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Characterizing the effects of opencast coal-mining and land reclamation on soil macropore distribution characteristics using 3D CT scanning

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A B S T R A C T

Opencast coal mining activities can cause severe changes to terrestrial ecosystems, leading to soil degradation. Soil pores play an important role in the transport and storage of water and nutrients. Soil macropore systems may be used as an indicator of soil quality, and soil macropore characteristics can reflect the quality of reclaimed soil in opencast coal mining areas. In this study, unmined, unreclaimed and reclaimed soils from the Antaibao opencast coal mine of the loess area from China were scanned to acquire information regarding soil macropores using a high-resolution, non-destructive computed tomography (CT) technique. The 3D distributions of different soil macropores were reconstructed using the Matlab platform, and the quantitative characteristics of soil macropores were determined by analyzing the number of individual detached soil macropore and the volume of individual detached macropore. The results indicated that 3D reconstruction technique can visually and accurately characterize the macropore system of compacted soils in opencast coal mining area. The number and volume of individual detached soil macropores can be acquired from a 3D soil model. The macroporosity of unreclaimed soils was poor due to the compaction of heavy machinery during mining activities, and it was about 3% based on CT technique. The macroporosity and functions of reclaimed soils significantly improved with increasing reclamation age. The number of individual detached soil macropores had a good linear relationship with macroporosity. With increasing macroporosity, the diversity of macropore sizes decreased and the volume of the largest individual detached macropore increased. To improve the macropore conditions of compacted soils, land reclamation (including land consolidation, surface soil covering, and vegetation planting) should be carried out as soon as possible.

1. Introduction

Opencast coal mining is a large-scale activity that seriously and rapidly impacts the ecological environment. Mining activities, including striping, excavating and dumping, can cause severe changes to terrestrial ecosystems, disorganizing original layers of soil profiles and aggravating soil and water loss (Wang et al., 2015a; Ibanez et al., 2006; Wang et al., 2015b). In China, opencast coal mines are primarily located in the Loess Plateau and other ecologically fragile regions. The vulnerable environment in these areas has deteriorated as a result of coal mining activities. During dumping in opencast coal mines, soil macroporosity is reduced to a large degree due to the compaction of heavy machinery. The three-phase ratio of soil was changed due to soil particle rearrangement, which directly influenced the physicochemical properties, nutrient, aeration and water movement of the compacted soils (Zhang et al., 2015; Muñoz et al., 2016; Smart et al., 2016).

The condition of soil pores is an indicator of soil quality, and it plays an important role in controlling nutrient cycling, water storage, gas exchange and mass transport (McSweeney and Jansen, 1984; Khormali et al., 2009; Ayoubi et al., 2012). The structure of compacted soils is characterized by decreased macroporosity, which leads to increased mechanical impedance and decreased fluid transport rates, resulting in reduced root growth and affecting vegetation restoration and soil macrofauna activities (Stirzaker et al., 1996; Frouz et al., 2008; Colombi et al., 2017). Therefore, it is necessary to study the macropore characteristics of compacted soils in opencast coal mine dumps and provide suggestions for land reclamation work. Some attempts have been made to develop methods to obtain soil macropore information (Radulovich et al., 1989; Bartoli et al., 1999; Pierret et al., 2002). The information on soil macropores was usually obtained by indirect

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methods that were linked to the soil density or volume (Pagliai et al., 2004). The water retention curve and mercury injection porosimetry were the most widely used methods to obtain pore size distributions (Bartoli et al., 1999; Fies, 1992; Radulovich et al., 1989; Watabe et al., 2000). However, these indirect methods cannot reflect the real distribution of soil macropores, and the results were often biased (Bartoli et al., 1999; Liu and Xu, 2002). Soil microtomy is one of the useful approaches that emerged with the development of soil micromorphology (Vogel, 1997); however, the process of sectioning was very complicated.

In the recent decades, X-ray computed tomography (CT) became a popular method (Perret et al., 2000; Peyton et al., 1994). Compared to traditional techniques X-ray tomography has many advantages, e.g., nondestructive 3D imaging and little or no sample preparation required (Pierret et al., 2002; Zeng et al., 1996). The soil pore structure is a connected and irregular 3D system. Non-destructive 3D imaging technology based on 2D scanning images, allowed for a more direct and accurate study on soil pores, including the severe compacted soils in opencast coal mining area. The 3D reconstruction technology can display the 3D distribution of the macropores, offering a new method to study the soil macropore structure. It has been used to visualize the soil macropore structure and quantify the 3D distribution characteristics of soil macropores (Pierret et al., 2002). Ojeda-Magana et al. (2014) reconstructed 3D macropore spaces using PFCM (Possibilistic Fuzzy C-Means) partitional clustering based on soil CT images. The geometric characteristics of soil macropores, including the macropore radius, length, tortuosity and retention curve, can be analyzed with a 3D reconstruction model (Ngom et al., 2011). The influences of the macropore structure on water flow (e.g., saturated hydraulic conductivity, gas diffusivity and air permeability) were also presented based on the constructed 3D network model (Cheng et al., 2012), and it was a reliable approach to predict preferential flow using the X-ray CT-derived macropore network characteristics (Naveed et al., 2016). Thus, it can be seen that the 3D reconstruction technique based on CT images markedly improved soil macropore studies (Ngom et al., 2011). Although some attempts have focused on the distribution characteristics of soil macropores in agricultural lands based on CT scanning technique (Abdollahi et al., 2014a; Munoz-Ortega et al., 2015; Kuka et al., 2013), the severely compacted soil pores in mining areas have rarely been studied.

Therefore, the objectives of our study were to (i) reconstruct 3D macropore distributions of compacted soils under different reclamation ages based on CT scanning images, (ii) quantify the soil macropore properties under different reclamation ages using 3D pore models and (iii) analyze the effects of land reclamation on the development of soil macropore properties.

2. Materials and methods

2.1. Study site

Three study areas were selected at the Pingshuo Antaibao opencast coal mine, which lies in the eastern part of the Loess Plateau in northern Shanxi Province (China), at geographic coordinates 112° 10′ 58″-113° 30′ E/39° 07′-39° 37′ N (Fig. 1): South dump (an outer dump with 23 years of reclamation; Y23), West dump (an outer dump with 20 years of reclamation; Y20) and an inner dump (not reclaimed; Y0). An unmined site (UM) in the Antaibao opencast coal mine was also selected. The parent material and soil properties are similar in the three dumps and unmined site. This area has a typical temperate arid to semi-arid continental monsoon climate. The annual mean temperature range is 5.4 °C to 13.8 °C, and the average annual rainfall is approximately 450 mm. The mining area is mainly chestnut soil with low soil nutrients (Wang et al., 2015a), and the soil weathering is extremely strong.

2.2. Soil sampling

A 10 m × 10 m plot was selected in the platforms of South dump, West dump and Inner dump and a flat of unmined site, respectively. The plots in the South dump, West dump and unmined site had similar vegetation configuration mode (*Robinia pseudoacacia*, *Ulmus pumila* and *Ailanthus altissima*), and it wasn't revegetated in Inner dump. The measures of land reclamation in three dumps, including land consolidation and surface soils covering, were similar, and all of the sampling plots selected in three dumps were covered with > 1 m of top loess on the surface during initial land reclamation. This covered loess was from the stripping surface soils before excavating and mining. A soil profile was excavated in middle position of each study plot, and the undisturbed soil cores, 2 cm in diameter and 10 cm in height, were collected vertically from the four profiles at the depths of 0–10 cm, 25–35 cm and 50–60 cm in July 2013. An acrylic cylinder was gradually pressed into the soil using a sampler with a minimum disturbance for the soil core during sampling. The soil samples were removed from the sampler, and the soils protruding from the top and bottom of the acrylic cylinder were cut. Three soil cores were sampled at each soil depth, and 9 soil cores were collected at each plot; therefore, there was a lot of 36 soil cores were collected in this study. The soil cores were wrapped with cling wrap and aluminum foil and kept at 10 °C until X-ray CT scanning.

At each soil horizon of four profiles, three soil samples were collected using the cutting ring to determine soil bulk density, and one mixed soil sample was also collected to determine the soil particle size distribution and soil organic matter. The soil particle size distribution of the samples was analyzed using a laser particle-size analyzer-Longbench Mastersizer 2000 (Malvern Instruments, Malvern, England). The soil texture was divided into three size classes based on international systems: clay (< 0.002 mm), silt (0.002–0.02 mm), and sand (0.02–2 mm). The soil bulk density was determined by the cutting ring method (Blake and Hartge, 1986), and the volume of the used cutting ring were 100 cm^3 with the diameter of 50.46 mm and the height of 50 mm. The total porosity was estimated according to the soil bulk density measured and soil specific weight (Danielson and Sutherland, 1986), and the soil specific weight was assumed to be 2.65 $g\,cm^{-3}$ (Zhou and Shangguan, 2007). Soil organic matter was determined by the potassium dichromate volumetric method (Nelson and Sommers, 1983); soil pH was determined with a potentiometer using 1:5 water extracts. The soil properties examined at different soil depths are shown in Table 1.

2.3. CT scanning

The 36 soil samples were scanned in helical mode at the Aerospace Research Institute of Special Materials & Processing Technology of China in September 2013. The CT scanner used for this study was a high-resolution X-ray digital core computed tomographer (GE Measurement & Control, German Phoenix Company, Germany). Helical scanning mode allowed for a multi-directional enhancement of the image quality. Each soil column was horizontally installed on the table of the CT scanner, so the natural soil profile was perpendicular to the X-ray plane. The CT scanning configuration parameter values were as follows: tube voltage, 180 kV; pixel size of the flat panel detector, ≤50 μm; number of pixels, 2200 ∗ 2200; pixel size of the minimum element, < 0.5 μm; field of view, 12 cm in diameter and 15 cm in height; and image reconstruction interval length, 0.05 mm. In present study, a total of 2000 cross-sectional CT images were generated for each soil core, covering the approximate 10-cm depth of each soil column (Munkholm et al., 2012). The pixel resolution of the CT images obtained from the cross-section of soil samples was 10 μm, and the CT scanning images of different soils are shown in Fig. 2.