Design, Construction and Preliminary Results for an Inclined Store-and-Release Cover Experimental Cell Built on an Abandoned Mine Site in Morocco

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ABSTRACT

In arid and semiarid climates, acid mine drainage (AMD; also called acid rock drainage, ARD) generated by mine tailings can be controlled by reducing water percolation. The use of store-and-release (SR) covers with capillary barrier effect is emerging as the most effective way to prevent water percolation through tailings under these climates. Four instrumented experimental cells made of phosphate wastes, as SR covers, were constructed on top (flat surface) of the abandoned Kettara mine site (near Marrakech, Morocco). Results confirmed the potential of phosphate mine waste as SR cover material to control water percolation. However, significant uncertainties remain about the influence of inclined conditions on the hydrogeological behavior of a SR cover at the mine, as the mine wastes at Kettara mine site are retained by dykes that reach a height of 10 m. Due to the slope inclination, water can accumulate above the tilt interface during extreme precipitation events, which could create a breakthrough of the capillary barrier; at this location, the cover is no longer effective to control water infiltration into the mine wastes. A field investigation was conducted to evaluate the influence of the slope on the Kettara SR cover's performance. An experimental field cell (10 m wide by 8 m long) inclined at an angle of 14.5 degrees was constructed on-site. The SR cover retained is made of 0.8 m of phosphate waste, placed over a capillary break layer made of coarse-grained materials. Cover performance was monitored using lysimeters, Tensiometers, suction and soil moisture sensors installed at four stations and at different depths. The paper presents the design, the construction and the instrumentation of an inclined SR covert. Preliminary results of the monitored parameters under natural conditions are also included. The field test showed that the slope influences water distribution in the cover with more water at the bottom of the slope. The inclined SR cover still effectively limited water percolation under natural conditions.

Keywords: Acid mine drainage -Experimental cell- inclined store-and-release- design and construction-mine site reclamation

INTRODUCTION

Acid mine drainage (AMD) from mine wastes is the main environmental problem facing the mining industry. It is a common practice to construct single or multi-layered engineered cover systems to control AMD from waste rocks and tailings. In dry climates, where the potential evaporation rate exceeds the annual precipitation, these cover systems are usually used to limit water percolation into mine waste disposal (e.g., Albright et al., 2004; Hauser, 2008). These covers use the physical process of evaporation or evapotranspiration to control water percolation into the reactive wastes (e.g., Morris and Stormont, 1997; Albright et al., 2004; Rock et al., 2012, Bossé et al., 2013). These cover systems are known as alternative covers, evapotranspiration (ET) covers, water balance, or store-and-release (SR) covers; this terminology (SR cover) will be used throughout this paper. The technology of SR covers has been applied with success to several mine sites such as Kidston Gold Mines (Australia) and Barrick Goldstrike Mines (Nevada, US) to control acid mine drainage (AMD) generation from sulfidic mine wastes (Zhan et al., 2001, 2006; Williams et al., 2006). The concept of this approach is to control water percolation by using a moisture-retaining layer (MRL) that acts as a sponge or a reservoir by storing water during precipitation events, and then releasing it back to the atmosphere by evaporation (e.g., Rock et al. 2012, Bossé et al., 2013). The water storage capacity in the MRL can be increased by the implementation of a capillary break layer (CBL) below the MRL. If the hydrogeological contrast between the two materials (MRL and CBL) is sufficient, capillary barrier effects (CBE) will control the water flow at the layers interface and increase the water storage capacity of the MRL. More details on CBE can be found in Morel-Seytoux, (1992) and Bussière (1999).

The abandoned pyrrhotite mine site, Kettara, is one of several abandoned AMD-generating mine sites in Morocco. The site is located in an arid climate (Bossé, 2014) approximately 35 km north-northwest of Marrakech (31°52′15″N–8°10′31″W). The region's climate is characterized by a bi-modal precipitation pattern with wet (October-April) and dry (May-September) seasons. The annual cumulative rainfall and the potential evapotranspiration (PET) are estimated at 334 mm and 2,178 mm respectively. The tailings pond area contains approximately 1,800,000 tons of mine wastes (Lghoul et al., 2012). These wastes were deposited at the surface without any concern about the environment (Hakkou et al., 2008, Bossé, 2014). This mine waste is considered as highly acid-generating, with negative net neutralization potential (NNP) values ranging from -453 to -22.5 kg $CaCO_3$/t (more information on Kettara mine waste characterization can be found in Hakkou et al., 2008). Indeed, this contaminated drainage is a source of pollution in this region that affects the surrounding ecosystems as well as the people living nearby the mine site (e.g. Khalil et al., 2013). One of the most promising reclamation options to control AMD generation at this Kettara mine site is the use of a SR cover system that integrates CBE. A very helpful factor facilitating the mine rehabilitation is the availability of alkaline mine wastes, generated by phosphate mines located nearby to be used for the MRL.

Four instrumented experimental cells (1D), made of phosphate wastes as SR covers, were constructed on top of the Kettara mine site to evaluate the use of the phosphate mine waste as MRL in the SR cover (Bossé, 2014). Results confirmed, for 1D conditions, that the phosphate limestone has the appropriate properties to become part of an efficient SR cover to reduce rainfall percolation and control AMD. However, uncertainties remain about the influence of inclined conditions on the hydrogeological behavior of a SR cover at the mine, as mine wastes at the Kettara mine site are retained by dykes (coarse mine wastes) that can reach a height of 10 m. Due to slope inclination, water can accumulate above the tilt interface during precipitation events, which would increase the water pressure at this location. When the pressure exceeds the water-entry value of the coarse-grained material, a breakthrough of the capillary break can occur at the interface, and the cover becomes no longer effective to control water percolation into the AMD-generating mine wastes (e.g., Ross, 1990; Steenhuis et al., 1991; Bussière, 1999; Aubertin et al., 2009; Maqsoud et al., 2011). In order to investigate the slope effect for the SR cover at the Kettara site, an experimental inclined SR cover was constructed. The objective of this article is to present the design and construction in the field of an instrumented inclined SR cover, and the preliminary results accumulated during the first months of monitoring. As mentioned earlier, one of the originalities of this work is mainly related to the use of phosphate limestone wastes generated by a sedimentary phosphate mine, located close to the abandoned Kettara mine site, to construct the cover system.

FIELD EXPERIMENTAL CELL DESCRIPTION AND MATERIALS CHARACTERIZATION

Design and construction

The work was initiated during March 2014 at the Kettara mine site to evaluate the slope effect on the hydrological behavior of a SR cover system. The tested SR cover is made of two layers: a MRL made of 0.8 m of phosphate mine waste placed over CBL made of Kettara's coarse grained mine waste. The slope is approximately 14.5 degrees and the field cell area is about 10 × 34 m (Fig 1). A 3D schematic representation of the inclined field instrumented SR cell is presented in Fig 1.

The field experimental cell was constructed directly on the retention dyke. The dyke is 8 meters high and made of the reactive coarse-grained material at Kettara mine site (Fig 1).

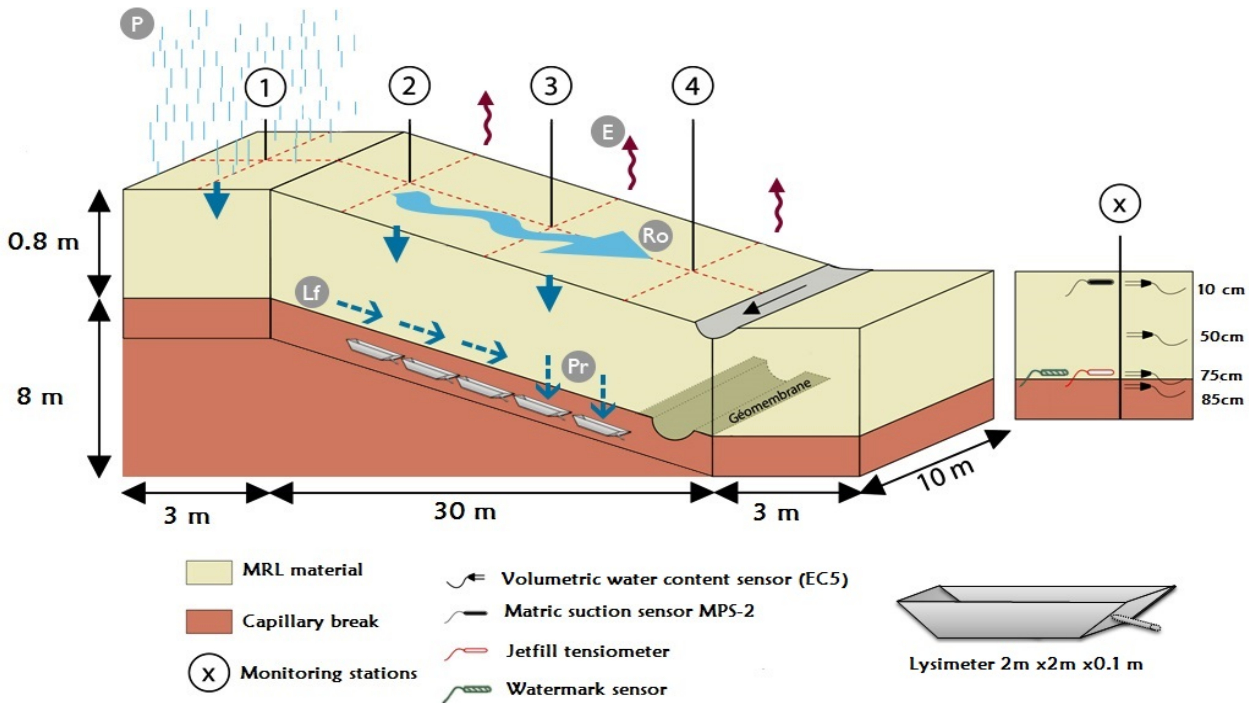


Figure 1 3D schematic representation of the field instrumented cell (E: evaporation; P: precipitation; R0: runoff; Pr : percolation; Lf: lateral flow); locations 1 to 4 on the slope are the monitoring stations

The MRL material was placed and compacted with a manual compactor to a dry unit weight of 15 kN/m^3. The experimental cell was constructed in different steps. The slope was first flattened and compacted (Fig 2-step 1) to a targeted porosity (n) of approximately 0.37 m^3/m^3 (dry unit weight = 18.3 kN/m^3). Five lysimeters were installed in the CBL material to monitor water percolation at the base of a cover system (Fig 2-step-2). The water collected may drain out of the lysimeters through a pipe by gravity. The phosphate limestone wastes were then placed and compacted at their natural water content (w ≈ 4%) to a porosity of approximately 0.41 m^3/m^3 (Fig 2–step-3). The material was compacted in successive lifts of about 20 cm thick to ensure a uniform density. Surface and lateral drainage systems were installed at the toe of the slope (Fig 1). The lateral drainage consists of the water that flows at the interface between the CBL and MRL due to the capillary barrier effects

(Fig 3.e). The surface drainage collector was installed to quantify the runoff water and to facilitate the calculation of the water balance (Fig 3.f).

Field instrumentation and monitoring

Field performance of the tested inclined SR cover is monitored by measuring the percolation through the CBL, the changes in moisture conditions (ΔS) within the cover layers, the internal lateral flow, run off and climatic conditions. Five lysimeters (2 m x 2 m x 0.1 m) were installed to measure water percolation into the underlying mine wastes at a depth of 90 cm from the cover surface (fig. 2 step 2). Daily precipitation (rainfall) i measured using an automated weather station (HOBO U30-NRC) installed at the Kettara mine site (fig 5.c; see Bossé, 2014 for more details). Changes in ΔS are estimated using ECH2O volumetric water sensors (EC5) (fig 3.a) and measured indirectly by matric suction sensors (MPS-2) (fig 3.b). Tensiometers and Watermark sensors are also used to measure matric suction in the inclined SR layers (fig 3.d). Tensiometers can measure suction between 0 and 80 kPa with an accuracy of 1 kPa, while the suction range of Watermark sensors is from 0 to 200 kPa (Bussière, 1999). The MPS-2 can measure suction between 10 kPa and 500 kPa (Bossé, 2014). Note that the three instruments (MPS-2, Tensiometers, and Watermarks) were soaked in water before installation to improve early measurements.

Before installation, EC5 sensors were calibrated for each material in the laboratory. The Tensiometers were inserted carefully at the required depth (75 below the surface) to ensure good contact between the high air-entry ceramic cups of the Tensiometers and the MRL material. Four EC5 sensors were placed at depths of 10, 50, 75 and 85 cm into the cover system, and a matric suction sensor (MPS-2) was placed at depth of 10 cm. To be able to compare measurements, JetFill tensiometers and Watermark sensors were placed beside each other at each monitoring station at a depth of 75 cm (close to the interface between the MRL and CBL). All monitoring stations were placed near the central axis of the cell. Manual monitoring of the Tensiometers and Watermark sensors is done three times per week while the monitoring frequency for the EC5 and MPS-2 sensors is a measured every 30 minutes

Materials characterization

The main properties of the inclined SR cover components (the phosphate limestone wastes, and Kettara coarse-grained mine) used in the experimental cell are summarized in Table 1. Material particle size distribution was determined using a Malvern Mastersizer laser particle size analyzer and by sieving (ASTM D 6913-04 2009). The specific gravity (Gs) was estimated with a Micromeritics Accupyc 1330 helium gas pycnometer (ASTM D5550-06 2006). The liquid limit (w_L), plastic limit (w_p) and plasticity index (PI) of materials were determined by Bossé et al., (2013) using ASTM standards (ASTM 4318-10-2010).

Step 1 Step 2 Step 3

Figure 2 Photos illustrating the field inclined SR cover construction steps

The specific gravity (Gs) and the percentage of fines (< 80 µm) of the phosphate limestone wastes were respectively estimated at 2.85 and 15%. The liquid limit wasless than 50%, the plasticity index was estimated to be 0.8 and the material is categorized as a non-plastic sandy silt according to the USCS classification (e.g., McCarthy 2007). The air-entry values (AEV- pressure at which the material starts to drain) of the phosphate and coarse tailing were-40 kPa and -0.1 kPa respectively. The water-entry values (WEV-pressure at which the water starts to enter) were -2000 kPa for the MRL material and -0.4 kPa for the CBL material (Bossé et al., 2013). The saturated hydraulic conductivity (k_{sat}) of the coarse-grained material (5.9 cm/s) was substantially greater than the one of the fine-grained material (5.7×10^{-6} cm/s; see tab 1). This important contrast in hydraulic properties between the two materials with different textures restricts water flow at the interface and enhances the water storage capacity of the fine grained layer (e.g., Khire et al., 1999). More information on phosphate limestone waste characterization can be found in Bossé, (2014)

PRELIMINARY RESULTS

After the construction of the experimental field cell, an important wetting event was simulated using drip irrigation tubes connected to a pump and installed on the inclined SR cover surface. Approximately 100mm of water over a period of 48 hours was applied to the tested area, to assess the behavior of the water diversion capacity of the cover. The hydrogeological behaviour of the inclined SR cover after the wetting event was also monitored.

Hydrogeological behaviour of the inclined SR cover during the wetting event

This section presents the behavior of the experimental cell test during the simulated wetting event. Figure 4 shows the fluctuation of volumetric water content (θ) within the inclined SR cover at 75 cm depth (fig 4.a) and 50 cm depth (fig 4.b) for the four monitoring stations (station 1 is located at the top and station 4 at the bottom; see fig. 1). The fluctuations of matric suction (ψ) measured with the watermark sensors (fig 4.c) and JetFill tensiometers (fig 4.d) are presented and compared for the 75 cm depth (close to the interface of the CBL and MRL). Note that a significant rainfall event occurred during construction which led to an increase in the moisture content in station 1, especially at the depth of 75 cm. The observed θ results at 50 cm and 75 cm depth are quite similar. During the wetting event, it took about 2 days to notice an increase in volumetric water content at station 2, 3 and 4 with a water arrival first at station 2, followed by station 3 and 4.

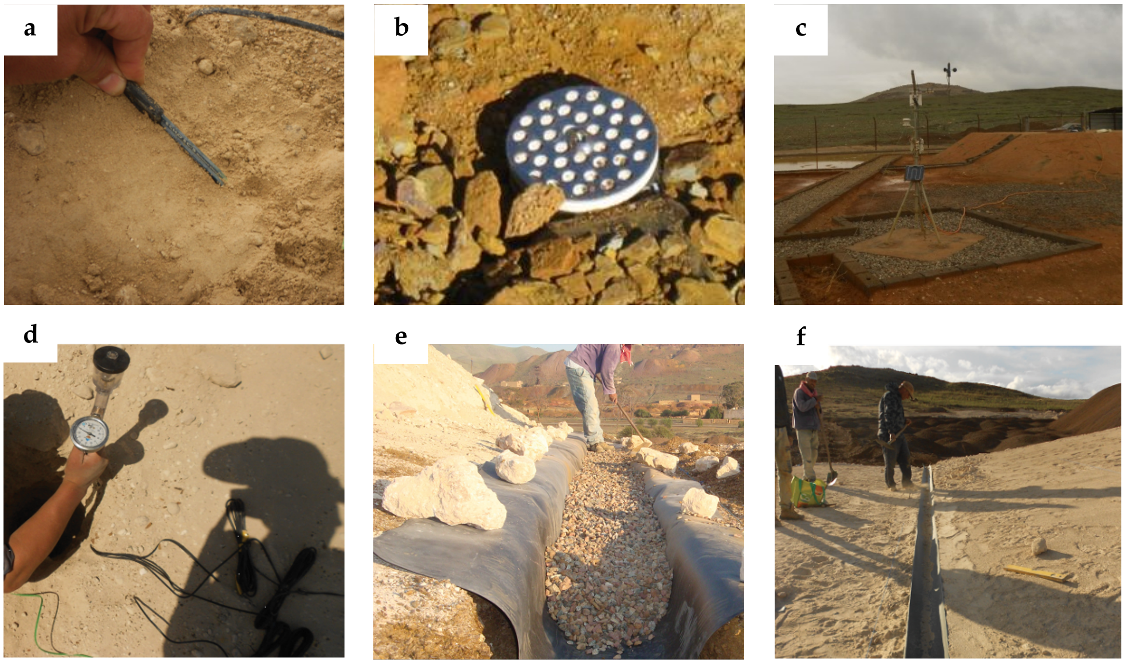


Figure 3 Photos illustrating the instrumentation used for the monitoring of the inclined SR cover: (a) Volumetric water content sensors (EC5) (b) Matric suction sensors (MPS-2) (c) Weather station (d) JetFill tensiometers (e) Lateral drainage collector (f) Surface drainage collector

Table 1 Basic properties of MRL (Phosphate limestone waste) and CBL (Kettara coarse-grained waste) materials

Parameter	Phosphate limestone waste	Kettara coarse-grained waste
Specific gravity	2.85	2.90
D_{60} [mm]	0.31	6.3
D_{10} [mm]	0.07	1.13
Fines content (< 80µm) (%)	15	7
w_L(%)*	26.4	-
w_p (%)*	25.6	-
PI (%)*	0.8	-
k_{sat} (cm/s)*	5.7×10^{-6}	5.9
AEV (kPa)*	-40	-0.1
WEV(kPa)*	-2000	-0.4
Classification (USCS)*	Sandy silt	Poorly graded gravel with sand
Mineralogy by order of importance**	Calcite/fluoapatite/ Dolomite/quartz	Pyrite/pyrrhotite/ chlorite-serpentine, quartz, talc

* Values from Bossé et al., (2013); ** Values from Hakkou et al., (2009)

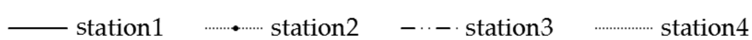
The wetting event did not have an impact on θ values at station 1 because water accumulates above this elevation; this behavior was also observed by Bossé, (2014) in a similar cover built on a flat surface. The magnitude of the volumetric water content increase is more pronounced at 50 cm than 75 cm depth but the MRL material didn't reach the saturation value (= porosity) of 0.41. It can also be observed that, as expected, the θ values are usually higher close to the bottom of the slope (station 3 and 4; typically between 0.30 and 0.35) than close to the top. This behavior is due to the diversion capacity of the inclined SR cover; theoretically, water flows along the interface between the MRL and CBL until the MRL become nearly saturated and the pressure at the interface reaches the water entry value of the CBL material (e.g. Steenhuis et al., 1991; Aubertin et al., 2009). Note that no water flow was observed in the different lysimeters and no change in terms of θ in the CBL was detected; confirming that the tested inclined SR cover was able to divert the water during the wetting event. Field lysimeter is a very important tool to evaluate the performance of cover systems. The design involves different parameters such as the geometry of the lysimeter, hydraulic properties of the backfill material, and boundary conditions (Bew et al., 1997). Suction inside and outside the lysimeter must be similar to avoid preferential outward flow. It is worth mentioning that during another wetting event of 155mm/48h simulated in November 2014, water percolation was detected in the 5 lysimeters (Knidiri, 2015). These results prove that even if the height of the lysimeters is small (0.1 m), the lysimeters function well enough to detect a breakthrough of the capillary barrier.

The trend of ψ evolution during the wetting event close to the interface between the CBL and MRL is similar for the four stations. After the wetting event, the ψ value starts to decrease from values between 40 and 85 kPa to values below 20 kPa due to water accumulation. The lowest values were observed near the bottom of the slope where θ increased the most (station 3 and 4). It is interesting to note that both equipments tested (Watermark sensors and Jetfill tensiometers) gave similar trends even if the absolute values can be slightly different.

The hydrogeological behaviors of the inclined SR cover during summer 2014

Figure 5 illustrates hydrogeological behavior of the tested inclined SR cover exposed to natural climatic conditions after the wetting event; rainfall measured during this period is presented in red. Results indicate a decrease of the θ few days after the wetting event due to evaporation during the dry summer conditions. The daily air temperature during this period ranged from 15°C to 33°C with an average of 23.5°C. The fluctuation of θ is more pronounced at 10 cm depth than at 50 cm and 75 cm depth; this is due to atmospheric forcing that affects essentially the surface of the inclined SR cover. However, the effect of evaporation is also present at 50 and 75 cm, particularly for stations located close to the bottom (station 3 and 4) where a constant decrease of the volumetric water content is observed. Hence, the inclined SR cover is presently regaining its full capacity to store further precipitations by transferring water to the atmosphere via evaporation.

In summary, preliminary results show that the hydraulic behavior of the inclined SR cover is influenced by the inclination of the slope. θ in the inclined SR cover is greater at station 3 and 4 which are located in the lower slope positions of the inclined cover. No lateral flow and no percolation were observed during this wetting event. Water accumulated and was diverted by the capillary barrier effects at the interface of the two layers (CBL and MRL) to the bottom of the slope. The suction results indicate that the breakthrough of the capillary barrier (or the Down Dip Limit (DDL), Ross, 1990) was nearly reached at the bottom of the tested inclined SR cover with suction value close to 0 at station 4. These preliminary results also indicate that the cover is presently releasing the water stored during the wetting event to the atmosphere via evaporation.



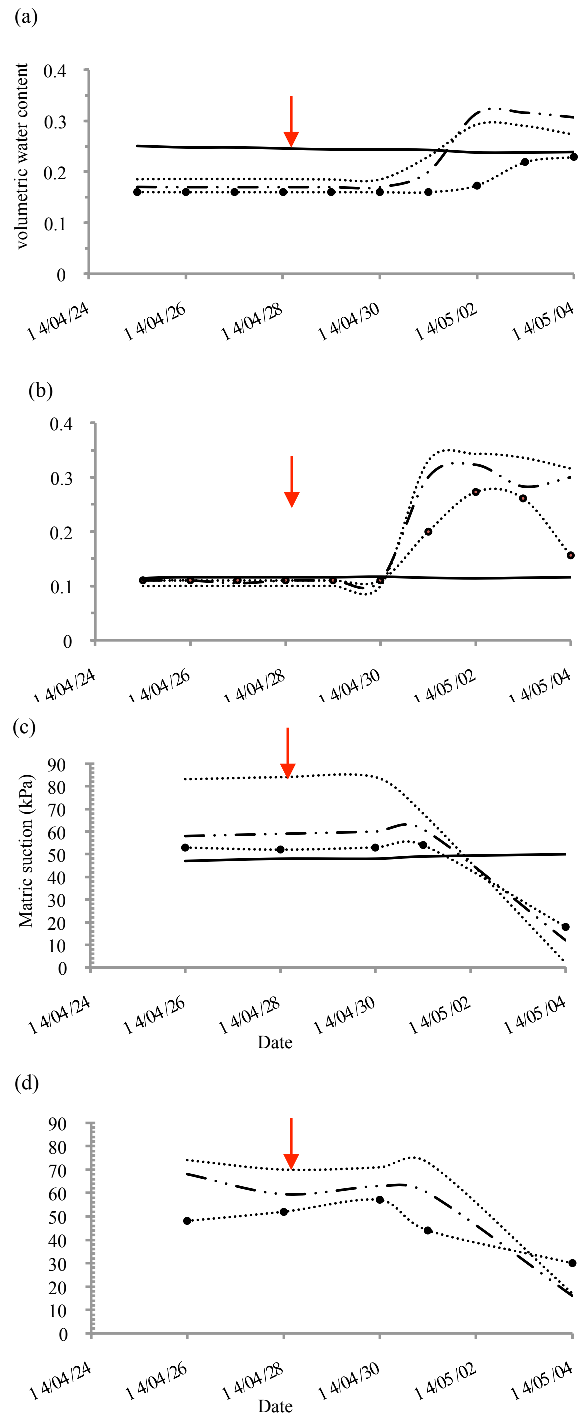


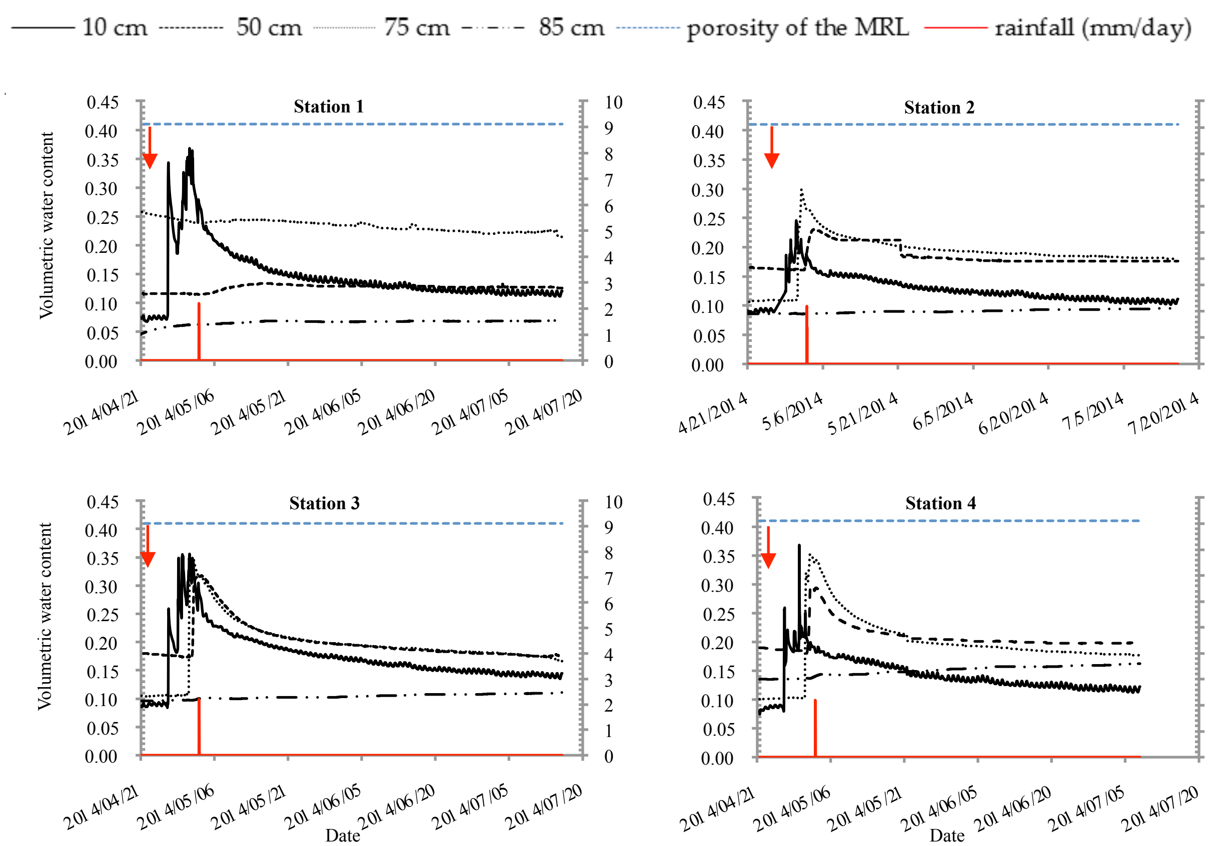
Figure 4 Measured volumetric water content at depths of 75 cm (a) and 50 cm (b) and measured matric suction at the depth of 75 cm with Watermark (c) and Jetfill (d) stations (the arrow in the figure indicates the wetting event)

FINAL REMARKS

The construction of an inclined SR cover in Kettara (Morocco) designed to investigate its slope effect was completed successfully and preliminary results confirm that the SR cover system is working properly to control water percolation. At this stage, measurements indicate that:

- Volumetric water content and suction obtained during the wetting event show that the sensors at 10, 50, 75 cm were affected by this event but the inclined SR cover was able to divert the water flux applied at inclined SR cover surface (100 mm per 48h) where no water percolation was collected in the lysimeters.
- Water was successfully diverted and stored within the phosphate limestone wastes, and is being presently released to the atmosphere during the dry summer period.

The hydrogeological monitoring of the system is underway. In addition, other wetting tests will be performed to investigate the diversion capacity of the tested inclined SR cover. A particular attention will be put on the DDL of the system. Numerical modelling will be also performed to better understand the hydrogeological behavior of inclined SR cover exposed to arid conditions.



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