static	Usually for larger diameter bored piles
Advantages	**Disadvantages**
Takes less space than static test (less reaction)	Not significantly cheaper than static load testing
Direct load-settlement output	One hit only before test must be re-setup*
Little correction required if pile "set" is low	Dynamic effects may be significant in some cases
Lower compression and tension stresses in pile compared to dynamic	Standard analysis method is quick but unsophisticated
Can do lateral load testing	No resistance distribution unless instrumented
Can test pile groups (load limit)	*some multi-hit devices available overseas

3.5 Dynamic Load Testing

Static load testing techniques are both expensive and time-consuming. As noted in the previous sections, these techniques have distinct advantages and benefits, but they are also not without their short-comings and difficulties.

Dynamic load testing techniques were developed as a rapid and relatively inexpensive alternative to static load testing in the late 1970's and early 1980's, and have been in use in Australia since 1982. Dynamic load testing, or PDA testing as it is more commonly known, is a prescribed method in AS2159-1995, and section

8.4 of that standard provides requirements for the equipment, procedures, acceptance, supervision, recording and reporting of these tests.

The primary purpose of dynamic pile testing is to determine the pile capacity. However, it will be seen in section 4 that dynamic pile testing also has (equally) important benefits in providing construction control for driven pile projects. Dynamic load testing was developed specifically for the testing of pre-formed driven piles, however, it can be, and has been applied to the testing of bored piles, CFA piles, and barettes. Such extensions are possible, but require a higher level of testing expertise and review, with a particular understanding of the critical assumptions.

The fundamental difference between static and dynamic testing methods is that the dynamic methods are conducted during pile driving, when the pile is in significant motion. At this time, the pile is subjected not only to static soil resistance forces, but also dynamic forces that result from the relative pile-soil motion. Static pile capacity is therefore not a direct output of the test. The fundamental challenge for this method is to isolate the static and dynamic components of driving resistance so that reliable estimates of static capacity can be predicted. The success of this task is highly dependent on the reliability of the models of static resistance and dynamic resistance used in the interpretation of the test measurements.

The analysis techniques for dynamic pile testing are all based on one-dimensional wave mechanics. When the pile driving hammer impacts, a stress-wave is generated which travels the length of the pile, and is reflected from any shaft resistance, from any change in cross-section, including damage, and from the pile toe. The reflected waves can be interpreted to determine resistance, and even the detailed distribution of shaft resistance along the pile length, and the component of toe resistance.

Approximate results are available in real-time using a closed-form analysis called the 'Case Method', which depends – sometimes highly – on a so-called damping factor, J, which is a function of soil type and a number of other factors. Case Method estimates provide a preliminary guide to pile capacity, and may be correlated against a more rigorous wave equation analysis called CAPWAP® or its equivalent TNOWAVE®. This desk-top PC analysis provides the most reliable estimate of total capacity, resistance distribution (by 1 metre segment), and a predicted load-settlement response. Given that the test is very rapid, this prediction does not include any estimate of creep movement.

The test has evident benefits in terms of cost and time. These can either result in lower project costs, or alternatively, and more reasonably, the testing cost can be spread over a large testing sample. In Australia, typically between 5 and 10% of piles on a driven pile project are tested using this method. International practice varies widely, with some countries testing as little as 0.5% (Korea), and other countries requiring testing of 25% (Sweden). The ability to test a significant sample – and 5 to 10% could be considered statistically significant – provides the designer and client with an increased level of confidence, which is another benefit of this type of test.

Two types of tests are undertaken – driving and restrike tests. Driving tests are during pile installation, whereas restrike tests are subsequent to pile installation (by hours, days, weeks or months). Generally restrike tests will provide the best estimate of long-term static capacity, as these will incorporate any time-dependent capacity changes (e.g. set-up or relaxation). Restrike tests can be nominated on any random pile after installation, depending on the installation records.

As noted, the test method does not provide a direct evaluation of static capacity, and this inevitably reduces the reliability of the test. This is reflected in the lower range of capacity reduction factors which are specified for dynamic pile tests (0.65 to 0.85) compared with static load tests (0.70 to 0.90). The difference is small, and some element of this small difference may be attributed to the greater overall level of confidence provided by the higher percentage of piles dynamically tested.

Dynamic Load Testing – Integrity Assessment

As indicated earlier, any change of cross-sectional area, or damage will generate a reflection to the incident compression wave from the hammer. A reduction in area (or modulus), or damage will generate a tension reflection. This can be clearly differentiated from the compressive reflections which are generated from shaft resistance. Based on the relative magnitude of the tensile reflection, and the timing of that reflection, both the severity and location of any damage can be inferred from PDA tests. An approximate estimate is provided in the field (designated the Beta factor), but wave equation analysis will provide a more reliable assessment of the damage feature.

Dynamic Load Testing - Instrumentation

The instrumentation required for dynamic pile tests comprises:

- re-usable bolt-on electrical resistance strain gauges (because of the dynamic nature of the strain record). The strain is converted to a force-time record;
- accelerometers to measure pile-head acceleration. This is then integrated to produce a velocity-time record. Different accelerometer technologies (piezoresistive, piezoelectric or capacitative) are used.

Figure 14 shows the instrumentation used for dynamic pile testing – in this case for offshore testing, with a duplicate set of gauges attached. Figure 15 shows a typical data acquisition and analysis unit used for dynamic pile testing.

In general, two strain transducers and two accelerometers are attached at least 1 pile diameter below the pile-head. Average measurements take account of any pile-bending induced by uneven hammer impacts. In some cases (e.g. for cast-in-situ piles and spiral-welded steel tubes), 4 strain transducers are usually required to ensure reasonable data quality.

Dynamic Load Testing – Summary of Issues

Features	**Requirements**
Pile loaded by short duration impact	Field computer with data acquisition for strain and acceleration measurements
Requires 1-2% of test load as impact weight (reaction)	Specialist testing house (or contractor in-house)
Test load using normal driving hammer or purpose built for cast-in-situ piles	Computer wave equation analysis program
Measurement of stress wave input and response of pile	Usually for driven piles, but can be extended to cast-in-situ piles
Advantages	**Disadvantages**
Rapid	Output indirect (force and velocity vs time)
Cheap	"Black box" to most engineers
Extensive (site variations, statistical approach)	Static behaviour is interpreted from dynamic response
Evaluate driving hammer	Requires experience and skill to evaluate
Evaluate pile stresses	Requires special care for testing of cast-in-situ piles
Evaluate pile condition	Can be manipulated if procedures not in place
Evaluate changes with time	
Evaluate resistance distribution (feedback)	
Direct link to Hiley	

4. Evaluation of pile integrity – Test options and Instrumentation

Physical coring provides direct evidence of defective concrete or construction. Coring is a direct physical testing method which may allow indirect confirmation of satisfactory pile performance based on a structural assessment only. No reliable evaluation of the geotechnical performance should be inferred from any of these tests. The core may be used to assess concrete quality by visual inspection, strength testing or chemical analysis. However, it must be remembered that the retrieved core represents only a small statistical sample of the pile cross-section.

Due to these limitations, researchers have developed a number of indirect techniques for assessment of pile construction since the late 1960's. These indirect techniques are all based on the evaluation of small-strain wave transmissions or reflections. A variety of indirect testing methods exist, and these are well summarized in Turner (1997).

The applications, limitations, advantages and disadvantages of each indirect testing technique differ, and will be summarized later. However, the following general points should be taken into account for indirect testing:

- indirect testing may provide a qualitative rather than strictly quantitative assessment of pile shape, integrity and condition;
- indirect testing is often applied to 100% of all piles on a project. Anomalous piles are identified by differences in response to a reference response determined for the majority of the pile population;
- assessments (of pile length or geometry or condition) are based on interpretation of acoustic wave transmissions or reflections.
- the nature of the anomaly that has generated the received reflection or modified the received transmission can only be inferred.
- the significance of anomalies is generally related to the size of the reflection or transmission effect, however, factors such as soil resistance may significantly affect the response.
- acoustic methods are limited in their sensitivity – for instance, vibration testing may be unable to detect defects smaller than 10 to 15% of the pile cross-section (the threshold value), even under ideal circumstances.
- anomalies inferred from measurement of responses in excess of the threshold value should be confirmed by physical testing (e.g. coring).
- interpretation of defect locations, or pile lengths is based on an assumed wavespeed. If the pile length is known, then it may be possible to back-calculate the wavespeed. Wavespeeds in piles will vary with method of transmission (1-dimensional or 3-dimensional), strain level, concrete strength and concrete age.

4.1 Cross-hole sonic logging

This test is referred to as the Sonic Logging Test (SLT) is AS2159-1995. The test is largely unknown in Australia, but is extensively employed overseas for large diameter bored piers.

Cross-hole testing (or sonic logging or sonic coring) is a technique which is used for the evaluation of construction defects in newly cast drilled shaft piles. This technique has the advantage of not being limited in depth of application. The test is performed by simultaneously lowering an ultrasonic transmitter and separate receiver down two tubes cast into the pile during original construction. Generally 4 tubes (often more for larger diameter piles) are cast into the pile by attaching them to the reinforcing cage which is lowered into the pile prior to concreting. The reinforcing cage serves as a rigid skeleton to which to attach the tubes so that the spacing between the tubes is fixed. The principle of operation is shown schematically in Figure 16. With 3 tubes embedded in the pile, a total of 3 unique ray paths can be evaluated, whereas with 4 tubes embedded in the pile, a total of 6 unique ray paths can be evaluated.

The transmitter emits a pulsed sinusoidal wave train with a predetermined frequency which corresponds to a wavelength of between 50 and 100mm. The receiver responds to the arrival of the wave train, by oscillating at the same frequency. Typical probes are shown in Figure 17. As the two probes are progressively lowered (or raised) within a pair of tubes, a continuous profile of the receiver response can be plotted. The positive and negative cycles of the oscillation are traditionally recorded as "waterfall" diagrams which are 1-bit (1 and 0, or black/white) diagrams showing these positive and negative components of the received sinusoidal wave train.

Two parameters of particular importance can be interpreted from the test results. Traditionally, and most simply, the time of first wave arrival (the FAT or first arrival time) can be computed. This is a simple matter of scaling the first response off the waterfall plots. Knowing the distance between the tubes, the FAT information can be used to evaluate the speed of the wave transmission, which exceeds the speed of one-dimensional compression waves generated in (1-dimensional) vibration testing. Any defective concrete or anomaly which exists between two tubes will either delay the wave (by causing the wave to travel a greater distance around the anomaly), or entirely block the wave from being received. England (1991) in a private communication reported in Turner (1997) recommends that only variations in transit time of more than 15 to 20% of the norm for the site should be further investigated. This recommendation seems to be widely adopted in the industry.

Although waterfall diagrams are still used, more recently developed sonic logging equipment systems generally have enhanced capabilities. The computation of received energy contained in the arriving wave requires more sophisticated electronics with greater sensitivity and resolution, as well as more advanced computational routines. Later equipment allows interpretative information, including FAT logs and Energy logs to be plotted. These plots include some filtering algorithms which can assist in revealing significant features. The additional interpretation of received energy, and wave amplitude can further assist in the interpretation of anomalies. Figure 18 is a screen shot showing plots of FAT, relative energy and the traditional "waterfall" diagram.

Turner (1997) describes anomalies such as soil inclusions, wash-out, bentonite, and honeycombing as the type of effects which may be detected by sonic logging. Of course, the effect of such defects will be a function of the volume of concrete affected. The technique does not necessarily identify all defects, especially defects which may be on the outer perimeter of the pile, and therefore not delay the transmission of the wave between the tubes, nor significantly reduce the energy transmission. Although such defects may not represent a large percentage of the cross-sectional area, they may be significant to the long-term durability of the pile if reinforcement is exposed or the cover reduced. For example, if the bores exhibited overbreak due to loss of stability of the borehole wall during excavation, this would not be detected by sonic logging. If any wall collapse caused intrusion of soil into the bore during concreting, but the intrusion did not impinge inside the reinforcing cage, this again may be undetectable by this system.

Problems can arise if the sounding tubes are not well coupled with the concrete (e.g. due to smear or local air voids), and movement of the geophone within the sounding tube could also cause variations in response. As with all indirect measurement systems, errors are possible due to equipment, analysis and interpretation problems, and only experienced personnel with well-maintained and reliable equipment should be used. Sonic coring tests are intrinsically indirect and there are no simple criteria to 'pass' or 'fail' piles on the basis of these tests alone. The sonic coring technique, however, provides a cost-effective screening test to identify piles which have imperfections within their acoustic integrity that may have some structural significance. Such piles normally warrant further investigation and engineering evaluation. It is recommended that the test results should be evaluated in conjunction with pile construction records and site investigation reports which can often indicate the possible causes and physical nature of acoustical irregularities.

Despite these limitations, sonic logging has the significant advantage of being able to test or assess a much larger percentage of the pile volume than is assessed by direct physical coring. Furthermore, under normal circumstances, sonic logging can confirm the length of pile cast.

4.2 Pulse Echo and Impulse Response Methods

The pulse echo (PIT) test and the impulse response method are physically similar NDT test methods, which have different associated analysis and presentation techniques. These test techniques are denoted SIT and SVT in AS2159-1995. These techniques are typically applied to cast-in-situ piles, particularly CFA piles, and are both simple and fast one-man operations. It is recommended that these techniques be applied to <u>every pile</u> on the site. Construction problems may be evidenced by differences from the underlying signature response of the pile population.

Both techniques are applied at the pile head by impacting a small hand-held hammer on a clean and sound surface. Some head preparation is necessary, however, this is usually minimal and may involve only spot grinding. The pile head response is measured using either an extremely sensitive accelerometer, or a geophone (induction coil). A schematic of the test arrangement is shown in Figure 19. It is noted that the impulse response method must use an instrumented hammer, whereas the use of an instrumented hammer is optional with the pulse echo method.

The pulse echo test is interpreted in the time domain, in much the same way as high-strain dynamic tests. Pile necks or defects reflect a tension response, whereas pile bulges reflect in compression (see Figure 20). Due to the effects of soil damping, the low strain signal returning from depth must be amplified, and exponential digital amplification techniques are used to enhance the signal and allow features at depth to become more prominent. The technique is semi-quantitative, and there is a risk that with injudicious data manipulation non-existent features can either be "created", or alternatively real features can be suppressed. Strict guidelines should be followed with respect to data acquisition, analysis and presentation, and independent review of the electronic data is recommended.

The impulse response method differs in that the response is interpreted in the "frequency domain" (see Figure 21). The nature and location of features are determined by examining the dominant harmonic and sub-harmonic frequencies of the response. The effect of any significant anomaly in the pile shaft will be to superimpose additional dominant modes of vibration, which will be a function of the length to the defect, and the nature of the anomaly (e.g. an increase or decrease in section).

As indicated, the nature of the physical feature which generates the acoustic reflection can only be inferred. Some knowledge of the construction or service history may assist in interpretation of the physical defect. In many cases, visual inspection – e.g. by coring – may be required to confirm the true nature of the defect. It should also be noted that the acoustic response represents an average section response, and a reduction in impedance due to loss of section in the heart of the pile, or by necking, or by reduction in material quality may be indistinguishable. These techniques are generally considered to be sensitive to changes in acoustic impedance of 15% or greater.

Pulse echo and impulse response methods may be applied in the following applications :

- Evaluation of pile lengths (timber, concrete or steel)
- Detection of defects, and partial or total loss of pile section
- Comparative evaluation of relative condition for piles in a group
- Comparative evaluation of pile-head stiffness for piles in a group
- Estimation of depth to stiff soil layers

Vibration and impulse response methods have the following limitations:

- Generally penetration of the wave, and hence evaluation of pile length and condition, is limited to length/diameter ratios of between 20 and 50 depending on the pile and soil conditions, due to attenuation of the impact signal by soil damping.
- The transmitted signal will be further diminished by any changes of impedance along the pile length which cause reflections (of energy). This further limits the ability of the method to discriminate features at depth.
- Vibration and impulse response methods are able to discriminate changes in pile impedance of 10-15% at best. It would be expected that the ability to detect anomalies decreases with depth because of attenuation of the signal.
- Vibration and impulse response methods may only be able to reliably detect features with an axial length of 0.8m to 1.0m because the pulse length of the input wave is 3 to 4m. A sinusoidal frequency of 2000Hz corresponds to a wave length of about 2m. By use of smaller hammers or higher frequencies, pulse/wave lengths may be reduced, and the length of discrimination reduced, however, the penetration of such short duration pulses may be poor.
- Vibration and impulse response methods may not be able to detect gradual changes in pile impedance
- The condition of the upper section of a pile may not be reliably determined, particularly if the pile has a large diameter. This is because in the upper section, the wave is radiating from a point contact to the full lateral extent of the pile, and does not travel as a plane wave in the upper section. The average mobility, N, may be used as a measure to estimate pile-head condition.
- Detection of the pile toe may be difficult if it is located in material with similar acoustic impedance.

- These tests do not provide information on pile capacity. Vibration and impulse response tests can be used to determine the comparative dynamic pile-head stiffness, which can possibly be used as a relative guide to selection of a pile for static load testing. Caution must be exercised against over-interpretation of the low-strain dynamic pile head stiffness values determined by transient response testing.
- Varying ground conditions can generate secondary reflections which may confuse the interpretation of these tests. Ellway (1987) suggests a 1:5 reduction in shear modulus (from upper to lower layer) will result in a complete reflection of the incident wave.
- Vibration and impulse response tests should as far as possible be applied and interpreted on the basis of the response of piles relative to the average response of the pile population. Because of the interaction of section, material and soil effects, caution must be exercised in absolute evaluations of single piles without reference to tests on other piles.

4.3 Parallel seismic testing

The parallel seismic test is an acoustic method based on measuring the effect of an impact on, near or above the head of a foundation in a borehole which has been drilled adjacent and approximately parallel to the foundation. The system set-up is shown schematically in Figure 22. A small hand-held hammer, similar to those used for seismic echo and impulse refraction energy tests imparts a quantum of energy. The impact may be on the top or side of the pile, if the pile is exposed. However, if the pile is buried or built into a cap, the impact may be on the cap or a structural component connected to the cap. It is only necessary that there be a path which allows energy transmission from the point of impact to the pile.

The impacting hammer must be equipped with a trigger which responds to the impact, and fixes the time of impact, and start of data recording. The data recording device may be any analogue or digital system, but a digital recording system would be most common and allow most rapid analysis.

The energy that is imparted to the system will travel through the structural foundation components, and is also radiated from the foundation elements through the surrounding soil. The speed of travel in the structural components will be significantly higher than the speed of travel in the soil because of the much higher modulus of the structural materials.

The borehole drilled parallel and adjacent to the foundation element (e.g. pile) to be evaluated is filled with water, and a receiver is positioned within the borehole. The water serves to "couple" the receiver to the soil medium, and to detect the pressure wave generated in the water. Olson et.al. (1998) discusses the use of an alternative set-up comprising geophones fixed to the inside of a PVC casing grouted within the borehole using bentonite or bentonite-sand, or back-filled with sand.

The first wave to arrive at the receiver after impact will take the wave which travels fastest from the point of impact to the receiver. Because of the faster transmission in the structural components, the path of the earliest wave will be one which maximizes travel in the structure and minimizes travel in the soil. This wave will effectively travel in the structure to the elevation of the receiver, and then move horizontally through the soil to the receiver. Later waves reach the receiver by less favourable paths. By repeating the test as the receiver is progressively raised from the base of the borehole by constant increments, the variation of the geophone response can be plotted as a function of time and location. A typical set of test responses is shown in Figure 23.

When the receiver is above the base of the structural element (e.g. pile toe), the time of arrival will reflect the additional travel length in the structural material. However, as the receiver is lowered below the pile toe, the increase in travel time will be a function of the increasing travel length in the soil from the pile toe to the receiver. This is evident as an abrupt change in the gradient of the interpreted line of first arrival times (see line signal received in Figure A18). The depth of the pile toe can be inferred from the depth at which there is a change in the gradient of the first-arrival time. The angle of refraction of the waves at the pile/soil interface will result in a slight overestimation of the foundation length. Interpretation of the technique relies on a significant differentiation of the stresswave speed in the pile and the surrounding ground. In general, there will be sufficient difference between pile and soil to allow effective interpretation of the parallel seismic test. However, the length of piles that are socketed or embedded in rock may be difficult to establish by this method.

4.4 Other integrity testing methods

- Bending Wave method
- Ultraseismic method
- High-strain dynamic pile testing (PDA) – see section 3.
- SASW (Spectral analysis of surface waves)
- Ground Penetrating Radar
- Borehole Radar
- Induction Field Test
- Seismic Tomography
- Nuclear Radiation Methods, including gamma ray
- Resistivity methods
- CCTV inspection

Low strain integrity testing – Summary of Issues

Features	**Requirements**
Used for evaluation of shape length and condition of new or existing foundations	Field computer with data acquisition for acceleration measurements
Range of technologies all based on small strain waves	Specialist testing house (or contractor in-house)
No single technique covers all cases	Generally some associated analysis program
Can establish pile length to +/- 5% in the right conditions	Usually for cast-in-situ piles, but also for driven (timber bridge or wharf) piles and other poles
Sensitive to changes in cross-section of about 15 to 20%	
Technique should be targeted to problem on a case-by-case basis	
Advantages	**Disadvantages**
Generally low cost	SE and IR techniques have limited penetration
Very fast	Requires expertise to interpret
Portable equipment	Indications of problems may be relative (to reference response) rather than absolute
SE and IR methods require minimal preparation	Problems should be confirmed by other evidence, e.g. coring
Rapid way to screen 100% of all piles for more detailed evaluation, as needed.	Beware over-interpretation!
	DOES NOT provide an estimate of capacity

5. Construction Control – Equipment and instrumentation options

The previous sections have described a range of tests for compliance testing with respect to pile capacity, load-deflection response and pile integrity. As important as these are to a foundation contract, a <u>true</u> quality assurance approach should require the following two elements :

1. Experienced and capable construction personnel and supervisory staff.
2. Monitoring and evaluation during the construction process.

The first requirement is fundamental, and sadly the expertise and experience of supervisory field staff seems to be in decline rather than on the ascendancy. Furthermore, with less static load testing being undertaken on cast-in-situ piles in particular, the valuable opportunities for field staff to receive regular feedback on the quality of the piles they produce are missing.

In the absence of these feedback opportunities, the development of technologies provide significant opportunities for objective measurements to be made during the construction process.

It is absolutely fundamental that early monitoring and evaluation be undertaken in order to provide immediate warning of any anomalies at the site, and to allow corrective action to be taken before the consequences to the foundation, the contract and the project program are magnified out of proportion.

The particular type of monitoring depends primarily on the type of foundation being installed. Some available systems will be discussed in the following parts :

5.1 Driven piles

Dynamic Pile Testing

Dynamic pile testing (PDA testing) has been discussed in sections 3 and 4 in the context of determination of pile capacity, load-deflection response and pile integrity. PDA testing can also provide a very effective construction control function, if properly considered and built in to the pile driving contract. This function is as important as its ability to estimate pile capacity, but is generally overlooked. Dynamic pile testing can measure or estimate the following parameters :

- maximum pile head compression stress (average and maximum bending);
- maximum average stress at the pile toe
- maximum section tensile stress along the pile shaft
- effective energy transfer from the hammer to the pile, and hence hammer efficiency
- pile damage and location
- pile set and temporary compression (to reference to site physical measurements)

By effective monitoring of piles <u>during the complete installation process</u>, it is possible to develop a comprehensive driving plan which will maximize the chance for the pile to be driven safely but efficiently. Efficiency is important for the contractor, but the need to ensure that the pile that reaches founding level has not been overstressed, and will therefore be durable for the life of the structure, is paramount.

The results of monitoring and capacity evaluation must also be effectively connected to the Hiley formula to ensure that a reasonable pile acceptance criterion is developed.

Monitoring must be conducted regularly throughout the contract to ensure that variations in hammer performance over time, as well as stratigraphic variations across the site are properly accounted for, and reflected, if necessary, in the acceptance criteria.

Dynamic pile testing equipment provides a complete approach to quality assurance and construction control for driven piles of all kinds.

5.2 Bored piles/drilled shafts

There are two particular aspects of bored pile construction which should be monitored to ensure adequate performance – the condition of the pile base and the condition and properties of the shaft or socket, if the pile is drilled to rock.

Socket Inspection Device (SID)

Drilled shafts may be designed to carry their load by a combination of shaft resistance and end bearing. If taken to reasonable quality rock, the end bearing may be a very significant component. However, if the construction control is poor, leaving a lot of debris at the base before and after concreting, the available end bearing may be extremely low, and may even be non-existent at deflections which are compatible with the structural performance. Ensuring base cleanliness is therefore an important aspect of bored pile construction, especially to rock.

The socket inspection device (SID) was developed by the Country Roads Board (now VicRoads) for the Westgate Freeway project. SID is an inspection bell which houses a high resolution video camera and is used to inspect the bottom cleanliness of drilled shafts prior to placement of concrete. The inspection bell is lowered from a service platform to the bottom of the shaft, and the operator can view the condition of the bottom via the camera. The bell is fitted with a depth gauge to indicate the thickness of debris on the shaft bottom. The SID also has the capability to sample the sidewalls of shafts in soil in order to evaluate the buildup of slurry along the sidewalls. A photo of the ground level equipment of the SID device is shown in Figure 24.

Shaft Callipering

This is a virtually unknown technique in Australia. Callipering is undertaken in order to establish the gross shape of the borehole prior to concreting. This is used to ensure that the borehole has not experienced any collapse which will affect the concreting process and the interpretation of low strain tests and may affect the performance of the pile.

Callipering can be undertaken by mechanical means, or more commonly and accurately by acoustic or sonic methods. Acoustic callipering must be performed in fluid, and will require calibration depending on whether the fluid is water, natural or synthetic drilling muds.

Socket Roughness Measurement

The capacity and load-deflection response of piles socketed into rock, particularly with long sockets is significantly dependent on the socket shaft resistance. The available resistance is a function not only of rock strength, but also rock jointing and socket roughness. The design method developed at Monash University for rock-socketed piles (Rocket) uses these parameters, including the socket roughness as program inputs.

The SocketPro device allows socket roughness to be accurately measured using laser profilometry. This equipment is shown in Figure 25.

5.3 Continuous flight auger (CFA) piles

The construction of continuous flight auger (CFA) piles requires a high degree of operator expertise. The success of the operation is dependent both on the torque, the rate of auger advancement and rotation during the initial drilling phase and the rate of lifting, concrete supply and pressure during extraction.

Because of the strong need for quality control of this type of piling, several companies manufacture equipment for the monitoring and control of CFA rigs, and a range of this equipment is used by some Australian foundation contractors.

The torque, the rates of rotation and the rates of advancement and extraction can be easily and reliably measured. Most systems measure these parameters.

By contrast, the rate of concrete supply, and the supply pressure are very difficult to monitor. Ideally, these parameters should be known at the auger tip. However, reliable measurements at this location have eluded all manufacturers to date. Concrete supply is measured either by measuring the number of pump strokes, and multiplying this by an assumed volume per stroke. The supply rate may be in error because of an incorrect calibration, 'short' pump strokes, or because of discontinuities in the line which mean that the volume delivered at the auger head is not the same as that measured at the pump. Alternatively, magnetic flow meters may be fitted in series behind the pump, and these can be calibrated against concrete or grout volume. Varying mix properties may affect the accuracy of the volume measurement, and discontinuities in the line may still make the delivered volume in error.

The concrete pressure is typically measured at the top of the 'gooseneck', as reliable measurement at the pile tip is complicated by the severe wear and tear at this location. The pressure at the pile tip should be in excess of the measurement at the gooseneck by the effective head of concrete/grout, assuming a full concrete/grout column. The effective head of concrete/grout is difficult to assess because of losses in the auger stem, and arching effects in the relatively small diameter tube. Arching will depend on the fluidity of the concrete. If the column of concrete/grout is not maintained, the pressure at the pile tip may bear no relationship to the pressure measured at the gooseneck.

Recognizing the fundamental problems with these measurements, one manufacturer has developed an alternative strategy for ensuring the integrity of the concreting process. The critical requirement for ensuring a sound shaft is that the tip be under positive pressure at all times. Assuming that the concrete is 'sealed' at the bottom of the auger, a positive concrete pressure will act to reduce the effective weight of the auger loaded with soil. The technique is based on a process of measuring this effective weight at regular intervals and during reverse auger rotation.

5.4 Screw piles

Steel screw piles have become a popular piling system for both domestic and commercial construction during the past few years. For some of these systems, the capacity is determined using empirically derived charts which relate installation torque to compression capacity. Having undertaken some experimental and analytical research on screwed-in piling, it is my view that torque is a poor predictor of compression capacity. As a consequence, any correlation should be demonstrated by sufficient correlations with static load testing in accordance with AS2159-1995. Such correlations should be auger-specific and either site- or geology-specific. Any change in auger dimension, flight angle or construction would require new correlations.

5.5 Pressed-in piling

Pressed in piling systems have also become available in Australia as an alternative to conventional piling systems. These systems were developed in China where there is significant experience of this type of pile. These systems are attractive with respect to minimization of the noise and vibration effects normally associated with precast concrete piling. In theory, pressing rather than driving a pile will also minimize stresses, just as Statnamic® testing will generate lower stresses than dynamic testing.

With this system, piles are pushed into the ground at a slow rate using grips powered by high capacity hydraulic jacks. The pile capacity is determined by manometer connected to the jacks. No specific deflection measurement is made, but 'refusal' is estimated visually.

As discussed in Section 3 with respect to static load testing, the use of manometers to measure jack load is not recommended. Load cells are required under AS2159-1995 for static load tests. Furthermore, the draft Chinese code on pressed-in piling requires such piles to be given up to 5 repeated cycles of load before the capacity can be assumed to be stabilized. In addition, the effective static capacity may be reduced, depending on the pile length, with short piles having the greatest reduction factor applied.

6. Foundation System Verification

Sections 3 to 5 have discussed techniques that are available to test and monitor individual piles. Where a piled foundation system comprises single piles acting essentially independently (i.e. at sufficient spacing), the performance of the system as a whole may be inferred directly from the testing of individual piles. The designer's confidence of the whole foundation system will be a function of :

- the performance of those piles tested, and the variability of the performance;

- the number of piles tested – both as an absolute number and as a percentage of the total pile population;
- the reliability of the test method(s) used;
- the representativeness of the piles tested;
- the variability of the ground conditions;
- the redundancy (or otherwise) of the system;
- the consequence of failure.

These factors may be incorporated into a statistically based analysis to ensure a satisfactory degree of confidence.

If the piled foundation system comprises piles which interact significantly as a group, further account must be taken of the effect of such group interaction on both the serviceability and capacity of the pile group. In general, but not always, deflections under service load will increase due to group effects, and ultimate capacity will be reduced relative to the capacity of the same number of piles acting individually.

It is always important to establish whether the group action may make critical a mechanism of failure which is not critical during the loading of an individual pile. Uplift capacity of piles in jointed rock, or the behaviour of pile groups founded on discrete layers underlain by softer materials would be two examples.

Extrapolation of group effects, and consideration of different failure mechanisms must be based on classical geotechnical analysis, hopefully based on a rigorous site investigation.

7. Conclusions

There are many aspects of foundation construction, construction control and verification that require compliance testing and instrumentation. The wide range of compliance testing and instrumentation have been highlighted in this paper, and the main features and requirements, advantages and disadvantages have been summarized.

It is important that in designing the quality assurance and testing regime for a foundation project, the functional requirements of the structure be considered, and the ground risk be understood in the context of the foundation type that is proposed.

By combination of the available techniques with the structure needs and the construction risk, an effective and co-ordinated compliance testing program can be developed to cover the issues of construction control, pile integrity, serviceability and pile capacity.

As this is a specialized area, guidance should be sought with respect to the development, execution and interpretation of the testing program.

8. Disclaimer

The opinions expressed in this paper are those of the author, and do not necessarily reflect those of Monash University.

9. Acknowledgments

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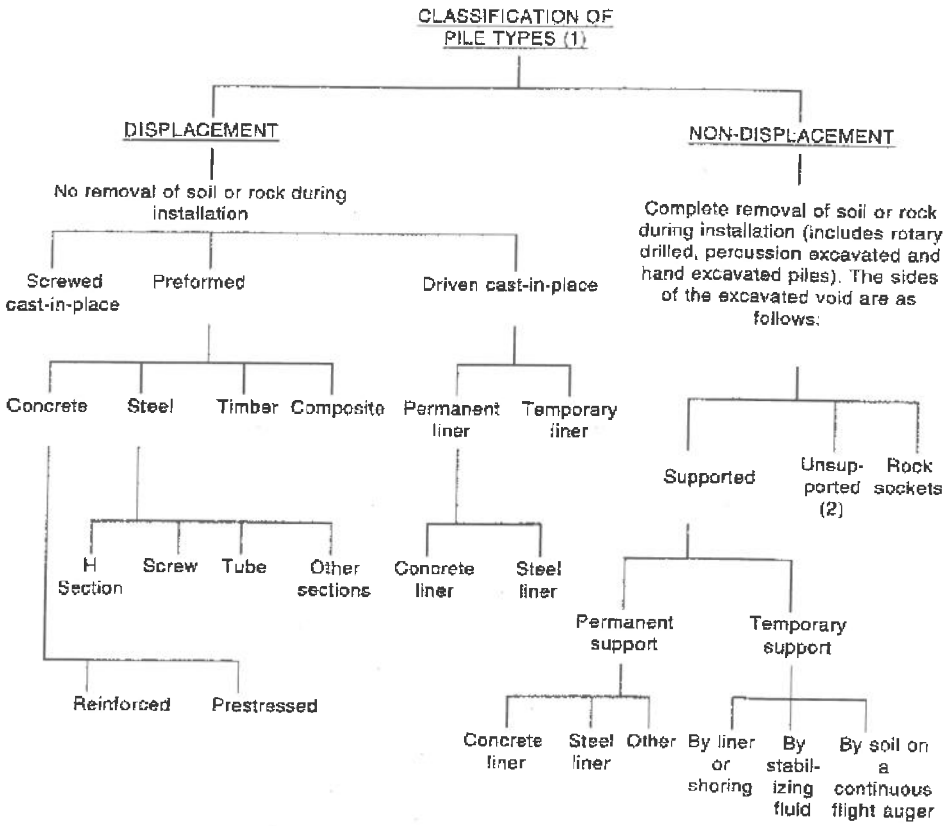

NOTES:

1 Pile types for which there is no established experience may not fall into these categories.

2 Unsupported. This classification refers to piles in which the ground is left exposed during excavation.

Figure 1 – after AS2159-1995 Figure 1.1 Classification of Pile Types

TABLE 4.1

RANGE OF VALUES FOR GEOTECHNICAL STRENGTH REDUCTION FACTOR ϕ_g

Method of assessment of ultimate geotechnical strength	Range of values of ϕ_g
Static load testing to failure	0.70–0.90
Static proof (not to failure) load testing (NOTE 1)	0.7–0.90
Dynamic load testing to failure supported by signal matching (NOTE 2)	0.65–0.85
Dynamic load testing to failure not supported by signal matching	0.50–0.70
Dynamic proof (not to failure) load testing supported by signal matching (NOTES 1 and 2)	0.65–0.85
Dynamic proof (not to failure) load testing not supported by signal matching (NOTE 1)	0.50–0.70
Static analysis using CPT data	0.45–0.65
Static analysis using SPT data in cohesionless soils	0.40–0.55
Static analysis using laboratory data for cohesive soils	0.45–0.55
Dynamic analysis using wave equation method	0.45–0.55
Dynamic analysis using driving formulae for piles in rock	0.50–0.65
Dynamic analysis using driving formulae for piles in sand	0.45–0.55
Dynamic analysis using driving formulae for piles in clay	Note 2
Measurement during installation of proprietary displacement piles, using well established in-house formulae	0.50–0.65

Figure 2 : AS2159-1995 Table 4.1. Range of values for geotechnical strength reduction factor, ϕ_g

TABLE 4.2

GUIDE FOR ASSESSMENT OF GEOTECHNICAL STRENGTH REDUCTION FACTOR (ϕ_g)

Circumstances in which lower end of range may be appropriate	Circumstances in which upper end of range may be appropriate
Limited site investigation	Comprehensive site investigation
Simple method of calculation	More sophisticated design method
Average geotechnical properties used	Geotechnical properties chosen conservatively
Use of published correlations for design parameters	Use of site-specific correlations for design parameters
Limited construction control	Careful construction control
Less than 3% piles dynamically tested	15% or more piles dynamically tested
Less than 1% piles statically tested	3% or more piles statically tested

Figure 3 : AS2159-1995 Table 4.2. Guide for assessment of geotechnical strength reduction factor, (ϕ_g)

Figure 4 (a) – static load test using rock anchors for reaction

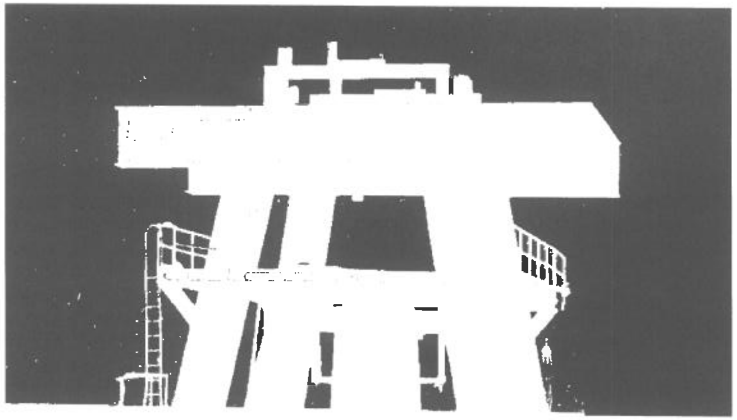

Figure 4 (b) – static load test using uplift piles for reaction

Figure 4 (c) – static load test using kentledge (concrete blocks) for reaction

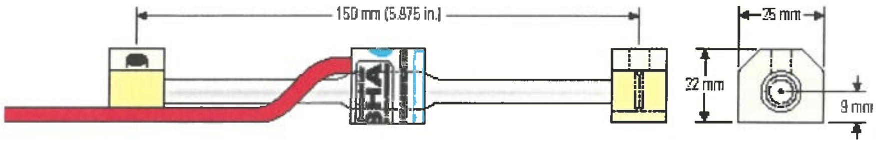

Figure 5. Schematic of a weldable vibrating wire strain gauge

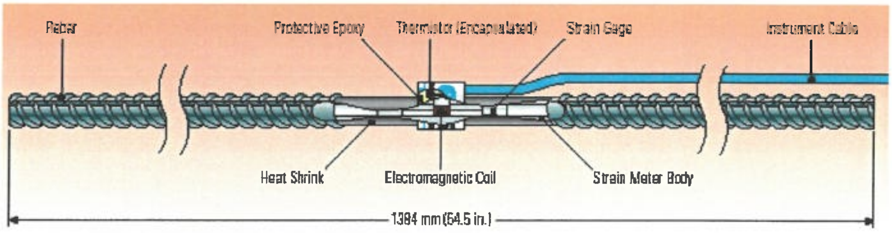

Figure 6. Schematic of a 'sister bar' vibrating wire strain gauge

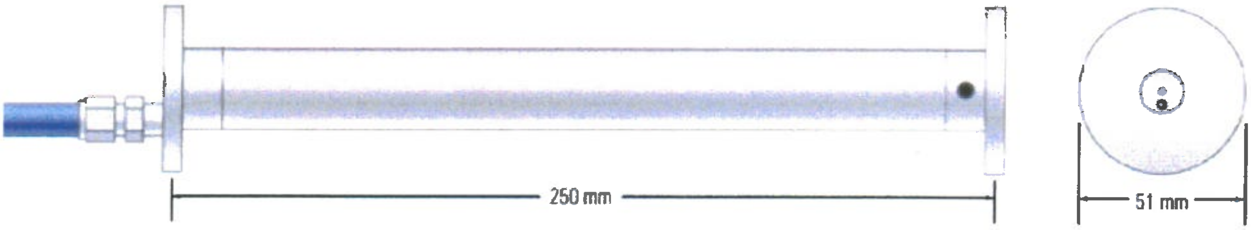

Figure 7. Schematic of a concrete embedment vibrating wire strain gauge

Figure 8. Components of a retrievable extensometer

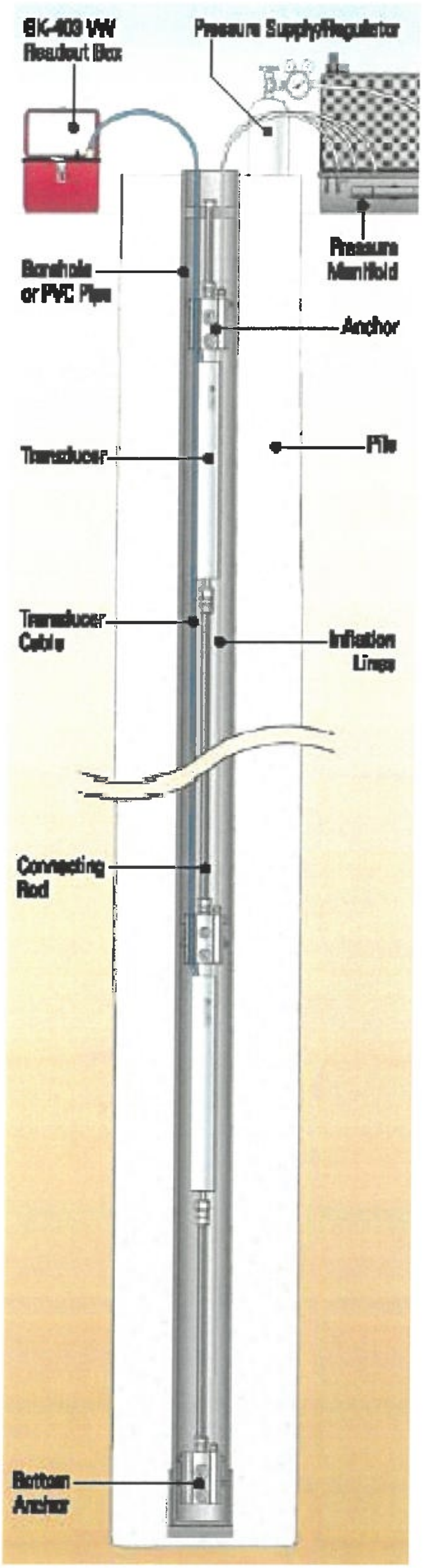

Figure 9. Schematic of retrievable extensometer

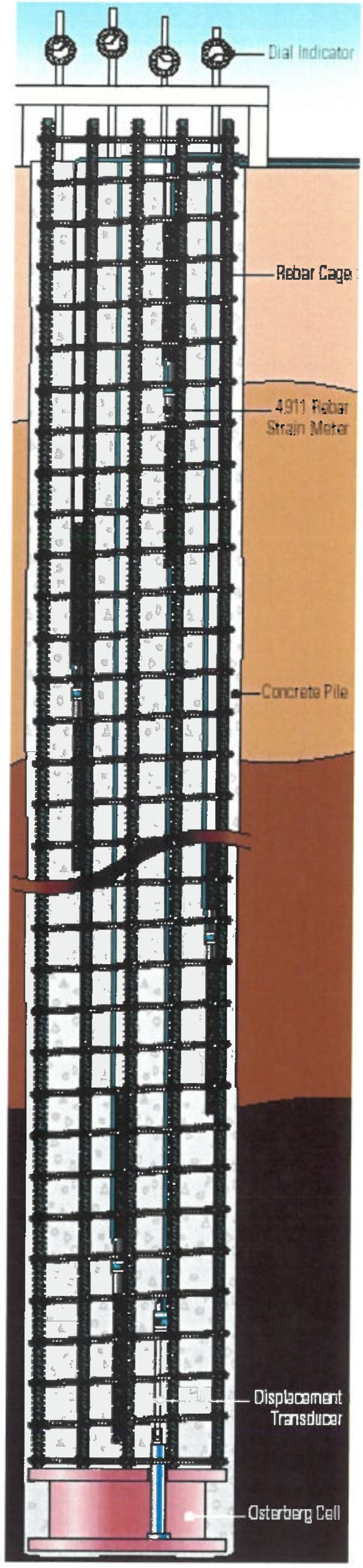

Figure 10. Schematic of O-cell test with use of telltales

Figure 11. Fibre optic sensor placed along reinforcing bar.

Figure 12. Two views of O-cells for bi-directional load tests

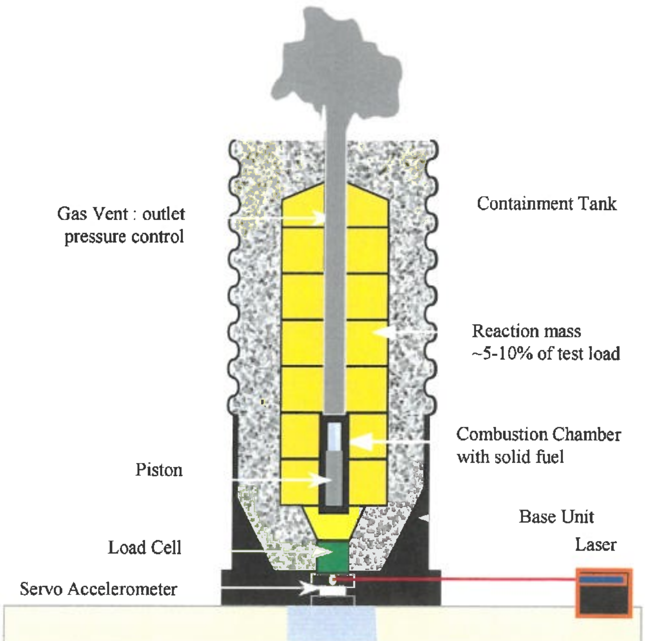

Figure 12 : Statnamic test schematic

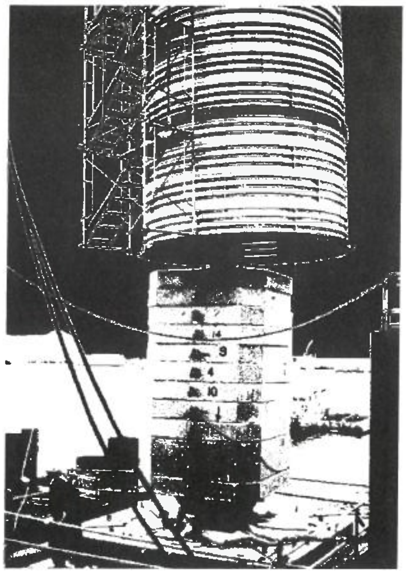

Figure 13. Views of Statnamic test set-up

Figure 14. Dynamic pile testing instrumentation.

Figure 15. Dynamic pile testing data acquisition unit

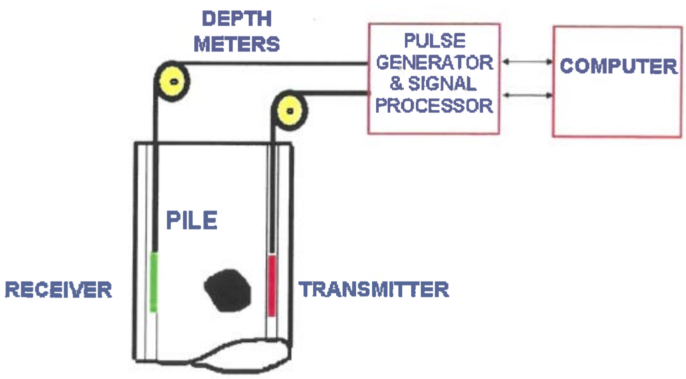

Figure 16. Schematic of cross-hole sonic logging

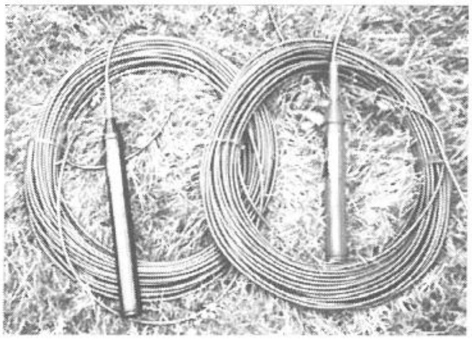

Figure 17. Cross-hole sonic logging probes

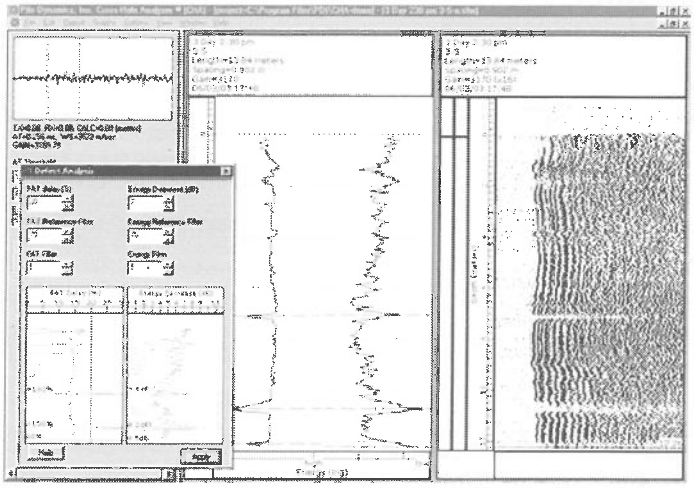

Figure 18. Plots of first arrival time (FAT), Energy and "waterfall" diagram

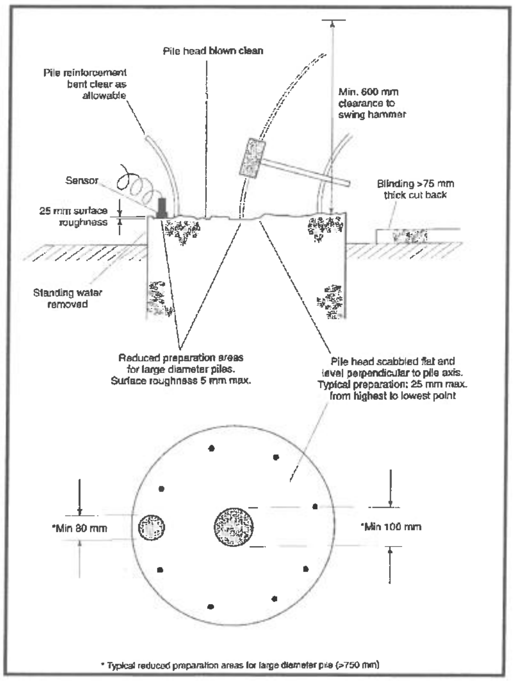

Figure 19. Pulse echo and Impulse Response method schematic.

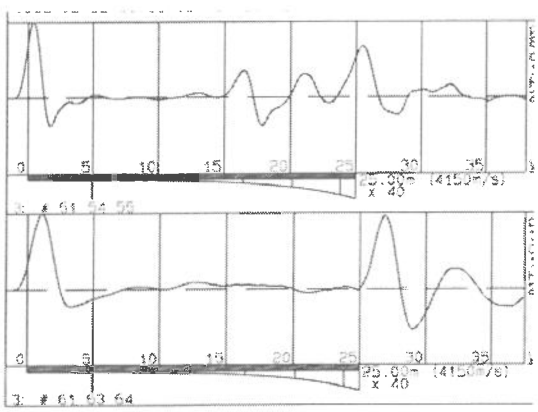

Figure 20. Pulse Echo tests showing responses for a defective pile (upper) and intact pile (lower)

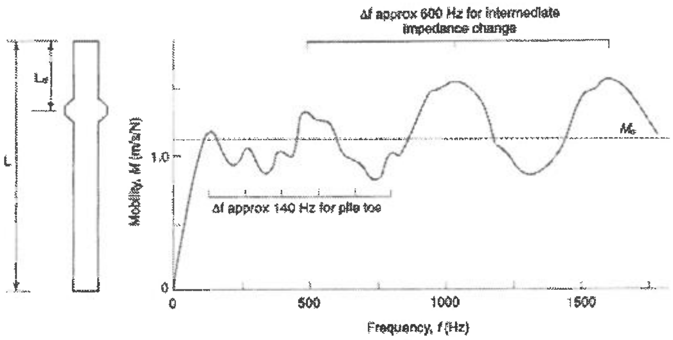

Figure 21. Impulse response test showing response for pile with a bulge in the frequency domain (after Turner, 1997)

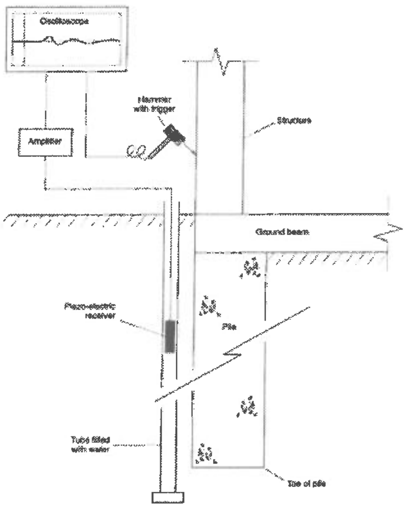

Figure 22. Schematic for Parallel seismic test (after Turner, 1997)

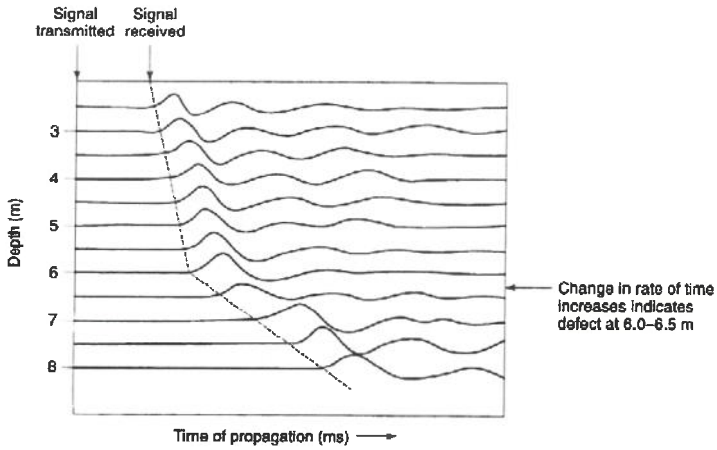

Figure 23. Classic response from parallel seismic test

Figure 24. The SID device – ground level equipment

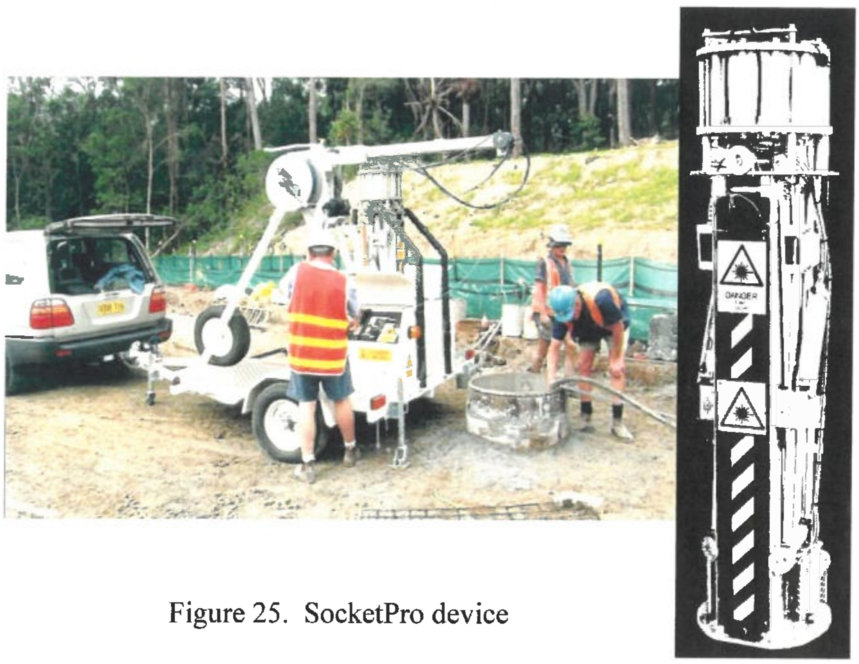

Figure 25. SocketPro device