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Geotechnical investigation and testing — Testing of geotechnical structures —

Part 4:
Testing of piles: dynamic load testing

Reconnaissance et essais géotechniques — Essais de structures géotechniques —

Partie 4: Essais de pieux: essai de chargement dynamique

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Contents

Page

Foreword

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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).

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This document was prepared by the European Committee for Standardization (CEN) Technical Committee CEN/TC 341, *Geotechnical investigation and testing*, 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 can be found on the ISO website.

Introduction

This document establishes the specifications for the execution of dynamic load tests in which a single pile is subject to an axial load in compression to measure strain, acceleration and displacement under dynamic loading and to allow an assessment of its compressive resistance. This document outlines how a dynamic load test is defined and specifies the equipment and testing procedures required. Informative non-prescriptive guidance is included on the analysis of dynamic load test results required to determine mobilized or ultimate measured compressive resistance of a pile.

Geotechnical investigation and testing — Testing of geotechnical structures —

Part 4:
Testing of piles: dynamic load testing

1 Scope

This document establishes the specifications for the execution of dynamic load tests in which a single pile is subject to an axial dynamic load in compression.

This document outlines the methods of testing required to allow assessment of pile resistance to be determined from the following methods and procedures described in EN1997-1:2004+A1:2013:

a) dynamic impact testing – determination of pile compressive resistance by evaluation of measurements of strain and acceleration and or displacement at the pile head with respect to time;

b) pile driving formulae – evaluation of pile compressive resistance from blow counts and hammer energy during pile driving;

c) wave equation analysis – evaluation of pile compressive resistance from blow counts by modelling of the pile, soil and driving equipment;

d) multi-blow dynamic testing – evaluation of pile compressive resistance from a series of blows designed to generate different levels of pile head displacement and velocity.

This document is applicable to piles loaded axially in compression.

This document is applicable to all pile types mentioned in EN 1536, EN 12699 and EN 14199.

The tests considered in this document are limited to dynamic load tests on piles only.

NOTE 1 ISO 22477-4 can be used in conjunction with EN1997-1:2004+A1:2013. 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 dynamic load tests will be considered equivalent to the measured compressive resistance $R_{c,m}$ after being subject to appropriate analysis.

NOTE 2 Guidance on analysis procedures for dynamic load testing results is given in Annexes A, B, D, E and F.

This document provides specifications for:

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

ii) 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.

EN1997-1:2004+A1:2013, *Eurocode 7: Geotechnical design — Part 1: General rules*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions in EN1997-1:2004+A1:2013 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 compressive 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 compressive resistance - deformation characteristics of the pile and the surrounding ground

Note 1 to entry: A test pile can be a trial pile or a working pile.

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

3.1.5
dynamic load
axial compressive impact load (or force) applied to the head of a pile by a driving hammer or drop mass

3.1.6
maximum pile load
highest axial compressive force applied to the pile during the test

Note 1 to entry: This is generally defined prior to the test.

3.1.7
dynamic load test
test where a pile is subjected to chosen axial dynamic load at the pile head to allow the determination of its compressive resistance

3.1.8
dynamic impact test
pile test with measurement of strain, acceleration and displacement versus time during the impact event

Note 1 to entry: The impact event is normally a hammer blow.

Note 2 to entry: This test is used to assess the compressive resistance of individual piles.

3.1.9
driving formula
formula that relates impact hammer energy and number of blows for a unit distance or permanent set for a single blow to pile compressive resistance

3.1.10
wave equation analysis
analysis of a dynamically loaded pile by a mathematical model that can represent the dynamic behaviour of the pile by the progression of stress waves in the pile and the resulting response of the soil

3.1.11
signal matching
operation to evaluate the shaft and base resistance of piles by modelling of the pile and soil with variation of parameters to match measured signals from pile head strain or displacement and acceleration measurements

3.1.12
impedance
the dynamic stiffness of a pile determined from the cross-sectional area, material stiffness and density.

Note 1 to entry: For a non-uniform pile the impedance can be different over the length of the pile.

3.1.13
mobilized compressive resistance
the resistance that is mobilized with the available energy of the impact device

3.1.14
ultimate measured compressive resistance
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 ultimate compressive resistance is not measured directly during a dynamic load test. The measured or mobilized compressive resistance obtained from dynamic load testing shall be analysed to remove the effects of dynamic soil dependent behaviour before it can be considered equivalent to the ultimate measured compressive resistance as outlined in the appropriate Annex.

3.1.15
design compressive static resistance
ultimate compressive resistance of a pile

Note 1 to entry: This shall be determined prior to load testing to allow specification of the appropriate magnitude of dynamic load test.

3.1.16
equivalent diameter
diameter of the 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.

3.1.17
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 measurement devices. Displacement measuring systems can be placed on the soil outside the reference distance without isolating (displacement compensating) measures.

3.1.18
displacement
axial movement of the pile head measured during testing

3.2 Symbols

a	acceleration
A	cross-sectional area of the pile at the level being considered
A_r	cross-sectional area of the pile reinforcement at the level being considered
c	velocity of the stress wave in the test pile
E_{dyn}	Young's modulus of the pile material at the measurement level being considered
E_k	kinetic energy
E_p	potential energy
F	force at the pile head derived from strain measurements
f_{yk}	the characteristic yield strength of the pile reinforcement
g	acceleration due to gravity (g = 9,8 m/s^2)
h	drop height (or stroke) the mass or hammer has fallen through
L	pile length
m	mass
$R_{c,m}$	measured ultimate compressive resistance of the ground in the test, or measured geotechnical resistance of the pile
t	time
v	velocity
Z	pile impedance
w	pile displacement or settlement
ε	strain

4 Testing equipment

4.1 General

The loading equipment shall be able to generate sufficient force and energy to be able to mobilize the compressive resistance to be verified.

If information on the ultimate measured compressive resistance of the pile is one of the aims of the test, the equipment shall have enough capacity to reach the ultimate measured compressive resistance and mobilize adequate settlement under dynamic loading with a single or a sequence of single blows.

The maximum pile load during a dynamic load test required to determine the ultimate measured compressive resistance can exceed the design compressive static resistance. The need to apply such high loads shall be considered when specifying equipment and pile materials.

If for a dynamic load test, one or more of the requirements in this document 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 dynamic load test.

Dynamic load testing systems rely on a mass to apply load to the head of the pile. This is either as part of a pile driving hammer referred to as an impact driving system or by dropping a mass, referred to as a drop mass system. Dynamic load testing can be undertaken during pile installation of precast concrete piles or steel piles (displacement piles) when driving with a hammer. Drop mass systems are used for the testing of cast-in-situ piles (bored piles, continuous flight auger or other cast-in-situ piles) or testing associated with re-driving. The type of load application used during testing can depend on several factors including the availability of pile installation or loading equipment and the phase of the construction project.

Three types of dynamic pile tests are given in EN1997-1:2004+A1:2013 which relate to the type of measurements and analysis undertaken and are referred to as dynamic impact tests, pile driving formula and wave equation analysis. These together with the multi-blow dynamic testing technique are presented in more detail in the annexes. The measurements taken, equipment and information required for a dynamic load test will be dependent on the specific dynamic load test being undertaken.

4.2 Loading

4.2.1 General

The selection of the loading equipment shall take into account:

— the aim of the test;

— the type of dynamic test and the analysis to be undertaken;

— the pile type;

— the ground conditions;

— the maximum pile load;

— the strength of the pile (material) and permissible stresses it can carry;

— the execution of the test;

— safety considerations.

The loading equipment shall generate adequate force and energy 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 measured compressive resistance of a pile. The equipment shall load the pile accurately with appropriate guidance of the drop mass along the direction of the pile axis. The eccentricity of the load shall be smaller than 10 % of the equivalent diameter. The deviation of the alignment of the force to the axis of the pile shall be smaller than 20 mm/m.

The stress generated in the pile under the maximum applied load shall not exceed the permissible stress of the pile material. For concrete piles in compression the maximum stress in the pile, including any prestress in the pile, shall not exceed 0,8 times the characteristic concrete strength in compression at the time of driving (as outlined in EN 12699). For concrete piles in tension the tensile force induced should not exceed 0,9 × f_{yk} × A_r minus any compressive prestress force. For steel piles the maximum stress in steel piles should not exceed 0,9 times the characteristic yield strength of the steel.

NOTE Where stresses are monitored during impact driving, these can be up to 20 % higher than the values stated above. The yield strength of materials can increase under dynamic impact loading.

To avoid potential damage to concrete piles, a simulation of the planned loading process can be undertaken by simulation using wave equation analysis. Based upon wave equation analysis, the loading scheme can be adjusted and re-simulated for example to avoid high tension stresses in a concrete pile.

4.2.2 Loading by an impact driving system

Impact hammers consist of a mass (ram) and lifting and releasing systems. They are defined by their mass and maximum stroke (drop height) or the respective potential energy (mass × acceleration × stroke) or kinetic energy immediately prior to impact.

The frequency of hammer blows should not exceed 120 blows per minute where an evaluation by a driving formula is to be considered.

4.2.3 Loading by a single or multiple blow drop mass

The mass of the drop mass should be chosen to be greater than 2 % of the design compressive static resistance of the pile (where the mass of the drop mass is expressed as a weight).

In very hard soils, piles resting on hard bedrock or where a pile is installed with a rock socket drop mass weights of 1 % of the required design compressive static resistance can be sufficient to mobilize pile resistance.

The applied energy or the stroke of the drop mass should be adjusted to achieve full mobilization of the pile skin friction and tip resistance.

4.3 Measurements

4.3.1 General

The measurements taken, equipment and information required for a dynamic load test will be dependent on the specific dynamic load test being undertaken.

During a dynamic impact test a minimum of three variables shall be directly measured relative to time (t):

— the strain at the pile head (ε);

— the acceleration of the pile head (a);

— the permanent pile displacement per dynamic load application (set per blow).

Where dynamic impact testing is analysed using the multi-blow dynamic load testing technique (Annex F) this will additionally include:

— the pile head displacement (w).

During a test where pile driving formula or wave equation analysis will be used a minimum of two variables shall be directly recorded:

— the permanent pile displacement per impact of the hammer referred to as set per blow(s);

— the mass of the piling hammer (or drop mass) and drop height (and/or energy rating).

Where piles are subjected to a single hammer blow or cycles of drop mass loading and are accessible, 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.

4.3.2 Measurements for dynamic impact tests

The transducers and signal processing shall satisfy the requirements from Table 1 to Table 3. Sampling shall commence a minimum of 10 ms before loading commences and continue for a minimum duration such that the pile has come to rest. The transducers shall have sufficient measuring range, in order to avoid re-adjustment or change of position during testing. All instrumentation shall be able to withstand pile installation and testing procedures. For diesel hammers the duration of pre-event sampling should be extended to a minimum of 35 ms, and extension of the corresponding duration of measurement to >125 ms. For longer piles the length of the pile should be considered when determining the duration of measurement. The particular minimum sampling rate adopted should take into account the type of pile and test being undertaken.

Table 1 — Dynamic impact test: signal processing general requirements

Parameter	Requirement
Sampling rate	≥5 000 samples per second
Duration of pre-event sampling	≥10 ms
Duration of the measurement	≥100 ms

Table 2 — Dynamic impact test: strain transducer requirements

Parameter	Requirement
Maximum strain	≥0,015
Resonant frequency	≥2 000 Hz

Table 3 — Dynamic impact test: acceleration transducer requirements

Parameter	Requirement
linearity	up to 2 000 g and 2 000 Hz

Table 4 — Dynamic impact test: displacement measurement using remote theodolite during load application

Parameter	Requirement
Sampling rate	≥10 000 samples per second
Accuracy	<1 mm

All equipment used for measuring strain, 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 on request prior to commencement of the test.

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 shall 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.

The strain (ε) as a function of time (t) induced in the pile head by the dynamic load, shall be measured by at least two strain transducers, mounted in an axial direction and diametrically opposed pairs (see

Annex C). The acceleration a as a function of time (t) of the pile head shall be measured by at least one acceleration transducer, mounted in an axial direction (see Annex C).

4.3.3 Measurements and recordings required for pile driving formula or wave equation analysis

The permanent pile displacement per impact of the hammer referred to as set per blow(s) is recorded by manually counting the number of blows for a unit distance of penetration for at least the last 1,0 m of pile penetration.

Distance markers should be clearly marked on the pile under test prior to testing. In continuous driving, blows are counted for a unit penetration. As an alternative, a penetration for a defined number of blows can be determined.

The set per blow is determined either by optical levelling to a reference point which is unaffected by pile driving operations or by visual observations of marks on the pile passing a stable reference beam which is unaffected by the pile testing process. The requirements for optical levelling are outlined in Table 5.

Table 5 — Dynamic load test displacement requirements for set per blow when determined by optical instrument levelling

Parameter	Requirement
Accuracy	≤1 mm

To determine the energy transferred to the pile from the dynamic loading it is necessary to know the mass of the ram or hammer and the drop height that mass or ram falls through.

The potential energy of the driving system:

$$E_p = m \times g \times h \quad (1)$$

where

E_p potential energy;

m mass of ram or hammer;

g acceleration due to gravity (g = 9,8 m/s^2);

h drop height (or stroke) the mass or hammer has fallen through.

The drop height or stroke is measured by a visual estimate only if the ram can be seen.

The kinetic energy of the mass or ram directly before impact is given by:

$$E_k = m \times v^2/2 \quad (2)$$

where

E_k kinetic energy;

v velocity of mass or ram before impact.

The velocity of the ram before impact can be measured by proximity switches installed as part of the hammer casing.

5 Test procedure

5.1 Preparation for testing

It is recommended that in advance of the test, an execution plan should be formulated that is consistent with the planned final report shown in Clause 7. The plan should include the following where appropriate:

a) test objectives;

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

c) topographic locations, types and specifications of the test piles;

d) allowable maximum values of the load and stresses on the pile and the pile displacement;

e) required pile displacement and applied load;

f) specification of the loading device;

g) specifications of the measurement devices and calibration certificates if applicable;

h) specifications of additional measurement-devices;

i) plan of the test site;

j) testing programme;

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

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

m) accessibility of the pile for sensor attachment;

n) procedures for preventing pile damage and detecting pile damage in the case of cast-in-situ piles;

o) assessment of feasibility of testing by wave equation analysis;

p) safety requirements.

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

5.2 Safety 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 and should be undertaken in accordance with EN 16228 where applicable.

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. Separate notification of dynamic load testing is not required where the testing forms part of a larger programme of displacement pile installation where notification has already occurred.

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 compressive load that will be applied during the test. As cast-in-situ piles (bored piles, continuous flight auger or other injection piles) are not normally designed for dynamic loading, pile heads should be reinforced by a steel casing. Prior to the test the allowable compression and tension stresses for the pile should be defined and compared to wave equation analysis for the pile. For cast-in-situ piles integrity testing should be undertaken before and after dynamic load testing.

NOTE During a dynamic load test, the test pile is loaded with a force which can exceed the static equivalent test loads. Test piles are to be designed to withstand the resulting higher stresses. For concrete piles a pile cushion is usually used to reduce and evenly distribute stresses.

For working piles the maximum accumulated final 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, perpendicular to the pile axis and undamaged. The heads of concrete piles shall be protected by a pile cushion. The test pile shall have enough length above the ground surface to attach the measurement devices. Proposed positioning of transducers and pile extension details are given in Annex C.

5.4 Timing of tests

5.4.1 General

The compressive resistance of a pile has the tendency to vary significantly depending on the time after installation at which it is tested. This should be given due consideration for dynamic load testing as testing can be carried out during pile installation or at some time later.

5.4.2 Driving — Continuous monitoring and end of initial driving test

In continuous pile driving for installation each individual impact can be considered as a separate dynamic load test. Usually a compressive resistance calculation is undertaken when the pile is penetrating what is considered a competent ground layer or when it achieves final penetration.

As the ground resistance can be reduced in continuous driving the pile compressive resistances determined during initial driving or at end of initial driving can be lower than that determined from static pile load tests. In certain soil conditions the compressive resistance at end of driving can also be larger than the compressive resistance in re-driving. The potential for difference in the measured characteristic compressive pile resistance due to the timing of testing should be given appropriate consideration.

5.4.3 Re-driving

Re-driving is a dynamic load test carried out some time after the installation of the pile and is a separate operation to testing during pile installation. It can be considered that a dynamic load test undertaken during re-driving is less influenced by the pile installation process if adequate time after installation is allowed to elapse. The optimum timing for re-drive dynamic load testing should be assessed for the specific ground conditions at the site.

Where re-driving gives lower pile resistance than that measured during driving for installation this shall be used as the basis for ultimate compressive resistance assessment (EN1997-1:2004+A1:2013, Clause 7). If re-driving gives higher results, these can be considered.

For certain ground conditions re-driving should be carried out. Re-driving should usually be carried out in silty soils, unless local comparable experience has shown it to be unnecessary.

NOTE Re-driving of friction piles in clayey soils normally results in reduced compressive resistance.

5.4.4 Bored or cast-in-situ piles

Between the installation of a bored or cast-in-situ 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 soil has sufficient time to recover from the process of pile installation and dissipation of pore-water pressures and other aspects, such as 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 6. Alternative time periods can be specified with appropriate justification.

Table 6 — Time periods between installation and testing of bored piles

Test pile type	Soil type	Minimum time [days]
Trial	Non-cohesive	7
	Cohesive	21
Working	Non-cohesive	5
	Cohesive	14
Alternative time periods can be specified with appropriate justification.		

6 Test results

6.1 Test results for dynamic load test with driving formula

The test results shall include records of the following:

— set per blow or blows for unit distance of penetration;

— energy per blow;

— calculated ultimate compressive resistance as $R_{c,m}$.

6.2 Test results for dynamic load test with wave equation analysis

The test results shall include records of the following:

— blows for unit distance of penetration with penetration;

— energy per blow with penetration;

— calculated ultimate compressive resistance, $R_{c,m}$.

6.3 Test results for dynamic load test with measurements at the pile head

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

— the average force derived from strain due to the loading system at the pile head as a function of time $F(t)$;

— the velocity as integrated from acceleration of the pile head as a function of time $v(t)$;

— force $F(t)$ and velocity $v(t)$ in a single graph where the velocity is scaled to the dimension of the force by the impedance $Z = E_{dyn} \times A/c$ (Annex D).

Where the cross section of a pile is a combination of materials the impedance based upon the properties of the combined materials shall be considered.

For the multi-blow dynamic load testing technique these measurements are also combined with:

— the displacement of the pile head as a function of time (where a remote theodolite is used), $w(t)$.

Results can be evaluated by:

— direct closed form solution by applying soil dependent estimated damping values (Annex D);

— signal matching (Annex E);

— multi-blow dynamic load testing technique (Annex F).

Where appropriate, all measured test results shall be available in hard copy charts and digitally in a readable text based format. 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 shall be reported. All other readings, such as local site temperature, tests on concrete samples, optical level readings, pile geometry, adjacent static tests on the site, when relevant, shall also be recorded in the test report.

7 Test reporting

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

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;
- — 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) Specifications 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 and modulus of elasticity if known), inclination (if inclined) 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.

d) information concerning the ground conditions:

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

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

e) specifications of the test:

— the postulated maximum force and resulting stresses in the pile;

— a description of the loading apparatus and measuring apparatus;

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

— calibration documents for the strain gauges, accelerometers and displacement measuring devices (if used);

— the distance between the pile and the displacement measurement device (if used);

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

f) test results:

— for evaluation by driving formula; verification of equivalence to static tests, driving record, energy per blow and justification of empirical parameters adopted. See Annex A;

— for the wave equation solution; description of calculation model adopted, driving record including energy, justification of dynamic parameters adopted. See Annex B;

— for evaluation by closed form solution the total resistance and the static resistance determined together with the applied damping factor adopted. See Annex D;

— for evaluation by signal matching; the derived load-displacement diagram, verification and sources of parameters chosen, for dynamic load tests of cast-in situ piles the assumptions concerning material properties and pile shape shall be described; the skin friction – tip resistance distribution; the match quality of the evaluation shown as a combined graph of measured and calculated pile behaviour. See Annex E;

— evaluation of pile performance by the multi-blow method; the derived load-displacement diagram separation of forces plot; correction of pile velocity plot; table of results showing dynamic resistance and permanent penetration for each blow. See Annex F;

— results from pile integrity testing where undertaken.

g) reasons for any deviation from this document (ISO 22477-4).

Annex A
(informative)

Driving formula

A.1 General

Annex A gives informative guidance on one method for analysing piles during driving as defined in EN1997-1:2004+A1:2013. 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 and installation as alternative methods may be adopted. Inclusion of the informative guidance on the analysis of pile driving should not discourage or inhibit the use, adoption or development of alternative analysis techniques. Further guidance on the use of driving formula can be found in EN1997-1:2004+A1:2013.

A.2 General concept of pile driving formula

A.2.1 General

The general basis for all pile driving formulae is an attempt to find a relationship (η) between the estimated transferred energy to the pile top (E_{tr}) and the dissipation of this energy to the soil as pile resistance (R_u) with respect to the pile top displacement (w) (Reference [5]).

The basic form of a resistance to energy relationship is given as Formula (A.1):

$$R_u = \eta \times E_{tr}/w \qquad \text{(A.1)}$$

A.2.2 Driving formula analysis

The input parameters required to determine the soil resistance are:

— E_k the kinetic energy of the ram at the moment of impact;

— C_r coefficient of restitution, representing the energy loss due to the interaction of the pile hammer system components (anvil, helmet, follower, cushioning);

— s the permanent set of the pile top after a blow;

— s_{el} elastic set of the pile during a blow;

— η an empirical efficiency/correlation factor depending on local soil conditions and pile/hammer configuration type.

A.2.3 Determination of the kinetic energy (E_k)

Assuming no energy losses during the drop of the ram the kinetic energy E_k directly before impact is equal to the potential energy at a specific drop height, as per Formula (A.2):

$$E_k = E_p \tag{A.2}$$

The potential energy is the energy of the ram at drop height, h, as per Formula (A.3) and (A.4):

$$E_p = m \times g \times h \tag{A.3}$$

where

E_p potential energy;

m mass of ram;

g gravity (g = 9,8 m/s^2);

h drop height (or stroke).

$$E_p = m \times g \times h = W \times h \tag{A.4}$$

where W is the ram weight.

NOTE 1 The ram drop height can be measured by proximity switch systems mounted on the hammer or optical systems measuring the height of the ram. In case of diesel hammers the drop height can be estimated from the blow rate.

The kinetic energy can also be determined by measuring the impact velocity of the ram (v), as per Formula (A.5):

$$E_{kin} = 0{,}5 \times m \times v^2 \tag{A.5}$$

NOTE 2 Impact velocities v can be measured by proximity switch systems mounted on the hammer, optical systems measuring the movement of the ram or accelerometers mounted on the ram.

A.2.4 Determination of the coefficient of restitution (C_r)

The energy loss due to the interaction of the pile hammer system components (ram guidance, anvil, helmet, followers, cushioning) is generally referred to as coefficient of restitution, C_r.

C_r can be obtained by measuring the drop height of a ram or by measuring the impact velocity of the ram in combination with measuring the transferred energy E_{tr} by pile driving analysis measurements. For one impact blow C_r is determined as per Formula (A.6):

$$C_r = E_{tr} / E_k \tag{A.6}$$

A.2.5 Determination of the pile set (s and s_{el})

For continuous initial driving the permanent set per blow is determined from the blows per unit penetration (blow count). In re-driving the permanent set per blow (s) can be determined by levelling after each blow in a single blow application. If an average permanent set is determined for a sequence of blows the total cumulative penetration for these blows should not exceed 50 mm.

The elastic set or temporary compression during a blow (s_{el}) has to be derived from pile top displacement measurements, which can be taken by physical measurements, by optical systems or accelerometers mounted near the pile top.

A.2.6 Determination of the empirical efficiency/correlation factor η

The empirical correction factor η has to be derived from calibration with a static load test (R_{stat}):

$$\eta = R_{stat} \times (s + s_{el})/(C_r \times E_k) \quad \text{(A.7)}$$

where the mobilized pile load deflection behaviour can be shown to correspond to the ultimate resistance of the pile, then R_u can be considered equivalent to the ultimate measured compressive resistance, $R_{c,m}$.

A.2.7 Calculation of the energy transferred E_{tr} to the pile

The energy transferred to the pile is given by:

$$E_{tr} = E_k \times C_r \quad \text{(A.8)}$$

A.2.8 Calculation of the soil resistance R_u

The energy absorbed by the pile and the ground is the dissipated energy which is assumed to be equivalent to the total compressive resistance R_u multiplied by the permanent set (s). Also as energy is needed for the elastic deformation elastic set (s_{el}) is added to the permanent set, so that the basic form of a compressive resistance to energy relationship is given as:

$$R_u = (\eta \times C_r \times E_k)/(s + s_{el}) \quad \text{(A.9)}$$

A.2.9 Additional factors to be considered

There are several additional factors that might have to be considered when using pile driving formula to estimate the ultimate or mobilized compressive resistance of a driven pile (Reference [6]), some of them are:

— The pile driving formula approach implies a simplification of the real pile and the real ground behaviour. The formula requires that applied forces and ground resistances act at the same moment which for pile driving is only the case for very short piles (rigid body behaviour);

— Efficiencies of driving hammers are difficult to obtain without additional measurements and energy absorption properties of piles and cushions can vary significantly;

— The formula does not take into account changes in ground properties in case of multiple layers.

Annex B
(informative)

Wave equation analysis

B.1 General

Annex B gives informative guidance on one method for analysing a dynamic load test as defined in EN1997-1:2004+A1:2013. 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. Inclusion of the informative guidance on the analysis of dynamic load testing should not discourage or inhibit the use, adoption or development of alternative analysis techniques. Further guidance on the use of wave equation analysis can be found in EN1997-1:2004+A1:2013.

B.2 General concept of wave equation analysis

Wave equation analysis is based on a mathematical model which simulates the impacting hammer and associated components, the pile components, the stress wave propagation in a pile and the behaviour of the ground.

The mathematical model is normally implemented in a computer code which for the calculation of compressive resistances shall comprise:

— Modelling of the ram, components such as anvils and helmets, cushioning and the pile to accurately generate a force time history for the pile top;

— A nonlinear soil or ground model to accurately calculate the permanent set for a single blow;

— Damping elements to define the dynamic component of the resistance;

— A soil model that allows for representation of soil fatigue/degradation in continuous driving so that an accurate estimate of pile compressive resistance can be determined.

This can be used to generate

— The displacement-time histories for the pile top and pile toe;

— A calculation of the permanent set at the time when the pile top or pile toe have come to rest;

Two methods are available to derive the compressive resistance by wave equation analysis:

1) Bearing graphs which give a relationship between transferred energy to the pile, final set per blow (blow count) and the pile's compressive resistance;

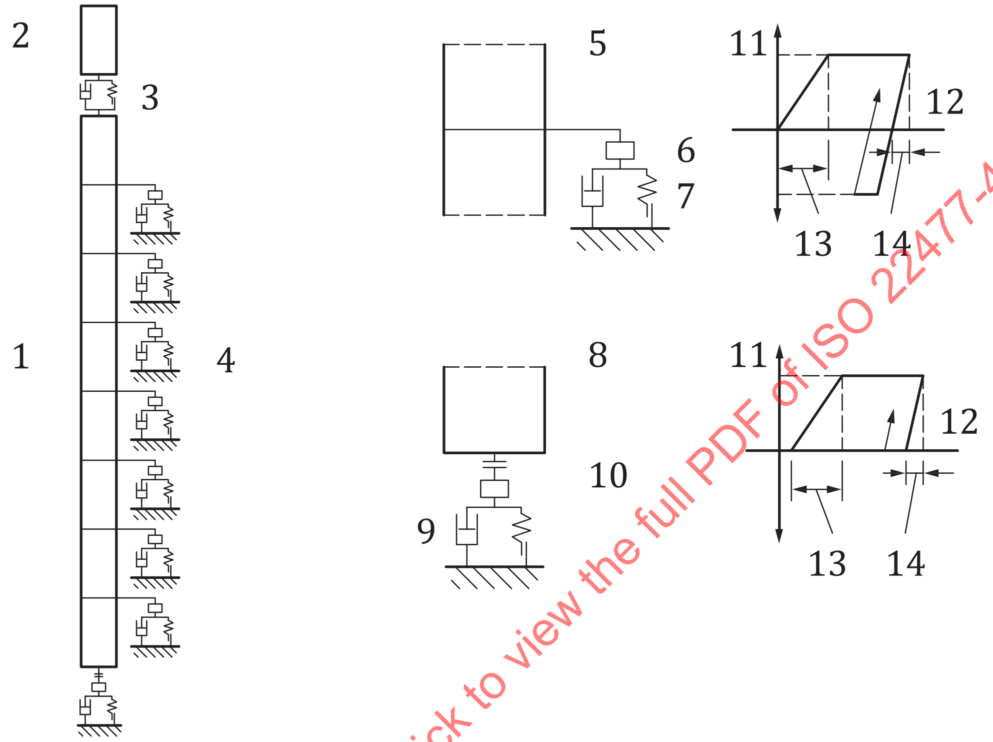
2) Blow count matching, by which the wave equation program simulates the driving process for multiple pile toe penetration levels. The calculated energy and calculated final set should match with measured energy and measured final sets. The derived static soil or ground model parameters in the simulations are used to calculate the pile's compressive resistance for each penetration level.

Both methods depend on the appropriate calculation of the final set per blow (blow count). Wave equation analysis or simulation is also carried out at the design stage and a driveability analysis can be carried out in an attempt to predict the driving of the pile from piling platform level to final penetration. This allows the matching of pile section to pile driving hammer required to install the pile in the ground conditions given in the site investigation data.

B.3 Mathematical model

B.3.1 Wave propagation algorithms

The algorithms to simulate wave propagation in the pile can be based on the lumped mass spring approach (Reference [7] and [8]), the continuous segment approach (Reference [9] and [10]) or the finite element approach (Reference [11] and [12]). Figure B.1 gives an example of the continuous segment model for a pile in the soil.



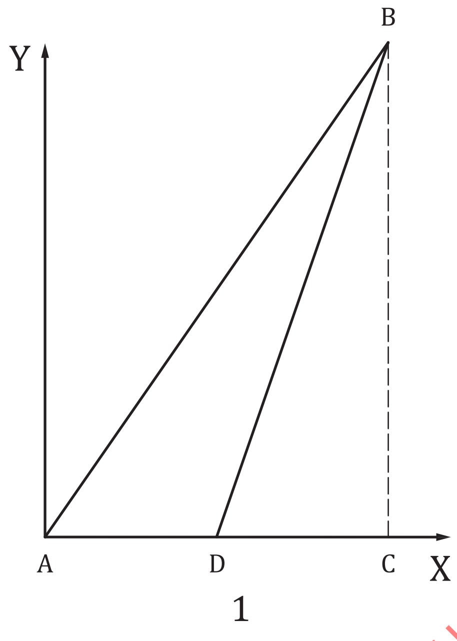
Key

1 pile model
2 ram model
3 cushioning model
4 soil model
5 shaft model
6 soil mass
7 spring and slider
8 tip model
9 viscous damper
10 base gap and soil mass
11 resistance
12 displacement
13 $quake_1$
14 $quake_2$

Figure B.1 — Basic model for the pile-soil interaction during driving

B.3.2 Mechanical modelling of ram components, cushioning and the pile

Ram, anvil, helmets can be modelled as segments or lumped masses and springs. Cushioning can be modelled as a discrete spring (Figure B.2) and combined with a discrete damper. The computer code models the impacting ram, the cushioning system, the pile in the ground and the stress wave propagation by taking account of the pile cross section, density and modulus of elasticity of the pile as well as the nonlinear static, dynamic and fatigue behaviour of the soil.



Key

1 coefficient of restitution = √(Area BCD/Area ABD)

X strain

Y stress

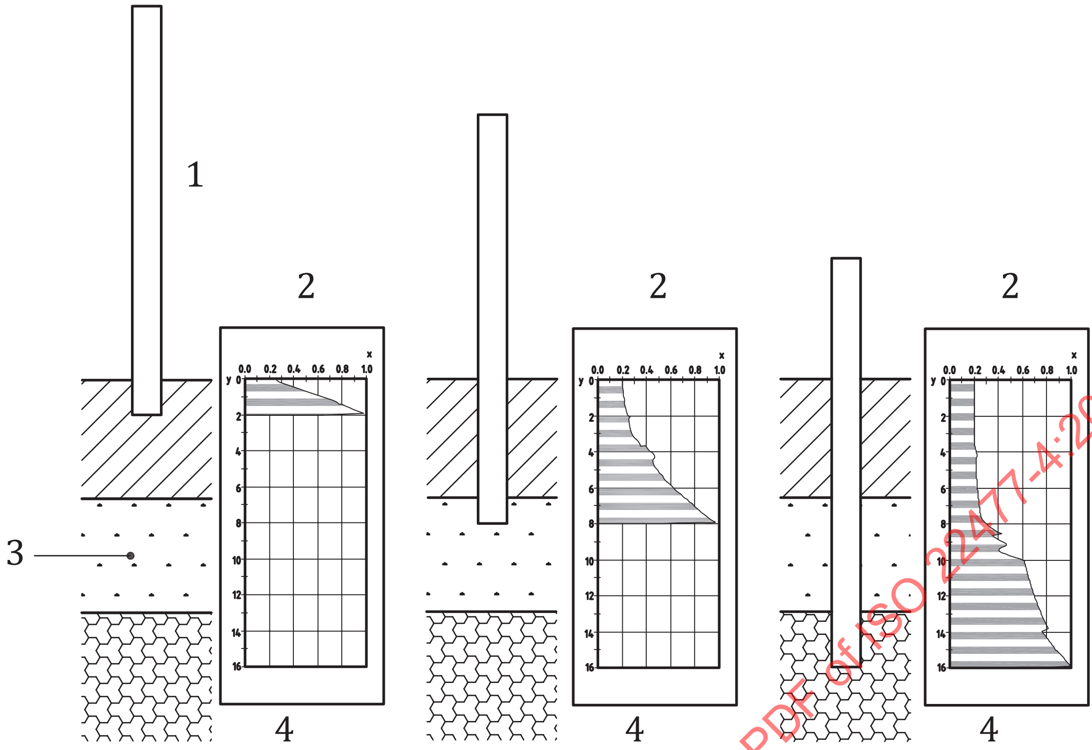
Figure B.2 — Example of a discrete spring cushion model

B.3.3 Modelling nonlinear soil behaviour

To represent the stress-displacement behaviour of the soil or ground, the static component is represented by a linear-elastic-ideally plastic spring and the dynamic component by a viscous damper and lumped mass (Figure B.1). The choice of static parameters such as soil yield stresses, quake and dynamic parameters shall be properly evaluated because they have significant influence on the calculated resistances and permanent set per blow.

B.3.4 Modelling soil fatigue behaviour

A soil or ground model that allows for soil fatigue/degradation during continuous driving can be included so that an accurate estimate of final pile resistance can be determined. As the soil degradation will be different for each soil layer (Figure B.3) and for each pile toe penetration level it is necessary to update for each soil layer at each pile toe penetration level (Reference [13] and [14]).



Key

1 pile

2 soil fatigue

3 soil

4 fatigue factor along pile axis

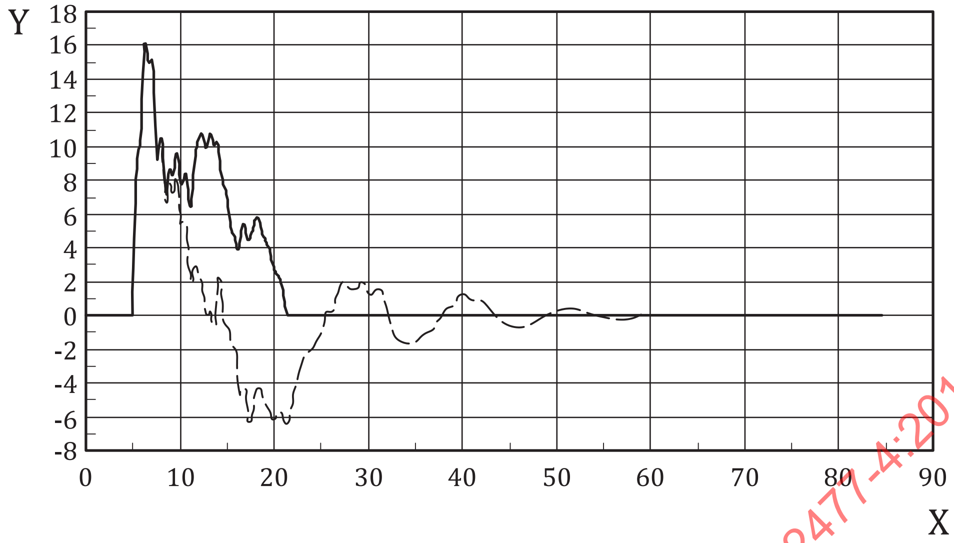
Figure B.3 — Example soil fatigue reduction factor for three pile toe penetration levels

B.3.5 Modelling of the soil layers

All relevant soil layers and those that are likely to be associated with the highest driving resistances should be represented by at least one penetration level where predictions are made.

B.3.6 Time histories

Time histories are used to compare and calibrate the simulation results with real measured signals such as impact forces, transferred energy and displacements (See Figures B.4 and B.5).



Key

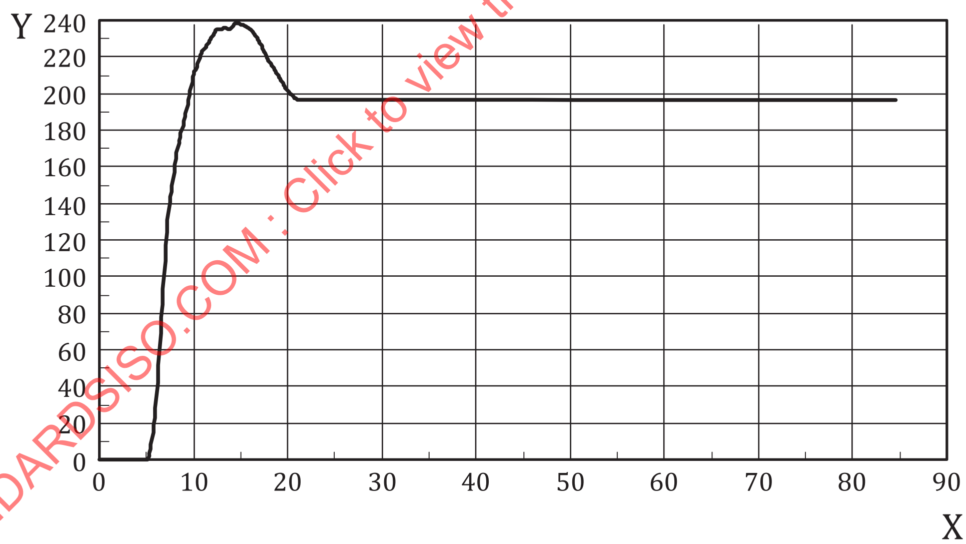
X time (ms)

Y force (MN)

——— force

— — Zv

Figure B.4 — Time history for impact force and velocity multiplied by the impedance at pile top



Key

X time (ms)

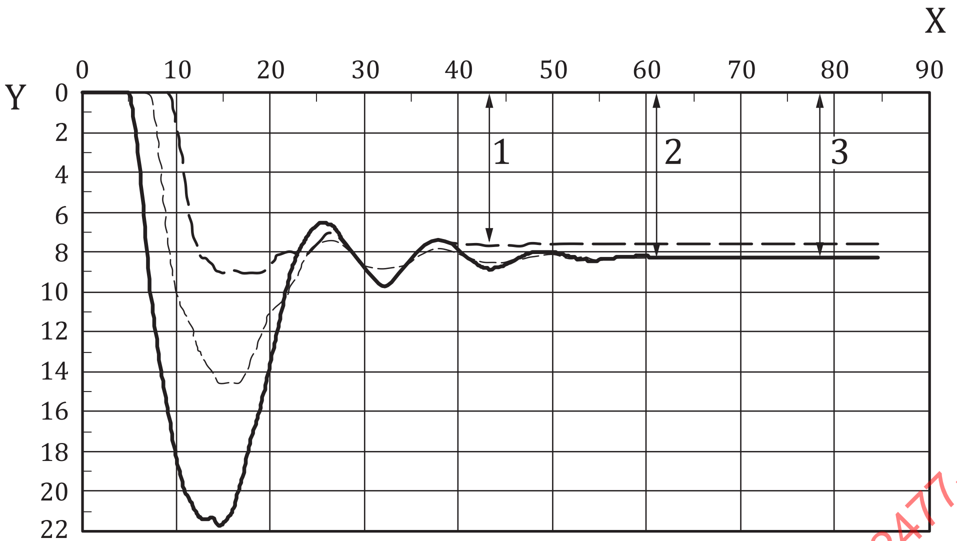
Y energy (kNm)

——— calculated

Figure B.5 — Time history for the energy transferred to the pile

B.3.7 Determination of permanent set at the pile top

The permanent set per blow is determined from calculated displacements when the pile has come to rest (Figure B.6).



Key

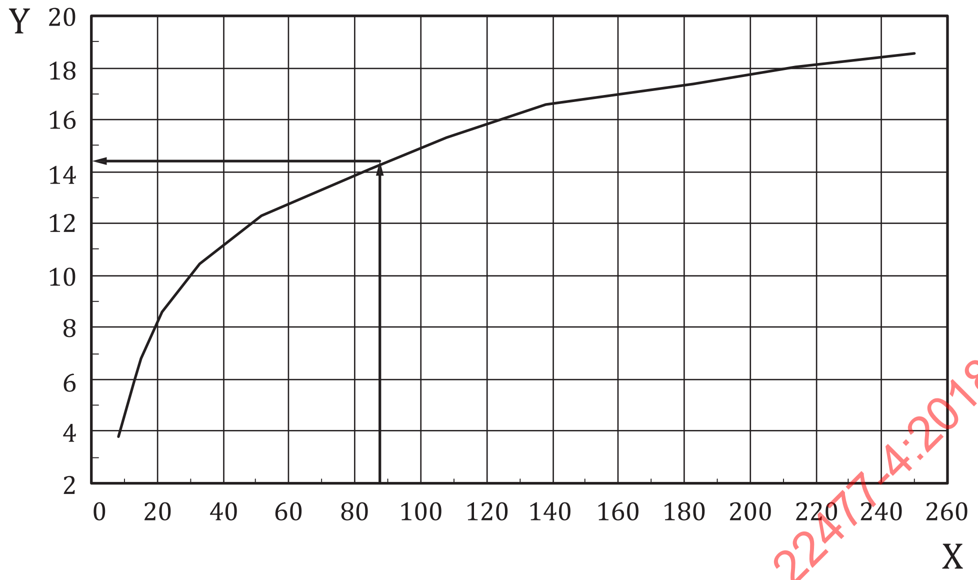
1 pile toe
2 pile middle
3 pile top
X time (ms)
Y displacement (mm)
——— Level = 0,000 m
_ _ _ Level = 11,311 m
— — Level = 23,000 m

Figure B.6 — Determination of permanent set for a hammer blow

B.4 Bearing graph method

With this method multiple wave equation simulation runs, each simulating a hammer blow, are made with increasing soil resistance for a certain ram, cushioning, pile configuration and a prescribed energy and pile toe penetration level. For each run the final set (blow count) is derived and the corresponding compressive resistance calculated from the static soil model parameters. The results are plotted in a bearing graph (see Figure B.7)

During real driving with a similar situation for hammer configuration, energy level and pile toe penetration level and by recording the blow count (final set) the actual mobilized compressive resistance can be estimated from the bearing graph (Figure B.7).



Key

X blow count (blows/0,25 m)

Y compressive resistance (MN)

Figure B.7 — Bearing graph (SRD) versus blow count [penetration = 16,000 (m), impact energy = 252,7 (kNm)]

For the blow count recorded during driving (in this case 87 blows for 250 mm, Figure B.7) a mobilized compressive resistance can be estimated from the simulated pile compressive resistance graph (in this case 14,2 MN).

B.5 Blow count matching method

This method can be applied when a complete driving record as energy per unit penetration over driving depth and blow count over driving depth are available.

Multiple wave equation runs, each simulating a hammer blow, are made for pile toe penetration levels where driving records are available. The energy of the hammer blow is assumed to equal the driving record energy. For each level the soil behaviour is varied such that a match is obtained between measured and calculated blow counts or set per blow (Figure B.8).

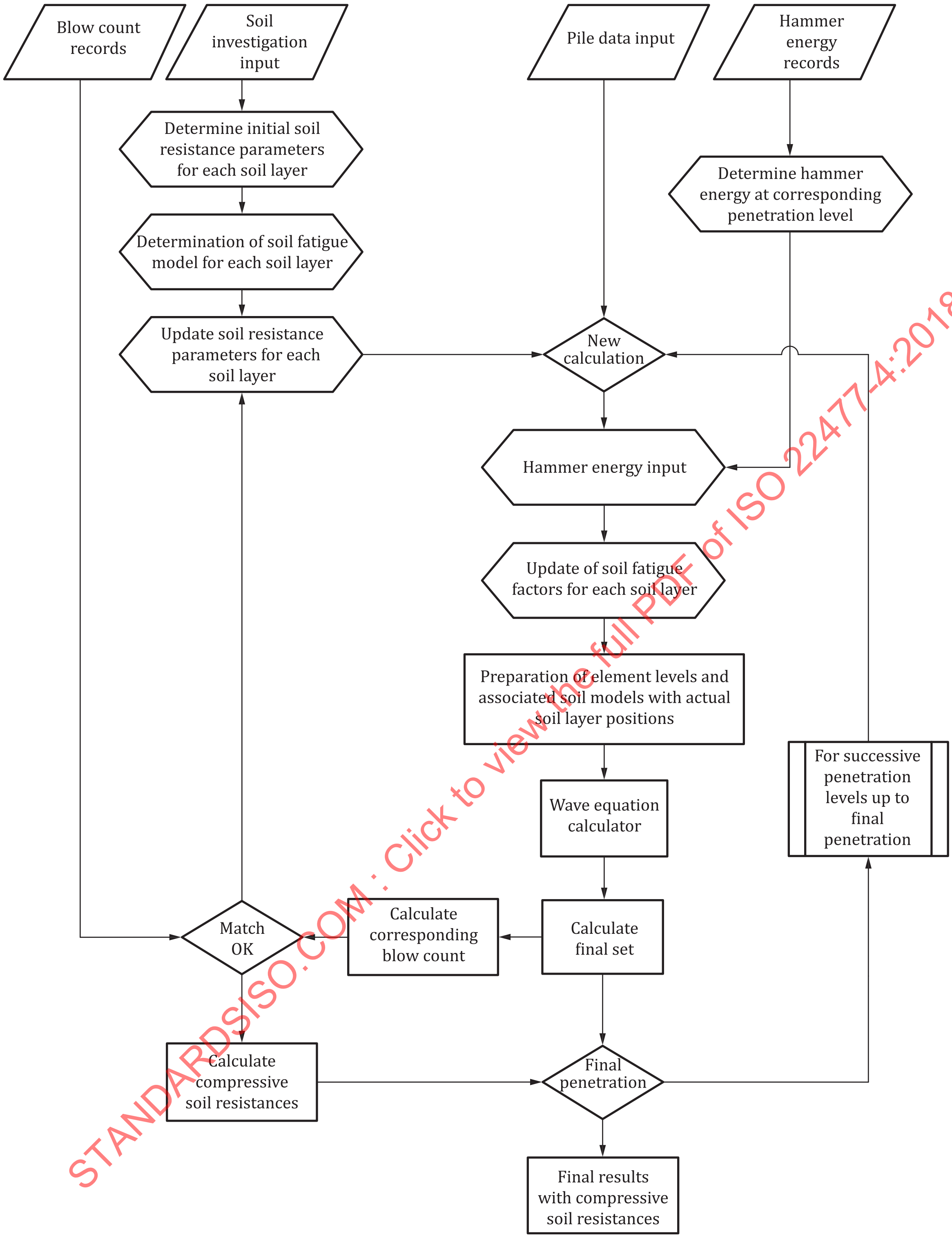


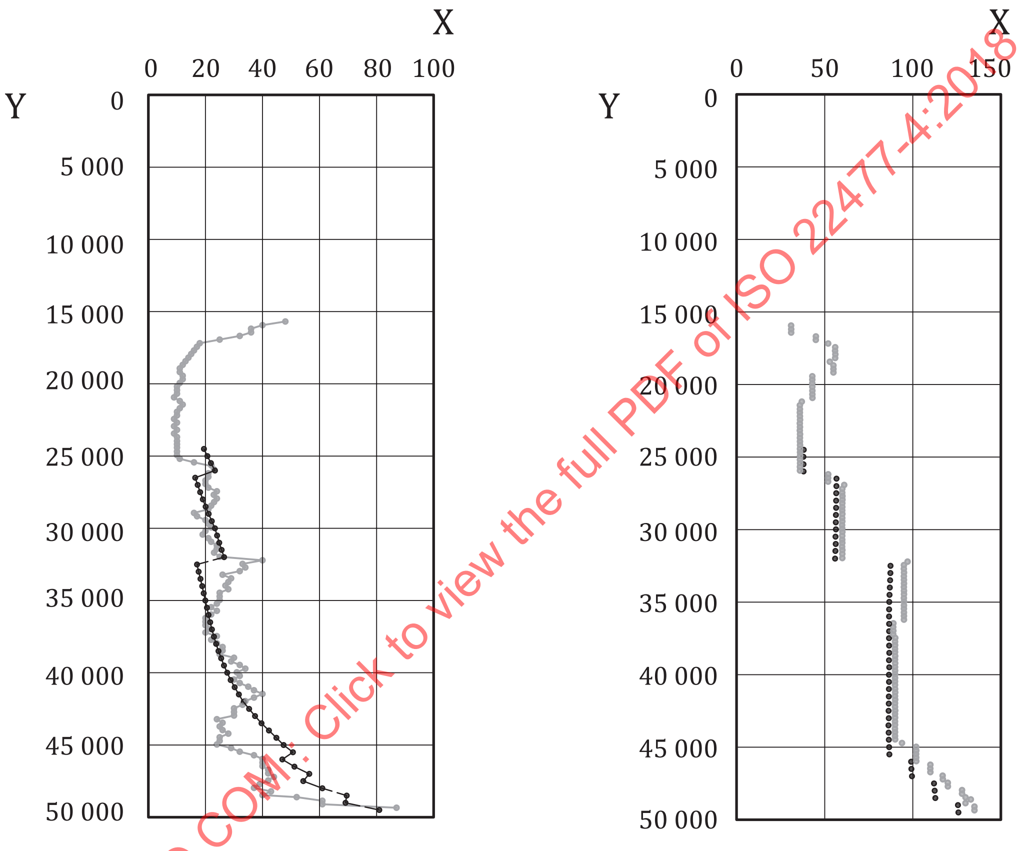
Figure B.8 — Driving record matching process

The basis of the calculation is the driving record obtained during pile driving as a combination of blows per unit penetration (set per blow) and energy per blow (Figure B.9).

During pile driving the blows per unit penetration are usually determined by manual observation although automatic systems with depth encoders and automatic counting are also used. The energy per blow is recorded along with the blow count by observation of stroke (for Diesel hammers counting blows per minute) or is provided by an output from the driving rig.

Resistances in the model are adjusted to give a complete representation of the driving record. As shown in Figure B.9 the energy settings are taken from the driving record. As the model considers energy losses due to the cushion and helmet the energy presented in Figure B.9 is less than the energy shown in the driving record which is taken from ram movements or stroke.

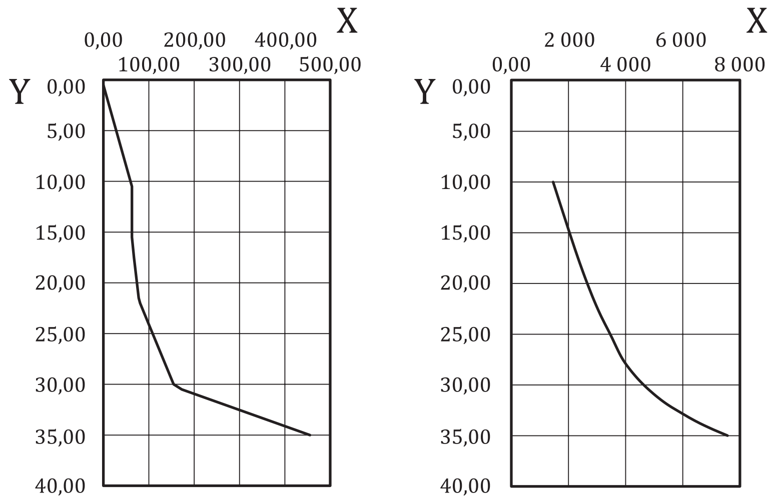
A soil profile, given as shaft resistance and tip resistance, is defined to match the blow count with depth. Thus skin friction and tip resistance are defined, giving a total ultimate compressive resistance of 7,567 kN (Figure B.10). In the example shown the purpose of testing was to determine the ultimate measured compressive resistance therefore the interruption due to splice welding at 33 m penetration was not considered.



Key

X	blows per 250 mm	X	energy per blow (kNm)
Y	depth below msl in mm	Y	depth below msl in mm
—•—	driving record	•	manufacturers output
--•--	wave equation calculation	•	energy in wave equation calculation

Figure B.9 — Input driving records of blow counts and energies



Key

X skin friction (kPa)

Y depth below ground level

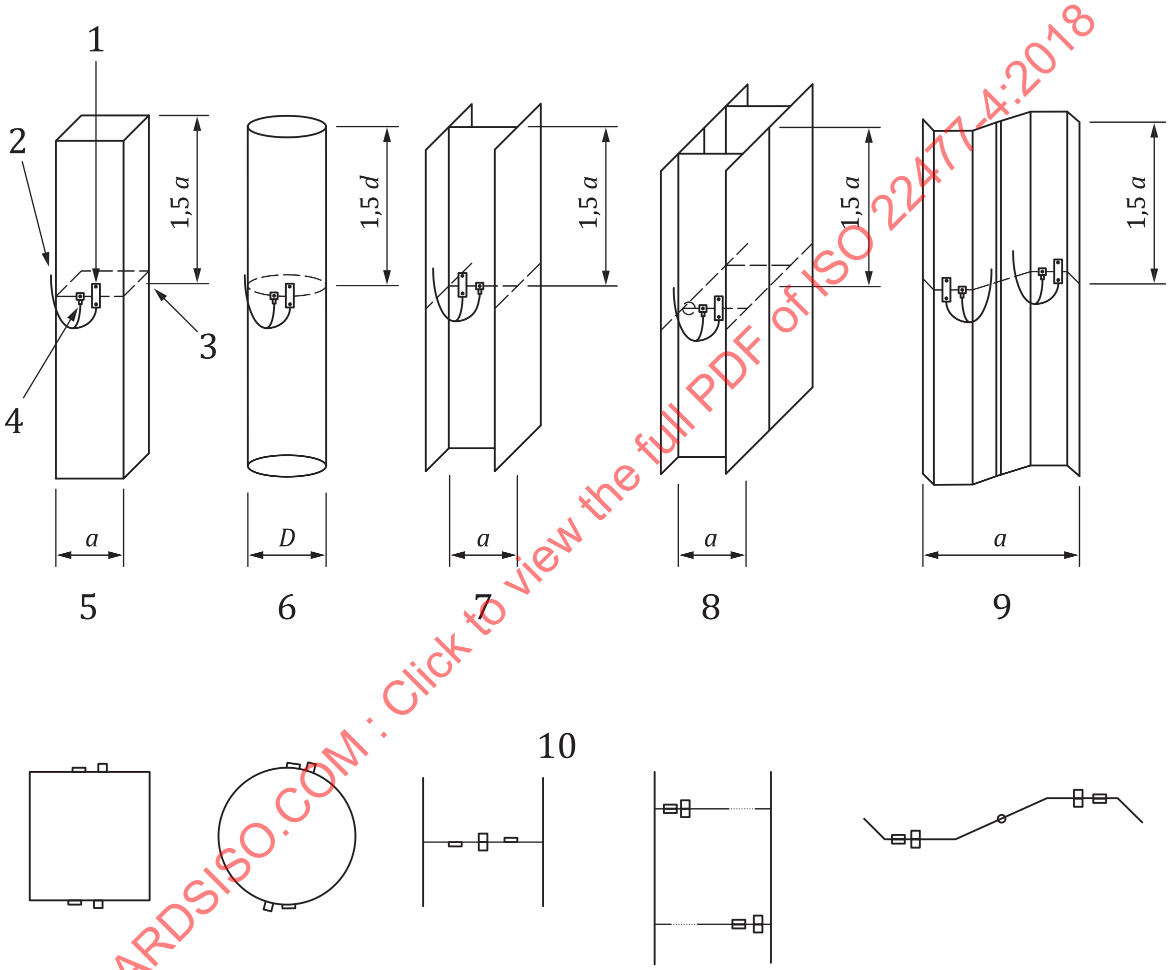
X total resistance (kN)

Figure B.10 — Derived driving record match of compressive resistances

Annex C
(informative)

Examples of transducer attachment and pile extension details

C.1 Transducer attachment details



Key

1 strain gauge
2 cable to logging computer
3 logging plane
4 acceleration sensor
5 precast concrete pile
6 tubular steel driven pile
7 steel pile, H-beam
8 steel pile, double H-beam
9 sheet pile wall, double sheet pile
10 plan view

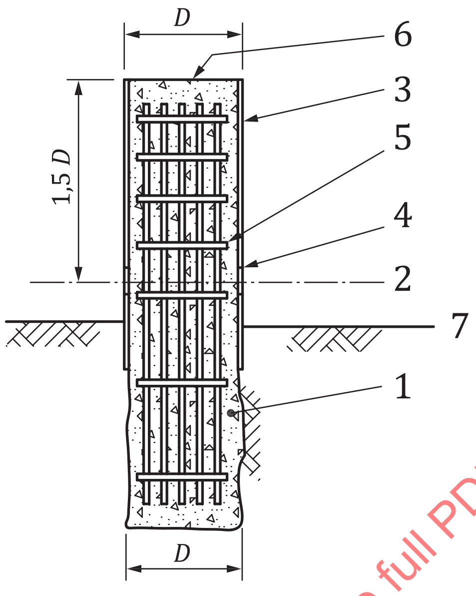
Figure C.1 — Examples of transducer attachment arrangements for various pile types

The positioning of transducers in Figure C.1 is for general guidance only and the distance of the transducers from the top of the pile should be given appropriate consideration in the case of large diameter or long piles where additional transducers may be required both axially and radially.

Transducers should be positioned to avoid vertical or spiral welds. For sheet piles the transducers should be situated directly under the hammer or drop mass where possible.

NOTE Strain and acceleration transducers can be combined into one unit.

C.2 Example pile extension detail



Key

1 piled foundation element
2 transducer attachment point
3 tubular casing for pile extension formation
4 openings cut in the casing
5 steel reinforcement
6 flat and horizontal surface
7 ground level

Figure C.2 — Example of an extension detail for a cast-in-situ-pile for dynamic load testing using strain gauges on the pile concrete

Where a pile head extension is required to a cast-in-situ pile to allow dynamic load testing the concrete should extend at least 100 mm above the pile reinforcement (see Figure C.2). The concrete used to form the extension should have similar characteristics to that of the pile being extended and should be poured into a suitable formwork or steel casing. The top surface of the extension should be formed such that it is flat and horizontal or perpendicular to the pile axis. Transducers should be attached directly to the concrete pile shaft below the concrete extension or directly to the concrete of the extension. An opening or orifice will need to be cut in the outer steel casing to allow transducer attachment. Where transducers are mounted on the extension concrete bonded to a steel casing the combined cross section and Young's modulus should be considered.

Annex D
(informative)

Evaluation by closed form solutions using empirical damping values

D.1 General

Annex D gives informative guidance on one method for analysing a dynamic load test as defined in EN1997-1:2004+A1:2013. 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.

This annex presents a method for analysing a dynamic load test by closed form solution approaches to determine the measured ultimate compressive resistance, $R_{c,m}$.

In the closed form solutions described, measured quantities for a single blow are used as an input to standard mathematical operations to determine the static pile resistance. The mathematical operations applied are derived from one-dimensional wave theory (References [15] and [16]).

The closed form solution approaches described are generally only applicable to uniform piles with constant material properties from pile top to base. Hence closed form solutions are not normally applicable to cast-in-situ concrete piles due to the potential for variation in concrete properties and pile cross section.

D.2 Fundamental considerations for closed form analysis approaches

In a dynamic pile load test strain $\varepsilon(t)$ and acceleration time histories $a(t)$ during a dynamic load application are measured at the pile head by at least two pairs of sensors at opposite sides of the pile (see 4.3.1, 4.3.2 and Annex C).

A force-time history $F(t)$ is calculated from measured strain $\varepsilon(t)$ using Formula (D.1):

$$F(t) = \varepsilon(t) \times E_{dyn} \times A \qquad (D.1)$$

where

E_{dyn} the pile Young's Modulus at the sensor cross section;

A the cross sectional area of the pile.

The velocity-time history at the pile head $v(t)$ is determined by integration of the measured acceleration with respect to time, as per Formula (D.2):

$$v(t) = \int a(t)\, dt \qquad (D.2)$$

By assuming that the pile can be represented by an infinite elastic rod and that the pile is in dynamic equilibrium it can be shown that the particle velocity $v(t)$ is proportional to force $F(t)$, as per Formula (D.3):

$$F(t) = v(t) \times Z \qquad (D.3)$$

The velocity in force units $v(t) \times Z$ is usually denoted $V(t)$ and can then been drawn at the same scale as the force $F(t)$ as shown in Figure D.1.

The proportionality factor Z in Formula (D.3) is the pile impedance (dynamic stiffness) and is dependent on the material properties and mass per unit length of the pile, as per Formulae (D.4) and (D.5):

$$Z = A \times c \times \rho = A \times E_{dyn}/c = A\sqrt{E_{dyn}\rho} \tag{D.4}$$

$$c = \sqrt{\frac{E_{dyn}}{\rho}} \tag{D.5}$$

where

ρ is the density of the pile material;

c is the wave propagation velocity in the pile material.

Force and velocity time histories at the pile top can be evaluated with respect to waves reflected by the mobilized soil friction or tip resistance by assuming the pile behaves as a prismatic rod of constant cross section and homogeneous material. Wave equation theory allows the derivation of mobilized pile resistance by utilising quantities taken at defined times during the time history of a dynamic event (Figure D.1 and D.2).

In closed form solutions the static pile resistance, R_{stat} is determined by removing the components of dynamic resistance, R_{dyn} from the total resistance R_{tot} as per Formula (D.6):

$$R_{stat} = R_{tot} - R_{dyn} \tag{D.6}$$

The total resistance is given by the forces and velocities at the times t_1 and t_2 (Figure D.1), and the impedance Z [Formula (D.4)]:

$$R_{tot} = 1/2(F_1 + Z \times v_1) + 1/2(F_2 - Z \times v_2) \tag{D.7}$$

The difference between times t_1 and t_2, (ΔT) is equal to the time required by the wave induced by the dynamic loading event to travel through the pile from the head to the base and back again (Figure D.1).

With $F_1 = F(t_1)$ and $v_1 = v(t_1)$ the total resistance is a function of the start time t_1. The start time t_1 is usually taken at the first maximum peak force. Depending on the measured time history it is also possible to determine a maximum of R_{tot} at a different time t_1.

The formula for the estimation of the dynamic resistance component typically contains an assumed damping factor [for example Formula (D.8)], derived from comparison of dynamic pile tests with static pile load tests or from explicit damping determination in the signal matching method (Annex E). These damping factors are primarily dependent on the soil or ground type, the pile type, pile material, pile shape, pile length, pile toe penetration and the ground stratigraphy.

Where the mobilized pile load deflection behaviour can be shown to correspond to the ultimate resistance of the pile, then R_{stat} can be considered equivalent to the ultimate measured compressive resistance $R_{c,m}$. If the ultimate state was not achieved the R_{stat} is considered a conservative estimate of $R_{c,m}$. In strain softening soil conditions adequate pile displacement is required to mobilize the ultimate limit state condition or where this is not achieved the results should be verified against the results of previous load testing where the ultimate limit state has been verified.

D.3 Examples of closed form analysis methods

D.3.1 CASE method

The CASE method (Reference [15]) assumes that the dynamic resistance R_{dyn} is proportional to the penetration velocity of the pile base v_b. The proportionality factor is the product of the impedance Z and the damping factor J_c. as per Formula (D.8):

$$R_{dyn} = J_c \times Z \times v_b \tag{D.8}$$

Ranges for the recommended damping factors derived from comparison of static and dynamic pile load tests are given in Table D.1. If as an alternative approach damping factors have explicitly been determined by dynamic load tests and signal matching it should be noted in the test report.

Using Formula (D.9):

$$v_b = v_1 + (F_1 - R_{tot})/Z \tag{D.9}$$

with input parameters determined from Formulas (D.1), (D.2) and (D.4) the value of R_{stat} can be determined from Formulas (D.6) and (D.7).

The evaluation is based on the time t_1 at the point of the first force maximum (see Figure D.1). The time t_2 is then as per Formula (D.10):

$$t_2 = t_1 + 2L/c \tag{D.10}$$

This evaluation method is also known as the R_{SP} method (Resistance Static taken at Peak 1). If t_1 is taken at any time other than the first force maximum the resistance R_{tot} and R_{stat} become a function of time. A maximum resistance with respect to time can be determined. This is known as the R_{MX} method (resistance maximum).

Table D.1 — Range of typical damping factors, J_c used with the CASE formula

Soil	J_c for R_{SP}	J_c for R_{MX}
sand	0,05 – 0,20	0,4 – 0,5
silty sand	0,15 – 0,30	0,5 – 0,7
silt	0,20 – 0,45	0,6 – 0,8
silty clay	0,40 – 0,70	0,7 – 0,8
clay	0,6 – 1,10	≥0,9
NOTE For J_c factors derived for the R_{SP} method see Reference [15] for J_c values derived for the R_{MX} method see Reference [17].		

Because of the ranges of the damping factors and the variability of soil or ground properties it is recommended that the actual damping factors applied are justified in the report e.g. by the results of a signal matching or experience of testing of similar piles in similar ground conditions.

Figure D.1 gives an example of measured time histories for a steel pile. The relevant pile properties are:

— Diameter: 762 mm (30”)

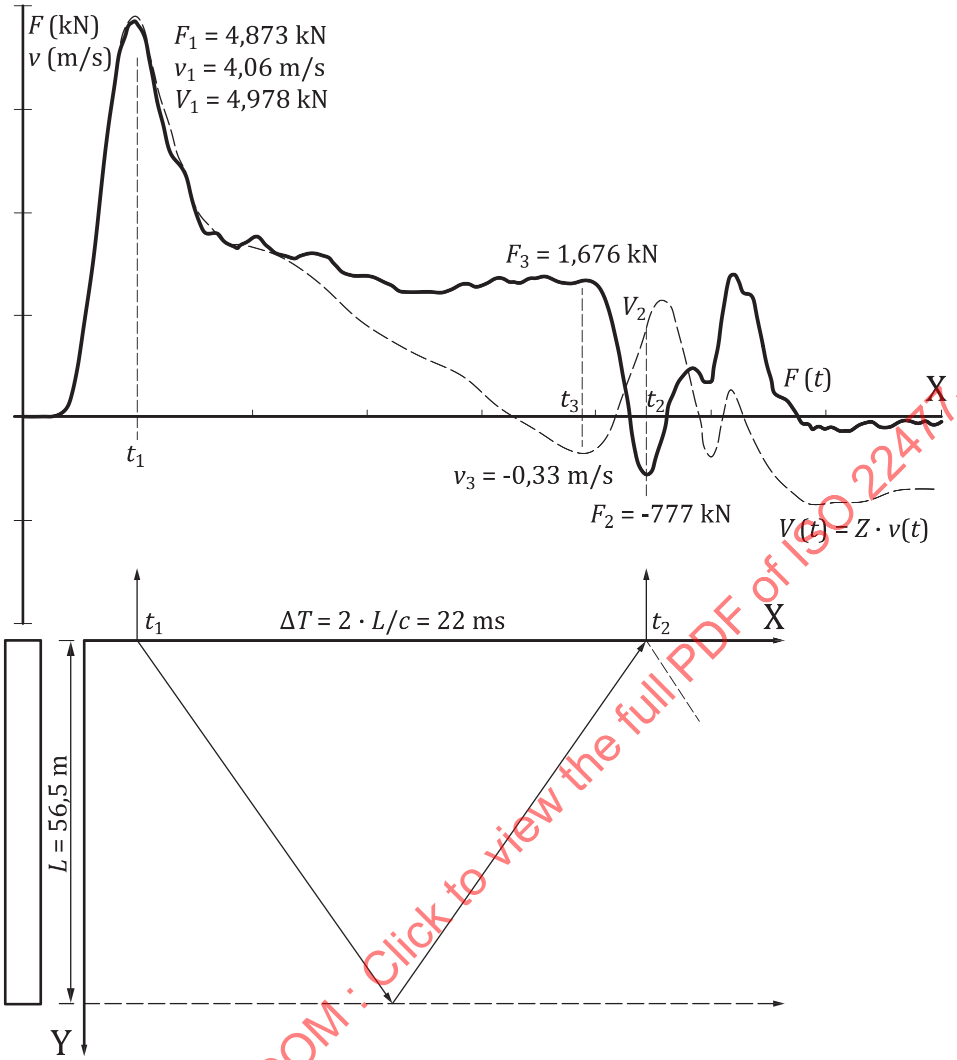
— Wall thickness 12,5 mm

— Cross section: 0,029 8 m^2

— Modulus of elasticity: 207,101 MN/m^2

— Wave speed: 5,136 m/s

The measured quantities used in Formulas (D.7) and (D.9) are indicated in Figure D.1. For an alternative formulation using induced and reflected waves (see flowchart in Figure D.2).



Key

X time (ms)

Y depth (m)

Figure D.1 — Examples of force and velocity time histories and the points required for the direct closed form solution of a 56,5 m long pile

D.3.2 TNO method

In the closed form solution referred to as the TNO method the dynamic resistance consists of both a skin friction and a pile tip related term. Further detail on this method and how it differs from the CASE method is shown in Figure D.3. Further information on the method can be found in Reference [16].

Using the TNO method the dynamic resistance is determined separately for the pile shaft $R_{s,dyn}$ and the pile base $R_{b,dyn}$:

$$R_{dyn} = R_{s,dyn} + R_{b,dyn} \quad (D.11)$$

The damping factors are related to the pile shaft and the pile base areas respectively. They are summarized in Table D.2.

Table D.2 — Range of typical damping constants – TNO formulas

Soil	C_s (TNO skin friction) [MN/m²/m/s]	C_b (TNO base resistance) [MN/m²/m/s]
Sand	0,002–0,010	0,4–2,0
Sandy silt	0,005–0,015	1,0–3,0
Silt	0,10–0,025	2,0–5,0
Silty clay	0,020–0,040	4,0–8,0
Clay	0,025–0,050	5,0–10,0

The TNO method damping constants are not comparable to those of the CASE method. The relationship between the respective pile tip cross-sectional area and shaft surface area requires that the pile/soil system damping properties are considered separately. The method also allows different damping influence to be considered for the shaft and the base situation.

For the pile base:

$$R_{b,dyn} = v_b \times A_b \times C_b \quad (D.12)$$

where

C_b damping constant for base resistance;

v_b velocity of pile base, Formula (D.9);

A_b area of the pile base.

For the pile shaft:

$$R_{s,dyn} = v_s \times A_s \times C_s \quad (D.13)$$

where

C_s damping constant for pile shaft;

v_s velocity at the pile shaft;

A_s area of the shaft embedded in the ground.

The governing velocity at the pile shaft is:

$$v_s = \frac{1}{2}(v_1 + F_1/Z) - \frac{1}{2}(F_3/Z - v_3) \quad (D.14)$$

The values F_3 and v_3 are taken from the velocity time histories at time t_3 ($t_3 < t_2$, within the time range $2L/c$), representing the maximum difference between force and velocity (Figure D.1).

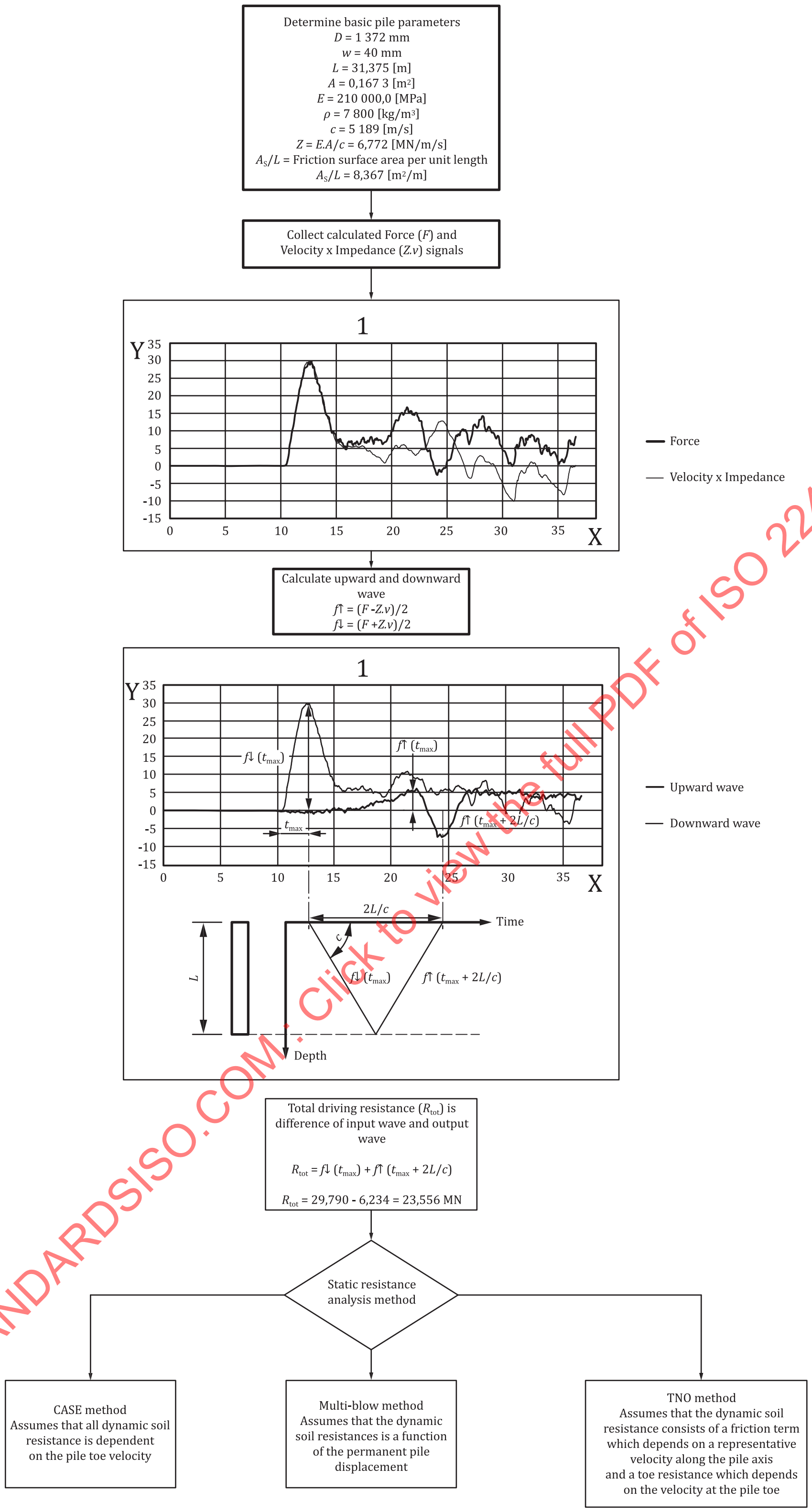


Figure D.2 — Flowchart showing the general approach to closed form analysis of a dynamic test

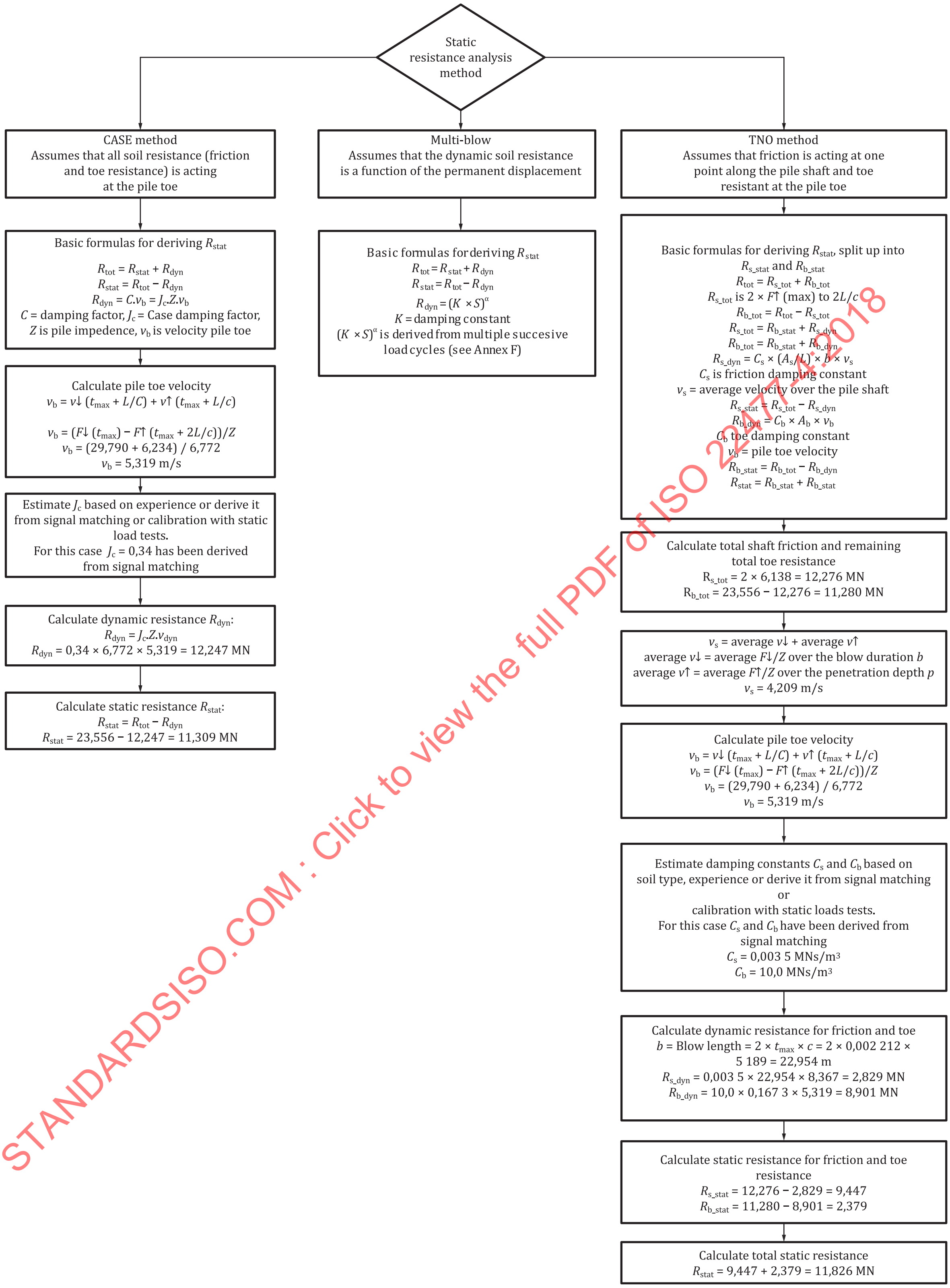


Figure D.3 — Flowchart demonstrating the differences in analysis for the CASE Method and the TNO method

Annex E
(informative)

Evaluation of the measurements by signal matching

E.1 General

Annex E gives informative guidance on one method for analysing a dynamic impact load test as defined in EN1997-1:2004+A1:2013. 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. Inclusion of the informative guidance on the analysis of dynamic impact load testing should not discourage or inhibit the use, adoption or development of alternative analysis techniques. Further guidance on the use of signal matching can be found in EN1997-1:2004+A1:2013.

Signal matching is a procedure for compressive resistance evaluation from dynamic impact load testing. In the procedure pile and soil are modelled (Figure E.1) and parameters within the model are varied to make a match to measured signals. The sensitivity of the solution shall be checked by comparing the pile behaviour to soil or ground investigation information.

The method is based upon simulating the behaviour of a pile in the ground in a computer model when subject to dynamic impact loading. The pile is discretized into individual elements, to which pile properties are assigned. Linear elastic behaviour is typically assumed for the pile elements. The length of the elements is specified by the individual software systems but may be selected to correspond to changes in encountered soil or ground profile or where changes in pile shaft profile occur.

E.2 Definitions

Homogeneous pile — pile with known material properties over the complete pile length

Inhomogeneous pile — pile for which material properties have to be estimated or assumed

Pile with known shape — pile with known shape (cross sectional dimensions) over the full pile length

Pile with unknown shape — pile for which the shape (cross sectional dimensions) over the full pile length has to be estimated or assumed

E.3 Pile model

In the dynamic impact load test the signals are measured at one level near the head of the pile (constant cross section). If the pile has impedance changes (e.g., change in cross sectional area or change in material), which are different to that for the cross sections at the level of measurement a specific pile model will have to be created for the signal matching process (Reference[18]).

NOTE 1 With prefabricated steel, concrete and timber piles, the pile is modelled with known cross sections and material properties (impedance, Z).

NOTE 2 With cast-in situ piles the cross section can vary along the pile length. The variance of the cross section can be determined by thermal integrity profiling, with callipers, consumption logs or by inspection of the obtained test results.

NOTE 3 With cast-in situ piles the impedance of the pile can be estimated by comparing the concrete consumption to designed consumption and by assessment of reflections from impedance changes in the low strain integrity test signals. Particular piling methods can also cause irregular pile shape and inhomogeneity, which has to be estimated based upon previous experience of the piling method or by exhuming a test pile.

For cast-in-situ piles, material properties (density and dynamic modulus of elasticity, E_{dyn}) of the pile at the measurement level can be estimated by laboratory tests on representative concrete samples. For steel the material properties are generally known and can be verified with the manufacturer. For precast concrete piles the dynamic modulus of elasticity can be obtained from laboratory tests or derived by stress wave propagation speed calculations and estimated by using Formula (E.1):

NOTE 4 With precast concrete piles the modulus of elasticity could change during the early months after production. The time between production and testing can be taken into account when obtaining data from the manufacturer of the pile.

$$E_{dyn} = \rho \times c^2 \quad \text{(E.1)}$$

where

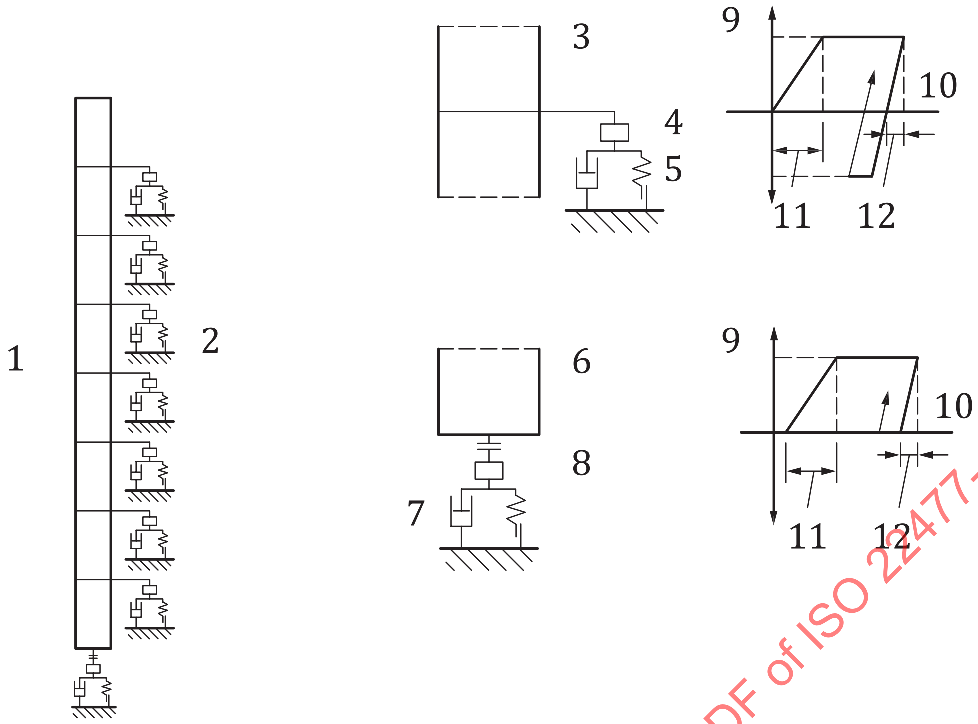
ρ is the density of the pile material;

c is the speed of propagation of the stress wave in the pile.

NOTE 5 The speed c can be obtained by using the time of occurrence of the toe reflection.

E.4 Soil model

To present the stress-displacement behaviour of the soil or ground, the static component of ground resistance is typically represented by a linear-elastic-ideally plastic spring and slider and the dynamic component by a viscous damper and a lumped mass. In normal practice, the elements adopted to represent the soil behaviour are springs, dampers and sliders (friction blocks), but elements for simulating a base gap may be incorporated to allow for variations in pile base resistance for example gaps between the pile base and rock and soft toe conditions (Reference [19]). A schematic representation of a pile-soil model is shown in Figure E.1.



Key

1 pile model
2 soil model
3 shaft model
4 soil mass
5 spring and slider
6 tip model
7 viscous damper
8 base gap and soil mass
9 resistance
10 displacement
11 $quake_1$
12 $quake_2$

Figure E.1 — Basic model for a pile subject to dynamic loading

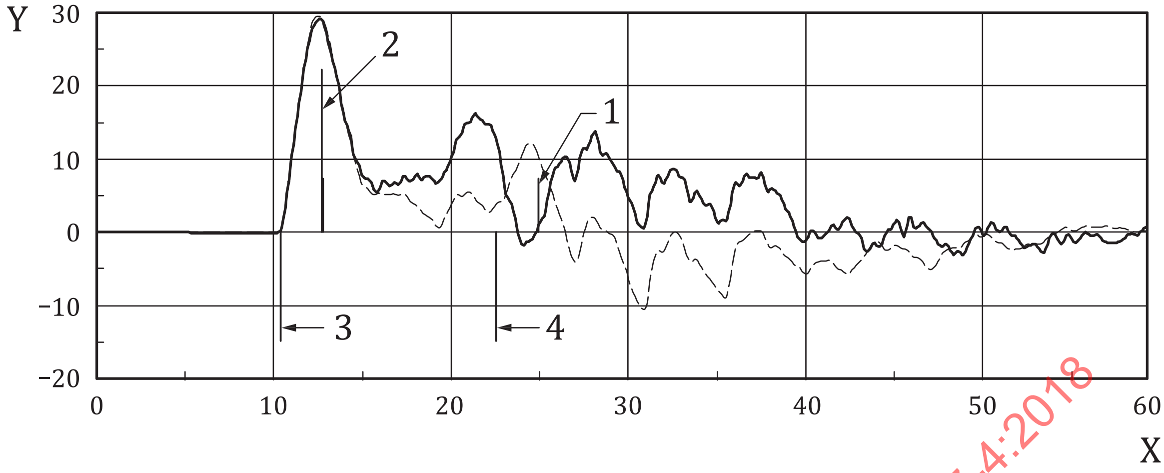
Definitions in Figure E.1:

$quake_1$	loading quake (typically 2–3 mm for a pile with diameter, *D* or, *D*/60–*D*/120);
$quake_2$	unloading quake (typical values of 0,3–1,0 times the loading quake for the pile tip and up to 1,0 times loading quake for the shaft);
base gap	gap between pile tip and soil;
viscous damper	linear viscous damper, which is dependent on pile tip velocity;
spring-slider	component of static soil resistance.

NOTE Typical loading $quake_1$ values presented above can lead to overestimation in case of open ended pipe piles or large diameter piles.

E.5 Signal matching process

The force-time history determined as outlined in Annex D (Figure E.2) is applied as an action and the system response is calculated for the upward wave, see Figure E.3. In Figures E.3 to E.5 the resulting upward force-time, downward force-time and velocity-time profiles are presented.



Key

1 $t_{max} + 2L/c$

2 max blow (t_{max})

3 start of blow (t_0)

4 $t_0 + 2L/c_1$

X time (ms)

Y force (MN)

——— force

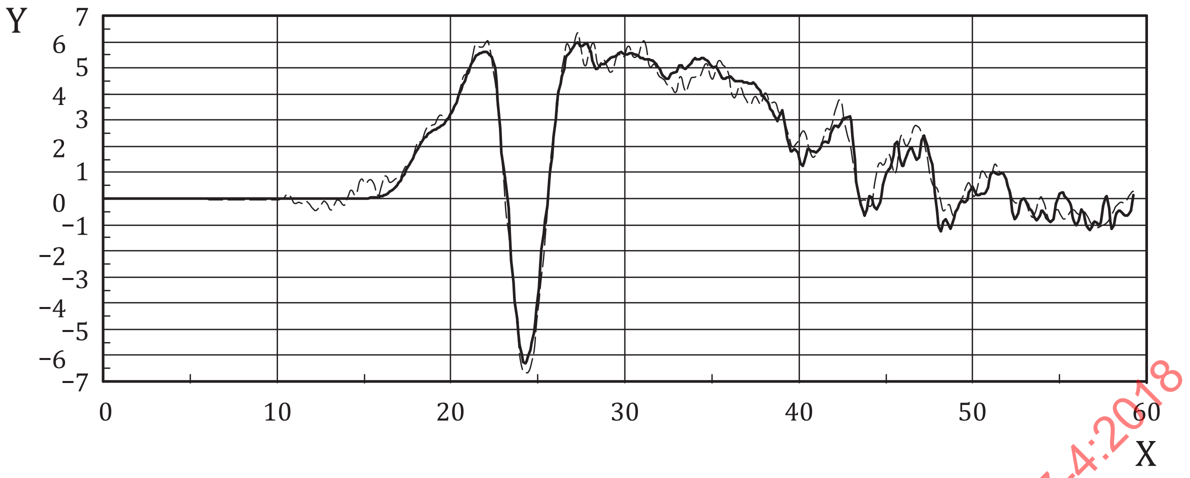
_ _ _ Zv

Figure E.2 — Force and Zv time history for an open ended steel tube (diameter of the pile 762 mm and wall thickness 12,7 mm)

By varying the input parameters, predominantly the soil or ground parameters (quake – the limit of elastic displacement, damping factors, stiffness of the springs and soil mass) the calculated curve is adapted to fit the measured curve (Reference [20]). The calculated set is also compared to the measured set of the pile with each test blow.

The specific signal matching programme used will have a recommended range for the user defined input parameters, which should be used taking into account the local soil or ground conditions by comparison to soil or ground investigation data.

NOTE In the specific signal matching programme used the variation of different parameters can be done automatically or manually and is often referred to as automatic or manual signal matching.



Key

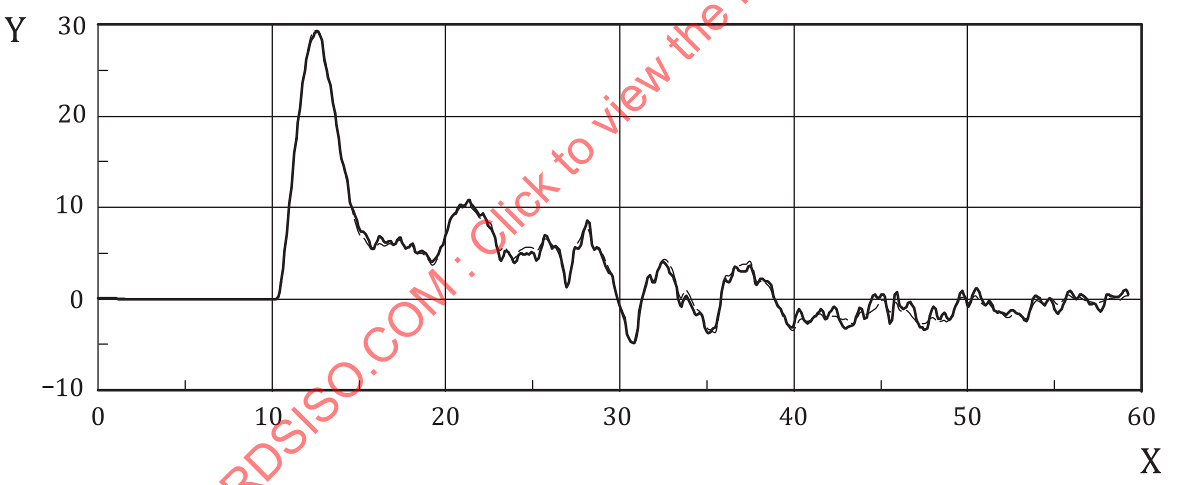
X time (ms)

Y force (MN)

—— wave up measured

– – – wave up calculated

Figure E.3 — Comparison of the measured wave up and the wave up calculated based upon the measured wave down time history using the pile-soil-model



Key

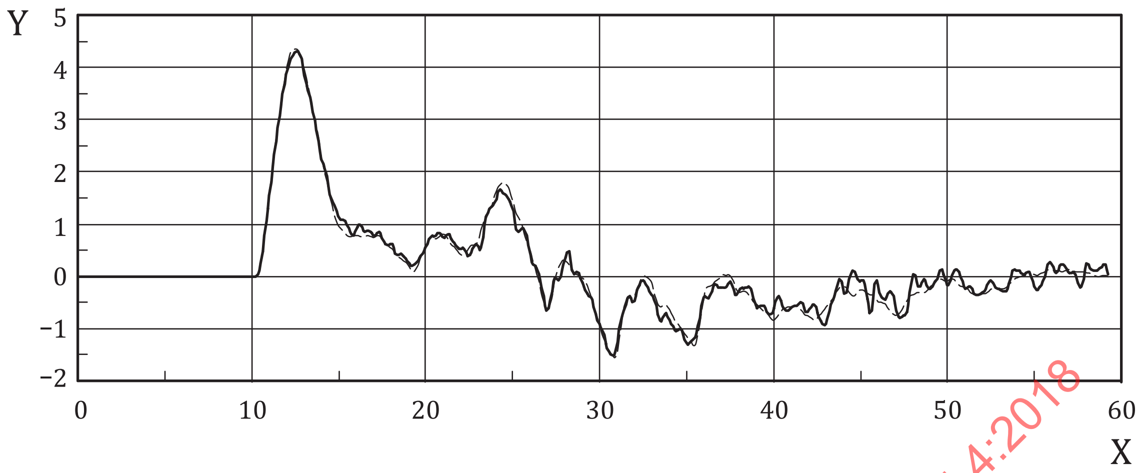
X time (ms)

Y force (MN)

—— wave down measured

– – – wave down calculated

Figure E.4 — Comparison of the measured wave down and the wave down calculated based upon the measured wave up time history using the pile-soil-model



Key

X time (ms)

Y velocity (m/s)

—— calculated velocity

– – – measured velocity

Figure E.5 — Comparison of the recorded pile velocity and the pile velocity calculated using the model

E.6 Sensitivity of the signal matching and comparison to geotechnical investigation information

The sensitivity of the predicted pile compressive resistance to the selection of different parameters should be checked. If the compressive resistance of the pile is sensitive to changes in the parameters, the lower and upper bound pile compressive resistance should be given. If the signal matching can be shown to be insensitive to parameter variation then the best match solution can be considered for determination of the pile compressive resistance (Reference [21]).

The distribution of resistance along the pile shaft and the resistance predicted at the tip of the pile should be compared to the information from geotechnical investigation. The resistances predicted for the tip and shaft, and the ratio of the tip to shaft resistance, should be checked to see if they are in reasonable agreement with those that would be anticipated from local ground conditions and experience.

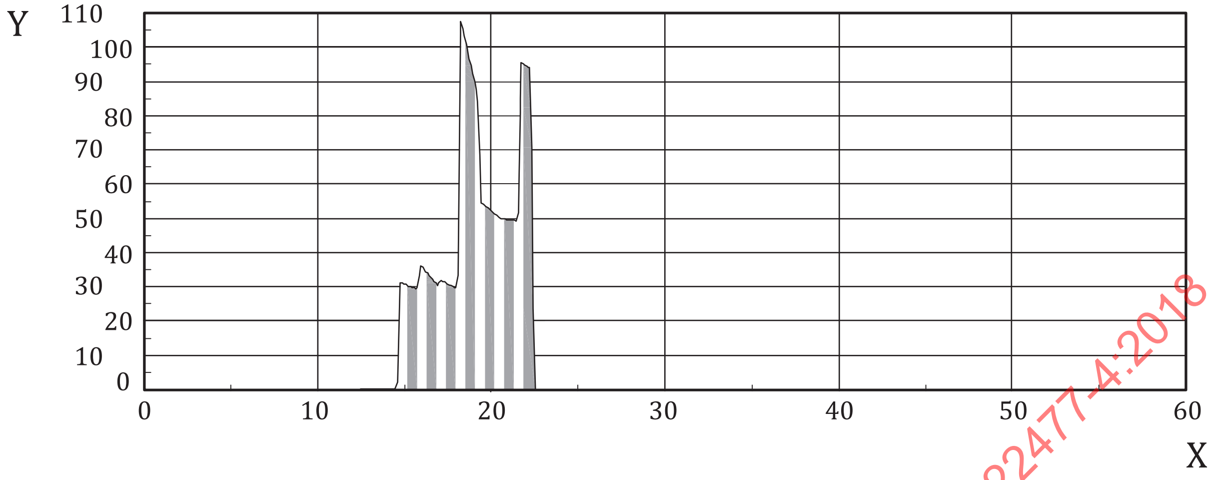
E.7 Output

Evaluation of the parameters determined gives the skin friction distribution (Figure E.6) over the pile length, the end bearing and calculated resistance-settlement curves for the pile head and tip (Figure E.7).

NOTE In some cases, for example, stiff soil layers near the tip of the pile, it can be difficult to distinguish tip resistance from shaft resistance in the vicinity of the pile tip.

Signal matching methods are also suitable for checking the empirical damping values used in the direct closed form solutions (Annex D), calibration of driving formula (Annex A) or wave equation solutions (Annex B). See Figure E.8 for a flowchart of a typical signal matching process.

Where the mobilized pile load deflection behaviour can be shown to correspond to the ultimate resistance of the pile, then R_{stat} can be considered equivalent to the measured ultimate compressive pile resistance $R_{c,m}$ (Reference [22]). If the ultimate state was not achieved the R_{stat} is considered a conservative estimate of $R_{c,m}$. In strain softening soil conditions adequate pile displacement is required to mobilize the ultimate limit state condition or where this is not achieved the results shall be verified against the results of previous load testing where the ultimate limit state has been verified.



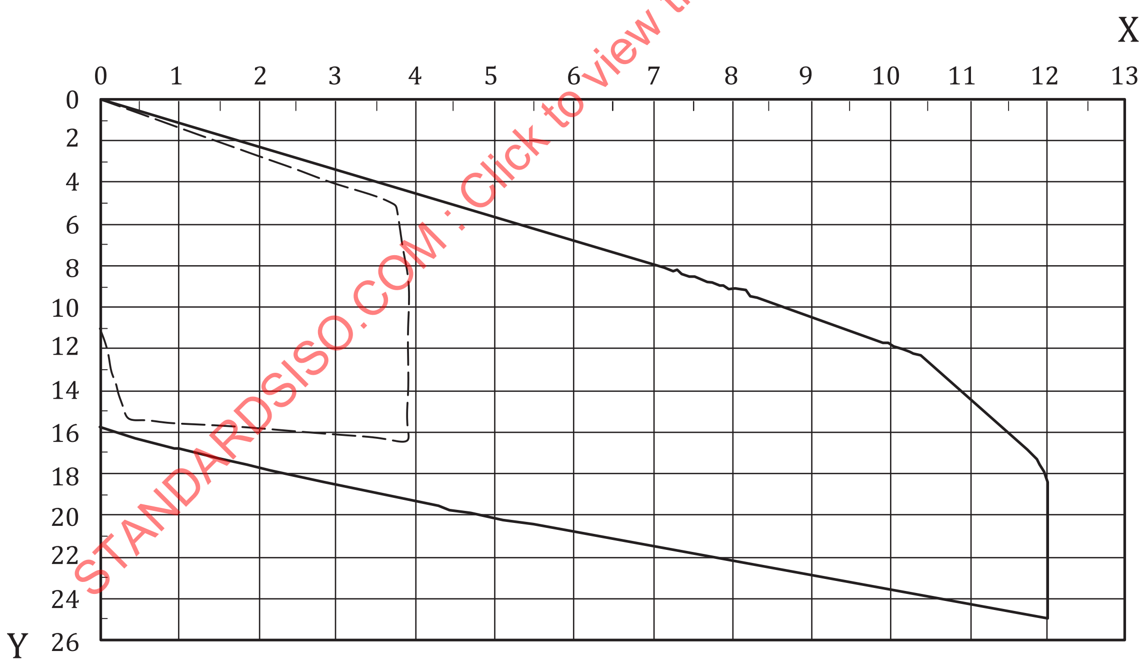
Key

X time (ms)

Y shaft resistance (kPa)

▮▮▮▮ calculated shaft resistance match

Figure E.6 — Result of signal matching process showing shaft resistance distribution as a function of time



Key

X load (MN)

Y displacement (mm)

—— pile head

– – – pile toe

Figure E.7 — Load-settlement curve from a dynamic impact load test as the result of the signal matching process

