INTERNATIONAL STANDARD

ISO 22477-4

First edition
2018-03

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

Reference number
ISO 22477-4:2018(E)

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Published in Switzerland

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Foreword

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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:

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

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:

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

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.