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Earthworks — Continuous Compaction Control (CCC)

National foreword

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Contents

Page

European foreword

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1 Scope

This technical specification provides guidance, specifications and requirements on the use of Continuous Compaction Control (CCC) as a quality control method in earthworks by means of roller integrated dynamic measuring and documentation systems.

The CCC method is suitable for soils, granular materials and rockfill materials which can be compacted using vibratory rollers.

NOTE A continuous Compaction Control (CCC) technology based on the measure of propel energy necessary to overcome the rolling resistance is also available and can be used as a quality control method in earthworks. The propelling power of the compactor provides an indication of the material stiffness and it is measured as a function of the machine ground speed, slope angle and rolling resistance. This method is not included in this document.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
vibratory roller
vibratory roller is a roller which generates:

a) vertical vibrations (circular exciters) with fixed amplitudes; or

b) horizontal vibrations (oscillation rollers) with fixed amplitudes; or

c) vibrations with a direction, amplitude and/or frequency that can be automatically or manually adjusted during operations

Note 1 to entry: Vibratory rollers operating with automatic amplitude and/or frequency mode are called 'intelligent rollers'.

2.2
measuring roller
vibratory roller which is equipped with a compaction measuring and documentation system which measures and maps the dynamic properties of the compacted surface

Note 1 to entry: See Figure 1.

2.3
Continuous Compaction Control
CCC
use of measuring rollers for quality control in earthworks

2.4
CCC measuring value
dynamic value which depends on the measuring principle, the type of roller, operating weight, amplitude, frequency and operating speed used, the type of soil or granular or rockfill material and its water content

Note 1 to entry: CCC measuring values determined by different systems are not necessarily equivalent.

2.5
stiffness of a soil
quotient of applied force (loading) and the corresponding deformation

2.6
dynamic stiffness of a soil
quotient of variation of dynamic soil reaction force and the corresponding variation of deformation (soil displacement)

2.7
compaction depth
depth below the point at which the drum meets the investigated surface over which the roller provides a significant compaction effect

2.8
measuring depth
depth below the point at which the drum meets the investigated surface over which the resulting response from the underlying materials still has an effect on the CCC measuring value

2.9
CCC inspection area
part of the production that has been processed under uniform conditions for which a unique compaction requirement is valid

2.10
fall-below spot
part of the control areas in which the CCC measuring value falls below a certain CCC target value

2.11
measuring area unit
part of a control area, the width of which equals the drum width of the roller and the length of which corresponds to the product of the operating speed and duration of the individual measurement

2.12
jump operation
roller drum that partially loses ground contact, which occurs with increasing soil stiffness

2.13
double jump
jump operation when the drum loses contact during a complete vibration cycle

Note 1 to entry: The roller drum hits the very stiff ground, rebounds and then makes a full cycle in the air before hitting the ground again

Note 2 to entry: When jump operation becomes more pronounced because of high soil stiffness double jump can occur, which usually significantly reduces the magnitude of the CCC measured values. In this way, the CCC measuring system can identify and indicate jumping operation.

2.14
positioning system
system for georeferencing the compaction or measuring roller on the area being processed

2.15
roller pass
one forward or backward operation of a vibratory roller over a certain distance

2.16
weak area
part of CCC control area, which presents lower CCC values than the rest of the control area

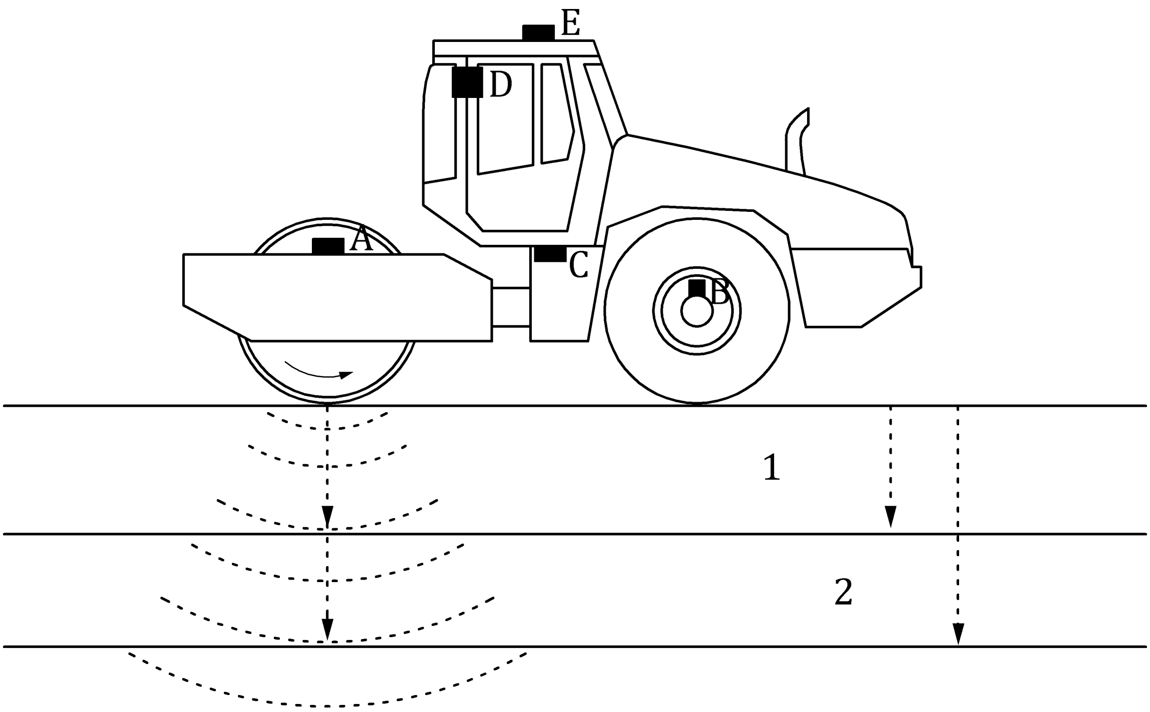
3 Fundamentals and principles of CCC measurements

Roller integrated continuous compaction control (CCC) is based on the dynamic interaction between the excited drum of a vibratory roller and the soil or granular or rockfill material that has to be compacted. The dynamically measured value determined from the movement behaviour of the drum shall be physically clearly defined.

Vibratory rollers are characterized by a drum that is excited by one or more eccentric masses rotating at constant speed. CCC rollers are equipped with acceleration transducers, processors and a display to provide a record of the drum to soil interaction (Figure 1).

During the roller pass of a vibratory roller there is a continuous exchange of kinetic energy between the roller drum and the roller/soil vibrating system.

Both the soil stiffness and the absorption of the roller vibration change with increasing compaction. By analysing the vibration behaviour, conclusions can be made about the compaction quality. This analysis can follow various principles. See Annex A.



Key

1 compaction depth

2 measuring depth

A acceleration transducer

B distance sensor

C processor

D display and recorder

E positioning systems (GNSS antenna)

Figure 1 — Single drum roller for CCC measurements (schematic diagram)

4 Influences on the CCC measuring value

4.1 General

The CCC measuring values can be used to evaluate the stiffness, the soil compaction process and the compaction quality. For proper interpretation of the CCC measuring values, the major influencing parameters need to be considered. The most important parameters are the weight, amplitude, frequency and operating speed of the roller, driving direction, measuring depth and layer thickness, the type of material, its water content and the evenness of soil surface.

4.2 Roller

4.2.1 General

There are three types of rollers as follows:

— Single drum rollers (vibratory rollers driven by rubber wheels) with a smooth drum, which may also be driven, provide the best results with respect to constant travel speed. Their higher mobility and generally problem-free use on slopes and loose surfaces are also advantageous. It is also possible to use vibrating pad foot rollers for certain materials.

— Tandem vibratory rollers with two smooth drums are usually less suitable. Under some subgrade and adverse terrain conditions (e.g. slopes) these rollers may sometimes suffer from “slip” of the driven drums. The travel speed then sometimes becomes difficult to control.

— “Intelligent” rollers are vibratory rollers which automatically adjust the compaction energy by changing the amplitude and/or frequency during the compaction process. When intelligent rollers are used for CCC, the amplitude and the frequency need to be fixed.

4.2.2 Static linear load of roller drum

The static linear load is a roller parameter which is the load of the drum plus the effective frame weight divided by the drum width.

The higher the static linear load, the larger the measuring depth.

NOTE The static linear load influences the motion behaviour of the drum, such that rollers with a light frame have a higher tendency to jump.

4.2.3 Vibration amplitude

The theoretical amplitude of the drum is a roller parameter which is a function of the drum mass, the eccentric mass and its eccentricity.

The magnitude of the amplitude influences the measuring depth and the motion behaviour of the drum and consequently the magnitude and range of the CCC measuring values.

NOTE The measuring depth is higher if the roller is operating with high amplitude. However, this mode of operation increases the risk of grain crushing and re-loosening of soil near the surface; and the drum has a higher tendency to jump than during operation with lower amplitudes.

4.2.4 Vibration frequency

The vibration frequency is a roller parameter which is the number of vibration cycles per second. The frequency affects the magnitude of the CCC values.

4.2.5 Operating speed

The operating speed affects the magnitude of the CCC measuring values. In general for much lower speeds higher measuring values can be expected.

4.2.6 Direction of roller

The operating direction affects the magnitude of the CCC measuring values.

If construction purposes require measuring passes to be performed when the roller is moving both forwards and backwards, then comparative passes with the roller travelling in each direction need to be performed beforehand; these are to check whether the magnitude of the CCC measuring values obtained during backwards passes differs from the values obtained during forward passes.

4.3 Measuring depth

The measuring depth depends particularly on the static linear load of the drum, the vibration amplitude and vibration frequency, the stiffness of the layer to be compacted and the stiffness of the underlaying materials.

Under uniform conditions, the measuring depth can be estimated according to Table 1, which shows, as an example, the values that can be achieved by smooth single drum vibrating rollers on gravelly soil placed in layers.

Table 1 — Examples of measuring depth to be expected (gravelly soil, smooth single drum vibrating rollers)

	Operating mass	Static linear load	Low amplitude (0,8 – 1 mm)	High amplitude (1,5 – 2 mm)
Light single drum rollers	< 10 t	15 – 30 kN/m	approx. 0,4 m to 0,6 m	approx. 0,6 m to 1,0 m
Medium weight single drum rollers	10 – 15 t	20 – 40 kN/m	approx. 0,4 m to 0,8 m	approx. 0,6 m to 1,5 m
Heavy single drum rollers	15 – 22 t	40 – 60 kN/m	approx. 0,6 m to 1,2 m	approx. 1,0 m to 2,0 m
Extra-heavy single drum vibratory rollers	> 22 t	60 - 80 kN/m	approx. 0,6 m to 1,2 m	approx. 1,0 m to 2,5 m

Non-uniform soil stiffnesses have a major influence on the measuring depth, so CCC should carefully be used on the bottom layer of an embankment and should only be used from the second layer on upwards when estimation of density is purpose of the measurement.

NOTE The measuring depth is usually greater than compaction depth (See Figure 1).

4.4 Soils, granular materials and rockfill materials

4.4.1 Type of material and water content

The type of soil and particularly the proportion of fine grained materials (<0,063 mm) and the water content influence the magnitude of the CCC measuring value.

For soils and granular materials with up to 15 % < 0,063 mm, good correlations between degree of compaction and CCC measuring value can typically be expected if the water contents are below the optimum water content. In such cases, there is also usually a good correlation between the CCC measuring value and static or dynamic deformation modulus.

For composite soils with more than 15 % < 0,063 mm and fine soils, special attention should be given to the water content. A correlation between CCC measuring value and degree of compaction is only possible under uniform soil and water conditions.

NOTE When satisfactory compaction of composite and fine soils is not possible because the water content of the material to be compacted is too high, a lower CCC measuring value is registered which does not increase but rather decreases as the number of passes increases.

Softened surfaces (after heavy rain) also exhibit a decrease of the level of CCC measuring values.

Wet composite and fine soils with high degrees of saturation can show a tendency to flow under the dynamic load of a vibratory roller and cannot produce reliable CCC measuring values.

4.4.2 Evenness and inhomogeneities on the layer surface

The roller drum shall have full contact with the layer surface, otherwise the CCC measurement values cannot be used.

The layer or zone to be measured by CCC should consist as far as possible of homogeneous material, since locally strongly varying contact conditions under the drum (e.g. sand on one side and cobbles on the other) produce CCC measuring values which cannot be used for compaction assessment, even if the surface is sufficiently level.

4.4.3 Resting time of the compacted layer

The resting time of the compacted layer can influence the CCC result especially if the water content is high.

The resting time between completion of compaction and the measuring pass shall be kept as short as possible, because this resting time may cause changes in the CCC measuring values. This could be due to the site condition (site traffic), weather influences or subsequent settlement. Weather and longer resting times between the completion of compaction and the subsequent measuring pass(es) influence the CCC measured values. The longer this period, the more problematic is the establishment of a reference to the original result.

5 Preconditions and requirements

5.1 Soils, granular materials and rockfill materials

5.1.1 Soil type

Roller integrated measuring systems can generally only be used for materials which are dynamically compactable with vibrating rollers. Because the CCC measuring value is influenced by the type of soil, the proportion of fines and the water content, special attention shall be given to composite soils with a fines proportion (<0,063 mm) > 15 % and to the water content.

The fill material should be as homogeneous as practicable, with no strongly varying material such as cobbles or boulders, accumulation of fine particles or widely varying water content. Otherwise the interpretation of the measured results is difficult.

CCC can be used on treated (stabilized) soils but only before the curing of the material.

5.1.2 Requirements for the layer surface

The soil surface shall be even, e.g. with no truck ruts; and the drum shall have contact with the ground over its entire width.

5.2 Requirements for CCC rollers

During the CCC measurements:

— the exciter frequency shall be kept constant within a range of $\Delta f < 2$ Hz;

— the amplitude shall be kept constant with a range of $\Delta a < 0,1$ mm;

— the operating speed shall be kept constant within a range of $\Delta v < 1$ km/h.

The vibration behaviour of the drum shall be reproducible. Periodical irregularities due to roller influences (e.g. worn out bearings, unbalanced drum) have to be rectified by appropriate repair; otherwise such rollers shall not be used as measuring rollers.

5.3 CCC Measuring and documentation system

5.3.1 Structure of the measuring and documentation system

The CCC system consists of the following system units which are linked to each other by appropriate connections (Figure 1):

— transducer (measurement of the drum acceleration);

— processor unit (calculation of the dynamic measuring value);

— display unit (display of the actual measuring value in real time for the roller driver, e.g. screen, analogue clock, paper strip);

— documentation unit (storage of measured data and geographic locations of the CCC measured values secured against manipulation, so that they are available for a subsequent evaluation);

— transducer for position-wise assignment for the dynamic measuring values within a roller track or positioning system;

— positioning systems such as global navigation satellite systems (GNSS), differential global navigation satellite systems (D-GNSS) or real time kinematic (RTK) systems and tachymeter systems also enable the documentation;

— for assembly and operation, the instructions given by the manufacturer of the measuring system are to be observed.

5.3.2 Requirements for the CCC measuring and documentation system

The requirements for the CCC system are as follows:

— Measurement and documentation of operating speed, frequency, selected theoretical amplitude and the dynamic measuring values as well as their position-wise assignment and the documentation of jump operation shall be guaranteed in such a way that no manipulation is possible.

— The general suitability of the CCC measuring and documentation system and the conformity of the roller to the requirements of this standard shall be proven by the manufacturer.

— CCC measuring values shall be determined and recorded with a frequency of at least 1 measuring value per 0,5 m track length.

— The measuring system shall enable digital data storage and documentation in real time.

— The measured values shall be assignable by means of coordinates; therefore, an exact mapping to the roller tracking is required.

— The absolute positional accuracy shall be better than 0,50 m in both the x and y directions.

— The input of the required roller parameters shall be possible and their compliance shall be documented.

— The measuring system shall enable a clear presentation of the required values and shall display them directly to the roller driver in real time.

— The travel speed shall be recorded and documented during the measurement.

— Jump operation shall be indicated and documented also with its entire position.

5.4 Reproducibility

Series of measurements determined immediately after each other on the same roller track shall have similar CCC measuring value curves, i.e. significant measuring values shall occur at the same positions during successive passes.

Otherwise, the reproducibility of the "soil-roller – measuring system" unit shall be checked with the specified amplitude, frequency and travel speed.

5.5 Personnel requirements

All persons involved in roller integrated continuous compaction control shall be familiar with CCC in accordance with their fields of responsibility.

6 CCC applications

The CCC method allows continuous integrated control of the compaction process and acceptance testing which covers all of the compacted area. Depending on the type and size of job site, the type of soil and the uniformity of soil to be compacted, there are four different approaches for using CCC for Quality Control (QC) and Quality Assurance (QA):

— CCC with calibration for indirect continuous density and stiffness control and QC and QA purpose:

  This requires prior calibration testing between the CCC measuring value and the end product specification. This method is suitable for stiffness measurements. This method is also suitable for indirect density measurement for consistent, granular soils and consistent composite soils with proportion of fines (≤0,063 mm) < 15 %. A calibration exercise has to be carried out for each type of material.

— CCC weak area analysis and documentation for QC and QA purpose:

  This method is used to find areas with lowest CCC measurement values where specified end product measurements are executed. This method is suitable for granular, composite and fine soils. Special attention needs to be given to the water content. Calibration is not required.

— CCC documentation of maximum compaction achievable for QC and QA purpose:

  This method involves the procedure to obtain CCC measuring values during compaction until the CCC value increases by no more than a specified percentage compared to the previous pass. This method is suitable for all type of granular and composite soils and rock fill material. Can be used for method specifications.

— Documentation of compaction method for QA purpose:

  This approach can be used to document method compaction specifications for QA purposes. The roller needs to be fitted with a global positioning system for this application.

7 CCC with calibration for indirect continuous density and stiffness control and QC and QA purpose

7.1 General

The CCC measuring values shall be calibrated against the required acceptance value(s) obtained by conventional tests such as static or dynamic deformation modulus, the degree of compaction or any other appropriate parameter. Linear regressions shall be performed to obtain these correlations. By this method a "full test" of a compacted layer with an indirect test procedure (i.e. the CCC measuring value) shall be used to decide whether the inspection area is accepted or rejected. The calibration is an essential precursor to the acceptance test and shall be performed in advance of use of CCC with calibration in the Works.

NOTE In principle, for consistent granular soil and consistent composite soils, it is possible to correlate the CCC measuring values to any conventional test parameter concerning compaction or bearing capacity. However for composite soils the influence of the water content on the CCC measuring values needs to be carefully considered. Great care is needed when performing plate load tests to achieve acceptable correlations with the CCC measuring values. Particular attention needs to be given to achieving an even, dry and tight surface on which to carry out the plate load test; and the different measuring depths of the plate load test and CCC roller also need to be considered.

7.2 CCC quality control and acceptance testing with calibration

7.2.1 Procedure

The application of roller integrated CCC with calibration performs quality control and acceptance testing (QC/QA). The procedure is divided into the following steps:

1. Calibration for the particular soil and construction site conditions and development of correlations according to 7.4 and 7.5.

2. Determination of the minimum CCC acceptance value (T_M) determined according to 7.5.

3. Testing of the compacted layer by the CCC measuring procedure (full test, number of CCC measurement values N).

4. Calculation of the mean value m and the standard deviation σ of all CCC measuring values (N) of the inspection area and calculation of the quality parameter z:

   $$z = m - 1.28\ \sigma \quad (1)$$

5. Presentation of all CCC measured values in an area plot.

6. A control area is accepted if the quality parameter z is greater than the minimum CCC acceptance value T_M ($z \geq T_M$).

   If the quality parameter z falls below the minimum CCC acceptance value T_M, the control area is rejected and shall be brought to a condition in accordance with requirements.

   The test can be performed directly integrated into the work process with the roller used for compaction, or using a separate measuring roller.

9. Evaluation of uniformity of the distribution of fall below spots in the control area by visual examination or by means of geostatistical methods.

7.2.1.1 Inspection areas

The construction/production areas have to be divided into reasonable CCC inspection areas covering the entire area.

The determination of the CCC inspection areas for the acceptance test has to be made jointly by the contractor and the supervisor (on behalf of the client).

The CCC inspection areas shall be mapped using the same operation settings as used in the calibration process.

7.2.2 Alternative decision rules

CCC represents a “full test” of the inspection area. This means, that information about the achieved compaction or load bearing status is available for any point within the inspection area. This information can be directly used for an assessment at any point. The following alternative decision rules can serve the purpose of assessing inspection areas:

1. Evaluation of the unweighted fall-below areas if Gaussian measuring values do exist; this rule is recommended because of its easy use (see B.1)

2. Evaluation of the unweighted fall-below areas in cases of arbitrary distribution of the measuring value or the total fall-below area ratio (see B.2)

3. Evaluation of the weighted fall-below areas in case of arbitrary distribution of the measuring values or the total fall-below area ratio; this decision rule is most suitable as a construction oriented criterion when using CCC (see B.3)

The decision rules are presented in the figures in Annex B.

7.3 Selection of the calibration test area

The calibration should be performed on the actual construction section and not somewhere else.

Commonly, a characteristic section with a length of 30 m and the width of the road (or embankment) should be selected as test area within the construction section. This section shall correspond to the average properties of the layers to be compacted within the whole construction section (subgrade).

The subsoil (subgrade) of the calibration test area should have sufficient homogeneity and load bearing capacity. Therefore the subsoil of each calibration test area shall be proof rolled by a CCC measuring pass.

The test area shall be divided in (integral) roller tracks whereby the maximum track width corresponds to the drum width. The minimum roller track width is determined such that the overlapping of adjacent roller tracks should not exceed 10 % of the drum width.

7.4 Calibration procedure

Before starting the calibration procedure, the appropriate layer thickness and the relevant type of roller shall be selected.

The calibration process involves construction of a calibration test area at least 30 m in length for each material type. The area should be compacted in at least three different roller lanes with varying compactive effort – light compaction (few passes), medium compaction (more passes), and high compaction (as many passes as are required to see no increase in the CCC measuring values) – using constant machine operating settings (i.e. constant frequency, amplitude and speed), see figure 2. CCC measuring values obtained in jump mode shall not be used. Low amplitude operation is recommended to avoid roller jumping during compaction. At least three to five measurements of, for example the deformation modulus from a static plate load test, or of the degree of compaction should be obtained in each of the low, medium, and high compaction lanes. Roller CCC data at each test point is then correlated with the plate load deformation modulus or degree of compaction measurements using linear regression analysis. The target CCC measuring value is then determined from the linear regression relationship for a pre-established target value of plate load deformation modulus or degree of compaction (see 7.5).

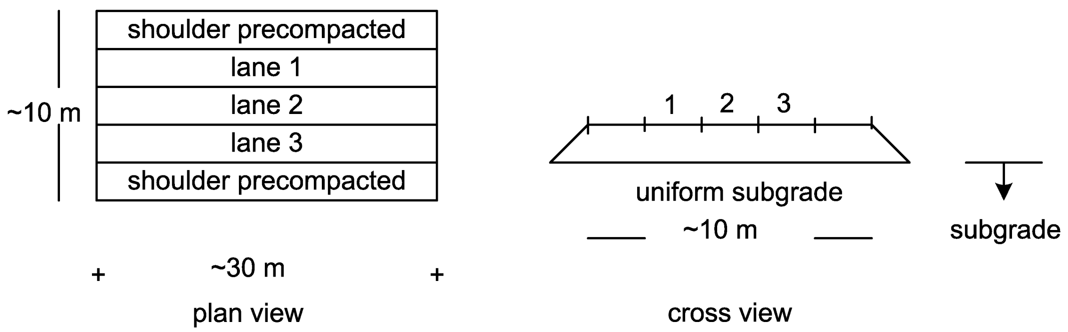


Figure 2 — Calibration test area

7.5 Development of correlations

7.5.1 General principles

Calibration provides the correlation between the CCC measuring value and the static or dynamic deformation modulus or the degree of compaction. This should provide the possibility:

1) to determine a required value for the CCC measuring value on the control area by using the required value for the degree of compaction or the deformation modulus demanded in the construction contract;

2) to be able to infer the deformation modulus or degree of compaction from the CCC measuring values obtained with the test roller.

This double objective shall be especially accounted for when using the regression analysis.

7.5.2 Quality and validity of correlation

The correlation of the CCC measuring values against the deformation modulus or the degree of compaction shall be determined as a linear regression in the form of

$$y = \mathrm{a} + \mathrm{b} \cdot \mathrm{x} \qquad (2)$$

The regression analysis should result in a coefficient of determination $r \geq 0{,}70$. If $r \geq 0{,}7$ cannot be achieved, additional tests should be carried out. If $r \geq 0{,}7$ is still not achieved even after additional tests, then CCC is not permitted for that material.

NOTE For certain less-critical applications, like for instance landfills for landscaping, a lower correlation coefficient of $r \geq 0{,}65$ could be accepted.

Validity of the correlation is only ensured if the following essential parameters used for preparing the calibration area correspond with the ones of the control area:

— soil type;

— water content for mixed and fine particle soils;

— thickness of the installed layer to be tested (deviations not in excess of ± 15 % from a thickness of 0,5 m);

— bearing capacity (CCC value) of the soil under the layer;

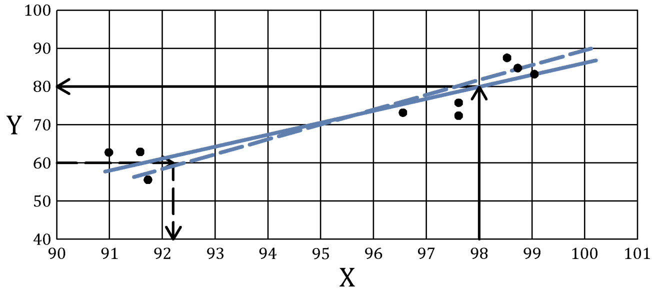
— measuring roller with machine dependent settings, like e.g. vibration frequency, amplitude and operation related settings like e.g. travel speed and travel direction;

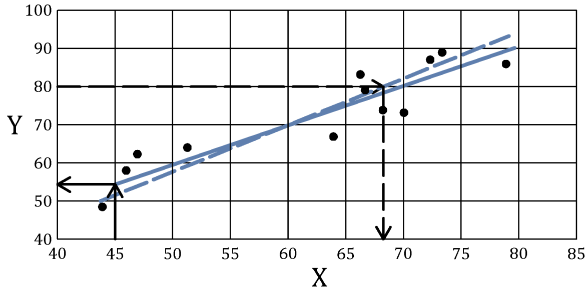
— the measuring system used to determine the CCC values;

— resting time after compaction.

7.5.3 Examples of correlations

The examples below show typical correlations between CCC measuring values and degree of compaction and between CCC measuring values and deformation modulus E_{V2} for gravelly sand. The equations for the regression lines have been obtained using the least squares (LS) method.





Key

——— direction of conclusion x to y

– – – – direction of conclusion y to x

Figure 3a) Correlation between CCC measured values and degree of compaction

Case 1 y = 3,1036 x + 224,08; r = 0,93

Density requirement: 98 % Proctor

CCC acceptance value T_M = 80

Figure 3b) Correlation between CCC measured values and E_{V2}

Case 2 y = 1,0049 x + 10,448; r = 0,88

Bearing capacity requirement: EV2 = 45 MN/m^2

CCC acceptance value T_M = 55

T_M is the 10 % minimum quantile CCC acceptance value which is determined by the calibration.

8 CCC weak area analysis and documentation for QC and QA purpose

8.1 General

Weak area analysis is a CCC method used to find areas with the lowest CCC measurement on a control area. It is assumed that these areas are those with the lowest stiffness or density. On these areas acceptance measurements of stiffness or density are performed. If the acceptance test meets the requirement, it can be assumed that the entire control area meets the requirement. No calibration of CCC is required for this method. The number of acceptance tests can be reduced. In case of stiffness requirements the weak area analysis is suitable for both heterogeneous soil and varying water content conditions. When the acceptance requirement is density, conditions have to be consistent.

8.2 CCC quality control and acceptance testing for weak area analysis

The following requirements need to be defined for this method:

— Maximum area or length of the inspection area (typically 5000 m^2 or 250 m).

— Number of weak areas where acceptance measurement shall be performed on the inspection area (typically 2-5).

— The minimum size of the weak area where acceptance measurements shall be performed shall not be too small to avoid performing acceptance measurements on a weak area that could relate to measurements errors from the CCC equipment. The definition of the size of a weak area is that the measured values are low for an area of at least 10 m^2.

— Acceptance measurements to be performed on the weak area.

— Acceptance requirement for the weak area acceptance measurements.

The weak area on a inspection area shall be identified from the measurement from the last pass with the roller.

NOTE This method can also be used to evaluate the homogeneity of stiffness and to find areas with too high compaction.

9 CCC – documentation of maximum compaction achievable for QC and QA purpose

9.1 General

This application of CCC serves the purposes of proving the maximum possible compaction that can be achieved with the roller used for a given type of soil, water content and layer thickness. The capacity of compaction equipment can thereby be tested and optimized. A calibration of the measuring roller is not required.

When using this procedure CCC measuring values are recorded during all passes to check the compaction increase. The range of measuring values and the average of these measuring values taken during the individual passes are compared with each other. If a considerable increase in the CCC measuring values can still be noticed, further compaction of the area is possible and required. With almost unchanged values it can be assumed that the available compaction equipment will not be able to achieve an increase in compaction.

This procedure is particularly beneficial on jobsites where the materials cannot be tested with direct test methods or only at considerable expense, such as rock fill, heterogeneously distributed layers, or soils with cobbles and boulders. A decision rule shall be determined from the comparison of CCC measuring values from successive passes, on condition that the suitability of the compaction equipment has previously been proven. This procedure shall be agreed in the construction contract.

9.2 CCC quality control and acceptance testing for documentation of maximum compaction for QA purpose

The following requirements shall be defined for this method:

— maximum layer thickness;

— minimum roller requirement (see Clauses 4 and 5);

— maximum relative increase of the CCC measurement values between two consecutive passes, in the same rolling direction (typically 5 % CCC measurement value increase);

— minimum area of the control area that has to comply with maximum relative increase requirement (typically 90 % of the control area).

10 CCC - documentation of compaction method

10.1 General

Compaction method specifications specify the procedure for the compaction of the fill or layer to be compacted such as type and mass (static linear load) of equipment, the equipment parameters such as vibration amplitude and frequency and operating speed, the thickness of the layer and the number of passes as a function of the type of material, the water content and the required quality of compaction.

Rollers with documentation system and automatic positioning system, such as Global Navigation Satellite Systems (GNSS), can be used for method documentation. The positioning accuracy shall be in accordance with 5.3.2.

10.2 CCC quality control and acceptance testing for method specification

Record and document number of passes performed according to method specification.

The documentation system shall display and record:

— position;

— number of passes on each spot of the inspection area;

— vibration amplitude setting and frequency;

— operating speed.

It is recommended to register also the measuring value in order to have CCC information as basis for the evaluation of the following layers.

11 CCC test report

The CCC test report shall include all essential data required to find out if all requirements are fulfilled or not as well as identification of the control area and the used equipment.

A test report shall be generated for each control area, which should include the following:

1) project, construction site;

2) client and contractor;

3) layer, level (relative height) and thickness;

4) position of test tracks and rolling direction in the control area;

5) type of material and water content in the layer;

6) date and time of execution of the control area;

7) weather conditions;

8) CCC results in graphical representation (printouts, line recordings, area plots), including statistics and distributions and/or calibrations when required;

9) machine or operation parameters (roller type, amplitude and frequency or power stage, speed, roller designation – e.g. serial number);

10) peculiarities of a measuring pass (jump operation, inconsistent speed, frequency deviations, flatness faults, water puddles, etc.);

11) determine whether requirements have been fulfilled or not.

Annex A
(informative)

Analysis of the vibration behaviour

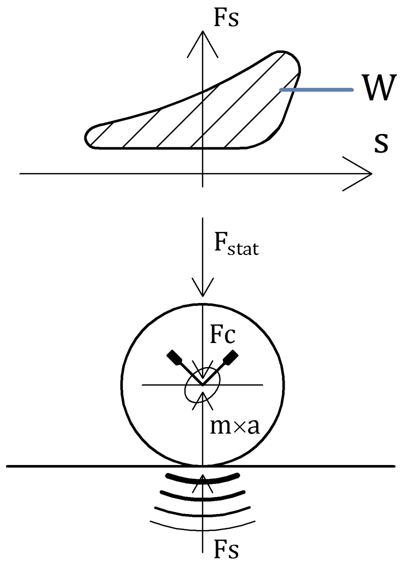
A.1 Principle of compaction energy

NOTE The work (energy) W rendered by the roller per period T is referred to as compaction power. The energy W is determined by the contact force between roller drum and soil and the movement of the roller and results from the integral of the force FB over the displacement s (Figure A.1):

$$W = \int FB \cdot d\,s \qquad \text{(A.1)}$$

In other words, the work W equals to the hatched area in the s-F_S diagram (Figure A.1). The values for F_S and s can be theoretically determined from the drum acceleration time-histories.

The effective compaction power transfer from the roller into the soil increases as the stiffness of the soil increases, because more energy per unit of time is transmitted to the soil elastically and by surface waves. The energy required for compaction decreases accordingly.



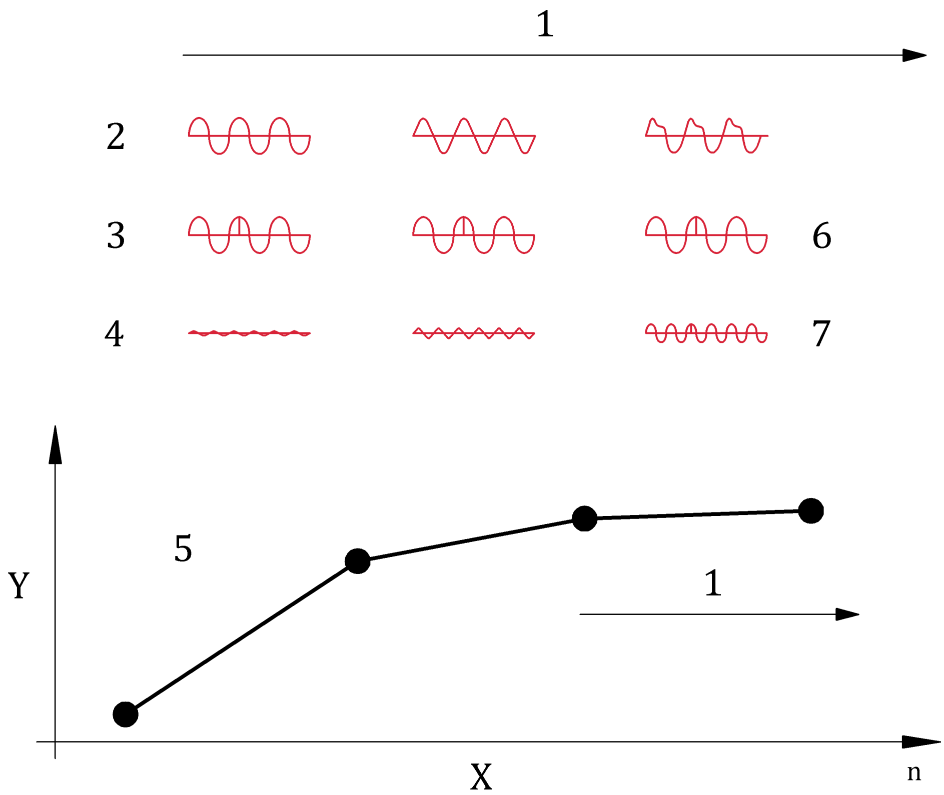
Key

Fs	soil reaction force
m	vibration drum mass
a	acceleration
Fc	centrifugal force
F_{stat}	static linear load
s	drum path displacement
w	work (energy)

Figure A.1 — Schematic representation of compaction energy

A.2 Principle of harmonic wave

NOTE In a non-compacted, loose soil the motion sequence of a vibrating roller drum is almost not affected by the soil stiffness and follows a sine wave (Figure A.2). With increasing stiffness the increasing resistance effect of forces between the roller and the soil and the nonlinearity of the soil properties change the harmonic movement. This causes the appearance of harmonic components.



Key

1 increasing compaction
2 measuring signal (acceleration transducer on the drum)
3 proportional fundamental wave
4 proportional 1st harmonic wave
5 uncompacted
6 A_0 ~constant;f_0 = operation frequency of the roller
7 $A_{1,n} < A_{1,n+1}$ $f_1 = 2 \times f_0$
X Number of passes
Y Compaction measuring value – Compaction or soil stiffness

Figure A.2 — Measuring principle for harmonic waves

NOTE The ratio of amplitude between the first harmonic component and the fundamental component can be used as a measure of the stiffness of the compacted layer.

A.3 Measuring the dynamic stiffness

NOTE The measuring system evaluates the vertical acceleration of the vibrating drum numerically and produces a force-displacement diagram for each revolution of the exciter. Increasing soil stiffness leads to a steeper force-displacement curve (Figure A.3). One characteristic for the evaluation of the dynamic stiffness of the soil is the ratio.

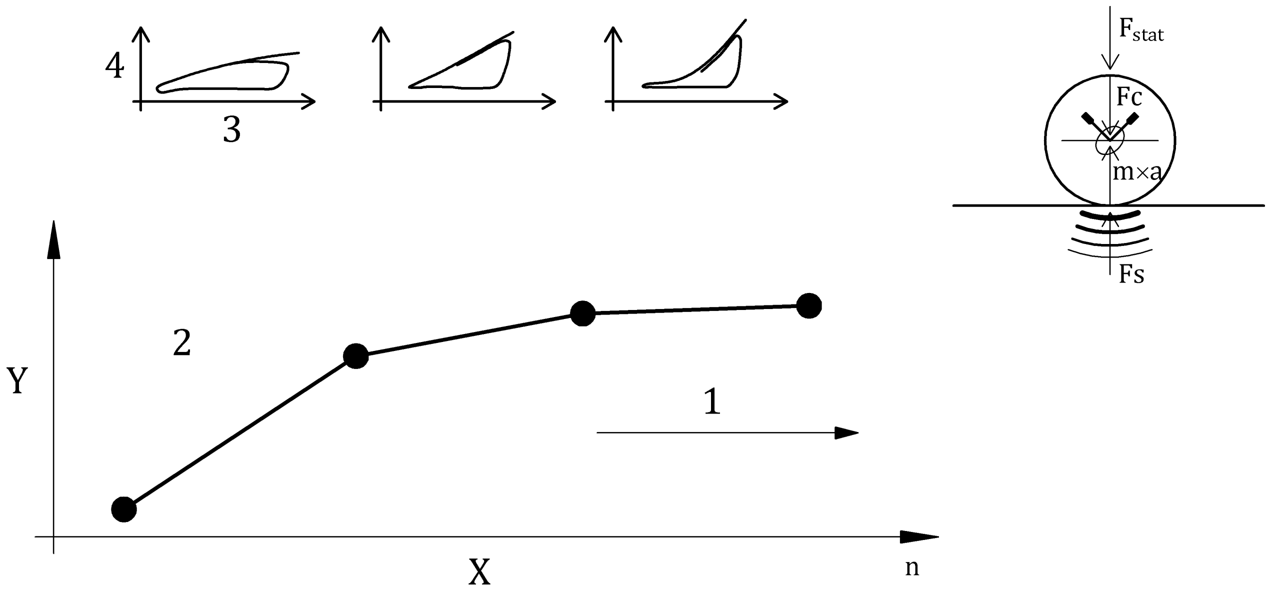
$$\Delta F_S / \Delta s \text{ in MN/m} \qquad (A.2)$$

where

F_S is the soil reaction force;

s is the drum path displacement.

By including the contact length between drum and soil, the dynamic stiffness modulus of the soil can be obtained in (MN/m²).



Key

1 increasing compaction
2 uncompacted
3 vibration dispacement
4 soil reaction force
X number of passes
Y compaction measuring value – Compaction of soil stiffness
Fs soil reaction force
m vibration drum mass
a acceleration
Fc centrifugal force
F_{stat} static linear load

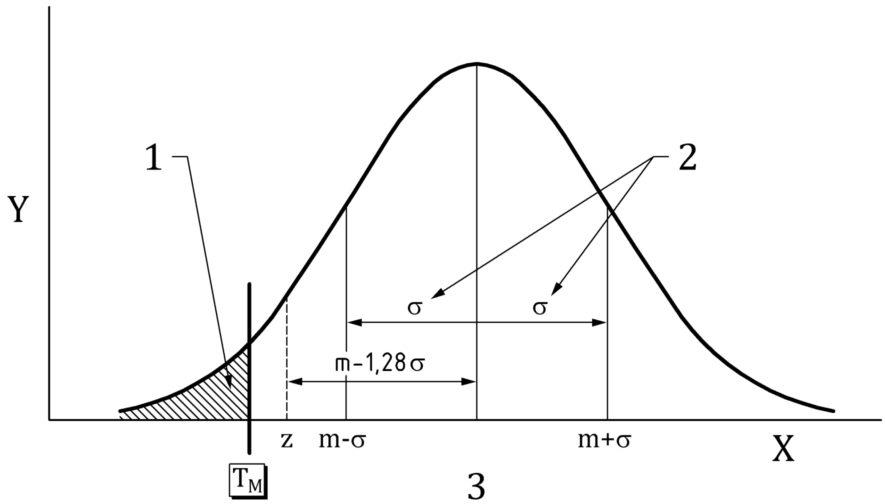
Figure A.3 — Measuring principle for dynamic stiffness

Annex B
(informative)

Statistical evaluation of CCC values based on decision rules for CCC application with calibration

B.1 Decision rules – Analysis of the unweighted fall-below areas if normally distributed measuring values exist

Within this scope CCC with calibration is used on each unit of the control area to determine a CCC measuring value and to assess the population. A Gaussian distribution is considered for the distribution of CCC measuring values, as shown in the examples in Figure B.1 and Figure B.2. The area below the curve corresponds with 100 % of the measuring values from the control area.



Key

1 fall-below ratio *P* = p (m,σ) < 10 %

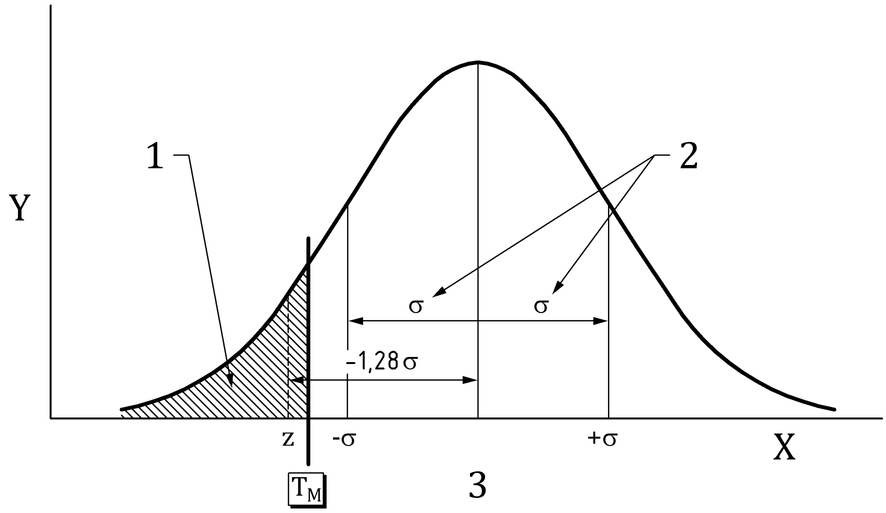
2 standard deviation σ

3 mean value m of CCC measuring values

X test characteristic (CCC measuring value)

Y probability density

Figure B.1 — Distribution of CCC measuring values of the population and fall-below ratio (fall-below area ratio): Control area is accepted, because m - 1,28 σ ≥ T_M



Key

1 fall-below ratio *P* = p (m,σ) > 10 %

2 standard deviation σ

3 mean value m of CCC measuring values

X test characteristic (CCC measuring value)

Y probability density

Figure B.2 — Distribution of CCC measuring values of the population and fall-below ratio (fall-below area ratio): Control area is rejected, because m - 1,28 σ < T_M

For the evaluation of measuring results the average and the root-mean-square (standard) deviation of all CCC measuring values have to be calculated. Since this test is a 100 % test, the average is designated with “m” and the root-mean-square (standard) deviation with “σ”.

The fall-below ratio (fall-below area ratio) shall not exceed 10 %. The fall-below ratio equals the partial areas below the quality parameter z (Figures B.1. and B.2, hatched area), which marks the 10 % fall-below ratio of the population and which is positioned at

$$z = m - 1{,}28\ \sigma \qquad \text{(B.1)}$$

where

m mean measuring value of all CCC measuring values of the control area;

σ standard deviation of all CCC measuring values of the control area.

According to this decision rule the calculated control parameter z = m − 1,28 σ shall be higher or equal the minimum quantile T_M for the CCC acceptance value determined by calibration. The decision rule for CCC quality control and acceptance testing with calibration is therefore:

Acceptance of control area, if

$$m - 1{,}28\ \sigma \geq T_M, \qquad \text{(B.2)}$$

(See Figure B.1) otherwise rejection (see Figure B.2).

The spots in which the demanded quantile value T_M is fallen short of (= fall-below spots), shall be uniformly distributed in the control area. This shall be visually assessed against an area printout. If the fall-below spots apparently are concentrated at certain locations of the control area, the corresponding areas shall be assessed separately. The partial area with apparently uniformly distributed fall-below spots shall be subjected to the decision rule. In partial areas with concentrations of fall-below spots the reasons for this shall be clarified, appropriate remedial action shall be taken and the partial area shall be tested again.

The statistic decision rule (B.2) is easy to use, enables the assessment of an area by means of one quality parameter and thus leads to a clear decision of whether to accept or reject a control area. One thereby profits from the fact that the compaction status at any point of the control area is accounted for as measuring value (100 % test); however, the fact that the location at which the measuring value was taken, is not utilized. The general advantage of the CCC method, namely the knowledge of the compaction status at any point of the control area is thereby almost not utilized at all.

In case of stronger deviation of the actual distribution of measuring values from the Gaussian distribution on which the decision rule is based, and without an assessment of the uniform areal distribution of fall-below spots in the control area, false decisions cannot be ruled out. In this case acceptance criteria shall favourably be used, which are independent from the distribution.

B.2 Evaluation of the unweighted fall-below areas in case of arbitrary distribution of the measuring values or the total fall-below area ratio

In case of the decision rule **"unweighted fall-below area ratio"** an upper limit for the total fall-below area ratio has been established. The number of measuring values falling short of the CCC acceptance value determined by calibration, divided by the total number of CCC measuring values taken in a control area, results in the percentage ratio, the fall-below area or fall-below ratio. The decision rule is:

Acceptance of the control area, if

$$p_{Ges} = \frac{N_{lim}}{N} = z \geq 10\ \% \qquad \text{(B.3)}$$

otherwise rejection

where

- p_{Ges} total fall-below area ratio;
- z quality parameter;
- N number of all CCC measuring values in a control area;
- N_{limit} number of measuring values in a control area, which are smaller than a predetermined limit (= minimum quantile T_M).

Concerning the two-dimensional distribution of the fall-below spots the same requirements apply as for the decision rule in B.1.

The fact that the compaction status at any point of the control area is accounted for as measuring value (100 % test) also applies for this decision rule; however, the fact that the location at which the measuring value was taken, is not utilized. Only the total fall-below area ratio is assessed and not the absolute magnitude of the fall-below ratio (exceedance) of the minimum quantile T_M.

B.3 Evaluation of the weighted fall-below areas in case of arbitrary distribution of the measuring values or the total fall-below area ratio

The decision rule **"weighted fall-below areas"** accounts for both the fall-below area ratio on the control area, as well as the extent of falling short of the minimum quantile TM at the fall-below points. The objective of this construction oriented criterion is the intention to accept an area falling only slightly below the minimum value, rather than an area with high fall-below values.

In order to achieve this goal, the quality of the control area is described by the average Z of the fall-below ratio, weighted by the area ratios.

The quality parameter Z can be represented with following variables:

i	is the number of the measuring point on the control area or number of the associated CCC-value;
N	is the number of CCC measuring values in the control area to be assessed;
F_i	is the CCC measuring value at point I;
A_i	is the area associated with the CCC measuring value;
A_{tot}	is the total area of the control area;
$Bi = A_i / A_{tot}$	is the relative fall-below area ratio associated with the CCC measuring value F_i in the control area;
T_M	is the minimum quantile.

$$U_i = \left\{ \begin{matrix} 0 & \text{for } F_i \geq T_M \\ \left(1 - \frac{F_i}{T_M}\right) & \text{for } F_i < T_M \end{matrix} \right\} = \text{fall-below ratio of the CCC measuring value below } T_M \quad \text{(B.4)}$$

With the parameter U_i the fall-below ratio Z weighted with the area ratios B_i is calculated as follows:

$$Z = \sum_{i=1}^{N} U_i \cdot B_i \quad \text{(B.5)}$$

Taking a constant length per CCC measuring value as a basis has the following result:

$$U = \sum_{i=1}^{N} U_i \quad \text{(B.6)}$$

$$B = \sum_{i=1}^{N} B_i \quad \text{(B.7)}$$

$$Z = \frac{1}{n} U \cdot B \quad \text{(B.8)}$$

where

n is the number of fall-below spots

The quality parameter Z is non-dimensional. Its value range is $0 \leq Z \leq 1$ or $0\ \% \leq Z \leq 100\ \%$.

The higher the value of Z, the poorer the compaction status in the control area, i.e. the higher the fall-below area ratio or the fall-below ratios U_i of the CCC measuring values below T_M.

If e.g. a value Z = 3 % is calculated, this descriptively means that the CCC measuring values achieved on the control area fall by 3 % below the minimum quantile TM by 3 %, on average weighted by the area ratios.

For a Z-based **decision rule** one shall also specify the associated “critical limit” q (= decision limit). The decision rule formulated with Z and q then reads:

Acceptance of the control area, if $Z \leq q$

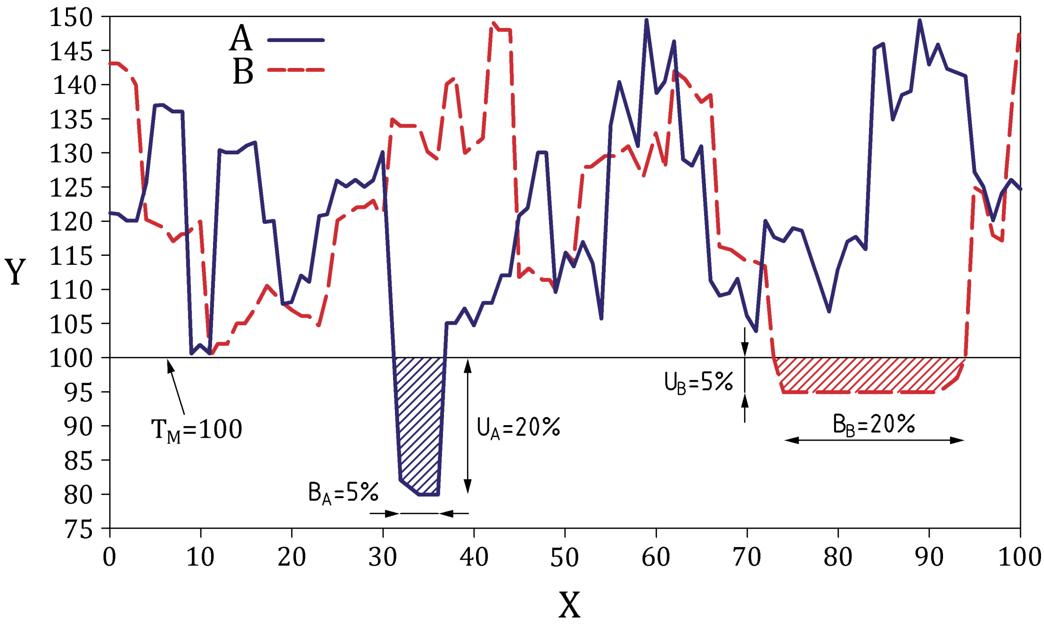
Rejection of the control area, if $Z > q$.

Examples for different fall-below area ratios and mean (weighted with the area ratios) fall-below ratios, which, as a control parameter Z, result in the value 0,01, are summarized in Table B.1.

Table B.1 — Case studies for identical test statistics for different fall-below area ratio B and fall-below ratio U

Case No.	Fall-below area ratio B	Mean fall-below ratio U	Quality parameter Z
a	5 %	20 %	0,01
b	10 %	10 %	0,01
c	20 %	5 %	0,01
d	50 %	2 %	0,01
e	100 %	1 %	0,01

In order to visualize how the same quality parameter, for example Z = 0,01 (z=1/n*B*U), can result in two different cases, Figure B.3 shows the values of lines a and c by means of the courses of measuring values A and B taken on two tracks.



Key

X track length

Y CCC – measuring value

Figure B.3 — Relative fall-below area ratio B and fall-below ratio U based on the two courses of measuring values (A and B)

Due to the descriptive meaning of Z the critical limit q can simply be established under construction related aspects. If e.g. a control area with a fall-below area ratio of 15 % is only to be accepted when the CCC measuring values fall below the minimum quantile T_M by maximum 5 %, the critical limit shall be set to q = 0,15 · 0,05 = 0,0075.

Table B.2 shows various guide values for the decision limit q at different quality levels and work horizons (e.g. embankment contact area, formation, subbase layer etc.).

Table B.2 — Guide values for the decision limit q

Application	Decision limit q
embankment contact area	0,015
formation	0,010
subbase layer	0,005

Figure B.4 shows two extreme cases in order to demonstrate the possibilities of the decision rule.

At a decision limit of q = 0,01 a control area is accepted in case A (Figure B.3), even though approx. 90 % of all measuring values fall on average approximately 5 % below the CCC requirement (Z = 0,0045). This fall-below ratio, however, is only minor and hardly of any relevance for the construction. Accepting this control area makes sense. All other decision rules in this code of practice would clearly reject such a control area.

In case B (Figure B.3) it is true that only 10 % of the areas fall below the requirement (fall-below area ratio B = 10 %), but the CCC measuring values taken at the fall-below spots fall below the demanded quantile value T_M on average by 30 %. This means Z = U * B = 0,03. With the decision rule “weighted fall-below area” the control area in case B with Z = 0,03 > q = 0,01 is rejected, under due consideration of the fall-below ratio. The other decision rules would mostly accept such areas, even though it would not be sensible under construction related aspects.

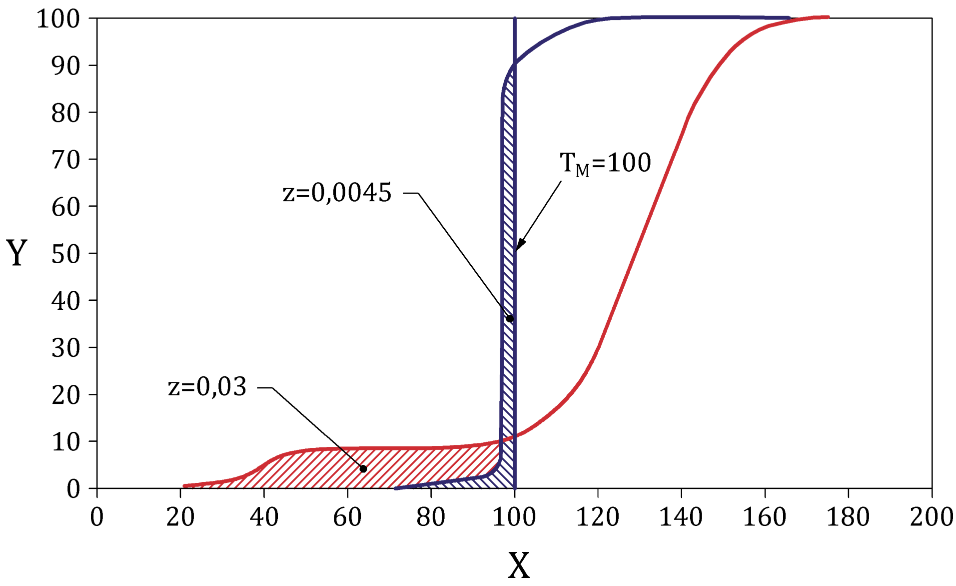


Figure B.4 — Two examples for the distribution of CCC measuring values to illustrate the decision rule “weighted fall-below areas” (see also Figure B.3)

The advantage of the decision rule “weighted fall-below areas” compared to the decision rule (B.1) is that the quality of conformity with the Gaussian distribution has no influence on the evaluation of control areas, because no assumption for a distribution of the population shall be made.

The decision of whether to accept or reject the control area is made on the basis of <u>one</u> control parameter. When only falling slightly below the CCC requirement, bigger fall-below areas are in this case tolerated than with bigger fall-below ratios. The lower the CCC measuring values in a fall-below area, the smaller the fall-below area shall be, if the control area is to be accepted.

Concerning the two-dimensional distribution of the CCC measuring values (fall-below areas) the same requirements apply as for the decision rule acc. to B.1. This means that the fall-below areas shall be almost evenly distributed over the control area.

This decision rule is most suitable as a construction oriented criterion when using CCC with calibration for indirect continuous density and stiffness control.

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