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TERRE project: interplay between unsaturated soil mechanics and low-carbon geotechnical engineering

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Abstract. The geotechnical construction industry is a major component of the overall construction sector and is strategically important in infrastructure development (transportation, flood and landslide protection, building foundations, waste disposal). Although industry and research in the overall construction sector have been investing significantly in recent years to produce innovative low-carbon technologies, little innovation has been created in geotechnical construction industry, which is lagging behind other construction industry sectors. This paper discusses the interplay between low-carbon geotechnical engineering and unsaturated soil mechanics based on the research carried out within the project TERRE (Marie Skłodowska-Curie Innovative Training Networks funded by the European Commission, 2015-2019,H2020-MSCA-ITN-2015-675762).

1 Introduction

The construction sector is one of the main sectors responsible for carbon emissions and accounts for 10% of the carbon footprint globally. This sector is therefore expected to play an important role in the EU's long term objective of reducing greenhouse gas emissions by 80-95% by 2050. In the light of this, technological innovation aimed at reducing carbon emissions can be viewed as a major strategy to boost competitiveness of the construction industry, within and outside Europe. This is the rationale behind the project TERRE funded by the European Commission (2015-2019). TERRE targeted the geotechnical construction industry, a major component of the overall construction sector, which is strategically important in infrastructure development (transportation, flood and landslide protection, building foundations, waste disposal) and explored novel design concepts for low-carbon geotechnical infrastructure. Little innovation has been created in geotechnical construction industry, which is lagging behind other construction industry sectors.

There are substantial intersections between low-carbon geotechnical engineering and unsaturated soil mechanics and these are discussed in this paper.

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Suction can be viewed as a natural untapped 'low-carbon' soil reinforcement that can be deployed to mitigate natural geohazard or reduce overdesign of man-made geostructures. For example, suction can be used to mitigate hazard associated with rainfall-induced shallow landslide, which often evolve into fast moving and highly destructive debris and mud flows. This is a 'diffuse' geohazard that calls for 'diffuse' remedial measures. Bio-engineering techniques can be then used to modulate soil suction via i) either increasing soil suction via plant transpiration or ii) hampering suction loss due to water infiltration by means of hydrophobic fungal-hyphal networks or rhizosphere-promoted lateral flow.

On the other hand, suction is generally neglected in geotechnical design of man-made geostructures. If taken into account, it can allow for significant financial and environmental savings. The main challenge in suction-based design is that suction can be potentially lost due to rainwater infiltration. The key is therefore to rely on suction through either accurate prediction of water flow regime or by deploying physical systems to regulate suction (e.g. capillary barriers).

Unsaturated soil mechanics also plays an indirect role in a number of 'low-carbon' technologies because these involve geostructures above the phreatic surface. Carbon emissions can be reduced by using locally sourced marginal earthfill geomaterials, i.e. geomaterials that are generally not used in traditional earthfill construction due to their relatively poor mechanical performance. However, if these geomaterials are enhanced by reinforcement or treatment, procuring and transporting of materials from borrow sites can be avoided with significant carbon saving. Marginal soils can be stabilised by using waste binder, biopolymer, and enzyme-induced calcite precipitation. Stabilisation involves soils in compacted unsaturated states and there is therefore a coupling with unsaturated soil mechanics. Biopolymer and enzyme-induced calcite precipitation can also be used to stabilise earthen construction materials in place of cement and lime to provide both strength and durability benefits.

Reinforcement of ground above the phreatic surface can also be achieved via plant roots that act as natural anchor systems (similar to geotextiles, nails, etc.) For the case of man-made 2-D slopes, the rooting zone pushes downward the potential failure surface thus generating an increase in the factor of safety. Plant roots generally grow in unsaturated soils and root mechanical response is therefore coupled with the unsaturated soil mechanics.

Energy and carbon can be captured by geotechnical structures during their operational life. Ideally, this should be achieved with no or minimal additional costs to attain partial compensation of capital carbon. Following this philosophy, carbon fixation into soils by vegetation is a very interesting approach for reducing the build-up of atmospheric CO_2. Vegetation may be designed for other geotechnical purposes (e.g. slope stabilisation) and the additional sequestration function could be combined with the hydro-mechanical effects. Geothermal energy is another option that allows geotechnical structures to contribute to overall carbon efficiency. If heat exchangers are cast in existing concrete components of geotechnical structures in the unsaturated upper portion of the ground (such as shallow footings or retaining diaphragms/walls), geothermal energy could be extracted or released with a minimal energy supply (electricity for the heat pump).

2 Suction as an untapped natural soil reinforcement

2.1 Natural slopes (rainfall-induced shallow landslides)

In shallow landslides, the failure surface tends to develop below the rooting zone and failure is generally triggered by infiltrating rainwater [1, 2] (Fig. 1a). Stability can then be enhanced by promoting water removal via vegetation, whose effect extends below the rooting zone as shown in Fig. 1b, or by hampering water infiltration via hydrophobic fungal-hyphal networks or rhizosphere-promoted lateral flow (Fig. 1c,d).

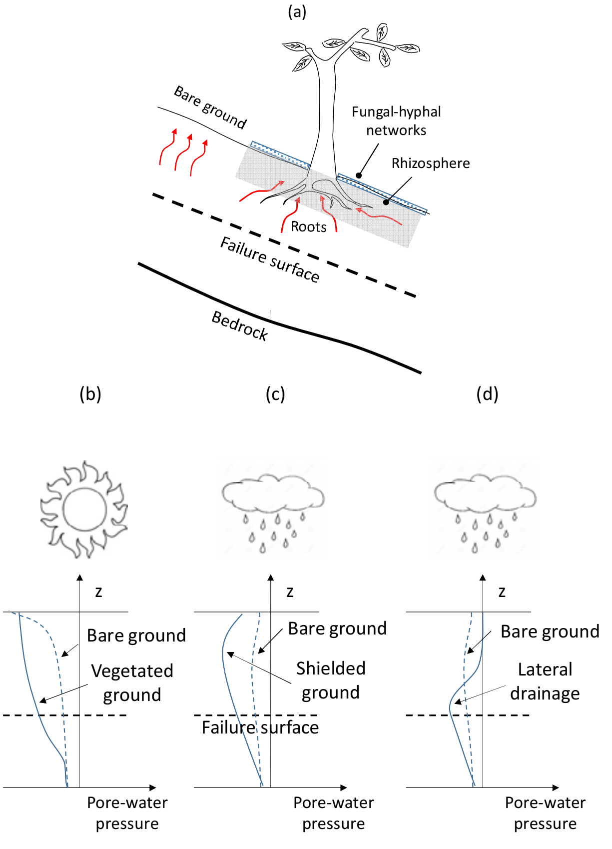

Fig. 1. (a) Hydrological mitigation of shallow landslide hazard. (b) Vegetation as suction-generator. (c) Biological barrier to rainwater infiltration. (d) Rainwater diverted by subsurface parallel flow in the rhizosphere

2.1.1 Vegetation as bio-mediated moisture pump

The ground surface is very frequently covered by vegetation and, as a result, transpiration plays a major role in ground-atmosphere interaction. The soil, the plant, and the atmosphere form a continuous hydraulic system, which is referred to as Soil-Plant-Atmosphere Continuum (SPAC). The SPAC actually represents the 'boundary condition' of the geotechnical water flow problem. Water flow in soil and plant takes place because of gradients in hydraulic head triggered by the negative water pressure (water tension) generated in the leaf stomata. To study the response of the SPAC, (negative) water pressure needs to be measured not only in the soil but also in the plant. Within TERRE, a novel technique to measure the xylem water pressure based on the use of the High-Capacity Tensiometer has been developed (Fig. 2a). This was benchmarked against conventional techniques for xylem water pressure measurements, i.e. the Pressure Chamber and the Thermocouple Psychrometer [3, 4].

(a) (b)

Fig. 2. Soil and plant monitoring at Monte Faito, Naples. (a) High-capacity tensiometers installed on chestnut. (b) Installation of TDR probes and conventional tensiometers in the ground (12/04/2018).

2.1.2 Hydrological reinforcement of natural slopes

The effect of the local vegetation (cultivated *Castanea sativa*) on slope stability was investigated on a test site in Mount Faito (Campania, Southern Italy). In the Campania region, shallow pyroclastic soil covers are susceptible to fast moving and highly destructive landslides triggered by prolonged rainfall periods followed by heavy short-term rainfall events [5]. Field monitoring was performed with the intent of showing that the distribution of roots of *C. sativa* is associated with the groundwater regime. The spatial and vertical distribution of root density and traits were quantified for *C. sativa* roots collected from several boreholes and suction and water content was monitored at various depths (Fig. 2b). An increasing root density was found to be associated to lower values of suction and higher gradients of infiltration, which can potentially have a negative influence on slope stability [6].

2.1.3 Engineered fungal-hyphal networks

Rainfall duration and intensity has been found to be a trigger factor for many landslides. [7] described in detail how the existence of wettable soils contribute significantly to the mechanisms of landslides triggered by intense rainfall, thereby making a case for the use of water repellent soils to improve the factor of safety of slopes. Fungal-hyphal networks in soil are capable of acting as less permeable barriers if effectively engineered or treated. Within TERRE, [8, 9] showed that the growth of hyphae induced extreme hydrophobicity in sand and contributed to reduction in the rate of infiltration and permeability of the soil; these results combined with the higher air entry value obtained from the SWRC of treated specimen imply that growth of fungal hyphae significantly modified the hydraulic behaviour of the sand interface. Furthermore, the results showed that hyphal growth caused delay in the advancement of infiltration front due to the formation of semi-permeable (or hydrophobic) hyphal-barriers, which acted as bio-clogs in soil pores, bounded soil particles together as aggregates, and contributed to enhanced stability of sands by preventing densification compared to what was observed for untreated specimens.

2.1.4 Rhizosphere as lateral drainage

A study has been carried out to characterise the interplay between macroscopic and microscopic effects of roots on a compacted silty sand subjected to low stresses [10]. Upon drying, roots produced mucilage that clogged pores thus affecting water retention and chemo-physical properties. Larger roots fissured the soil, thus creating macropores and preferential paths for water to flow. During desiccation, concurrent drying of roots and soil generated further macropores affecting water retention properties. Changes of hydraulic soil properties observed at the macroscale (e.g. air entry value decrease and increase in hydraulic conductivity) could successfully be linked with observed microstructural features. The increase in hydraulic conductivity of the rhizosphere can promote lateral flow and enhance slope stability factor of safety as discussed by [1].

2.2 Man-made slopes (cut slopes and embankments)

2.2.1 Retaining structures

The work carried out within TERRE has focused on the experimental assessment of the performance of retaining structures subjected to environmental actions (evapotranspiration and rainfall). As a first step, the water retention behaviour of a silty soil was investigated to compute the soil thrust on a retaining wall during rainfall events [11]. A series of analytical uncoupled hydro-mechanical analyses were performed to estimate the change in the thrust applied by an unsaturated soil on a retaining wall under several infiltration rates. An appropriate modelling of the soil water retention behaviour revealed to be crucial for the computation of lateral earth thrust.

2.2.2.Capillary barriers for embankments and cut slopes

Capillary barrier systems (CBS) may be potentially used for suction control purposes, maintaining suction in the ground during rainfall events (Fig. 3). In order to model accurately the hydraulic behaviour of CBSs, improved hydraulic constitutive models were developed within

TERRE following a critical review of the hydraulic behaviour of unsaturated soils. These improved hydraulic constitutive models include a better description of the hydraulic conductivity at low degree of saturation and the inclusion of water retention hysteresis using a bounding surface approach.

These models, after being validated against experimental data and implemented in the numerical FEM code Code_Bright, were used in numerical analyses to show the significant impact on the modelling of the hydraulic behaviour of CBSs [12]. In addition, a simplified analytical method was proposed and was used, together with rigorous numerical methods to show the impact of various parameters on the gain obtained using multi-layered CBSs. It was shown that, for certain conditions, this gain can be very large.

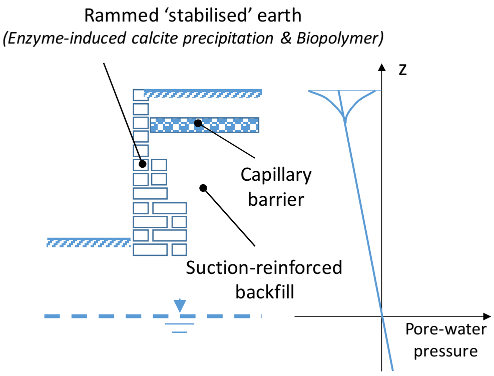

Fig. 3. Suction-reinforced retaining structures with capillary barrier to preserve suction

2.2.3 Flood embankments

The utilisation of negative pore-water pressures in the design of a flood embankment has the potential to result in appreciable savings in terms of embodied carbon. The inclusion of suction in the design allows the embankment to be constructed with steeper slopes, thereby reducing the cross-sectional area and hence the quantity of materials used. The savings could be very significant: there is potential for savings of over 50% when the new design is compared to those conducted using outdated 'steady-state' methods without suction [13]. The embodied carbon which could be saved by including suction in the design could be the equivalent of several million car-kilometres per kilometre of embankment constructed. To reap the full benefits of 'suction reinforcement', the method of designing flood embankments must be modernised. When using the 'steady state' design approach the possible benefits of suction reinforcement are limited. If the 'transient' method is used, the savings due to suction were found to be almost 40%. Thus to fully realise the benefits of 'soil suction design', methods of analysis must be improved via the knowledge transfer between academia and industry [14].

3 Unsaturated soil mechanics at the interface with low carbon geotechnical engineering

3.1 Stabilisation of marginal soils via alkaline activated waste binder

Soft clay-rich soils are frequently encountered in construction sites but cannot be directly used as earthfill materials due to their poor mechanical performance. Common stabilisers such as Ordinary Portland Cement and lime are associated with high carbon dioxide emissions and energy intensive processes. In the low carbon agenda, the development of novel technologies that are both cost- and carbon-efficient is of prime importance. TERRE has investigated the use of a calcium-rich fly ash binder from coal combustion activated by a sodium-based alkaline solution for soil treatment.

To this end, a multi-scale analysis was carried out to jointly explore the physicochemical evolution of the mix, its microstructure, and mechanical performances [15]. At a particle level, calcium-rich particles from fly ash constitute the reactive part of the mix. Their dissolution releases calcium that subsequently combines with silicon and potentially aluminium to form chains whose structure resembles the one of Calcium Silicate Hydrate encountered in Portland Cement and responsible of mechanical improvement. At a macroscopic level, those changes led to significant improvement of the treated soil with respect to compressibility and shear strength. This confirmed a positive feasibility potential of using calcium-rich fly ash-based alkali activated binder for soil stabilisation.

3.2 Earthen construction materials

3.2.1 Enzyme-induced calcite precipitation

This study investigated the effects of soil grading on earthen material compacted at high pressures and the use of bio-stabilisation. The results indicated that the densification of earthen materials at high compaction pressures leads to earthen materials with strength comparable to conventional building materials such as fired bricks, concrete blocks or stabilised earth. It was also noted that soil grading plays a vital role in obtaining earthen materials for hyper-compaction with enhanced mechanical properties. These materials are sensitive to ambient humidity, and hence careful consideration needs to be given to this during design and service of these materials. Preliminary investigations of bio-stabilisation techniques using enzyme induced calcite precipitate showed improved durability performances of stabilised earth material [16].

3.2.2 Biopolymer

This work focused on a new technique for stabilising earthen materials, namely biopolymer stabilisation [17].

The use of biopolymers was considered for their simple application procedures and enhanced stabilisation effects. The results from the strength tests indicate that both biopolymers used in the study (guar gum and xanthan gum) have improved the compressive strengths of the treated earthen materials and led to comparable strengths to cement treated earthen materials. However, only xanthan gum improved the tensile strength of the treated materials. For biopolymers, stabilisation occurs through a combination of hydrogel bonding and soil suction and the nature of hydrogel bonding is affected by the intrinsic characteristics of the biopolymer chosen. Durability tests also indicated improved performances of biopolymer treated materials in comparison to unamended versions.

3.3 Mechanical reinforcement via plant roots

In the Netherlands, there are about 4000 km of engineered sheet piles made of timber to support canal banks. Hardwood timber is often used owing to its high natural durability and favourable strength properties. This hardwood timber is imported from other continents including South America and Africa with high carbon cost due to transpiration emissions. There is therefore scope for the use of locally available, environmental friendly material for protecting the stream banks.

On the other hand, abundant riparian vegetation grows along the stream banks. A variety of shrubs, grasses and trees constitute the riparian vegetation. Vegetation reinforce the soil both mechanically through its roots and hydrologically by inducing negative pore water pressure in the soil. A bio-engineering approach involves the use of timber sheet pile in combination with vegetation to form soil retaining structures (Fig. 4). This is based on the assumption that as the vegetation grows, it contributes to the soil stability by sharing the load along with the timber material. Over time, the wood of the sheet pile will be attacked by fungi and/or bacteria, reducing its cross sectional area, thereby reducing its contribution to the retaining structure. Consequently, a load transfer from the timber sheet pile to the root-reinforced ground will occur. Such a system could possibly replace the conventional earth retaining structures along the stream banks [18].

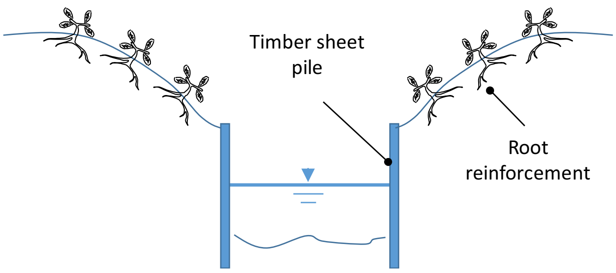

Fig. 4. Root reinforcement taking over degrading timber sheet piles

3.4 Geothermal energy extraction from shallow geotechnical structures

Geothermal energy is recognised to be one of the most important renewable and sustainable energy sources on earth [19]. TERRE has explored particular type of shallow geothermal applications, i.e. energy geostructures (EG). These are innovative civil engineering structures in contact with the soil that couple the structural role with a heat exchanger role. Closed-loop heat exchanger pipes are attached to the reinforcing cage and a fluid is circulated inside exchanging the heat with the surrounding materials. Possible applications of EG are (but not limited to): (i) heating and cooling of civil engineering structures (residential and commercial buildings, industries, etc…), (ii) production of hot water for agricultural needs, (iii) deck, bridges and infrastructure de-icing of the pavement structure.

Every new structure is in contact with the soil, which means that whenever a geotechnical structure such as piles or retaining walls has to be built, the thermal activation may guarantee to satisfy a good portion of the energy needs in an environmentally-friendly way. Most of energy geostructures involve (at least partially) the unsaturated upper portion of the soil profile, i.e. the zone above the phreatic surface where pore-water pressure is negative (suction) [20]. TERRE has focused on thermo-active walls, termed energy walls (EW), in particular singly- and multi-floored underground structures [21].

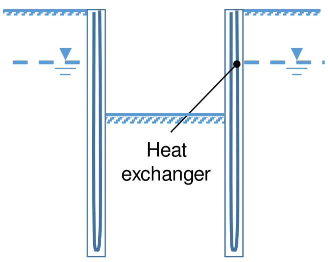

Fig. 5. Energy wall (EW) concept.

3.5 Earth embankments as a carbon sink

'Geotechnical' soils used for earth structures (e.g. flood embankments, and railway and roadway embankments) are heavily disturbed soils frequently moved from other areas or dug and brought to the surface. This changes their chemical composition, microbiology, and fertility. These soils and the plants used for revegetation can be chosen and planned to maximize ecosystem services, with particular attention to Soil Organic Carbon (SOC) storage. [22] discussed the possibility of using geotechnical soils to store SOC via i) selection of plants that efficiently fix and move C into soil, ii) inoculation of different microbiological communities that influence C cycle, iii) selection of different soil with higher potential for organomineral interaction and C protection, and iv) use of soil improvers (like recycled concrete and furnace slag) to increase C storage. However, no specific studies have been implemented so far to investigate the SOC potential of geotechnical soils and how to maximise it.

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The main input of C in soil is represented by plants, which regulate the uptake and fixation of CO_2 in different organic forms via photosynthesis, using water and atmospheric CO_2 as 'raw materials' and light as an energy source (Fig. 6).

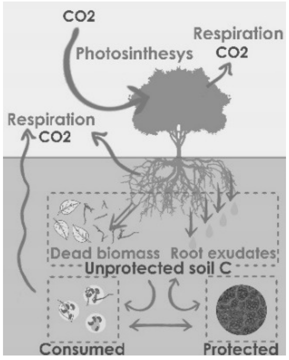

Fig. 6. Schematic layout of Carbon cycle in soils**.**

Plants also regulate the input of SOC via two main processes: 1) plant biomass from roots and shoots as a form of litter, forming the soil particulate organic matter and 2) root exudates and other substances released by roots during plant growth [23, 24] Within TERRE, [25] has investigated the potential for designing efficient C sequestering embankments, starting with the main issue of soil and plants selection.

4 Operational tools

In addition to the development of new design concepts through cutting-edge research, TERRE has worked towards the development of tools for industrial applications as there are relatively few tools available in the geotechnical engineering industry for carbon-driven design at present. Tools have included new techniques for geoinfrastructure design incorporating optimisation for minimum energy/carbon [26, 27], a Decision Support System for geo-infrastructure carbon-driven project appraisal [28], and method for carbon footprint assessment of geotechnical construction [29].

5 Conclusions

The paper has presented a number of approaches for low-carbon design of geotechnical structures and geohazard remedial measures. Suction can be viewed as a low-carbon natural soil reinforcement. Shallow landslide hazard can be mitigated by generating suction via transpiration and/or by preventing suction loss due to rainwater infiltration via hydrophobic fungal-hyphal networks and rhizosphere-promoted lateral flow. At the same time, suction-based design of man-made geostructrures can avoid significant overdesign provided suction can be relied upon either through accurate prediction of water flow regime or by deploying systems to control suction (e.g. capillary barriers). A number of low-carbon approaches involve unsaturated soils and are therefore 'coupled' with unsaturated soil mechanics. These include i) stabilisation of marginal soils using waste binder, biopolymer, and enzyme-induce calcite precipitation, ii) plant root mechanical reinforcement, iii) geothermal energy extraction from shallow geotechnical structures, and iv) earth embankments as a carbon sink.

Acknowledgements

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