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Modelling and monitoring behavior of vegetated slopes in variable weather conditions

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ABSTRACT: Soil erosion and shallow landslides are the most common forms of instability encountered during the life cycle of earthworks. It is generally well established that vegetation can contribute towards minimization of the risks associated with instability on earthworks slopes, although holistic consideration of geo-environmental conditions and connection with hydro-meteorological hazards is still lacking. The aim of this study is to investigate the link between the vegetation planted on earthwork slopes and the likelihood of failure of the earthwork in form of erosion or shallow landslide. To achieve this aim, experiments on vegetated and fallow earthwork slopes in contrasting geo-climatic conditions were carried out. These included setting up, monitoring, sampling and testing under simulated rainfall and dry conditions. The results of this study will help designers, engineers, land use planners, and landscape architects in reaching decisions that consider multi-disciplinary approach to earthwork design and construction.

1 INTRODUCTION

Although the contribution of the vegetation in the reduction of erosion and shallow landslides has a long both empirical and scientific documented history, there is still a lack of coupled consideration of geo-environmental conditions and connection with the hydro-meteorological hazards. For that purpose, parallel investigations have been started in Scotland and N. Macedonia, where the influence of planted vegetation on stability of earthwork slopes under different atmospheric conditions has been monitored. These were carried out in-situ and in laboratory, where tests on both vegetated and fallow earthwork slopes for two contrasting geo-climatic regions of Europe were performed. Complex equipment was set up, enabling continuous monitoring within the soil. Unlike the field work, the fluctuating atmosphere conditions in laboratory had to be simulated.

Having in mind the experiences and risks of infrastructure instability and the wide range of associated topics/factors, e.g.: erosion and shallow landslide typology and processes ((aggregate) stability, erodibility, soil strength, slope angle/cover, etc); hazards/risks for earthworks, climate change drivers (environmental and hydro-meteorological); hazard/risk mitigation, the aim of this study was to investigate a limited set of environmental and hydro-meteorological hazards and their effects on earthworks with a view of proposing a mitigation approach that involves vegetation as a stabilisation agent.

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2 APPLIED MATERIALS AND MODELS

Within this very limited scope, the objectives of the research were as follows: a) for the case study in Scotland, to set up and monitor the effects of hydro-meteorological hazards on the erosion and shallow landslide risk on a major live linear infrastructure construction site; b) for the case study in N. Macedonia to model variable hydro-meteorological hazards in laboratory environment for the purpose of slope design and monitor development of erosion and/or shallow landslide and parameters in the soil before, during, and after simulated rainfall events.

2.1 *Description of the site in Scotland*

- Motorway cutting (Slope 1; Figure 1) formed in mineral podzols near Luncarty (NO 09252 29729); slope length 445 m; slope angle 1:2; slope height: 6.0 – 8.5 m; aspect: west-facing.
- In situ testing from 12 locations on 5 occasions between July and January: moisture content, shear stress (peak and residual), penetration resistance.
- Bulk samples were collected but not analysed and the monitoring was curtailed as a result of the Covid-19 pandemic (site closed).

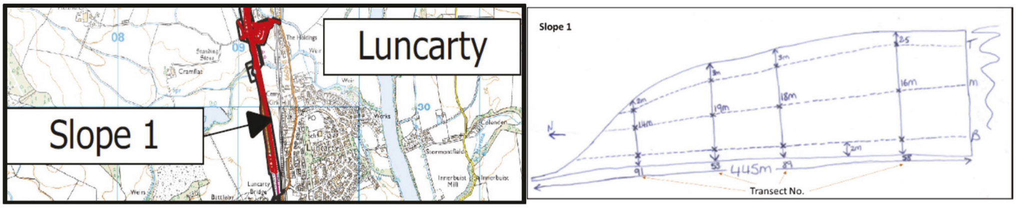

Figure 1. Case study area location in Scotland (left) and the general earthwork arrangement with monitoring point location (right).

2.2 *Description of site and laboratory model in Macedonia*

- Cutting formed in silty (sandy silt, marked as 1) and sandy (silty sand, marked as 2) materials on express road in process of construction; slope length 340 m; slope angle 1:1; slope height: 6.0 - 8.0 m; aspect: south-facing (Figure 2a).
- Two containers were prepared LxWxD=100x50x25 cm, where materials 1 and 2 were separately placed. Drainage is enabled both at the surface and at the bottom end, through a pipe.
- Sensors placed at middle depth of each soil layer, at two positions along model: sensors 1 (at upper part) and 2 (nearby toe) in mat.1, while sensors 3 (upper) and 4 (toe) in mat.2 (Figure 2b).
- Local hydro-meteorological reports were analyzed for modelling rainfalls *via* sprayers.
- Tests were performed for cases of bare soil and vegetated slope, and with dried vegetation when a heater was used to simulate the effect of the sun (Figures 2c–2d), while eroded material, run-off water and filtered water through soil were collected with dishes placed below each container.

3 RESULTS AND ANALYSIS

3.1 *Highway slope (Scotland)*

The shear strength of the exposed cutting did not change significantly with the changes in moisture content near the crest and at mid-slope (Figure 3a). However, the shear strength decreased with the increase in moisture content near the toe of the slope. While the shear

a) b) c) d)

Figure 2. a) Geotechnical profile of case study area in Macedonia (PPR – sandy silt and PRP – silty sand); b) Placing sensors; final lookout of slopes after test with dry vegetation: c) material 2 (sampling nearby the sensor 3); d) material 1 (sampling in the upper part, nearby the sensor 1).

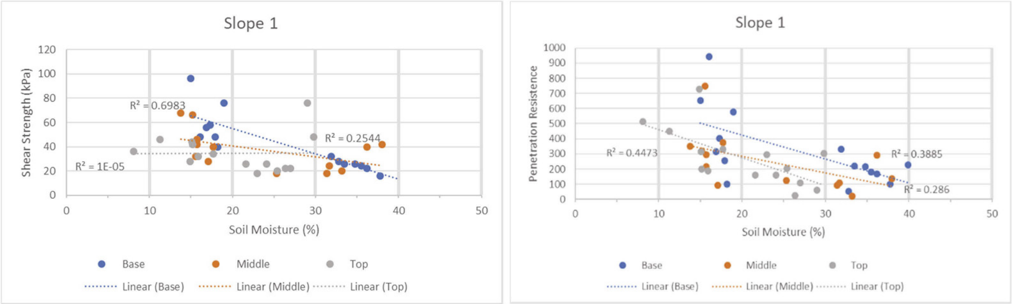

Figure 3. Relationship between the soil moisture (%) and: a) shear strength; b) penetration resistance (N) at different locations on the slope during monitoring.

strength of the exposed slope averaged approximately 40 kPa across the slope, there were a number of readings below 20 kPa during the monitoring period.

The penetration resistance of the exposed cutting showed a decreasing trend with the increase in moisture content of the soil but these trends, although similar across the slope, were not statistically significant. In general, the penetration resistance appeared to be the lowest near the crest and the highest near the toe of the slope (Figure 3b).

3.2 *Laboratory model for slope (Macedonia)*

The testing program in the laboratory considered simulating rainfalls with 30 $l/m^2/h$. The first test was performed on a bare soil on 30.11.2020. Planting of vegetation begun on 05.12.2020, and rainfalls were simulated on a slope with thriving vegetation on 08.01.2021. In the next period, the grass was left to dry, but for simulating prolonged sunny periods, daily heating of the surface was conducted. The final test was performed on 01.04.2021 on a slope with dry vegetation.

The sensors installed in the model continually registered the soil suction (Figure 4). As could be noticed, the sensors near the toe (No.2 and No.4, respectively) exhibit lower suction. This means that the lower part of the slope, despite the surface runoff and the underground piped drainage, contains more water than the upper part and it is exposed to lower shear strength.

Furthermore, after the initial rainfall on fallow soil, the sensors in both slopes registered sudden reduction in soil suction. Subsequent drainage and drying enabled slight increase in the suction, with a gradient slightly increased after planting the vegetation - this was probably due to evapotranspiration of the vegetation – after which it appeared that the suction reached a constant value. The rainfall event on green slope did not significantly decrease the suction, which may be a result of both the above- and below-ground vegetation parts, preventing the drops to reach the soil and absorbing the water that has infiltrated the soil. Moreover, as long as the vegetation was green, the suction was constant, forming conditions for long term stability - an effect even more visible in the sandy material. As the vegetation dries out, this positive effect decreases and disappears.

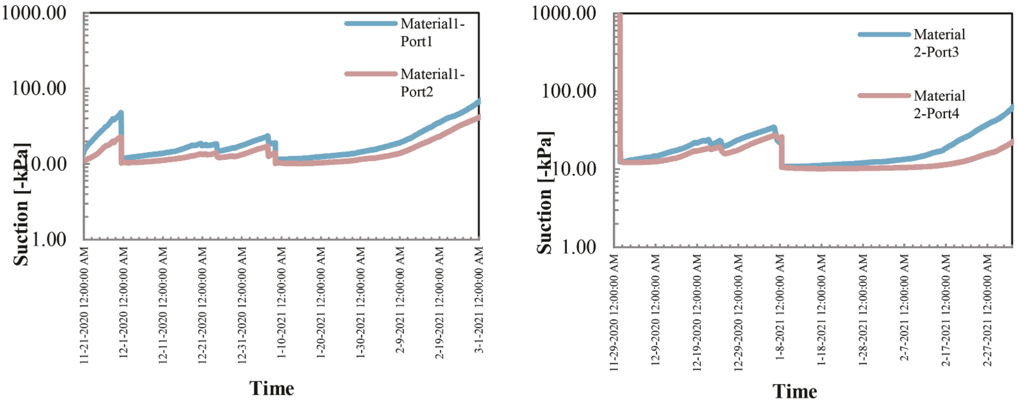

Figure 4. Measured suction during the laboratory experiment.

4 DISCUSSION AND CONCLUSIONS

Natural variability was recorded in soil strength across the slope in Scotland with locations where the strength dropped below 20 kPa due to the hydro-meteorological conditions (rainfall, water retention capacity), or disturbances during earthwork operations. The soil behavior at the toe of the slope appeared to be connected to the drainage (wetter soil at toe) but may pose a risk if the soil is shown to loose strength due to increase in moisture.

Longer-term monitoring is needed to ascertain any significant connection between the penetration resistance and soil moisture content. A decrease in penetration resistance would allow for better conditions for the vegetation to grow and an increase in moisture content would also provide for the physiological needs of the root systems.

The relationship between the shear strength and penetration resistance across the slope gives a rise to a concept of biodiversity employed in the context of slope protection and stability against shallow landslides and erosion: the crest of the slope may be a better environment for grasses and low vegetation to thrive due to low penetration resistance (slope protection from erosion initiation and rill formation due to the surface runoff and sediment entrapment) while the toe of the slope may be better suited for shrubs and trees (providing toe support and arching effect, while their strong structural roots anchoring the slope).

The aim of the laboratory experiment was to model the typical life cycle of a slope in transportation infrastructure: bare soil, slope with vegetation and slope with dry vegetation, at realistic climatic scenarios. These models showed the many very positive influences of the vegetation system, but also suggested that there may be a requirement of a suitable irrigation system during the maintenance and operation stage of a transportation project in regions with extreme conditions such as cyclic change of heat waves and intense rainfall, which are expected to be frequent.

Although these findings highlighted similar trends in contrasting environments, the limitations posed by the pandemic restricted the breadth and depth of the envisaged research. Both experiments, however, demonstrated the importance of relevant monitoring and testing.

While there were complex multi-organizational relationships on site which made getting support for monitoring/testing challenging, the laboratory experiment had challenges related to the reproducibility and applicability which could have been solved only with verification in situ. Additional to demonstrating good practice of carrying thematic laboratory and *in situ* testing in parallel, this study also showed that specific vegetation-related monitoring and testing have to form part of the earthwork design from the onset of a geotechnical project. Future work will see the development of relevant sampling, testing, and monitoring protocols which will incorporate vegetation and its effects on the soil properties and lead to more sustainable and resilient geotechnical design.

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