AS 2159—2009
(Incorporating Amendment No. 1)

Australian Standard®

Piling—Design and installation

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PREFACE

This Standard was prepared by the Standards Australia Committee CE-018, Piling, to supersede AS 2159—1995.

This Standard incorporates Amendment No. 1 (October 2010). The changes required by the Amendment are indicated in the text by a marginal bar and amendment number against the clause, note, table, figure or part thereof affected.

The objective of this Standard is to provide requirements for design and installation of piles for supporting structures. The object of this revision is to align with updated AS 1170 Standards and reflect changes in practice since the previous edition.

Major changes to the previous edition are as follows:

(a)   Revision of the overall Standard.

(b)   Revision of the setting of strength reduction factors, that is, the selection of the 'safety' level appropriate to the installation being designed.

(c)   Revision of the negative skin friction requirements.

(d)   Revision of durability requirements to assist designers to achieve predicted life.

(e)   Include requirements for newer pile types and installation methods including steel screw piles, jacking, screwing and screwed cast in place.

(f)   Requirement for some testing to be 'normative'.

(g)   Inclusion of new types of test including rapid pile testing.

The terms 'normative' and 'informative' have been used in this Standard to define the application of the appendix to which they apply. A 'normative' appendix is an integral part of a Standard, whereas an 'informative' appendix is only for information and guidance.

Statements expressed in mandatory terms in notes to tables are deemed to be requirements of this Standard.

Notes to the text contain information and guidance and are not considered to be an integral part of the Standard.

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FOREWORD

Decisions in pile design are based on design formulae, empirical and practical experience, and the accumulated records of a large number of applications of proprietary systems (both successful and otherwise). As such, there is a great need for flexibility, experience, engineering judgement and commonsense in designing and constructing a piled footing system. In a real sense, these requirements are in conflict with the need to make unqualified mandatory statements and, as a result, many of the stipulations of this Standard are short and simple when, in other cases, extensive arrays of multiple choices are provided. Where applicable, explanatory notes are added to some clauses in this Standard and additional commentary is provided.

STANDARDS AUSTRALIA

Australian Standard
Piling—Design and installation

S E C T I O N   1   S C O P E   A N D   G E N E R A L

1.1 SCOPE

This Standard sets out minimum requirements for the design, construction and testing of piled footings for civil engineering and building structures on land or immediate inshore locations. It does not extend to offshore (deepwater) construction.

NOTES:

1   AS 5100 series should be considered for the design of footings for road bridges.

2   Where the strength or serviceability of an existing structure is to be evaluated, the general principles of this Standard should be applied. The actual properties of the materials in the structure should be used.

3   The durability requirements are appropriate for structures with design life within ±20% of the target design life.

1.2 NORMATIVE REFERENCES

The normative documents referenced in this Standard are the following:

NOTE: Documents referenced for informative purposes are listed in the Bibliography.

AS

1012	Methods of testing concrete (all Parts)
1163	Structural steel hollow sections
1170	Structural design actions
1170.4	Part 4: Earthquake actions in Australia
1289	Methods of testing soils for engineering purposes
1289.6.3.1	Part 6.3.1: Soil strength and consolidation tests—Determination of the penetration resistance of a soil—Standard penetration test (SPT)
1289.6.5.1	Part 6.5.1: Soil strength and consolidation tests—Determination of the static cone penetration resistance of a soil—Field test using a mechanical and electrical cone or friction-cone penetrometer
1379	Specification and supply of concrete
1450	Steel tubes for mechanical purposes
1554	Structural steel welding
1554.1	Part 1: Welding of steel structures
1579	Arc-welded steel pipes and fittings for water and waste-water
1604	Specification for preservative treatment
1604.1	Part 1: Sawn and round timber
1720	Timber structures
1720.1	Part 1: Design methods
1726	Geotechnical site investigations

AS
2758   Aggregates and rock for engineering purposes
2758.1   Part 1: Concrete aggregates

2832   Cathodic protection of metals
2832.2   Part 2: Compact buried structures
2832.3   Part 3: Fixed immersed structures

3600   Concrete structures

3818   Timber—Heavy structural products—Visually graded
3818.3   Part 3: Piles

3972   Portland and blended cements

4100   Steel structures

5100   Bridge design
5100.5   Part 5: Concrete
5100.6   Part 6: Steel and composite construction

AS/NZS
1170   Structural design actions
1170.0   Part 0: General principles

1594   Hot-rolled steel flat products

3678   Structural steel—Hot-rolled plates, floorplates and slabs

3679   Structural steel
3679.1   Part 1: Hot-rolled bars and sections
3679.2   Part 2: Welded I sections

4671   Steel reinforcing materials

ASTM
C 566-97   Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying

1.3 DEFINITIONS

For the purpose of this Standard, the definitions below apply.

1.3.1 Bored cast in place pile

A pile, with or without a liner, formed by excavating or boring a hole in the ground and subsequently filling it with plain or reinforced concrete.

1.3.2 Cased pile

A pile formed in the ground by installing a liner and partially or wholly filling it with plain or reinforced concrete after excavation.

1.3.3 Cone penetration test (CPT)

A test in accordance with AS 1289.6.5.1, to determine the penetration resistance of a soil.

1.3.4 Continuous flight auger pile (CFA)

A pile formed in the ground by drilling with a hollow flight auger that is subsequently and progressively withdrawn, with the cavity below the auger tip being gradually filled with concrete or cement grout injected under pressure.

1.3.5 Design action

Combination of the nominal loads and other actions multiplied by the appropriate load factors.

1.3.6   Design action effect (E_d)

Action effect computed from the design values of the actions or design loads.

1.3.7   Design geotechnical strength ($R_{d,g}$)

The product of the design ultimate geotechnical strength ($R_{d,ug}$) and the geotechnical strength reduction factor (ϕ_g).

1.3.8   Design life

Period of time during which a structure or a structural element, when designed, is assumed to perform for its intended purpose with expected maintenance but without major structural repair being necessary.

1.3.9   Design serviceability load (E_{ds})

The load on a pile corresponding to the serviceability limit state.

1.3.10   Design structural strength ($R_{d,s}$)

The product of the design ultimate structural strength ($R_{d,us}$) and the structural strength reduction factor (ϕ_s).

1.3.11   Design ultimate geotechnical strength ($R_{d,ug}$)

An estimate of the ultimate geotechnical strength assessed using calculations in accordance with Section 4 of this Standard.

1.3.12   Design ultimate structural strength ($R_{d,us}$)

The limit state at which static equilibrium is lost, or at which structural elements fail.

   NOTE: The design ultimate structural strength may be assessed using calculations in accordance with Section 5 of this Standard.

1.3.13   Driven cast in place pile

A pile formed by driving a liner, which is either permanent or temporary, and filling with plain or reinforced concrete.

1.3.14   Driven preformed pile

A prefabricated pile installed in the ground by driving.

1.3.15   Durability

Ability of a structure or a structural element to maintain adequate performance for a given time under expected actions and environmental influences.

1.3.16   End-bearing pile

A pile where the major component of the resistance of the pile is contributed by the force developed at the base of the pile.

1.3.17   Footing

A part of a structure in direct contact with and transmitting load to the supporting foundation.

1.3.18   Foundation

The soil, subsoil or rock, whether built-up or natural, upon which a structure is supported.

   NOTE: The term 'foundation' is commonly used to mean both the footing and the ground supporting the footing.

1.3.19   Friction pile

A pile where the major component of the resistance of the pile is contributed by the force developed along the shaft of the pile.

1.3.20 Ground anchor

A tendon anchored into the ground by bond and used to provide a reaction for test loading piles.

1.3.21 Large displacement piles

Preformed or cast in place piles, generally with a solid cross-section dimension of at least 300 mm, installed by driving, screwing, pushing, vibrating or similar methods, which cause a displacement such that significant stresses are induced in the surrounding soils, which may increase the load capacity of the pile and cause displacement of the surrounding soils.

1.3.22 Limit state

Condition for which a system is designed, and beyond which it ceases to fulfil its intended function and becomes unfit for use.

NOTE: There are recognized limit states, e.g., for fire, serviceability, stability and strength.

1.3.23 Pile

A structural member that is driven, screwed, jacked, vibrated, drilled or otherwise installed in the ground so as to transmit loads to the underlying soil or rock and provide a foundation for structure.

1.3.24 Pile group

Number of piles installed in close proximity and usually having a common pile cap.

1.3.25 Pile head

Top of a pile.

1.3.26 Pile heave

Displacement (usually vertical) of a pile caused by the driving, or by external ground movements, of piles in close proximity.

1.3.27 Raking pile

A pile installed at an angle to the vertical.

1.3.28 Serviceability limit state (SLS), serviceability

A limit state beyond which specified service criteria are no longer met, such as unacceptably large displacements, vibrations, cracking, spalling and other local damage.

1.3.29 Set

Permanent penetration of a driven pile or liner per blow of the hammer.

1.3.30 Small displacement piles

Preformed or cast in place piles, generally with a hollow cross-section or a solid cross-section dimension less than 300 mm, installed by driving, screwing, pushing, vibrating or similar methods, which cause a small displacement such that significant stresses or displacements are not induced in the surrounding soils.

1.3.31 Standard penetration test (SPT)

A test in accordance with AS 1289.6.3.1, to determine the penetration resistance of a soil.

1.3.32 Steel screw piles

Preformed small displacement piles installed by rotating a steel pipe, which has one or more spiral flights (helices) welded to it.

1.3.33 Temporary compression

The temporary pile-head deflection during a hammer blow, comprising elastic deflection of the pile cushion, the pile and the soil.

1.3.34 Test pile

Pile subjected to a loading test with the primary purpose of establishing the load deformation characteristics, and/or the ultimate structural strength of the pile, and/or the ultimate geotechnical strength of the pile/soil system.

1.3.35 Test ultimate geotechnical strength ($R_{t,ug}$)

An estimate of the ultimate geotechnical strength assessed from a load test carried out in accordance with Section 8 of this Standard.

1.3.36 Toe

The base of the pile.

1.3.37 Ultimate geotechnical strength (R_{ug})

The resistance developed by an axially or laterally loaded pile or pile group at which static equilibrium is lost or at which the supporting ground fails.

1.4 NOTATION

The symbols used in this Standard are listed below. Unless a contrary indication appears elsewhere, the symbols used in this Standard shall be as defined below. The notations in Clause 3.3, relating to load and combinations in AS 1170.4, have not been incorporated in this table.

TABLE 1.1

NOTATION

Symbol	Term	Text reference
A_b	Plan area of pile base	Clauses 4.4.1, 4.4.2
A_b'	Net area of pile base resisting uplift, i.e., the difference between cross-sectional areas of the pile base and the pile shaft	Clause 4.4.2
A_g	Area of the pile cross-section	Clause 5.3.3(b)
ARR	Average risk rating for overall design	Clause 4.3.2, Table 4.3.2 (C)
A_s	Surface area of pile in intimate contact with soil	Clauses 4.4.1, 4.4.2
A_{sc}	Cross-sectional area of compression reinforcement	Clause 5.3.3(b)
c	Pile wave speed	Paragraph C2.2, Appendix C
d	Pile diameter	Clause 5.6.3.2, Table 8.4.3.1
d_b	Diameter of longitudinal steel	Clause 5.3.7
d_t	Pile base (toe) diameter	Tables 8.4.3.1, 8.5.2
D_d	Dowel diameter	Clause 5.6.3.2
D	Overall minimum width of pile in plane of bending	Clause 5.2.2(b)
E	Average Young's modulus of pile	Tables 8.4.3.1, 8.5.2

(*continued*)

TABLE 1.1 (*continued*)

Symbol	Term	Text reference
E_d	Design action effect	Clauses 1.3.6, 3.2.2(b), 5.4.2.3, 3.2.2(d), 4.3.1, 5.2.1, 8.3.3.4, Paragraph B8, Appendix B, Tables 8.3.3.2, 8.3.3.4 and E1, Appendix E
E_{ds}	Design serviceability load	Clauses 1.3.9, 4.6.3(a), Paragraph B8, Appendix B, Tables 8.3.3.2, 8.3.3.3, 8.4.3.1, 8.5.2 and E1, Appendix E
F_{eh}	Bending moments, shear forces and axial actions induced by heave due to unloading of ground due to excavation	Clauses 3.3.1.2(d), 3.3.2(b)
F_{em}	Bending moments, shear forces and axial actions induced by lateral ground movements	Clauses 3.3.1.2(c), 3.3.2(b)
F_{es}	Compressive and tensile actions in the pile induced by vertical ground movements	Clauses 3.3.1.2(b), 3.3.2(b)
F_{nf}	Actions due to negative friction	Clauses 3.3.1.2(a), 3.3.2(b), 4.6.3, Tables 8.3.3.3, 8.4.3.1 and E1, Appendix E
f_b	Ultimate base pressure for compression pile	Clause 4.4.1
f_{bt}	Ultimate base pressure for uplift pile	Clause 4.4.2
f'_c	Characteristic concrete strength	Table 6.4.3
f'_{cm}	Characteristic strength of concrete at relevant age	Clause 7.3.3.1(a), Table 7.3.3.1
$f_{m,s}$	Average skin friction for condition of full mobilization—Compression pile	Clause 4.4.1
$f_{m,st}$	Average skin friction for condition of full mobilization—Tension pile	Clause 4.4.2
f_{sy}	Yield stress for reinforcement in concrete piles	Clauses 7.3.3.1(b), 7.3.2.
g	Acceleration due to gravity (9.8 m/s^2)	Paragraph C5.4, Appendix C
h	Depth to cut-off	Clause 7.2.1(b)
IRR	Individual risk rating for risk factor	Clause 4.3.2, Tables 4.3.2(A), 4.3.2(B)
k	Concrete placement factor	Clause 5.2.1, 5.3.2, 5.3.6
K	Testing benefit factor	Clause 4.3.1
l_1	Minimum edge distance to head of pile	Clause 5.6.3.2
L_{nf}	Length of the test pile in contact with ground expected to undergo long-term settlement	Tables 8.4.3.1, 8.5.2
L	Pile length	Tables 8.4.3.1, 8.5.2, Paragraph C2.3, Appendix C
M_d	Design bending moment	Clause 5.2.2
N_d	Design axial load	Clause 5.2.2(b)
p	Percentage of total piles tested that meet the specified acceptance criteria	Clause 4.3.1

(*continued*)

TABLE   1.1   *(continued)*

Symbol	Term	Text reference
P_g	Maximum test load for assessment of geotechnical ultimate limit state $R_{t,ug}$	Clauses 8.3.3.1, 8.3.3.2, 8.3.3.4, 8.5.2, Paragraph A3.1, Appendix A, Paragraph B1, Appendix B, Tables 8.4.3.1, 8.5.2, A1, A2, Appendix A
p_o	Total overburden pressure at base level	Clause 4.4.1
P_{max}	Pile jacking installation force	Clause 7.3.4.1
P_s	Maximum test load for assessment of pile performance at serviceability limit state $= E_{ds}$	Clauses 8.3.3.1, 8.3.3.2, Paragraph B1, Appendix B, Tables 8.3.3.2, 8.3.3.3, 8.4.3.1, 8.5.2, A1, A2, A3, Appendix A, B1, Appendix B
P_u	Maximum test load for assessment of design geotechnical ultimate limit state	Clauses 8.3.3.1, 8.3.3.2, Paragraph A3.1, Appendix A and Paragraph B1, Appendix B Tables 8.3.3.2, 8.3.3.3, 8.4.2, 8.4.3.1, A1, Appendix A
$R_{d,g}$	Design geotechnical strength of pile	Clauses 1.3.7, 3.2.2(c), 3.2.2(d), 4.3.1, Table E1, Appendix E
$R_{d,s}$	Design structural strength of pile	Clauses 1.3.10, 3.2.2(c), 3.2.2(d), 5.2.1, 5.4.2.3, Table E1, Appendix E
$R_{t,ug}$	Ultimate geotechnical strength of a pile as assessed from a load test carried out in accordance with Section 8 of this Code	Clauses 1.3.35, 8.4.2.2, 8.4.3.5, Tables 8.3.3.2, 8.3.3.3, E1, Appendix E
R_{ug}	Ultimate geotechnical strength of pile. This is estimated either by calculation ($R_{d,ug}$) or by test ($R_{t,ug}$)	Clauses 1.3.37, 7.3.4.1, Tables 8.3.3.2, 8.4.2, E1, Appendix E
R_{us}	Ultimate structural strength of pile	Clauses 5.2.1, 5.3.1, 5.3.2, Table E1, Appendix E
$R_{d,ug}$	Design ultimate geotechnical strength of pile (ultimate load capacity)	Clauses 1.3.7, 1.3.11, 4.3.1, 4.3.3, 4.4.2, 4.4.4, 8.2.4, Table E1, Appendix E
$R_{d,g,c}$	Design ultimate geotechnical strength of combined pile and raft foundation	Clause 4.4.4, Table E1, Appendix E
$R_{d,us}$	Design ultimate structural strength of pile	Clause 1.3.10, 1.3.12,
$R_{d,ug,s}$	Design ultimate geotechnical strength of shallow or raft footing, for the net area in contact with the supporting ground	Clause 4.4.4, Table E1, Appendix E
$R_{d,ug,sz}$	Design ultimate geotechnical strength of pile in stable zone, i.e., the soil strata not subject to externally imposed ground settlements	Clause 4.6.3, Table E1, Appendix E
S_u	Ultimate value of various actions appropriate for particular combinations	Clause 3.3.2(b)
W	Weight of pile	Clauses 4.4.1, 4.4.2
w_i	Weighting factor for individual risk ratings	Clause 4.3.2, Tables 4.3.2(A)
γ_p	Coefficient of jacked pressure	Clause 7.3.4.1

(continued)

TABLE 1.1 *(continued)*

Symbol	Term	Text reference
δ	Pile movements	Clause 3.2.3
ϕ_g	Geotechnical strength reduction factor for single piles or pile groups	Clauses 4.3.1, 4.4.4, 4.6.3, 8.3.3.4, Paragraph B8, Appendix B, Table 8.3.3.2
ϕ_{gb}	Basic geotechnical strength reduction factor given in Clause 4.3.2	Clauses 4.3.1, 4.3.2
ϕ_{gs}	Geotechnical strength reduction factor for the shallow or raft footing	Clause 4.4.4
ϕ_s	Structural strength reduction factor for single piles or pile groups	Clauses 1.3.10, 5.2.1, 5.3.1, 5.3.4, 5.3.5, 5.4.2.3
ϕ_{tf}	Intrinsic test factor	Clause 4.3.1

1.5 CLASSIFICATION OF PILES

1.5.1 General

The classification of pile types used in this Standard is illustrated in Figure 1.5. Pile types are broadly classified into 'displacement' and 'non-displacement' piles and further subdivided on the basis of the method of pile installation and formation.

1.5.2 Displacement piles

Displacement piles are defined as those that displace the ground through which they are being installed. To operate as a displacement pile, the displaced volume shall approximate the pile volume.

Displacement piles may be installed by hammering, pushing, screwing, vibrating or other means to force them into the ground.

Displacement piles may be one of the following:

(a) *Preformed* Solid and hollow sections that are installed in the ground and left in position. Such piles may be extended by splicing on additional lengths of piling. Preformed piles may be fabricated from—

    (i) concrete, reinforced or prestressed;

    (ii) steel—H Section, tube and other sections;

    (iii) timber; or

    (iv) a combination of concrete, steel or timber sections.

(b) *Driven cast in place* Pile formed in situ by driving a tubular liner to form a void, which is then wholly or partially filled with concrete or grout. The liner may be either—

    (i) *permanent*—made of concrete or steel with open or closed ends of constant or tapered section; or

    (ii) *temporary*—steel tube extracted during concreting or grouting, with or without an expanded base.

(c) *Screwed cast in place* Piles formed in situ by screwing a threaded tube into the ground with concrete placement as the screw head is withdrawn.

1.5.3 Non-displacement piles

1.5.3.1 *General*

Piles formed in situ by removing soil, using either rotary drilling, percussion, reverse circulation, grabbing, chiselling and mechanical or hand excavation methods, to form a void, which is then filled with concrete or grout. During removal of the soil, the sides of the excavated void may or may not be supported.

1.5.3.2 *Supported*

The support may be either—

(a) *permanent*—using steel, concrete or other liners; or

(b) *temporary*—using—

(i) steel, concrete or other liners or timber shoring;

(ii) drilling fluids; or

(iii) continuous flight augers.

1.5.3.3 *Unsupported*

Piles in which the ground is left exposed during excavation.

1.5.4 Partial displacement, post-grouted and preloaded non-displacement piles

Various techniques, such as partial displacement augers, post-grouting of the shaft or base and preloading the base of non-displacement piles, are used to improve the performance of non-displacement piles.
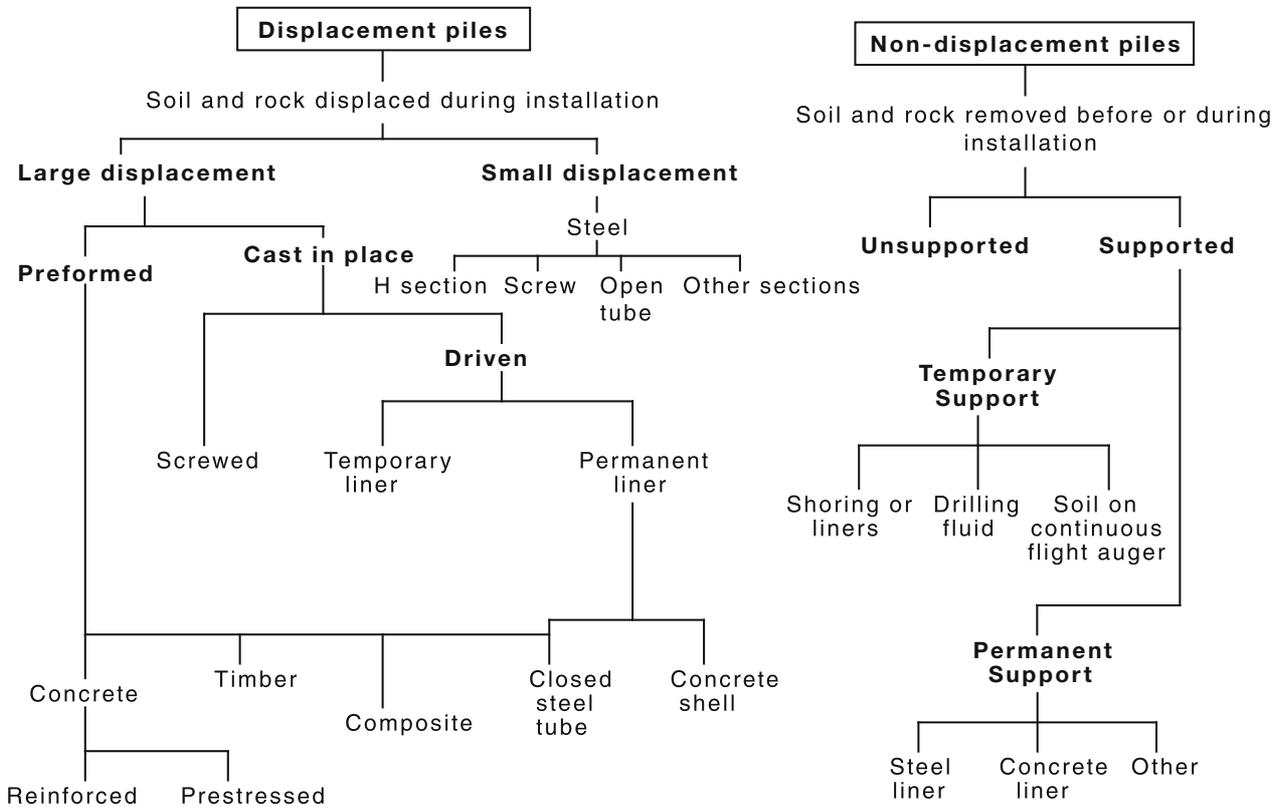

FIGURE 1.5 CLASSIFICATION OF PILE TYPES

SECTION 2   SITE INVESTIGATION

2.1 GENERAL

For any site on which it is proposed to install piles, site investigation shall be carried out to provide sufficient information to fulfil the requirements of Clause 2.2. When planning the site investigation, existing relevant information shall be taken into account.

NOTE: The intention of this Section is to ensure that adequate information is available for design and construction.

2.2 INFORMATION REQUIRED

Appropriate site investigations shall provide information on geotechnical conditions according to AS 1726, as follows:

(a)   The geotechnical design of piles.

(b)   Assessment of geotechnical conditions for pile construction or installation.

(c)   Some additional site-specific aspects, including—

(i)   potential for ground heave—damage to adjacent structures or neighbouring piles;

(ii)   vibration effects—potential for damage to adjacent structures;

(iii) expansive soil problems;

(iv)   potential difficulties with pile cap construction;

(v)   groundwater conditions;

(vi)   negative friction effects;

(vii) near-surface conditions or lateral load design, if relevant;

(viii) possible obstructions to installation, e.g., boulders or old footings or piles;

(ix)   potential for slope instability;

(x)   effects of excavation or scour;

(xi)   effects of contaminated sites;

(xii) an assessment of the site surface for the provision of a safe work platform for piling equipment;

(xiii) potential for acid sulfate soils; and

(xiv) potential for weak or compressible layers, or caverns below the pile base, including soils below lava flows.

(d)   Assessment of the potential effects of site conditions on pile durability.

NOTE: The site investigation should obtain information on all materials that might influence the strength and serviceability performance of the structure. Due account should be taken of the range of foundation options that might apply. This should include testing of the soil and groundwater for aggressive agents, including sulphate, chloride and pH, to ensure appropriate exposure classification in regard to durability.

SECTION 3   DESIGN REQUIREMENTS AND PROCEDURES

3.1 OBJECTIVE OF PILE DESIGN

The objective of pile design is to provide a footing that will safely support the superstructure over its design life.

3.2 GENERAL DESIGN REQUIREMENTS

3.2.1 General

The footing shall be durable, and of adequate strength, and the footing performance shall be compatible with the superstructure so that it remains serviceable and can perform its intended function.

The design shall take into account, as appropriate, the following:

(a) *Ultimate strength*   The limit state at which static equilibrium is lost or at which there is a failure of the supporting ground or structural elements. To be of adequate ultimate strength, the probability of structural or geotechnical failure of the piles shall be acceptably low throughout the intended design life of the structure. The ultimate strength of piles shall be checked for both structural and geotechnical adequacy.

(b) *Serviceability*   The limit state at which deformation of the piles will cause damage or loss of serviceability in the structure.

(c) *Durability*   The piles shall be able to withstand the expected wear and deterioration throughout the intended design life of the structure.

(d) *Other*   Other relevant design requirements.

The relevant action effects for ultimate and serviceability limit states and deflection limits to be used in the design of the piles shall be determined from the analysis of the supported structure.

> NOTE: Where foundations are being designed separately to the supported structure, the values of ultimate and serviceability loads, and deflection and differential deflection limits, should be indicated on the drawings, or otherwise provided in order to facilitate the design.

3.2.2 Design for ultimate strength

Single piles, pile groups and individual piles within a pile group shall be designed for both structural and geotechnical strength as follows:

(a) The design load for strength shall be determined from Clause 3.3.2 using the appropriate loads and other actions listed in Clause 3.3.1.

(b) In the design of a single pile or pile group, the various factored design loads and other actions (including the effects of eccentricities due to construction tolerances) shall be applied to that single pile or pile group, and the design action effect (E_d) determined for each pile or pile group for each load case.

(c) The design geotechnical strength ($R_{d,g}$) and the design structural strength ($R_{d,s}$) shall be determined in accordance with the requirements of Sections 4 and 5, as appropriate.

(d) The pile or pile group shall be proportioned so that the design geotechnical strength and the design structural strength are not less than the design action effect, that is—

$$R_{d,g} \geq E_d; \text{ and} \qquad \qquad \ldots 3.2.2(1)$$

$$R_{d,s} \geq E_d \qquad \qquad \ldots 3.2.2(2)$$

In addition to the design of each pile in a group, the geotechnical strength of the group as a single unit shall be analysed for failure under the design action effect for the pile group.

The geotechnical design strength of the group shall comply with the provisions of Clauses 4.4.3 and 4.4.5. It is permissible to allow for the sharing of a load between piles and pile caps, or for the sharing of a load among piles, provided an analysis demonstrates that the complete pile system operates within the general principles of this Standard even though individual piles may not.

3.2.3 Design for serviceability

Single piles and pile groups shall be designed for serviceability by controlling or limiting pile movements (δ) including differential and total settlements, horizontal displacement and rotation.

Under the serviceability loadings resulting from the load combinations for serviceability design determined from Clause 3.3.3, pile movements shall be limited to ensure that the foundations and the structure remain serviceable throughout their design lives in accordance with the requirements of Section 4.

3.2.4 Design for durability

Piles shall be designed for durability in accordance with Section 6.

3.2.5 Design for other relevant requirements

Any special design criteria, such as stability, scour, fatigue, cyclic loading or seismic actions, shall be considered. Where relevant, these shall be taken into account in the design of the piles in accordance with the principles of this Standard and other appropriate engineering principles.

3.3 ACTIONS AND COMBINATIONS FOR STRENGTH AND SERVICEABILITY DESIGN

3.3.1 Actions and loads

3.3.1.1 *General*

The design of a pile for ultimate strength and serviceability limit states shall take account of appropriate action effects arising from the following:

(a)   All actions specified in AS/NZS 1170.0 and other relevant actions.

(b)   Permanent actions of pile and pile cap.

(c)   Ground movement, including negative friction, expansive soils, and vertical and lateral earth movements that may arise from various sources.

(d)   Handling.

(e)   Installation.

(f)   Any other additional loads and actions that may be applied, e.g., impact, dynamic loading, water pressures and scour.

3.3.1.2 *Ground movement*

Allowance shall be made for actions induced by ground movements, as follows:

(a)   Where a pile is situated in ground undergoing settlement, allowance shall be made for actions (F_{nf}) due to negative friction acting on the pile.

(b)   Where a pile is situated in swelling soils, such as reactive clays or those subjected to frost action, allowance shall be made for the compressive and tensile actions (F_{es}) that may be developed in the pile.

(c)   Where a pile is subjected to lateral ground movements, allowance shall be made for bending moments, shear forces and axial actions (F_{em}) induced by such movements. These bending moments, shear forces and axial actions shall be determined using an appropriate soil-structure analysis.

(d)   Where a pile is subjected to heave due to unloading of the ground via excavation, allowance shall be made for bending moments, shear forces and axial actions (F_{eh}) induced by such movements.

NOTE: When using raking piles, vertical ground movements may also cause bending moments and/or shear forces in the pile together with axial actions. Caution should be exercised in such cases.

(e)   Where displacement piles are installed at relatively close spacings, consideration shall be given to vertical and lateral displacements, compression and tensile actions, and bending moments induced in piles that have already been installed. If assessed to be necessary, measures shall be taken to mitigate the above effects.

3.3.1.3   *Handling*

Stresses induced in a pile by handling during manufacture, transport and on site, as appropriate, shall be determined by taking account of the number and location of lifting points, the mass of the pile and the length of the pile.

The calculated stresses in a pile due to handling shall be multiplied by an appropriate load factor to allow for impact. The minimum load factor for handling shall be 1.5.

The maximum stresses imposed by handling shall not exceed the values given in Clause 7.3.2.

3.3.1.4   *Installation*

For driven piles, allowance shall be made for the stresses induced during installation.

Compressive and tensile driving stresses may be obtained from a wave-equation analysis or directly measured during pile driving, using dynamic pile testing equipment.

The maximum stresses imposed by driving shall not exceed the values given in Clause 7.3.3.

3.3.2   Load combinations for strength design

The load combinations for strength design shall be as follows:

(a)   The design actions for ultimate strength design of piles shall be the combination of factored loads that produces the most adverse effect on the pile in accordance with AS/NZS 1170.0.

(b)   Where there are actions induced by ground movement (see Clause 3.3.1.2), they shall be computed as follows:

(i)   *For structural design*   (see Section 5)

(A) $S_u = 1.2\ F_{nf}$ negative friction actions

(B) $S_u = 1.5\ F_{es}$ compressive and tensile actions

(C) $S_u = 1.5\ F_{em}$ bending moments, shear forces and axial actions

(D) $S_u = 1.5\ F_{eh}$ bending moments, shear forces and axial actions

(ii)   *For geotechnical design* (see Section 4)   Loads induced by soil movements shall not be taken into account.

NOTE: The negative friction action (F_{nf}) should be determined with due conservatism, particularly where possible set up and/or time-dependent strain softening are not accounted for explicitly.

(c)   Where other additional actions are to be applied and no load factor is given in AS/NZS 1170.0 for these actions, a load factor of 1.5 shall be assigned.

3.3.3   Load combinations for serviceability design

The design actions for serviceability design of piles shall be taken from the appropriate combinations of actions for short-term situations and long-term situations in accordance with this Clause with the actions as given in AS/NZS 1170.0 and including unfactored actions due to any of the ground movements referred to in Clause 3.3.1.2, as appropriate.

Unless otherwise specified, earthquake serviceability actions need not be taken into account.

SECTION 4   GEOTECHNICAL DESIGN

4.1 GENERAL

The geotechnical design of a pile or pile group involves consideration of both strength and serviceability. The design shall take into account pile-soil interaction.

4.2 ASSESSMENT OF GEOTECHNICAL PARAMETERS

Values of the soil and rock parameters used in design shall be selected, based on the following considerations:

(a)   Geological, hydrogeological and geotechnical background information.

(b)   The possible modes of failure.

(c)   Results of laboratory and field measurements, taking into account the accuracy of the test method used.

(d)   A careful assessment of the range of values that might be encountered.

(e)   The ranges of in situ and imposed stresses likely to be encountered.

(f)   The potential variability of the parameter values.

(g)   The extent of the zone of influence governing the soil behaviour, for the limit state being considered.

(h)   The influence of workmanship on artificially placed or improved soils.

(i)   The effects of construction activities on the properties of the in situ soil.

(j)   Changes in site conditions, such as excavation, filling or groundwater fluctuation.

(k)   The sensitivity of the calculated result to the relevant parameter.

NOTES:

1   In general, the value of a geotechnical parameter should be a conservatively assessed value of that parameter. Engineering judgement needs to be exercised in making such an assessment, with geotechnical engineering advice being obtained as required.

2   Many soil parameters are not constants, but depend on factors such as the level of stress or strain, the mode of deformation, drainage conditions, and time.

3   It should be recognized that a low value of a geotechnical parameter is not always necessarily a conservative value. For example, in cases involving pile driveability, dynamic earthquake loads or negative skin friction and other loads due to ground movements, conservatism may require the selection of a high value of a particular parameter.

4   Bending moments in buried structures are sensitive to the relative stiffness of the structure and the surrounding soil. The design should consider variation in the stiffness parameters of both the soil and the structure.

5   Except where specifically noted, the term soil includes soil and rock. In many cases, weak weathered rock can be analysed as for soil; however, special techniques may be required for the analysis of strong rock.

4.3 GENERAL PRINCIPLES OF GEOTECHNICAL STRENGTH DESIGN

4.3.1 Design geotechnical strength

A pile shall be proportioned such that the design geotechnical strength ($R_{d,g}$) is not less than the design action effect ($E_{d)}$) as detailed in Clause 3.2.2, that is—

$$R_{d,g} \geq E_d \qquad \qquad \text{. . . 4.3.1(1)}$$

The design geotechnical strength ($R_{d,g}$) shall be calculated as the design ultimate geotechnical strength ($R_{d,ug}$) multiplied by a geotechnical strength reduction factor (ϕ_g), according to the following equation:

$$R_{d,g} = \phi_g \, R_{d,ug} \qquad \qquad \text{. . . 4.3.1(2)}$$

The geotechnical strength reduction factor (ϕ_g) shall be determined as follows:

$$\phi_g = \phi_{gb} + (\phi_{tf} - \phi_{gb})K \geq \phi_{gb}$$

where

ϕ_{gb} = basic geotechnical strength reduction factor as given in Clause 4.3.2

ϕ_{tf} = intrinsic test factor

= 0.9, for static load testing (see Section 8)

= 0.75, for rapid load testing (see Section 8)

= 0.8, for dynamic load testing of preformed piles (see Section 8)

= 0.75, for dynamic load testing of other than preformed piles (see Section 8)

= 0.85, for bi-directional load testing (see Section 8)

= ϕ_{gb}, for no testing

K = testing benefit factor

= $1.33p/(p + 3.3) \leq 1$, for static or rapid load testing

= $1.13p/(p + 3.3) \leq 1$, for dynamic load testing

p = percentage of the total piles that are tested and meet the specified acceptance criteria

Where one or more piles tested fail to meet the specified acceptance criteria, the procedure set out in Clause 8.3.4 shall be followed.

NOTES:

1   The geotechnical strength reduction factor for dynamic load testing relates to high-strain dynamic pile testing systems that involve direct measurement of strain and acceleration at the pile head, and a signal matching process involving simulation of the measured upward travelling stress wave. Alternative dynamic testing systems may be used, but in such cases a geotechnical strength reduction factor should be adopted based on a demonstration of the uncertainties of those systems relative to the high-strain dynamic testing systems described. In no case shall the geotechnical strength reduction factor adopted be higher than the stipulated value for high strain dynamic testing.

2   Where there is a satisfactory correlation between static and dynamic tests, ϕ_{tf} may be increased by 0.05.

4.3.2   Assessment of basic geotechnical strength reduction factor (ϕ_{gb})

The basic geotechnical strength reduction factor (ϕ_{gb}) shall be calculated using a risk assessment procedure as set out below:

(a)   Rate each risk factor in Table 4.3.2(A) on a scale from 1 to 5 for the nature of the site, the available site information and the pile design and installation procedures adopted. This will produce an individual risk rating (IRR) according to the assessed level of risk, as set out in Table 4.3.2(B)

(b)   Determine the overall design average risk rating (ARR) using the weighted average of the product of all of the risk weighting factors (w_i) shown in column 2 of Table 4.3.2(A) times the relevant individual risk rating (IRR), as follows:

$$ARR = \Sigma(w_i \mathrm{IRR}_i)/\Sigma w_i \qquad\qquad \ldots 4.3.2$$

(c)   Determine the basic geotechnical strength reduction factor (ϕ_{gb}) from Table 4.3.2(C) depending on the level of redundancy in the piling system. Systems with a high degree of redundancy would include large pile groups under large caps, piled rafts and pile groups with more than 4 piles. Systems with a low level of redundancy would include isolated heavily loaded piles and piles set out at large spacings.

TABLE   4.3.2(A)

WEIGHTING FACTORS AND INDIVIDUAL RISK RATINGS FOR RISK FACTORS

Risk factor	Weighting factor (w_i)	Typical description of risk circumstances for individual risk rating (IRR)		
		1 (Very low risk)	3 (Moderate)	5 (Very high risk)
Site				
Geological complexity of site	2	Horizontal strata, well-defined soil and rock characteristics	Some variability over site, but without abrupt changes in stratigraphy	Highly variable profile or presence of karstic features or steeply dipping rock levels or faults present on site, or combinations of these
Extent of ground investigation	2	Extensive drilling investigation covering whole site to an adequate depth	Some boreholes extending at least 5 pile diameters below the base of the proposed pile foundation level	Very limited investigation with few shallow boreholes
Amount and quality of geotechnical data	2	Detailed information on strength compressibility of the main strata	CPT probes over full depth of proposed piles or boreholes confirming rock as proposed founding level for piles	Limited amount of simple in situ testing (e.g., SPT) or index tests only
Design				
Experience with similar foundations in similar geological conditions	1	Extensive	Limited	None

(*continued*)

TABLE 4.3.2(A) (*continued*)

Risk factor	Weighting factor (w_i)	Typical description of risk circumstances for individual risk rating (IRR)		
		1 (Very low risk)	3 (Moderate)	5 (Very high risk)
Method of assessment of geotechnical parameters for design	2	Based on appropriate laboratory or in situ tests or relevant existing pile load test data	Based on site-specific correlations or on conventional laboratory or in situ testing	Based on non-site-specific correlations with (for example) SPT data
Design method adopted	1	Well-established and soundly based method or methods	Simplified methods with well-established basis	Simple empirical methods or sophisticated methods that are not well established
Method of utilizing results of in situ test data and installation data	2	Design values based on minimum measured values on piles loaded to failure	Design methods based on average values	Design values based on maximum measured values on test piles loaded up only to working load, or indirect measurements used during installation, and not calibrated to static loading tests
Installation				
Level of construction control	2	Detailed with professional geotechnical supervision, construction processes that are well established and relatively straightforward	Limited degree of professional geotechnical involvement in supervision, conventional construction procedures	Very limited or no involvement by designer, construction processes that are not well established or complex
Level of performance monitoring of the supported structure during and after construction	0.5	Detailed measurements of movements and pile loads	Correlation of installed parameters with on-site static load tests carried out in accordance with this Standard	No monitoring

NOTE: The pile design shall include the risk circumstances for each individual risk category and consideration of all of the relevant site and construction factors.

TABLE 4.3.2(B)

INDIVIDUAL RISK RATING (IRR)

Risk level	Individual risk rating (IRR)
Very low	1
Low	2
Moderate	3
High	4
Very high	5

TABLE   4.3.2(C)

**BASIC GEOTECHNICAL STRENGTH REDUCTION FACTOR (ϕ_{gb})
FOR AVERAGE RISK RATING**

Range of average risk rating (ARR)	Overall risk category	ϕ_{gb} for low redundancy systems	ϕ_{gb} for high redundancy systems
ARR ≤1.5	Very low	0.67	0.76
1.5 < ARR ≤2.0	Very low to low	0.61	0.70
2.0 < ARR ≤2.5	Low	0.56	0.64
2.5 < ARR ≤3.0	Low to moderate	0.52	0.60
3.0 < ARR ≤3.5	Moderate	0.48	0.56
3.5 < ARR ≤4.0	Moderate to high	0.45	0.53
4.0 < ARR ≤4.5	High	0.42	0.50
>4.5	Very high	0.40	0.47

4.3.3   Assessment of design ultimate geotechnical strength ($R_{d,ug}$)

The design ultimate geotechnical strength of a pile ($R_{d,ug}$) shall be assessed by one or more of the following procedures:

(a)   Analysis using data from a site investigation.

(b)   Analysis based on dynamic data obtained during installation of test or working piles, via—

   (i)   a pile driving formula;

   (ii)   a wave equation analysis based on measured blow counts;

   (iii)   a closed form dynamic solution based on measured dynamic force and velocity data; or

   (iv)   analysis based on stress-wave matching of dynamic test data.

(c)   Analysis using data collected during pile installation.

(d)   Analysis using data from a static, rapid or bi-directional load test.

   NOTE: Procedures (b) and (c) above are generally applicable for the design ultimate geotechnical strength for axial loading only.

For proprietary piling systems that use indirect correlations with measured pile installation parameters to estimate the ultimate strength of a pile, such correlations shall be supported by appropriate data obtained from static load tests carried out at the site or in-ground conditions that can be demonstrated to be similar to those at the site, in accordance with Section 8.

$R_{d,ug}$ shall be computed as set out in Clauses 4.4.1 to 4.4.7. Consideration shall also be given to the factors in Clauses 4.4.8 to 4.4.10.

4.4   DESIGN REQUIREMENTS FOR STRENGTH

4.4.1   Design ultimate geotechnical strength in compression

The design ultimate geotechnical strength of a pile ($R_{d,ug}$) loaded in compression shall be determined as follows:

$$R_{d,ug} = f_{m,s}A_s + (f_b + p_o)A_b - W \qquad \qquad \text{. . . 4.4.1(1)}$$

   NOTE: It is often sufficiently accurate to assume that $W = A_b p_o$ so that Equation 4.4.1(1) becomes—

$$R_{d,ug} = f_{m,s}A_s + f_b A_b \qquad \qquad \text{. . . 4.4.1(2)}$$

In the determination of A_s, in the absence of other data, the surface area from ground surface level to 1.5 pile diameters shall be assumed to be ineffective. For a pile that is to be subjected to cyclic lateral loading, due allowance shall be made in the determination of A_s for the separation that may occur between the pile and the surrounding ground in the vicinity of the ground surface.

In computing A_b, consideration shall be given to the type of pile and the possibility that only a part of the gross cross-sectional area may be effective in providing end-bearing resistance.

In computing both A_s and A_b for steel and concrete screw piles, and for steel tube and H-piles, consideration shall be given to alternative modes of failure of both the shaft and the base.

In assessing $f_{m,s}$ and f_b, consideration shall be given to the pile type, the method of installation, the soil type and other factors which may influence $f_{m,s}$ and f_b, such as the installed condition of the pile shaft and base.

Where a pile is founded on a stratum that overlies a softer or weaker stratum, allowance shall be made for the possible reduction of f_b due to the presence of the softer or weaker stratum.

The possibility of buckling of a pile subjected to compressive loading shall be given consideration when determining the ultimate structural strength as set out in Section 5.

4.4.2 Design ultimate geotechnical strength in uplift

The design ultimate geotechnical strength ($R_{d,ug}$) of a pile loaded in sustained uplift shall be determined as follows:

(a)   For a pile without an enlarged base in soil:

$$R_{d,ug} = f_{m,st} A_s + W \qquad \qquad \text{. . . 4.4.2(1)}$$

(b)   For a pile with an enlarged base in soil, the lesser of—

$$R_{d,ug} = f_{bt} A_b + W \text{ ; and} \qquad \qquad \text{. . . 4.4.2(2)}$$

$$R_{d,ug} = f_{bt} A_b' + f_{m,st} A_s + W \qquad \qquad \text{. . . 4.4.2(3)}$$

In assessing $f_{m,st}$ and f_{bt}, consideration shall be given to the pile type, the method of installation, the soil type, and other factors that may influence $f_{m,st}$ and f_{bt}.

For piles subjected to transient uplift loading, Equations 4.4.1(2) and 4.4.2(3) may be used with an appropriate value of f_{bt}, provided the pile base is embedded in a material of low permeability such that a base suction can develop and be maintained during the duration of the loading.

For a pile in rock or fissured clay, consideration shall be given to the provisions of Items (a) and (b) above, and also to the possibility of failure occurring by pullout of a cone of rock or fissured clay attached to the pile.

NOTES:

1   In uplift, the load displacement behaviour is typically more brittle than in compression.

2   The cone pullout mode of failure may be critical for shallow piles socketed into rock or fissured clay.

3   For piles in sand, very stiff to hard clay or rock, $f_{m,st}$ is often less than $f_{m,s}$ because of the Poisson and other effects.

4   For tapered piles, the effect of the taper in further reducing shaft resistance should be considered.

5    $R_{d,ug}$ should be computed for both short-term and long-term conditions and the lesser value adopted.

6   In assessing shaft friction in uplift ($f_{m,st}$) from dynamic load testing of open-ended steel piles with an internal soil plug, allowance should be made for the proportion of measured shaft resistance that results from internal friction between the pile and the soil plug. In the absence of other information, the shaft resistance over the length of the soil plug should be taken as 0.8 times the measured shaft resistance over that length.

4.4.3 Design ultimate geotechnical strength of a pile group in compression or uplift

4.4.3.1 *General*

In determining the design ultimate geotechnical strength of a group of piles in compression or uplift, account shall be taken of the effects of group action. In the absence of an alternative method, the design ultimate geotechnical strength shall be taken as the lesser of—

(a)   the sum of the design ultimate geotechnical strength of the individual piles in the group; and

(b)   the design ultimate geotechnical strength of a block containing the piles and the soil between them.

Consideration shall be given to pile type, the method of installation, the soil type, layering of the geotechnical profile, interaction between the piles and the effects of any eccentric and horizontal loadings.

NOTES:

1   Eccentric loading is unlikely to adversely affect the ultimate geotechnical strength of a group unless the load eccentricity exceeds about one-quarter of the group width in the direction of the eccentricity.

2   The presence of soft or loose layers of soil below the pile toe may have a more significant effect on the ultimate geotechnical strength of a block than on the ultimate geotechnical strength of a single pile.

3   Generally, a spacing of less than 2.5 diameters for friction piles is not recommended unless an analysis of interaction effects indicates that overall pile group performance is not adversely affected. For piles deriving their resistance mainly from end-bearing, the spacing should not be less than twice the base size of the pile, unless interaction effects for those groups have been analysed.

Where a group has a cap cast directly onto a stratum supporting the piles, and this stratum is assessed to be unlikely to settle away from the pile cap, it shall be permissible to make allowance for the additional resistance provided by the cap. In the absence of an alternative method, the design ultimate geotechnical strength of the group shall be taken as the lesser of—

(i)   the sum of the design ultimate geotechnical strengths of the individual piles in the group, plus the design ultimate geotechnical strengths of the net area of the pile cap (gross area less the area occupied by the piles); and

(ii)   the design ultimate geotechnical strength of the block containing the piles and the soil between them, plus the design ultimate geotechnical strength of the area of the cap outside the perimeter of this block.

4.4.3.2 *End-bearing piles*

For a group of end-bearing piles on rock, or on dense sand or gravel with equally strong material beneath, where there is an absence of alternative methods of calculation, the design ultimate geotechnical strength of the group for compressive axial loading shall be taken as the sum of the design ultimate geotechnical strengths of the individual piles in the group.

4.4.3.3 *Soft material at depth*

Where a pile group is founded on a stratum that overlies a softer or weaker stratum, allowance shall be made for the possible reduction in ultimate base resistance due to the presence of the softer or weaker underlying stratum.

4.4.4 Combined pile and raft foundation

Piles may be used to provide additional support beneath a raft foundation in order to control total and differential settlements. The design of such a combined foundation shall satisfy—

(a)   the geotechnical strength criterion in Clause 4.3.1; and

(b)   the serviceability criterion in Clause 4.5.

The design ultimate geotechnical strength of the combined pile and raft foundation ($R_{d,ug,c}$) shall be calculated as follows:

$$R_{d,ug,c} = \phi_{gs}R_{d,ug,s} + \phi_{g}R_{d,ug} \qquad \qquad \ldots 4.4.4$$

$R_{d,ug,s}$ shall be computed by means of an appropriate analysis, using the results of suitable field and/or laboratory tests.

The value of ϕ_{gs} shall be selected from the values of ϕ_{g} in Clause 4.3 for static analysis, taking into account the relevant risk factors for the raft only.

The value of $R_{d,ug}$ shall be computed as set out in Clause 4.4.1.

The value of ϕ_{g} shall be chosen as set out in Clause 4.3.

NOTE: Where the stratum beneath the raft is assessed to be likely to settle away from the raft, the settlement required to mobilize $R_{d,ug,s}$ may be very large, and the serviceability criterion may be critical.

4.4.5 Negative friction

Consideration shall be given to whether pile-ground contact friction resistance from settling ground can be relied upon in determining the design ultimate geotechnical resistance for ultimate limit state design.

In the absence of other information, the design ultimate geotechnical strength of the pile in compression or in uplift shall be assumed to be unaffected by negative friction and shall be computed as set out in Clauses 4.4.1 and 4.4.2 for a single pile, Clause 4.4.3 for a pile group, and Clause 4.4.4 for a combined pile raft foundation.

NOTE: The pile-ground contact friction resistance may be reduced for piles with a tapered shaft.

The additional axial forces induced in a pile by negative friction shall be considered in the structural design of the pile.

The settlement of a pile or pile group subjected to negative friction is often the key design consideration and shall be assessed as set out in Clause 4.6.3.

NOTE: Appropriate surface coatings may be applied to the part of the pile shaft in the settling ground zone to reduce negative skin friction.

4.4.6 Soil swelling

In the absence of other information, the design ultimate geotechnical strength of a pile in compression or uplift shall be assumed to be unaffected by swelling of the soil around the pile.

The additional axial forces induced in a pile by soil swelling shall be considered in the structural design of the pile.

The head movement of a pile subjected to soil swelling shall be assessed as set out in Clause 4.6.4.

> NOTE: Where swelling of the soil surrounding a pile is expected to occur after installation and the pile is under uplift loading, the ultimate geotechnical resistance may not be mobilized until large upward movements of the pile head have occurred under applied loading.

4.4.7   Design ultimate geotechnical strength for lateral loading

For a pile subjected to lateral loading, its design ultimate geotechnical strength shall be determined as the lesser of the following two values:

(a)   The design ultimate geotechnical strength for 'short pile' failure, in which the ultimate lateral resistance of the soil surrounding the pile is fully mobilized along the entire length of the pile.

(b)   The design ultimate geotechnical strength for 'long pile' failure, in which the ultimate structural strength of the pile section at some point along the pile shaft is fully mobilized before the ultimate soil resistance along the entire length of the pile.

For a pile group, in the absence of an alternative method, the design ultimate geotechnical strength shall be taken as the lesser of the following values:

(i)   The sum of the design ultimate geotechnical strength of the individual piles in the group.

(ii)   The design ultimate geotechnical strength of a block containing the piles and the soil between them.

Consideration shall be given also to the possibility that the near-surface soil may have reduced lateral resistance because of environmental effects. For a pile that is to be subjected to cyclic lateral loading, consideration shall be given to the possibility that separation may occur between the pile and the surrounding ground in the vicinity of the ground surface.

Consideration shall be given to pile type, the method of installation, the soil type, layering of the geotechnical profile, interaction among the piles and the effects of any eccentric loading.

4.4.8   Cyclic loading

Consideration shall be given to the effects of cyclic loading on the axial and lateral design ultimate geotechnical strengths of both a single pile and a pile group.

Consideration shall be given also to the possibility that the near-surface soil may have a reduced axial and lateral resistance because of environmental effects and that separation may occur between the pile and the surrounding ground in the vicinity of the ground surface.

In particular, appropriate caution shall be exercised in assessing the design ultimate geotechnical strength of both a pile and a pile group subjected to cyclic uplift loading or to 'two-way' cyclic axial loading involving both compressive and uplift loading, or to a loading regime that leads to cyclic reversals in sign of the shear stress over all or part of the pile-soil interface.

4.4.9   Dynamic loading

Consideration shall be given to the effects of dynamic loading on the axial and lateral ultimate geotechnical strengths of a pile.

> NOTE: In some cases, the high rate of dynamic loading may increase the geotechnical strength as compared to the case of static loading.

4.4.10 Earthquake loading

A pile shall be designed for adequate strength, stiffness and ductility under load combinations including earthquake design actions.

Consideration shall be given also to the effects of earthquake loading on the design axial and lateral ultimate geotechnical strengths, and to the induced bending moment in a pile. Both 'inertial' effects, via loads applied to the pile by the supported structure and 'kinematic effects', via ground movements generated by the earthquake acting on the pile, shall be considered. The additional shear forces and bending moments induced in the pile shall be considered in the structural design of the pile.

Consideration shall be given also to the possible effects of loss of soil support during the earthquake, due to liquefaction or partial loss of soil strength.

4.5 GENERAL PRINCIPLES OF GEOTECHNICAL DESIGN FOR SERVICEABILITY

4.5.1 Design actions

The load combinations for serviceability design, as determined from Clause 3.3.3, shall be used for determining pile deflection (settlements, lateral deflections and rotations).

4.5.2 Design criteria

Both a single pile and a pile group shall be designed for serviceability by controlling or limiting pile movements so that deflections do not exceed the deflection limits.

4.5.3 Deflection limits

Limits for the total and differential settlement, lateral deflection and rotation of both a pile and a pile group, subject to axial compression, uplift, lateral, cyclic, dynamic, torsional or other actions, shall be appropriate to the structure and its intended use.

4.5.4 Geotechnical parameters for serviceability limit states

Calculations of settlement, differential settlement, lateral deflection and rotation of both a pile and a pile group shall be carried out using geotechnical parameters that are appropriately selected and to which no reduction factor is applied. In selecting such parameters, account shall be taken of the pile type, the ground conditions, the installed condition of the shaft and base and the directions and types of loading.

4.6 DESIGN REQUIREMENTS FOR SERVICEABILITY

4.6.1 Deflection of a pile

Settlements, lateral deflections and rotations shall be estimated by calculation or assessed from a load test. Account shall be taken of group action, the influence of any underlying compressible layers, variable stiffness of individual strata and any other relevant site-specific conditions.

In assessing the deflection and differential settlement of a structure supported by piles, consideration shall be given to the effects of the stiffness of the structure.

4.6.2 Combined pile and raft footing

Where a footing is designed as a combined pile and raft footing, the settlements and differential settlement of the footing shall be estimated from an analysis in which account is taken of the interaction among the raft, the piles and the soil.

4.6.3 Settlement due to negative friction

Where a pile or group of piles is subjected to negative friction as a result of the settlement of the surrounding ground, the serviceability design shall include the effects of such negative friction in combination with the applied loads.

A non-linear pile-soil interaction analysis is the preferred method of design. Where piles are designed primarily to act as settlement reducers within a pile group or pile raft foundation system, a soil-pile interaction analysis shall be carried out.

For other cases, in the absence of non-linear pile-soil interaction analysis, the procedure shall be as follows:

(a) The following condition shall be satisfied—

$$R_{d,ug,sz}\, \phi_g \geq (E_{ds} + F_{nf}) \qquad \ldots 4.6.3$$

where the design ultimate geotechnical strength for the stable zone ($R_{d,ug,sz}$) shall be assessed by one or more of the procedures in Clause 4.4.1, and ϕ_g shall be assessed using the risk assessment procedure set out in Clause 4.3.

(b) The settlement of a pile or pile group subjected to negative friction shall be approximated as the sum of the following three components:

(i) The compression of the pile shaft due to the design action.

(ii) The compression of the pile shaft due to the computed forces arising from negative friction.

(iii) The settlement of the portion of the pile shaft in the 'stable zone' (that is, the part of the ground profile that does not induce negative friction) under the sum of the design action and the maximum computed force in the pile arising from negative friction (F_{nf}).

NOTES:

1 The stable zone is the section of the ground profile that does not induce negative friction. The top of the stable zone is to be taken as the bottom of the ground undergoing settlement unless determined otherwise by soil-pile interaction analysis.

2 The design requirement in Equation 4.6.3 is to ensure that the length of the pile in the stable zone (see Note 1) has sufficient geotechnical strength to prevent creep movement under the design action effect for long-term serviceability actions (E_{ds}).

3 For piles in a group, the settlement due to negative friction may be considerably less than that of a single isolated pile, especially for interior piles that tend to be 'shielded' by piles nearer the edge of the group. Similarly, the axial force developed by negative friction may be considerably less for the interior piles within a group than for an isolated single pile.

4.6.4 Pile heave due to soil swelling

Where a pile or group of piles is subjected to heave as a result of swelling movements of the surrounding ground, the serviceability design shall include the effects of such swelling movements in combination with the applied loads.

A pile-soil interaction analysis is the preferred method of design. In the absence of such an analysis, the settlement of a pile or pile group subjected to swelling movements shall be approximated as the greater of the following:

(a) The heave of the ground at the 'neutral point' in the ground, that is, the depth at which the shaft friction on the pile changes from positive (upward) to negative (downward).

NOTE: Applied uplift loading tends to raise the 'neutral point' and increase the heave of the pile or pile group.

(b)   The sum of the following three components:

(i)   The extension or compression of the pile shaft due to the design action.

(ii)   The extension of the pile shaft due to the computed forces arising from soil swelling.

(iii)   The upward movement of the portion of the pile shaft in the 'stable' soil (that part of the soil profile not subjected to swelling) under the design action and the maximum computed force in the pile arising from soil swelling.

4.6.5 Deflection due to cyclic, impact, dynamic, earthquake, torsional or other loads

Where a pile or pile group is subjected to cyclic, impact, dynamic, earthquake, torsional or other loads, deflections and rotations shall be estimated by calculation or assessed from an appropriate load test. Due allowance shall be made for the effects of the type and direction of loading on the relevant geotechnical parameters.

Assessment of earthquake risk for sites within Australia shall be made in accordance with AS 1170.4.

SECTION 5   STRUCTURAL DESIGN

5.1 SCOPE OF SECTION

This Section sets out ultimate structural strength requirements for the design of piles.

5.2 GENERAL PRINCIPLES OF STRUCTURAL STRENGTH DESIGN

5.2.1 Design structural strength

A pile shall be proportioned such that its design structural strength ($R_{d,s}$) is not less than the design action effect (E_d) as detailed in Clause 3.2.2 (i.e., $R_{d,s} \geq E_d$).

The design structural strength ($R_{d,s}$) shall be calculated as the ultimate structural strength (R_{us}) multiplied by a structural strength reduction factor (ϕ_s) and a concrete placement factor (k), according to the following equation:

$$R_{d,s} = \phi_s k R_{us} \qquad \qquad \ldots 5.2.1$$

where

ϕ_s and R_{us} are determined in accordance with Clauses 5.3.1, 5.4, 5.5 and 5.6

For concrete and grout piles, k shall be within the range 1.0 to 0.75 and shall be determined in accordance with Table 5.3.2. For piles other than concrete and grout k shall be 1.0.

5.2.2 Design bending moment (M_d)

In addition to other relevant design action effects, a pile shall be designed for a bending moment (M_d) of the greater of Item (a) or Item (b), as follows:

(a)   The sum of—

    (i)   the moment at any section caused by the load combination for strength design in Clause 3.3.2; and

    (ii)   the moment generated in a pile caused by the out-of-position tolerance given in Clause 7.2.1 and other specified tolerance or measured displacement from the design location.

(b)   A moment about each principal axis of $N_d \times 0.05D$ where N_d is the design axial load on a cross-section and D is the overall minimum width of the pile shaft in the plane of the bending moment.

NOTES:

1   The moment due to out-of-position location should be calculated by a structural analysis of the pile or pile group and the above structure, taking relative stiffness of the pile and beam or slab and fixity between the members into account.

2   In the absence of such an analysis, the design moment at the head of the pile for a single pile and groups of two or more piles in one line should not be less than the following:

    (a)   Single pile – $N_d \times$ the pile tolerance in any direction.

    (b)   Two or more pile group – $N_d \times$ the pile tolerance on an axis perpendicular to the line of the piles.

3   Where the pile cap, beam or slab arrangement above the pile are very stiff compared with the pile, or where piles are in groups of three or more, it may be relevant to assume that out-of-position tolerance moments generated within the piles are small without the necessity for a rigorous structural analysis.

4   Where piles are attached to a pile cap, the pile-to-pile cap connection should be designed to accommodate all design actions between the pile and the pile cap.

5.2.3 Buckling of a pile

Where a pile has a freestanding portion above ground level or is installed in very soft soils, consideration shall be given to the possibility of buckling in the determination of the pile strength in compression and bending. Particular care shall be taken in the use of preformed piles with compression only joints.

5.2.4 Pile splice

A preformed pile may be spliced, provided the pile splice is designed for the following:

(a) *Mechanical joints* are designed so that they provide a permanent connection between the pile lengths.

(b) *The design actions at the splice level* In determining the design actions, the final splice position is taken into account and, unless it can be shown that the splice will be located at a known level, it is designed for the maximum design action effect in the section.

(c) *Pile driving stresses* The effects of transmission of the driving stress waves and any tension stresses generated during driving are taken into account.

(d) *Compression only joints* If compression only joints are used for precast concrete piles, then there is an installation plan, including restrike testing and surveying, that shows that the pile segments are intact and in contact at the end of installation, and consideration is given to installation effects and effects from future ground movements such as swelling soils.

   NOTE: The impact of heave when driving piles in groups is particularly important.

5.3 CONCRETE AND GROUT PILES

5.3.1 General

The general design of reinforced concrete and prestressed concrete piles shall be in accordance with AS 3600, except as specified in this Clause. The ultimate structural strength (R_{us}) shall be calculated in accordance with, and the value of ϕ_s shall be selected from, AS 3600.

Where CFA piles are constructed using grout rather than pumped concrete, the strength of the grout used for design in accordance with AS 3600 shall be based on characteristic cylinder strengths determined in accordance with AS 1012. Where grout strength is determined using cubes rather than cylinders, the cube strength results shall be converted to equivalent cylinder strengths by multiplying the cube strengths by a factor of 0.81.

5.3.2 Cast in place piles

The general design of driven cast in place, cast in place displacement piles, cast in place intermediate and non-displacement concrete and grout piles shall be in accordance with AS 3600, except as specified in this Clause.

The ultimate structural strength (R_{us}) for piles in bending or compression shall be calculated in accordance with AS 3600 using the characteristic design strength of the grout or concrete multiplied by the concrete placement factor (k) assessed from Table 5.3.2, taking into account the pile construction type including any instrumentation available during construction, the method of concrete placement and the amount of pile shaft integrity testing that is to be carried out. The concrete installation factor shall only be applied to the characteristic concrete or grout strength, and shall not be applied to the strength of any steel reinforcement.

TABLE 5.3.2

ASSESSMENT OF CONCRETE PLACEMENT FACTOR (k)

Pile construction method	Circumstances in which $k = 1$ is appropriate	Circumstances in which $k = 0.75$ is appropriate
All	Successful use of specified construction methods in similar ground conditions.	No successful use of specified construction methods in similar ground conditions.
	At least 5% of piles are integrity tested over the full length of the shaft by an appropriate means.	No dynamic load-testing or integrity-testing to be performed.
CFA and cast in place displacement piling	Full, real time monitoring of auger extraction rate, concrete/grout pressure, volume, pile depth and drilling parameters to be undertaken.	Piles installed with partial monitoring. (e.g. measurement of concrete/grout pressure and volume only).
Bored piles constructed under drilling fluid	Regular on site testing of drilling fluid, embedment depth of tremie tube to be regularly monitored and recorded during concreting. Hard copies of construction records to be maintained.	No regular testing of drilling fluids or monitoring of tremie and concrete depths during concreting. Hard copies of construction records not to be maintained.
Preformed Driven	Monitoring of driving stresses during pile installation in difficult ground conditions to check that high compression and/or tension stresses will not lead to pile damage.	No monitoring of driving stresses during pile installation in difficult ground conditions.

NOTES:

1   The above table assumes that the method of pile construction adequately addresses the major construction risks on the site. If this is not the case then an alternative method of construction should be adopted

2   CFA piles constructed without either full or partial monitoring are not recommended

3   If shaft integrity testing cannot be carried out over the full length of the pile shaft the designer shall consider using a k factor of less than 1.0. Choice of the k factor shall consider the percentage of piles to be integrity tested, the length of the pile shaft over which the integrity testing can be carried out and the level of load in the pile shaft at the maximum depth of integrity testing.

5.3.3 Reinforcement requirement

Steel reinforcement used shall comply with AS/NZS 4671. Where reinforcement is required, the cross-sectional area of the longitudinal reinforcement in a pile (A_{sc}) shall be as follows:

(a)   For precast reinforced concrete piles, it shall—

     (i)   be not less than $0.014A_g$; and

     (ii)   not exceed $0.04A_g$ unless it can be shown that the amount and disposition of the reinforcement will not prevent the proper placing and compaction of the concrete.

(b)   For other piles, it shall—

     (i)   be not less than $0.005A_g$ where a pile is fully embedded in the ground;

     (ii)   be not less than $0.01A_g$ for the portion of a pile projecting above the ground; and

        NOTE: At a depth of three pile diameters below the ground surface, the limit on longitudinal reinforcement may be reduced to $0.005A_g$.

(iii) not exceed $0.04A_g$ unless it can be shown that the amount and disposition of the reinforcement will not prevent the proper placing and compaction of the concrete.

NOTE: For concrete strengths in excess of 65 MPa consideration should be given to the provision of additional confining reinforcement to meet ductility requirements in accordance with AS 3600.

5.3.4 Partially reinforced pile

Pile reinforcement may be curtailed one development length below a level where bending moments from all loads and eccentricities and tensile loads from uplift heave and others cease to be significant, and provided the design axial load in the unreinforced section does not exceed $0.5\ kf'_c\phi_sA_g$.

NOTE: Consideration should be given to loads, moments and other actions induced by possible horizontal or vertical ground movements, including earthquake-induced ground movements, and an assessment made of the need for longer reinforcement.

5.3.5 Unreinforced piles

An unreinforced pile shall be permitted where the design action effect does not exceed $0.45\ kf'_c\phi_sA_g$.

5.3.6 Cast in place screw piles

For cast in place screw piles, the design structural strength shall be determined in accordance with AS 3600, based on the minimum shaft cross-sectional area, using a characteristic concrete strength times the concrete strength placement factor k determined from Table 5.3.2.

5.3.7 Lateral restraint of longitudinal reinforcement and tendons

Where piles project more than two pile shaft diameters above final ground formation level, the minimum size of the tie or helix shall conform to AS 3600 requirements for columns for the portion of the pile above the ground and for a depth of three pile shaft diameters below the ground surface. Elsewhere, the bar sizes given in Table 5.3.7 shall apply for concrete strengths up to 65 MPa. The maximum tie spacing or pitch of a helix shall be $15d_b$.

Where concrete strength in excess of 65 MPa is used, the requirements of AS 3600 shall be considered, together with any confining action provided by the soil or rock around the pile shaft.

NOTE: For cast in place screw piles, shaft diameter refers to the minimum pile shaft diameter.

TABLE 5.3.7

BAR SIZES FOR TIES AND HELICES FOR CONCRETE STRENGTH BELOW 65 MPa

Pile size mm	Longitudinal bar diameter mm	Minimum diameter of tie or helix mm
Up to 500	Less than 32	5
Up to 500	32 to 36	6
501 to 700	All	6
701 and above	All	10

5.4 STEEL PILES

5.4.1 General

Steel sections shall be designed in accordance with AS 4100.

The structural design strength shall be calculated using the gross cross-sectional area less an allowance for loss of section due to corrosion, as specified in Clause 6.5.

5.4.2 Steel screw piles

5.4.2.1 *Actions and loads*

The pile shaft, helix, connections and splices shall be designed for the actions and loads specified in Clause 3.3 and for loads induced during installation. The maximum loads induced in the pile and its components during installation shall be designed in accordance with AS 4100.

5.4.2.2 *Shaft*

Steel shafts not filled with concrete shall be designed in accordance with this Clause (Clause 5.4). Shafts filled with plain or reinforced concrete shall be designed in accordance with Clause 5.5.

The shaft design shall take into account axial and lateral loads and bending moments and of possible reduced ground support resulting from the installation process.

5.4.2.3 *Helix*

The structural design strength ($R_{d,s} = \phi_s R_{u,s}$) of the helix shall be not less than the design action effect (E_d) on the pile. The thickness of the plate used for design shall be the net thickness after making an allowance for corrosion, as specified in Clause 6.5. The welded joint between the helix and the plate shall be designed to support the design loads and installation loads in accordance with AS 1554.1, Category SP. Where fillet welds are used, the throat thickness shall be increased by the allowance for loss of section due to corrosion in the pile shaft and helix, as specified in Clause 6.5.

> NOTE: Where a test load is required to be higher than the design action effect, a stronger helix may be required on the test piles.

5.4.2.4 *Connections and splices*

When piles are to be installed in two or more lengths, the connections and splices shall be designed to transfer the design action effect at the joint without slippage and distortion. The design shall consider the loss of section due to corrosion of the pile shaft, bolts, welds and other components as specified in Clause 6.5.

5.5 COMPOSITE STEEL AND CONCRETE PILES

Design of composite piles shall comply with AS 5100.6. The design shall ensure adequate structural strength to transfer the design actions across the interface between materials. The structural design strength for steel sections shall be calculated using the gross cross-sectional area less an allowance for loss of section due to corrosion, as specified in Clause 6.5.

> NOTE: In partially concrete-filled steel tube piles, where the load must be transferred from the concrete section to the steel tube, the bond between the concrete and steel should take into account possible concrete shrinkage by using an appropriate steel or concrete adhesion value. Shear or bearing connectors may also be required to transfer the load.

5.6 TIMBER PILES

5.6.1 General

Timber piles shall be designed in accordance with AS 1720.1, except as specified in this Clause.

5.6.2 Timber pile splices

In addition to the requirements of Clause 5.2.4, joints in timber piles shall conform to the following:

(a)   Where a pile is made up of more than one section, the mechanical joint shall be designed for the design action effect at the joint.

(b)   Where tube splices are used, account shall be taken in the design of the reduced tension and bending capacity of the joint.

Where the pile is shaved, any reduction of area shall be taken into account.

> NOTE: The strength reduction factor for joints takes into account the shaving factor, as defined in AS 1720.1, and the increased proportion of heartwood.

5.6.3 Connection details

5.6.3.1 *Compression, lateral and bending loads*

Where the pile terminates in a concrete pile cap, the depth and contact surface preparation of the pile projection into the cap shall be designed for compression, lateral and bending loads.

Where a pile terminates with other connection details, such as timber or steel headstocks, the connection shall be designed in accordance with the requirements of AS 1720.1.

5.6.3.2 *Tension loads*

Connection details into a concrete cap and connection details into timber or steel headstocks above ground level shall be designed in accordance with the requirements of AS 1720.1.

Where a pile terminates in a concrete pile cap, the design tension load on a steel dowel passing through the pile head into the concrete shall be determined using the design requirements of AS 1720.1 for bolts. Minimum edge distance (l_1) for the dowels to the end of the pile shall be $8D_d$. The pin shall extend a minimum distance (d) into the concrete cap.

SECTION 6   DURABILITY DESIGN

6.1 GENERAL

This Section sets out requirements for plain, reinforced and prestressed concrete and steel piles with a design life of 50 and 100 years, and timber piles having a design life as detailed in Clause 6.6.

For other pile materials, the general principles of durability design set out in this Section shall be followed.

6.2 GENERAL PRINCIPLES OF DURABILITY DESIGN

The durability of piles shall be determined taking into account the aggressivity of the ground and the environmental conditions. Appropriate measures shall be taken to achieve the design life. The piles shall be designed to remain in a safe and serviceable condition to the end of their design life.

The design for durability of the structure that the piles support shall also apply to any section of the piles exposed above ground level.

Unless otherwise specified in this Section, piles above ground level shall be treated as columns, in accordance with appropriate material design standards. Where piles are spliced, the durability requirements of Clauses 6.4, 6.5 and 6.6, as relevant, shall apply to the splice material.

NOTE: Issues such as a maintenance-free period and client-acceptable levels of damage due to loss of durability may need to be taken into account.

6.3 ACID SULFATE SOILS

In certain areas, particularly in coastal marine deposit areas, the presence of considerable amounts of iron sulfides is possible. Disturbing or exposing these soils to air or changing groundwater level conditions may cause the formation of sulfuric acid.

Piles installed in acid sulfate soil locations shall require specific durability design to resist acid attack. The effects of the method of pile construction on the formation of sulfuric acid shall be considered.

NOTES:

1   The acid sulfate risk varies around Australia and local state authorities provide good background on the extent and types of assessment that may be undertaken.

2   Excavation and movement of acid sulfate soils are subject to strict environmental controls that normally expect chemical treatment to avoid contamination of streams and drains (see AS 4482.1 for sampling and investigation of such soils). Consultation with the local environmental authority is generally required prior to the excavation or use of such soils.

3   Driven piles produce no spoil and expose the surrounding soil to significantly less air than bored piles during construction.

4   Bored piles with suitable corrosion and durability allowances may be considered.

5   Whether the groundwater in the acid sulfate environment is relatively static or fluctuates will also serve as a guide to future ground aggressiveness.

6   The soil testing should include testing for both actual and potential acid sulfate aggressiveness.

6.4 DESIGN FOR DURABILITY OF CONCRETE PILES

6.4.1 General

Durability shall be allowed for in the design of concrete piles by assessing the exposure classification for a pile in accordance with Clause 6.4.2, and for that exposure classification complying with the requirements for—

(a)   minimum concrete strength and reinforcement cover in Clause 6.4.3(a);

(b)   restrictions on content of certain chemicals in Clause 6.4.3(b);

(c)   cover for concrete placement in Clause 6.4.3(c);

(d)   limitation on crack width in Clause 6.4.3(d); and

(e)   selection of concrete aggregates in Clause 6.4.3(e).

6.4.2 Exposure classification for concrete piles

The exposure classification of the surface of a concrete pile shall be determined from Table 6.4.2 (A), 6.4.2 (B) and 6.4.2 (C). For the range of chemical conditions in the soil surrounding the piles, the condition leading to the most severe aggressive conditions shall be allowed for, and allowance shall be made for likely changes in groundwater levels.

For concrete piles subject to a very severe exposure classification, the particular exposure environment shall be taken into account. Consideration shall be given to the suitability of concrete materials, mix proportions, methods of placement, cover and curing. Consideration shall also be given to the possible use of protective surface coatings to the piles or other protective measures.

TABLE   6.4.2(A)

EXPOSURE CLASSIFICATION FOR CONCRETE PILES—
PILES IN WATER

Exposure conditions	Exposure classification
Sea water—Submerged	Moderate
Sea water—Tidal/splash zone	Severe
Fresh water—Treat as in Table 6.4.2(C), Type A	Mild

TABLE   6.4.2(B)

EXPOSURE CLASSIFICATION FOR CONCRETE PILES—
PILES IN REFUSE FILL

Exposure conditions	Exposure classification
Domestic waste	Severe
Industrial waste	Very severe

（sidebar）Accessed by TAFE NSW - SYDNEY INSTITUTE ULTIMO 2 on 16 Mar 2011

TABLE 6.4.2(C)

EXPOSURE CLASSIFICATION FOR CONCRETE PILES—PILES IN SOIL

Exposure conditions				Exposure classification	
Sulfates (expressed as SO_4*)		pH	Chlorides in groundwater	Soil conditions A†	Soil conditions B‡
In soil ppm	In groundwater ppm		ppm		
<5000	<1000	>5.5	<6000	Mild	Non-aggressive
5000–10 000	1000–3000	4.5–5.5	6000–12 000	Moderate	Mild
10 000–20 000	3000–10 000	4–4.5	12 000–30 000	Severe	Moderate
>20 000	>10 000	<4	>30 000	Very severe	Severe

*   Approximately 100 ppm SO_4 = 80 ppm SO_3

†   Soil conditions A—high permeability soils (e.g., sands and gravels) which are in groundwater

‡   Soil conditions B—low permeability soils (e.g., silts and clays) or all soils above groundwater

NOTES TO TABLES 6.4.2(A), 6.4.3(B), AND 6.4.2(C):

1   This is a simplistic and sometimes conservative approach to the definition of aggressivity. It is common to find more than one chemical in the service environment and the effect of these chemicals may be modified in the presence of others. For example, sulfate ions become aggressive at levels of 600 to 1000 ppm when combined with magnesium or ammonium ions. In the presence of chloride ions, however, attack by sulfate ions generally exhibits little disruptive expansion with the exception of conditions of wetting and extreme drying where crystallization can cause surface fretting of concrete.

2   Corrosion damage by chlorides is only relevant to the steel reinforcement and steel inclusions. If there is no reinforcement or the reinforcement is otherwise adequately protected (e.g., by a coating or cathodic protection) the chloride content is not relevant to the exposure classification.

3   Chemical concentrations relate only to the proportion of chemical present that is water-soluble.

4   Acidic ground conditions can be caused by dissolved 'aggressive' carbon dioxide, pure and very soft waters, organic and mineral acids and bacterial activity. Care is required in the assessment of pH under pile installation and lifetime conditions since pH can change over the lifetime of the pile. Therefore the pH should not be assessed only on the basis of a present-day test result, rather the ground chemistry should be considered over the design life of the pile. Testing for pH should be carried out either in situ or immediately after sampling as there is otherwise a risk of oxidation with time, leading to apparent acidity, which does not correctly represent in situ conditions.

5   pH alone may be a misleading measure of aggressivity without a full analysis of causes (e.g. still vs. running water).

6   Contamination by the tipping of mineral and domestic wastes or by spillage from mining, processing or manufacturing industries presents special durability risks due to the presence of certain aggressive acids, salts and solvents, which can either chemically attack concrete or lead to a corrosion risk. Certain ground conditions cannot be properly addressed by reference only to Tables 6.4.2 (A), (B) and (C). These conditions include, for example, areas where acid-sulfate soils exist, contamination by industrial and domestic waste, or spillage from mining, processing, or manufacturing industries. This presents special durability risks due to the presence of certain aggressive acids, alkalis, salts and solvents, which can lead to either chemical attack of concrete or lead to a corrosion risk. In the absence of site-specific chemical information, the exposure condition should be assessed as 'severe' for domestic refuse and 'very severe' for industrial/mining waste tips. Chemical analysis of the latter may, however, allow a lower risk classification.

7   For piles in disturbed soil, consider the assumption of soil conditions A, where accelerated corrosion is possible.

8   Attention is drawn to regions of dry land salinity where the chloride concentrations in the soil can be greater than seawater (e.g., Western Sydney, Murray River basin). This can affect the upper few metres of a pile where the aggressive salts accumulate.

9   Cathodic protection should not fall below the levels recommended in AS 2832.5.

6.4.3 Durability requirements

Durability of concrete piles shall be promoted by adherence to the following requirements:

(a) *Protective measures*   Protective measures shall be chosen—

  (i)   by adoption of the minimum requirements of Table 6.4.3 in regard to concrete strength and cover for reinforcing steel and tendons depending on the design life required; or

  (ii) by a design life assessment of concrete durability, utilizing proven numerical procedures (e.g., chloride diffusion modelling), supplemented by laboratory assessment under conditions that imitate the design life conditions (e.g., chloride diffusion testing).

  NOTE: Use of supplementary cementitious materials may increase durability. In the case of some road authorities, use of supplementary cementitious materials is a requirement for concrete that is in contact with soil. Use of supplementary cementitious materials leads to considerably lower 1–3 day strength (than 100% Portland cement concrete) and this may significantly affect the manufacture, storage and transport of precast concrete piles. Concrete strengths alone may not be the sole means of determining cover requirements and satisfying durability requirements. 100 year design life cathodic protection of steel reinforcement in piles is an option.

(b) *Restrictions on chemical content in concrete piles*   Restriction on chemical content shall be as given in AS 3600 for a 50 year design life and AS 5100.5 for 100 year design life.

(c) *Minimum cover to reinforcement for concrete placement*   For concrete placement the following shall apply:

  (i)   The cover and arrangement of steel shall be such that concrete can be properly placed and compacted.

  (ii) The cover shall be not less than the maximum of 1.5 times the nominal aggregate size and the cover given in Table 6.4.3.

  (iii) For severe and very severe exposure classifications, consideration shall be given to using an inert liner and/or coating in addition to the specified concrete cover.

(d) *Crack width*   Crack width shall not exceed 0.3 mm.

(e) *Concrete aggregates*   Concrete aggregates shall comply with AS 2758.1 with exposure classifications as detailed in AS 3600 and cross-referenced in this document. Aggregate water absorption shall be specified in the works document.

TABLE 6.4.3

CONCRETE STRENGTH AND REINFORCEMENT COVER IN PILES

Exposure classification	Minimum concrete strength (f'_c) MPa		Minimum cover to reinforcement, mm			
			50 year design life		100 year design life	
	Precast and prestressed piles	Cast in place piles	Precast and prestressed piles	Cast in place piles	Precast and prestressed piles	Cast in place piles
Non-aggressive	50	25*	20	45	25	65
Mild	50	32	20	60	30	75
Moderate	50	40	25	65	40	85
Severe	50	50	40	70	50	100
Very severe (see Note 1)	>50 (preferably >60)	>50 (preferably >60)	40	75	50	120

*   For reinforced piles, use $f'_c = 32$ MPa minimum

NOTES:

1   Consideration shall be given to using an inert liner and/or coating for severe and very severe exposure classifications, in addition to the specified concrete cover.

2   Concrete containing substantial quantities of supplementary cementitious material generally exhibits superior durability; however, compressive strength is developed slowly and in this case it is appropriate for f'_c to be specified at an age greater than 28 days.

3   There is a limit to the depth of cover that can be used—excessive cover will lead to spalling during pile driving, and therefore cover has been limited for precast concrete piles.

6.5 DESIGN FOR DURABILITY OF STEEL PILES

6.5.1 General

Durability shall be allowed for in the design of steel piles by assessing the exposure classification for a pile in accordance with Clause 6.5.2 and for that exposure classification, complying with the requirements of one or a combination of the following:

(a)   Corrosion allowance for uncoated steel in accordance with Clause 6.5.3;

(b)   Coating systems in accordance with Clause 6.5.4

(c)   Cathodic protection systems in accordance with Clause 6.5.5.

Expected design life shall be calculated from loss rates and the additional allowance made so that strength requirements are met at the expected end of life of the pile.

6.5.2 Exposure classification for steel piles

The exposure classification of the surface of a steel pile shall be determined from Tables 6.5.2(A), 6.5.2 (B) and 6.5.2 (C). For the range of chemical conditions of piles in soil, the condition leading to the most severe aggressive conditions shall be allowed for and consideration shall be given to possible changes in groundwater levels.

TABLE 6.5.2(A)

EXPOSURE CLASSIFICATION FOR STEEL PILES—PILES IN WATER

Exposure conditions	Exposure classification
Sea water—submerged	Severe
Sea water—tidal/splash zone—Cold water (south of 30°S)	Severe
Sea water—tidal splash zone—Tropical/Subtropical water (North of 30°S)	Very severe
Fresh water—soft running water	Moderate

TABLE 6.5.2(B)

EXPOSURE CLASSIFICATION FOR STEEL PILES—PILES IN REFUSE FILL

Exposure conditions	Exposure classification
Domestic waste	See Note 2
Industrial waste	See Note 2

TABLE 6.5.2(C)

EXPOSURE CLASSIFICATION FOR STEEL PILES—PILES IN SOIL

Exposure conditions				Exposure classification	
pH	Chlorides Cl		Resistivity ohm.cm	Soil condition A*	Soil condition B†
	In soil ppm	In groundwater ppm			
>5	<5000	<1 000	>5 000	Non-aggressive	Non-aggressive
4–5	5000–20,000	1 000–10 000	2 000–5 000	Mild	Non-aggressive
3–4	20,000–50,000	10 000–20 000	1 000–2 000	Moderate	Mild
<3	>50,000	>20 000	<1 000	Severe	Moderate

* Soil conditions A—high permeability soils (e.g., sands and gravels) that are in groundwater

† Soil conditions B—low permeability soils (e.g., silts and clays) or all soils above groundwater

NOTES TO TABLES 6.5.2 (A), 6.5.2 (B) AND 6.5.2 (C):

1 Where high levels of sulfates exist (>1000 ppm), sulfate-reducing bacteria may be present and active, sometimes leading to microbiologically induced corrosion. In such cases, classify as 'mild' for low permeability soils and 'moderate' for high permeability soils.

2 Contamination by the tipping of mineral and domestic waste or by spillage from mining, processing or manufacturing industries presents special durability risks due to the presence of certain aggressive acids (both organic and inorganic), salts and solvents, which can chemically attack steel. In the absence of site-specific chemical information, the exposure condition should be assessed as 'severe' for domestic refuse tips and 'very severe' for industrial/mining waste tips. Chemical and microbiological analysis of the latter may, however, lead to lower risk classification.

3 For piles in disturbed soil, consider the assumption of soil A conditions where accelerated corrosion is possible.

6.5.3 Corrosion allowance for steel piles

Where no protective coating or cathodic protection is applied, allowance shall be made for loss of section during the design life. Where a pile coating is provided, consideration shall be given to the likely life of the coating and allowance made for loss of pile section thereafter, if appropriate.

Where no protection systems are to be applied to steel piles, allowance shall be made for uniform corrosion and loss of section. In the absence of other information, corrosion allowance shall be as tabulated in Table 6.5.3. In areas where site-specific corrosion rates are known, those site-specific rates may be used. Corrosion on the internal faces of a fully sealed closed-form pile may be assumed to be negligible.

Where piles are electrically connected to a dissimilar metal, the resultant beneficial or adverse galvanic effect shall be taken into consideration.

NOTES:

1   Localized pitting corrosion is commonly experienced on submerged steel piles subjected to accelerated low water corrosion. Localized corrosion may also be found in the pile embedded zone close to the soil-water or soil-air interface where microbial activity is high and where scouring can maintain high corrosion activity. Such localized corrosion is not covered by the corrosion allowances given in Clause 6.4, which are averaged rates for situations where generalized corrosion occurs.

2   A cathodic protection system for steel piles is only fully effective up to approximately mid-tide level in sea or tidal waters and up to ground level in soils above the groundwater table.

TABLE 6.5.3

CORROSION ALLOWANCES FOR STEEL PILES

Exposure classification	Uniform corrosion allowance (mm/year)
Non-aggressive	<0.01
Mild	0.01–0.02
Moderate	0.02–0.04
Severe	0.04–0.1
Very severe[3]	>0.1

NOTES:

1   The allowances in Table 6.5.3 may be reduced, as appropriate, where adequate corrosion protection systems (coatings or cathodic protection) are to be used. Coatings will reduce corrosion allowance while they remain in good condition. Coating damage, deterioration and breakdown will result in the corrosion rate increasing and, in such circumstances, the corrosion allowances in Table 6.5.3 shall apply.

2   To allow the implementation of cathodic protection after construction it is good practice to provide electrical continuity throughout the piled system at the time of construction. In providing electrical continuity, consideration shall be given to the likelihood of stray current corrosion, especially if the completed structure is of significant length and adjacent to a cathodically protected system or within close proximity to direct current electrified traction or power supply systems.

3   For very severe conditions a site-specific assessment should be sought.

6.5.4 Coating protection systems

Consideration shall be given to the type of coating, method of application, thickness of coating, surface preparation, expected life under service conditions and the possibility of damage to the coating during installation. If it is considered that the life of the coating will be less than the required design life for the pile, appropriate allowance shall be made for corrosion.

Where a coating is to be applied to steel piles above ground level and above the low watermark, it shall be a coating that is appropriate for the environment and materials used.

NOTES:

1 Coating systems should comply with the requirements of AS/NZS 2312.

2 The following coating systems for submerged and below ground steel piles are in order of increasing 'time to first maintenance':

(a)   Epoxy mastic.

(b)   High-build high-solids epoxy.

(c)   Corrosion-inhibiting fabrics (e.g. petrolatum-tape).

(d)   Polyethylene.

6.5.5 Cathodic protection

Where cathodic protection is to be applied, it shall conform to the following:

(a)   Underground steel cathodic protection systems shall comply with AS 2832.2.

(b)   Submerged steel pile cathodic protection systems shall comply with AS 2832.3.

6.6 DESIGN FOR DURABILITY OF TIMBER PILES

6.6.1 Design life

Durability shall be considered in the design of timber piles by making appropriate allowance in the selection of the timber and in the chemical treatment (where used).

6.6.2 Timber selection and treatment

Timber piles shall be either treated or untreated having due regard to the soil and groundwater into which they are driven (as defined in AS 1604.1), the species of the pile and the type and permanency of the structure they support.

NOTES:

1 Where a timber pile is installed to a depth such that it is permanently below the ground watertable, chemical preservation may not be necessary as the timber will not be subject to conditions where degradation will occur. Any portion of the pile extends above this level will be subjected to environmental conditions including the potential for decay and termite attack.

2 The durability of an untreated hardwood timber pile in contact with the ground above the water level can vary appreciably depending on the timber species used. AS 5604 categorizes timbers into groups of similar durability. For timbers in the most durable group, a design life of 25 years or more against decay and termites would be expected.

3 AS 5604 gives guidance on life expectancy for different species of timber in ground contact; local experience may also provide useful guidance.

6.6.3 Timber preservation

Timber preservation for a pile shall be in accordance with AS 1604.1, hazard level H5 for a pile not in contact with sea water and hazard level H6 in the case of marine exposure, where risk of marine borer attack exists (see AS 3818.3).

6.6.4   Treatment after cut-off

The head of a pile, which has been treated with a preservative, after cutting off to the required level, shall be coated with a suitable preservative and covered with a water-resistant membrane prior to casting the pile caps.

6.6.5   Marine piles

Where possible, all attachments and cross-bracings shall be positioned above the high tide mark.

NOTE: Where additional protection is needed for the piles, physical barriers, such as plastic wraps and concrete jacket, may be used.

S E C T I O N   7   M A T E R I A L S   A N D   C O N S T R U C T I O N   R E Q U I R E M E N T S

7.1 GENERAL

7.1.1 Concrete

Materials for plain, reinforced and prestressed concrete shall comply with the requirements of AS 3600 and AS 1379. Steel reinforcement shall comply with the requirements of AS/NZS 4671.

7.1.2 Grout

Materials for grout shall comply with AS 3600 and AS 3972 or ASTM C566-97. Grout fluidifier shall comply with ASTM C566, except that expansion shall not exceed 4%.

7.1.3 Steel

Steel for piles and pile fitments shall comply with the requirements of AS 1163, AS 1450, AS 1579, AS 4100, AS/NZS 1594, AS/NZS 3678, AS/NZS 3679.1 and AS/NZS 3679.2.

7.1.4 Timber

Timber for piles shall comply with the requirements of AS 1604.1, AS 1720.1 and AS 3818.3.

7.2 TOLERANCES AND DEFECTS

7.2.1 Positional tolerances

Unless otherwise specified, the permissible positional deviation for a pile at cut-off level shall be as follows:

(a) *For a pile installed from land with a cut-off level no more than 2 m below piling platform level*—75 mm in plan position and within 4% inclination for vertical piles and 7% inclination for raked piles.

   NOTE: Where a pile projects above the ground, a tighter inclination tolerance may be required.

(b) *For a pile installed from land, with a cut-off level at or more than 2 m below piling platform level*—$[75 + 20(h–2)]$ mm in plan position and within 4% inclination for vertical piles and 7% inclination for raked piles, where h is the depth to cut-off in metres.

(c) *For a pile installed from floating plant*—150 mm in plan position and within 4% inclination for vertical piles and 7% inclination for raked piles.

(d) *For a non-circular pile section, where orientation of the major axes is specified for strength or positional requirements*—rotational deviation from the specified alignment shall not exceed 10°.

   NOTE: The structural pile design should take into account the tolerances on pile installation (see Clause 5.2.2).

7.2.2 Cut-off levels

Unless otherwise specified, a pile shall be trimmed to a tolerance of 25 mm from the design cut-off level. Special care shall be taken to ensure that the full cross-sectional area of the pile is at cut-off level.

7.2.3 Trimming and capping

When trimming a concrete or grout pile, care shall be taken to prevent cracking or otherwise damaging the concrete or grout below cut-off level or damaging the steel reinforcement. Any damaged concrete or grout shall be removed and the pile adequately repaired. Weak concrete or grout and laitance in cast in place piles shall be cut away to expose sound concrete or grout.

The head of a timber pile shall be cut off square to sound wood and the cut face shall be coated with a suitable preservative and covered with a water-resistant membrane prior to the casting of the pile cap.

All soil and other debris shall be removed from the top of a pile before constructing the pile cap.

7.2.4 Variation in pile depths

If the installed pile depth is inconsistent with the design depth, a reassessment of founding depth, strength, serviceability and durability shall be made. If necessary, additional geotechnical investigation shall be undertaken to determine the cause of the variation.

7.2.5 Defective piles

Where a pile exceeds the above tolerances, is damaged or is otherwise defective, a reappraisal of the strength, serviceability and durability of the pile shall be performed.

Where the strength, serviceability or durability are found to be unsatisfactory, the pile shall be rectified, downgraded or replaced with one or more supplementary piles, as appropriate.

7.3 DISPLACEMENT PILES—PREFORMED

7.3.1 Dimensional tolerances

Unless otherwise specified, concrete, steel or timber preformed pile sections shall be supplied to the following tolerances:

(a) *Length*　Not less than the specified length.

(b) *Cross-sectional dimensions*:

　　(i)　Concrete and steel piles—+10, −5 mm of the specified dimensions.

　　(ii)　Timber piles—mean diameter not less than the specified diameter, and the minimum diameter in substantially oval piles not less than 80% of the specified diameter.

(c) *Straightness*　The tolerance on straightness of any portion and of the completed length of a pile shall be as follows:

　　(i)　Concrete and steel piles—1/250 of the length up to a maximum deviation of 50 mm.

　　(ii)　Timber piles—a straight line joining the centres of the butt and the toe cross-section to fall entirely within the pile for piles of 13 m or more in length, and within 50 mm of the centre-line of the section for shorter piles.

(d) *Timber piles*　The maximum deviation of crooks or kinks shall not exceed the values set down in AS 3818.3.

(e) *Joints*:

　　(i)　Where a pile is made up of more than one section, the maximum angular deviation at the joint shall not exceed 1 in 100, subject to the tolerance for the complete pile as stated in Items (c)(i) and (c)(ii).

   (ii) For timber piles using tube splices, as well as the above angular tolerance, each timber end within the splice shall not be out of square by more than 1 in 50. Tubes shall fit tightly onto the timber section.

(f) *Ends*   Pile ends shall not be out of square by more than 1 in 50.

7.3.2 Handling and storage

Piles shall be handled and stored so that they are not overstressed and in such a way as to prevent permanent distortion of any part.

Care shall be taken to avoid damage to the outer surfaces of piles in storage and during handling. If damage occurs, which is detrimental to the design requirements, it shall be repaired prior to installation of the pile.

Pile reinforcement shall be designed so that under the maximum computed pile handling stresses, as specified in Clause 3.3.1.3, the reinforcement is not stressed above the lesser of $0.5f_{sy}$ and 250 MPa.

> NOTE: This Clause is intended to limit cracking during handling. Cracking could reduce pile durability after installation.

7.3.3 Installation by driving

7.3.3.1 *Installation stresses*

The type and weight of hammer used for driving a pile shall be such that the driving energy produced is sufficient to install the pile without causing damage to the pile material. The suitability of the hammer shall be confirmed by wave equation analysis prior to installation of the piles.

The driving energy shall be controlled as follows:

(a) *Concrete*   During driving, the maximum stress in concrete piles shall not exceed $0.8 \times f'_{cm}$ in compression, and in tension the stresses shown in Table 7.3.3.1 where f'_{cm} is the compressive strength in megapascals at the time of driving. The crack width shall not exceed the lesser of 0.3 mm or 0.01 times the concrete cover, expressed in millimetres.

(b) *Steel*   During driving, the maximum stress in steel piles shall not exceed $0.9f_{sy}$.

(c) *Timber*   During driving, the maximum compressive stress generated in timber piles shall not exceed 0.9 times the characteristic strength in compression parallel to the grain $\left(f'_c\right)$ specified for the stress grade of the timber piles, as defined in AS 1720.1. Unless close fitting tube splices are used, where piles are jointed, the compressive stress at the joint section shall not exceed 0.8 times the characteristic strength in compression parallel to the grain $\left(f'_c\right)$ specified for the stress grade for pile timbers.

TABLE 7.3.3.1

CONCRETE—MAXIMUM TENSILE DRIVING STRESS

Pile type	Tensile stress MPa
Reinforced concrete piles:	
(a) Reinforcement quantity ≤2%	$0.8\sqrt{f'_{cm}}$
(b) Reinforcement quantity >2%	$\sqrt{f'_{cm}}$
Prestressed concrete piles	Initial prestress (less initial losses)

NOTE: Where stresses are actually measured during driving, the above values may be increased by up to 10%.

Reinforcement for precast concrete piles shall be determined in accordance with Clauses 3.3.1.3, 3.3.1.4 and 5.3.

7.3.3.2 *Founding criteria*

The following requirements apply:

(a)   The geotechnical strength of single piles shall be assessed by using the measured set (net penetration of the pile per hammer blow) during installation.

(b)   The required set and the temporary compression of the pile per hammer blow shall be determined from one of the following:

   (i)   Dynamic analysis (wave equation analysis or dynamic driving formula).

   (ii)   Measurements taken during high-strain dynamic testing.

   (iii)   Installation records of piles subjected to static load testing.

(c)   The pile shall be driven until the set and the temporary compression of the pile per hammer blow reach the values determined in Clause 7.3.3.2(b).

Where a required set and temporary compression of pile per hammer blow is specified, the effects of pile type, hammer type, mode of operation and ground condition shall be taken into account.

Where practicable, one or more piles shall be restruck after a specified period to assess the effects of time on pile capacity. If the blow count varies on restrike, the ultimate geotechnical strength shall be reassessed.

7.3.3.3 *Pile heave*

The order of driving piles shall be such as to minimize any lateral or vertical heave of a pile or pile group. Where heave of pile groups is likely to occur, pile top level readings shall be taken after driving and again after neighbouring piles have been driven. For piles that have risen significantly, the ultimate geotechnical strength shall be re-assessed by re-driving or load tests, or both. Where necessary, all heaved piles shall be re-driven to the original required depth and/or resistance.

Where lateral displacement occurs during driving, the structural strength of the pile shall be assessed and appropriate corrective action taken.

7.3.4 Installation by jacking

7.3.4.1 *Jacking force*

Piles installed by pushing or jacking shall have handling and installation stresses taken into account. In particular, where damaged sections can cause a loss of strength or durability, or both, cracking or spalling of concrete shall be repaired prior to further installation.

Jacked-in piles shall be designed in accordance with the strength and serviceability requirements detailed in Section 4, with the additional requirement that the pile jack installation force (P_{max}) shall be determined as follows:

$$P_{max} = 0.74 \gamma_p R_{ug}$$

where

γ_p =   coefficient of jacked pressure, determined from correlations from static loading tests, but not less than 1.4 or in the absence of such correlations, taken as follows:

=   1.5 for piles greater than 15 m length

=   1.75 for piles between 8 and 15 m length

=   2.2 for piles less than 8 m length

Jacked-in piles shall be subjected to repeated jacking at the maximum jacking force (P_{max}) The number of cycles shall be not less than 5. P_{max} shall be maintained for not less than 15 s. A time interval of not less than 2 min shall elapse between cycles.

> NOTE: Jacked-in piles are generally installed by hydraulic jacking against the reaction provided by self-weight of the installing rig plus kentledge.

The installation procedure shall not be interpreted to be equivalent to a static loading test as defined in Clause 8.3. The performance of jacked-in piles shall be determined in accordance with the requirements of Section 8 and, in the absence of performance limits stated in the specification, acceptance criteria shall be in accordance with Clause 8.4.3 for static testing and Clause 8.5.2 for high-strain dynamic testing.

7.3.4.2 *Calibration of rig*

The piling rig shall have a pressure gauge to measure the hydraulic ram pressure. This gauge shall be calibrated on an annual basis. Because of potential hydraulic losses, the installation force shall be calibrated over the full range of pressures against a calibrated load cell placed at the head of the piles.

7.3.4.3 *Pile movements*

Pile heave shall be observed and the requirements of Clause 7.3.3.3 shall be applicable.

Depending on prevailing soil conditions, the high bearing pressures imparted to the soil from the weight of the rig may result in vertical and lateral ground movements. These ground movements have the potential to displace previously installed piles. This potential shall be assessed prior to commencement of piling installation and lateral displacements shall be measured periodically to ensure that no adverse effects result. Where the vertical and lateral movements of the previously installed piles prove to be in excess of acceptable limits, further analyses or testing shall be carried out to assess the adequacy of the piles.

7.3.5 Installation by screwing

7.3.5.1 *Dimensional accuracy*

The following tolerances shall apply in addition to those specified in Clause 7.3.1:

(a)   Steel sections and plates used to manufacture the piles shall be in accordance with the appropriate Standard.

(b)   The diameter of the helix shall be not smaller than 5 mm from the design diameter.

(c)   The pitch of the helix shall be not more than ±10 mm from the pitch specified by the designer.

7.3.5.2 *Handling and storage*

The piles shall be handled and stored in accordance with Clause 7.3.2.

7.3.5.3 *Installation*

7.3.5.3.1 *General*

A piling schedule shall be compiled prior to commencement of installation, which shall include the minimum pile founding depth, and minimum setting torque. This torque shall be the re-torque value.

> NOTE: Steel screw piles should not be used in conditions where the helix is unable to be fully seated into the founding medium such as sloping rock surfaces.

7.3.5.3.2 *Installation stresses*

The pile installation equipment shall deliver sufficient torque to install the pile without causing damage to the pile material.

The installation equipment torque measuring device shall be calibrated regularly, at no greater than 6 monthly intervals.

7.3.5.3.3 *Construction monitoring*

Except where it is specified that a pile is to be founded at a specific level, site monitoring shall be carried out by measuring the torque as the pile is installed, and comparing it to the torque assessed in accordance with Clause 7.3.5.3.4.

Where practicable, one or more pile shall be re-torqued after a specified period to assess the effects of time. If the torque varies, the ultimate geotechnical strength shall be reassessed.

7.3.5.3.4 *Installation torque*

An assessment shall be made of the torque that is required to install the piles to the founding stratum, to ensure the piles will be installed through the overlying strata without overstressing the shaft. Consideration shall be given to the possibility of ground relaxation, which could affect the long-term capacity of the pile.

7.4 DISPLACEMENT PILES—DRIVEN CAST IN PLACE

7.4.1 Dimensional accuracy

Driven cast in place piles shall be constructed to the following limits of accuracy:

(a) *Cross-sectional dimensions* Not less than the specified dimensions at any point in the pile length.

(b) *Straightness* Tolerance on the straightness of the liner at the commencement of driving shall be 1/250 of the length of the liner. The tolerance on straightness of any portion and of the completed length of a pile shall be 1/100 of the length of the pile.

7.4.2 Liners

A driven cast in place pile shall be installed using a temporary or permanent liner, as follows:

(a) The liner shall be of tubular section and of sufficient thickness, strength and rigidity to prevent distortion by ground pressure or by forces induced during the installation process.

(b) The liner shall be free from significant distortion or any internal projections that might prevent the proper formation of the pile.

(c) If specified, the toe of the liner shall be fitted with a pile shoe, which shall be capable of withstanding the forces resulting from the installation process, and designed to provide a watertight joint with the liner.

(d) The liner shall be installed in accordance with Clause 7.3.3.

(e) Unless otherwise specified, soil inside the liner shall be removed prior to concreting. If the soil cannot be removed, the liner shall be withdrawn and re-driven.

7.4.3 Construction

During construction, the following shall be observed, where appropriate:

(a) Reinforcing steel shall be inserted into the liner and fixed in its correct position, coaxial with the liner and with the specified cover.

(b) Concrete shall be placed to fill the entire volume of the pile without the formation of voids caused by entrapped air or lack of compaction. The volume of concrete shall be recorded.

(c) Concrete shall be placed in such a manner that the position of the reinforcement is maintained.

(d) The concrete shall be placed in sufficient quantity and with sufficient fluidity to ensure that, if the liner is withdrawn, the concrete is not lifted with the liner and there is no separation of the concrete and no inflow of soil or water.

(e)   To avoid damage caused by ground heave and any other movement generated by driving, the sequence of pile installation shall be such that adjacent piles are not disturbed until the concrete in these piles has taken an initial set.

   NOTE: Typically, this will be within 6 to 15 pile diameters of adjacent piles, depending on ground conditions.

(f)   The location of the load applied to the soil by construction equipment shall be far enough away from the pile being installed and from recently constructed piles to avoid displacement or squeezing of the column of concrete.

7.5 DISPLACEMENT PILES—SCREWED CAST IN PLACE

7.5.1 General

Displacement screw piles are formed by screwing a purpose-designed auger head, connected to the end of a kelly bar system into the ground, displacing soil during installation. When the required founding depth has been reached, an end plate or sacrificial tip is dislodged from the auger head. Concrete is then pumped or placed into the kelly bar. The kelly bar is slowly withdrawn until it is fully removed from the soil, leaving a liquid column of concrete in the soil. Appropriate reinforcing steel is placed either immediately prior to concreting or upon completion of concreting, depending upon loading and proprietary piling system requirements.

7.5.2 Dimensional accuracy

Displacement cast in place screw piles shall be constructed to the following limits of accuracy:

(a)   *Cross-sectional dimensions*   Not less than the specified dimension at any point over the pile length. For helically shaped screw piles this shall apply to both the nominal root diameter and the diameter of the outer helix.

(b)   *Straightness*   The tolerance on straightness of any position and of the completed length of a pile shall be 1/100th of the length of the pile.

7.5.3 Construction

Displacement cast in place screw piles shall be installed in accordance with the following:

(a)   Unless specified otherwise, a pile shall be constructed up to ground surface level.

(b)   To avoid damage caused by ground heave and any other movement generated by driving, the sequence of pile installation shall be such that adjacent piles are not disturbed until the concrete in these piles has taken an initial set.

   NOTE: Typically, this will be within 6 to 15 pile diameters of adjacent piles, depending on ground conditions.

(c)   The location of the load applied to the soil by construction equipment shall be far enough away from the pile being constructed and from recently constructed piles to avoid displacement or squeezing of the column of concrete.

(d)   During drilling the kelly bar shall not be raised, to ensure that the sacrificial tip or end-plate shall not be dislodged, as this will allow soil and/or water to enter the kelly system.

(e)   A measure of the drilling resistance shall be made over the entire length of the pile during drilling.

(f)   Drilling shall continue until the required founding depth is obtained. Concreting shall commence immediately after augering or placement of reinforcing steel, as appropriate. Care shall be taken to ensure that the pressure of the concrete at the bottom of the auger is kept higher than the combined soil and water pressure acting at any depth over the pile.

(g) During concreting, the auger shall be slowly withdrawn by rotation. The direction of rotation will depend on the proprietary system being used. Auger extraction shall be smooth and at a constant rate to maintain a positive pressure at the bottom of the auger head. Should the extraction of the auger head be such that the concrete pressure is less than the soil and water pressure, the auger shall be withdrawn fully from the soil and the pile redrilled.

(h) The volume of concrete used in the piles shall be determined to an accuracy of 5% and recorded.

(i) The concreting operation shall be continuous and uninterrupted. Should interruptions occur, the auger head shall be redrilled back into the concrete for a minimum of 0.5 m.

(j) The measured volume of concrete placed in any pile shall be not less than 105% of the nominal volume of the pile.

(k) Unless otherwise specified, reinforcing steel shall be located centrally into the concrete column. Spacers shall be used to provide the necessary cover.

(l) After completion of each pile, precautions shall be taken to prevent objects from falling into the liquid concrete column.

7.5.4 Sampling and testing

During installation, samples shall be taken from the concrete in accordance with specified requirements to determine the characteristic strength.

Samples shall be cylinders taken and tested in accordance with AS 1012.

7.6 NON-DISPLACEMENT PILES

7.6.1 Dimensional accuracy

Unless otherwise specified, non-displacement piles shall be constructed to the following limits of accuracy:

(a) *Cross-sectional dimensions* Not less than the specified dimensions at any point in the pile length.

> NOTE: Where it is required that a socket be formed in material below the level to which a liner has been installed, it may be impracticable to construct the shaft and the socket to the same dimensions because of the clearance required for excavation equipment. Allowance should be made for this in the pile design.

(b) *Straightness* The tolerance on straightness of any portion, and of the completed length of a pile, shall be 1/100 of the length of the pile.

7.6.2 Support systems

To maintain stability of non-displacement piles in soil conditions that would otherwise collapse, an effective support system shall be used. The support system shall comply with the following:

(a) *Liners* The liners shall comply with the requirements of Clause 7.4.2.

(b) *Shoring* Shoring shall be of sufficient thickness, strength and rigidity to prevent distortion by ground pressure or by forces induced during the installation process. The dimensions shall be such as to enable the full pile cross-section to be formed without restriction.

(c) *Drilling fluids* The constituents of drilling fluids, including drilling muds or water, and the methods of mixing and circulation, shall be such as to provide stability of the shaft until it is filled with concrete as follows:

(i)   During construction of a pile, the level of the drilling fluid shall be maintained to ensure the stability of the excavation.

The level of the drilling fluid shall be maintained at least 1.0 m above the watertable at all times during the construction process.

(ii) When using drilling mud as the drilling fluid, tests to determine density, viscosity and pH value shall be undertaken at the commencement of the project and until a consistent working pattern is established. Thereafter, tests for density, viscosity and pH shall be carried out regularly. If there is a change in the established working pattern, an additional test for pH shall also be carried out.

(iii) The density, viscosity and sand content of the drilling fluid shall be such as not to impair the proper and complete placing of the concrete in the pile. A sample of fluid shall be taken from the base of the pile immediately prior to concreting to establish that these parameters are within acceptable limits.

(d)   *Continuous flight auger*   Support by continuous flight auger shall comply with the requirements of Clause 7.6.6.

7.6.3   Excavation of the pile shaft

Precautions to be considered when excavating a pile shaft include the following:

(a)   Excavation shall not take place close to other piles that have recently been cast, and which contain workable or unset concrete, if such excavation is likely to cause a flow of concrete or otherwise damage the pile. Unless specified otherwise, no pile shall be installed within three diameters of adjacent piles until the concrete or grout in these piles has taken initial set.

(b)   Where ground conditions are such that the ground near the top of the hole is unstable, then a liner not less than 1 m long shall be placed at the top of the pile excavation to prevent collapse of the soil. The liner shall extend 150 mm above the working level to prevent surface debris from entering the excavation during construction.

NOTE: Alternatively, a cast in place or precast concrete guide wall may be used to fulfil this purpose.

(c)   Water that has entered or infiltrated into a pile excavation shall be removed immediately prior to concrete placement, if practicable. If the inflow of water is sufficiently large to prevent such removal, the pile excavation shall be filled with water to at least 1 m above the ground watertable and concrete placed by tremie methods in accordance with Clause 7.6.5(i).

7.6.4   Base and shaft preparation

A pile shall be founded in and underlain by material such that the strength and serviceability design criteria for the pile are satisfied. Where soil or rock properties are found to be inferior to the design requirements, pile excavation dimensions shall be increased to satisfy the design criteria. Where specified, the material below the base shall be proved for a predetermined depth.

The pile shaft and base shall be cleaned of loose material and debris to ensure that the strength and serviceability criteria can be effectively satisfied.

7.6.5   Construction

During construction, the following requirements, where appropriate, shall be met:

(a)   Reinforcing steel shall be fixed in its correct position and with the specified cover.

(b)   Concrete shall be placed to fill the entire volume of the pile without the formation of voids caused by entrapped air, lack of compaction or segregation. The volume of concrete shall be recorded.

(c)   Concrete shall be placed in such a manner that segregation of the concrete does not occur and that the position of the reinforcement is maintained.

(d)   Unless otherwise specified, a pile constructed in a stable cohesive soil without the use of a temporary liner [other than that specified in Clause 7.6.3(b)] or other form of support shall be concreted as soon as practicable on the day the excavation is completed. The concrete shall be placed so that it does not cause the excavation to collapse or cause spoil or other foreign matter to contaminate the concrete.

(e)   The volume of concrete used in the pile shall be determined to an accuracy of 5% and recorded.

(f)   The measured volume of concrete placed in any pile shall be not less than 105% of the nominal volume of the pile.

(g)   The concrete shall be placed in sufficient quantity and with sufficient fluidity to ensure that, if the liner is withdrawn, the concrete is not lifted with the liner, there is no separation of the concrete and there is no inflow of soil or water.

(h)   For concrete that is cast under water or drilling fluid, concrete placement shall commence as soon as practicable after de-sanding and placement of the reinforcement. If delays in concreting occur, further desanding or recirculation prior to placement of concreting shall be considered.

(i)   Concrete that is cast under water or under drilling fluid by tremie or pump methods shall be placed without withdrawal of the tremie pipe or pump hose from the concrete during the concrete discharge. Concreting shall commence with the base of the tremie or pump hose on the bottom of the pile. Concrete placement shall continue with gradual withdrawal of the tremie or pump hose until all laitance and contaminated concrete is above the pile cut-off level. During concreting, the tremie or pump hose shall be embedded a minimum 2 m below the surface of the concrete over the duration of the pour. The depth of embedment of the tremie tube or pump hose shall be monitored and recorded over the full depth of the pour.

        Should the embedment of the tremie or pump hose be less than 2 m at any stage the tremie or pump hose shall be removed, resealed, recharged and reinserted below the surface of the concrete.

        Concrete placed by this method shall not be vibrated.

(j)   Concrete placed by tremie shall have a cementitious content of not less than 400 kg/m^3.

7.6.6 Continuous flight auger piles

7.6.6.1 *Installation*

A continuous flight auger pile shall be installed in accordance with the following:

(a)   Unless specified otherwise, a pile shall be constructed up to commencement level of drilling.

(b)   The sequence of pile installation shall be such that adjacent piles are not disturbed. Unless specified otherwise, no piles shall be installed within 3 diameters of adjacent piles until the concrete or grout in these piles has taken initial set.

(c)   The location of the load applied to the soil by construction equipment shall be far enough away from the pile being drilled and from recently constructed piles to avoid displacement or squeezing of the column of concrete or grout.

(d)   The diameter of the auger shall be not less than the specified pile diameter.

(e)   When the auger has reached the pile toe level, the pile hole shall be filled with concrete or grout in an uninterrupted operation during extraction.

(f)   During extraction, the auger shall not rotate in a direction counter to that used to advance the auger.

(g)   The rate of injection and rate of auger withdrawal from the soil shall be coordinated so as to maintain at all times a positive pressure at the lower end of the auger flight. The pressure in the delivery line shall be measured by a pressure gauge or similar approved device, which shall be visible at all times to the operator responsible for controlling the withdrawal of the auger.

(h)   The auger hoisting equipment shall be capable of withdrawing the auger smoothly and at a constant rate. Should injection pressure fall during extraction, the auger shall be immediately redrilled and the section of the pile where the injection pressure was reduced shall be reformed.

(i)   The pumping equipment shall incorporate a measuring device so that the volume of concrete or grout used in the piles can be determined with an accuracy of 5%.

(j)   The measured volume of concrete or grout placed in any pile shall be not less than 105% of the nominal volume of the pile.

(k)   Unless otherwise specified, reinforcing steel shall be inserted after construction of the concrete or grout column. In all soils, other than predominantly sandy types, spacers shall be used as required to provide the necessary cover to reinforcement.

(l)   After completion of each pile, precautions shall be taken to prevent objects from falling into the column of liquid concrete or grout.

7.6.6.2 *Sampling and testing*

During installation, samples shall be taken from the concrete or grout and tested to determine the characteristic strength.

For concrete piles, samples shall be in the form of cylinders taken and tested in accordance with AS 1012.

For grout piles, samples shall be in the form of cubes or cylinders tested in accordance with AS 1012.

7.7 RECORDS OF DATA

7.7.1 Displacement piles

7.7.1.1 *Driven displacement piles*

During the installation of driven displacement piles, the following information shall be recorded:

(a)   Date of driving the pile.

(b)   Location and dimensions of the pile.

(c)   Depth driven.

(d)   Characteristics of driving equipment.

(e)   Final penetration for the last 10 blows and temporary compression for one of the blows, or as specified.

(f)   Type and condition of the packing on the pile head and of the dolly or follower, if used.

(g)   Sequence of driving in pile groups.

(h)   Concrete mix properties and slump and volume, if applicable.

(i)   Any apparent deviation from specified location and inclination.

(j)   Any other relevant information.

A penetration record of blows per metre (or less) for the full length of the pile shall be taken for the first pile and other selected piles on the site.

7.7.1.2 *Jacked displacement piles*

During the installation of jacked displacement piles, the following information shall be recorded

(a)   Date of installation of the pile.

(b)   Location and dimensions of the pile.

(c)   Depth installed.

(d)   Characteristics of jacking equipment.

(e)   Type and condition of the packing on the pile head.

(f)   Sequence of installation in pile groups.

(g)   Concrete mix properties and slump and volume, if applicable.

(h)   Any apparent deviation from specified location and inclination.

(i)   Any other relevant information.

A penetration record of jacking force for the full length of the pile shall be taken for all piles.

7.7.1.3 *Cast in place screw displacement piles*

During the installation of cast in place screw piles, the following information shall be recorded:

(a)   Date and time of commencing auger drilling.

(b)   Locations and dimensions of the pile.

(c)   Drilled depth.

(d)   Unless specified otherwise, drilling resistance over the full depth of the pile. Drilling resistance may comprise penetration rates, drilling pressures, torque, etc., as appropriate for each piling system.

(e)   A record of the concrete volume placed over the full depth of the pile.

(f)   The time and duration of any delays during pile construction.

(g)   Any other relevant data.

7.7.2 Non-displacement piles

During the installation of non-displacement piles, the following information shall be recorded:

(a)   Date and time of commencing and completing the pile excavation.

(b)   Location and dimensions of the pile.

(c)   Excavated depth.

(d)   Installation method.

(e)   Details of the soils and rocks penetrated.

(f)   Details of any roughening of the shaft.

(g)   Nature and extent of base cleaning.

(h)   Continuous records of depth of trammie embedment, height or concrete within pile shaft and cumulative volume of concrete placed.

(i)   Concrete or grout mix properties and volume and slump, if applicable.

(j)   Method, date and time of end of excavation, commencement and completion of concreting or grouting, and whether any break occurred in the filling process.

(k)   Water level, if any, at the time of concreting or grouting.

(l)   Any other relevant information.

S E C T I O N   8   T E S T I N G

8.1 SCOPE

This Section applies to—

(a)   pile load testing to assess the pile serviceability;

(b)   pile load testing to assess design geotechnical strength;

(c)   pile load testing to assess ultimate geotechnical strength; and

(d)   pile load testing to confirm adequacy of construction methods;

(e)   pile shaft integrity testing.

> NOTE: Due to the uncertainty associated with the capacity of installed piles, it is advantageous to perform testing. Testing has the potential to provide information on the serviceability and ultimate limit states performance of piles. To reflect this, Section 4 provides for adjustment of the geotechnical strength reduction factor on the basis of the degree of testing.

8.2 GENERAL REQUIREMENTS

8.2.1 Selection and construction of test piles

Where test piles are nominated as representative piles in advance of construction or installation, those test piles shall be constructed in the same manner and to the same standard of construction used for the piles that they represent.

Where test piles may be nominated subsequently to construction or installation, the construction records shall be reviewed to select piles for testing with a view to establishing either the expected performance of the represented piles, or the lower-bound performance of the represented piles.

Piles that have anomalous construction records may also be tested in order to evaluate their individual conformance with the nominated acceptance criteria.

8.2.2 Effect of changed conditions

The result of a pile test is specific to the geotechnical and groundwater conditions at the time of the test. Changes in site conditions, such as excavation, filling or groundwater fluctuation may affect the performance of the pile. To the extent which such changes are known or predictable and are significant, they shall be taken into account in assessing the long-term performance of the pile.

8.2.3 Performance of the tests

Testing shall be performed following the procedures set out in this Section and the appropriate Appendix, as set out in Clauses 8.4, 8.5, 8.6, 8.7 and 8.8. Data shall be accurately recorded and a report prepared.

> NOTE: It is essential that a high degree of competence be employed in the use of test equipment, its set-up on site, the progress of the test, the accuracy of readings, the interpretation of the test data, and the preparation of the report.

8.2.4 Requirement to test

The following principles apply:

(a)   Pile testing to verify geotechnical strength and shaft integrity is encouraged, and testing benefit factors are specified in Clause 4.3.1 to allow the use of higher geotechnical strength reduction factors for such testing. If the design ultimate geotechnical strength ($R_{d,ug}$) is not verified by pile testing, the basic geotechnical strength reduction factor, as given in Clause 4.3.2, shall be adopted in design.

(b) Where the basic geotechnical strength reduction factor is 0.4 or less, no testing is required unless otherwise specified, e.g., for providing the adequacy of construction practices.

(c) Where the basic geotechnical strength reduction factor is greater than 0.4, the following testing shall be undertaken:

(i) In the absence of tests to verify design ultimate geotechnical strength, testing shall be performed to verify pile serviceability for all foundations with average risk rating of 2.5 or greater. The relevant acceptance criteria nominated in Clauses 8.4.3 and 8.5.2 shall apply. The minimum rate of testing will depend on the average risk rating, as tabulated in Table 8.2.4(A).

(ii) Testing shall be performed to verify the integrity of pile shafts. Assessment of pile shaft integrity may be by high-strain dynamic pile testing (see Clause 8.5), or other methods of integrity testing (see Clause 8.8).

NOTE: Low-strain head impact testing methods may not yet be able to assess the integrity of the full shaft length of a pile, e.g., long piles or piles socketed in rock.

(iii) The designer shall select the percentage of pile shafts to be tested for integrity from the range of values shown in Table 8.2.4(B) taking into consideration the average risk rating of the site, the type of pile and method of pile construction, the degree of installation monitoring to be carried out, and the ratio of design action effect to the factored structural strength of the pile shaft.

TABLE 8.2.4(A)

PILE TESTING REQUIREMENTS FOR SERVICEABILITY

Average risk rating	2.50–2.99	3.00–3.49	3.50–3.99	4.00–4.49	≥4.5
Percentage of piles to be tested for serviceability	1	2	3	5	10

TABLE 8.2.4(B)

PILE SHAFT INTEGRITY TEST REQUIREMENTS

Pile type	Lower range of integrity testing (5 to 15% of piles tested)	Upper range of integrity testing (15 to 25% of piles tested)
Preformed single length piles installed by driving, jacking or screwing	Design load governed by pile geotechnical capacity	Design load governed by pile shaft structural capacity
Segmental preformed piles installed by driving, jacking or screwing	Full moment and tension joints, design load governed by geotechnical capacity, construction monitoring carried out	Simple compression only joints, design load governed by pile shaft structural capacity
Bored piles with no temporary shaft support required (dry stable non-water-bearing holes)	Design load governed by pile geotechnical capacity	Design load governed by pile shaft structural capacity
Bored using temporary casing or drilling fluid for shaft support and tremie poured	Design load governed by pile geotechnical capacity, careful construction control with full records of testing of drilling fluid, base cleaning and concrete tremie pouring	Design load governed by pile shaft structural capacity, minimal construction records
CFA or partial displacement screw piles	Design load governed by pile geotechnical capacity, full comprehensive installation monitoring	Design load governed by pile shaft structural capacity

NOTES:

1   The Designer shall consider all of the relevant factors listed in the above Table, not just one, in selecting the percentage of piles to be tested.

2   Consider using upper range of testing percentages with high average risk rating sites.

3   High-strain dynamic pile tests carried out to verify pile serviceablility loads may also be considered in the percentage of piles to be tested for shaft integrity.

4   Integrity test methods capable of testing the entire length of the shaft, or at least that part of the pile shaft where the ultimate pile axial load is in excess of 50% of the shaft structural capacity, are preferred.

8.3 PILE LOAD TESTING

8.3.1 Types of pile load testing

The appropriate pile load test shall be selected from one or more of—

(a)   static testing—

(i)   compression test;

(ii)   tension test; and

(iii)   lateral load test;

(b)   high-strain dynamic testing;

(c)   rapid load testing; and

(d)   integrity testing.

8.3.2 Information required

When a pile load test is required, the type of testing and associated details shall be specified in a schedule of load test requirements (see Figure A1 in Appendix A), hereafter called 'The Schedule'.

NOTE: The information listed in Figure A1 may be provided on the design drawings.

8.3.3 Test load

8.3.3.1 *General*

The test loads (P_s, P_g) shall be as specified in the schedule or, where not specified, shall be the nominated values in Tables 8.3.3.2 or 8.3.3.3.

Where the purpose of the test is to measure the ultimate geotechnical strength, the test load P_u shall be estimated in advance. Sufficient allowance shall be made in all aspects of the test set-up for the actual value to exceed the estimate. Under no circumstances shall the load P_u cause the structural strength of the section to be exceeded, taking into account any relative eccentricity or load inclination of the applied load from the central pile axis.

Where maximum test loads applied, for tension or for lateral load tests, are higher than the default values specified in Tables 8.3.3.2 and 8.3.3.3, consideration shall be given to the potential effects of permanent pile deflection on pile performance.

8.3.3.2 *Without negative friction*

The test loads (P_u, P_s, P_g) shall be as specified, or where not specified, shall be as set out in Table 8.3.3.2.

TABLE 8.3.3.2

TEST LOADS WITHOUT NEGATIVE FRICTION

P_s	$=$	E_{ds}
P_g	$=$	E_d/ϕ_g for compression load testing
	$=$	$1.2E_d$ for tension or lateral load testing
P_u	$=$	$R_{t,ug}$ ultimate geotechnical strength of a pile as assessed from a pile load test to geotechnical failure

where

E_{ds}	$=$	design action effect under serviceability actions
P_s	$=$	load for assessment of pile serviceability
E_d	$=$	design action effect under ultimate limit state actions
ϕ_g	$=$	geotechnical strength reduction factor for single piles or pile groups
$R_{t,ug}$	$=$	tested ultimate geotechnical pile capacity
P_u	$=$	load for assessment of ultimate geotechnical strength
P_g	$=$	load for assessment of design geotechnical strength

NOTE: Where maximum test loads applied for tension or lateral load tests are higher than the default values specified above, consideration shall be given to the potential effects of permanent pile deflection on pile performance.

8.3.3.3 *Where negative friction is expected to occur*

Where the test pile is in ground undergoing settlement that will develop negative friction on the pile, the test may be undertaken with the pile either isolated from, or in contact with, the ground undergoing long-term settlement. The serviceability test load shall be as set out in Table 8.3.3.3.

TABLE 8.3.3.3

TEST LOADS WITH NEGATIVE FRICTION

P_s	=	E_{ds} for compression tests on piles isolated from the ground undergoing long-term settlement
P_s	=	$E_{ds} + 2F_{nf}$ for compression tests on piles in contact with the ground undergoing long-term settlement
P_u	=	$R_{t,ug}$
P_g	=	To be determined for compression testing by taking into account the required ultimate strength in the stable zone (see Clause 4.6.3) and making due allowance for the shaft resistance that will occur through the settling ground above the stable zone during the relatively short duration of the load test
	=	$1.2E_d$ for tension or lateral load testing

where

P_s	=	load for assessment of pile serviceability
P_u	=	load for assessment of ultimate geotechnical strength
P_g	=	load for assessment of design geotechnical strength
E_{ds}	=	design action effect under serviceability actions
F_{nf}	=	maximum pile load due to negative friction
$R_{t,ug}$	=	tested ultimate geotechnical pile capacity

NOTE: There are a number of alternative strategies that can be employed in order to test piles that are expected to experience loading from settling ground during the structure's life. These include the following:

(a) Isolating the pile from the settling ground by pre-boring or sleeving is the preferred option.

(b) Compensating for the effects of the soil loading, by adopting a serviceability load of $E_{ds} + 2F_{nf}$ as shown in Table 8.3.3.3.

(c) Instrumenting the test pile along its length to evaluate shaft resistance distribution.

(d) Undertaking high-strain dynamic pile testing in accordance with Clause 8.4 to evaluate shaft resistance distribution.

8.3.3.4 *Hammer energy*

For high-strain dynamic pile testing, the hammer energy shall be sufficient to mobilize a pile soil resistance equivalent to the maximum test loads given in Table 8.3.3.2 (i.e., $P_g = E_d/\phi_g$) or in Table 8.3.3.3 where negative friction is expected to occur.

8.3.4 Acceptance of piles

The criteria for acceptance of test piles shall be in accordance with Clauses 8.4, 8.5, 8.6, 8.7 or 8.8, as appropriate. Piles not meeting these criteria shall be considered as defective piles in accordance with Clause 7.2.5. Piles deemed to be represented by the test pile shall also be reassessed accordingly.

Only tests performed on piles meeting the relevant acceptance criteria shall be considered to be valid tests. One of more valid tests shall be undertaken in substitution for any test on a pile that fails to meet the relevant acceptance criteria.

8.3.5 Effects of test set-up

Account shall be taken of the effects of the test set-up when interpreting the results of pile load testing.

Test set-ups such as those involving the use of reaction piles or kentledge may influence the behaviour of the test pile and the effects of the reaction systems shall be allowed for in interpreting the pile load-settlement behaviour.

8.4 STATIC LOAD TESTING

8.4.1 Use of static loading

Unless otherwise specified in the schedule of load test requirements, an incremental maintained static load test procedure, as given in Clause 8.4.2 and Appendix A shall be used to assess the performance of a pile foundation under the design serviceability limit state and the design geotechnical ultimate limit state, or to determine the ultimate geotechnical strength of the pile foundation.

Static load testing shall be carried out in accordance with the appropriate test procedure given in Appendix A.

Static load testing shall be used to—

(a)   evaluate pile performance at preliminary or later stages of work; or

(b)   proof-test nominated piles as work proceeds.

8.4.2 Test procedure

8.4.2.1 *Proof load test*

The primary objectives of this test are as set out in Table 8.4.2.

The test shall be performed using the load schedule for compression, tension or lateral loading as detailed in Appendix A.

Where a pile must sustain significant cyclic or surge loading, an appropriate loading sequence shall be included, which will allow the assessment of the additional displacements under these loads.

The test pile shall be designed to safely carry the applied load without exceeding its structural strength.

NOTES:
1   Due account should be taken of bending moments resulting from the possible eccentricity of the test load in determining the maximum test load to be applied to the pile head.
2   The load schedule may be varied by specifying an alternative loading program in the schedule (see Figure A1, Appendix A).

8.4.2.2 *Ultimate geotechnical strength test*

The primary objective of this test is to determine the ultimate geotechnical strength of the pile ($R_{t,ug}$) as set out in Table 8.4.2.

The test shall be performed using the load schedule for compression, tension or lateral loading as detailed in Appendix A.

The test pile shall be designed to safely carry the applied load without exceeding its structural strength.

NOTES:
1   Due account should be taken of bending moments resulting from the possible eccentricity of the test load in determining the maximum test load to be applied to the pile head.
2   The load schedule may be varied by specifying an alternative loading program in the schedule (see Figure A1, in Appendix A).

TABLE   8.4.2

TYPES OF STATIC LOAD TEST

Test type	Main assessment objectives	Applied test load
Proof	Deflection of pile at serviceability load	See Clauses 8.3.3.2 and 8.3.3.3
	Confirmation of design ultimate geotechnical strength and corresponding deflection	
Ultimate	Ultimate geotechnical strength of pile	$P_u = R_{ug}$

8.4.3 Acceptance criteria

8.4.3.1 *Proof tests*

The pile performance under compressive test loading shall be deemed to comply with this Standard provided all the criteria specified in the schedule or in Table 8.4.3.1 are satisfied. Any criteria specified in the schedule shall take precedence over the values in Table 8.4.3.1.

Where the pile is subjected to negative skin friction, limits on the maximum movement of the test pile when loaded to the serviceability load shall be specified as part of the pile test acceptance criteria, taking into account the provisions for negative friction of Clause 4.4.5.

For tension and lateral load tests, the acceptance criteria shall be specified prior to the test.

If the acceptance criteria are not met, then a reassessment of the design geotechnical strength shall be made.

NOTES:

1   The acceptance criteria for a pile in service will usually depend on structural considerations and the default values in Table 8.4.3.1 should be reviewed in relation to the structural requirements.

2   When specifying acceptance criteria for tension tests it should be noted that the movements to mobilize the ultimate geotechnical strength may be small.

TABLE   8.4.3.1

ACCEPTANCE CRITERIA—COMPRESSION PROOF LOAD TEST

Load	Maximum deflection mm
$P_s = E_{ds}$ (Clause 8.3.3.2)	$P_s L/AE + 0.01d$ [1]
$P_s = E_{ds} + 2 F_{nf}$ (Clause 8.3.3.3)	$P_s L/AE - 0.5 F_{nf} L_{nf}/AE + \text{max. } (0.01d_t, 5)$
0 (after removing P_s)	Max. $(0.01d_t, 5)$
P_g	$P_g L/AE + 10 + 0.05d$
0 (after removing P_u)	$10 + 0.05d$

NOTES:

1   Movement to include no more than 2 mm creep over 3 h 45 min (after load has been in place for 15 min).

2   The effect of group loads on settlements shall be considered when specifying the acceptable settlement of a single pile.

3   Alternative acceptance criteria may be required in assessing the performance of piles installed through settling ground.

4   d_t is the pile base diameter and, for steel screw piles, shall be taken as the steel flange diameter, not the lesser shaft diameter.

5   L_{nf} is the length of the test pile in contact with ground expected to undergo long-term settlement. For a test pile isolated from this settling ground $L_{nf} = 0$.

6   Max $(0.01d_t, 5)$ is the greater of $0.01d_t$ and 5 mm.

8.4.3.2 *Ultimate geotechnical strength tests*

Acceptance criteria are not relevant for these tests as the primary aim of these tests is to measure the load-deformation response up to the ultimate geotechnical strength and assess the latter.

8.4.3.3 *Tension tests*

The acceptance criteria for tension load tests shall be specified prior to the test.

> NOTE: When specifying the acceptance criteria for tension piles that develop their capacity principally by skin friction, it should be noted that the movements to mobilize the ultimate geotechnical strength may be small.

8.4.3.4 *Lateral tests*

The acceptance criteria for lateral load tests shall be specified prior to the test. The effects of the fixity of the pile head during a lateral test (usually free) compared to the fixity in service (often partially restrained or fixed) shall be considered when establishing the acceptable deflection limits.

8.4.3.5 *Definition of ultimate geotechnical strength*

The pile test measurement of ultimate geotechnical strength of the pile ($R_{t,ug}$) shall be the greater of—

(a)   the maximum pile-top load which can be sustained for a period of 10 min; and

(b)   the pile-top load corresponding to a pile-top deflection limit, which would cause failure of the supported structure.

In the absence of a structure-specific estimate of the pile-top deflection causing failure of the supported structure, the pile-top deflection limit shall be no greater than $0.05D$ for preformed and installed piles and $0.10D$ for cast in place piles.

The maximum safe test load shall be determined by consideration of both the overall stability of the test arrangement and of the structural capacity of the pile including appropriate allowances for eccentricity and misalignment.

If the maximum safe test load is applied at a deflection less than the pile-top deflection limit, the maximum safe test load shall be adopted as the ultimate geotechnical strength of the pile ($R_{t,ug}$).

8.5   HIGH-STRAIN DYNAMIC PILE TESTING

8.5.1   General

High-strain dynamic pile testing, which mobilizes all or part of the available pile static capacity, shall be used when specified or required for any of the following:

(a)   To proof-test nominated piles as work proceeds

(b)   To predict the ultimate geotechnical strength at a preliminary or later stage of work.

(c)   To provide an indication of resistance distribution.

(d)   To monitor pile stresses during installation (and thus avoid pile damage).

(e)   To assess hammer energies and confirm input for driving formulae.

(f)   To estimate and confirm parameters used in wave equation analysis.

(g)   To check assumptions made concerning pile driveability.

(h)   To assess pile integrity.

High-strain dynamic pile testing shall be carried out in accordance with Appendix B.

8.5.2 Acceptance criteria

Where acceptance criteria are not specified in the schedule, the pile head movements at P_s and P_g, calculated from analysis of dynamic test data, shall not exceed those given in Table 8.5.2.

Any criteria specified in the 'Schedule' shall take precedence over the above values.

TABLE 8.5.2

ACCEPTANCE CRITERIA—HIGH-STRAIN DYNAMIC LOAD TEST

Load	Maximum deflection mm
$P_{s\,=\,}E_{ds}$ (Clause 8.3.3.2)	$P_sL/AE + \mathrm{max.}\,(0.01d_t, 5)$
$P_s = E_{ds} + 2F_{nf}$ (Clause 8.3.3.3)	$P_sL/AE - 0.5F_{nf}L_{nf}/AE + \mathrm{max.}\,(0.01d_t, 5)$
0 (after removing P_s)	Max. $(0.01d_t, 5)^6$
P_g	$P_gL/AE + 10 + 0.05d_t$
0 (after removing P_g)	$10 + 0.05d_t$

NOTES:

1. Alternative acceptance criteria may be required in assessing the performance of piles installed through settling ground.

2. The effect of group loads on settlements shall be considered when specifying the acceptable settlement of a single pile.

3. 'd_t' is the pile base (toe) diameter, and for steel screw piles shall be taken as the steel flange diameter, not the lesser shaft diameter.

4. 'L_{nf}' is the length of the test-pile in contact with ground expected to undergo long-term settlement. For a test-pile isolated from this settling ground, $L_{nf} = 0$.

5. Max. $(0.01d_t, 5)$ is the greater of $0.01d_t$ and 5 mm.

6. This deflection is the measured set after dynamic testing to serviceability load.

7. In the absence of more detailed analysis, the pile head deflection should be taken as the accumulated permanent displacement over all blows delivered prior to the blow selected for analysis.

8.6 BI-DIRECTIONAL LOAD TESTING

8.6.1 General

Bi-directional load tests are non-destructive tests that are carried out by the reaction supplied by one or more sacrificial hydraulic jacks cast into the pile. The most common configuration of jacks involves casting of the required number of jacks at the base of the pile; however, series of jacks may be cast at any level in the pile shaft depending on test requirements.

Bi-directional testing measures the vertical displacement of the pile shaft and the load inducing that displacement. Similarly, end-bearing resistance is determined by measuring the load versus movement characteristics of the pile when a jack is placed at or near the pile toe.

8.6.2 Performance criteria

The test is usually performed to determine ultimate capacity. Performance criteria in those circumstances shall be specified prior to the test being carried out.

For bi-directional tests performed on all piles other than those tested for ultimate capacity, unless otherwise specified, the interpreted load-settlement curve of the pile head from the tests shall be deemed to comply with this Standard provided the criteria in Table 8.4.3.1 are satisfied.

8.7　RAPID LOAD TESTING

8.7.1　General

Rapid pile loading tests produce a force on a foundation by imparting a long force pulse to the foundation by means of impact of a cushioned dropped mass or reaction against an accelerating mass.

Rapid pile testing may be used on individual vertical or inclined piles or pile groups for the following:

(a)　Evaluating the response under axial compression loads. Results may be used to estimate the static load-movement performance and soil damping characteristics of a foundation.

(b)　Evaluating performance under lateral loading (e.g., to simulate loads resulting from impact, wind, earthquake and other transient forces).

The test may be used at preliminary or late stages of work or as a proof-test on nominated piles or pile groups during the piling work.

Rapid load testing shall be carried out in accordance with Appendix C.

8.7.2　Acceptance criteria

The pile performance shall be deemed to comply with this Standard provided criteria in Clause 8.5.2 are satisfied.

8.8　INTEGRITY TESTING

8.8.1　General

Pile integrity testing is a method of testing a pile as installation proceeds with the aim of indirectly assessing one or more of the following:

(a)　The structural integrity of the pile.

(b)　The relative shape of the pile shaft and an estimate of the physical dimensions of the pile, or both.

(c)　The pile length.

(d)　The continuity of the pile.

(e)　Characteristics of the low strain pile-soil system response.

Where specified or adopted in the selection of structural strength reduction factors used in design or required under Clause 8.2.4, pile integrity testing shall be performed in accordance with Appendix D.

8.8.2　Test procedure

Where integrity testing is required, the test to be adopted shall be one of the following:

(a)　Pulse echo method.

(b)　Impulse response method.

(c)　Sonic logging method.

(d)　Alternative tests as specified.

8.8.3 Acceptance criteria

The pile shall be deemed to have satisfactory integrity provided the results do not indicate likely impediment of the ability of the pile to perform its intended function.

    NOTE: Examples of impediment of integrity include—

(a)   a lack of structural integrity;

(b)   disadvantageous change in physical dimensions; or

(c)   discontinuity or inconsistency in materials used for the pile.

Where the pile is not deemed to have satisfactory integrity, further integrity investigation shall be carried out using an alternative procedure.

Further investigation may include one or more of the following:

(i)   Retrimming of the pile head and retesting.

(ii)   Excavation to permit visual inspection at the depths where discontinuities are indicated.

(iii) Coring of the pile.

(iv)   Load testing.

Should the results of these further investigations indicate the pile to not be satisfactory, remedial works shall be carried out. This work may include—

(A)   replacement of the pile;

(B)   post grouting of the pile shaft; and

(C)   providing a structural solution, for example, bridging beams to ensure that loads are supported satisfactorily.

APPENDIX A

STATIC LOAD TEST

(Normative)

A1 GENERAL

This Appendix sets out test methods for proof and geotechnical ultimate static load tests.

Details of the testing procedure and any modification shall be set out on the 'Schedule of load test requirements' A typical form for schedule of load test requirements is shown in Figure A1.

A2 PREPARATION AND APPARATUS

A2.1 Preparation for testing

The pile head shall be prepared to allow application of the load coaxial with the pile axis for compression or tension tests and perpendicular to the pile axis for a lateral load test. The preparation shall enable the test load to be transmitted to the pile (e.g., through a steel bearing plate or other arrangement) with negligible local damage or distortion to the pile head.

NOTE: Any extension of the pile for the purpose of carrying out the test should be coaxial with the original pile and be of sufficient strength to sustain the proposed test loading.

A2.2 Reaction system

The test load shall be applied to the pile by jacking against a reaction system. The resultant force shall be coaxial with the pile for tension and compression tests and perpendicular to the pile for lateral load tests.

The reaction system may comprise ground or rock anchors, kentledge or reaction piles.

The reaction system shall be stable and shall provide safe access as required for testing personnel.

Minimum distances from the test pile centre-line to anchorages, kentledge supports and reaction piles shall be as follows:

(a) *Anchorages*   Where ground anchors are used to provide a test reaction—

   (i)   no part of the bonded section of the anchor shall be closer to the centre-line of the pile than 3 times the shaft diameter of the pile; and

   (ii)   where the test pile has an enlarged base, no part of the bonded section of the anchor shall be closer to the pile base centre-line than a distance equal to the base diameter.

   NOTE: If two anchors are used, one at each end of the loading beam, precautions should be taken to prevent any tendency for lateral buckling of the beam.

(b) *Kentledge*   Where kentledge is used to provide a test reaction—

   (i)   loads shall not be applied by supporting the kentledge directly on the pile or pile cap;

   (ii)   no part of the kentledge support system shall be closer to the pile centre-line than a distance of 2.5 times the shaft diameter of the pile; and

(iii) the weight of the kentledge shall be transferred to the ground in a manner such that—

    (A) the load is transferred symmetrically around the pile head;

    (B) the stability of the kentledge is maintained at all times; and

    (C) any tendency of the kentledge to tilt or sway is minimized.

(c) *Reaction piles* Where reaction piles are used to provide a test reaction, the centre-to-centre spacing between vertical reaction piles and the test pile shall be not less than the greater of—

    (i) 5 times the test pile diameter; and

    (ii) 2.5 m.

NOTES:

1　Non-displacement piles should be used to provide reaction for test loading in preference to displacement piles. Non-displacement piles may be installed before or after the pile to be tested.

2　If displacement reaction piles are to be used then, wherever practicable, they should be installed prior to the installation of the test pile.

3　Where a working pile is used as a reaction pile that is loaded in tension, displacement of the pile should be monitored throughout the test, and appropriate measures (e.g., redriving the pile) should be taken to ensure that any permanent displacement of the reaction pile does not affect its in-service performance.

4　Where reaction piles are used, the design of the reaction piles should consider potential interaction with the test pile and, if possible, the zones where soil resistance is developed for the test pile and the reaction piles should be separated as far as practicable. It is preferable that reaction anchors with anchor zones located below the tip of the test pile are used, rather than reaction piles.

Departures from these minimum distances shall be permitted provided an assessment of the interaction between the test pile and the reaction system is made. Details of any such interaction assessment shall be included in the pile test report.

A2.3　Equipment for loading and test measurement

A2.3.1 *General*

Equipment for applying the test load shall—

(a) have a load capacity not less than the maximum required load specified in the Schedule;

(b) be capable of accommodating the maximum required pile movement specified in the Schedule plus the displacement of the reaction system that occurs during loading;

(c) be capable of applying a controlled increase or decrease in load; and

(d) be capable (in the case of a sustained load test) of maintaining a constant load for the specified period.

A2.3.2 *Measurement of load*

Load cells shall be used to measure load and shall maintain stable calibration during testing.

The load measuring device shall—

(a) unless otherwise specified, be accurate to within 2% of the indicated load and of stable construction; and

(b) have a calibration certificate issued within the preceding six months.

NOTE: A calibrated jack and manometer system is not considered to fulfil the requirements of this Clause.

SCHEDULE OF LOAD TEST REQUIREMENTS

This schedule shall be completed where applicable.

1 **Pile type and size:**_____

2 **Method of installation:** _____

3 **Type of test:**_____

    (1)   Compression test.

    (2)   Tension (uplift) test (detail in Item 6 below if requirements differ).

    (3)   Lateral load test (detail in Item 7 below if requirements differ).

    (4)   Other (e.g., dynamic testing), as detailed in Item 8 below.

4 **Maximum load and pile movement:**

    (1)   The loading system shall have a capacity of at least......................................kN.

    (2)   The overall loading and measuring system shall be capable of accommodating a pile movement (measured at the pile head or cap) of at least........................mm.

    (3)   Movement shall be measured with a system capable of delivering an accuracy of ....0.1 mm.

5 **Commencement of loading:**

The minimum period between installation of the test pile and commencement of the pile test shall be.. days.

6 **Tension (uplift) load test program:**

    _____

    _____

    _____

7 **Lateral load test program:**

    _____

    _____

8 **Requirements different from or additional to those specified in AS 2159:**

    _____

    _____

9 **Acceptance criteria (if different from Section 8):**

    _____

    _____

10 **Required qualifications of persons to supervise and carry out the testing:**

    _____

    _____

FIGURE A1 SCHEDULE OF REQUIREMENTS—EXAMPLE

A2.3.3 *Measurement of pile displacement*

The following shall be observed:

(a) *General* The displacement of the pile shall be monitored by precise levelling or by a system of dial gauges, or electrical transducers in conjunction with a reference frame in order to provide an accurate measure of the absolute displacement and any rotation or tilt of the pile head. The displacement measuring devices shall—

    (i) be accurate to within the lesser of 0.1% of the pile shaft diameter and 0.1 mm;

    (ii) have sufficient travel to accommodate the maximum pile head movement or the required differential displacement between the test pile and a reference frame; and

    (iii) be shielded from direct sunlight or other environmental influences.

Where dial gauges or electrical transducers are used, a minimum of three such gauges or transducers, spaced equally around the pile and equidistant from the axis of loading, shall be utilized.

NOTE: Approximate pile head displacements may additionally be determined using two parallel reference wires, one on either side of the pile, and held under constant tension. The wires should be positioned against scales fixed to the pile head. Supports for the reference wires should conform to the requirements for the reference frame (given in Item (b) below).

(b) *Reference frame* Pile displacements may be measured relative to a reference frame that is independent of the reaction system and the test pile. The reference frame shall be—

    (i) shielded from the direct sunlight or other environmental influences;

    (ii) sufficiently robust to minimize distortion due to temperature differences;

    (iii) mounted preferably a minimum of five pile shaft diameters from the pile and any part of the reaction system, to minimize ground movement effects; and

    (iv) checked for movement by independent levelling during the test with such movements applied as a correction to the apparent pile head movements.

(c) *Level datum* A level datum shall be established on a permanent object or other well-founded structure or deep datum point. Movements of the pile head or the reference frame shall be related to this datum using a precise level located approximately equidistant from the datum and the test.

A secondary measurement system shall be used throughout the test to check that there has been no displacement in the reference frame.

A3 LOADING PROGRESS AND RECORDING OF DATA

A3.1 General

The application of test loads to the pile shall be as given in Table A1 for proof and ultimate tests unless other wise prescribed in the schedule. The test loads P_s, P_g and P_u shall be computed by reference to Table 8.3.3.2 for test loads without negative friction, or Table 8.3.3.3 for test loads with negative friction.

A3.2 Load application

Following application of each increment, the load shall be sustained at a constant magnitude until the rate of movement of the pile head is less than 0.5 mm per 15 min, commencing 5 min after applying any load increase, but in no case less than the minimum specified holding time.

TABLE A1

LOADING PROGRAM—COMPRESSION TEST PROCEDURE

	Load	Minimum load duration Min
Stage S1 (proof and ultimate tests): Loading to P_s	20% P_s	20 min
	40% P_s	20 min
	60% P_s	20 min
	80% P_s	20 min
	100% P_s	4 h
Stage S2 (proof and ultimate tests): Unloading from P_s	30% P_s	10 min
	0% P_s	20 min
Stage G1 (proof and ultimate tests): Loading to P_g	30% P_g	20 min
	40% P_g	20 min
	50% P_g	20 min
	60% P_g	20 min
	70% P_g	20 min
	80% P_g	20 min
	90% P_g	20 min
	100% P_g	1 h
	110% P_g	20 min
	Further increments of 10% P_g	20 min each increment
Stage U1 (ultimate tests only): Loading to P_u	P_u or maximum allowable test load	Hold only if P_u exceeds maximum available test load
Stage U2 (ultimate tests only): Unloading from to P_u	0	10 min
Stage G2 (proof and ultimate tests): Unloading from P_g	Loading decrements of 20% P_g	10 min each decrement
	100% P_g	10 min
	80% P_g	10 min
	60% P_g	10 min
	40% P_g	10 min
	20% P_g	10 min

TABLE A2

LOADING PROGRAM—LATERAL OR TENSION TEST PROCEDURE

	Load	Minimum load duration Min
Stage S1 (proof and ultimate tests): Loading to P_s	20% P_s	10 min
	40% P_s	10 min
	60% P_s	10 min
	80% P_s	10 min
	100% P_s	1 h
Stage S2 (proof and ultimate tests): Unloading from P_s	50% P_s	10 min
	0% P_s	10 min
Stage G1 (proof and ultimate tests): Loading to P_g, where $P_g = 1.2E_d$ (see Table 8.3)	30% P_g	10 min
	40% P_g	10 min
	50% P_g	10 min
	60% P_g	10 min
	70% P_g	10 min
	80% P_g	10 min
	90% P_g	10 min
	100% P_g	1 h
Stage G2 (proof and ultimate tests): Unloading from P_g	80% P_g	10 min
	60% P_g	10 min
	40% P_g	10 min
	20% P_g	10 min
	0% P_g	10 min

A3.3   Recording during the loading stages

Simultaneous records of load, pile head movement and time shall be taken—

(a)   immediately upon reaching the load;

(b)   at intervals of 1, 2 and 5 min and, where appropriate, 10 and 15 min after reaching load;

(c)   where appropriate, at 15 min intervals thereafter up to 1 h;

(d)   where appropriate, at 30 min intervals after 1 h; and

(e)   immediately prior to each load application.

Check measurements of the reference frame shall be taken at the end of each loading increment.

During the test, graphs shall be made of load versus time and movement versus time as an aid to monitoring pile and pile test performance. Such graphs may be used to detect instability in the pile or reaction system and to modify or abort the test.

A3.4   Recording during unloading stages

During unloading stages, as a minimum, the load, movement and time shall be recorded immediately on reaching the load decrement and immediately prior to the removal of the next load decrement.

A4 REPORT

A report shall be prepared containing all relevant information including the following:

(a) Description of the static test procedure.

(b) Details of any available site investigation data at or near the test location.

(c) A description of the test pile.

(d) A description of the forming or driving of the pile.

(e) The results of any testing of pile materials.

(f) Details of the test reaction system, including any technical assessment made of the effects of the reaction system on potential pile performance.

(g) Details of the measurement system and reference frame.

(h) Type of loading schedule carried out or details of the procedure adopted.

(i) A record of the time, test load and pile head movement relationship throughout the test. The record shall clearly indicate whether the results are uncorrected readings or readings that have been corrected for calibration, movement of datum points, or other influences.

(j) Where specified, an interpretation of the results of the test.

(k) Reference to this test method, i.e., Appendix A, AS 2159.

APPENDIX B

HIGH-STRAIN DYNAMIC PILE TESTING

(Normative)

B1 GENERAL

This Appendix sets out test methods for high-strain dynamic testing of piles to test performance under serviceability load and/or to demonstrate a strength above serviceability load, up to the ultimate geotechnical strength of the pile.

The test load (P_s, P_g or P_u) shall be as given in Clause 8.3.3 and acceptance criteria as given in Clause 8.5.

Details of the testing procedure and any modification shall be set out on the 'Schedule of load test requirements' A typical form for the schedule of load test requirements in given in Figure A1.

B2 PILE PREPARATION

Pile preparation for testing shall include all practical steps to ensure that the hammer and pile are aligned to prevent bending of the pile during the test blows, and that the hammer strikes a flush sound surface perpendicular to the pile axis. The pile head should be capable of withstanding the bursting stresses generated at the pile head during hammer impacts.

NOTE: Where possible, transducers should be attached to the pile shaft a minimum of 1.5 diameters below the pile head.

B3 HAMMER ENERGY

The dynamic pile test shall be carried out using hammer energy sufficient to mobilize the pile strength requirements as described in Clause 8.5 or as otherwise specified in the Schedule.

The ultimate geotechnical strength of the pile will only be measured if sufficient energy is delivered to the pile in a single blow to mobilize all of the available pile shaft and base resistance. If sufficient impact energy is not available, other methods of analysing the dynamic data shall be used to estimate the ultimate geotechnical strength.

B4 NEGATIVE FRICTION

Where the test pile is in ground undergoing settlement that will develop negative friction on the pile, the dynamic test shall include rigorous analysis using full signal matching. Sufficient impact energy shall be applied to the pile to mobilize resistance in the stable zone of the test pile, at least equal to the ultimate geotechnical strength requirement in the stable zone (see Clauses 4.4.5 and 4.6.3). The amount and distribution of shaft resistance in the unstable zone shall be estimated by signal matching.

NOTE: The shaft friction distribution shall be compared with that obtained from design to assess the reasonableness of the estimate.

B5   TIME AND PURPOSE OF TESTING

Dynamic testing may be carried out during pile installation (driving or end of driving test) or at any time thereafter (restrike test).

NOTES:

1   Testing during pile driving sequences is encouraged in order to establish hammer performance, monitor compression and tension stress levels, driving plans and acceptance criteria.

2   The long-term geotechnical strength of the pile may be predicted by dynamic testing during installation, but is generally more reliably predicted by restrike testing.

3   Restrikes should preferably be undertaken 24 h or more after initial driving.

B6   APPLICATION OF DYNAMIC TESTING

Dynamic pile testing was developed primarily for the evaluation of preformed driven piles of uniform section during driving or on restrike.

NOTES:

1   This testing technique has been successfully applied to other pile types, including timber piles (tapered) and cast in place piles. The successful interpretation and analysis of such piles has to be accompanied by reliable information on the pile geometry.

2   The dynamic interaction of screw pile flanges with soil is complex and poorly understood. The use of high-strain dynamic pile testing of screw piles should only be accepted in combination with static load testing, and where a reliable correlation between the two testing methods for the particular site and screw pile geometry can be demonstrated.

B7   INSTRUMENTATION

The instrumentation for a dynamic pile test shall consist of a sufficient number of transducers, arranged around the pile, to reliably establish the average section transient strain (or force) and acceleration (or velocity or displacement). The transducer signals shall be recorded for subsequent analysis. Four-strain transducers shall be used for spiral welded and cast in place piles.

All transducers shall be calibrated at least every 2 years, and immediately following any repairs. Any instrumentation used in situations where overstressing has occurred, or is suspected, shall be checked to determine if calibration is necessary before further use.

B8   TEST PROCEDURE

The test procedure shall follow that specified in the Schedule, bearing in mind the primary objectives of the test, namely—

(a)   to assess the performance of the pile footing under the design serviceability load; and

(b)   to demonstrate a resistance equal to at least the design geotechnical ultimate limit state.

The dynamic pile test shall be carried out by impact from an appropriate pile-driving hammer or drop-weight, of sufficient energy to satisfy the specifications in the Schedule.

Unless otherwise specified, testing shall commence with small drop heights (low impact energy blows) to verify pile hammer alignment and energy transfer. Drop heights shall then be increased until the test data indicate a static resistance equal to or greater than the design serviceability action effect (E_{ds}) has been verified. Drop heights shall then be increased until the test data indicate a pile soil resistance equal to or greater than E_d/ϕ_g has been verified. Care shall be taken during the test not to exceed pile compression or tension stress limits and to ensure alignment of the hammer and pile is maintained to minimize bending of the pile during the test.

B9 REPORT

A report shall be prepared containing all relevant information including the following:

(a) Pile details, including pile number, type, size, length, penetration and location of test gauges.

(b) Installation details, including date and time, driving system, together with each component above the pile head (cushions, helmet, hammer, follower and similar), hammer stroke or drop, pile set and temporary compression.

(c) Test details as for Item (b), if the test was performed subsequent to installation or if details for the test differed from the normal installation procedure.

(d) For each pile test, the maximum compressive and tensile stresses in the pile, the maximum pile head velocity, pile head displacement and the energy transfer.

NOTE: These should be either for a representative blow or be averaged over a number of blows.

(e) An assessment of pile integrity (or damage) at the time of testing.

(f) The method of interpretation of results and the maximum mobilized resistance by this method.

(g) Any assumptions critical to the interpretation of results (e.g., damping factor). Justification for such assumptions should be provided.

(h) Where rigorous analyses are performed, the full results of such analyses and the following additional information:

(i) Predicted pile head movement at the maximum serviceability limit state and at the maximum mobilized resistance.

(ii) Shaft and end bearing components of the maximum mobilized resistance.

(i) Reference to this test method, i.e., Appendix B, AS 2159.

APPENDIX C

RAPID PILE TESTING

(Normative)

C1 GENERAL

This Appendix sets out test methods for rapid pile testing.

The test force shall have the form and characteristics given in Paragraph C2.1.

C2 DEFINITIONS

For the purposes of this Appendix the definitions below apply.

C2.1 Rapid force

A force pulse of sufficient duration to result in the full length of the pile being maintained in compression for a duration of at least five multiples of the natural period of the foundation. The force is applied in a continuously increasing and gradually decreasing manner. A typical rapid axial compressive force is shown in Figure C2.1.
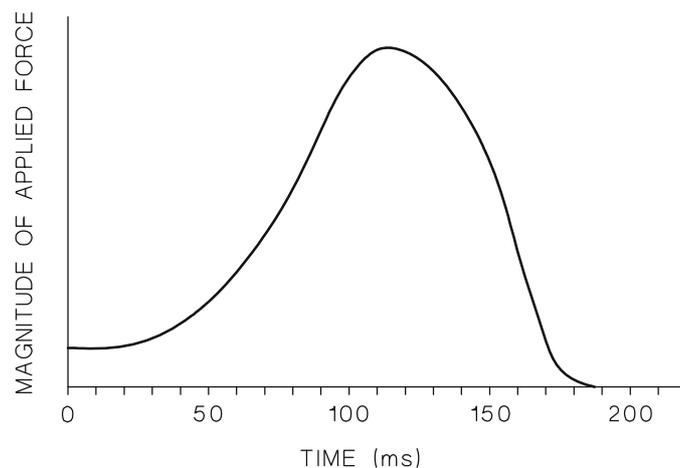

FIGURE C2.1 TYPICAL RAPID AXIAL COMPRESSIVE FORCE

C2.2 Wave speed

A pile material property that reflects the speed at which a strain wave propagates through a pile.

C2.3 Natural period

Represents the time required for the pile to complete one vibration cycle. For axial loading of a pile the natural period is equivalent to $2L/c$ seconds/cycle where L is the pile length and c is the wave speed.

C3 SAFETY

NOTE: Testing should be carried out to appropriate safety standards and the test equipment manufacturer's specifications should be complied with.

C4   EQUIPMENT

C4.1   General

The equipment used shall be capable of applying a peak testing force in accordance with Paragraph C2.1. Typical methods of generating a rapid force include pressure of gases produced by combustion and pressure induced by a cushioned impact from a dropped mass. The equipment used shall be capable of applying a peak testing force in accordance with project requirements.

C4.2   Equipment using pressure of gases produced by combustion

This test involves burning of a solid fuel in a combustion chamber, creating large pressures that accelerate reaction masses mounted on the pile, simultaneously applying an equal and opposite force to the pile. The force and pile displacements are measured by a pressure transducer and laser level respectively.

The equipment shall feature the following:

(a)   Pressure chamber, consisting of a piston bolted to the top of a pile. The piston contains a chamber for solid propellant fuel and a load cell and pressure transducer.

(b)   Reaction masses, typically 5% to 10% of the target peak force.

(c)   Venting system and silencer to release pressurized gas and to muffle the noise from the combustion.

(d)   A mechanism to protect the foundation from damage from the masses returning to rest.

C4.3   Equipment using a drop mass

The equipment shall comprise the following:

(a)   A drop mass, usually between 5% and 10% of the targeted peak force mounted in a guiding frame to ensure a concentric blow to the head of the pile.

(b)   Springs of the required stiffness to ensure a blow of the required duration.

(c)   A means of catching the mass.

(d)   Load cell and optical measuring device.

C5   MEASURING SYSTEMS

C5.1   Measurement of force

The measurement of applied force shall comprise a calibrated force transducer located between the test equipment and the head of the pile. The force transducer shall have a response time of less than 0.1 ms and have an accuracy of not less than 2% of the peak applied force.

Any instrumentation shall be calibrated at least every 2 years and immediately following any repairs. Any transducers, used in situations where overstressing is suspected, shall be checked to determine if calibration is necessary before further use.

C5.2   Measurement of pile movement

Pile movements shall primarily be measured using calibrated displacement transducers having a precision of at least 0.25 mm and response time of less than 0.1 ms. The displacement transducer shall be positioned centrally on the pile. The displacement shall be measured using a stationary reference, which shall be positioned at sufficient distance from the test foundation so that measurements are not subject to disturbance. Typically, the stationary reference is located at 20 m from the test foundation. Should site restrictions not permit the use of a stationary reference, acceleration transducers may be used as the primary displacement measuring system. Details shall be noted in the report.

C5.3 Pile groups

For tests performed on pile groups, multiple transducers shall be used to enable measurement of differential movements of the pile caps.

C5.4 Measurement of acceleration

Accelerometers shall be used as a secondary system for measurement of pile head displacement. Two accelerometers shall be attached securely on opposite sides of the pile shaft. The resonant frequency of the accelerometers shall be greater than 5 kHz and shall be linear to an acceleration of at least 50 g.

Should a discrepancy occur between the primary and secondary displacement transducers, the primary transducer is generally taken as the more accurate result, unless there is sufficient reason to suspect a malfunction.

C6 RECORDING OF RESULTS

The applied force, displacement and acceleration versus time shall be recorded, as well as the permanent displacement resulting from the test.

Signals from the transducers shall be collected and stored by a storage system connected to a system to display the results. The data acquisition system shall be capable of acquiring a recorded signal of at least 50 ms of pre-event data and 300 ms of post-event data.

Signals from transducers shall be recorded in either analogue or digital form. When digitizing, the recommended sample frequency is 4000 Hz or greater, but shall be not less than 2500 Hz.

Signals from the transducers shall be displayed during the test and capable of displaying results with respect to time. Displays shall also be capable of displaying measured force versus displacement.

C7 ANALYSIS OF RESULTS

The measured applied force and pile head displacements shall be used to analyse pile performance under the rapid loading test.

Analyses of the results to account for the effects of inertia shall be carried out in strict accordance with the test equipment manufacturer's recommendations or established published methods relevant to those tests.

C8 REPORT

A report shall be prepared containing all relevant information, including the following:

(a) Pile details, including pile number, type, size and founding depth.

(b) Installation details, including date and construction details. There shall be a full description of the formation or driving of the pile.

(c) Details of soils data from the nearest adjacent bores or soil test locations, including groundwater depths.

(d) Design loads that the piles were installed to and loading schedule as required by this code.

(e) Description, calibration data and last date of calibration of all components of the apparatus for obtaining measurements and apparatus for recording, reducing and displaying data.

(f) Location of displacement and acceleration transducers.

(g) Location and distance of stationary reference.

(h) Testing date.

(i) A graphical representation of force vs. time, including an indication of any pre-load on the pile due to the weight of the test apparatus and/or reaction mass (if applicable).

(j) Graphical representation of displacement vs. time.

(k) Measured rapid force vs. displacement plot.

(l) Graphical representation of velocity vs. time and acceleration versus time.

(m) Any unusual occurrences during the installation of the pile and during the rapid loading tests.

(n) The methods of analyses used to assess inertial effects.

(o) The predicted load-settlement performance of the pile(s) under static loading conditions, where appropriate.

(p) Reference to this test method, i.e., Appendix C, AS 2159.

APPENDIX D

INTEGRITY TESTING

(Normative)

D1 SCOPE

This Appendix sets out test methods for integrity testing of piles.

D2 GENERAL REQUIREMENTS

D2.1 Preparation for testing

The method of testing shall be determined from the Schedule.

Where the method of testing requires the positioning of sensing equipment on the pile head (sonic echo and impulse response methods), the head shall be clean, free from water, laitance, loose concrete, overspilled concrete and blinding concrete, and readily accessible for the purpose of testing.

Where the method of testing requires the pile length to be logged, tubes shall be cast into the pile to allow the passage of a sonic pulse from a transmitter to a receiver through the material of the pile.

D2.2 Time of testing

In the case of cast in place concrete or grout piles, integrity tests shall be performed after the concrete or grout has achieved a characteristic strength of at least 25 MPa and no less than one week after casting of the pile.

D2.3 Report

A report shall be prepared containing all relevant information including the following:

(a)   Identification of the pile tested.

(b)   A description of the test pile.

(c)   Full details of the ground conditions, nominal pile dimensions and construction methods.

(d)   Details of the test applied (e.g., vibrator position and frequency).

(e)   Details of the equipment used (e.g., hammer characteristics).

(f)   Any departure from the normal procedure.

(g)   A record of the test results (including any data necessary for interpretation, e.g., number of blows).

(h)   Details of any signal processing.

(i)   Identification of any abnormal acoustic reflectors or transmitters detected.

(j)   An assessment of the significance of reflectors or transmitters detected, with respect to the ability of the pile to perform its intended function.

(k)   Reference to the test method used, e.g., 'Pulse echo method', Appendix D, AS 2159.

D3 PULSE ECHO METHOD

D3.1 General

Where an integrity test by the pulse echo method is specified, testing shall be carried out as specified.

D3.2 Site testing

A hand-held hammer shall be used to impact the pile head at or near the pile centre in such a manner as to generate a sharp stress-wave, free from distortion, and of as short a wavelength as possible. The hammer weight may be varied depending on the characteristics of the pile. The hammer may be instrumented with an accelerometer.

A sensor such as an accelerometer or geophone shall be used to record the pile-head movement response. The sensor may be placed near the pile edge, or close to the point of impact. A characteristic response shall be obtained by averaging the response of a minimum of three impacts.

The impact and sensor locations, the hammer characteristics and the number of blows shall all be reported.

D3.3 Signal processing

Data is typically presented as the time response of pile-head velocity. The pile-head velocity response shall be enhanced using appropriate filtering and magnification to assist with interpretation of the signal.

Care shall be taken to ensure that such signal processing does not remove important features from the record or conversely generate features that may be misinterpreted as having structural significance. As much as possible, signal processing parameters shall be applied consistently on a project-wide basis to all piles.

D4 VIBRATION METHOD

D4.1 General

Where an integrity test by the vibration method is specified, testing shall be carried out as specified.

D4.2 Site testing

The required impulse shall be generated by applying an electrodynamic vibrator on the pile head and generating sinusoidal stress waves of constant amplitude. The vibrator shall be placed on a level bed of epoxy resin or similar, in the centre of the pile, aligned with its axis, and precisely levelled. The vibrator shall be capable of being varied over a typical frequency range of between 20 Hz and 2000 Hz, and of applying a force of 50 N to 100 N to the pile head. The vibrator shall incorporate an accelerometer to determine the peak applied force, and the maximum force applied shall be kept constant across the applied frequency range.

A sensor such as an accelerometer or geophone shall be used to record the pile-head movement response. The sensor may be placed on a peripheral plate near the pile edge. Two sets of tests shall be conducted, with the sensor placed on plates on opposing diameters.

The vibrator and sensor locations, the vibrator characteristics and the test frequencies shall all be reported.

D4.3 Signal processing

Data is typically presented as the ratio of pile-head velocity and force as a function of vibration frequency, known as a mobility diagram. The signal response shall be enhanced using appropriate processing to assist with interpretation of the mobility diagram generated.

Care shall be taken to ensure that such signal processing does not remove important features from the record or conversely generate features that may be misinterpreted as having structural significance. As much as possible, signal processing parameters shall be applied consistently on a project-wide basis to all piles.

D5 IMPULSE RESPONSE METHOD

D5.1 General

Where an integrity test by the impulse response method is specified, testing shall be carried out as specified.

D5.2 Site testing

A hand-held hammer shall be used to impact the pile head at or near the pile centre in such a manner as to generate a sharp stress-wave, free from distortion, and of as short a wavelength as possible. The hammer weight may be varied depending on the characteristics of the pile. The hammer may optionally be instrumented with an accelerometer.

A sensor such as an accelerometer or geophone shall be used to record the pile-head movement response. The sensor may be placed near the pile edge, or close to the point of impact. A characteristic response may be obtained by averaging the response of a number of impacts.

The impact and sensor locations, the hammer characteristics and the number of blows shall all be reported.

D5.3 Signal processing

Data is typically presented as the ratio of pile-head velocity and force as a function of impulse frequency, known as a mobility diagram. The signal response shall be enhanced using appropriate processing to assist with interpretation of the mobility diagram generated.

Care shall be taken to ensure that such signal processing does not remove important features from the record or conversely generate features that may be misinterpreted as having structural significance. As much as possible, signal processing parameters shall be applied consistently on a project-wide basis to all piles.

D6 SONIC LOGGING METHOD

D6.1 General

Where an integrity test by the sonic logging method is specified, testing shall be carried out as specified. This method includes both cross-hole sonic logging and single-hole sonic logging.

D6.2 Site testing

The piles shall be prepared by fixing closed and water-filled PVC or steel tubes to the reinforcing cage for the length of the pile prior to concreting. The number and arrangement of the tubes used in cross-hole sonic logging depends primarily on the pile diameter. Small diameter piles may be tested using single-hole sonic logging.

Piezoelectric probes, one being a sonic emitter and one being a sonic receiver shall be used. During testing, the probes shall be raised in unison from the pile base to the pile top at a constant rate that ensures that measurements are taken at approximately every 10 mm to 20 mm of pile depth. For cross-hole sonic logging, the probes shall be at the same level in parallel tubes. Each combination of tube pairs shall be so tested. For single-hole sonic logging, the probes shall be vertically separated by a constant distance.

The probe characteristics, tube type, location and lengths, the order of testing, and the raising rate shall all be reported.

D6.3 Signal processing

Data is typically presented as time responses of the received signal (known as a waterfall diagram) or an integration of the received signal that indicates energy received. Both plots are shown as a function of pile depth. The signal response shall be enhanced using appropriate filtering and magnification to assist with interpretation of these outputs.

Care shall be taken to ensure that such signal processing does not remove important features from the record or conversely generate features that may be misinterpreted as having structural significance. As much as possible, signal processing parameters shall be applied consistently on a project-wide basis to all piles.

D7 ALTERNATIVE TEST METHODS

There are a number of other forms of test that may be applied in order to provide an indirect evaluation of pile integrity as defined in Clause 8.6.1. These may be applied with due recognition of their application characteristics, their limitations, advantages and disadvantages. These methods shall be applied on site in accordance with recommended practice, and signal processing shall be in accordance with the general principles noted in this Appendix.

APPENDIX E

LIMIT STATES—SYMBOLS AND DEFINITIONS

(Informative)

To facilitate interpretation of this Standard, Table E1 below lists some of the symbols and definitions that apply to limit state and which are used herein, together with more colloquial terminology that may be more familiar to users of this Standard.

TABLE E1

TERMS

Symbol	Definition	Common terminology
E_d	Design action effect	Ultimate load combination (factored up) acting on pile or pile group. Also, forces and moments induced in piles by applied loads and ground movements
E_{ds}	Design service load	Load combination to be used for serviceability
F_{nf}	Actions due to negative friction	Maximum downdrag force induced in pile by negative friction
$R_{d,g}$	Design geotechnical strength of pile	Factored-down design geotechnical capacity of pile
$R_{d,s}$	Design structural strength of pile	Factored-down design structural capacity of pile
$R_{t,ug}$	Ultimate geotechnical strength of pile as assessed from load test	Measured ultimate pile capacity (geotechnical) from load test
R_{ug}	Ultimate geotechnical strength of pile	Ultimate geotechnical capacity of pile, as estimated from calculation or load test
$R_{d,ug}$	Design ultimate geotechnical strength of pile	Unfactored geotechnical capacity of pile, to be used for design
$R_{d,g,c}$	Design geotechnical strength of combined pile and raft foundation	Factored-down design geotechnical capacity of pile-raft foundation
$R_{d,ug,s}$	Design ultimate geotechnical strength of shallow footing or raft	Unfactored ultimate capacity of shallow footing or raft, to be used in design
$R_{d,ug,sz}$	Design ultimate geotechnical strength of pile in stable zone	Unfactored geotechnical capacity of portion of pile in stable zone, to be used in design
R_{us}	Ultimate structural strength of pile	Unfactored ultimate structural capacity of pile, assessed from calculation or test

BIBLIOGRAPHY

AS
2832   Cathodic protection of metals
2832.5   Part 5: Steel in concrete structures

3735   Concrete structures retaining liquids

5100   Bridge design (all parts)

5604   Timber—Natural durability ratings

AS/NZS
1170   Structural design actions
1170.1   Part 1: Permanent, imposed and other actions
1170.3   Part 3: Snow and ice actions

2312   Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings

AMENDMENT CONTROL SHEET

AS 2159—2009

Amendment No. 1 (2010)

CORRECTION

SUMMARY: This Amendment applies to Equation 4.6.3.

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NOTES

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