INTERNATIONAL STANDARD

ISO 22477-10

First edition
2016-09-15

Geotechnical investigation and testing — Testing of geotechnical structures —

Part 10:
Testing of piles: rapid load testing

Reconnaissance et essais géotechniques — Essais de structures géotechniques —

Partie 10: Essai des pieux: essai de charge rapide

Reference number
ISO 22477-10:2016(E)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

ISO 22477-10 was prepared by the European Committee for Standardization (CEN) in collaboration with ISO Technical Committee TC 182, *Geotechnics*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

A list of all parts in the ISO 22477 series, published under the general title *Geotechnical investigation and testing — Testing of geotechnical structures*, can be found on the ISO website.

Introduction

This part of ISO 22477 outlines how a rapid load pile test is defined and specifies the equipment and testing procedures required. Informative, non-prescriptive guidance is included on the analysis of rapid load pile test results required to determine mobilised or ultimate compressive resistance of a pile.

Geotechnical investigation and testing — Testing of geotechnical structures —

Part 10:
Testing of piles: rapid load testing

1 Scope

This part of ISO 22477 establishes the specifications for the execution of rapid load pile tests in which a single pile is subject to an axial load in compression to measure its load-displacement behaviour under rapid loading and to allow an assessment of its measured compressive resistance ($R_{c,m}$) and corresponding load-displacement behaviour.

This part of ISO 22477 is applicable to piles loaded axially in compression.

All pile types mentioned in EN 1536, EN 12699 and EN 14199 are covered by this part of ISO 22477.

The tests in this part of ISO 22477 are limited to rapid load pile tests only.

NOTE 1 This part of ISO 22477 can be used in conjunction with EN 1997–1. Numerical values of partial factors for limit states from pile load tests to be taken into account in design are provided in EN 1997–1. For design to EN 1997–1, the results from rapid load pile testing will be considered equivalent to the measured compressive resistance, $R_{c,m}$, after being subject to appropriate analysis.

NOTE 2 Guidance on analysis of the rapid load testing results to determine measured compressive resistance and corresponding load-displacement behaviour is given in Annex A.

This part of ISO 22477 provides specifications for the following:

a) investigation tests, whereby a sacrificial test pile is loaded up to ultimate limit state;

b) control tests, whereby the pile is loaded up to a specified load in excess of the serviceability limit state.

NOTE 3 Generally, an investigation test focuses on general knowledge of a pile type; a control test focuses on one specific application of a pile.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

There are no normative references in this document.

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 1997-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
trial pile
pile installed before the commencement of the main piling works or a specific part of the works for the purpose of investigating the suitability of the chosen type of pile and for confirming its design, dimensions and bearing resistance

Note 1 to entry: The trial pile might be sacrificed to achieve ultimate limit state.

3.1.2
working pile
pile that will form part of the foundation of the structure

3.1.3
test pile
pile to which loads are applied to determine the resistance deformation characteristics of the pile and the surrounding ground

Note 1 to entry: A test pile can be a *trial pile* (3.1.1), or a *working pile* (3.1.2).

3.1.4
pile load
axial compressive load (or force) applied to the head of the pile during the test

3.1.5
rapid load
force applied to the pile in a continuously increasing and then decreasing manner of a suitable duration (typically less than 1 s) relative to the natural period of the pile which causes the pile to compress over the full length and translate approximately as a unit during the full loading period

3.1.6
maximum compressive load
maximum axial compressive load (or force) applied to the pile during the test, generally defined prior to the test

3.1.7
rapid load test
pile loading test where a pile is subjected to chosen axial *rapid load* (3.1.5) at the pile head for the analysis of its capacity

3.1.8
ultimate measured compressive resistance of a pile
corresponding state in which the pile foundation displaces significantly with negligible increase of resistance

Note 1 to entry: Where it is difficult to define an ultimate limit state from a load settlement plot showing a continuous slight increase, a settlement of the pile top equal to 10 % of the pile base diameter should be adopted as the “failure” criterion.

Note 2 to entry: The maximum compressive resistance measured during a *rapid load test* (3.1.7) is not necessarily equal to the ultimate measured compressive resistance of a pile. The measured resistance obtained from rapid load testing must be analysed to remove the effects of inertia and soil dependent behaviour before it can be considered equivalent to the ultimate measured compressive resistance as outlined in Annex A.

3.1.9
design compressive static resistance of a pile
ultimate compressive static resistance of a pile that shall be determined prior to load testing to allow specification of appropriate magnitude *rapid load test* (3.1.7) cycles

3.1.10
equivalent diameter
diameter of an equivalent circle of which the area equals the area of the relevant pile section

Note 1 to entry: The equivalent diameter for a circular pile is the outer diameter of the pile, for a square pile the diameter which gives the same area as the square pile (as long as the longest side is smaller than 1,5 times the shortest side) is the equivalent diameter.

3.1.11
minimum reference separation distance
distance which separates a stationary reference point from a point that will be significantly displaced by the testing method

Note 1 to entry: Only stationary points can be used for reference of *displacement* (3.1.12) measurement devices. Displacement measuring systems can be placed on the soil outside the reference distance without isolating (displacement compensating) measures.

3.1.12
displacement
axial displacement of the pile head measured during testing

3.2 Symbols

a pile acceleration

c_p velocity of the stress wave in the test pile

c_s velocity of the shear wave in the ground

D diameter or equivalent diameter of the test pile

F_c pile load in compression

$F_{c,\max}$ maximum compressive load

g acceleration due to gravity

L total length of the test pile

$R_{c,m}$ measured ultimate resistance of the ground in the test, or measured geotechnical resistance of the pile

r_{ref} minimum reference separation distance

t time

t_f duration of the rapid load application

t_g duration of the falling of the mass for a falling mass equipment

w pile displacement

4 Testing equipment

4.1 General

The equipment should generate a rapid load at the pile head where the duration of the load fulfils Formula (1):

$$10 < \frac{\left(t_{\mathrm{f}} \times c_{\mathrm{p}}\right)}{L} \leq 1\,000 \tag{1}$$

If information on the ultimate compressive resistance of the pile is one of the aims of the test, the equipment shall have enough capacity to reach the ultimate compressive resistance under rapid loading.

The force applied to the pile head during a rapid load test for measuring the ultimate compressive resistance might exceed the design compressive static resistance of a pile by a factor of two to three due to soil specific rate effects. The need to apply such high loads shall be considered when specifying equipment and pile materials.

If for a rapid load test one or more of the requirements mentioned in this part of ISO 22477 is not met, it should be proven that this shortcoming has no influence on the achievement of the objectives of the test, before the results can be interpreted as a rapid load test.

For long piles where the criteria in Formula (1) is exceeded or where rock sockets result in non-uniform strains within the pile, embedded pile instrumentation and specialized analysis will be required. Additional instrumentation should conform to 4.3.

Rapid load testing systems rely on a mass to apply load to a pile. This is either through launching a mass upwards, referred to as a launched mass system, or by dropping a mass, referred to as a drop mass system. In both cases, the upward or the downward movement of the mass is controlled to produce the required load duration in 4.1. To avoid eccentric loading of piles and additional safety considerations, the movement of the mass should be guided during launched mass testing and drop mass testing.

4.2 Loading

The selection of the loading equipment shall take into account the following:

— aim of the test;

— ground conditions;

— maximum pile load ($F_{c,\text{max}}$);

— strength of the pile (material);

— execution of the test;

— safety considerations.

The loading equipment shall generate a force which fulfils the requirements in 4.1 and is able to apply the required maximum compressive force to mobilize a specified compressive resistance or the ultimate compressive resistance of a pile.

If a test pile is tested by several cycles beginning with a low magnitude force cycle, the maximum force of each proceeding cycle should be larger than the maximum force of the preceding cycle. Where cycles of loading are applied, this should be undertaken in a manner that removes the potential for uncontrolled reloading of the pile. This will require the device to have a mass catching mechanism.

The equipment shall load the pile accurately along the direction of the pile axis. The eccentricity of the load shall be less than 10 % of the equivalent diameter. The deviation or eccentricity of the alignment of the force to the axis of the pile shall be less than 20 mm/m. Eccentric loading of the pile is allowed where this has been specifically allowed for during pile design and it has been verified that this will not unduly effect the performance of the testing equipment.

The stress in the pile under the maximum applied load shall not exceed the permissible stress of the pile material.

4.3 Measurements

Prior to a rapid load test, two variables shall be directly measured where the reaction mass comes into contact with the pile head prior to testing (not required for all equipment types):

— the force applied to the pile head;

— the displacement of the pile head;

During a rapid load test, a minimum of three variables shall be directly measured relative to time (t):

— the force applied to the pile head (F_c);

— the displacement of the pile head (w);

— the acceleration of the pile head (a).

The transducers and signal processing shall satisfy the requirements from Table 1, Table 2, Table 3 and Table 4. Sampling shall commence a minimum of 50 ms before loading commences and continue for a minimum duration of 500 ms. Where duration of the loading event means that the duration of sampling exceeds 500 ms, the duration of sampling shall be increased to capture the entire event and allow for the required post event sampling. All transducer sampling shall be synchronised. The transducers shall have sufficient measuring range, in order to avoid re-adjustment during testing. All instrumentation must be able to withstand pile installation and testing procedures.

Table 1 — Rapid load test transducer and signal processing general requirements

Parameter	Requirement
Sampling rate	≥4 000 samples per second
Duration of pre-event sampling	≥50 ms
Duration of post-event sampling	≥300 ms
Cut off frequency low pass filter	≥1 kHz

Table 2 — Rapid load test load transducer and signal processing load requirements

Parameter	Requirement
Maximum load	>maximum test load
Linearity	<2 % of maximum value reached
Hysteresis	<2 % of maximum value reached
Response time	<0,1 ms

Table 3 — Rapid load test acceleration transducer and signal processing requirements

Parameter	Requirement
number of transducers	≥1
resonant frequency	>5 kHz
linearity	up to 50 g

Table 4 — Rapid load test transducer and signal processing displacement requirements

Parameter	Requirement
Range	>50 mm or $D/10$, whichever is greater
Accuracy	±0,25 mm
Response time	<0,1 ms

Before and after each load cycle, the level of the pile head shall be determined relative to a point outside of the minimum reference separation distance by optical levelling. The optical levelling measurements shall be controlled by reference to one or more fixed reference points and should be undertaken to an accuracy of ±1 mm.

The base of a test displacement measuring system (where this is placed on the ground surface) should not be placed closer than the minimum reference separation distance from the pile. This shall be verified at the test site. If the minimum reference separation distance for a test displacement measuring system cannot be reached or vibration-free measurement cannot be undertaken, the test displacement measuring system should be placed on or fixed to a vibration-free surface such as an adjacent pile.

The minimum reference separation distance shall be measured from

— the pile, when the test is undertaken with a launched mass, or

— supporting component of the equipment which is nearest the pile, when the test is undertaken with a falling mass.

The value of the minimum reference separation distance should be a minimum of 15 m and

— equal to or greater than the distance which the shear waves in the soil travel during the duration of the loading (t_f), when the test is undertaken with a launched mass, thus $r_{ref} = c_s \times t_f$, or

— equal to or greater than the distance which the shear waves in the soil travel during the duration of the falling of the mass (t_g) and the subsequent loading (t_f), when the test is undertaken with a falling mass, thus $r_{ref} = c_s \times (t_g + t_f)$.

The load applied to the pile shall be determined directly by a purpose built calibrated load cell which does not form part of the pile. The use of pile mounted strain gauges to derive externally applied loads for steel or precast concrete piles shall only be considered in special circumstances where a load cell is unavailable and the stiffness of the pile material is known from manufacturer's certification or has been verified directly through material element testing for the piles under test. For cast insitu concrete piles, a purpose built calibrated load cell should be used or where pile mounted strain gauges to derive externally applied loads are used, these should be calibrated against load cell readings for the specific piles under test.

Surface mounted strain gauges should be mounted in diametrically opposed pairs. Where embedded strain gauges are used to compliment test results or where the criteria exceeds in Formula (1), strain gauges or strain gauge devices should be fixed to the reinforcement bars or embedded in the concrete of concrete piles or attached to the walls of steel piles at least in diametrically opposed pairs at each depth to be considered. Where strain gauge devices are cast in concrete, it is advised that a minimum of three devices should be used at each depth to be considered. To determine load from strain, the cross section and the pile material modulus of elasticity shall be assessed. All the materials present in the pile shall be considered in this determination.

NOTE 1 Strain-transducers based upon vibrating wire technology are generally not suitable for rapid load test monitoring and strain gauge based instruments are preferred.

All loading and settlement (as a result of loading larger than 1 % of the expected static bearing capacity of the pile) after installation of the pile shall be measured. This includes all types of static preloading of the pile. In addition, any additional equipment or component parts of the loading system connected to or in contact with the pile during the application of load that can to contribute the inertial resistance of the pile shall be of known mass. The mass of this additional equipment or component parts must be recorded as part of the pile testing results.

All equipment used for measuring load, displacement and acceleration in the test shall be calibrated. The equipment shall be checked on a regular basis. The results of these checks shall be registered and kept with the most recent calibration. This data shall be made available prior to commencement of the test. Where applicable, the load measurement device should be calibrated against a suitable master device giving full traceability.

NOTE 2 Calibration of the load measurement device can be done according to a National Standard or ISO 7500.

The time between the checks and calibrations is not prescribed, since the duration of validity of a calibration can depend on the type of measurement device and manufacturers' recommendations. However, checks should be sufficiently detailed that it can be verified that all measurement devices are operating correctly during the test. It is preferred that all checks are carried out directly before the test to avoid influence of transport and time. In some circumstances, e.g. frequent use or change of components or presumed damage, additional calibration and checking might be required.

5 Test procedure

5.1 Preparation for testing

In advance of the test, an execution plan shall be formulated that is consistent with the planned final report shown in Clause 7. The plan shall include the following:

— test objectives;

— the ground and groundwater conditions with reference to the relevant site investigation reports;

— scheduled testing date;

— topographic locations, types and specifications of the test piles;

— allowable maximum values of load and displacement of the pile(s);

— required pile displacement and applied load;

— specification of the loading device;

— specifications of the measurement devices and calibration certificates, if applicable;

— specifications of additional measurement-devices;

— number of loading steps and target maximum load per step;

— verification of the acceptability of the required pile displacement and applied load with respect to the allowable maximum values;

— duration of test cycle measurement and sampling frequency;

— plan of the test site;

— testing programme;

— list of key personnel, showing who is responsible for supervision, safety, test execution, data recording and other tasks;

— safety requirements;

— legally required licences for equipment handling, where relevant;

— logistical requirements on site (for example, flat ground, vehicle requirements and limitations, lifting plan, working space around the pile, etc.).

It is recommended that the execution plan is made available at least seven days prior to commencement of testing.

5.2 Safety and integrity requirements

5.2.1 People and equipment in the surrounding area

Safety of personnel and equipment in the surrounding area shall be given due consideration during execution of the test. The distance between the nearest person and the test equipment shall be at least twice the height of the test equipment measured from ground level.

People in neighbouring buildings that are likely to be affected by testing shall be informed of the nature of testing and the programme of tests to be undertaken.

Disturbance to vibration sensitive processes in neighbouring buildings should be prevented where possible. Where testing is undertaken close to existing buildings, consideration should be given to the age, integrity and sensitivity of the structure.

5.2.2 Test pile

The test pile should be designed, manufactured and installed such that the test pile should not be damaged by the maximum load that will be applied during the test pile.

During a rapid load test, the test pile can be loaded with a force which might exceed the static equivalent test loads by a factor of two or more. Test piles should be designed to withstand the resulting higher compressive stresses.

For working piles, the maximum displacement of the pile head shall be agreed before commencement of the test. The displacement of the pile head shall not exceed 10 % of the (equivalent) diameter under normal circumstances without prior approval from all parties concerned.

5.3 Preparation of the pile

The pile head shall be flat, plane and perpendicular to the pile axis.

The integrity and capacity of the pile shall be sufficient to carry the planned test load. If installation of the pile has raised doubts about pile integrity, the pile shall be tested acoustically or by other means, or the rapid load test shall be carried out by multiple steps with increasing pile load.

NOTE Concerns about the integrity of a pile can be due to unexpected behaviour during construction, such as deviation away from anticipated behaviour in terms of driving resistance, amount of concrete used and progress during drilling. The deviation could be a deviation from expected values or a deviation of a specific pile from other piles constructed at the construction site or similar site.

The test pile shall have enough length above the ground surface to attach the measurement devices. All acceleration transducers shall be installed firmly against or on the pile head and clearly visible.

Between the installation of the test pile and the beginning of the test, adequate time shall be allowed to ensure that the required strength of the pile material is achieved and the ground has sufficient time to recover from the process of pile installation and dissipation of pore-water pressures and other aspects, such as mechanical heat from boring or hardening concrete. During this period, the pile shall not be disturbed by load, impact or vibration, or other external influence.

Time periods between installation and testing of a pile should be taken from Table 5. Alternative time periods can be specified with appropriate justification.

Table 5 — Time periods between installation and testing of a pile

Test pile type	Soil type	Pile type	Minimum time (days)
Trial	Non-cohesive	All	7
	Cohesive	Bored	21
		Driven	35
Working	Non-cohesive	All	5
	Cohesive	Bored	14
		Driven	21
NOTE Alternative time periods can be specified with appropriate justification.			

5.4 General preparation for testing

Sensitive parts of the test equipment shall be protected from weather (rain, wind, direct sunlight) and other disturbance.

All components of the system shall be protected against damage during all stages of construction and testing. Special attention shall be paid to cables.

Any other site activities that might influence the measurements, e.g. vibrations by nearby traffic or ongoing pile driving, should be avoided where possible. Alternatively, testing should be timed to avoid periods of significant site operations.

5.5 Working pile integrity after testing

The pile shall be tested acoustically if the pile integrity is questioned as a result of the pile load test.

NOTE Concerns about the integrity of a pile can be due to unexpected behaviour during rapid load testing. Concern could arise due to a deviation from expected values or a deviation of a specific pile from other piles tested at the construction site or similar site.

6 Test results

The test results shall record the following time-based measurements, where a common base to all time measurements shall be applied:

— force applied by the loading system at the pile head as a function of time;

— displacement of the pile head as a function of time;

— acceleration of the pile head as a function of time.

All measured test results shall be available in hard copy charts and digitally in a readable text-based format immediately after testing. All results shall be corrected for calibration factors and presented in engineering units. Calibration corrections applied to the measured signals shall be recorded in writing and within the digital data records. Measured results in engineering units should be made available in open access format, such as ASCII, prior to any further analysis.

The measurements of pile levels by independent optical measurement before and after each cycle shall be reported. All other readings, such as local site temperature, tests on concrete samples, opitical level readings, pile geometry, adjacent static tests on the site, when relevant, shall also be recorded in the test report.

The rapid load force-settlement diagram shall be drawn. This diagram shows the measured pile head displacement against the measured pile head force, without correction. Where multiple cycles of loading are applied to a single pile, individual force-settlement diagrams for each cycle should be presented. In addition, a single diagram should be produced which combines all of the individual force-settlement diagrams without correction, with the initial displacement for each cycle calculated based upon the elevation of the pile head prior to application of the individual load cycle.

NOTE More information on interpretation is outlined in Annex A. Effects such as rate effects (including creep), excess pore water pressures and inertia effects (due to acceleration) can be introduced by the rapid load test and can be different from what is expected from an equivalent static load test.

A copy of all results shall be recorded in the test report and stored on a back-up medium in an open access format such as ASCII.

Where required, the velocity of the pile head shall be calculated by integration of the measured accelerations with respect to time. The velocity and acceleration of the pile head shall be calculated by differentiation of the measured displacements with respect to time only where accelerometer-based measurements do not give satisfactory results. Derivation of pile velocity from direct acceleration measurements shall be the preferred option. Calculation of the displacement of the pile head by double integration of the measured accelerations with respect to time is allowed only if the final set is checked by a direct optical measurement of the displacement.

7 Test reporting

A factual report shall be written for all load tests. Where appropriate, this report shall include the following:

a) reference to all relevant standards;

b) general information concerning the test site and the test programme:

— topographic location of the test including definition of the level datum that is used as a reference for elevation measurements;

— general description of the site;

— purpose of the test;

— test date;

— the intended and realized testing programme;

— name of the organization which carried out the test;

— name of the organization which supervised the test;

c) information concerning the ground conditions:

— the ground and groundwater conditions with reference to the relevant site investigation reports;

— description of the ground conditions, in the particular the vicinity of the test pile;

d) specification of the test pile(s):

— the pile type, reason for testing and its reference number;

— the topographic position and level of the test pile referenced to a local datum;

— pile data, such as geometry (including as a minimum the total pile length, L, and diameter, D, or equivalent diameter), level of the pile top and base, pile material (including material density if known) and reinforcement arrangement;

— date of installation;

— description of the pile installation and of any problems encountered during the works;

— installation records, such as driving logs, concrete consumption, drilling progress;

— test reports on pile material quality or specification (where applicable);

— report for integrity investigation if undertaken prior to testing;

e) specification of the test:

— the postulated maximum test load;

— the number of load cycles and the foreseen loading levels;

— pile cap details;

— a description of the loading and measuring apparatus and reaction or mass system;

— information on the potential energy potential for each cycle (drop height, mass, amount of fuel);

— calibration documents for the load cells, accelerometers and displacement measuring devices;

— the distance between the pile and the displacement measurement device;

— details of the installation of the pile testing equipment by drawings and/or photographs;

f) test results:

— as defined in Clause 6, including the digital data in numerical form and engineering units;

— the rapid load-displacement diagram for each cycle from the measured signals and diagrams required for multi cycle testing on a single pile if undertaken;

— the displacement of each cycle as a result of rapid loading;

— the results of the high precision optical levelling;

— report for integrity investigation if undertaken after testing;

g) reasons for any departure from this part of ISO 22477.

If the report includes an interpretation of the measured tests results, the following information shall also be added to the test report:

— the method used for the interpretation;

— the derived static load-displacement diagram;

— details of the treatment of rate effects or soil dependant corrections;

— details of the treatment of inertial effects;

— details of the treatment of effects due to excess pore water pressure (where considered).

Annex A
(informative)

Analysis of rapid load test results

A.1 General

Annex A gives informative guidance on one method for analysing rapid load test results (see Reference [5]). This informative guidance is not meant to be prescriptive or limit the type of analysis technique which may be adopted. Further guidance on appropriate analysis techniques should be sought from the specialist pile testing contractor undertaking the testing as alternative methods such as signal matching have been applied but experience may be limited (see References [5],[6] and [7]). Inclusion of the informative guidance on the analysis of rapid load testing should not discourage or inhibit the use, adoption or development of alternative analysis techniques.

The measured results obtained from a rapid load pile test should not be considered equivalent to the measured compressive resistance, $R_{c,m}$, without appropriate correction for the effects of increased pile acceleration and velocity in excess of those induced in a static pile test.

A.2 Unloading Point Method (UPM) for determination of the compressive pile behaviour

A.2.1 General

Rapid load test results can be analysed using the Unloading Point Method (UPM) to derive the measured compressive resistance, $R_{c,m}$, and the corresponding load deflection behaviour. The approach can be used for either a single load cycle or multiple load cycles (undertaken on a single pile) as required. The analysis technique to determine the measured compressive resistance, $R_{c,m}$, and the corresponding load deflection behaviour is based upon that outlined in Reference [5].

A.2.2 Analysis of a single load cycle

Rapid load testing may proceed by the application of a single cycle of loading or by multiple cycles of loading. This subclause covers the analysis of a single cycle of loading.

The process of analysis of a single load cycle is outlined in Figure A.1 to Figure A.3 included to clarify the steps of the analysis process. The process is as follows.

a) Obtain the measured signals from the rapid load test.

b) Calculation of the inertia corrected mobilised pile resistance at the unloading point.

- Obtain the pile properties required to calculate the mass of the pile, m (pile cross sectional area, pile length, density of the pile material, records of the concrete volume used to form the pile) and the mass of any other components contributing to the inertial resistance of the pile.

- Obtain the variation of force (F), velocity (v), displacement (w) and acceleration (a) with time (t) for a single load cycle.

- Determine the time ($t_{w\text{-max}}$) during the test where the measured pile velocity becomes 0 m/s or a value close to this. Referred to as the unloading point.

- Determine the magnitude of the force measured at $t_{w\text{-max}}$, $F_{c,\, tw\text{-max}}$.

- Determine the magnitude of the acceleration at $t_{w\text{-max}}$, $a_{tw\text{-max}}$.

— Solve Formula (A.1) to determine the inertia corrected pile resistance at $t_{w\text{-max}}$.

$$R_{c,ic,tw-\max} = F_{c,tw-\max} - \left(m \times a_{tw-\max}\right) \quad (A.1)$$

where

$a_{tw\text{-max}}$ is the acceleration measured during the test at $t_{w\text{-max}}$;

$F_{c,\,tw\text{-max}}$ is the magnitude of the force measured during the test at $t_{w\text{-max}}$;

m is the mass of the pile and any other components contributing to inertial resistance of the pile;

$R_{c,\,ic,\,tw\text{-max}}$ is the inertia corrected pile resistance at $t_{w\text{-max}}$;

$t_{w\text{-max}}$ the time some time after the commencement and before the end of the load application phase of the test where the pile velocity effectively becomes 0 m/s or a value close to this.

c) Correction of the inertia corrected pile resistance for the soil dependant empirical parameter.

— Determine the soil dependent empirical parameter based upon Table A.1 recommendations and calculate the corrected derived static pile resistance, $R_{c,\text{corrected}}$ as per Formula (A.2).

— Determine the magnitude of the displacement at $t_{w\text{-max}}$, $w_{tw\text{-max}}$.

$$R_{c,\text{corrected}} = \eta \times \left(R_{c,ic,tw-\max}\right) \quad (A.2)$$

where

$R_{c,\text{corrected}}$ is the corrected mobilised resistance at $w_{tw\text{-max}}$;

$w_{tw\text{-max}}$ magnitude of the pile displacement at $t_{w\text{-max}}$;

η soil dependant empirical parameter.

Where the mobilised pile load deflection behaviour at $t_{w\text{-max}}$ can be shown to correspond to the ultimate resistance of the pile, then $R_{c,\text{corrected}}$ may be considered equivalent to the measured compressive pile resistance $R_{c,m}$.

The parameters shown in Table A.1 should only be adopted where it can be demonstrated that rapid load testing was undertaken on the same type of pile, of similar length and in comparable soil conditions as those that were used to determine the parameters as outlined in Reference [5].

Table A.1 — Selection of soil dependant empirical parameter *η*

Soil type	Clay	Sand
Empirical factor, η	0,66	0,94
Standard deviation	0,32	0,15
Coefficient of variation	0,49	0,15
Number of cases	12	22
Number of sites	6	10

NOTE 1 The values shown in this table are based upon data presented in Reference [5] Table C.2 for clay soild and Table C.3 for sand.

NOTE 2 Only cases with pile head displacements greater than 5 % of the equivalent pile diameter are considered in this table.

NOTE 3 The variation of values in this table is significant for clay soils particularly. An alternative suggestion for a selection method for empirical factor for clay based upon measured soil properties can be found in Reference [6]. The majority of the values presented in this table are derived from pile tests on driven piles.

NOTE 4 Guidance on analysis in clays and layered soils is also given in Reference [8].

d) Determination of initial pile stiffness.

If an approximation of the complete corrected load-displacement behaviour during the test is required, then further analysis steps are necessary to construct a hyperbolic based approximation of the load displacement behaviour (see Figure A.3). Firstly, it is necessary to determine the initial pile stiffness at low displacement levels.

The hyperbola is described by $F = w/(p + q \times w)$ where p is the inverse value of the initial pile stiffness k_c and q is the inverse value of the hyperbola asymptote. In a hyperbola diagram with coordinates w/F and w, a pure hyperbola will be represented by a straight line. Background information on this technique can be found in Reference [9]. The required steps are as follows.

— Plot the displacement of the pile (w) divided by the inertia corrected pile resistance ($R_{c,ic}$) for the complete test versus the pile displacement up to $w_{Fc\text{-max}}$ where $_{Fc\text{-max}}$ is the maximum measured force.

— Determine the magnitude of the $w/R_{c,ic}$ axis intersection with a best fit linear line to determine the value for the hyperbola parameter, p, which represents the inverse of the initial pile stiffness, k_c.

e) Determination of the inertia corrected load displacement curve.

The procedure for determination of inertia corrected load displacement curve is as follows.

— Determine the initial stiffness parameter as outlined above.

— Calculate the remaining the hyperbola formula parameter q as given in Formula (A.3):

$$q = 1{,}0 \big/ R_{c,ic,tw-\max} - p \big/ w_{tw-\max} \tag{A.3}$$

— Draw the resulting hyperbola load displacement curve using Formula (A.4):

$$R_{c,ic} = w \big/ \left[p + \left(q \times w \right) \right] \tag{A.4}$$

f) Determination of the corrected compressive load displacement curve.

The procedure for determination of the corrected compressive load displacement curve is as follows.

— Calculate the hyperbola parameter $q_{\text{corrected}}$ as per Formula (A.3) with $R_{c,ic,tw\text{-max}}$ replaced by $R_{c,\text{corrected}}$;

— Draw the resulting corrected compressed load displacement curve using Formula (A.4) with parameters determined for $R_{c,\text{corrected}}$.

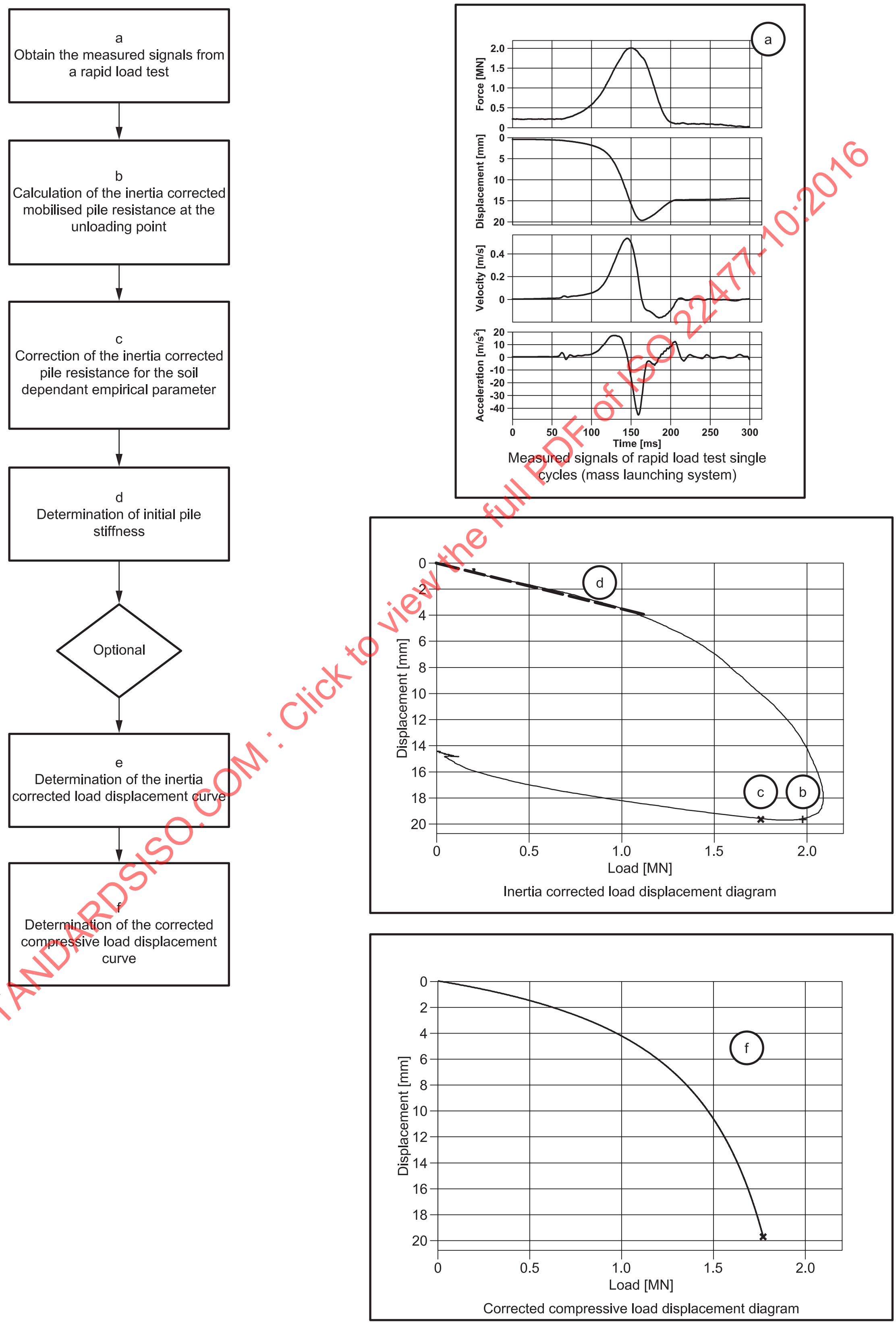

Figure A.1 — Flow chart showing the analysis process for a single cycle of rapid load testing

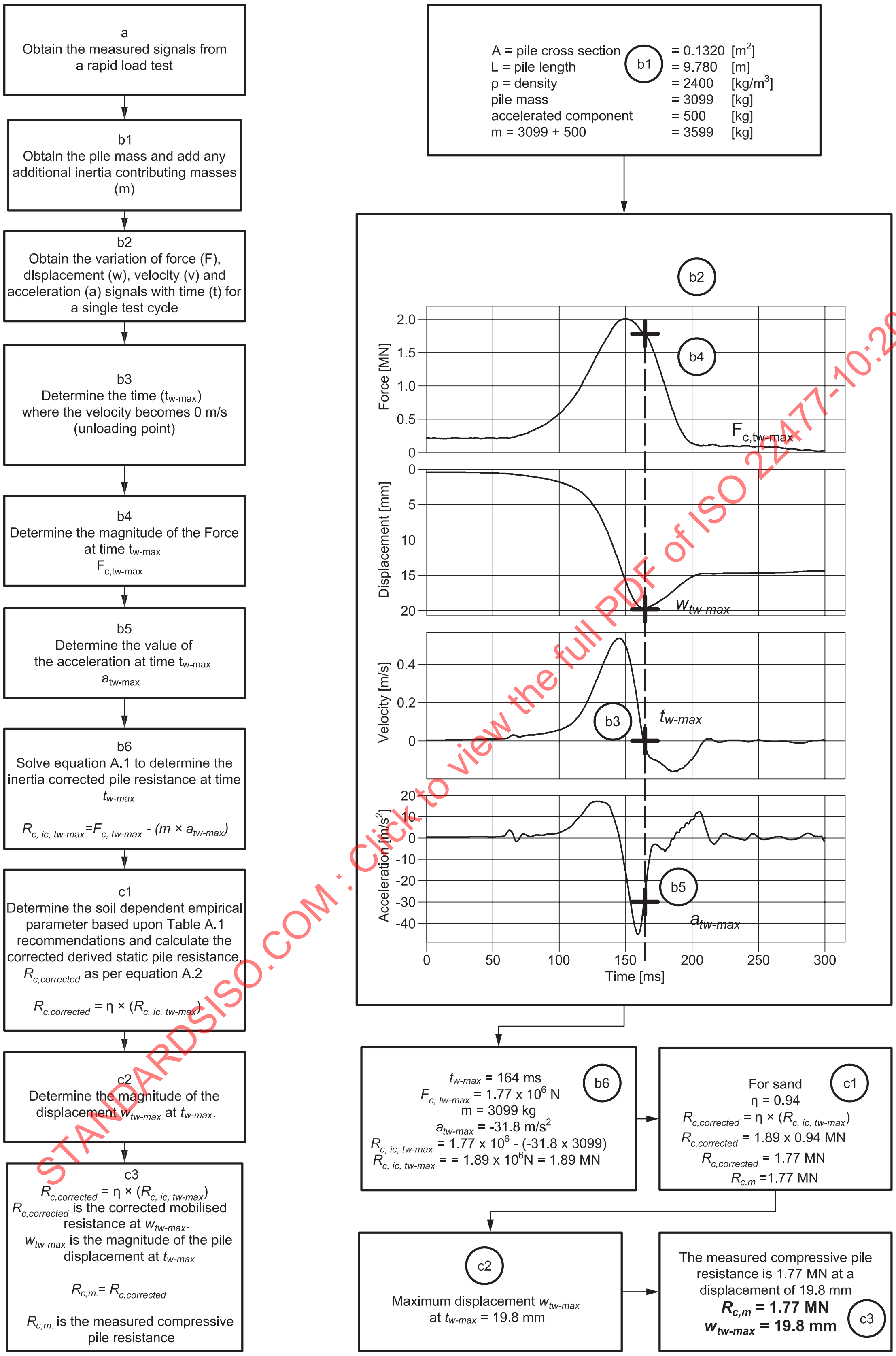

Figure A.2 — Analysis process for a single cycle using example data and calculation of $R_{c,m}$

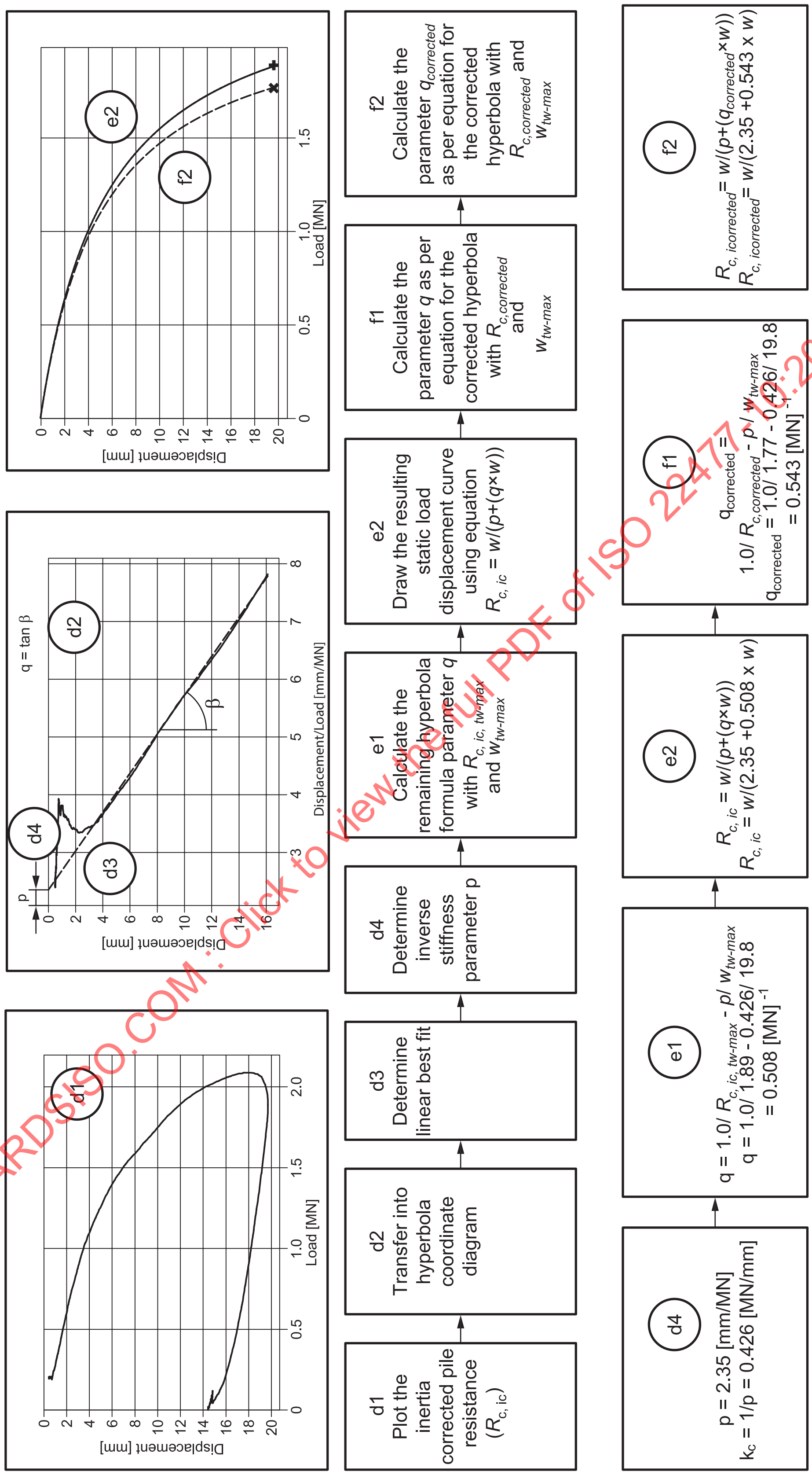

Figure A.3 — Single cycle load displacement calculation using example data

A.2.3 Analysis of multiple load cycles

The analysis for multi cycle testing where multiple load cycles are applied consecutively to the same pile follows the principals as outlined above. The overall process and differences between the single and multi-cycle analysis are highlighted below.

The process of analysis of multiple load cycles is outlined below with Figure A.4 to Figure A.6 included to clarify the steps of the analysis process.

a) Obtain the measured signals from the rapid load test with multiple load cycles.

b) Plot the load displacement behaviour for each successive load cycle with each new load cycle starting at the final displacement of the previous load cycle.

c) Analyse all of the load cycles individually and determine $R_{c,ic,tw\text{-max}}$ and corresponding $w_{tw\text{-max}}$ for each load cycle and plot these points in a load displacement diagram.

d) The measured compressive resistance $R_{c,m}$ corresponds with $R_{c,\text{corrected}}$ from the last cycle.

e) Transfer the points into a hyperbola diagram and determine a best fit linear line through these points and determine the p and q parameters for the hyperbola.

f) Draw the hyperbola in the load displacement diagram.

g) Draw the corrected derived load displacement curve with p and $q_{\text{corrected}}$.