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Hydrological monitoring of an outdoor, large scale desiccation crack experiment

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Abstract

Climate-driven deterioration from desiccation cracking, together with increased climate variability, is a growing threat to the stability of infrastructure embankments by imposing irrecoverable spatial and transient changes in soil hydromechanical properties. Current research into the relationship between climate change, slope deterioration and soil water retention capacity within a cracked slope, at a scale comparable to field embankments, is limited. Understanding this relationship is crucial in order to formulate a deterioration and remediation framework for infrastructure assets' experiencing desiccation cracking. Preliminary results are presented in this paper from a large-scale (4500 x 2000 x 1200 mm), heavily instrumented slope within an outdoor lysimeter located at the UKCRIC National Green Infrastructure Facility, Newcastle University, UK. The lysimeter is an opportunity to monitor the hydrological regime and water retention capacity of a cracked slope in situ, under natural and simulated weather events. Initial results from desiccation crack and hydrologic monitoring indicate the importance of monitoring antecedent soil moisture conditions as they can increase the impact of infiltration and future desiccation cracking on the overall stability of an embankment slope.

Keywords: Slope Stability, Desiccation Cracking, Hydrological Monitoring, Soil Infiltration

1. Introduction

Maintaining the operational serviceability of key transport networks is becoming increasingly challenging due to climate driven deterioration processes within infrastructure embankments. Locally sourced, medium to very high plasticity, compacted clay fills are commonly used in UK infrastructure embankment construction due to their availability (Dyer et al, 2009). However, clay soils are highly responsive to seasonal changes in soil moisture content. Sustained dry periods cause shrinkage and formation of desiccation cracking within the clay, which has a resultant effect on an embankment's stability during wet periods by encouraging rapid rainwater infiltration via preferential flow, swelling and loss of suction contribution to shear strength (Bouma, 1980; Cheng et al, 2020; Stirling et al, 2020; Zeng et al, 2020).

The action and ensuing impacts of shrink-swell behaviour are set to proliferate under UK climate change projections of warmer and wetter winters, hotter and drier summers, and more frequent high-intensity rainfall events (Met Office, 2019). Therefore, research must be focused on investigating the spatial and temporal relationship between climate change, embankment deterioration and reduced ability to generate suction to secure the long-term serviceability of these assets.

Within existing literature, small-scale laboratory experiments have proved valuable for controlling and understanding the environmental and soil conditions that impact desiccation crack formation. However, these laboratory experiments have highlighted that experimental scale (Cui et al, 2014; Zeng et al, 2020; Tang et al, 2021), mechanical boundary effects (Li and Zhang, 2011; Zeng et al, 2020); sample thickness (Kodikara et al, 2000; Lakshmikantha et al, 2009; Zeng et al, 2020), initial soil moisture content and compaction degree (Kodikara et al, 2000; Louati et al, 2018; Cordero et al, 2020) all influence the developmental characteristics of desiccation. Additionally, typical laboratory methods used for re-saturation do not allow for mapping of fluid flow through cracked soils nor generate the drying gradients known to control crack nucleation and propagation (Lakshmikantha et al, 2009; Tang et al, 2020). Consequently, discrepancies in desiccation are observed between laboratory experiments and full-scale field embankments. This highlights the importance of developing methodologies which consider the scale and construction specifications of field embankments.

A limited number of studies are available in the literature which utilise experimental scales comparable to that of field embankments. Although comparable in scale, the ground conditions and nature of field sites varies greatly within these studies from tests conducted on flat plains (Flury et al, 1994), ground excavations (Konrad and Ayad, 1997), outdoor lysimeters (Cordero et al, 2018; Luo et al, 2021) and non-compacted cut-slopes (Ng et al, 2003). The remainder of available research focuses on desiccation cracking within compacted embankment slopes (Zhan et al, 2006; Dyer et al, 2009; Hughes et al, 2009; Li and Zhang, 2011; Eminue et al, 2018; Stirling et al, 2018; Stirling et al, 2020; Yu et al, 2021). Many of these studies have implemented a detailed in-situ

monitoring regime to study the relationship between infiltration, runoff, water content and suction distribution within a cracked slope. These monitoring regimes are notably short-term, use simulated weather conditions and are localised to a small section of the slope. However, moisture distribution is spread heterogeneously across a slope due to both gravitational redistribution and the opening and closure of desiccation cracks (Flury et al, 1994; Wells et al, 2013; Luo et al, 2021). Furthermore, the impacts of soil structure degradation and instability due to desiccation cracking are known to heighten over increasing cycles of drying-wetting and with time (Stirling et al, 2020). Therefore, real-time and long-term hydrological monitoring which allows deterioration to be quantified through an embankment under background climatic conditions, and during the onset of extreme weather, is required.

To address the aforesaid research gaps, this study has been designed to provide real-time hydrological and desiccation crack monitoring of a large-scale slope, constructed within an outdoor lysimeter. This paper presents a description of the experimental setup and the initial results, with further long-term monitoring planned. This will aid the understanding of spatial deterioration of soil structure within an embankment at the material and slope scale, over time, due to both desiccation cracking and the cyclic action of wetting and drying.

2. Methodology

2.1 Material

The fill material used in the construction of the lysimeter was the Ampthill Clay – a smooth, dark grey mudstone with some siltier iterations and occasional calcareous concretions – sourced from Needingworth Quarry near Cambridgeshire. Ampthill Clay is known to be present within embankments local to its source, for example the M4 and M40 corridors (Nicholls, 1994), thus highlighting its relevance for use in this research. It should be noted, no pre-processing of the Ampthill Clay was carried out prior to installation as per typical construction practices to allow for a comparable heterogeneity of that in live assets.

In accordance with BS 1377-2:1990, the Ampthill Clay is classified as being of high to very high plasticity, with Liquid and Plastic Limits of 71% and 27%, respectively. The plasticity of the Ampthill Clay categorises the material as highly susceptible to shrink-swell behaviour and desiccation cracking. Following BS1377-4:1990, the Ampthill Clay has a maximum dry density of 1.52 Mg/m³ at 26% optimum moisture content. Particle size distribution testing identified a composition distribution of 64%, 31% and 5% clay, silt and sand, respectively.

2.2 Lysimeter Construction

Figure 1A illustrates the construction of the slope within a large-scale (4500 x 2000 x 1200 mm) outdoor lysimeter located at the UKCRIC National Green Infrastructure Facility at Newcastle University, UK. The base of the lysimeter slopes towards a central drain, which was overlain by a layer of gravel (4 – 400 mm sized), which reached a maximum depth of 100 mm above the drain. The drain and gravel layer were installed to provide a drainage pathway for rainwater that fully infiltrated the slope. Situated above the drainage layer and below the clay slope was a sheet of permeable, needle-punched, nonwoven geotextile to prevent blockage within the basal drainage layer due to washout of fines.

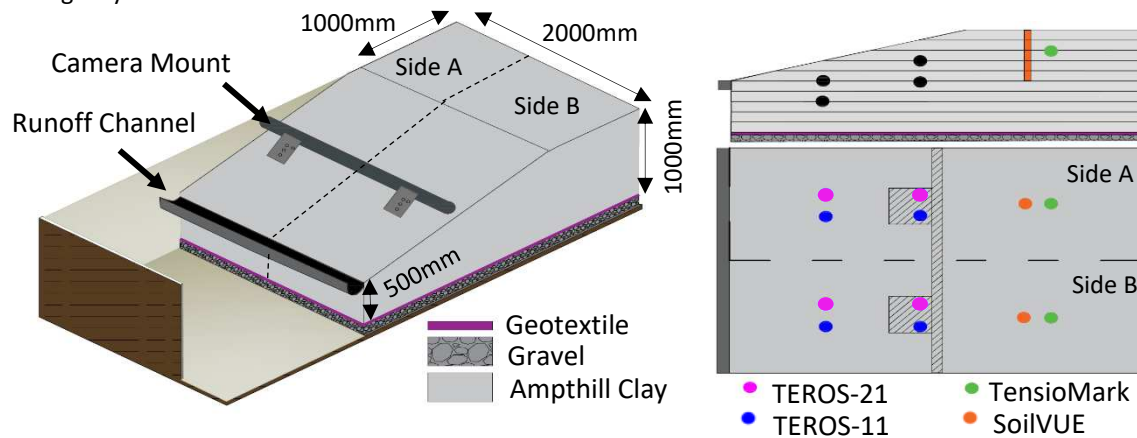


Figure 1: A) 3D view of lysimeter setup with soil types, B) plan and cross-sectional view of sensor locations.

A 1:4 slope was constructed above the geotextile by compacting ten layers of Ampthill Clay, each 100 mm thick. Four soil sample rings were taken in-situ at the top of each compacted layer which gave an average bulk density

and gravimetric moisture content of 1.786 Mg/m³ and 39%, respectively. The clay was compacted wet of optimum as per construction guidance for highly plastic clays to allow for most of the swelling to occur prior to placement and compaction. The slope geometry consisted of a slope crest of 1000 mm in height and depth, and a slope toe of 500mm height.

2.2 Lysimeter Instrumentation

Provided in Figure 1B is a cross-sectional and plan view of sensor locations within the slope. For identification purposes, the slope was divided into Side A and B. Instrumentation type and location within Side A and B was identical, and were chosen to capture changes in soil water retention behaviour through the lower, upper and crest areas of the slope. At the midpoint of the slope crest, a water content profiler based on time-domain reflectometry (SoilVUE) was installed to record volumetric water content, permittivity, electrical conductivity, and temperature profiles to a depth of 500 mm. At 200 mm depth, a TensioMark sensor was located to measure soil suction in the slope crest. At depths of 200 mm and 400 mm, within the lower and upper slope, soil suction (TEROS-21) and volumetric water content (TEROS-11) sensors were installed 200 mm apart and 400 mm from the lysimeter edge and overall midpoint. The TEROS-11 sensors also provided measurements of temperature and electric conductivity. Loss of suction generation capability across repetitive dry-wet cycles is a key indicator of slope deterioration. Therefore, suction and volumetric water content sensors were purposely co-located at the same depth to construct a time series of soil water retention curves in which the rate of deterioration across the slope can be quantified.

Located on an adjacent lysimeter is a weather station providing hourly records of environmental variables – air temperature, wind, solar radiation, relative humidity, and rainfall. These will be compared with sensor data within the lysimeter to determine the effect of environmental conditions on the formation of desiccation cracks.

2.2 Crack Monitoring

Fixed camera mounts, secured to a centrally located structural pole, were installed over Side A and B at 250 mm above the slope surface (Figure 1A/B). This allowed regular photographing of a consistent frame to record the evolution of the surface crack pattern through time, and over multiple dry-wet cycles. At this stage of the work, qualitative analysis of the change in crack pattern was conducted via visual comparison of the time-series of photographs. Quantitative methodology for crack analysis is still under development.

3. Results and Discussion

3.1 Crack Pattern Evolution

Figure 2 documents the change in crack pattern which was observed between 22/09/2021 and 14/10/2021 during a transition across a dry-wet-dry cycle. The non-polygonal first-generation crack pattern (CP1) (Figure 2A) – characterised by large primary cracks encapsulating finer secondary cracks – shifted to a second-generation (CP2) polygonal pattern with a narrow distribution of crack size (Figures 2C and 2D). Pattern CP2 has reoccurred after all wetting-drying events since 14/10/2021. The surface cracks in CP1 fluctuated in size until 05/10/2021 where they completely healed before the emergence of CP2, as shown in Figure 2B. Surface depressions marking the positions of the large primary cracks of CP1 remain visible on the slope to date. General degradation of the slope surface was visible over this time.

The recorded shift in crack pattern between drying events may be the result of a combination of contributing factors, the first being the coinciding environmental conditions during wetting and drying, which are presented in Figure 3. The yellow lines mark the four cracked states present in Figure 2. A sustained period of lower rainfall, higher evapotranspiration and more negative effective rainfall is present during the formation of CP1 than CP2, suggesting evaporative drying was also greater. Environmental conditions are a key driver locating the formation and maturation of desiccation crack patterns by controlling the distribution of suction gradients within the slope. This was demonstrated in Yu et al (2021) where slope aspect relative to incoming solar radiation and prevailing wind controlled the resultant location and intensity of cracking.

The intensity and duration of rainfall is also noted as an influencing factor in the formation of desiccation cracks. The crack size within CP1 fluctuated from 28/09/2021 until 04/10/2021 in response to short and low intensity rainfall events which only resulted in cycles of partial crack closure and reopening. A similar trend is noted after the formation of CP2. This suggests the tensile strength of partially closed cracks under low intensity rainfall is not improved, causing reopening along the same path. This was found in studies using low-intensity drip or spray irrigation on cracked soils (Greve et al, 2010; Wells et al, 2013; Qi et al, 2020). However, prior to the formation of CP2, an extended period of high intensity rainfall caused closure of CP1, and rapid generation of previously

undetected runoff suggesting the slope became saturated quickly. High intensity rainfall can induce flash flooding of, and preferential flow through, cracks where deposition of fines, fast swelling and therefore possible collapse of crack walls occurs. The remnants of CP1 as surface depressions is indicative of this by suggesting changes in the structural properties of the backfill material, as also found by Qi et al (2020). Consequently, the crack pattern can shift during crack flooding events as the change in soil properties of backfill may no longer be zones of weakness within the slope.

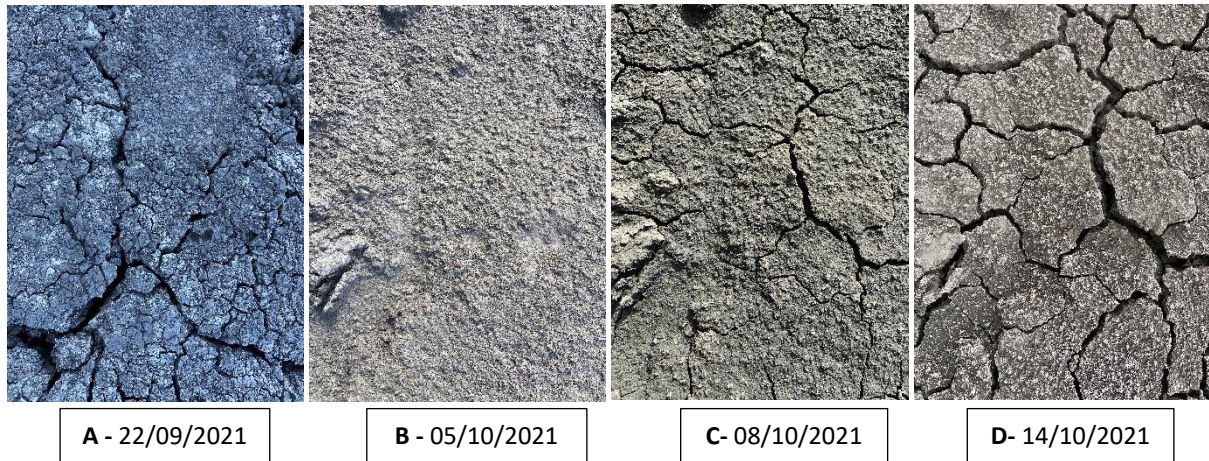


Figure 2: Evolution of cracking on slope Side B where: A) CP1 on 22/09/2021; B) CP1 healing on 05/10/2021; C) CP2 formation on 08/10/2021; D) CP2 maturation on 14/10/2021.

Desiccation cracks form when the tensile stress exceeds the tensile strength of the soil. Tensile stress can develop as a result of heterogeneity in suction gradients within the soil driven by drying boundary conditions or as a result of structural heterogeneity. Upon re-wetting, the presence of desiccation cracks can influence the near-surface lateral distribution of saturation. Preferential flow can create localised plumes of elevated water content which decrease with distance from the crack locality. Therefore, cracks become wetter than the surrounding intact soils shifting the location of drying gradients, maximum tensile stress and therefore point of crack initiation at commencement of the next drying cycle. This was found by Wells et al (2013) where drier centres of cracked polygons became the point of initiation for future cracks in subsequent drying cycles.

3.2 Hydrological Response of Slope under a Dry-Wet-Dry Cycle

Demonstrated in Figure 4 is the suction and volumetric water content (VWC) profiles for Side B within the upper and lower slope at 200 and 400 mm depth, in addition to the VWC profiles for the slope crest at 50, 100, 200, 300, 400 and 500 mm. During the first drying cycle (DC1) the environmental conditions are indicative of a sustained period of evaporative drying – no rainfall, high potential evapotranspiration, and negative effective rainfall. Overall, the VWC sensors for this period show an increase in water content with depth. Between 28/09/2021 and 04/10/2021 the environmental conditions alternate between short-duration, low intensity wetting and drying. For the lower and upper slope, VWC remains relatively constant during this period at both 200mm and 400mm depth as do sensors located below 200 mm in the crest. However, the shallow depth sensors within the slope crest (50 – 200 m) exhibit high sensitivity to changes in water content and therefore record these temporary fluctuations between wetting and drying, the effect of which decreases with depth.

A notable increase in VWC is recorded in all sensors on 05/10/2021 which coincides with the onset of an extended period of high intensity rainfall, lower potential evapotranspiration and positive effective rainfall. Additionally, the first detection of significant runoff occurs during this rainfall event, the value of which increases with rainfall duration. Response time to precipitation increases with sensor depth, with the shallower sensors (50-200 mm) at all slope localities reaching an instantaneous peak before entering a gradual decline in VWC which continues throughout the secondary drying period (DC2). For sensors below 200mm, a gentle increase in VWC occurs to an ultimate value which is sustained through DC2. All sensors record higher VWC's during DC2 compared to DC1. Transitioning into DC2, a cease of runoff, low rainfall, higher evapotranspiration and negative effective rainfall is recorded.

Suction profiles are high during DC1 with greater suction recorded in the upper than lower slope and at 200 mm depth compared to 400 mm. The profiles remain relatively constant until the sustained period of high intensity

rainfall on 05/10/2021 where a rapid decrease occurs at 200 mm and a minor decline at 400mm for both the upper and lower slopes. These lower suctions are sustained throughout DC2.

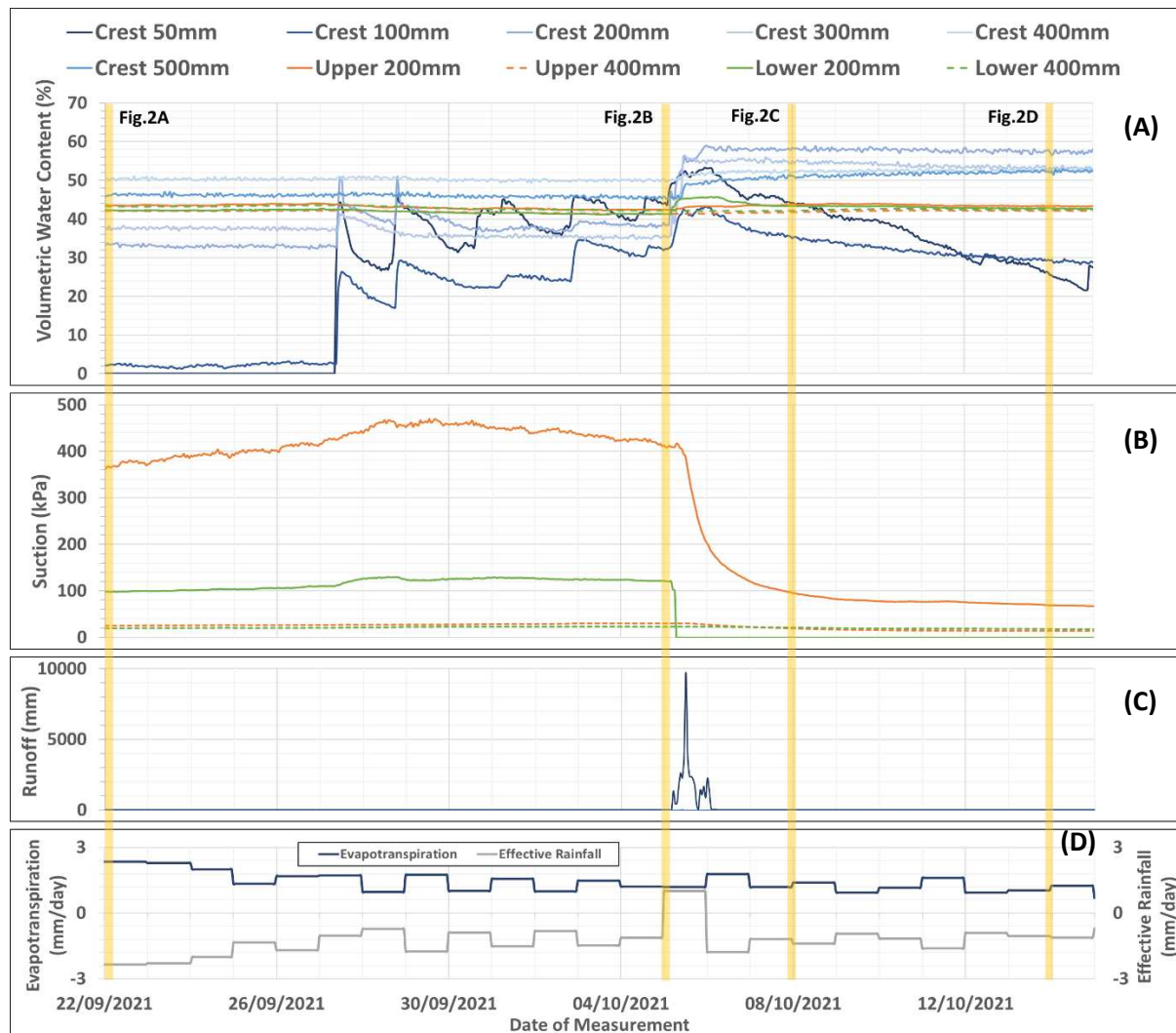


Table 1: VWC (A), Suction (B), Runoff (C), Evapotranspiration and Effective Runoff (D) time series data between 22/09/2021 until 15/10/2021. Yellow Lines refer to crack pattern evolution in Figure 2.

Fluctuation of VWC is greatest in the near surface of the slope as the shallow layers are highly susceptible to changes in local environmental conditions. During drying cycles, VWC decreases, and suction develops first within the upper 200 mm of the slope due to direct exposure and surface exchange with wind and solar radiation. This generates the gradual increase in VWC with depth observed in most embankment slopes (Ng et al, 2003; Hughes et al, 2009; Luo et al, 2021). The VWC is higher in the crest for the same depth within the upper and lower slope due to the flat geometry encouraging ponding of precipitation instead of runoff. Therefore, infiltration can continue through the crest and be redistributed through the slope after ceasing of rainfall.

For highly plastic clays, such as the Ampthill Clay, surface evaporation can generate desiccation cracks, as observed in the upper 200mm of the lysimeter. Desiccation cracks increase the evaporative surface, further decreasing the VWC at surface of the slope. The permeability and hydraulic conductivity of clay is inherently low however, desiccation cracks also increase the infiltration capacity providing a conduit for water flow in the near surface. The delayed response to the onset of rainfall within the deeper VWC sensors is related to the low hydraulic conductivity and slope geometry which governs pattern of fluid movement through the slope. This is observed within field slope experiments of similar size and sustains higher VWC and lower suctions at depth than surface layers after precipitation events (Hughes et al, 2009; Zhan et al, 2006; Stirling et al, 2018).

Despite precipitation events of similar magnitude occurring prior to 05/10/2021, no runoff is recorded. Runoff is a function of; (1) the initial VWC of the soil at the onset of rainfall which governs how much additional water

a slope can accommodate, (2) the infiltration capacity of the soil which is a function of permeability, hydraulic conductivity and presence of macro permeability (e.g. desiccation cracks). During DC1, the VWC at the surface of the slope crest is less than 5% and CP1 was present which allowed a gradual increase in VWC over the period of short-duration rainfall events without fully saturating the soil or exceeding the infiltration capacity. At the onset of the high intensity rainfall on 05/10/2021 VWC was near saturation and CP1 had healed significantly reducing the soil's capacity to accept infiltrating water resulting in runoff. A decrease in surface VWC and formation of CP2 during DC2 again increased soil infiltration capacity. This highlights the importance of monitoring antecedent conditions as they can increase the impact of less frequent, high intensity rainfall events on the overall stability of embankment slopes.

3.3 Limitations of Lysimeter Experimentation

As with any outdoor experiment there are risks of vandalism, however the lysimeter experiment is of low maintenance and easily accessible if problems arise. It should be noted that the Amphill Clay is poor medium for vegetation growth. The lysimeter frame has shown to provide some shelter from environmental conditions.

4. Conclusions

The initial results from hydrological monitoring of a large-scale, heavily instrumented slope within an outdoor lysimeter are presented, which effectively allows deterioration due to desiccation cracking and changes VWC and suction to be quantified.

Regular photographic imaging of the slope allows visualisation of crack pattern evolution as the slope transitions through time and over numerous dry-wet cycles. The change in crack pattern from CP1 to CP2 is thought to be the result of a combination of factors – changing of ambient environmental conditions, the duration and intensity of precipitation events and redistribution of saturation and suction gradients. Longer-term monitoring will aim to provide clarification if further alternation of crack pattern occurs with time through the different climatic seasons.

Hydrologic monitoring of the lysimeter slope revealed shallower depths are highly susceptible to changes in environmental conditions compared to deeper slope depths due to high exchange rate with atmospheric conditions and the formation of desiccation cracking. Mapping the occurrence of runoff within the slope highlighted the importance of monitoring antecedent soil conditions over time and at the onset of infiltration. If a soil is near-saturation at the onset of a high intensity extreme rainfall event, the embankment slope is at higher risk of instability due to rapid loss of suction.

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