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NF P 94-105
April 2012

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ICS: 93.020

Grounds: Investigation and testing

Measuring compaction quality

Method using variable energy dynamic penetrometer — Penetrometer calibration principle and method — Processing results — Interpretation

E : Soils : investigation and testing — Inspection of compaction quality — Method using a variable energy dynamic penetrometrer — Principle and method for calibrating the penetrometer — Explotation of results — Interpretation

D : Boden : Erkundung und Prüfungen — Kontrolle der Verdichtungsqualität — Dynamische mit ungleichmäßiger Energie — Prinzip und Eichungsverfahren des Penetrometers — Ergebnisauswertung — Auslegung

French Standard certified

By decision of AFNOR Executive Director on March, 14th 2012
To be effective on April, 14th 2012.

Replace the experimental standardisation XP P 94-10, of May 2000.

Corresponding work

As of the date of issue of the hereby document, no European nor international work related to the same subjects exists.

Analysis

The hereby document defines a method for measuring ground compaction, a sounding method using a dynamic penetrometer with variable energy.

Descriptors

International Technical Thesaurus: ground, test, quality inspection, compaction, penetration, measurement, procedure, test system, measuring instrument, calibration, characteristic, utilisation conditions.

Amendments

In relation to the replaced document, review and change of status.

Corrections

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Road construction earthworks : EXECUTIONS OF EARTHWORKS BNSR CTT

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Contents

1 Scope of application

The present document discusses dynamic penetrometer soundings conducted to measure the compaction quality of materials, untreated or lime treated before maturing, installed and compacted.

The document concerns variable energy dynamic penetrometers, equipped with a measuring system that enables the resistance to dynamic penetration to be measured, as a function of depth.

The present document applies to the inspection of the compaction of general infills, notably comprising works for the purposes of road, rail or hydraulic (building of dams and earth dykes) construction, and for the infill of excavations and trenches.

Sounding is limited in depth, as a function of the nature of the materials penetrated and the equipment used, and by the driving conditions defined in 6.1.2.2.

The method enables dynamic penetrometers to be used in one or more of the following functions:
— assess layer thicknesses (function A);

— **check that the defined densification objective is achieved** (function B). In this case, the materials used must be classified as defined in standard NF P 11- 300, the densification objectives must be known (percentage of Proctor's optimum density or reference to objectives q_2, q_3 and q_4, as defined in standard NF P 98-331, 6.2.5) and the hydric condition of the materials at the time of testing must be known;

— check that compacting is compliant with that obtained on a reference section specific to the site (function C).

2 Standards references

The present document contains elements from other publications, by dated or undated reference. These standards references are mentioned at the appropriate points in the text, and the publications are listed below. For dated references, subsequent amendments or revisions of any of the publications shall only be applicable to this document if they have been incorporated by amendment or revision. For undated references, the latest issue of the reference publication shall be applicable.

NF P 11-300*, Execution of earthworks —Classification of materials used in the building of infills and the forming of layers for road infrastructures.*

NF P 11-301*, Execution of earthworks — Terminology.*

NF P 94-049-1*, Ground: Investigation and testing — Measuring water content of materials by weight.*
— Part 1: Method by dessication using a microwave oven.

NF P 94-049-2, *Ground: Investigation and testing —Measuring water content of materials by weight.*
— Part 2: Method using a cooker ring or radiating panels.

NF P 94-050*, Ground: Investigation and testing — Measuring water content of materials by weight —Stoving method.*

NF P 94-063*, Ground: Investigation and testing — Measuring compaction quality — Method using constant energy dynamic penetrometer — Principle and method of calibrating penetration density graphs —Processing of results — Interpretation.*

NF P 94-093*, Ground: Investigation and testing — Determining material compaction references — Proctor's test (normal) — Proctor's test (modified).*

NF P 98-231-1, *Tests relating to road surfaces — Compacting characteristics of materials other than those treated using hydrocarbon binders — Part 1: Proctor's test (modified) adapted to gravel and sand used as road base layer.*

NF P 98-231-2*, Tests relating to road surfaces — Determining the compacting characteristics of materials other than those treated using hydrocarbon binders — Part 2: Compacting test using the rotary shear press (PCG).*

NF P 98-231-3, *Tests relating to road surfaces — Determining the compacting characteristics of base materials other than those treated using hydrocarbon binders — Part 3: Determining the reference maximum density and resistance to compacting by vibration compression test with controlled parameters (VCPC).*

NF P 98-331, *Road surfaces and related construction — Trenches: excavating, infilling, covering.*

3 Definitions — Terminology — Symbols

For the purposes of the present document, the following terms and definitions shall be applicable.

3.1 Resistance to dynamic penetration

Resistance to dynamic penetration q is the value computed by the penetrometer data measurement system, at each stroke of the striking mass, as a function of the penetration of the tip and the energy applied at the head of the rod, using the driving formula, known as the Dutch formula.

3.2 Penetration resistance graph

The penetration resistance graph is the curve for the distribution of resistance to dynamic penetration q, as a function of depth z, in the coordinate system and based on the plotting principles defined in 6.3.1.

3.3 Critical depth

In homogeneous ground (nature, water content and density), and neglecting lateral friction, the resistance to dynamic penetration increases, from the surface, to reach a certain constant value from the critical depth. The critical depth depends on the compaction of the material, the size of the particles and the diameter of the tip.

A penetration resistance graph can be roughly plotted, in semi-logarithmic coordinates, using a bilinear relationship with three parameters:

— q_0 Resistance at surface;

— q_1 Resistance at depth;

— Z_c Critical depth.

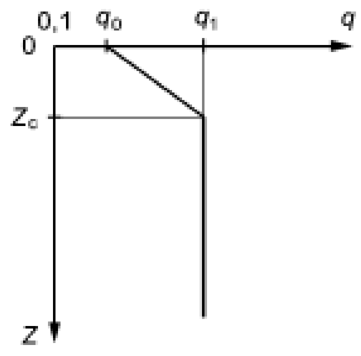


Figure 1 – Penetration resistance graph

3.4 Resistance to dynamic penetration for a classified material: specific values

3.4.1 Limit value

The limit value q_L of the resistance to dynamic penetration is, at a given depth Z, the minimum value below which q must not fall, for the density value ρ_{min} to be reached (function B).

3.4.2 Reference value

The reference value q_R of the resistance to dynamic penetration is, at a given depth Z, the approximate mean value of q when density corresponds to a specified mean value ρ_{mean} (function B).

q_R is used to facilitate interpretation and completes the use of q_L.

3.4.3 Densification objectives

The densification objectives are defined in relation to the normal or modified Proctor's test in standard NF P 98-331.

3.4.4 Standard cases for a given piece of equipment

Each case is defined by a densification objective and a material classification, in nature and condition, as specified in standard NF P 11-300 or, for prepared materials (fully or partially crushed), by a compacting resistance DC1, DC2 or DC3. This value is determined using the tests described in standard NF P 98-231-2 or standard NF P 98-231-3, or by reference to a known material.

The name of a geotechnically identified material may be used instead of the classification, when it is considered alone (see Article 8).

3.4.5 Case catalogue (function B)

The case catalogue (function B) is the set of values of q_L and q_R given by the calibration of equipment with known characteristics, in the various standard cases. The method used to define values q_L and q_R is described in Article 8.

3.4.6 Catalogue of relationships $\rho_d = f^{-1}(q)$

The equipment can also be calibrated using a semi-probabilistic method (see Article 8 and Appendix C). In this case, a catalogue of relationships (obtained by regression) is used (where ρ_d is the dry density of the material), together with their confidence coefficients, and using the material class and its hydric condition at the time of the penetration test as input arguments.

3.5 Symbols

A is the section of the tip (expressed in square meters)

a is the deviation between the resistance limit value q_L and the measured value q (expressed in megapascals)

b is the deviation between the resistance limit value q_L and the reference limit value q_R (expressed in megapascals)

d is the tip diameter (expressed in millimeters)

d_t is the outer diameter of the driving rods (expressed in millimeters)

D_{ci} is the compacting resistance

E is the energy applied to the system (expressed in joules)

e is the specified layer thickness (expressed in meters)

e' is the plastic penetration (expressed in meters)

F is the excess thickness frequency (expressed as a percentage)

f' is the excess thickness frequency per overthickness level (expressed as a percentage)

h is the depth inspected (expressed in meters)

L_1 is the length of the cylindrical part of the tip (expressed in millimeters)

L_2 is the length of the tapered part of the tip (expressed in millimeters)

M is the striking mass (expressed in kilograms)

N is the number of dynamic penetrometer tests

n is the number of compactor strokes

P is the mass of the driving head + rods + tip (expressed in kilograms)

q_i is the densification objective

q is the value of the resistance to dynamic penetration (expressed in megapascals)

q_0 is the value of the resistance to dynamic penetration at the surface (expressed in megapascals)

q_1 is the value of the resistance to dynamic penetration at depth (expressed in megapascals)

q_L is the dynamic penetration resistance limit value (expressed in megapascals)

q_R is the dynamic penetration resistance reference value (expressed in megapascals)

q_a is the dynamic penetration resistance value measured at the bottom of the layer (expressed in megapascals)

q_b is the dynamic penetration resistance value measured at the top of the underlying layer (expressed in megapascals)

q'_m is the mean value of q for all the driving on an inspection penetration resistance graph (expressed in megapascals)

q'_a is the value of q_a at the bottom of any layer on an inspection penetration resistance graph (expressed in megapascals)

q_m is the mean value of resistances q on a reference penetration resistance graph, for all driving on an integer number of layers (expressed in megapascals)

$\overline{q_m}$ is the mean q_m value of the various reference penetration resistance graphs (expressed in megapascals)

$\sigma(q_m)$ is the standard deviation computed using single q_m values

$\overline{q_a}$ is the mean q_a value at the bottom of the various layers on the reference penetration resistance graphs (expressed in megapascals)

$\sigma(q_a)$ is the standard deviation corresponding to the previous mean value

V is the driving velocity (expressed in meters per second)

W_{opn} is the water content at Proctor's normal optimum (expressed as a percentage)

Z is the depth (expressed in meters)

Z_c is the critical depth (expressed in meters)

r is the dry density value of the material (expressed in metric tons per cubic metre)

ρ_{min} is the minimum dry density value of the material (expressed in metric tons per cubic metre)

ρ_{mean} is the mean dry density value of the material (expressed in metric tons per cubic metre)

ρ_{OPN} is the dry density value at Proctor's normal optimum (expressed in metric tons per cubic metre)

ρ_{REF} is the reference dry density value (expressed in metric tons per cubic metre)

4 Principle of the test and checking method

a) Principle of the test

The principle of the test involves forcing a spike into the material, by driving an assembly of rods. At the head of the rod assembly, the driving energy is provided by the impact of a ram or a hammer. This energy is partially transmitted to the tip which, with each stroke, penetrates a certain distance into the ground. The penetration distance varies as a function of the ground resistance to dynamic penetration.

b) Principle of method used to check compacting quality
The method involves using the penetration resistance graph for the following three functions:

4.1 Function A

In function A, differences in the variation of resistance to dynamic penetration at the transition between layers are used to assess the thicknesses compacted.

4.2 Function B

In this function, the materials actually used have to be identified as specified in standard NF P 11-300, and their hydric condition at the time of the test must also be known.

In function B, the penetration resistance graph is compared, for the required dry density values, with values q_L and q_R extracted from the calibration catalogue specific to the equipment:

— either the catalogue of standard cases subjected to the test, if using the method of calibration by plotting the limit and reference lines (see 9.2) ;
— or the catalogue of relationships $\rho = f^{-1}(q)$, if using the method of calibration by semi-probabilistic approach (see Appendix D).

4.3 Function C

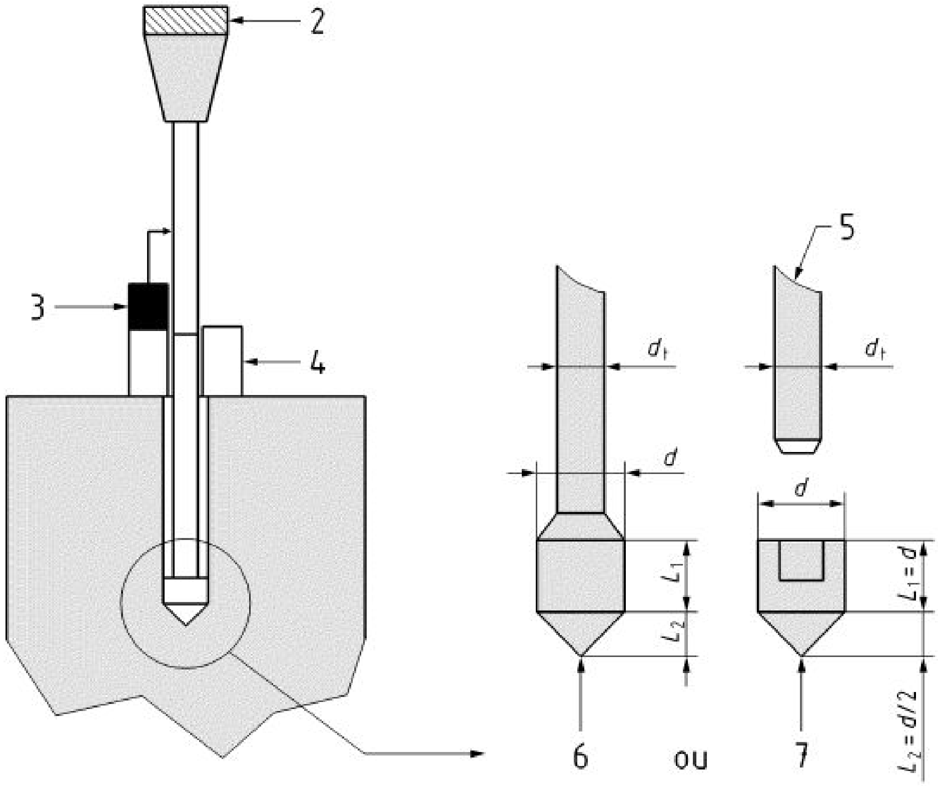
In function C, the penetration resistance graphs for the inspected part are compared with all the penetration resistance graphs created using the same equipment on a reference section specific to the site. The materials must be reused in exactly the same way as recommended for the inspected part.

Function C is usable in all cases, particularly if the catalogue of cases or of relationships $\rho = f^{-1}(q)$ (function B) does not contain the material class inspected, or does not reflect the specific nature of a material.

5 Equipment and measuring systems

5.1 Equipment block diagram

Figure 2 shows the various component elements of the variable energy dynamic penetrometer, in the operational sounding configuration.



Legend

1 Driving system (ram or hammer)

2 Measurement system for energy applied at each impact

3 Measurement system :
— penetration of tip with each stroke,
— depth reached by tip

4 Rod guidance

5 Tip holder rod

6 Fixed point
or
7 Expendable tip

Figure 2 — Equipment diagram

5.2 Description

The equipment characteristics are described below, and also in Appendix A which specifies tolerances and utilisation limitations

5.2.1 Description and principle of the method

The variable energy for the dynamic penetrometer is supplied by the impact of a ram or hammer on a driving head that is integral with an assembly of rods, equipped with a penetration tip. With each stroke, the equipment measures the energy applied to the system in the penetration direction and also the penetration of the assembly of rods.

The resistance to dynamic penetration is computed using the “Dutch formula”:

$$q = E\frac{M}{Ae'(M + P)}$$

The application of this driving formula assumes that:

— the ground exhibits perfect plastic characteristics during the penetration,

— lateral friction on the rod assembly is negligible,

— all the energy applied is transferred to the tip by the driving system, the impact being considered to be infinitely soft.

Finally, the pressure between layers in the ground must also be negligible, and the system must therefore not be used in ground subject to water saturation (see NF P 11-300).

5.2.2 Driving system

The driving system is an integral part of the equipment. In particular, the hammer has a fixed mass and is specific to the equipment.

5.2.3 Drive rods

The drive rod outer diameter d_t must be less than the tip diameter d divided by 1.4 for expendable tips and by 1.1 for fixed tips.

The drive rods are screwed together to form a rigid rod assembly during penetration.

5.2.4 Tips

The tips are pointed (see Figure 2) and can be rigidly mounted on the lower rod (fixed tips), for shallow inspections (between 1 m and 3 m depending on the nature of the ground).

The tapered section length (L_2) is equal to half the tip diameter (see Figure 2) and is topped by a cylindrical section, length (L_1), which is the same diameter as the tip.

Two types of tip are used (see Appendix A) and both terminate in a tapered section:

— expendable tips ;

— fixed tips.

5.2.5 Measuring system

With each stroke, the equipment measures:

— the drive energy applied to the system along the penetration direction ;

— the penetration of the rod assembly.

The equipment technical documentation must specify the measuring principle adopted for these two values and the calibration and scheduled checking methods applied for the measuring system sensors.

6 Procedure

6.1 Conducting the test

6.1.1 Preparing the test

6.1.1.1 *Preliminary equipment checks*

The elements listed below are inspected and entered on the test card:

— rods used must be straight (visual inspection) ;

— tip diameter selected ;

— condition of assembly screw threads on rod ends.

6.1.1.2 *Identification of measurement point*

The location of the sounding is identified on a dimensioned drawing. When inspecting infills during construction, the sounding head dimension should also be shown on the drawing.

6.1.1.3 *Special case of structure treated in the upper part*

In the case of a highly resistant structure in the upper part of the tested infill, a preliminary vertical boring must be executed, with a diameter not less than 1.5 times the tip diameter. Where necessary, any disturbance on the upper part of the infill zone being inspected, and due to the boring of the preliminary hole, should be taken into account.

6.1.2 Executing the test

6.1.2.1 *Executing the driving*

The following checks should be conducted :

a) when starting with the first rod, and each time a rod is added, the tip holder rod must be in the intended sounding direction and keep to that direction during driving. If the rod deviates from the sounding angle, the test should be stopped and restarted close by. Maximum angular deviation is 10° from the intended sounding direction ;

b) the rods must be firmly screwed together (tight) ;

c) the driving energy should be modulated so that the penetration per stroke is between 0.1 cm and 2 cm ;

d) lateral friction between the material and the rod assembly is acceptable. From 2 m depth, each time another rod is added the rod assembly should be rotated through 360°, either manually or using a torque wrench. In this case, the maximum torque value and, where appropriate residual torque should be recorded. The conditions under which driving must be stopped are defined in 6.1.2.2.

6.1.2.2 *Stop driving*

Driving must be stopped when any of the following conditions is met:

— the depth objective is reached;

— on a hard point, when no penetration exceeding 1 mm per stroke is obtained for five consecutive strokes;

— if lateral friction between the material and the rod assembly becomes excessive (the rod assembly cannot be rotated using one hand). If torque wrench checking is used, the stopping criteria are defined by the manufacturer.

6.1.3 Inspection after each sounding

When the rod assembly is extracted, the rods should be visually inspected to ensure that they are straight, and that the threaded assembly sections are in good condition.

6.2 Scheduled inspections and checks

The following elements should be checked monthly during periods of utilisation, or once for every 100 m of linear penetration:

- rods should be straight and assembly threads in good condition ;
- tips should be checked for wear ;
- the condition of the striking head should be checked ;
- the striking energy and penetration measurement system should be tested as specified by the manufacturer.

Acceptable utilisation tolerances are specified in Appendix A.

In addition, the equipment should be inspected annually, or if a fault or malfunction is identified during a scheduled inspection.

6.3 Results

The results are represented as shown in the example in Appendix B.

6.3.1 Plotting the penetration resistance graph

6.3.1.1 *Graph abscissa and ordinate values*

The vertical ordinate values are graduated in meters, with intermediate graduations as a function of the maximum depth to be measured.

The horizontal abscissa values show resistance to dynamic penetration q on a logarithmic scale and increasing from left to right. The abscissa has at least one interval of values between 0.1 MPa and 20 MPa, with intermediate graduations at 0.5 MPa, 1 MPa, 5 MPa and 10 MPa.

Unless otherwise specified by the authority requesting the tests, it is recommended that all graphs relating to the same zone should be plotted to the same scale.

6.3.1.2 *Smoothing the penetration resistance graph — Corrections as a function of depth*

The manufacturer's manual should specify the standard (and optional, where applicable) processing performed by the equipment computer.

7 Test report

The test report shall at least contain the following minimum information:

— reference to the present document,

— type of equipment used and main characteristics (striking mass, tip diameter, mass and length of each extension rod) ;

— date of test ;

— name of organisation having conducted the test ;

— test reference and coordinates ;

— depth and angle of inclination required for the sounding ;

— functions used (A, B and/or C) ;

— the penetration resistance graph, completed in function B, as a function of selected calibration method :

• either by plotting the limit and reference lines (see 9.2.1) ;

• or by the curves of $q_{Lx\%}$ and qR (see Appendix D), incorporating any variations in material and hydric condition, as a function of the test depth ;

— layer thicknesses specified in function A should be shown ;

— the compacting objectives and the class of materials penetrated should be specified. In functions B and C, the following should also be indicated :

• the name of the organisation that determined the materials classification, and the date of the samples used to define this classification ;

• the name of the organisation that determined the hydric condition of the material, as a function of the depth and the method used ;

• in function B, the names of the organisations that calibrated the equipment used, and the method used: plotting of limit and reference lines (see 9.2) or semi-probabilistic approach (see Appendix D) ;

• in function B, the types of fault identified :

— the result, from depth 2 m, of the lateral friction check tests with each additional extension rod (see 6.1.2.1) and, if measured, the maximum torque and any residual torque for the rotation of the rod assembly in the material ;

— the stop sounding conditions (see 6.1.2.2).

8 Calibration of equipment

Only function B necessitates the preliminary calibration of the equipment.

This may be carried out:

— either by a laboratory (recommended method, due to the small size of the equipment),

— or using a test (or calibration) panel.

The laboratory calibration method is described in Appendix C and D.

The principle of the test panel calibration method is described in standard NF P 94-063 — Article 8 and is not reproduced here.

9 Processing of results — Interpretation

9.1 Using the penetrometer in function A

Function A can only be used with vertical soundings

Results processing is based solely on the penetration resistance graphs and involves computing the actual layer thicknesses (when they are perceptible, see 9.1.1.2.2 below), to compare them with the specified values and to determine the frequency and location of non-compliant layers throughout the construction work inspected.

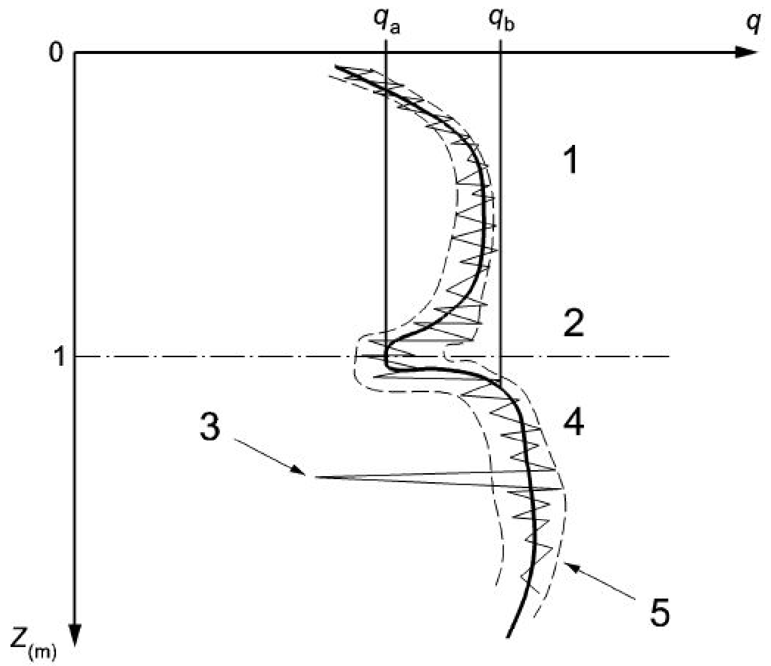
9.1.1 Method

An excess layer thickness is computed based on the upper and lower layer transitions. Layer transition is determined based on the difference in resistance to dynamic penetration on each side of the transition.

9.1.1.1 ***Definitions*** *(Figure 3)*

Penetration resistance graph background noise: envelope of fluctuations in the resistance to dynamic penetration around a smoothed penetration resistance graph, shown as a percentage (%) of the mean value q for the concerned area.

q_a and q_b are determined after smoothing (manual or automatic) of the penetration resistance graph, with all unlikely points removed.



Legend :

1 Upper layer

2 Layer transition

3 Unlikely point

4 Lower layer

5 Background noise

Figure 3 — Penetration resistance graph indicating layer transition at depth 1 m

9.1.1.2 ***Interpretation***

9.1.1.2.1 *Identifying a layer transition*

The value of the ratio q_a/q_b is analysed in relation to the penetration resistance graph background noise around the layer transition:

— if background noise is less than +20%, then layer transition is considered to exist if q_a/q_b is less than 0.7;
— if background noise exceeds ±20%, then layer transition is considered to exist if q_a/q_b is less than 0.5.

The validity of the layer transitions determined can be supported by elements such as: adjacent penetration resistance graphs, using function B or C.

9.1.1.2.2 *Identifying a perceptible thickness*

A perceptible thickness is identified by the difference between two layer transitions, determined as in 9.1.1.2.1, and between which the penetration resistance graph does not indicate the existence of an intermediate layer transition.

9.1.1.2.3 *Excess layer thickness*

This is the thickness value computed in 9.1.1.2.2, which exceeds the thickness specified for the construction work. For the remainder of the interpretation (see 9.1.2), only excess thicknesses will be used.

9.1.2 Presentation of results

9.1.2.1 ***Excess thickness frequency***

On a construction site, inspected by a number N of penetrometer tests, excess thickness frequency is defined by:

$$f_{(\%)} = 100.\frac{\Sigma excess\ thicknesses\ (>e)\ on\ the\ N\ tests}{\Sigma cumulative\ depths\ of\ the\ N\ tests}$$

9.1.2.2 ***Excess thickness frequency by overthickness level***

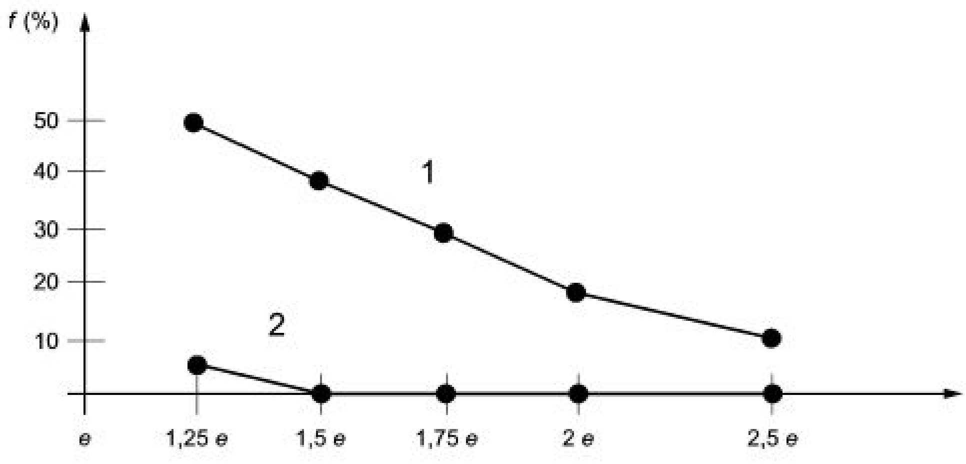
Overthickness classes are predefined in relation to the specified thickness :

e - 1,25.e - 1,5.e - 1,75.e - 2.e - 2,5.e - 3.e

The frequency of thicknesses exceeding the above predefined value is given by the formula:

$$f_{(\%)} = 100.\frac{\Sigma\ thicknesses > predefined\ thicknesses\ (N\ tests)}{\Sigma\ cumulatives\ depths\ of\ N\ tests}$$

The representation of f’ as a function of overthickness classes (Figure 4) refines the overall result obtained in 9.1.2.1.



Legend
1 Case of infill with many overthicknesses
2 Case of infill with few overthicknesses

Figure 4 — Overthickness frequency curves (given as an example)

9.2 Using the penetrometer in function B

The test report must specify the method used:

Either the method which uses the case catalogue, called reference lines method (see 9.2.1)

Or

the method that uses the relationships catalogue $\rho = f^{-1}(q)$, called semi-probabilistic method (see 9.2.2).

9.2.1 Processing results obtained using the reference lines method

The results are processed using penetration resistance graphs and values q_L and q_R corresponding to the standard cases identified and the depths inspected.

9.2.1.1 *Method*

9.2.1.1.1 *Conditions required*

Function B can be used if :

— the materials are classified as specified in standard NF P 11-300 or in DC_1, DC_2 and/or DC_3. The hydric condition for ground with a condition sub-class is that existing at the time of the inspection. For marginal materials, compliance in relation to standard site cases must be proved by investigation ;

— the values q_L et q_R exist for the standard case ;

— the parasite friction along the rod assembly is acceptable (see 6.1.2.2).

If these conditions are not met over the entire depth, partial interpretation is possible in function B, in the zones in which the above three conditions are met.

9.2.1.1.2 *Interpretation*

The penetration resistance graph is compared with the assembly position of the parts of lines q_L and q_R that are successively concerned, in order to confirm that the compaction result is as expected or, if this is not the case, to assess the importance of the difference identified.

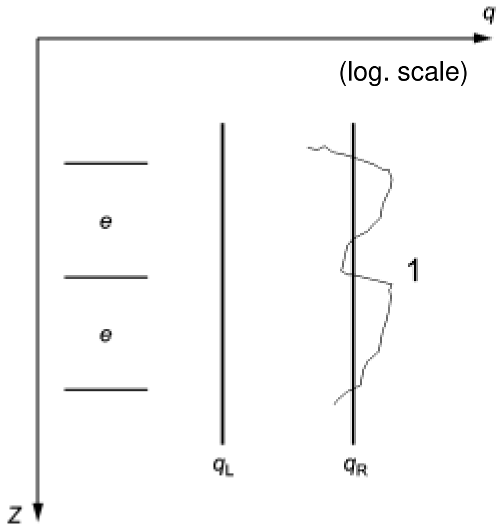
Four types of problem are defined below, as a function of the relative positions of the penetration resistance graph and q_L et q_R, in ascending order of importance.

9.2.1.1.2.1 *Result as expected*

Criteria :

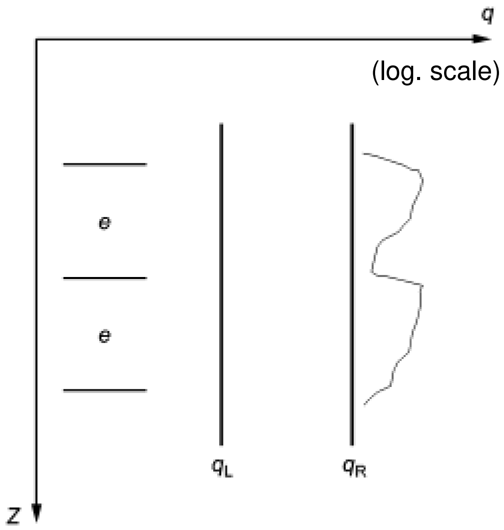
– the penetration resistance graph is always above q_L ;

– layer thicknesses are as predicted (see function A, Article 1).



Legend
1 Thickness compliant

a) Compliant situation



b) Situation possible but not necessary

Figure 5 — Penetration resistance graphs — Results with no problem

9.2.1.1.2.2 Result with type 1 fault

Criteria :

— the penetration resistance graph is always above q_L,

— layer thicknesses are always more than 20% above the specified values.

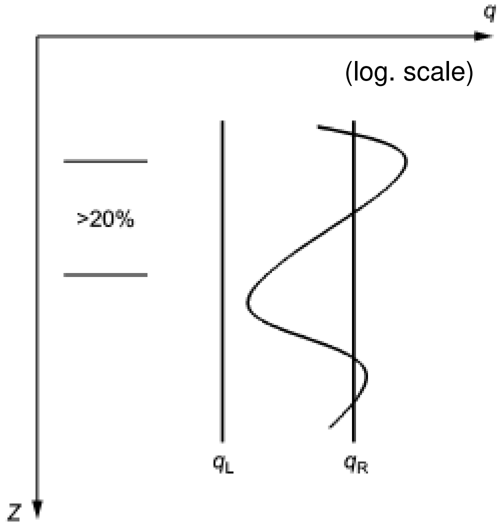


Figure 6 — Penetration resistance graph — Result with type 1 fault

9.2.1.1.2.3 Result with type 2 fault

Criteria:

— the penetration resistance graph is below q_L by a difference "a" that is less than the difference "b" between q_L and q_R and in total for a height of less than 30% of the depth inspected "h".

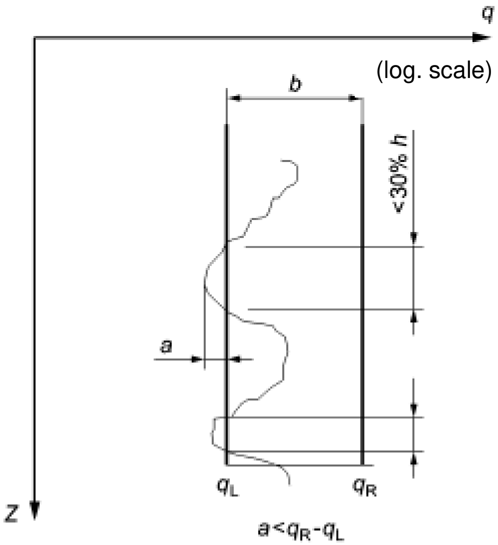


Figure 7 — Penetration resistance graph — Result with type 2 fault

9.2.1.1.2.4 Result with type 3 fault

Criteria :

— the penetration resistance graph is below q_L by a difference "a" that is greater than the difference "b" between q_L and q_R, or in total for a height of more than 30% to 50% of the inspected depth "h", irrespective of the value of excess.

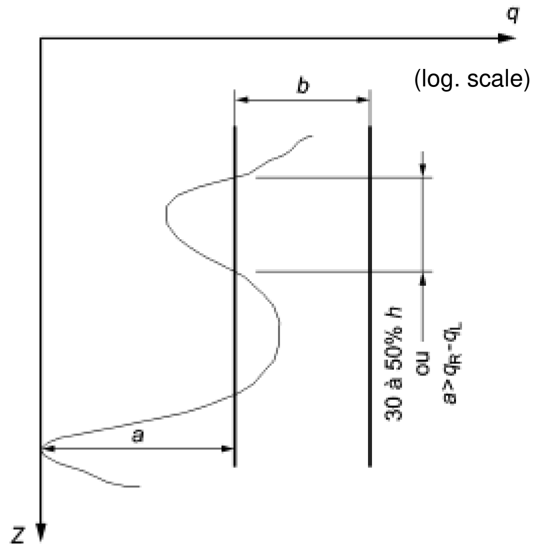


Figure 8 — Penetration resistance graph — Result with type 3 fault

9.2.1.1.2.5 Result with type 4 fault

Criteria:

— the penetration resistance graph is below q_L over more than 50% of the inspected depth "h".

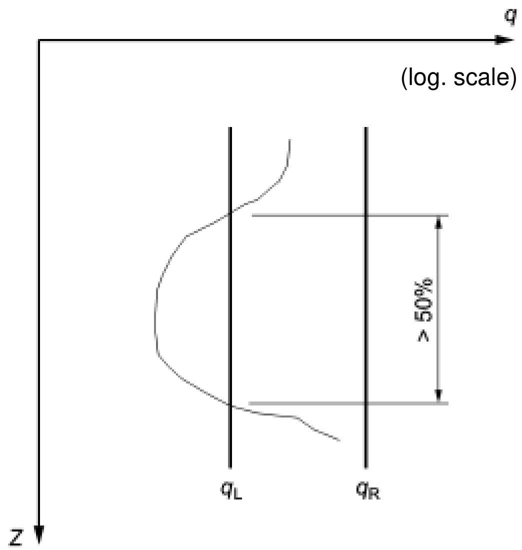


Figure 9 — Penetration resistance graph — Result with type 4 fault

9.2.1.1.2.6 Supplementary remarks

— the upper 10 cm to 20 cm of the infill (depending on the materials) should not be included in the interpretable zones with the above criteria;

— when values q_L and q_R are both known for a given material, and the values for their material class are also known, then the values for the material shall take precedence for the purposes of interpretation.

9.2.1.2 ***Presentation of results***

Every penetration resistance graph shall be annotated “no fault” or the type of fault identified shall be indicated, as appropriate.

9.2.2 Processing of results for the semi-probabilistic method

The method is described in Appendix D.

9.3 Using the penetrometer in function C

The penetration resistance graphs for the inspected zone are compared directly with a number of penetration resistance graphs obtained on a reference panel specific to the site on which the required density was achieved. These are known as reference penetration resistance graphs.

9.3.1 Method

9.3.1.1 ***Conditions required***

Function C may be used if:

— the material in the inspected zone is of the same nature and condition as that of the reference panel;

— the friction along the rod assembly remains acceptable, as specified in 6.1.2.2.

If these conditions are not met over the entire depth, partial interpretation is possible in function C, in the zones in which the above two conditions are met.

The class and sub-class of the materials penetrated should be inspected based on at least one sample for a penetrometer test group on an infill or a trench. Water content is measured by layer of 0.50 m, and with each change of material. The sampling method used shall be specified on the test sheet.

If the compacted material is shown to be heterogeneous, the number of samples may be increased as appropriate. In some cases, the sampling ratio may reach, or even exceed, one sample for two penetrometer soundings.

9.3.1.2 ***Reference panel***

The reference panel uses the same material as in the zone to be inspected, with the same application and compacting equipment. The instructions (thickness “e”, number of runs “n”) and the required water content should be strictly respected.

In the case of solid constructions involving various materials, a reference panel should be prepared for each material used.

9.3.1.2.1 *Minimum dimensions of reference panels*

9.3.1.2.1.1 Solid infill

For very high and/or large area infills, minimum dimensions are: length not less than 25 m, width not less than three times the head compacting width, with no overlapping of the compactor runs, overall height exceeding 2 m with no less than six basic layers of the specified thickness “e”.

For small infills, minimum height is reduced to 15 m, the width and height are those of the construction, with no more than three compactor runs for the width and not exceeding a height of 3 m.

9.3.1.2.1.2 Trenches

The dimensions of the reference trench are:

• length 15 m ;

• max. width and depth are those of the trench to be executed on the site.

9.3.1.2.1.3 Material

The material is identified geotechnically for classification (class and condition sub-class). For materials that change, identification is based on samples taken after application.

For each layer, the water content is measured via three separate samples, and thickness is computed by levelling (or equivalent method) progressively, as the layers are extracted.

9.3.1.2.2 *Compacting workshop*

The equipment and procedures used are recorded.

9.3.1.2.3 *Number of points*

No fewer than five penetrometer soundings should be made at different positions to confirm that thicknesses after compacting are as specified.

9.3.1.3 *Interpretation*

9.3.1.3.1 *Visual interpretation*

Each penetration resistance graph for the zone inspected is compared by superimposing it on all the reference penetration resistance graphs.

Compacting is considered to be satisfactory if:

— the penetration resistance graph falls within the envelope of the reference penetration resistance graphs;

— if for the deep section, no resistance to dynamic penetration is less than the minimum value of q obtained on all the reference penetration resistance graphs. For the upper section (oblique section at the start of the penetration resistance graph), results should be compared for the same depth.

If only one penetration resistance graph shows compacting differences, another test should be conducted in the doubtful zone (at around 1 m from the previous test, for example), and/or a check should be made to ensure that the differences in resistance to dynamic penetration are not due to a cause other than the actual compacting (nature or condition of ground, for example). Further sampling may be necessary to confirm the nature and condition of the ground penetrated.

9.3.1.3.2 *Statistical interpretation*

It is possible to use statistical methods by limiting the analysis to the deep (vertical) zones causing an interpretation problem, and after having conducted any supplementary tests that may be necessary.

If q'_m and q'_a are defined in the zone concerned on a penetration resistance graph ;
and if q'_m, $\overline{q_m}$, $\sigma(q_m)$, $\overline{q_a}$ and $\sigma(q_a)$ are defined for the same zone in depth on the reference penetration resistance graphs, then compacting is compliant if :

$$\text{all } q'_a > \overline{q_a} - 2\,\sigma(q_a)$$

$$\text{and } q'_m > \overline{q_m} - 2\,\sigma(q_m)$$

However, if the result is bordering on non-compliance in relation to the previous criteria, it is recommended that at least two supplementary check tests be conducted and, if these are also satisfactory, the mean values of the three check tests should be compared with those of the reference penetration resistance graphs.

9.3.1.3.3 *Supplementary remarks*

The dispersal of the reference panel results is acceptable when the following two conditions are met:

$$\sigma(q_m) < 0{,}15\,\overline{q_m}$$
$$\sigma(q_a) < 0{,}20\,\overline{q_a}$$

When the function C method is used, and values obtained by calibrating standard cases exist, thus also enabling interpretation using function B of the penetration resistance graphs, the interpretation in function C shall take precedence.

9.3.2 Presenting the results

The results are presented in the following documents:

— a layout drawing of the penetration resistance graphs (reference panel and parts inspected) and materials sampling ;

— the reference penetration resistance graphs ;

— the penetration resistance graphs for the inspected part. These shall retain the same scales as the reference penetration resistance graphs, and shall be annotated “satisfactory” or “unsatisfactory” for one or more zones in depth. Zones not meeting the conditions defined in 9.3.1.1 are marked “zone not inspected” ;

— the water content and sampled materials classification curves. These shall be to the same depth scale as the penetration resistance graphs.

Annexe A

(informative)

Main characteristics of variable energy dynamic penetrometers

Tableau A.1 — Main characteristics of variable energy dynamic penetrometers

	Element	Symbol	Units	Envelopes		Utilisation tolerances
				Min.	Max.	
Hammer or Ram	Mass	M	kg	1	25	±1%
Anvil	Mass of anvil assembly + rods at start of driving	-	kg	-	1.5 M	±2%
Rods	Length	L_t	m	0.25	2	±0.1%
	Mass per metre	-	kg	-	2.5	±1%
	Outer diameter	d_t	mm	-	≤ 0.9d	±2%
Tips	Outer diameter	d	mm	15	62	±2%
	Area of straight section	A	cm²	2	30	-
	Length of tapered section	L_2	mm	d/2		+2% -10%
	Length of cylindrical section	L_1	mm	d		+2% -10%

The measuring system performance is such that:

— q is known by the precision.

Table A.2 — Values of q

Range of q	Precision
> 10 MPa	0.5 MPa
1 to 10 MPa	0.2 MPa
< 1 MPa	0.1 MPa

– depth z, in relation to the driving origin, is known with precision :

Table A.3 — Values of z

Range of z	Precision
< 2 m	± 0.5%
2 to 5 m	± 0.3%
> 5 m	± 0.2%

— the investigation depth may descend down to 4 m to 5 m in fairly compact ground (see conditions for stopping driving in 6.1.2.2).

— the utilisation envelope covers fine and medium texture earth, up to a maximum diameter of 50 mm to 80 mm (false refusal possible on isolated stone).

Finally, the manufacturer's documentation specifies whether the equipment can be used for inclined penetrometer soundings and, if so, the maximum angle of inclination in relation to the vertical.

Annexe B

(information)

Presentation of results (example)

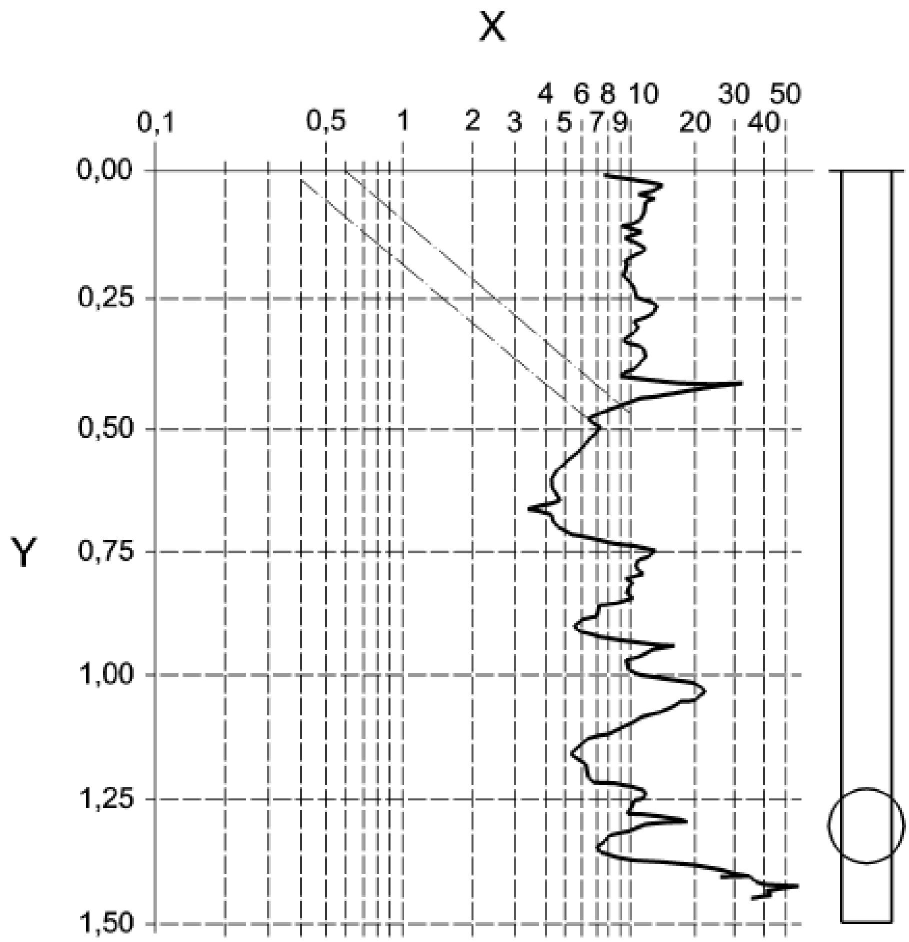


Table B.1 — Compaction inspection using variable energy dynamic penetrometer

Date :	Organisation :
File :	Operator :
Site :	
Test N° :	
Identification	
X Y Z	

	Mass	Section	Length
Rod			
Tip			
Driver			

Type of equipment: Calibration (method, laboratory): Function: A / B / C
Height of infill: Width of infill: Number of layers compacted: Nature of network: Depth. Supplementary line:

TEST		
	Target	Reached
Depth		
Stopping conditions: Preliminary hole:		

X Resistance (MPa)

Y Depth (m)

	Material class	Compacting objectives	Material analysis	Hydric condition	Predicted thickness	Actual thickness	Types of fault
Couche 1 :							
Couche 2 :							
Couche 3 :							
Couche 4 :							
Couche 5 :							
Target angle		Date of analysis :					

Depth (m)						
Assessment of friction						
Comments :						

CONCLUSION:	
Operator name: Supervisor name	Signature:

Annexe C

(information)

Method for calibrating the variable energy dynamic penetrometer In the laboratory

C.1.1 Reminder and general

The reason for calibrating the variable energy dynamic penetrometer is to determine the values q_L and q_R (as defined in 3.4) or the relationships (as defined in D 1), so as to create or complete the catalogue for a piece of equipment with defined characteristics.

The case catalogue, associated with a piece of equipment with given characteristics, may contain:

— standard cases in which values q_L and q_R, or the relationship, have been established to be representative of an “average” material of the class concerned, and for various hydric conditions. These cases are identified by their classification and sub-classification (hydric condition) or the water content value;

— standard cases in which the values q_L and q_R, or the relationship $\rho_d = f^{-1}(q)$, are only defined for one specific material and one or more hydric conditions. This may involve an industrial by-product, a material presenting a specific characteristic or a material that doesn’t correspond to the “average” case for the class.

These cases are identified by the specific name of the material that has been geotechnically identified.

Due to the small size of the equipment, it is both possible and advantageous to have it calibrated in a laboratory. The method is described in detail below.

C.1.2 General presentation of the method

Using a model representative of the resistance to dynamic penetration when penetrating uniformly compacted ground (Figure 1), for each material, the values q_L and q_R should be determined or the curves ρ - q_0 and ρ – q_1 should be plotted, using an experiment procedure conducted in the laboratory, and based on the following main phases:

a) identification and classification of material (NF P 11-300) ;

b) conduct normal or modified PROCTOR’s test (NF P 94-093 or NF P 98-231-1);

c) setting up in a test mould: five series are prepared for five different compacting energies and for various water contents;

d) compacting using a method that gives good consistency ;

e) for each compacting energy, i.e. for each of the five series, three penetrometer tests are conducted with the equipment being calibrated ;

f) the material dry density (NF P 94-053) and water content (NF P 94-050) are both measured directly ;

g) determine z_c. The curves are plotted after analysis and statistical processing for each density and water content value ;

h) the reference and limit lines are then plotted for the values corresponding to q_2, q_3 and q_4 by interpolation, if necessary, between the previous results.

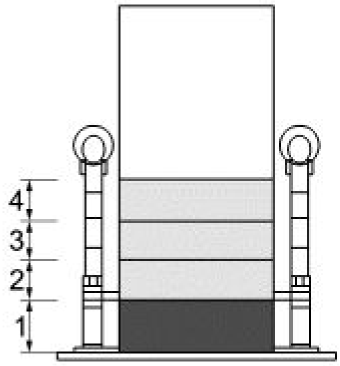
This procedure gives reference and limit curves for all possible materials, and for any compacting value q_2, q_3 and q_4, or for any other value between 80% and 110% of Proctor’s Normal optimum.

C.1.3 Selecting the test mould

The test mould must be sufficiently large for the penetrometer test to be considered to be conducted in a semi-infinite environment. As an example, for the range of earth textures covered by the equipment and a tip area A ≤ 4 cm² and diameter d ≤ 50 mm, the test mould (see Figure C.1) must not be smaller than the following dimensions:

— diameter : 35 cm ;

— height : 70 cm.



Legend

1 Layer 1

2 Layer 2

3 Layer 3

4 Layer 4

Figure C.1 — Laboratory testing mould

C.1.4 Classification of material

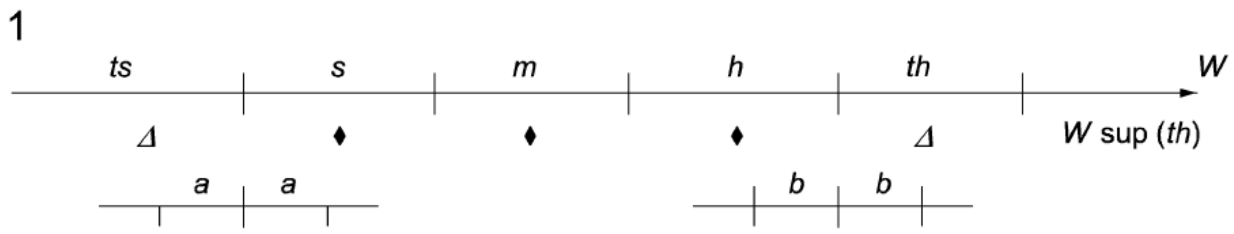
The classification is used to define the material and is based on the criteria specified in standard NF P 11-300: granulometric testing, tests to determine Atterberg's limits and Proctor's tests, using Blue and/or sand equivalent.

C.1.5 Water content variation range

The water content of the material on use is a normal inspection parameter.

For the purpose of penetrometer calibration testing on ground sensitive to water, it is accepted that the water content variation range be extended beyond the normal ground acceptance interval for compacting with Proctor's normal energy, in order to confirm the material characteristics curves and ensure that the inspection system, once calibrated, will identify all situations (including those of compacting conducted well outside the acceptable water content ranges).

When calibrating the equipment for ground sensitive to water, it is recommended that five hydric condition sub-classes be adopted: ts, s, m, h and th, with reference to standard NF P 11-300 and by analogy with standard XP P 94-063 (see 8.2.2.2).



Legend

♦ Wmean of a sub-class delimited in NF P 11-300

Δ Wmean defined for sub-classes ts and th (dependant on saturation conditions)

1 Condition sub-class

Figure C.2 — Wmean of sub-classes
(as per standard NF P 94-063)

For each class of material, these five hydric conditions are also expressed as percentages of W_{OPN}.

C.1.6 Variation of compacting energy

The compacting energies applied during calibration testing must cover a broad spectrum in order to obtain the density variations necessary to study the correlation with resistance to dynamic penetration.

Many experiments and tests conducted on fine earth texture (see notably bibliography reference [4]) have shown that a range of five energies, selected as a function of the following principles, met the above criterion:

— primary "energy", corresponding to loose material, little compacted if at all;

— the next four energies, giving a consistent material, the dry density of which gradually reaches a value between 80% and 110% of ρ_{OPN}.

C.1.7 Installation and compacting in the mould

The principle of the method is close to that of Proctor's test. Five series are prepared for five different compacting energies.

For each mould, an initial water content value is measured before compacting.

Compacting must be consistent and careful, to achieve constant density inside the mould.

When the material is installed, an additional height of 15 cm allows compacting to be conducted evenly up to the top of the mould. The extra height is then removed and the material is properly levelled.

The mould is weighed in order to compute the material density. When the mould is removed, three or four samples are taken at various levels, and the water content is measured for each sample.

C.1.8 Penetrometer test

For each compacting procedure (given ground — compacting energy — hydric condition), three conventional penetrometer tests are conducted, arranged at the angles of a triangle. These three tests will only be taken into account if they all give the same result (within 10%). In addition, the signal must have a shape that is easy to identify (q_0, q_1 and z_c). If this is not the case, the three tests are ignored.

C.1.9 Data processing

Work is conducted on a given condition sub-class (as per the classification in standard NF P 11-300), i.e. on five moulds (one mould per compacting energy value) and a total of 15 penetrometer tests.

The values for q_1 (resistance in depth) are examined first. Curves are plotted for the relationship $\sigma - q_1$ (see Figure C.3).

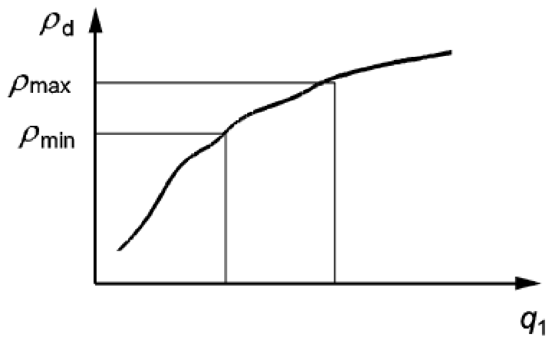


Figure C.3 — Relationship between ρ and q_1
(in depth and for a given material and hydric condition)

C.1.9.1 ***Method by plotting the limit and reference lines*** *(computing of values q_L and q_R)*

By interpolation, values of q_1 can be defined which correspond, for a given material, to the compacting objective references q_2, q_3 and q_4 in the LCPC-SETRA guide [1], or to any other reference, or to any other value between 80% and 110% of the O.P.N.

Values q_0 and z_c are notably dependent on the tip diameter, and are obtained by analogue interpolation (z_c based on the average over the 15 tests). The limit curve corresponds to the value q_1/k, with k respectively equal to 1.3 — 1.4 — 1.6 for sub-classes th — h — m,s,ts (which corresponds to around 98% ρ_{ref}, the reference dry density less 2%).

For the remainder, the detail of the method is a simple adaptation of the calibration method specified in experimental standard XP P 94-063, applicable to penetration density graphs.

C.1.9.2 ***Semi-probabilistic method***

This method attempts to determine relationships $\rho = f^{-1}(q)$ at constant hydric condition, with appropriate confidence ratings, based on the results of calibration tests and by statistical regression. It is described, for information, in Appendix D.

Annexe D

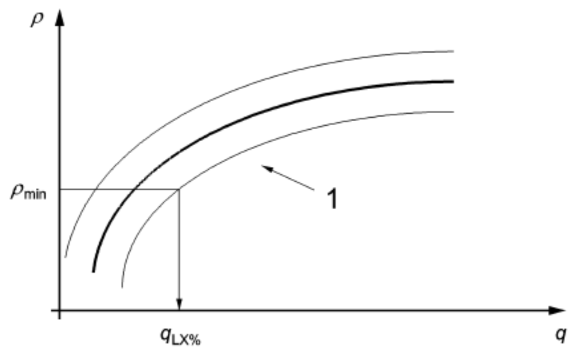
(information)

Processing in function B of variable energy dynamic penetrometer results Using the semi-probabilistic method

D.1.1 Definitions and terminology specific to the method

D.1.1.1 *Resistance to dynamic penetration: limit value (for a classified material)*

The limit value $q_{LX\%}$ of the resistance to dynamic penetration (see Figure D.1) is, at a given depth z, the minimum value below which q must not fall so as to indicate, with a confidence rating of x%, that the minimum density level ρ_{min} is reached (function B). This value is deduced from the lower envelope curve for the material tested and is taken from the catalogue of relationships $\rho_d = f^{-1}(q)$, together with its confidence rating (see definition in D.1.3).

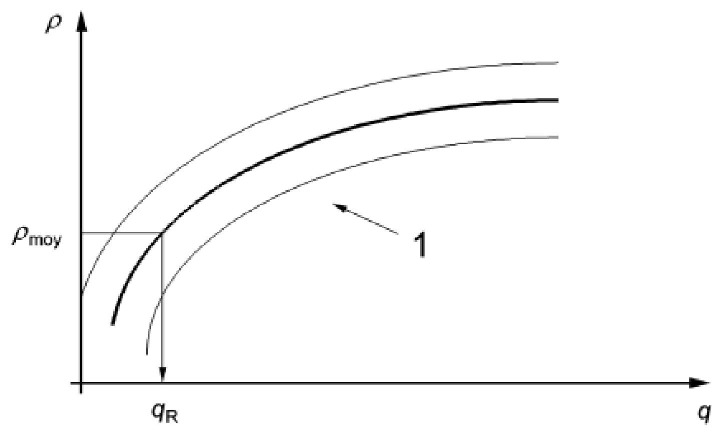


Legend
1 Confidence rating at X%

Figure D.1 — Definition of limit value $q_{LX\%}$

D.1.1.2 *Resistance to dynamic penetration: reference value (for a classified material)*

The reference value q_R for the resistance to dynamic penetration (see Figure D.2) is, at a given depth z, the mean value of q when the density corresponds to a specified mean value ρ_{mean} (function B). This value is deduced from the mean curve for the material tested and is taken from the catalogue of relationships $\rho_d = f^{-1}(q)$ (see definition in D.1.3).



Legend
1 Confidence rating at X%

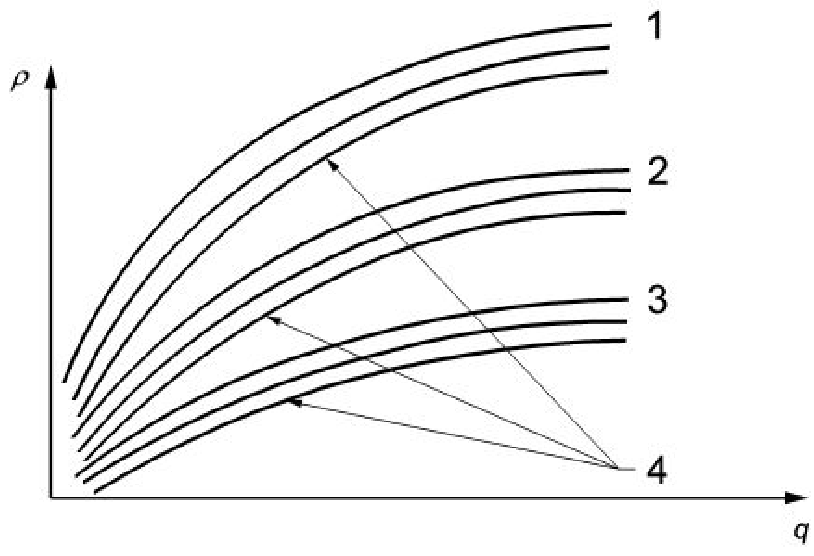
Figure D.2 — Definition of reference value q_R

q_R is used to facilitate interpretation and completes the use of $q_{Lx\%}$.

D.1.1.3 Catalogue of relationships $\rho_d = f^{-1}(q)$

D.1.1.3.1 *Définition*

The catalogue of relationships $\rho_d = f^{-1}(q)$ is obtained by laboratory regression or on test panels, together with their confidence ratings at 80% and 90% (see Figure D.3), with the material class and its hydric condition at the time of the penetrometer test as entry arguments. These relationships are assumed to be applicable irrespective of the test depth (beyond the critical depth), providing the dynamic penetrometer's utilisation envelope is not exceeded and friction is not significant.



Legend
1 W_{OPN+2} (or sub-class h)

2 W_{OPN} (sub-class m)

3 W_{OPN-2} (or sub-class s)

4 Confidence ratings

Figure D.3 — Curves for a given material class

D.1.1.3.2 *Creating the catalogue in the laboratory*

Details of the calibration tests conducted in the laboratory are given in Appendix C.

For each material class and hydric condition tested on the laboratory moulds:

— the combinations (ρ_i, q_i) are extracted;

— the curves $\rho_d = f^{-1}(q)$ are constructed by regression on the points with coordinates (ρ_i, q_i), and the types of relationship (regression curve, linear regression on the logs. of the variables, etc.), the physical envelope of validity of the relationships, and the limit values, are selected;

— statistical tests are conducted on the regression curves or lines (relationship performance), thus enabling confidence ratings to be defined at 80% and 90%.

The minimum number of combinations (ρ_i, q_i) to define the regressions is 20 per material and hydric condition value.

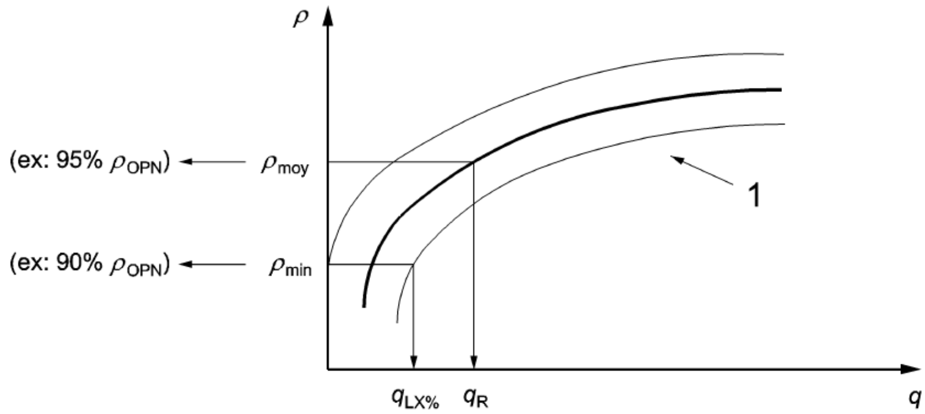
Regression refusal/acceptance criteria must be defined as a function of the regression method adopted.

The method enables a catalogue of relationships $\rho_d = f^{-1}(q)$ to be defined with two entry arguments: material class and hydric condition (sub-class).

D.1.2 Processing of results and interpretation

D.1.2.1 ***Principle***

The penetration resistance graph is compared with values $q_{Lx\%}$ (with confidence interval at x%) and q_R, deduced from the catalogue of relationships $\rho_d = f^{-1}(q)$ for the same equipment, for the required dry density values, respectively the minimum ρ_{min} and mean ρ_{mean} values (see Figure D.4). The materials actually used must be identified (as per standard NF P 11-300), and their hydric condition at the time of the test must be known.



Legend
1 Confidence rating at X%

Figure D.4 — Catalogue curve utilisation principle

D.1.2.2 ***Method***

D.1.2.2.1 *Conditions required*

Function B can be used if :

— the material is classified as specified in standard NF P 11-300 or NF P 98-231-3 ;

— the water content values at the time of the inspection were determined on the sounding profile ;

— the values $q_{Lx\%}$ exist in the catalogue of relationships $\rho_d = f^{-1}(q)$ and for the hydric conditions observed;

— the parasite friction along the rod assembly remains acceptable.

If these conditions are not met over the entire depth, partial interpretation is possible in function B, in the zones in which the four conditions mentioned above are met.

D.1.2.2.2 *Interpretation*

When inspecting the compacting of dam or dyke infills, only one fault level is considered, as defined below (in D.2.2.2.2). When inspecting the compacting of road or trench infills, the principle of four fault levels can be applied, as defined in standard NP P 94-063.

The penetration resistance graph is compared, layer by layer, with the values (with confidence interval at x%) and q_R successively concerned, in order to confirm that the compacting result is as expected.

D.1.2.2.3 *Result without fault*

The test is considered to be without fault for the layers concerned if the following three criteria are met simultaneously for the layers:

— layer thicknesses are always as predicted (see function A in the present document);

— the penetration resistance graph is always above $q_{Lx\%}$ for the layers concerned (including at the bottom of the layer);

— the mean dynamic penetration resistance value over the thickness of the layers concerned is not less than q_R.

The acceptance/rejection criteria relating to water content, which are particularly important for hydraulic constructions (dams and dykes), must be specified separately.

D.1.2.2.4 *Result with fault*

A fault is detected on one or more layers if any one of the three criteria mentioned above is not met for the layers concerned.

D.1.2.3 ***Complementary remarks***

The upper 10 cm to 20 cm (depending on the materials) correspond to the signal forming zone and should not be included in the zones interpretable using the above criteria.

D.1.2.4 ***Expression of results: compacted layer acceptance/rejection criteria***

These criteria must be specified in the contractual technical document applicable to the works (specifications, special technical clauses, etc…).

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