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Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation —

Part 3: **Measurement of displacements across a line: Inclinometers**

Reconnaissance et essais géotechniques — Surveillance géotechnique par instrumentation in situ —

Partie 3: Mesurages des déplacements perpendiculairement à une ligne par inclinomètre

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Foreword

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

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

This document was prepared by Technical Committee ISO/TC 182, *Geotechnics.*

A list of all parts in the ISO 18674 series can be found on the ISO website.

Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation —

Part 3: Measurement of displacements across a line: Inclinometers

1 Scope

This document specifies the measurement of displacements across a line by means of inclinometers carried out for geotechnical monitoring. General rules of performance monitoring of the ground, of structures interacting with the ground, of geotechnical fills and of geotechnical works are presented in ISO 18674-1.

This document also refers to deflectometers (see Annex B) to supplement inclinometers for the determination of horizontal displacements across horizontal measuring lines.

NOTE In general, there are two independent displacement components acting across measuring lines. Inclinometers allow the determination of the two components for vertical measuring lines. For horizontal lines, inclinometers are limited to the determination of the vertical component only.

If applied in conjunction with ISO 18674-2, this document allows the determination of displacements acting in any direction.

This document is applicable to:

— checking geotechnical designs in connection with the Observational Design procedure;

— monitoring of geotechnical structures prior to, during and after construction (e.g. natural slopes, slope cuts, embankments, excavation walls, foundations, dams, refuse dumps, tunnels);

— deriving geotechnical key parameters (e.g. from results of pile load tests or trial tunnelling);

— identification and monitoring of active shear planes in the ground.

NOTE This document fulfils the requirements for the performance monitoring of the ground, of structures interacting with the ground and of geotechnical works by the means of inclinometers as part of the geotechnical investigation and testing in accordance with References [1] and [2].

2 Normative references

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

ISO 18674-1:2015, *Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation — Part 1: General rules*

ISO 18674-2:2016, *Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation — Part 2: Measurement of displacements along a line: Extensometers*

ISO 22475-1:2006, *Geotechnical investigation and testing — Sampling methods and groundwater measurements — Part 1: Technical principles for execution*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 18674-1 and ISO 18674-2 and the following apply.

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

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

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

3.1
inclinometer
system for monitoring displacements across a measuring line by means of inclination measurements in the field

Note 1 to entry: The system essentially consists of an instrument with one or more *tilt sensors* (3.2), a guide tube, a means to measure the position of the instrument in the guide tube and a read-out device.

Note 2 to entry: Data from inclinometers require evaluation, which can be done using proprietary software or spreadsheets.

3.2
tilt sensor
gravity-activated electric sensor for inclination measurements

3.3
probe inclinometer
system comprising a probe with one or more built-in *tilt sensors* (3.2) for step-by-step measurements of the inclination on a measuring line

Note 1 to entry: Also known as a traversing inclinometer.

Note 2 to entry: Vertical probe inclinometers measure displacements in horizontal directions.

Note 3 to entry: Horizontal probe inclinometers measure displacements in vertical directions (settlements or heave).

Note 4 to entry: An alternative to horizontal probe inclinometers is a hydrostatic probe system.

Note 5 to entry: See also Reference [3].

3.4
in-place inclinometer
IPI
inclinometer system comprising a single element, or a series of elements, with one or more built-in *tilt sensors* (3.2) in each element, for measurement of the inclination at specific locations on a measuring line without removing the instrument

Note 1 to entry: In-place inclinometers exist which can measure at all inclinations, but when in near-horizontal position, deflections from the azimuth cannot be measured.

3.5
uniaxial inclinometer
system for inclination measurements in a single plane

Note 1 to entry: Common for horizontal measuring lines.

3.6
biaxial inclinometer
system for inclination measurements in two planes 90° to each other

Note 1 to entry: Common for vertical measuring lines.

3.7
inclinometer casing
guide tube appropriate to the inclinometer system being used

Note 1 to entry: Commonly, the inner side of inclinometer casings have four longitudinal keyways. Commercially available casings differ with regard to material, dimension, type of coupling, number of keyways etc. (see 5.4).

Note 2 to entry: The corners of casings with square section can be considered as keyways.

3.8
gauge length
L
distance between adjacent contact points of the instrument

Note 1 to entry: For *probe inclinometers* (3.3), L is commonly 0,5 m or 1,0 m.

3.9
base length
distance between adjacent measuring points used in the evaluation procedure

Note 1 to entry: For *probe inclinometers* (3.3), the base length is equal to the *gauge length* (3.8).

4 Symbols

Symbol	Name	Unit
A	measuring plane of the probe which coincides with the plane of the guide wheels	—
a	lateral displacement component in Plane A	m
B	measuring plane of the inclinometer probe normal to Plane A	—
b	lateral displacement component in Plane B	m
d	depth, distance	m
F	subscript for follow-up measurement	—
h	height with respect to sea level	m
i	number of a measuring point	—
L	gauge length of an inclinometer or deflectometer probe	m
l	distance between measuring points	m
n	total number of measuring points along a measuring line	—
R	subscript for reference measurement	—
t	elapsed time	s
t_F	date and time of a follow-up measurement	—
t_R	date and time of a reference measurement	—
u, v, w	displacement component in x-, y- and z-direction, respectively	m
x, y, z	local coordinates of a guiding tube or borehole	m
α	tilt angle of the probe axis in Plane A	° (degree)
β	tilt angle of the probe axis in Plane B	° (degree)
ψ	angle between guide tube coordinate x and plane A of the inclinometer	° (degree)
θ, ρ	auxiliary quantities	° (degree)

5 Instruments

5.1 General

5.1.1 Probe and in-place inclinometers should be distinguished from each other (see Table 1 and Figures 1, 2 and A.1).

Table 1 — Inclinometer types

No.	Type	Sub-type	Principal measuring procedure	Automatic data acquisition
1	Probe (see 5.2)	Inclinometer — Vertical inclinometer — Horizontal inclinometer	Probe moved inside a guide tube from one measuring point to the next (see Figures 1 and A.1). Repeated measurements within the measuring period.	Not common
2	In-place (see 5.3)	In-place inclinometer (IPI) — Vertical inclinometer — Horizontal inclinometer — Combined	Instrument inserted into a guide tube and held in measuring position throughout the measuring period	Common

NOTE A combined IPI is a series of elements in which some elements act as vertical and some act as horizontal inclinometers.

5.1.2 Changes of tilt shall be measured by comparison of the measured values with those of the reference measurement. Displacements of the measuring points across the measuring line shall be deduced in accordance with Annex A.

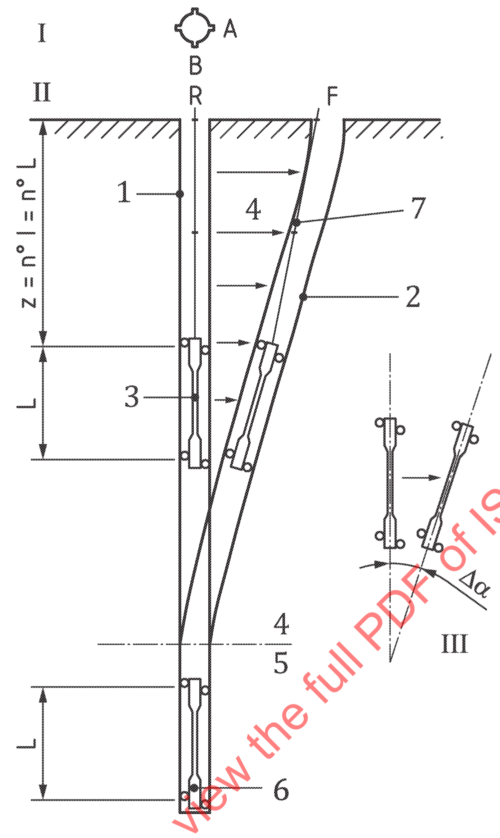
5.1.3 The point to which the measurements are related shall be denoted the “reference point”.

5.1.4 For absolute displacement measurements, the coordinates of the reference point shall be independently determined or assumed as fixed and verified.

NOTE If the reference point is assumed to be at the deepest measuring point, surveying of the inclinometer head can serve as a check.

5.1.5 The sensing element shall consist of a housing with either one (uniaxial configuration) or two (biaxial configuration) built-in tilt sensors. In the case of a biaxial configuration, the tilt sensors shall be installed with axes perpendicular (90°) to each other.

5.1.6 The installation planes of the tilt sensors shall be denoted as the instrument Planes A and B, whereby Plane A shall coincide with the plane of the guide wheel assemblies (see 5.2.5). The planes shall be durably marked onto the inclinometer housing, e.g. by the mark "A+" showing the positive A direction.



Key

1	undeformed inclinometer casing	I	top view of inclinometer casing
2	deformed inclinometer casing	II	side view
3	inclination measuring element	III	detail of inclinometer element in R- and F- positions
4	area of the ground subject to displacements	A	A+ direction
5	undeformed deeper ground for base fixity	B	B+ direction
6	reference point (here, the axis of the bottom wheel is set at the lowest measuring position)	L	gauge length
7	depth measuring device	R	initial position of inclinometer casing at the reference measurement
Δα	change of inclination	F	position of inclinometer casing at a value change measurement

Figure 1 — Measuring concept for inclinometers (schematic)

5.2 Probe inclinometers

5.2.1 Inclinometer probes shall be moved incrementally along the measuring line, whereby each increment shall not exceed the gauge length *L* of the probe.

5.2.2 The depth measuring device shall have permanent and wear-resistant depth measuring marks. The spacing of the marks should be equal to the gauge length *L* of the probe.

5.2.3 The length of the depth measuring device and the spacing between the marks shall be checked throughout the measuring project. Changes shall be recorded.

NOTE 1 Monitoring displacements by probe inclinometers requires good repeatability of the probe's positioning at the respective measuring points (see 6.5.2.3 and 7.4).

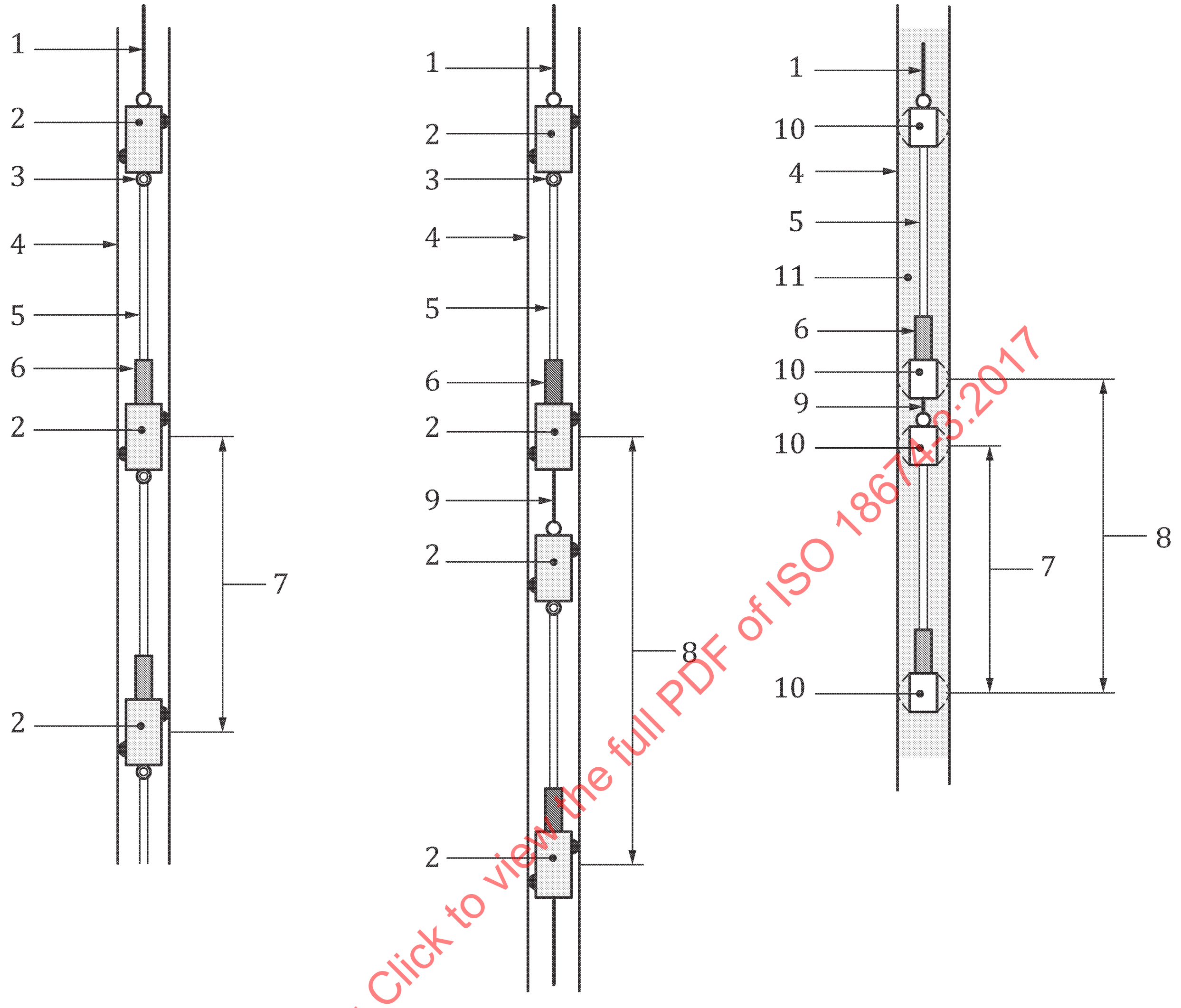
NOTE 2 The use of a cable gate or a suspension pulley can help to ensure good positioning.

5.2.4 Inclinometer casing shall be used as guide tubes (see 5.4).

5.2.5 The inclinometer probe shall be equipped with two spring-loaded guide wheel assemblies. The width of the guide wheels shall fit the keyways of the inclinometer casings. The force of the springs should ensure a central positioning of the probe in the casing, even for extended monitoring periods with repeated measuring runs.

5.3 In-place inclinometers

5.3.1 The principal setup of in-place inclinometers should be as in Figure 2.



a) IPI with wheel assembly and continuous string of sensors

b) IPI with wheel assembly and discontinuous string of sensors

c) IPI without wheel assembly and discontinuous string of sensors

Key

1	top suspension	7	gauge length, L
2	wheel assembly	8	base length
3	universal joint	9	intermediate suspension
4	guide tube	10	expanding joint or skid
5	connecting element	11	embedment material
6	sensor		

Figure 2 — Principal setup and components of in-place inclinometers (IPIs)

5.3.2 It shall be ensured that the lengths of the connecting elements remain constant throughout the measuring project (no elongation, no shrinkage).

5.3.3 For a continuous string of measuring elements [see Figure 2 a)], the flexibility of the measuring elements shall be negligible.

NOTE This requirement applies in particular to horizontal strings (see Reference [4]).

5.3.4 For a discontinuous string of measuring elements [see Figure 2 b) and c)], engineering judgement shall be used to integrate angular changes into displacements.

5.3.5 Gauge lengths should not exceed 2 m. Within an installation, they can be varied to adjust to local conditions.

NOTE Shorter lengths will commonly lead to better results.

5.3.6 The long-term reliability of the sensor signals should be considered. Intermittent removal of the instrument for re-calibration should be avoided and is only permissible if especially justified and documented.

NOTE An approach to checking the long-term reliability is to make measurements in two adjacent guide tubes; one for the IPI and one for a probe inclinometer ("diversification"; in accordance with ISO 18674-1:2015, 5.4).

5.4 Inclinometer casing

5.4.1 The section of the casing shall be selected against the background of the specific measurement requirements and the expected ground movements across the measuring line (see also 6.3.1.1).

5.4.2 The material of the casing shall fulfil the following requirements:

— be neutral to groundwater and other soil components;

— be durable during complete measuring period;

— be robust for installation;

— be flexible for bending.

NOTE 1 Acrylonitrile butadiene styrene (ABS) is a common inclinometer casing material.

NOTE 2 Metal casings, especially aluminium casings, can corrode, for example, by short-circuiting between ground layers with different electric potentials or by aggressive groundwater.

5.4.3 If the inclinometer casing has internal keyways, the spiralling of the keyways shall be less than 0,25°/m. The string of casings should be assembled so that the keyways are continued over the joints.

5.4.4 When selecting the casing, the flexibility of the assembled string, including the backfill material (see 6.3.2.5 and Annex C), should be considered with respect to the site conditions.

5.4.5 If using telescopic couplings, the design of the couplings, their telescopic travel and the method of fixing should be such as to allow the string of casings to readily compress or extend in the direction of the measuring line by an amount equal to the ground compression or extension.

NOTE 1 Telescopic couplings can have major detrimental effects on the accuracy of measurements and on the tracking and depth positioning control of the probe.

NOTE 2 The addition of external corrugated sleeving to flush-coupled casing can eliminate damage caused by ground settlement. However, there is no need to extend the sleeving into the undeformed deeper ground (see Figure 1).

5.4.6 Prior to installation, the casings should be stored in a safe and secure place, laid horizontally and supported to avoid deformations due to self weight. They should also be protected from direct sunlight.

5.5 Measuring range, accuracy and repeatability

5.5.1 Table 2 provides some order of magnitude information regarding accuracy and repeatability of inclinometers. Inclinometer measurements shall be in accordance with Table 2.

Table 2 — Requirements of inclinometer measurements

Type	Line	Issue	Inclinometer	
			Vertical	Horizontal
Probe	1	Accuracy of the instrument (probe or IPI element)	±0,02 % full scale (e.g. ±0,1 mm/m for ±30° range)	
	2	*Repeatability (precision) of a complete survey along a measuring line:* Difference between the cumulated displacements of a measuring point relative to a reference point 30 m apart, when repeatedly carrying out the survey under repeatability conditions (see 5.5.2)	±2 mm	±10 mm
In-place	3	*Repeatability (precision) of a string of IPI elements, measuring range ±10°, spaced at 2 m:* Difference between the cumulated displacements of a measuring point relative to a reference point 30 m apart, when repeatedly carrying out the survey under repeatability conditions (see 5.5.2)	±2 mm	±2 mm
Probe and in-place	4	*Stability of sensor signal:* Difference after a 24 h period under repeatability conditions	±0,1 mm/m	

5.5.2 The repeatability of a measuring value (see Lines No. 2 and 3 in Table 2) should be established within the reference measurement (see 6.5.2.5).

NOTE 1 Repeatability conditions comprise, i.e.

— identical observer;

— identical measurement procedure;

— identical instruments;

— identical influencing quantities.

NOTE 2 The values are specified for measurements in the A-axis. The B-axis measurements are commonly less accurate. Achieving the specified values for the secondary axis (B-axis) requires dedicated measurements with the wheels in the corresponding keyways.

6 Installation and measuring procedure

6.1 General

Particular attention should be paid to the selection of suitable guide tubes and their installation as they are critical for the quality of the measurements.

6.2 Installation of guide tubes at accessible surfaces and in concrete

6.2.1 When installing guide tubes at the surface of above-ground engineered structures, attention should be paid to a durable fixation. An exposure of the tubes to environmental impacts such as direct sunlight should be avoided, e.g. by protective covers.

6.2.2 When installing guide tubes in reinforced concrete, the tubes can be either placed inside a void former that is pre-installed before the concreting or fixed directly to the reinforcement. If the guide tubes are placed prior to concreting, care should be taken to avoid damage by mechanical effects or by curing temperatures.

6.2.3 When using a void former, the annulus between the guide tube and the void former shall be completely filled with a suitable material. The backfill material shall be documented.

NOTE Void formers are commonly used for depths greater than 20 m or if the concrete structure is more than 1 m thick.

6.2.4 On sheet piles, the installation of the guide tube can be done prior to piling with protection or, after piling, inside a void former. A pre-installed square steel tube can also be used as a guide tube.

6.3 Installation of guide tubes in boreholes

6.3.1 Drilling of boreholes

6.3.1.1 The diameter of the borehole shall be selected based on the intended measuring system and the ground conditions. An oversized annulus between the borehole and wall guide tube should be avoided.

NOTE 1 The bigger the borehole and the guide tube diameters, the lower the risk of an early blockage of the guide tube by ground displacements across the borehole axis.

NOTE 2 Small diameter boreholes and guide tubes, e.g. those with guide tube diameter of 48 mm, are generally considered inappropriate in soils and rocks; however, not necessarily in cases in which displacements are expected to be very small and distributed over broad zones, such as in concrete.

NOTE 3 The larger the annulus between guide tube and borehole wall, the more likely the risk that small lateral displacements are disguised in the inclinometer measurements. See Reference [5].

6.3.1.2 The borehole and its guide tube (see 6.3.2) should extend into that part of the ground or structure which is expected to remain stable throughout the monitoring project. The extension should be at least six times the gauge length, *L*, i.e. at least 3 m for a 0,5 m probe and 6 m for a 1,0 m probe.

NOTE 6.3.1.2 aims to establish a base fixity which assists in the evaluation of the inclinometer measuring data and serves to detect and quantify systematic errors (see 7.4).

6.3.1.3 The drilling procedure should be specified individually for each measuring location. Drilling shall be carried out and documented in accordance with ISO 22475-1. For vertical installations the inclination of the borehole should be kept within ±2° of vertical, at any point along the borehole.

NOTE Drilling with core recovery provides direct information on the ground conditions and enables a better interpretation of the measuring results.

6.3.1.4 Prior to the installation of the guide tube, the borehole shall be carefully cleaned, for example, by flushing with water or compressed air.

6.3.2 Installation of guide tubes

6.3.2.1 The inclinometer casing should be installed with one keyway in the reference direction. In vertical boreholes, the reference direction should be the direction of the anticipated principal movement. In horizontal and inclined boreholes, the reference direction should be the “top” of the borehole (in accordance with ISO 18674-1:2015, Figure B.1). The keyway which is in the reference direction shall be the reference keyway and shall be durably marked, for example, by cutting a notch at the top of the guide tube into that keyway or by identifying it by a water-resistant and wear-resistant mark.

6.3.2.2 Installation procedures shall minimize twisting of the string of inclinometer casing. No attempt shall be made to re-orientate the reference keyway after the guide tube has been assembled and installed.

NOTE The measurement of the deviation between the keyway and reference direction which might become apparent after the installation is commonly carried out geodetically or by means of a compass.

6.3.2.3 For guide tubes greater than 50 m in length, the twist of the keyways along the casing shall be checked by independent measurements.

NOTE 1 Measurement of casing twist is commonly carried out by means of spiral or compass probes.

NOTE 2 To enhance the quality of the measurements, it is good practice to carry out twist measurements for casing lengths greater than 20 m.

6.3.2.4 After inserting the guide tube, any drill casing shall be removed. Care shall be taken not to rotate the guide tube in the borehole when lifting the drill casing.

NOTE It can be necessary to remove the drill casing in stages while backfilling (see 6.3.2.5) below the drill casing.

6.3.2.5 The annulus between the guide tube and borehole wall shall be completely backfilled to ensure conformity between the movement of the ground and the measurement. The composition of the backfill material shall be documented and its properties considered in relation to the surrounding medium.

NOTE 1 One of the purposes of backfilling is to re-establish separations between different aquifers in accordance with ISO 22475-1:2006, 5.5.4.

NOTE 2 Common backfill materials are low-strength cement-based mortar and cement-bentonite suspensions. Granular backfill material can be used in specific circumstances (see Annex C).

NOTE 3 Possible quality control and preventative measures:

— comparing the geometric volume of the annulus and that of the backfilled material;

— in fractured ground and soils with a high permeability, insertion of a geotextile hose to retain the grout.

NOTE 4 When installing the backfill, it is good practice to use a tremie pipe and to grout under pressure from the bottom of the borehole up, in order to ensure complete backfilling of the annulus. For boreholes deeper than 35 m, it is good practice to use multiple tremie pipes at multiple heights along the tube.

6.3.2.6 In order to prevent snaking of the guide tube due to buoyancy forces, buoyancy of the guide tubes shall be compensated by filling the tubes with clean water, by ballasting the base and/or anchoring the base of the guide tube string. No attempt shall be made to push the top of the casing after insertion. It shall be ensured that no backfill material, dirt, soil or rock particles, etc. get inside the guide tube, for example, by the use of a top cap.

NOTE 1 Any snaking of the guide tubes seriously reduces the accuracy of the inclinometer measurements.

NOTE 2 Support of the guide tube base can be achieved by lowering a steel pipe inside the tube down to the bottom cap (reinforced to ensure that it does not become damaged while lowering the steel pipe), by use of a casing anchor and/or by initial backfilling of the bottom parts of the annulus between the guide tube and the borehole (i.e. backfilling in stages).

6.3.2.7 When selecting and installing the guide tube, it shall be ensured that the following are achieved:

a) Prevent collapse of the guide tube under the pressure of back fill suspensions.

NOTE 1 Possible preventative measures:

— provide internal support by filling the guide tube with water;

— use appropriate material or wall thickness for the guide tubes;

— sequential backfilling in lifts of limited height (e.g. <30 m).

b) Sufficient sealing of the couplings, including the end caps (top and bottom), in order to prevent any ingress of backfill material into the guide tube which can render the entire guide tube useless.

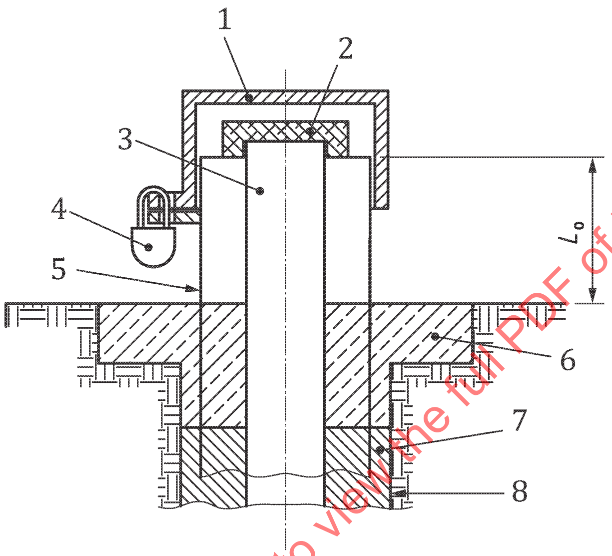
NOTE 2 Possible preventative measures:

— multiple and clean taping of the coupling joints and gluing of the coupling connections;

— selection of guide tubes with an integral O-ring seal between the casing segments.

6.3.3 Securing borehole measuring locations

The head of a guide tube shall be protected by a cap to prevent material falling into the tube. If vandalism is of concern, the cap should be lockable (see Figure 3).



Key

1 top cap, lockable
2 cap of inclinometer casing
3 inclinometer casing
4 lock
5 protective sleeve
6 concrete bed
7 backfill
8 borehole

Figure 3 — Example of a lockable inclinometer head

6.4 Installation of in-place inclinometers

6.4.1 Interference between the IPI connecting elements and the guide tube shall be avoided at installation and over the full range of expected displacements.

NOTE At the installation, the initial profile of the guide tube is determined by a probe inclinometer and used to choose appropriate connecting elements (e.g. length, diameters, measuring range).

6.4.2 When the in-place inclinometer elements have been installed into the guide tube, it shall be ensured that the string of elements is in tension or compression (depending on the model of instrument) in accordance with the manufacturer's instructions.

For near horizontal measuring lines, setting rods may be required for positioning the in-place inclinometer elements inside the guide tube.

For near vertical measuring lines where the uppermost in-place inclinometer element does not coincide with the top of the guide tube, a suspension cable will be required to correctly position the string of in-place inclinometer elements.

6.4.3 When the in-place inclinometer elements have been positioned in the guide tube, they shall be fixed in that position and the position shall be documented.

NOTE Fixation can be achieved by firmly attaching the cable or the setting rods to the collar of the guide tube.

6.5 Carrying out the measurement

6.5.1 Instrumentation check and calibration

6.5.1.1 For general function checks and calibrations, see ISO 18674-1:2015, 5.6.

6.5.1.2 Inclinometer probes shall be regularly re-calibrated. If not otherwise specified by the manufacturer, the maximum interval shall be two years. If the instrument was not in use for more than two years, re-calibration shall be carried out immediately prior to the measuring survey. Re-calibrations are also necessary after repair or the exchange of any mechanical or electrical components (including cable).

6.5.2 Measurement

6.5.2.1 The measurements shall be carried out according to Annex A and in conjunction with the requirements of ISO 18674-1:2015, Clause 7.

6.5.2.2 For probe inclinometers, the guide tube shall be surveyed by the probe using a step-by-step procedure. The stability of the readings is critical for a correct measurement. Therefore, at the beginning of a survey, the probe shall be brought to the point furthest from the collar of the guide tube and left there to adjust to the ambient temperature until the readings are considered to be sufficiently stable. The probe shall then be moved sequentially to each respective measuring point in the direction of collar of the guide tube. On reaching the collar of the guide tube, the probe is removed from the guide tube, reversed (i.e. rotated by 180°,), returned to the measuring point that is furthest from the collar of the guide tube and the sequence is repeated in the reversed position to complete the inclinometer survey of the guide tube.

NOTE 1 The time of the probe to adjust to the ambient temperature varies and depends on site and probe conditions.

NOTE 2 The purpose of the reversal of inclinometer probes between the two runs of a complete measuring survey is to eliminate zero point deviation within the system. For vertical inclinometers, the reversal is turning the probe through 180° around its longitudinal axis (the cable entry is unchanged), while for horizontal inclinometers the reversal is turning the probe through 180° in the horizontal plane (changing the cable connection from one end to the other).

6.5.2.3 The tolerance of depth positioning of the probe in a measuring point shall be ±5 mm.

6.5.2.4 Each measuring point shall be approached by the probe in a specified (commonly upward) direction. If the measuring point is accidentally overrun, the probe shall be reversed beyond the missed measuring point and then again moved in the specified sense into the measuring position. Readings shall be taken while the probe is at rest and the readings are stabilized.

6.5.2.5 For establishing a reliable reference set, there should be, in the reference measurement, at least two repetitions of the initial measuring survey whereby each survey consists of a normal (0°) and a reverse (180°) run along the guide tube under repeatable conditions (see 5.5.2). The two surveys shall be within the acceptable range of measuring precision (see Table 2).

NOTE It is good practice to carry out an additional reference measurement with an independent probe that can be used as a backup.

6.5.2.6 Probe inclinometer readings shall be scrutinized. Check-sums shall be used as the basis for the acceptance test of the readings and for identifying erroneous measurements. If readings are incorrect or in doubt, the inclinometer survey shall be repeated.

NOTE 1 The check-sum is the sum of the normal (0°) and reverse (180°) readings taken at the same measuring point. Ideally, the sum is zero since the readings have opposite signs. In practice, however, variations in the positioning of the probe and zero offsets of the probe contribute to non-zero check-sums.

NOTE 2 Common practice is plotting the check-sums of all measuring points over the depth of the inclinometer guide tube. In normal circumstances, each combination of probe and guide tube has a unique check-sum signature, which is repeatable in each follow-up measurement. Typically, the check-sum varies randomly about a mean value. Small variations do not usually indicate a problem, however, spikes in the plot are indicative of inconsistencies in the readings.

NOTE 3 For check-sum analysis, see Reference [6].

6.5.2.7 The cumulated displacements of an inclinometer survey and the stability of the reference point should be verified by independent measurements.

NOTE Geodetic control of the cumulated lateral displacements is common at the collar of a vertical borehole.

6.5.2.8 For in-place inclinometers, the measurements are commonly made automatically by means of data loggers. A critical appraisal of the readings in the first logging cycles shall be made, as well as plausibility checks in subsequent cycles prior to reporting.

NOTE Some in-place inclinometers can be read using hand-held data readers, computers and/or mobile telephones.

7 Data processing and evaluation

7.1 The evaluation of the measuring data shall be carried out according to Annex A.

7.2 A record of the following data are required in addition to the requirements of ISO 18674-1:2015, Clause 8.

a) For each measuring survey:

— ID of the instrument;

— identification of the measuring line, e.g. measuring borehole;

— definition of reference point and its displacement condition;

— angle between the A+ direction of the probe and the reference direction

b) For each measuring point:

— measuring depth;

— relative lateral displacements Δu_i and Δv_i according to Formulae (A.1) and (A.2) (common designation: “differential displacements”);

— absolute lateral displacements u_i and v_i according to Formulae (A.6) and (A.7) and, if applicable, also according to Formulae (A.8) and (A.9) (common designation: "integrated displacements");

— amount and direction of the lateral displacement vector (vector sum of u_i and v_i);

— for probe inclinometers, sum of normal (0°) and inverse (180°) measurements ("check-sum").

7.3 The evaluated results shall be presented in tables and/or graphics.

EXAMPLE See Annex E.

NOTE It is good practice to represent angular measurements and variations together with an uncertainty band. The uncertainty band can, for example, be defined as the standard deviation of the checksum over a length of fixed tube".

7.4 The results of probe inclinometer measurements should be diagnosed on systematic errors and corrected, if applicable.

NOTE 1 See Reference [6].

NOTE 2 Generally, a measurement error is made up of two components: random error and systematic error. Random errors cannot be corrected, but can be minimized in better installations and by repeated measurements. Systematic errors can be corrected by mathematical procedures, provided the causes of the errors are known. In inclinometer measurements, the most common systematic errors are caused by:

a) shift of the calibration bias of the tilt sensor (bias shift error);

b) drift of the sensitivity of the tilt sensor (sensitivity drift error);

c) shift of the guide tube inclination (rotation error);

d) change in the depth positioning of the probe (depth-positioning error).

According to Reference [6], bias shift (a) and rotation (c) errors are relatively easy to detect and correct with proper proprietary software or spreadsheets. Sensitivity drift (b) is relatively rare, is usually difficult to detect, but is easy to correct. The depth positioning error (d) is considered to be the most difficult error to deal with, as there can be several causes for it such as increasing deflection of the guide tube or an elongation or shrinkage of the measuring cable.

NOTE 3 The magnitude and style of displacements measured over the base fixity depth (see 6.3.1.2) is important in the diagnosis and analysis of systematic errors.

8 Reporting

8.1 Installation report

The installation report shall be in accordance with ISO 18674-1:2015, 9.1.

8.2 Monitoring report

The monitoring report shall be in accordance with ISO 18674-1:2015, 9.2.

Annex A
(normative)

Measuring and evaluation procedure

A.1 Course of a measuring line

A.1.1 The course of a measuring line shall be surveyed by moving the inclinometer probe along the measuring line in a step-by-step procedure from one measuring point to the next (see 5.2.1).

A.1.2 In each measuring step, the following angles shall be measured:

— tilt angle α of the probe axis in Plane A (see Figures 1 and A.1);

— tilt angle β of the probe axis in Plane B (for biaxial inclinometer probes only).

A.1.3 The angles measured in the respective measuring points can be graphed as a polygon from a reference point under consideration of the base length (see 3.9 and Figure A.1).

A.1.4 The reference point should be either the collar of the guide tube or the deepest measuring point.

A.2 Displacements across a measuring line

A.2.1 By comparison of follow-up and reference measurements, changes in the course of the measuring line can be determined and, thus, also displacements of the measuring points across the measuring line.

A.2.2 *Relative displacements* between adjacent measuring points shall be determined by means of the changes of the angles α and β. There are two independent displacement components across the measuring line, u and v. The relative displacement components Δu_i and Δv_i between the two adjacent measuring points i and $i - 1$ shall be calculated from the change of the angles $\Delta\theta_\mathrm{i}$ and $\Delta\rho_\mathrm{i}$ occurring in the time span between follow-up measurement i_F and reference measurement i_R as given in Formulae (A.1) and (A.2) [see Figure A.1 b)]:

$$\Delta u_i = l_i \times \sin \Delta\theta_\mathrm{i} \tag{A.1}$$

$$\Delta v_i = l_i \times \sin \Delta\rho_\mathrm{i} \tag{A.2}$$

where

l_i is the distance between measuring points i and $i - 1$.

For probe inclinometers, it is as given in Formulae (A.3), (A.4) and (A.5):

$$l_i = l_{i-1} = l_{i-2} = \ldots\ldots\ldots\ldots = l_1 = L \tag{A.3}$$

$$\Delta\theta_i = \theta_{iF} - \theta_{iR} \tag{A.4}$$

$$\Delta\rho_i = \rho_{iF} - \rho_{iR} \tag{A.5}$$

where

θ	is the inclinometer angle α;
ρ	is the inclinometer angle β;
R	is the reference measurement;
F	is the follow-up measurement.

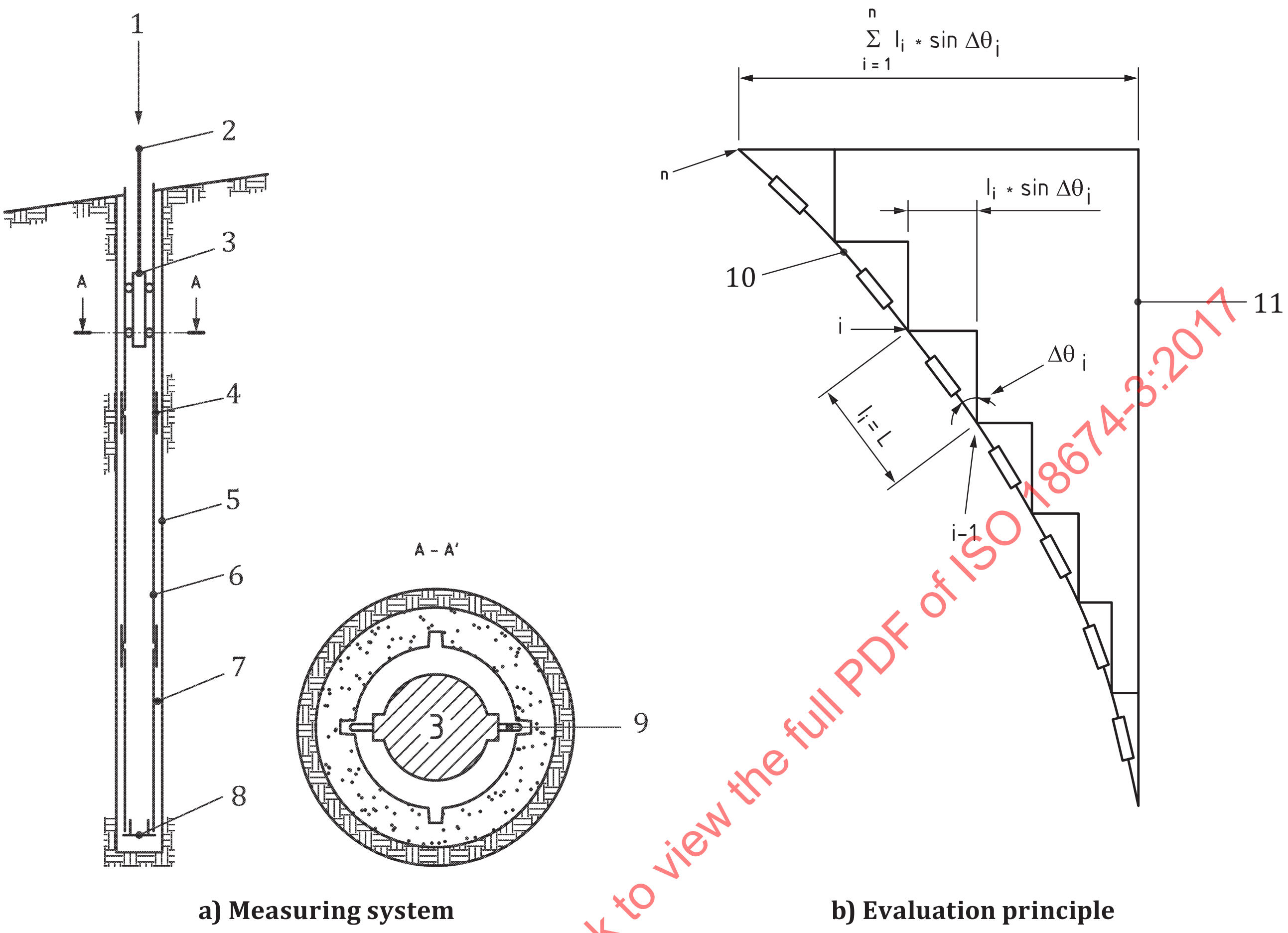
A.2.3 The *absolute* displacement components u_i and v_i of a measuring point *i* across the measuring axis shall be determined by summation of the relative displacement components Δu_i and Δv_i (see A.2.2) in relation to a reference point. It is as given in Formulae (A.6) and (A.7):

$$u_i = \Delta u_i + \Delta u_{i-1} + \Delta u_{i-2} + \ldots\ldots\ldots + \Delta u_1 + u_0 = \Sigma\, \Delta u_i + u_R \tag{A.6}$$

$$v_i = \Delta v_i + \Delta v_{i-1} + \Delta v_{i-2} + \ldots\ldots\ldots + \Delta v_1 + v_0 = \Sigma\, \Delta v_i + v_R \tag{A.7}$$

where

u_R and v_R are the displacement components of the reference point in direction of the x- and y-axis, respectively.



Key

1 readout device; data logger
2 measuring cable
3 inclinometer probe
4 coupling
5 borehole
6 inclinometer casing
7 backfill
8 end cap
9 guide wheel assembly
10 actual course of inclinometer casing
11 vertical

NOTE Adjusted from Reference [3].

Figure A.1 — Measuring system and evaluation principle of a vertical inclinometer

A.3 Displacements in A and B directions of vertical inclinometers

A.3.1 The probe of a vertical inclinometer consists of a housing in which two tilt sensors are permanently installed in two mutually perpendicular planes. Both planes encompass the longitudinal axis of the probe (which itself coincides with the guide tube axis z). They are denoted as the probe's Planes A and B (in the strict sense: "Az" and "Bz"-planes). From the measured tilt values and the evaluated displacement components a_i and b_i in the probe's measuring directions A+ and. B+, respectively, the displacement components of the ground u_i and v_i shall be determined according to Formulae (A.8) and (A.9) (see Figure A.2):

$$u_i = \cos \psi \times a_i + \sin \psi \times b_i \qquad (A.8)$$

$$v_i = \cos\psi \times b_i + \sin\psi \times a_i \quad \text{(A.9)}$$

where

ψ is the angle between the guide tube coordinate x and the probe direction A^+;

a_i and b_i are the displacement components in the probe directions A^+ and B^+ in measuring point i.

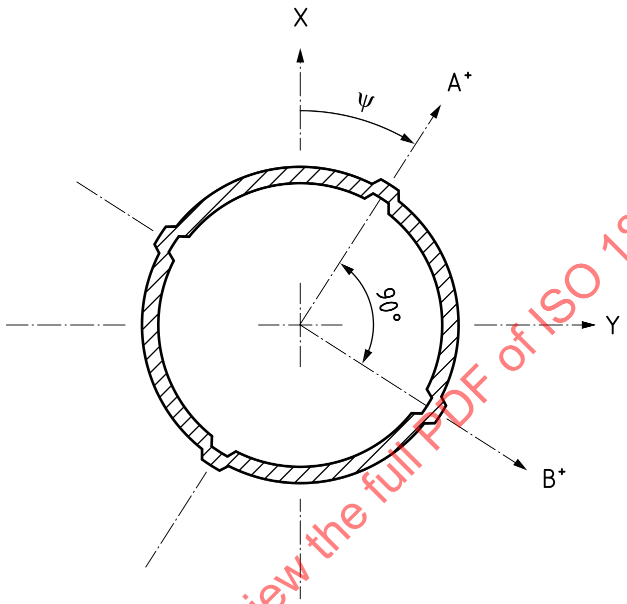


Figure A.2 — Transformation of the displacements for the general case of differentially oriented probe and borehole axes

Annex B
(normative)

Deflectometers

B.1 Terms, definitions and symbols

B.1.1
deflectometer
system for monitoring displacements across a measuring line by means of deflection measurements in the field

Note 1 to entry: The system essentially consists of an instrument, a guide tube, a means to measure the position of the instrument in the guide tube, read-out device and evaluation software. The instrument can be either a probe or in-place measuring elements.

Note 2 to entry: The two independent displacement components which are acting across a measuring line can be monitored by a deflectometer irrespective of the orientation and inclination of the measuring line.

B.1.2
deflectometer sensor
sensor which measures angles between two adjacent bars irrespectively from gravity and is encased in a universal joint

B.1.3
probe deflectometer
system comprising a probe for step-by-step measurements on a measuring line

Note 1 to entry: See Figure B.1 a).

Note 2 to entry: The probe consists of two rigid bars of equal length and three equally spaced contact points of which the centre point is equipped with a deflectometer sensor.

B.1.4
in-place deflectometer
system comprising a single deflectometer element, or a series of elements, for measurement of the deflection at specific locations on a measuring line without removing the instrument

Note 1 to entry: See Figure B.1 b) and c).

B.1.5
deflectometer casing
guide tube appropriate to the deflectometer system being used

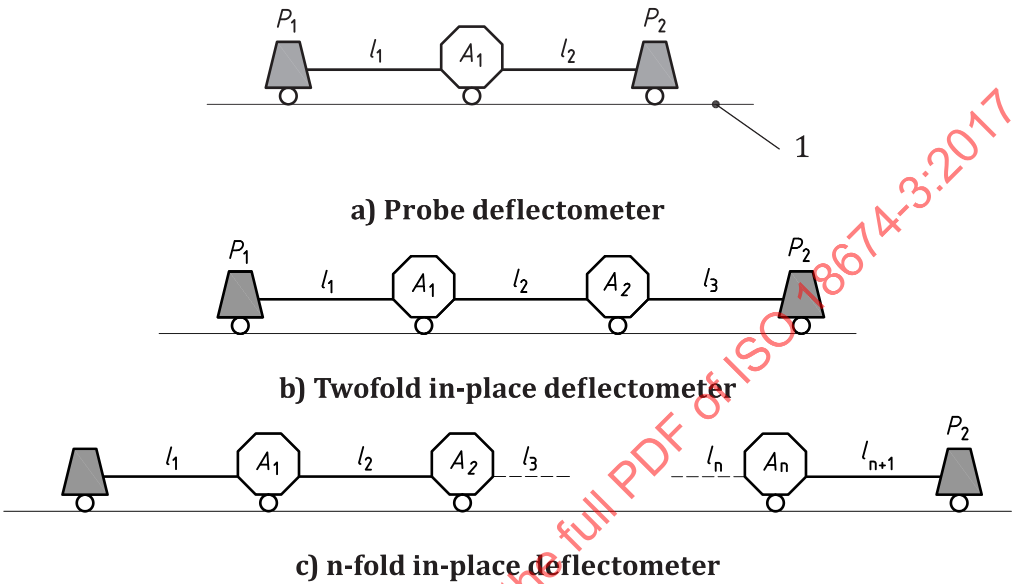
Table B.1 — Symbols for deflectometers

Symbol	Name	Unit
γ	angle between adjacent deflectometer bars in the vertical plane	° (degree)
δ	angle between adjacent deflectometer bars in the horizontal plane universal joint	° (degree)

B.2 Instruments

B.2.1 Deflectometers can be used for the measurement of displacements across horizontal and inclined measuring lines. For vertical measuring lines, vertical inclinometers should be used.

B.2.2 Equivalent to Table 1, probe and in-place deflectometers should be distinguished from each other. The principal setup should be as in Figure B.1.



Key

1 base of inner surface of guide tube

P_1, P_2 contact point without sensors

A_1, A_2, A_n contact point with universal joint and angle sensors

l_1, l_2, l_3, l_{n+1} length of connecting element (spacer bar) = gauge length, L

Figure B.1 — Principal setup and components of a deflectometer

B.2.3 Where applicable and if not advised otherwise by B.2.4 to B.2.9, 5.1 to 5.5 shall be implemented.

B.2.4 Changes of angles shall be monitored by comparison of the measured values with those of the reference measurement. Displacements of the measuring points across the measuring line shall be deduced in accordance with B.5.

B.2.5 The sensing element shall consist of a universal joint with two encased angle sensors installed 90° to each other. The sensors shall measure the deflection of the two spacer bars relative to each other, which are attached to the universal joint.

B.2.6 The installation planes of the sensors shall be denoted as the instrument Planes A and B, whereby Plane A shall incorporate the contact point assembly of the deflectometer element.

NOTE In the measuring position of the horizontal boreholes, Plane A is vertical and Plane B horizontal. The sensor of Plane A measures the change in inclination that of Plane B measures the change in azimuth.

B.2.7 The angle sensor of Plane A may be supplemented (for redundancy) or substituted (for cost-efficiency of the instrument) by a tilt sensor mounted on a spacer bar attached to the universal joint.

B.2.8 Besides the two angle sensors (see B.2.5), deflectometer probes shall also be equipped with a sensor for the measurement of the rotation (rolling) of the probe around its longitudinal axis.

B.2.9 Deflectometer systems and their measurements shall meet the requirements specified in Table B.2.

Table B.2 — Requirements of deflectometer measurements

	Line	Issue	Requirement
Probe or in-place	1	Accuracy of the instrument	±0,02 % full scale (e.g. ± 0,1 mm/m for ± 30° range)
	2	*Repeatability (precision) of a complete survey along a measuring line:* Difference between the cumulated displacements of a measuring point relative to a reference point 30 m apart, when repeatedly carrying out the survey under repeatability conditions	For Plane A: ± 5 mm For Plane B: ± 10 mm
In-place	3	*Stability of the sensor signals in baseline measurements:* Maximum difference after a 24 h period under repeatability conditions	±0,1 mm/m

NOTE 1 For repeatability conditions, see 5.5.2.

NOTE 2 With regard to the criterion of Line 2, it is good practice to carry out these tests in a slightly curved string of guide tubes which is fixed to a solid (sub-) horizontal surface. The course of the string is geodetically determined to allow a comparison with the deflectometer survey.

B.3 Installation and measuring procedure

B.3.1 Where applicable and if not advised otherwise by B.3.2 to B.3.5, 6.1 to 6.4 shall be implemented.

B.3.2 A deflectometer casing shall be used. It can be either an inclinometer casing (see 5.4) or a circular casing without keyways provided that the latter has a smooth inner surface. If inclinometer casings are used, it shall be ensured that, at installation, one pair of the keyways is aligned vertically with a tolerance of ±5°.

B.3.3 The deflectometer probe shall be positioned in the respective measuring points with a depth positioning tolerance of ±5 mm and an orientation tolerance of its top-bottom axis of ±5°.

NOTE 1 By use of a string of setting rods and through the control of the probe's rolling, it is, even in greater depths, possible to position the deflectometer probe accurately in the measuring points.

NOTE 2 A transformation of the measured data in line with Formulae (A.8) and (A.9) and Figure A.2 is not required.

B.3.4 The measurements shall be carried out in line with B.5 and in accordance with ISO 18674-1:2015, Clause 7.

B.3.5 Measurements with probe deflectometers require the orientation of the probe to be reversed between the two runs of a complete survey to eliminate zero point deviation within the system. For the reversal, the probe shall be rotated through 180° in the horizontal plane (changing the cable connection from one end to the other).

NOTE The mode of reversal is identical to that of the horizontal inclinometer (see 6.5.2.2, NOTE 2).

B.4 Reporting

See Clause 8.

B.5 Measuring and evaluation procedure

B.5.1 Course of a measuring line

B.5.1.1 The course of a measuring line shall be surveyed by moving the deflectometer probe along the measuring line in a step-by-step procedure from one measuring point to the next (equivalent to 5.2.1).

B.5.1.2 In each measuring step, the following angles shall be measured:

— deflection angle γ in the spherical joint in Plane A (vertical plane; deviation in tilt);

— deflection angle δ in the spherical joint in Plane B (deviation in azimuth).

B.5.1.3 The angles measured in the respective measuring points can be graphed as a polygon from a reference point under consideration of the gauge length, L.

B.5.1.4 The reference point should be the collar of the guide tube.

B.5.1.5 The reference direction of the polygon should be the initial direction at the collar of the guide tube.

B.5.1.6 B.5.1.1 to B.5.1.5 describes the procedure for the determination of the course of the measuring line relative to the collar of the guide tube (location and initial direction). For absolute direction (azimuth) measurements, the coordinates of the guide tube collar *and* the initial direction shall be determined geodetically.

B.5.2 Displacements across a measuring line

B.5.2.1 By comparison of follow-up and reference measurements, changes in the course of the measuring line can be determined and, thus, also displacements of the measuring points across the measuring line.

B.5.2.2 *Relative displacements* between adjacent measuring points shall be determined by means of the changes of the deflection angles γ and δ. There are two independent displacement components across the measuring line, u and v. The relative displacement components Δu_i and Δv_i between the two adjacent measuring points i and $i - 1$ shall be calculated from the change of the angles $\Delta\theta_\text{i}$ and $\Delta\rho_\text{i}$ occurring in the time span between follow-up measurement i_F and reference measurement i_R as given in Formulae (A.1) and (A.2).

B.5.2.3 The *absolute* displacement components u_i and v_i of a measuring point i across the measuring axis shall be determined by summation of the relative displacement components Δu_i and Δv_i (see B.5.2.2) in relation to a reference point. It is given in Formulae (A.6) and (A.7).

NOTE The determination of the displacement components u_R and v_R of the reference point is necessary and sufficient for inclinometer measurements; however, it is not for deflectometer measurements. For the latter measurements, there is the need for one additional boundary condition. In this regard, it is common to specify the direction of the measuring line in the reference point. If, for instance, the borehole collar is the reference point, it is common practice to determine both the position of the reference point and the initial direction of the borehole axis geodetically.

Annex C
(informative)

Backfill materials

C.1 Common backfill materials are low-strength cement-based mortar and cement-bentonite suspensions.

EXAMPLE See Table C.1.

Table C.1 — Examples of typical cement-bentonite grout mixes for inclinometers

Applications		Soils			Rocks
		Soft	**Medium**	**Hard**	
Material (ratio by weight)	Water (water-cement ratio)	~6,6	~3,0	~2,5	1,0 > ~0,6
	Ordinary Portland cement	1,0	1,0	1,0	1,0
	Bentonite	~0,4	~0,35	~0,3	~0,05 > ~0,05
28 day compressive strength (kPa)		~30	~300	~700	~1 000 < ~7 000

NOTE 1 Partially adapted from Reference [7].

NOTE 2 Additional mixes are reviewed in References [5] and [8].

NOTE 3 Local experience and practice assist in the selection of an appropriate backfill material.

NOTE 4 The quantities specified in Table C.1 are based on the procedure where the cement is added to the water first and the bentonite is subsequently added to the cement/water mix. This is because the strength and stiffness of the grout are determined by the initial water/cement ratio.

C.2 To facilitate pumping in long backfilling tubes of comparatively small diameter (length > 15 m; inner diameter = 16 mm), it is advisable to add a fluidiser to the suspension.

C.3 All constituents are to be added to the water slowly and the mix be stirred continuously so as to prevent the formation of any lumps.

C.4 Sufficient bentonite is added to provide a creamy mix, which is pumpable.

NOTE Bentonite is added primarily to restrict “bleed” (sedimentation of the solids, leaving ponded water at the surface). The amount of bentonite required to provide this depends on the ambient temperature and the acidity of the water (so will be variable).

C.5 Granular backfill material may be used in special conditions and is only permissible if there is no concern of linking aquifers of different levels.

EXAMPLE Washed gravel 3/7 mm or 4/8 mm.

C.6 Granular backfill material could be used in exceptional geotechnical circumstances such as in heavily fractured rock, in karstic ground, or in granular soils with a high permeability. In this situation, a possible preventative measure against the risk of a washout of the backfill material is the use of a geotextile hose.

NOTE Advantages of using granular backfill in comparison to cement suspensions:

— less equipment required in the installation (positive for areas that are difficult to reach);

— less problems with buoyancy;

— small backfill jobs can be done without any equipment.

C.7 Sufficient compaction of granular backfills is essential. Insufficiently compacted granular backfill can lead to sagging of the backfill material, arching of the material at the couplings and subsequent buckling of the guide tubes.

NOTE 1 Sagging of insufficiently compacted material can be triggered by blasting at adjacent construction sites or by lowering of the groundwater table.

NOTE 2 Possible preventative measures:

— use of continuous flush-coupled guide tubes without external sleeves;

— extra wide borehole diameter to reduce the risk of arching of the granular backfill material.

Annex D
(informative)

Geo-engineering applications

Table D.1 provides an overview of the various inclinometer and deflectometer types in some common geo-engineering applications. The classification, as shown in Table D.1, can assist in the instrument selection. In the case that a geo-engineering application is not included in Table D.1, the closest application can be considered for the selection.

Table D.1 — Guide for the selection of inclinometers and deflectometers in geo-engineering applications

Application	Inclinometer				Deflectometer (see Annex B)	
	in-place		probe		in-place	probe
	V	H	V	H		
Slope stability (slips and slides)	+	±	+	−	±	−
Dams and levees (stability monitoring)	+	±	+	±	±	−
Embankments for infrastructure (stability – road and rail)	+	±	+	±	±	±
Deep excavations (wall stability)	+	−	+	−	−	−
Stability of structures close to excavations	+	+	+	−	−	−
Embankment settlement profiles	−	+	−	+	−	−
Tank base settlement profiles	-	+	−	+	−	−
Tunnelling (effects on surrounding strata and structures)	+	±	+	±	+	±
Pile load testing (mainly horizontal load tests)	+	±	+	−	±	−
Verticality check (diaphragm wall, pendulum borehole)	±	−	+	−	−	−
Direction control of borehole (top-bottom relationship)	±	−	±	±	−	−
Direction control of borehole (vertical *and* horizontal components)	−	−	−	−	−	+
Ground heave	−	+	−	±	±	±
Mine workings (surface and sub-surface ground movements)	±	+	+	±	±	−
In situ tests (e.g. plate load tests)	±	+	−	±	±	−

V Vertical

H Horizontal

For geo-engineering applications:

+ Likely to be suitable

± Possibly suitable

− Likely to be unsuitable

Annex E
(informative)

Measuring examples

E.1 General

Examples of the various types of inclinometers and deflectometers and typical applications are presented as follows:

a) vertical inclinometer: Displacement measurements in a natural slope subject to creep (E.2);

b) horizontal inclinometer: Monitoring of settlements at the base of a refuse dump (E.3);

c) in-place deflectometer: Measurement of horizontal ground displacements ahead of tunnelling (E.4);

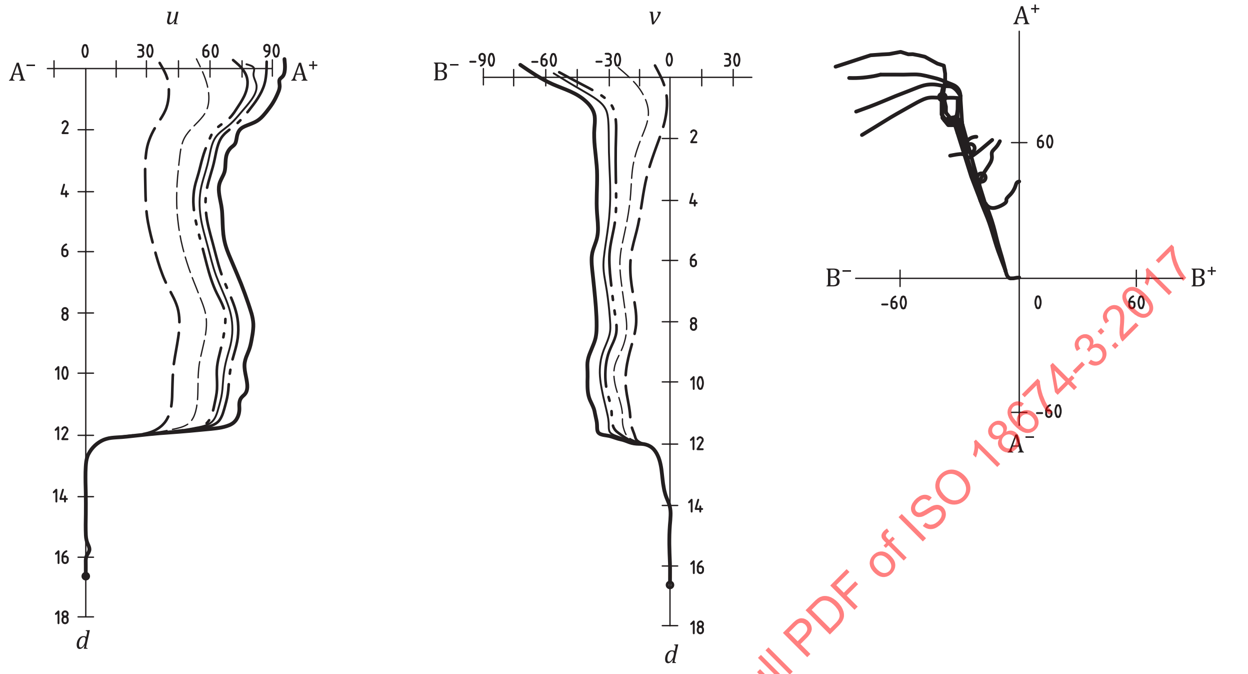
d) vertical inclinometer: Displacement measurements in retaining walls of urban excavation (E.5).

Each example contains information that is typically included in a report in accordance with ISO 18674-1:2015, Clause 9.

E.2 Vertical inclinometer: Displacement measurements in a natural slope subject to creep

Measuring purpose	Monitoring of a creep slope. Identification of the location of shear planes in the ground and evaluation of the shear velocity
Instrument	Biaxial vertical inclinometer with guide wheel assembly; L = 0,5 m; instrument No. 2097
Borehole	Vertically down-dipping, diamond drilled borehole with core recovery, $ø_{outer}$ = 146 mm, water flushing, casing $ø_{inner}$ = 136 mm
Depth of borehole	18,5 m
Guide tube	ABS inclinometer casings, $ø_{inner}$ = 74 mm, $ø_{outer}$ = 82 mm, with couplings
End depth of tubing	16,75 m
Coordinate axis	A^+ of casings oriented in dip direction of slope
Measuring procedure	Carrying out a number of value change measurements in intervals of about two weeks. Each measurement is carried out in normal (0°) and inverse (180°) mode. Manually triggered automatic data recording.
Evaluation	Computation of the horizontal displacement components by comparison between reference and value change measurements. Graphical presentation of the relative ("differential"; not shown in Figure E.1) and absolute ("integrated") ground displacements in Profiles A and B [Figure E.1 a) and b)] and in plan view [Figure E.1 c)].
Reference point	Deepest measuring point at 16,5 m depth (= fix point).
Reference direction	Vertical

Dimensions in millimetres



a) A-direction b) B-direction c) Plan view

Key

u displacement component in A direction

v displacement component in B direction

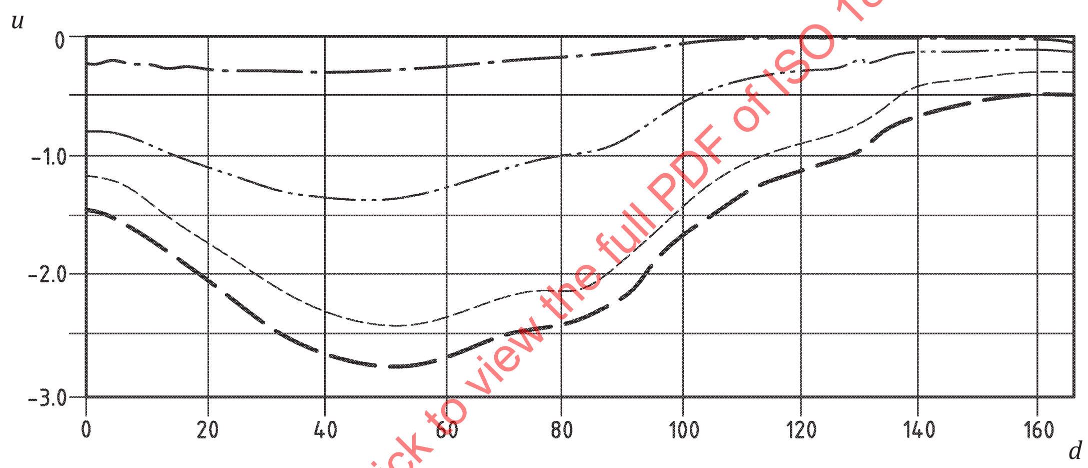
d depth of inclinometer casing

Figure E.1 — Displacements of the ground in a creeping slope

E.3 Horizontal inclinometer: Monitoring of settlements at the base of a refuse dump

Measuring purpose	Monitoring of the displacements in vertical direction (settlements) of the impermeable base of a refuse dump resting on top of an uncompacted fill. Control of the gradient of the base water drain.
Instrument	Uniaxial horizontal inclinometer with two pairs of three-point guide wheel contacts 120° apart; L = 1,0 m; intrinsically safe probe.
Installation	Placement of circular guide tubes immediately above the impermeable mineral base layer.
Guide tube	HDPE-tube 125 mm × 11,4 mm, PN 10, in sections of 6,0 m, connected by electric-welded joints, $ø_{inner}$ = 102 mm, $ø_{outer}$ = 125 mm, smooth connections at the inner tube surface
Length	166 m
Coordinate axis	Inclinometer axis A⁺ in axial direction of tubing

Measuring procedure	Follow-up measurements in intervals of about six months. Each measurement is carried out in normal (0°) and inverse (180°) mode. Moving of the probe in the guide tube by cables and pulley at the deep end of the tubing. Positioning of the probe in the measuring points via cable marks. Manually triggered automatic data recording.
Evaluation	Computation of the vertical displacements (settlements) by integrating the stepwise differential displacements between reference and follow-up measurements from the reference point. Graphical presentation of the settlements (see Figure E.2).
Reference point	Collar of the guide tube with geodetically determined settlements (about −1,5 m at value change measurement No. 20).
Reference direction	Direction of the tubing at the reference measurement.



Key

d horizontal distance

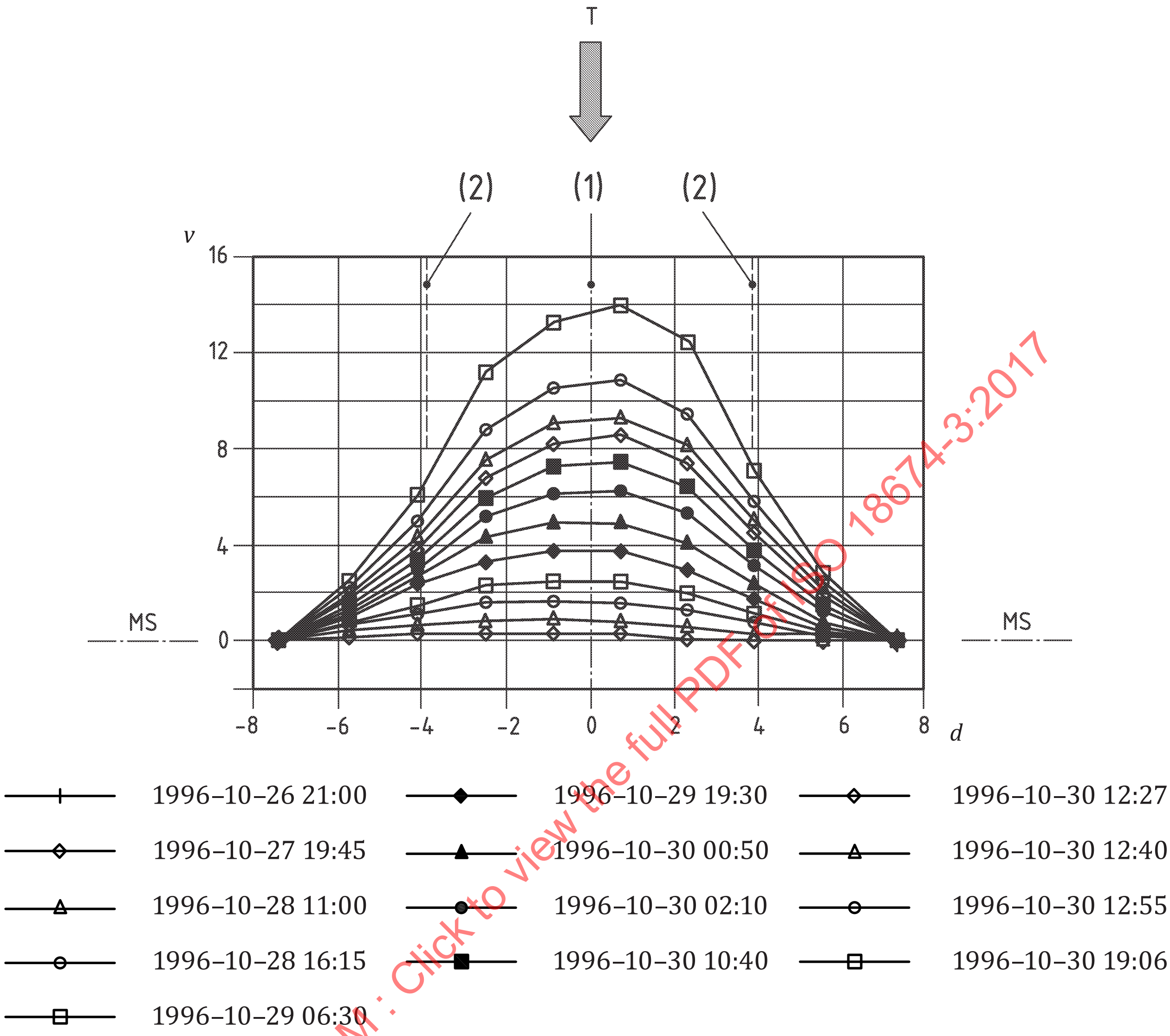
u settlement

Signature	No. of value change measurement	Time elapsed since reference measurement	
		Days	Years
—— · ——	1	120	0,3
—·· ——	7	1 546	4,2
- - - - - -	13	2 864	7,8
— — — — —	20	3 970	10,9

Figure E.2 — Evolution of the settlement profile at the base of a refuse dump

E.4 In-place deflectometer: Measurement of horizontal ground displacements ahead of tunnelling

Measuring purpose	Monitoring of horizontal ground displacements ahead of an advancing tunnel which is excavated between two already existing tunnels. Spacing between the two existing tunnels: ~15 m.
Instrument	In-place deflectometer, consisting of nine measuring elements. Length of each measuring element = 1,6 m. Deflectometer sensor: Biaxial angle potentiometer.
Borehole	Horizontal rotary drilling across the two existing tunnels, $ø_{outer}$ = 101 mm, (air flushing) with casing $ø_{outer}$ = 89 mm
Guide tube	Thin-walled circular guide tube, $ø_{inner}$ = 82 mm, with smooth inner surface.
Probe direction	A^+ upwards, B^+ horizontally to the right (as seen from the borehole collar).
Measuring procedure	Measurement of the relative horizontal and vertical displacement components. Automatic data acquisition. Geodetic measurement of the coordinates of the borehole collars in the two existing tunnels.
Evaluation	Computation of the absolute ground displacement vectors in dependency of the advancing tunnel. Graphical presentation of the ground displacements in sections (not shown), in-plan view (Figure E.3), and of the displacements of selected measuring points in dependency of the tunnel excavation phases (Figure E.4).
Reference points	Borehole collar and borehole end.
Reference direction	Uniquely determined by the two reference points.



Key

d distance from tunnel axis

v horizontal displacement

MS measuring section

T direction of tunnelling

(1) tunnel axis

(2) tunnel sidewalls

t date and time of value change measurement

Figure E.3 — Horizontal section showing the horizontal displacements of the ground ahead of tunnelling and displacement profiles at various points in time of the tunnel face approaching the measuring section