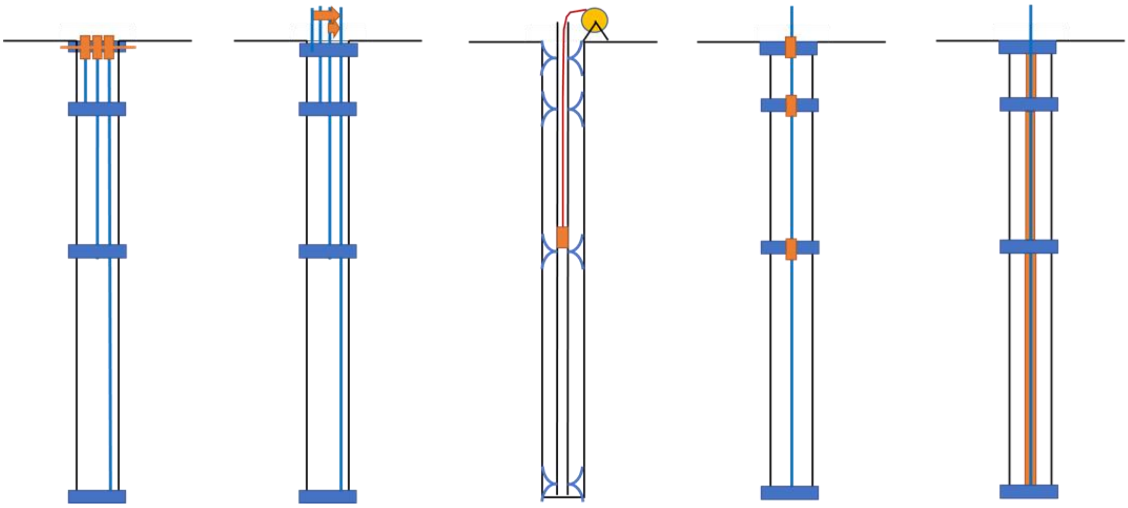
Evaluation of alternative extensometer designs and methods

desk study report for Regio Deal Bodemdaling Groene Hart project 44



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Summary

Project 44 of *Regio Deal Bodemdaling Groene Hart* (RDBGH) strives to improve understanding of ‘soft soil’ land subsidence through subsidence monitoring. This occurs both locally at (5) monitoring sites, and regionally, using remote sensing techniques. At each monitoring site, an extensometer is installed. The extensometer monitors how the thickness of individual soil layers (depth intervals) within the Holocene strata changes with time and thereby contributes to long-term subsidence of the land surface. The monitoring sites are equipped with additional sensors to monitor various hydrological and soil parameters. The aim is to thereby gather data to improve understanding of the land subsidence process(es) such as peat oxidation, and shrinkage and compaction of clay and peat.
At the RDBGH sites, an extensometer design is installed that is also deployed at monitoring sites of the Netherlands research programme on Greenhouse Gas Dynamics in Peatlands and Organic Soils (NOBV). The rationale of this design is included in an appendix to the report. Using a similar design ensures that monitoring results are comparable and provide useful data to infer differences in subsidence behavior among the sites and among the research programmes.

This report presents a desk study into possible alternative extensometer designs and approaches. Focus is on monitoring of subsidence processes in (Holocene) soft soils. The intent of the study is to provide input for installation and testing of an alternative extensometer at one of the RDBGH monitoring sites. The desk study, therefore, focuses on aspects like costs, performance, durability, and complementarity of capabilities relative to the currently used design at the RDBGH sites. The study involved review of literature and internet search. The outcome is the following:

Extensometers fundamentally combine two components:

- Anchors that attach to the soil at different depths (minimum of two).
- A methodology that directly or indirectly measures the vertical displacement of each anchor relative to an anchor at a different depth.

In addition to the RDBGH extensometer (type 1), five alternative extensometer types (2 – 6) have been distinguished: four single-borehole setups and one multiple borehole setup (settlement-plate type). The alternative types differ in the approach of displacement sensing. Differences also exist in anchor types and sensing techniques that are (or can be) applied.

Two anchor types (groutable and hydraulic) are generally unsuitable for application in soft soils (peat and clay) due to poor coupling to the borehole wall. Soft-soil anchor types (borros, spider, packer, (settlement) plate/disc) differ in the height over which they couple to the borehole wall. The relatively large coupling length of spider and packer anchors limit the precision/resolution of anchor position in the borehole. This reduces the precision of the height between two anchors for which height changes are monitored. The minimum spacing possible between two anchors – this determines the smallest layer thicknesses that can be monitored – also varies with anchor type. Although the height resolution of borros anchors is fairly small, their design prevents them to be used within short vertical distance of each other or in proximity of an anchor of different type.

For each of the five alternative extensometer types, an inventory has been made of commercially available and institutionally deployed (research) instruments. And relevant qualities/characteristics of the five alternative extensometer types have been judged. These include minimum possible anchor spacing, number of anchors per borehole, accuracy of

anchor displacement measurement, displacement range, feasibility of automatic monitoring and cost aspects.

Based on the results, the potential added value of the alternative extensometer types has been assessed. Most types are judged to have no or little merit relative to the (type 1) design that is used at the RDBGH monitoring sites. The greatest potential added value is assigned to a multi-borehole, settlement-plate setup (type 6). The most important quality of this setup is flexibility of anchor spacing and anchor resolution, allowing the monitoring of thin layers. This becomes a clear added value when automatic sensing can be achieved.

A type 2 setup (multi-point extensometer setup with alternative sensing) fitted with magnetostrictive displacement sensors may also have added value. Due to the large measurement range this setup could be advantageous in settings with large magnitude (high rate) subsidence and/or where large seasonal movements occur. Establishing the practicability of these described type 6 and type 2 setups is part of the remaining challenge.

Inhoud

1 Introduction

1.1 Background of the desk study

In the research programme *Regio Deal Bodemdaling Groene Hart* (RDBGH), project 44 is concerned with measurement and monitoring of vertical land movement and (long-term) land subsidence. The activities include efforts to improve capabilities of radar satellite-based monitoring (InSAR) with the aim to establish comprehensive spatial coverage of land (surface) deformation and land subsidence in the focus area ‘het Groene Hart’. Additionally, in project 44 ground-based monitoring techniques are being deployed at five monitoring sites[1] to provide local ‘ground-truth’ and to gather information on the subsurface processes. Details of the monitoring network are provided in a separate report. Central to the ground-based monitoring is the use of an extensometer, which records how the thickness of individual soil layers (depth intervals) evolves with time and, thereby, contributes to the land surface movement (Figure 1).

To instrument the new RDBGH sites, a borehole extensometer was chosen that was previously deployed in the Netherlands research programme on Greenhouse Gas Dynamics in Peatlands and Organic Soils (NOBV)[2]. The instrument was explicitly designed for measuring vertical displacements in soft organic soils and is described in paragraph 4.1.1; experiences and considerations that led to the design are provides in Appendix A. One of the reasons for this choice for the RDBGH sites were the positive experiences and results obtained with the extensometer. Another reason was that adherence to a common instrument (design) ensures monitoring results are comparable across different monitoring sites (NOBV and RDBGH). The latter is important as homogeneous datasets hold the greatest potential to recognize and learn about commonalities and differences in the soil behavior in different settings.

Figure 1: Field plot with extensometer at land subsidence monitoring site Berkenwoude.

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[1] Bleskensgraaf, Berkenwoude, Cabauw, Hazerswoude, and Gouda. A sixth site was aimed for in the inner city of Gouda but has not been realized to date.

[2] Dutch: Nationaal Onderzoeksprogramma Broeikasgassen Veenweiden

Despite these advantages, the choice of the “NOBV-extensometer” also has the disadvantages of ‘putting all one’s eggs in one basket’. Valuable questions to ask, for instance, are (A) might there be better extensometer designs in terms of lower costs[3] of installation and use (maintenance) for the same performance, and (B) do simpler and/or lower-cost designs exist that are of value despite lesser performance on accuracy, resolution, or reduced service life? To address these questions, in project 44 an additional task was included to carry out a desk study of alternative extensometer designs and to install and evaluate an alternative design at one of the RDBGH field sites.

1.2 This report

This document reports the findings of the desk study introduced in paragraph 1.1. The desk study involved investigation of documentation on commercially offered extensometers and literature study. Focus of the report is on soft-soil extensometer application to about 15 m depth that is of interest in the RDBGH (and NOBV and other soft-soil studies). Special deep borehole extensometer methods are not addressed in this report.

Chapter 2 starts by introducing six extensometer types (based on differences in design/approach). Type 1 represents the current RDBGH extensometer setup. Chapter 2 also includes an overview of anchor and displacement sensor types that were encountered in the study.
To judge if specific variants could be of interest for soft-soil land subsidence as conducted in the RDBGH programme, various characteristics are of interest, such as the number of anchors that can be placed in a single borehole, the minimum spacing of these anchors, vulnerability of sensors, and costs of installation and maintenance. A comprehensive set of ‘evaluation characteristics’ is given in Chapter 3.
Chapter 4 then returns to the six extensometer types introduced in Chapter 2. For each type, examples are given of commercially available and institutionally deployed (research) instruments encountered in literature and online. And for each type, the evaluation characteristics of Chapter 3 are judged and tabulated.
Chapter 5 closes with a summary of the general findings, remarks, and an appraisal of the potential added value of the alternative design types.

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[3] Low(er) costs are helpful to develop a larger network of extensometers that cover a greater range of settings and conditions.

2 Types of extensometers and their components

Extensometers fundamentally combine two components:

- Anchors (or markers)[4] that attach to the soil at different depths (minimum of two).
- A methodology that directly or indirectly measures the displacement of each anchor relative to an anchor at a different depth.

In this report, the focus is on single-borehole extensometers, where all anchors are placed at different depths in a single borehole. However, multi-borehole extensometers and generalizations thereof, can be of interest as well and are discussed paragraph 2.3.

2.1 Multi-point- and inline-extensometers

For commercially available single-borehole extensometers two broad types are commonly distinguished: multi-point (MP) extensometers and inline (IL) extensometers. MP extensometers measure displacement of each anchor relative to a single reference anchor, where the reference is usually either at the bottom or at the top of the borehole. IL extensometers measure shortening or lengthening directly for segments between adjacent anchors. IL extensometers may therefore also be referred to as segmented extensometers. For IL extensometers, the net displacement of the 'land surface' relative to the deepest anchor is the sum of the individual measures for the segments.

2.2 Five different setups to measure displacement

Figure 2 illustrates five different setups or design-types based on ways in which displacements are measured, three designs of MP extensometer and two designs of IL extensometer. From left to right:

1. Classical MP-setup which measures the vertical displacement of each anchor via an attached stiff rod; the rod displacement is measured with a vibrating wire or linear potentiometer transducer at the extensometer head. The transducers are fixed to the extensometer head. Displacements of all anchors are therefore measured relative to the extensometer head; it is the common reference for all anchors. Resulting displacements are usually converted to displacements relative to the deepest anchor. If the extensometer head is anchored at some level near the surface, that anchor can be considered the reference level[5]. This design is commonly used at engineering structures (tunnels, slabs).
2. MP-setup which uses 'unconventional' sensing methods to measures displacements of the anchor-rods at the well head relative to either the deepest or shallowest anchor.
3. MP-design which measures/senses the vertical position of each anchor in a central access tube in which a sensor is lowered.
4. IL-design which measures the vertical displacement of a (segment) rod attached to the directly underlying anchor at the top of the anchor at the top of the rod with a transducer.

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[4] The term as used here refers to any measurement point, including the reference point. This may also be the bottom of a pile pushed till refusal into the bottom of a borehole or the 'foundation' of a wellhead cap.

[5] When deformation of the topmost interval shown in Figure 2 is not of interest, anchoring of the head/transducers to the soil is not required.

5. IL-design which measures shortening/extension of segments by sensing strain within a deformable segment (cable).

The first type is currently in use in RDBGH project 44 and NOBV. The other types can be considered alternative designs. A 6th type is introduced below.

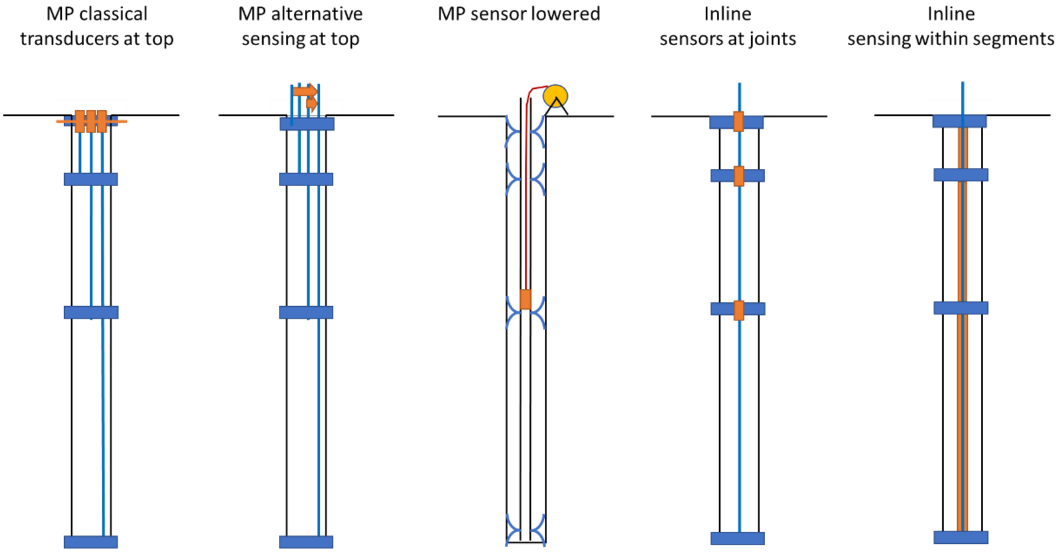


Figure 2: Five extensometer types (single borehole). MP = multi-point.

2.3 Sixth setup: Multi-borehole extensometers

The above extensometer types are (single) borehole extensometers where all anchors are installed in a single borehole. Anchors can also be distributed among two or more relatively closely spaced boreholes. When displacements are measured relative to a single anchor and borehole spacing is much smaller than the largest difference in anchor depth, the instrument may be referred to as a multi-borehole extensometer. Figure 3 depicts a deep, two-borehole extensometer in Lancaster, California (Galloway and Burbey, 2016). The reference “anchor” is a concrete slab at the land surface.

As a generalization of multi-borehole extensometry, repeated geodetic leveling can be used to measure vertical displacement of ‘settlement plates’ (anchor with stiff rod), each placed at the bottom of an individual borehole of different depth. However, the reference then is an external benchmark, and it becomes less obvious to consider the configuration to be a single instrument. However, when boreholes are close together in a dedicated design, the functionality may approach that of a borehole extensometer. In paragraph 4.6, this approach is included as design type 6.

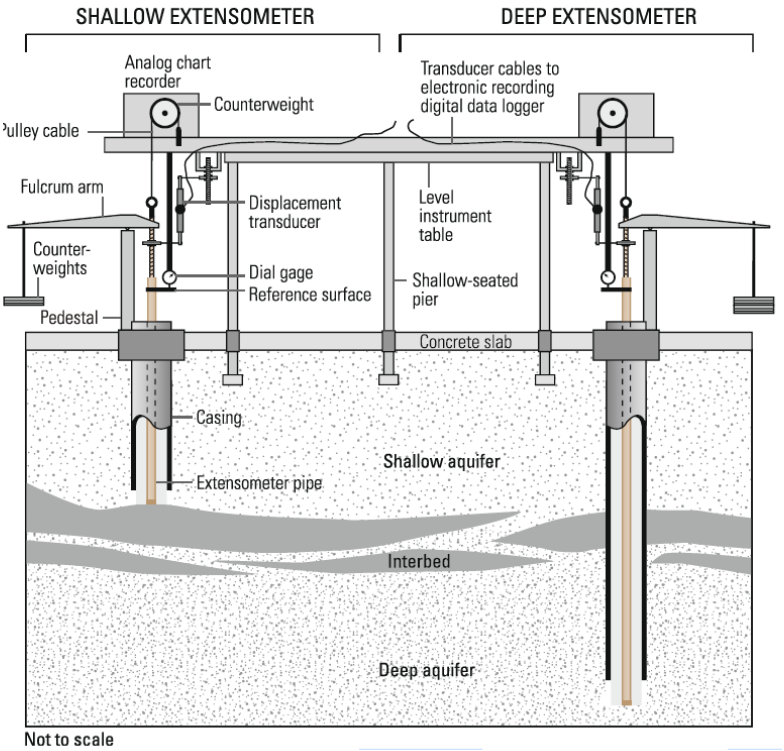


Figure 3: Schematic of counter-weighted, two-stage, borehole pipe extensometer, Lancaster, California (Galloway and Burbey, 2016).

2.4 Sensor types

Like anchors, various options for sensor choice and sensing techniques are available for extensometers. These include:

- Linear potentiometer displacement sensors
- Vibrating wire displacement sensors
- Magnetostrictive position sensing
- Magnetic position sensing
- Distributed fiber optic sensing

These sensor and sensing techniques are elucidated in chapter 4.

2.5 Anchor types

Several anchor types are introduced here, several of which are specifically designed for or may have potential for application in soft soils.

Borros anchor

Specific for soft soil (peat, soft clay). Deep penetration of the prongs should ensure good anchorage. Hydraulic pressure is applied to extend 3 (single action; left) or 6 (double action; right) prongs from the anchor body into the borehole wall. Fully extended, the prongs protrude ca. 150 mm from the anchor body at three places.

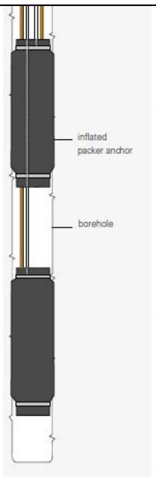
Hydraulic (expanding tube/bladder) anchor

Recommended for use where grouting may be difficult (e.g., fractured rock). The anchor consists of a spool of high strength plastic around which a sealed, pressure tight, soft copper tube is wrapped. Attached to the copper bladder is a high-pressure nylon inflation line and check valve. Inflation is done with a hydraulic pump which causes the copper bladder to expand and unwind, filling the space between the spool and the borehole wall. Anchoring is by friction.

Spider anchor

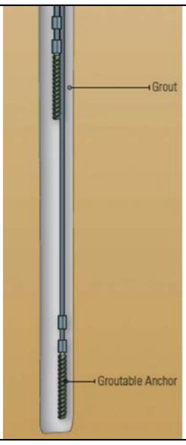
Suitable for soft soils. The anchor consists of three mechanically activated spring-loaded arms.

Packer anchor



Suitable for heavily fractured rock and overhead installations (e.g., in tunnels). And suitable for very soft soils. The borehole is filled with very soft grout, then the extensometer is installed, and the packer anchor(s) inflated with a ‘grout type material’ that should not deform or shrink.

Groutable anchor



This anchor operates by friction relative to the grout and is not directly anchored to or in the borehole wall. Therefore, it is considered unsuitable for use in soft soils as the required stiff grout column is expected to interfere with soil movement. It is shown here because it has been used still in relatively soft soil.

3 Evaluation characteristics

Chapter 2 documents that many options exist for extensometer design, displacement sensing/sensors and anchor types. To judge if specific choices could be of interest for soft-soil land subsidence as conducted in the RDBGH programme, the following characteristics are considered:

Minimum anchor spacing
This sets a limit to the vertical resolution. It determines, for instance, if the deformation of a single relatively thin peat layer can be monitored separately from adjacent mineral layers. Or if predominantly unsaturated zone deformation (shrink-swell) can be monitored separately from deformation of deeper saturated strata.

Precision/resolution of anchor position
This affects the accuracy of interval spacing. Some anchors, notably packers, connect to the borehole wall over a considerable height. Even though the middle of the anchor may be chosen to determine a unique position, the effective vertical position is known with limited precision. This then also applies to the soil interval that is monitored.

Maximum number of anchors per borehole
This limits the total depth that can be monitored for a given resolution, or this limits the resolution for a given total monitoring depth.

Risk of poor anchor-borehole wall coupling
If there is a possibility that anchors move relative to the soft soil, measurements are less reliable.

Displacement accuracy
Displacement accuracy determines what deformation can be reliably detected, for instance mm-level or cm-level deformation.

Displacement range
If the maximum displacement (both directions) that can be measured is limited, it means the extensometer must be decommissioned (or, if possible, retrofitted) when the maximum displacement (subsidence) has been reached, or will not be able to record large-magnitude dynamical movements.

Feasibility of automatic recording
Some designs are less amenable to automatic monitoring/logging. If manual measurements are required, this strongly reduces the temporal resolution of the monitoring.

Risk of sensor disturbance
Sensors that are sensitive to external disturbances may be more prone to failure or may require more maintenance.

In addition to these characteristics, a cost indication is relevant. No detailed information of costs has been acquired. But some designs clearly are more costly to purchase or build than others. Similarly, sometimes differences in costs of installation can be judged in a relative sense.

4 Evaluation of the six design types

In this chapter, more specific information is provided for the six design types defined in chapter 2. Examples are given of commercially available and institutionally deployed (research) instruments encountered in literature and online. Relevant characteristics are judged and tabulated.

4.1 Type 1. Classical MP setup

4.1.1 Extensometer design in use in RDBGH project 44 and NOBV

Design type 1 (paragraph 2.2 and Figure 2) is currently in use in RDBGH project 44 and in NOBV.
The basic assembly is obtained from Geosense and has been installed with some modifications to optimize use in soft organic soil (Appendix A). Figure 4 gives a general impression of the (reference) head assembly of a design type 1 extensometer.

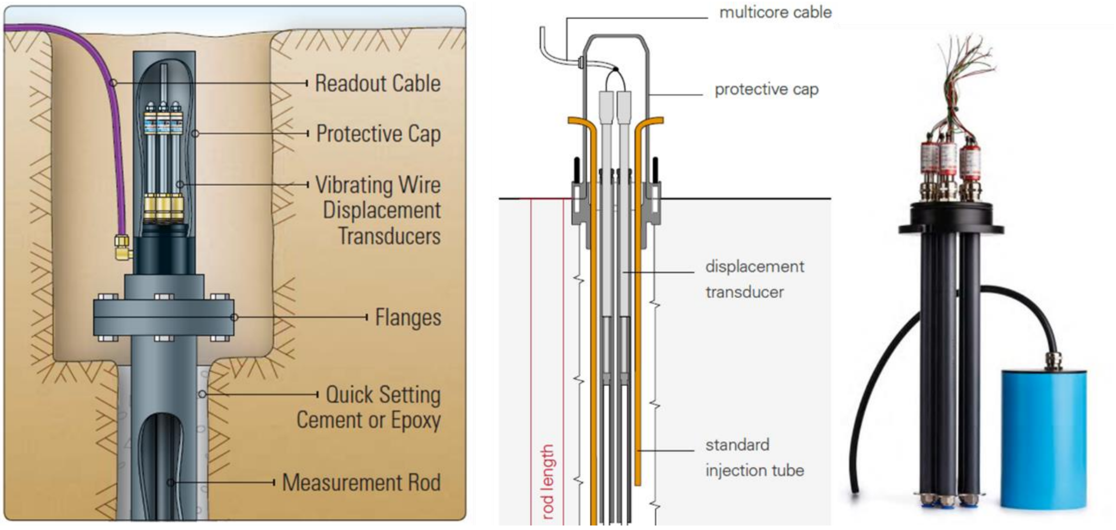


Figure 4: Examples of what an extensometer head assembly looks like (type 1). Panel figures from different providers. The right panel is from Geosense.

The installed extensometers are fitted with stainless steel rods. At one NOBV site (Rouveen) vibrating wire displacement transducers are used, at other sites linear potentiometers. Up to four different anchor types are used for a single extensometer (Figure 5). From bottom to top:

1. Massive cone. This is generally used for the deepest anchor and installed with a CPT-sounding vehicle or by hand.
2. Borros anchor (single).
3. Horizontal plate/disk (2 x 12 cm strip; up to 0.4 m depth). Lowered in a hand-dug hole of the same dimensions and then partially rotated.
4. Large (50 cm x 50 cm) perforated stainless steel plate/mesh.

The latter large plate is buried at shallow depth (~ 5 cm) to avoid recording movement by vegetation growth and decay. The extensometer head assembly is attached to this shallowest anchor (Figure 6). All movements, therefore, are recorded relative to this shallow anchor. To establish optimal coupling of the borros anchors with the soil, these anchors are placed by hand 'drilling' a small diameter borehole (~3 cm diameter) for each anchor using a gouge auger. That is, the extensometer string is not installed in a pre-drilled, large-diameter borehole as is usually done with commercially available extensometers. An advantage of the adopted installation method is that grouting of the borehole, which might compromise the performance of the extensometer, can be omitted. Only the part of the borehole at the deepest anchor in the sand is grouted.

The rods move relatively freely in protective tubing (sheaths) to limit friction of the stiff rods relative to the grout or soil. A flexible ribbed tube was used to ensure that the tube can also shorten and extend to some extent (up to a limit) with the deforming soil and grout.

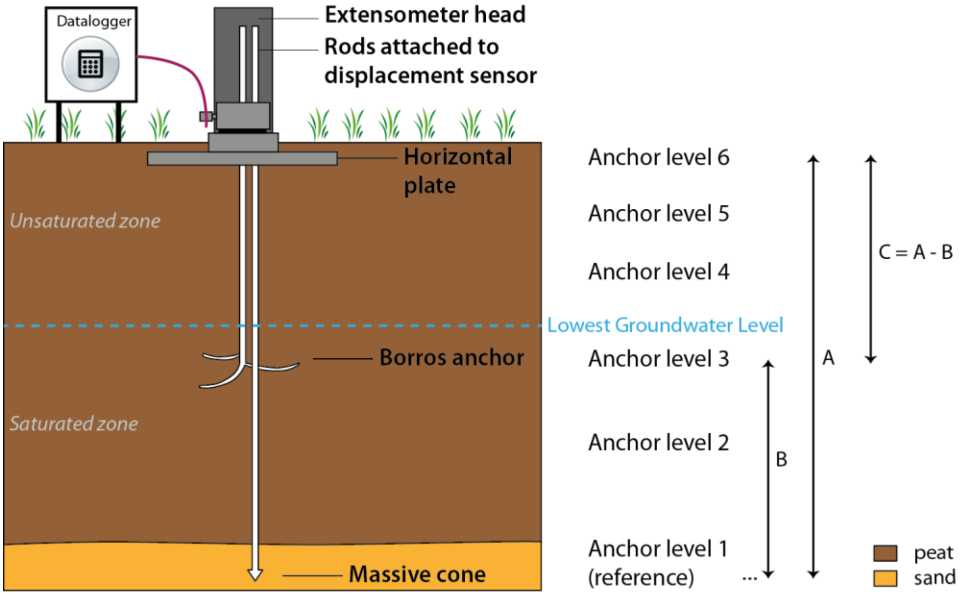


Figure 5 Graphical depiction of the four anchor types that are used at the RDBGH monitoring sites.

Figure 6 Image of buried perforated stainless-steel plate/mesh to which the head assembly of the extensometer is attached (location Rouveen, NOBV).

Characteristics:

Item	value
Commercial / institutional	Modified commercial
Documented use	Yes[1]
Minimum anchor spacing*	Borros: 50 cm Horizontal disk: multiple disks not feasible
Precision/resolution of anchor position	Borros: 3 cm Horizontal disk: 3 mm
Maximum number of anchors per borehole#	6
Risk of poor anchor-borehole wall coupling	Presumably low, but basically unknown
Displacement accuracy	0.1 mm
Range (maximum displacement)	Ca. 200 mm (large = long sensor length ~ 80 cm)
Feasibility automatic recording	yes
Risk of sensor disturbance	Potentiometer can be sensitive to moisture

1 NOBV reporting; soon available

* depends also on amount of height loss/subsidence

including top plate and deepest cone

Cost indication:

Item	value
Instrument (+ logger/power)	Ca. 12 k€
Installation	Ca. 3 k€
Maintenance (solely instrument not plot)	Low, but little experience to date

4.1.2 Variants of type 1

There are several commercial manufacturers of type 1 extensometers. All manufacturers listed below (not necessarily an exhaustive list) offer two types of transducer: vibrating wire and linear potentiometer. Both types of sensors are offered with choices of range and resolution – generally, the larger the range, the lower the resolution.
Apart from stainless steel rods, usually also fiberglass rods are offered. The latter can be pre-assembled, coiled and shipped; stainless steel rod systems generally need to be assembled on site. Stainless steel rods should be expected to be superior for monitoring subsidence (shortening) since there is less opportunity for the rods to deform horizontally (bending). These sensors and rods are combined with the anchor types listed below.

Geosense (XB2 extensometer)
Anchor types: groutable, packer, borros
Sisgeo (MPBX extensometer)
  Anchor types: groutable, packer
Geocon (Rod-type borehole extensometers)
  Anchor types: borros, hydraulic, groutable
RST Instruments (borehole extensometers)
  Anchor types: borros, hydraulic, groutable, spider
DGSI (Rod extensometer)
  Anchor types: groutable, hydraulic

Only borros, packer and spider are considered of interest for application of type 1 extensometers in soft soil.

Characteristics:

Item	value	remark
Commercial / institutional	commercial	
Documented use	no	
Minimum anchor spacing*	Borros: 50 cm Packer: 200 cm Spider: 60 cm?	hart to hart
Precision/resolution of anchor position	Borros: 3 cm Packer: 20 cm Spider: 25 cm	
Maximum number of anchors per borehole#	Sisgeo: 5 Geocon: 4 - 6 RST: 7	Not always clear if head assembly is included
Risk of poor anchor-borehole wall coupling	Borros: low Packer: low Spider: high Hydraulic: high	
Displacement accuracy	< 0.5 mm	dep. range and sensor
Range (maximum displacement)	to 200 mm to 250 mm to 150 mm to 200 mm to 300 mm	Sisgeo potentiometer Geocon potentiometer Sisgeo fibrating wire Geocon fibrating wire RST Instruments
Feasibility automatic recording	yes	
Risk of sensor disturbance	low	

* depends also on amount of height loss/subsidence

including top plate and deepest cone

Cost indication:
Not very different from the RDBGH design in use. The costs of packer and spider anchors are a bit less than borros anchors.

4.2 Type 2. MP using alternative displacement sensing at the top

Although vibrating wire transducers and linear potentiometers are widely used in commercial MP-extensometers, there is no fundamental reason why they would be the only possible choice to measure anchor displacements at the top of the extensometer.

One, partially documented, alternative was found in which a magnetostrictive linear position sensor is used. This alternative is described first. Subsequently, other ideas regarding displacement sensing are briefly discussed.

4.2.1 Magnetostrictive linear position sensing

A two-point borehole extensometer (type 2) is being used at the experimental field site in Zegveld (Van Deijl et al., 2022a). And two of these instruments are also deployed near Molenaarsgraaf in the Alblasserwaard (Eertwegh and van Deijl, 2022b). The reference point (base of pile/rod) is in the Pleistocene sand, the shallow “anchor” takes the form of a metal wire mesh positioned at the land surface (Figure 7). Hence, in this application the total deformation of the Holocene soft soil layers is monitored as a single unit. A magnetostrictive linear position sensor (MRPS) is used to monitor the change in vertical position of the top anchor. The extensometer was designed and produced by Gé van den Eertwegh (KnowH2O).

Figure 7. 2-point extensometer at Zegveld which uses a magnetostrictive linear position sensor to monitor the deformation (Gé van den Eertwegh, KnowH2O).

A magnetostrictive position sensor measures distance between a position magnet and the head end of the sensing rod (Figure 8). The position magnet does not touch the sensing rod, so there is no force exerted on the rod or position magnet (and parts do not wear out). The sensing rod is mounted along the motion axis to be measured, and the position magnet is attached to the member that will be moving. The head includes an electronics module, which reports position information.

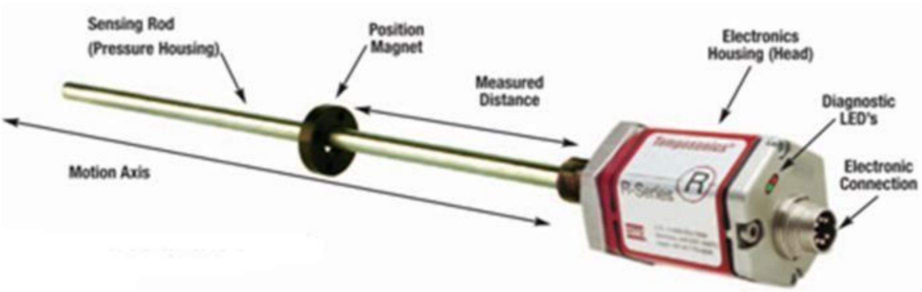


Figure 8 Components of a magnetostrictive linear position sensor (websource).

Apart from the ‘non-contact’ aspect of the sensing, another advantage of MRPS relative to vibrating wire or potentiometer sensing seems to be the relatively unlimited range of measurement (a large stroke is possible). Moreover, the sensing is rather insensitive to moisture and dirt. Limitations would be mainly caused by subsurface design (tubing – anchor interaction; grout deformation).

Characteristics of MPRS sensing in an extensometer setup:

Item	value	remark
Maximum number of anchors per borehole	Unclear, but likely rather limited for a single borehole setup.	Possible mutual interference; space requirement; rather long sensors
Displacement accuracy	0.1 mm	
Range (maximum displacement)	>300 mm	Large stroke possible
Feasibility automatic recording	yes	
Risk of sensor disturbance	Very low	

Cost indication:
The costs of a MRDS sensor with a stroke of 100 mm is about € 850. This compares to a cost of about € 200 for a linear potentiometer with a stroke of 200 mm.

4.2.2 Further ideas regarding sensing methods

Three alternative displacement sensing methods are briefly discussed here. No examples have been encountered in a literature search. A fourth option, not discussed, is a wire potentiometer (comparable to regular linear displacement potentiometer but using a wire rather than a rod).

Manual measurements

This obviously is the simplest method (Figure 9). The main disadvantage is a low temporal resolution. Advantages are no need for power, no risk of sensor disturbance/failure, somewhat lower cost, no obvious range limitation, and no forces exerted on rods/anchors during measurement.

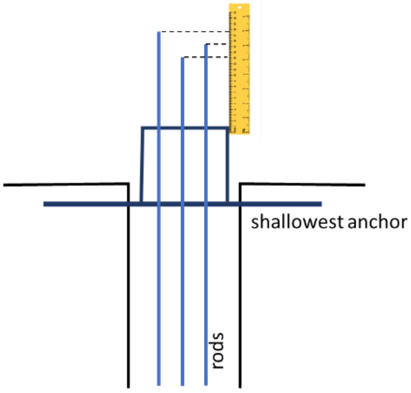


Figure 9 Manual displacement measurement.

Photoelectric distance sensing

This method can be combined with automatic recording (Figure 10). Feasibility and advantages/disadvantages relative to other automatic sensing methods have not been studied.

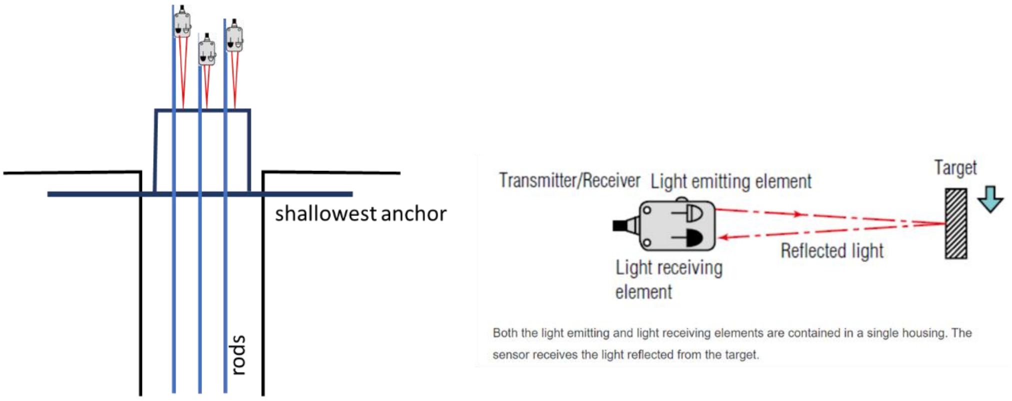


Figure 10 Concept of photoelectric distance sensing in an MP extensometer setup.

Cost indication:
Photoelectric sensors with proper specifications are rather expensive (~ 1 k€ per sensor).

Hydrostatic sensing

Hydrostatic liquid pressure sensing is widely used to monitor settlement or heave of structures such as embankments or buildings (Figure 11). The setup consists of a fluid reservoir that connects by tubing to individual level cells. Each cell is fitted with a pressure sensor. When an individual cell moves vertically relative to the reservoir (or one of the cells that serve as a reference), the pressure head changes and can be converted to a corresponding elevation change relative to the elevation of the reference. Application of such a system with a single borehole extensometer is not obvious as each anchor-rod would have to be fitted with a level cell, which is hard or impossible to accommodate in a single borehole extensometer. However, the method may be of interest for application in multi-borehole extensometer designs.

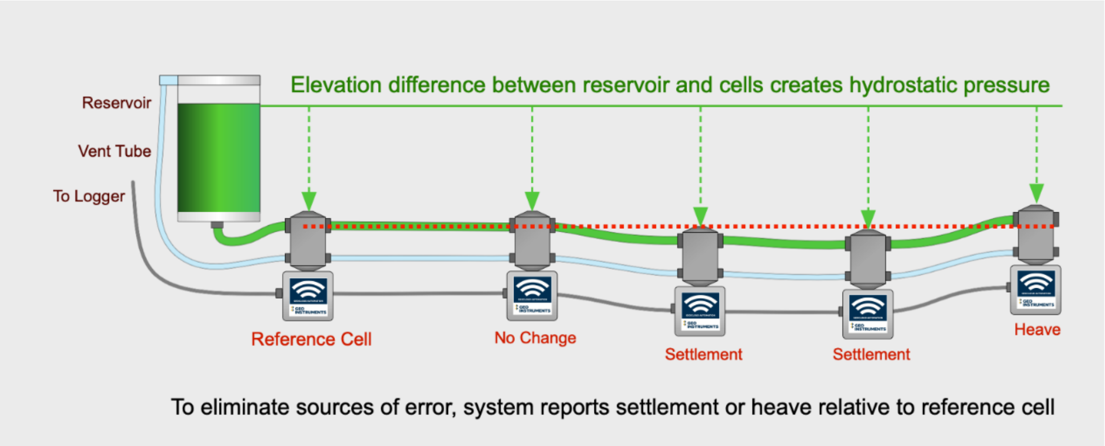


Figure 11 Concept of hydrostatic pressure sensing of vertical displacement (from: https://www.geo-instruments.com/technology/hydrostatic-level-cells)

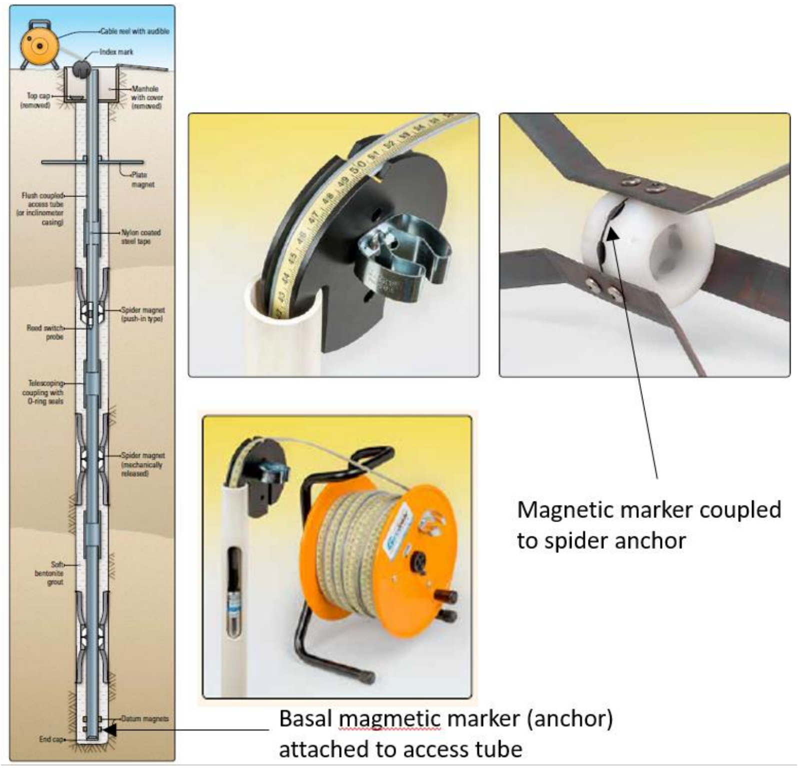
[Geo Instruments](https://www.geo-instruments.com) reports very high displacement accuracy (resolution 0.024 mm). A potential disadvantage for long-term deployment is periodic replacement of the deaired liquid (typically yearly). Also, the weight of the cells may be an issue as it adds to the weight of rod-anchor systems. Appropriate attachment needs to be designed and produced as well.

Cost indication:
Pressure sensors are about €600 each, and about €900 for very high accuracy ones.

4.3 Type 3. MP, sensing in access tube

A commercial example of this type was found via internet search.
Geokon (magnetic extensometers)

The anchors, which are fitted with a magnetic marker, can slide along a central access tube in the grouted borehole. Depth readings of the markers are done manually by lowering a sensor on a measuring tape. The access pipe can be fitted with telescoping couplings with O-ring seals to allow it to extend and contract a bit over multiple segments (reduced friction with grout and borehole wall). A basal magnetic marker in that case serves as reference for the displacements.



Magnetic marker coupled to spider anchor

Basal magmetic marker (anchor) attached to access tube

Figure 12: Magnetic extensometer (Geokon).

Characteristics:

Item	value	remark
Commercial / institutional	commercial	
Documented use	no	
Minimum anchor spacing	60 cm	> with telescoping
Precision/resolution of anchor position	23 cm	half height of anchor
Maximum number of anchors per borehole	dep. depth and spacing	
Risk of poor anchor-borehole wall coupling	Relatively high	Spring load seems relatively small; grout should be less stiff than soil.
Displacement accuracy	ca. 3 mm	

Range (maximum displacement)	(?)	
Feasibility automatic recording	no	
Risk of sensor disturbance	no	

Cost indication:
Probably less expensive than type 1 or 2. But extra personnel costs for manual measurements.

Recently, an institutional magnetic extensometer for applied scientific research in Taiwan has recently been reported (Hung et al., 2021). The extensometer has been installed in (three) 300 m deep boreholes, using 25 magnetic anchors in each borehole. The paper reports that monitoring occurs semiautomatically. However, according to the description the measurements are done manually, albeit with the support of a digital electromagnetic detection system which is broadcasted to the surface, allowing high precision depth assessment.

4.4 Type 4. IL, sensors at joints (anchors)

One example of this type was found via internet search.
RST Instruments (inline extensometer)
Anchor types: borros, hydraulic, groutable, spider (not 100% clear all are applicable)
Transducer: vibrating wire

Rods (segments or extensions) with a vibrating wire displacement sensor are coupled in a string.

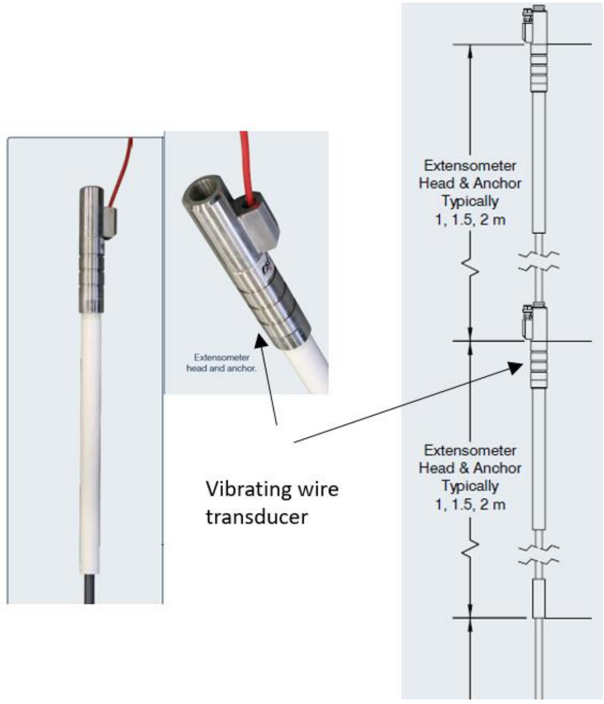


Figure 13: Vibrating wire inline extensometer (RST Instruments).

Characteristics:

Item	value	remark
Commercial / institutional	commercial	
Documented use	no	
Minimum anchor spacing	100 cm (?)	
Precision/resolution of anchor position	Borros: 3 cm Hydraulic: 5 cm Spider: 23 cm Packer: 20 cm	
Maximum number of anchors per borehole (including head assembly fixture)	Limited by spacing and anchor type?	Not limited by multiple rods such as with MP
Risk of poor anchor-borehole wall coupling	Borros: low Hydraulic: high Spider: rather high Packer: low	
Displacement accuracy	0.1 mm	per segment[6]
Range (maximum displacement)	25 - 200 mm	per segment[7]
Feasibility automatic recording	yes	
Risk of sensor disturbance	(?)	

Cost indication:
No information gathered.

4.5 Type 5. IL, sensing within segments (between anchors)

Two applications of this type of extensometer have been reported in scientific literature, both using distributed fiber optic sensing (DFOS strain):

1. China	Liu et al., (2020); Liang et al., (2022)
2. Mississippi Delta	Zumberge et al. (2022)

China
The extensometer was installed and operated in a 100 m deep borehole in Tianjin, China since December 2017. The design is schematically shown in Figure 14. Jackets attached to the cable with 5 m spacing (fixed points) served as groutable anchors. The distributed measured strain was integrated over depth sections, illustrated schematically in Figure 15. The initial strain serves as reference. Special attention was given to the properties of the grout, but no details are provided. Some results after two years of operation are shown in Figure 16. Results were shown to be very compatible with measurements with a ‘regular’ extensometer at short distance (< 10 m) with anchors at 3, 33, 60 and 95.5 m depth.

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[6] High accuracy possible per segment, but from bottom borehole upwards increasing as square root of number of segments.

[7] Over total height the sum of ranges for segments; therefore, possible to achieve very large range.

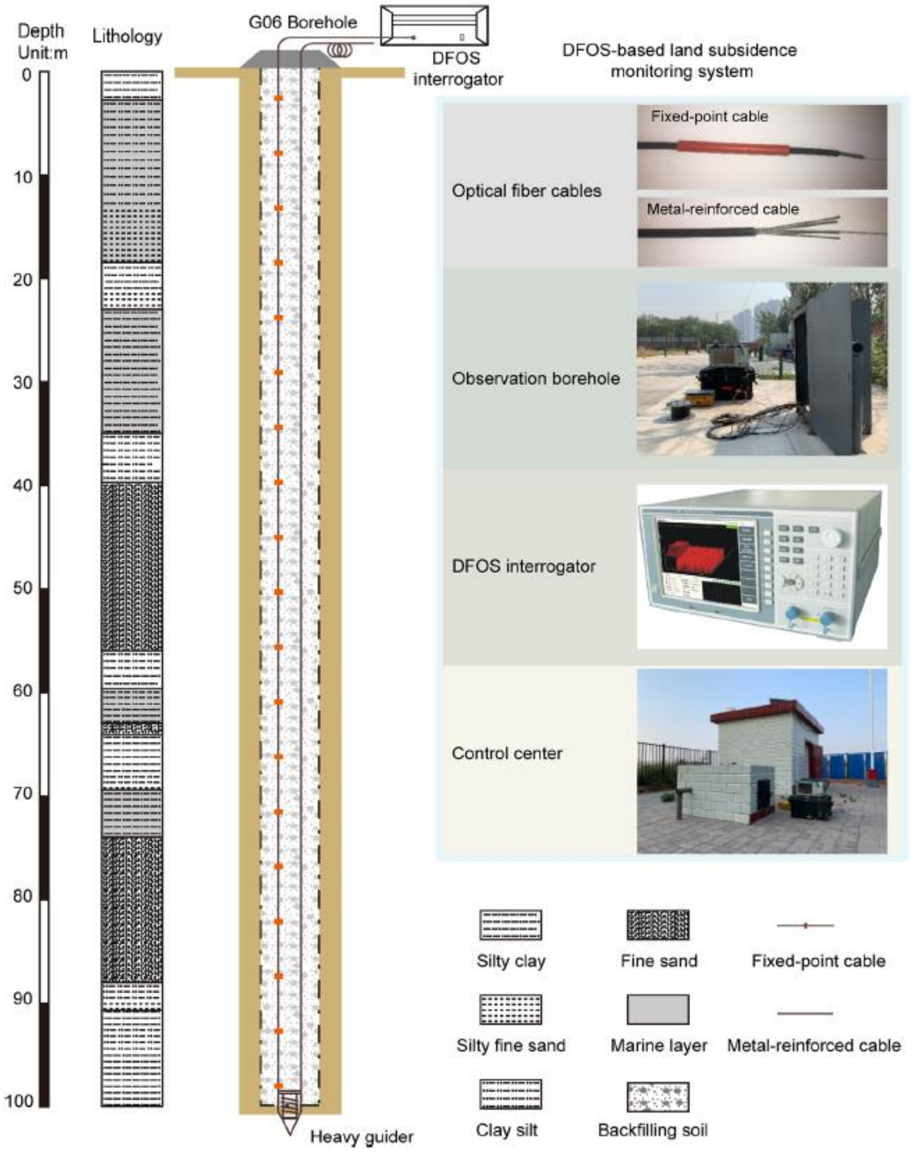

Figure 14: Fiber optic inline extensometer (Liu et al., 2020).

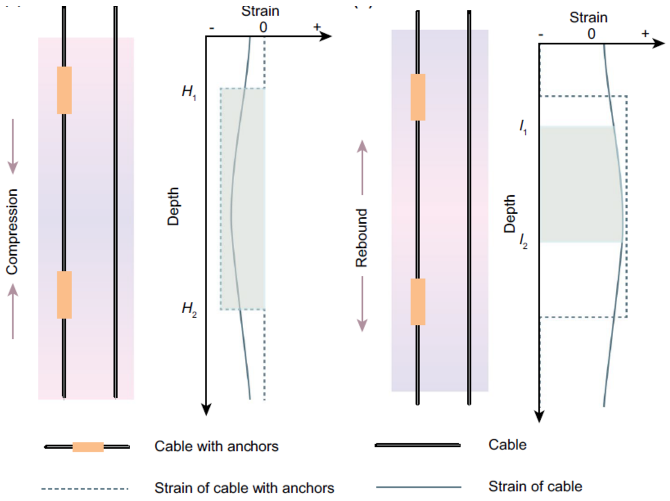

Figure 15: Illustration of displacement estimation between anchors using integration of strain (Liu et al., 2020).

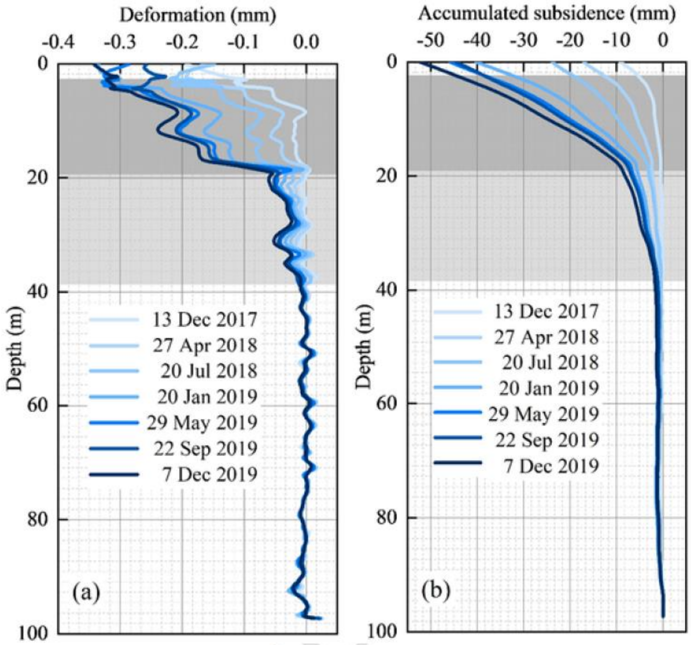

Figure 16: Deformation and accumulated subsidence as a function of depth obtained using the fiber optic inline extensometer of Liu et al. (2020). Deformation likely should be reported in units of mm/m.

Mississippi Delta

The extensometer in the Mississippi Delta application used a multi (3) borehole setup to record deformation in a Holocene (soft-soil) sequence to about 38 m depth (Figure 17).

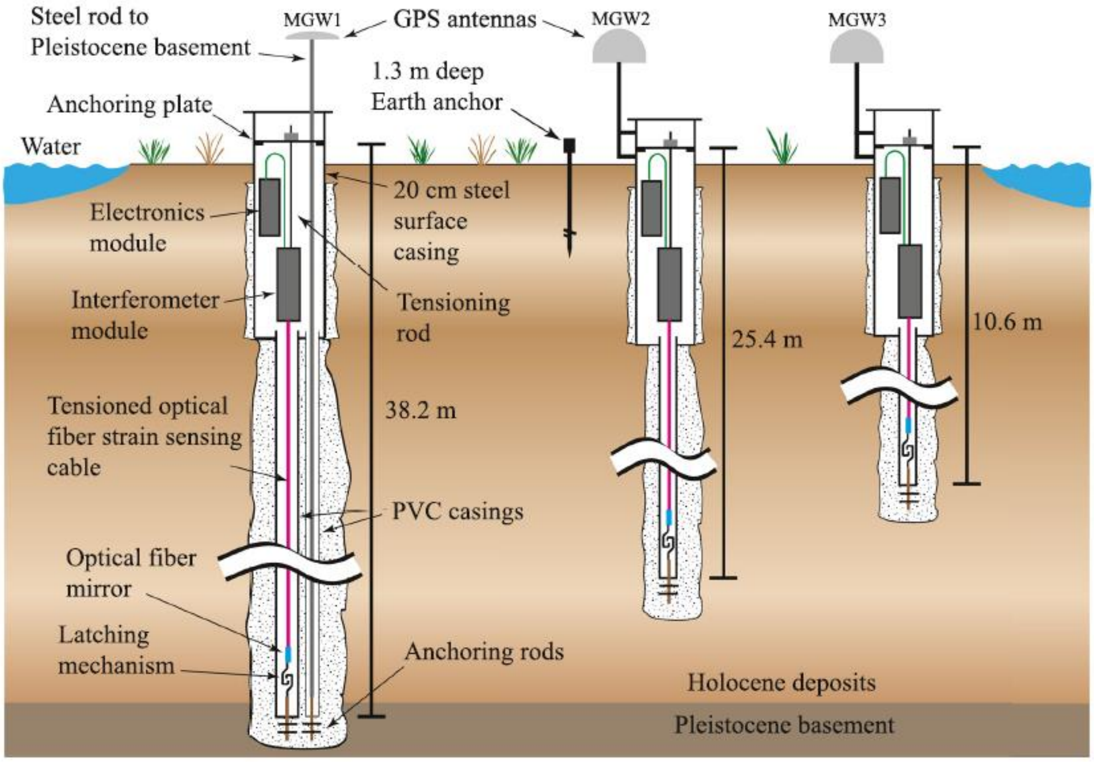

Figure 17 Extensometer setup using fiber optic strain sensing in The Mississippi Delta (Zumberge et al., 2022).

Two ‘anchors’ are used per borehole. Each borehole, therefore, measured a single interval. The top anchor consists of a ~3 m long steel casing, cemented into the shallow ground. Figure 17 suggests the deep anchor is placed near the base of the borehole in the backfill. However, no details are provided about the anchor type, its placement, borehole, and grouting. Measured displacements after five years of recording were found to be minimal (< 0,25 mm/yr).

Although the reported results of both applications look very promising, characteristics or specifications of this type of extensometer design and technique are rather unclear. This is discussed below the table.

Characteristics:

Item	**value**	**remark**
Commercial / institutional	Institutional/scientific	
Documented use	yes	
Minimum anchor spacing	Unclear	
Precision/resolution of anchor position		
Maximum number of anchors per borehole	Limited by minimum anchor spacing and feasibility of soft-soil anchor installation	
Risk of poor anchor-borehole wall coupling in soft soil	Presumably very high due to cable stresses	Discussed below
Displacement accuracy	< 0.1 mm/m	
Range (maximum displacement)	Limited by strain range	Discussed below
Feasibility automatic recording	yes	
Risk of sensor disturbance	Minimal with subsidence (needs 220 V)	Discussed below

Cost indication:
Likely high costs for permanent DFOS interrogator.
Likely low costs for maintenance.

Anchoring

- Groutable anchoring as used in the Chinese study will not work for very soft soils (peat/soft clay) and relatively large strains/displacements. Friction anchoring in the grout means the grout should be rather stiff with very low viscosity. However, with such properties the grout is expected to show less deformation than the surrounding soft soil, in particular when large displacements develop over time. A key question, therefore, is if it would it be possible to use borros, spider of hydraulic anchors with fiber optic cable.
  For the Mississippi Delta application, the anchoring to soft soil (marine mud deposits) is unclear. The authors state that ‘while there is no way to know if the anchor points at the base of the boreholes are stable, the consistency of the results among all of the measurements indicates that they are not moving relative to one another’.
- Intra-cable stresses will change dynamically with seasonal deformation (can be ~3 % in peat) and will need to be relatively high initially to accommodate significant long-term layer thickness loss. The forces exerted on the soft-soil anchors are an important concern because it may compromise adequate anchor-borehole wall coupling. Other extensometer types have a design where such stresses or forces are kept very small (free movement of rods in sleaths) or are virtually absent (type 2).

Range

- What would be the possible range of strain (shortening/extension) that can be measured? In many settings in the Netherlands dynamic strain of about 3% seem to occur, and if subsidence of 10 cm due to peat oxidation should be registered over many years, strain of several 10’s of % would be needed. One might expect that the compressional strain of fibre-optic cable measurement is relatively small. The cable would buckle in grout with low stiffness/high viscosity needed for soft-soil anchoring. If the range is on the order of 1%, applicability is limited for Holocene soft soil extensometry.

4.6 Type 6. Multi-borehole settlement plate type design

This type of design has been used primarily for detailed monitoring at relatively shallow depth. Features of the design of two studies are elucidated.

Figure 18 shows a setup for measurements in a 1.5 m thick peat layer (Kennedy and Price, 2005) where a ‘sight wire’ stretched between posts anchored in mineral soil was used for reference. Aluminum rods were used to minimize weight effects. The shallow three rods were anchored using 2.5 cm long plastic drywall screw grommets into which the rods were fixed. To provide stability for the rod installed at 5 cm depth, the rod protruded 5 cm below the peat anchor. The four deepest anchors consisted of a 5 cm section of flighted aluminum augur (=screw).

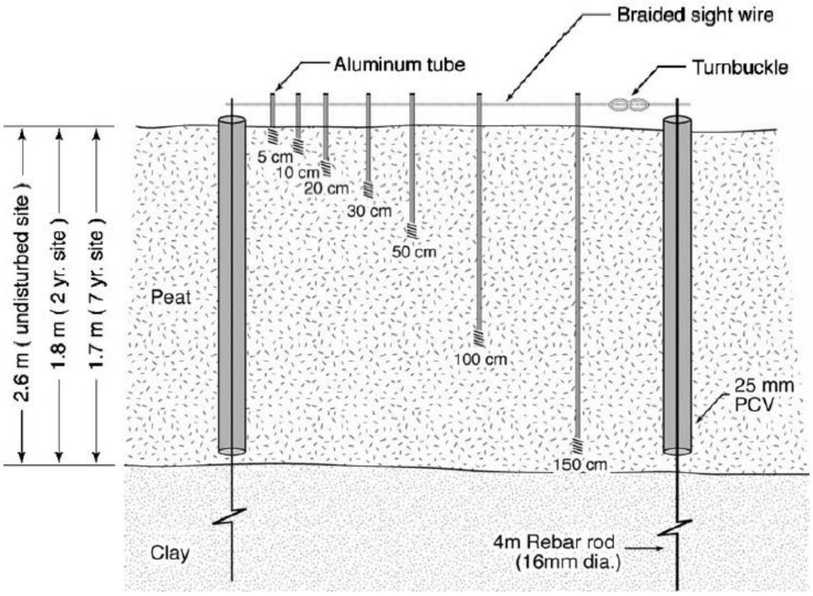

Figure 18: Schematic of the multi-borehole settlement plate setup used by Kennedy and Price (2005).

Te Brake et al. (2012) used rods to monitor vertical movement in clayey strata near Purmerend, Noord Holland, the Netherlands. The settlement plates were installed at 10, 20, 30, 60, 100 and 150 cm depth. The ground anchors consisted of metal rods with two 95 mm diameter discs at one end; one disk could rotate freely, and one was fixed to the rod. When a ground anchor was lowered in a 100 mm diameter auger hole it was coupled to the soil by rotating the rod, forcing both discs into the undisturbed sides of the hole (one anchor and rod is shown in Figure 19). After refilling the hole, a triangular frame was placed over the rod, resting on the undisturbed soil around the refilled hole on three pins. The length of the rod above the triangular frame, *L*, was measured between marked points on the triangular frame and at the top of the rod using a digital caliper to record the change in thickness of the layer between the anchoring depth and the “soil surface”. Note that each rod has its own reference: the ‘base of the triangular’ frame at the rod.

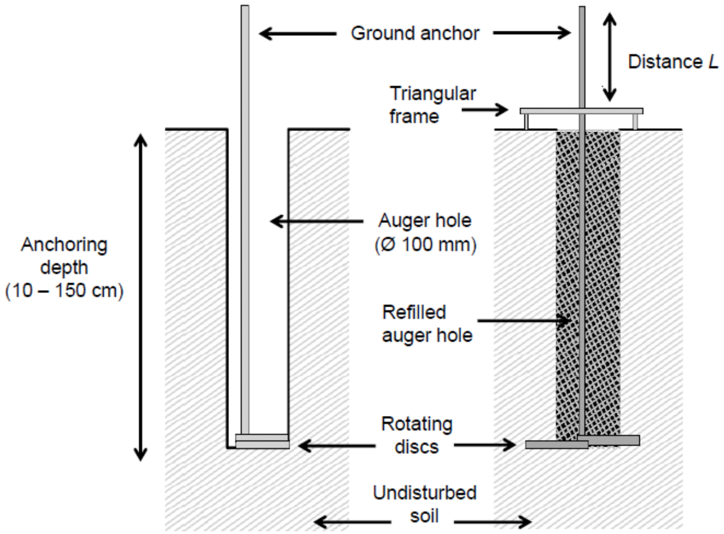

Figure 19: Schematic of the design of one of the settlement plates used in the study of Te Brake et al. (2012).

Characteristics:

Item	**value**	**remark**
Commercial / institutional	Institutional/scientific	
Documented use	yes	
Minimum anchor spacing	~ cm	
Precision/resolution of anchor position	< 1 cm	
Maximum number of anchors per borehole	1	Multi-borehole virtually unlimited
Risk of poor anchor-borehole wall coupling	Very low	
Displacement accuracy	~ mm	Depends on method and reference. Use of multiple references implies lower reliability/accuracy in measuring deformation of layers.
Range (maximum displacement)	unlimited	
Feasibility automatic recording	?	Not known
Risk of sensor disturbance	Depends on method	

Cost indication:
Depends on the number of boreholes and required depth(s).
Personnel costs for manual measurements.
Feasibility automated measurements unclear.

5 Discussion and conclusions

5.1 General findings

- Five different classes/types of single-borehole extensometer have been distinguished (Figure 2). Most of them can come with different choices of anchors, sensors, and sensor quality. A settlement-plate type multiple borehole setup is adopted as a sixth type. However, no examples with automated monitoring have been encountered for the latter type.
- There are marked differences in the qualities of the five (single-)borehole extensometer types. The overall advantages and disadvantages of the setups are summarized below in paragraph 5.3.1.
- The documented soft-soil anchor types are a key factor limiting the vertical resolution – this is the smallest layer thicknesses that can be monitored - that can be achieved with single borehole extensometers. Packer-type anchors and spider anchors couple to the soil over a relatively large section of the borehole (~ 40 cm). Borros anchors achieve a more localized coupling to the soil, but their design prevents them to be used within short vertical distance of each other or in proximity of and anchor of different type.

5.2 Remarks

- Experience with a classical multi-point extensometer (type 1) using packer-anchors will be developed in the parallel RDBGH project 10 "*Uitbreiding en monitoring van proefvakken*". In this project about 10 locations where subsided road sections are renovated, and elevated using light-weight materials, are monitored using extensometers. A type 1 extensometer (MPBX, Sisgeo) was chosen for most locations because it allows the well head of extensometer and the sensors to be completed below the road level in a practical way. Packer anchors were chosen rather than borros anchors for two reasons: (1) anticipated unfeasibility of manual placement of the borros anchors below the road foundation, often with extensive peat; (2) with the required automated placement of the anchors in the pre-drilled large diameter borehole, the prongs of the borros anchors would extend but a short distance into the soft soil (risk of poor coupling). The packer anchors ensure better coupling. The borehole was grouted with a soft grout.
- In the framework of the NOBV programme, experience is a type-6 setup is currently being gained at Zegveld, where settlement plate displacements are measured with GNSS loggers. That is, a satellite-based geodetic reference frame is used.
- Virtually nothing is known about the quality of anchor-soil coupling of soft-soil anchors. The only check that seems feasible is to judge if the measured soil layer behaviors seem to make sense. However, this does not guarantee sufficient quality. Measurement techniques that avoid or strongly limit forces exerted on the anchors should be preferred given this concern.
- In case the extensometer borehole needs to be backfilled after or during placement, grout properties are expected to be very important. Fill properties will generally differ from that of the surrounding soil and may interfere with the system response. Grout deformation properties and permeability play a role. Well thought-out choices are important, and should match expected deformations, both in the short- and long term. Independent study of the influence of fill properties is not evident. In settlement plate setups, the backfill likely is of lesser concern since the anchor (base plate) is sitting

at the base of the fill. Concerns about the backfill then primarily reside in disturbance of moisture conditions at shallow depth, for instance by enhanced infiltration via the borehole.

5.3 Evaluation of the alternatives

5.3.1 Summary of advantages and disadvantages of the extensometer types

Advantages	Disadvantages

1. Classical MP setup (used at the RDBGH sites)

• Forces on anchors small	• Limited number of anchors due to multiple rods
• Possible to adjust if max range is reached	

2. MP using alternative displacement sensing at the top

• Small or no forces on anchors	• Limited number of anchors due to multiple rods
• Large measurement range (magnetostrictive sensing)	•

3. MP sensing in access tube

• Number of anchors not limited by rods	• Low temporal resolution (manual)
• Simple installation	• Human factor in measurement (manual)
• ‘No’ forces on anchors	• Relatively low deformation resolution
•	• Only spider anchors (low spatial resolution)
•	• Correct functioning over time
•	• Potential poor coupling with soil

4. Inline, sensor at joints/anchors

• Large measurement range possible	• Sensors not accessible after installation; cannot be adjusted
• High accuracy possible	• Large number of wires in borehole (need protection)
•	• Accuracy/precision decreasing upward
•	• Vertical resolution (> 1 m)

5. Inline, sensing in segments (fiber optic)

• Number of anchors not limited by rods	• Forces on anchors; ground coupling
•	• Limited range/strain
•	• Costly in case of continuous monitoring

6. Settlement plate type

• Number of anchors potentially large	• Ambiguity due to lateral anchor distribution
• High vertical resolution	• low temporal resolution (manual)
• Accurate anchor position	• Human factor in measurement (manual)

5.3.2 Appraisal of the potential added value of the alternative design types

The appraisal of potential added value of the alternative design types in this section is relative to the value of the type 1 design that is used at the RDBGH monitoring sites.

Extensometer type 2 (multipoint; alternative sensing)
When fitted with magnetostrictive displacement sensors, type 2 extensometers may have some added value due to the large measurement range (stroke) of the sensor. This would be advantageous in settings with large magnitude (high rate) subsidence and/or where large seasonal movements occur. However, if use of magnetostrictive sensing has negative consequences for the number of anchors that can be used – this is unclear at present - this would limit the added value in that sense.
Other automated sensing methods such as hydrostatic sensing or optical sensing is unlikely to have added value. Manual sensing could be of interest in applications where low-resolution subsidence information needs to be gathered over a long period of time (> 10 year).

Extensometer type 3 (multipoint; sensing in access tube)
This type is judged to have little merit for application in subsidence research. Automated sensing is impracticable for this extensometer type. And effective (long-term) coupling of spider anchors with the soil is a concern (e.g., low expansive force of the spring mechanism and potential deterioration of this mechanism). Evaluation of this concern would nevertheless be of value, for instance through comparison with a type 1 or type 2 extensometer in a long-term test.

Extensometer type 4 (inline; sensors at joints)
Added value of this extensometer type is judged to be very small or absent. Inaccessibility of sensors due to their installation at depth in the borehole is considered a drawback. If installation of a prepared extensometer string of this type with a large number of anchors can be done relatively easily and reliably, this could be of some value.

Extensometer type 5 (inline; fiber optic sensing)
This extensometer type is expected to have no or little merit for subsidence monitoring of the relatively shallow Holocene soft soils due to concerns about anchoring and costs. However, improved soil coupling may be possible if packer anchors can be used. Costs may be saved in applications where low temporal resolution suffices and the sensing (laser) unit does not need to be present permanently.

Extensometer type 6 (multi-borehole settlement plate)
The most important quality of this extensometer type is flexibility in the choice of anchor spacing. Together with the precision accuracy of the ‘anchor’ position, in principle, layers of arbitrary thickness can be monitored. This becomes a clear added value when automatic sensing can be achieved. Hydrostatic sensing (Figure 11) would be an interesting option.

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Appendix A

Experiences and considerations that led to the ‘current’ extensometer design that is deployed at monitoring sites of NOBV and RDBGH.

In 2018 Deltares started exploring soft soil extensometry at a field site in a peat meadow near Rouveen using institutional funding. Since then, the extensometer design was improved/modified stepwise based on the experiences gained. Improved versions were installed at other locations near Rouveen – these sites were included in the NOBV programme –, at other NOBV sites, and more recently at the sites of the RDBGH. The experiences and considerations that led to the ‘current’ design are elucidated here in three steps. First some general considerations are described.

General considerations and conventional approaches
The first choices that have to be made when a (soft soil) extensometer is desired, is the anchor type and the method of placement. Generally, extensometers are emplaced in a borehole. Drilling is done to the level of the deepest anchor that is to be placed in the sand that underlies the soft-soil sequence, and that serves as a reference for the measurements on the higher anchors. All anchors are placed in the drill pipe. The deepest anchor consists of a massive cone. This cone is installed with a CPT-sounding vehicle or manually driven until refusal. The drill pipe is pulled, and the anchors – elucidated below - are inflated/squeezed, depending on the anchor type. The external diameter of the borehole typically is 125 mm. A grouting may be required, for instance with a soft grout. However, this may result in a significant disturbing column relative to in the soft peat soil, for instance, in which the measurements are taken.

Almost all suppliers supply borros anchors, grout anchors, hydraulic anchors, snap-ring anchors, magnetic rings (spider) and packer anchors.

Only the borros anchor can be pushed away in soft soil, whether or not after pre-drilling with a gouge of the same diameter. Installation by hand this way can be done up to a maximum of approximately 6 m below ground level and is particularly interesting since this avoids the disturbing effects of a large diameter borehole. In sand and heavier clay soils, there is a risk that the pipe used to press the pins will detach.

Borros anchor

First series
In Rouveen, where the first extensometer was installed, the soft soil layer sequence is only about 3 to 4 meters thick. Here it was possible to drive/hammer away the deepest anchor by hand. At several levels, borros anchors were placed (manually pushed away as described above). The desired anchor depth of 0.40 m below ground surface (bgs) proved too shallow to use a borros anchor. Those anchors are too long as the top of the anchor would hit the anchor plate at 0.05 m bgs. Therefore, a tailor-made anchor was used at 0.40 m bgs, consisting of a vertical rod with a steel strip of approximately 20 x 120 mm perpendicular to it.

To install this anchor, a trench the size of the strip was dug to the desired depth. The strip is then twisted about 60 degrees into the undisturbed soil at that depth with a handle.
In order to be able to measure ground level movement, the measuring head (extensometer head) is mounted on a perforated stainless-steel plate[8] that serves as an anchor. Placement at ground level would lead to spurious measurements due to the growth of grass and roots. To avoid such effects, an installation depth of 0.05 to 0.07 m was chosen.
All suppliers provide a hose to avoid friction of sagging soil on the rods between the anchors and the measuring head. The hoses are often a kind of PE water pipe and quite sturdy and difficult to extend or shorten. Because fairly large settlements are expected, a sturdy hose may compromise extensometer performance. Therefore, a more compressible/extendible corrugated hose was used instead.

For the 1st series of four extensometers that were installed in Rouveen in 2018, equipment was purchased from Geokon, an USA-based company which has a representative in the Netherlands. Although the quality of their products is considered high, they are reluctant to heed requests for adjustments of their standard designs. Also, only American thread sizes (e.g., 10-32) are used, which hampers combination with metric sized components.
For displacement sensing, vibrating wire (VW)[9] transducers were chosen with a range/stroke of 50 mm. The stroke was deemed fitting as displacements were not expected to exceed one cm per year at Rouveen.

Second series
First measurements with the installed extensometer at Rouveen revealed larger magnitude vertical movements than anticipated. Summer/winter, wet/dry fluctuations of several centimeters were recorded. Therefore, a switch was made to sensors with a stroke of 100 mm.
The total sensor length of a VW sensor with a range of 50 mm is about 300 mm. For VW sensors with a stroke of 100 mm, the sensor length increases to 450-550 mm (and for 200 mm stroke to 900-1100 mm). Installation of these longer sensors proved unfeasible because coupling between sensors and anchor rods is needed deeper below ground level (in the borehole). Therefore, a switch was made to more compact TX2 potentiometric sensors (from another supplier). They are quite compact and IP67 (dust-/moisture resistance).
There are sensors that are better able to withstand moisture, but they were not included because, among other things, they have up to a few kilos more resistance due to extra seals. The diameter of these sensors with higher moisture resistance is also too large, so they do not fit properly in the housing.

Third series
Despite the longer stroke of the sensors, some of them still ran out of range in the first half of the year. For the 3rd series, therefore, even longer-stroke TX2 sensors were used with a range of 200 mm. Because these sensors do not fit into the Geokon extensometer head, a switch was made to the larger measuring head of Geosense, England. Fixing discs are made in the Deltares workshop for fastening of the sensors in the measuring head (which is not designed for TX2 sensors).
The latest adjustment of May 2022 is an extra 50 mm disc between the stainless-steel anchor plate (at approx. 0.05 m bgs) and the measuring head, which puts the housing a bit more above ground level and makes the anchor rods easier to install.

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[8] Perforated sheet AISI 304; circular perforation 8 mm diameter / spacing 12 mm / open area 40%
[9] VW is the standard sensor that is delivered by Geokon.