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TECHNICAL COMMUNICATION

Instrumentation of Sealing Layers Made of Two Different Amendments (Green Liquor Dregs and Bentonite) to Till for Reclamation of Sulfidic Mine Waste

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Abstract
In Sweden, a dry cover solution is commonly used to stop sulfide oxidation and the production of acid rock drainage from unattended sulfidic mine waste. Recycling a non-hazardous industrial residue, such as green liquor dregs (GLD) generated during pulp production, in this cover solution is beneficial for both the mining industry where there is a great need for cover materials and the pulp production industry. The objectives of this field study were to install and evaluate the instrumentation of sealing layers made of GLD- and bentonite-amended till, and to evaluate the practical aspects of two different methods of installation: monitoring wells and pits. This practical field study demonstrated that it is difficult to properly seal the drill holes after installing the probes in observation wells and suggests that a better (easier and less costly) alternative for future instrument installation in a sealing layer might be to excavate a pit in the protective layer after installation of the soil cover and then drill the probes into the sealing layer from that pit.

Keywords ARD · Industrial residues · Field application · Monitoring · Dry cover · Reclamation

Introduction

The mining industry is the main producer of waste in Sweden and half of that mine waste is deposited and must be properly disposed of (Swedish EPA 2020). This mine waste can contain sulfide minerals that have the potential to produce acid rock drainage (ARD) if left in contact with water, oxygen, and oxidizing bacteria, e.g. acidithiobacillus (Akcil and Koldas 2006; Moodley et al. 2018; Saria et al. 2006). ARD is a multifactor pollutant as metals and metalloids can become mobile and affect the environment physically, chemically, and ecologically (Moodley et al. 2018; Saria et al. 2006). Soil covers are typically used to reduce the oxygen flux to the underlying reactive wastes in the relatively humid climatic conditions that exists in Sweden (Bussière et al. 2006; Collin and Rasmuson 1987; Dagenais et al. 2006). These covers usually consist of different layers, where the layer closest to the waste rock is called a sealing layer. Above the sealing layer, a protective layer is placed to protect the sealing layer from erosion, root, and/or frost penetration. The sealing layer in Sweden typically consists of a clayey till, or some other fine-grained compacted material that is kept close to saturation to prevent oxygen diffusion to the mine waste (Aachib et al. 2004; Aubertin and Mbonimpa 2001; Corey 1957). However, as the availability of a clayey till in the vicinity of the mines is often limited, there is a great need for alternative materials. Inert, non-hazardous industrial wastes, such as green liquor dregs (GLD), a residue from pulp production, has previously been shown to be suitable for a sealing layer (Mäkitalo et al. 2014, 2015a, b, 2016; Moyo et al. 2023; Nigéus et al. 2023a, b; Virolainen et al. 2020). It is fine-grained (d100 < 63 µm), has a higher water retention capacity (WRC) compared to materials with similar particle size, has a low hydraulic conductivity (10^{-8} and 10^{-9} m/s; Mäkitalo et al. 2014), and a low oxygen diffusion coefficient when close to saturation (Virolainen et al. 2020). Its low shear strength and high water content, however, makes it difficult, in a soil mechanical point of view, to use in a sealing layer on its own (Mäkitalo et al. 2014).

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Previous studies have however shown positive results when ≈ 10 weight percentage (wt.%) of GLD is mixed with till (Mäkitalo et al. 2015a, b; Nigéus et al. 2023a, b, c). Using an industrial residue in mine remediation is beneficial and serves a circular economy.

When evaluating the performance of a soil cover, the oxygen concentrations and water content are important factors to monitor. Keeping the sealing layer close to saturation limits the amount of oxygen diffusion to the mine waste (Aachib et al. 2004; Aubertin and Mbonimpa 2001; Corey 1957). Reducing oxygen transport to the waste material and minimizing water infiltration are the main functions of a soil cover in humid environments (Bussière et al. 2006; Collin and Rasmuson 1987; Dagenais et al. 2006). In northern Swedish climate, the winters are long (November to April) and cold (below zero degrees), which makes the temperature in the protective layer important to monitor to prevent cracks when the frozen soil water melts in the summer, which reduces the water retention properties and increases the hydraulic conductivity and diffusive oxygen flux (Benson and Othman 1993).

In this study, the instrumentation of a cover application on a waste rock dump in the Näsliden mine, northern Sweden was evaluated. The cover solution consists of sealing layers made of two different materials, a mixture of till and 10 wt.% of GLD, and a mixture of till and 4 wt.% of bentonite. This field application is described further in Nigéus et al. (2023c, in preparation). The objectives of the present study were: (i) to install and evaluate the practical aspects of instrumenting sealing layers made of GLD- and bentonite-amended till, and (ii) to evaluate the practical aspects of two different methods of installation: monitoring wells and pits. The evaluation and monitoring of mine waste covers are well studied (e.g., Adu-Wusu and Yanful 2007; Demers et al. 2017; Dobchuk et al. 2013; Kalonji-Kabambi et al. 2021; O'Kane et al. 1998; Power et al. 2017), but no work has yet been published on the instrumentation of a GLD-till mixture in mine waste remediation and the effectiveness of this instrumentation. Several studies have also successfully used some form of monitoring wells to install instruments in the cover system (e.g. O'Kane et al. 1998; van der Raddt 1988). Dobchuk et al. (2013) and Bussière et al. (2006) excavated a trench to install instruments in the mine waste and its cover systems. A practical comparison of these two methods of instrumentation has however not yet been published.

Materials and Methods

Materials

The materials used in the two experimental areas were a local silty till amended with 10 wt.% of GLD and the same silty till amended with 4 wt.% of bentonite (Fig. 1). The installation in the bentonite-amended till was used as a comparison when measuring the effect of the GLD mixture as a sealing layer material. The bentonite used was a *Danto-Con Seal N* from Odense in Denmark and the GLD was from the BillerudKorsnäs papermill in Karlsborg, northern Sweden. A summary of the physical characterization of the two mixtures used are presented in Table 1. The till and the amendments were mixed with an ALLU excavator bucket DH 4-17-X75. More information regarding the materials' chemical and physical characterization, the dimensioning, mixing, and application of the sealing layer are presented in Nigéus et al. (2023c, in preparation).

Figure 1 and Table 1 should be installed near here during the final printing process.

Instruments

The manufacturers, quantities and the accuracy of the instruments that were used in the instrumentation are presented in Table 2.

Application of the Instruments

In August 2016 and October 2017, an instrumented experimental area was constructed within the dry cover at the Näsliden mine (Fig. 1). The plan was to use only GLD-amended till as a sealing layer on the waste rock dump of the Näsliden Mine. However, due to the great variation of the GLD as a waste product, mainly in total solid content, such that the waste in the planning phase of the project (laboratory experiments, small scale application, and mixing-experiments performed in 2016), as described in Nigéus et al. (2023c, in preparation), was different from the waste that was to be applied on a full scale as a sealing layer in year 2017. Therefore, to be able to complete the cover application within a reasonable time scale, GLD-amended till was used only in the small experimental area (Fig. 1A) constructed in August 2016. The rest of the waste rock dump was covered with 4 wt.% bentonite-amended till in October 2017 (Fig. 1B).

An observation well and a pit were installed in both the GLD- and bentonite-amended till (Fig. 2). The monitoring wells (height (h) 2.7 m; diameter (∅) 1.5 m) were placed on the mine waste before application of the bentonite-amended till cover (Fig. 3A). The sealing layer was then applied and compacted around the wells by hand-driven machinery (Fig. 3C). The observation well with instruments that were to be applied to the sealing layer of the GLD-amended till (MW1; Fig. 1) was placed at the border of the August 2016-applied experimental area with the GLD-amended till. The probes were then drilled into the facing wall of that sealing layer made of GLD-amended till (Fig. 2). The pipes

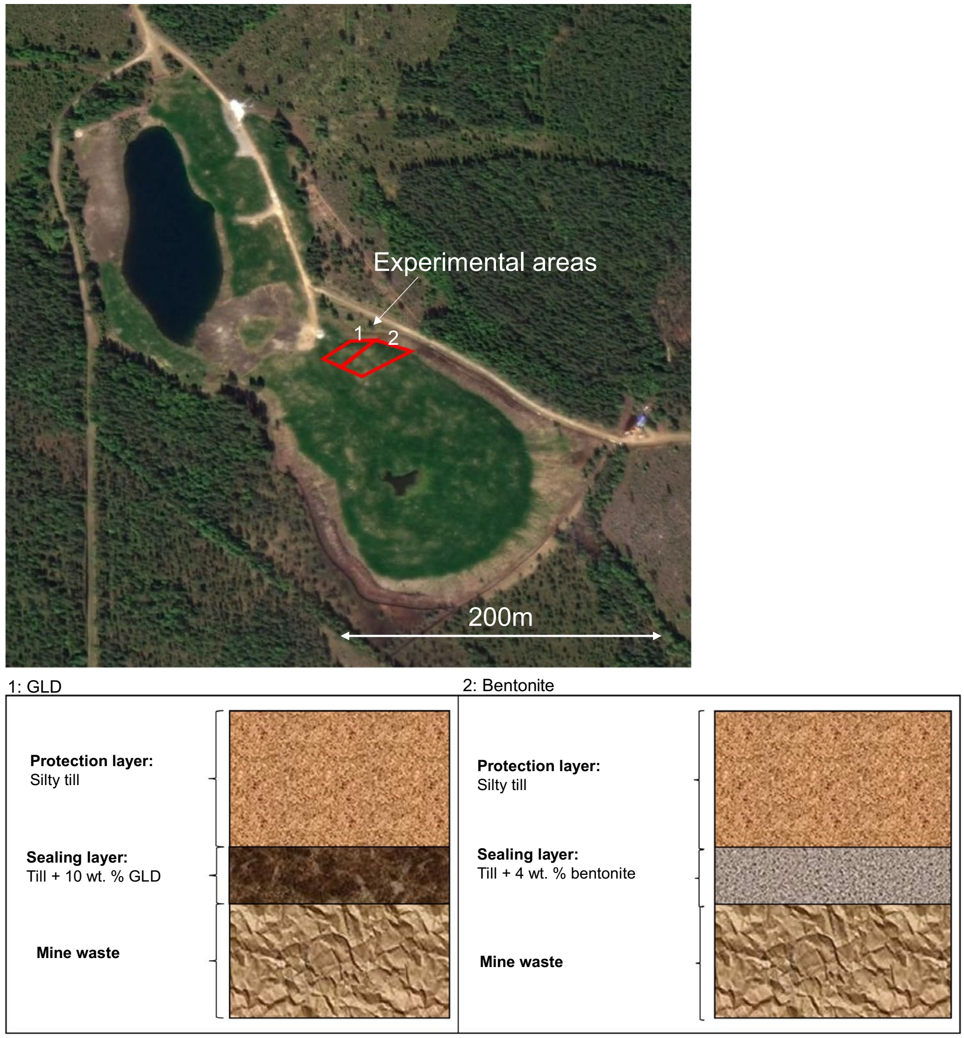

Fig. 1 A satellite picture and a profile of the Näsliden mine and experimental area. The lake in the satellite picture is the tailings pond and the green surface south of it is the waste rock area

Table 1 Physical characterization of the different sealing layer materials used in this study; saturated hydraulic conductivity (k_{sat}; m/s), dry density (ρ_d; g/cm^3), bulk density (ρ; g/cm^3), and molding water content (w; %)

Material	k_{sat} (m/s)	ρ_d (g/cm^3)	ρ (g/cm^3)	w (%)
Till + GLD	2.7×10^{-8}	1.97	2.19	11
Till + bentonite	1.2×10^{-9}	2.13	2.48	17

seen in Fig. 3A were cut off (as can be seen in Fig. 3B, C), to enable easier compaction around the wells.

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After complete application of the cover, two pits were dug with an excavator to a depth of ≈ 200 mm from the top of the sealing layer (Fig. 4C, D). The pits did not reach the sealing layer or the mine waste below because the mining company did not want the sealed mine waste to be disturbed during excavation. To install the measuring probes, holes were drilled with a machine-driven drill of 40 mm ∅ and 800 mm length, and when necessary (with probes thicker than 40 mm, or boreholes longer than 800 mm), a 60 mm ∅ manual drill was used. Tubes leading to the monitoring wells collected the cables from the instruments and were connected to the loggers there (Fig. 3B). The pits were then backfilled with the excavated material.

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From the observation wells and pits, four temperature probes (PT1000, EMS Brno) and two soil moisture probes (SM150T, Delta T-devices) were installed at different depths in vertical profiles (Fig. 4). Below and on top of the sealing layer, eight oxygen probes (SO110, Apogee instruments) were installed (Fig. 2). This was done horizontally before the sealing and protective layers were applied, to prevent oxygen diffusion through the cables. Two data loggers (Railbox RB32P4, EMS Brno) powered by solar panels were installed in the observation wells and the probes were connected to these loggers. Barometric air pressure was collected from the weather station at the mine site. Sealing foam (Fig. 3D) and

Table 2 The instruments used in this study

	Model	Manufacturer	Quantity	Accuracy
Temperature probes	PT1000	EMS Brno	16	±0.15 °C
Soil moisture probes	SM150T	Delta T-devices	8	±3%
Oxygen probes	SO110	Apogee	12	52–58 mV in 21% O_2, 2.6 mV per % O_2, 26 µV per 0.01% O_2
Data loggers	Railbox RB32P4	EMS Brno	2	

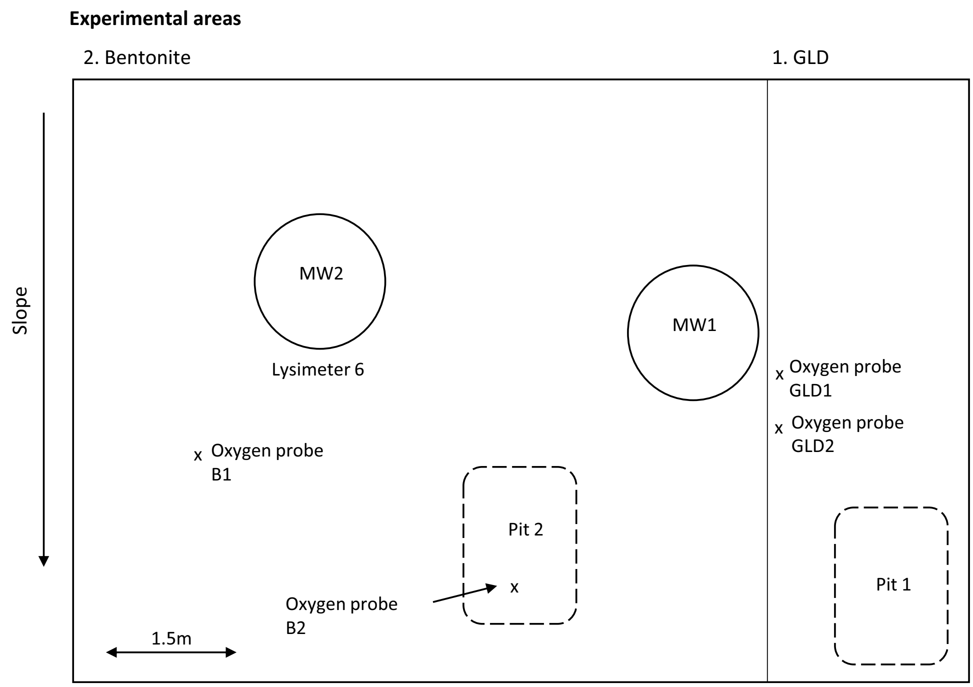

Fig. 2 Overview of the experimental areas in the sealing layers of the bentonite- (2) and GLD- (1) amended tills. Monitoring well 1 (MW1) was placed at the border of the sealing layer of GLD-amended till and the instruments were drilled into this layer

silicon was used to seal the boreholes and the tube connections from the pits. Insulation was applied to the parts of the well above the soil surface to prevent atmospheric influences on the temperature measurements.

Results and Discussion

The temperature probes were installed in the protective layer to be able to monitor the frost penetration and if the thickness of the protection layer was enough to protect the sealing layer from cracks caused by frozen water. Soil moisture probes were installed in the sealing layer at two different depths to measure soil moisture content and from that calculate the degree of saturation. Previous studies have shown that 85% degree of saturation is enough to ensure minimal oxygen diffusion through the layer (Aachib et al. 2004; Aubertin and Mbonimpa 2001; Corey 1957), and by that deter the oxidation of sulfides and ARD formation in the mine waste (Akcil and Koldas 2006; O'Kane 1995; Yanful 1993). The oxygen probes were installed below and on top of the sealing layer, to be able to calculate the oxygen flux. The oxygen diffusion coefficient can then be estimated using Fick's first law (Elberling and Nicholson 1996) and the volumetric water contents, porosity, and degree of saturation,

Both a monitoring well and a pit was chosen as a way of installing the instruments as both had successfully been used in previous studies (Dobchuk et al. 2013; O'Kane et al. 1998; van der Raddt 1988). A positive aspect of a monitoring well is the possibility of horizontal installation of the probes, minimizing the amount of preferential flow through cables. Another positive aspect is the theoretical possibility to reinstall or replace malfunctioning probes. The data logger is also protected within a monitoring well. However,

Fig. 3 **A** A picture of one of the monitoring wells installed in the dry cover. **B** One of the pits and the cables from the instruments that led to the monitoring wells. **C** The hand-compacted sealing layer closest to the wells. **D** The connection from the probes to the wells were insulated first with local material and then with foam insulation and silicon to keep them sealed from atmospheric influence

some difficulties were encountered during the instrumentation of the monitoring wells. One was that it was difficult to seal the bore holes with local material. Therefore, foam insulation and silicon were used in the bore holes of the wells to ensure that they were sealed, and that no oxygen would diffuse from the wells through the bore holes and the cables. Another possible downside of a monitoring well is that it can act as a pathway of water and oxygen through the dry cover to the mine waste. Pits on the other hand are cheaper, both considering material- and labor, as the only cost for the pits are the expenses of an excavator. Also, the disturbance to the sealing layer during installation was minimal, as only the protective layer was excavated, and the pits were backfilled after installation of the instruments. The boreholes were backfilled as well, as much as was possible, and are expected to be compacted by the pressure of the cover once it has stabilized. However, the instruments in the pit had to be installed vertically instead of horizontally, as the mining company did not want the mine waste underneath to be disrupted once it had been covered. This vertical installation might have created a possible preferred pathway for the percolating water, which might lead to an overestimation of the soil moisture content.

Some things in this field study did not go as planned. For example, the plan was to install instruments in both the slope and plateau of the dry cover. But due to the shortage of GLD with the right properties [see Nigéus et al. (2023c, in preparation) for more information], the instruments were installed in the GLD-amended till and the bentonite-amended till instead of the GLD in most of the sealing layer. The GLD-amended till that was applied in 2016, was applied on a slope, and therefore the instruments in the bentonite-area also needed to be installed on a slope to allow the results to be compared. The effect of the slope should be considered when analyzing the data from the instruments. Previous studies have shown high seasonal groundwater in toe slopes due to groundwater discharge and runoff (e.g. Dobchuk et al. 2013). Another

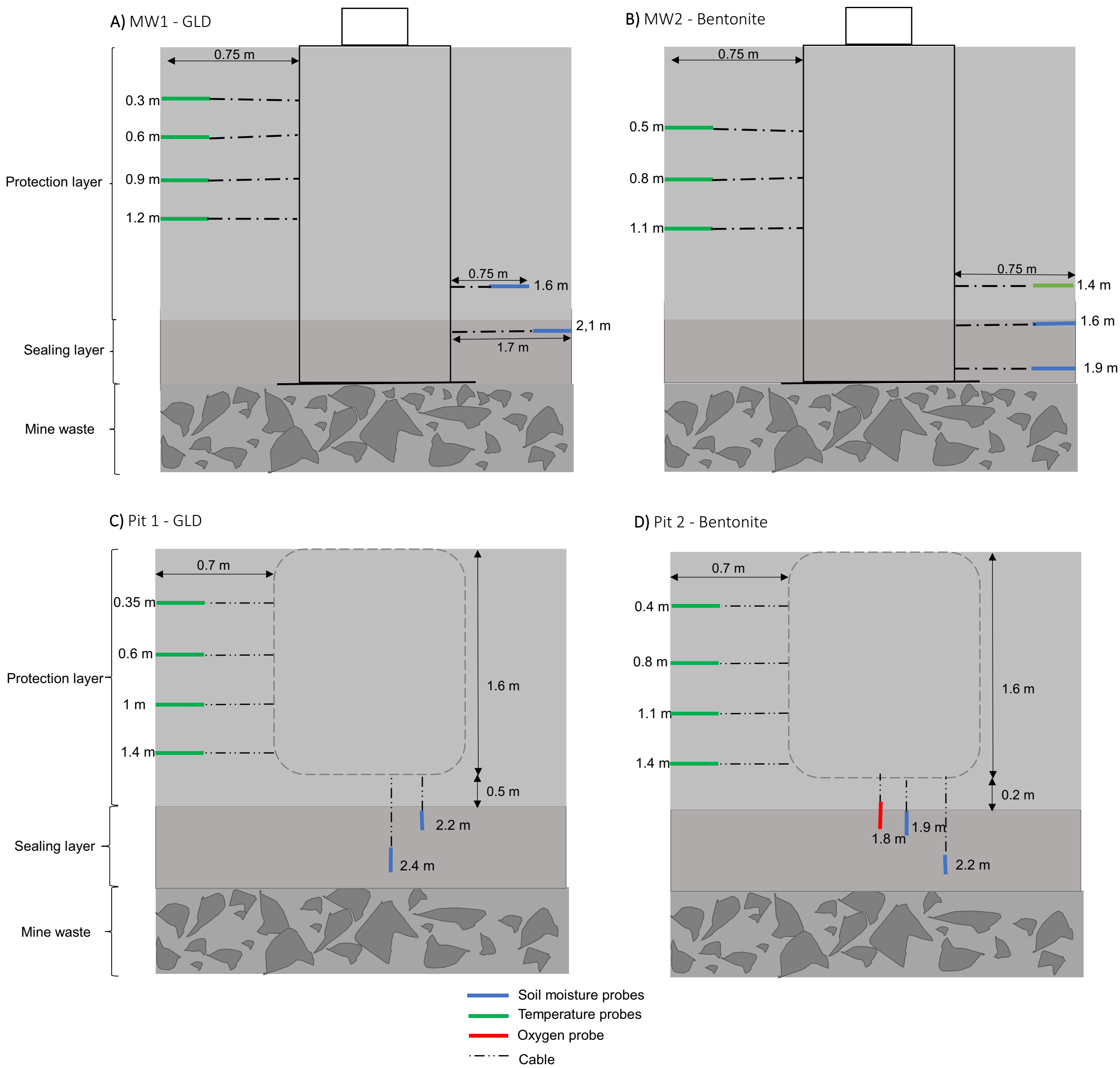

Fig. 4 A schematic picture in profile of the two monitoring wells, **A** MW1 and **B** MW2, and the two pits, **C** Pit 1 and **D** Pit 2. in the GLD- and bentonite-amended areas. The soil moisture probes are blue, the temperature probes green, and the oxygen probe red

unplanned factor was that only one, instead of two, soil moisture probes was installed in the GLD-amended sealing layer from the well (Fig. 3A). At the moment, the probes will allow soil moisture values in the sealing layer and in the lower part of the protective layer to be compared, which should be a good enough indicator if the sealing layer works as expected, since the monitoring well was installed next to the GLD-amended experimental area, not in it. However, it turned out to be difficult to find the GLD-mixture from the well, and only one borehole reached this layer. Yet another factor that did not go as planned was that one oxygen probe was installed afterwards instead of before the dry cover was applied (oxygen probe B2 upper; Fig. 2). The area of installation was to be used as a transport route for heavy machinery when the cover was applied, and the oxygen probe could be damaged if installed before the application of the cover. The measuring values are not expected to be affected as the oxygen probe was installed above the sealing layer and the pit was filled up and compacted with an excavator after installation.

Conclusions

An evaluation of the practical instrumentation aspects of this study suggests that future installation of instruments in a sealing layer should involve excavating a pit in the protective layer after the soil cover is installed and then drilling the probes into the sealing layer. The pit would then be backfilled, with the cables leading to the surface where the data logger is installed. Monitoring wells and installing instruments through them is by experiences from this field study, not the best option. It was more labor-intensive and costly than planned and created an unnecessary potential of leakage through the boreholes and through the walls of the monitoring well. However, the possibility of the percolating water having a preferred pathway through the cables when the instruments are installed vertically from the pits should also be considered. Monitoring of the actual data will allow an accurate and full evaluation/comparison of these two ways of installing the instruments (Nigéus et al. 2023d, in preparation).

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Data availability Data is available by email to corresponding author on reasonable request.

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