Geoderma 308 (2017) 171–186

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Coupling X-ray computed tomography and freeze-coring for the analysis of fine-grained low-cohesive soils

Adrien Liernur[a,b,*], Andreas Schomburg[c], Pascal Turberg[a], Claire Guenat[a], Renée-Claire Le Bayon[c], Philip Brunner[b]

[a] Laboratory ECOS & WSL Institute, Station 2, École Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering (ENAC), 1015 Lausanne, Switzerland

[b] Center for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Rue Emile Argand 11, CH-2000 Neuchâtel, Switzerland

[c] Functional Ecology Laboratory, Institute of Biology, University of Neuchâtel, Rue Emile Argand 11, CH-2000 Neuchâtel, Switzerland

ARTICLE INFO

Editor: Morgan Cristine L.S.

Keywords:
Freeze-core
X-ray computed tomography (CT)
Soil structure
Soil sampling technique
3D soil model
Alluvial soil

ABSTRACT

This paper presents the coupling of freeze-core sampling with X-ray CT scanning for the analysis of the soil structure of fine-grained, low-cohesive soils. We used a medical scanner to image the 3D soil structure of the frozen soil cores, providing X-ray CT data at a millimetric resolution over freeze-cores that are up to 62.5 cm long and 25 cm wide. The obtained data and the changes in gray level values could be successfully used to identify and characterize different soil units with distinctly different physical properties. Traditional measurements of soil bulk density, carbon and particle size analyses were conducted within each of the identified soil units. These observations were used to develop a 3D model of soil bulk density and organic matter distribution for five freeze-cores obtained at a restored floodplain in Switzerland. The millimetric X-ray CT scanning was applied to detect the impact of freeze-coring on the soil structural integrity. This allows identifying undisturbed zones, a critical precondition for any subsequent assessment of soil structure. The proposed coupling is thought to be applicable to a wide range of other low-cohesive soil types and has a large potential for applications in hydrogeology, biology or soil science.

1. Introduction

Soil structure and the associated physical properties are crucial for soil ecosystem services such as habitat for organisms (Voroney, 2007) or soil fertility (Bronick and Lal, 2005). Soil structure formation and aggregation processes are key factors controlling soil stability and erodibility and directly influence the development of the soil as an ecosystem (Barrios, 2007; Bronick and Lal, 2005). The identification of different soil structure types and the quantification of *in-situ* soil structure characteristics are therefore of critical importance to better understand the complex interactions between soil structure and the associated soil ecosystem services. Detailed observations of the *in-situ* soil structure additionally provide crucial information to quantify the effects of anthropogenic impacts such as soil compaction. In this regard, the ability to extract soil samples with very low structural disturbances is a prerequisite for the analysis of the soil structure.

Techniques for the extraction of undisturbed soil samples vary depending on the scale of the analysis, the sampling environment and the cohesion of the soil (Clayton et al., 1982). Commonly used soil pits and thin soil layers for macro and micro soil structure analysis are limited to rather cohesive soils and unsaturated environments. In low-cohesive soils such as Fluvisols, Arenosols, Regosols or Histosols classified according to the World Reference Base (IUSS Working Group WRB, 2014), the conservation of the original soil structure remains a challenging task and, to the best of our knowledge, no sampling technique allows for the undisturbed soil sample extraction for these soil types.

A promising extraction method, although not tested yet in these soils, comes from the freeze-core sampling technique as described in Humpesch and Niederreiter (1993). In this approach, a hollow lance is rammed into the soil, and liquid nitrogen is injected within the lance to freeze the surrounding soil by conduction. The frozen soil core is then pulled out of the soil. This extraction technique was initially developed and used for river and lake sediments analysis (Ryves et al., 2002; Stocker and Williams, 1972). It also found applications in soil science and for the analysis of the hyporheic zone, for example for the identification of the vertical distribution of microbial communities or chemical pollutants (Franchini and Zeyer, 2012; Gan et al., 2006; Moser et al., 2003). In a more recent study, Strasser et al. (2015), used the freeze-cores for the

* Corresponding author at: Laboratory ECOS & WSL Institute, Station 2, École Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering (ENAC), 1015 Lausanne, Switzerland.

E-mail address: adrien.liernur@gmail.com (A. Liernur).

http://dx.doi.org/10.1016/j.geoderma.2017.08.010
Received 17 March 2017; Received in revised form 25 July 2017; Accepted 4 August 2017
Available online 12 September 2017
0016-7061/

geohydraulic characterization of river bed sediments.

Freezing the soil before extracting the sample in principle allows obtaining undisturbed samples. However, several aspects can undermine the integrity of this sampling approach. The freezing and thawing process itself can affect the soil structure. The impact of freezing on the soil structure integrity has been addressed by Singh et al. (1982) in saturated sands and they concluded that the freezing process does not significantly impact the soil structure as long as the pressure around the sample remains constant and the porewater is free to drain during the entire process. In addition to the freezing process, ramming the lance into the soil can also disturb the soil integrity. The insertion of the freezing lance into the soil is leading to an ineluctable process-related structural disturbance due to the displacement and compaction of the soil beneath the lance. This disturbance of the soil structure at the proximity of the freezing lance has already been observed and to avoid biased results, a non-sampling zone around the lance has often been defined (Franchini and Zeyer, 2012; Strasser et al., 2015). In order to sample undisturbed areas within the freeze-core, Strasser et al. (2015) first melted the core and then used a core-cutter to extract subsamples at sufficient distance from the lance and observed that this procedure did not affect the integrity of the soil structure. However, in heterogeneous soils as studied here, this procedure could potentially lead to structural disturbances related to the thawing and the mechanical extraction of subsamples. We therefore suggest to first image the whole freeze-core by X-ray Computed Tomography (CT) and subsequently extract subsamples in selected regions for further structural analyses on the still frozen soil cores to avoid potential disturbance of the core.

Recent developments in X-ray CT provide the means to image soils in 3D by non-destructive means. This technology led to significant advances in soil sciences as reviewed in Helliwell et al. (2013). The process of CT image acquisition is described in detail in Ketcham and Carlson (2001). CT scans provide a 3D intensity map of the soil where gray level variations are essentially related to changes in material density (Rogasik et al., 2003; Sander et al., 2008; Turberg et al., 2014). In the following text, the term radiodensity, as a commonly-used term to measure the transparency of a material to X-rays, will be used to refer to the soil bulk density imaged by X-ray data and expressed by changes in gray level values. The latest scanners used for X-ray CT analysis in soil sciences allow having millimetric to micrometric representations of the soil structure, providing the technical means for soil structure characterization across vastly different spatial scales (Helliwell et al., 2013).

In this paper, we employ X-ray CT scans for freeze-cores to indirectly characterize, without any destructive effect, the detailed structure of the soil. Such a coupling has been proposed in an early article by Escher (1996) who determined the pore-size distribution of freshwater-sediments based on X-ray CT. However, the rapid advances in CT scanning allow for an entirely new level of investigation. Applying the proposed coupling on selected low-cohesive and highly heterogeneous alluvial soils, the aim of this article is twofold. First, the potential of this coupling at evaluating the soil heterogeneity and identifying soil units with distinctly different soil structure characteristics is evaluated. This allows for a discretization of the soil heterogeneity into clearly defined soil units characterized by specific soil structure types. Second, the ability to observe and evaluate the impact of the freeze-coring extraction method on the soil structure integrity is assessed. This allows to spatially isolate undisturbed regions of the cores where undisturbed soil subsamples can be extracted and used for further analyses. To address both parts, millimetric X-ray CT data from a medical scanner were first acquired to image the freeze-core over its entire volume. Micrometric X-ray CT analysis and complementary soil laboratory analyses were then conducted on selected undisturbed soil regions within different soil units to validate the millimetric X-ray CT observations with further precise quantitative evaluations. The study was conducted on alluvial soils from a restored alluvial floodplain area along the Thur River, Switzerland.

2. Material and methods

2.1. Overview of the experimental design

Five freeze-cores were extracted along the Thur River at a distance of about 4 m from the river as illustrated in Ⓐ in Fig. 1 and were placed

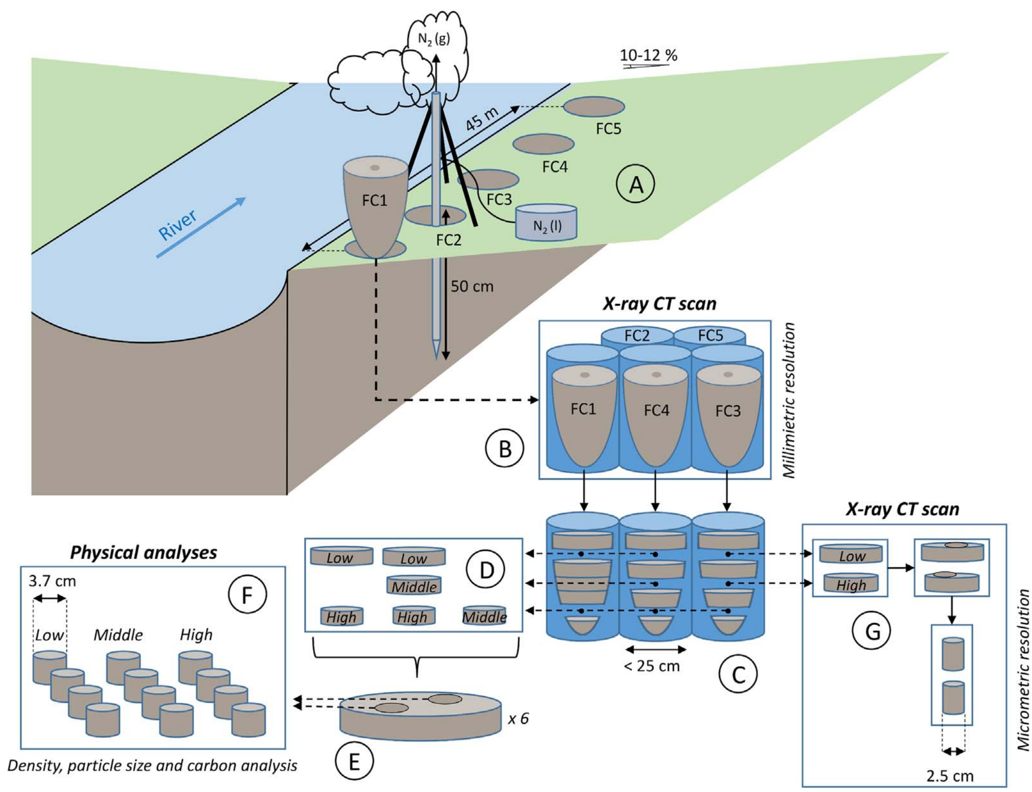

Fig. 1. Schematic representation of the experimental setup. The five extracted freeze-cores are mentioned as FC1, FC2, FC3, FC4 and FC5. The terms "*Low*", "*Middle*" and "*High*" correspond to the 3 different categories of soil imaged by different radiodensities.