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The effects of land subsidence and rehabilitation on soil hydraulic properties in a mining area in the Loess Plateau of China

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A B S T R A C T

Land subsidence caused by underground coalmining gives rise to severe surface deformation and results in a number of soil cracks, which markedly affect soil hydraulic properties; moreover, land rehabilitation is an effective measure to restore the ecological function of impacted lands. To analyze the effects of land subsidence and rehabilitation on soil hydraulic properties, an underground coalmine in the Loess Plateau of China was selected to conduct a field plot experiment. Four plots were designed, including one unmined plot (UMP), two subsided plots (SPI and SPII) and one rehabilitated plot (RHP), and 16 sampling points were located in each plot. The bulk density (BD), soil moisture retention curve (SMRC), field capacity (FC), saturated hydraulic conductivity (K_s) and soil disintegration rate (SDR) at the depths of 0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm at each sampling point were measured, and soil pore size distribution (PSD) based on SMRC was analyzed. The correlation analysis among soil hydraulic properties and the path analysis of effects of subsided cracks on the hydraulic properties were carried out in this study. Land subsidence increased the variability of soil hydraulic properties; whereas, they became relatively uniform after land rehabilitation. Land subsidence significantly altered soil hydraulic properties, increasing BD, K_s, SDR and soil micropores and decreasing FC; however, land rehabilitation can improve soil hydraulic properties and increase the use efficiency of soil water, decreasing BD, K_s, SDR and increasing FC and soil macropores. The cracks related to subsidence and vegetation had significant effects on soil hydraulic properties, especially BD; the crack width and vegetation coverage had a marked effect on BD.

1. Introduction

With the incentive of rapid economic development, increasingly more natural resources were consumed heavily in China, especially coal which accounts for 74% of total energy consumption of primary energy (Hu and Wei, 2003; Li et al., 2007). Underground mining is an efficient mode for the exploitation of mineral resources; however, this mode of resource extraction can form large underground mined-out areas, which inevitably lead to severe land subsidence (Wang et al., 2015b; Zhang et al., 2015a). The largest subsidence area related to coal mining in the world is found in China. The land area affected by subsidence is currently 700,000 km^2 and is continually increasing at a rate of 130 km^2 annually (Wang et al., 2015a). Land subsidence results in substantial ecological and environmental problems, such as lifting the groundwater level and soil erosion (Shepley et al., 2008; Wu et al., 2009). Moreover, most of these subsided lands are located in high-quality arable land area in China.

Mining induced subsidence results in the disturbance of the surface soil, and the soil hydraulic parameters, including soil water content, field capacity and soil hydraulic conductivity, can be seriously affected; and can change the transport path of soil water and nutrient, thereby affecting the fertility and health of the soil and balance of soil-plant system (Chen et al., 2015; Xu et al., 2014). Thus, the study on the effects of coal mining subsidence and site restoration on soil hydraulic characteristics has great significance for carrying out scientific and precise land rehabilitation, improving plant growth and promoting coordinated and sustainable development of ecological ecosystem in subsided areas.

In China, the Loess Plateau area is rich in coal resources (Wang et al., 2015d). The frequent mining activity has led to severe deformation of ground surface, including surface subsidence and tilt, subsidence pits and cracks, and so on (Z. Chen et al., 2014, C. Chen et al., 2014). The soil environment is damaged by land subsidence, which resulted in the leakage of water and nutrients in farmland and the quality of arable land degraded year by year (Hu et al., 1997). Currently, some attempts on infiltration and spatial distribution of soil

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moisture have been conducted in some underground coalmine areas, and the effects on soil physical properties and hydraulic properties of coal mining and land rehabilitation have been extensively studied in some opencast coalmines (Chen et al., 2008; Gates et al., 2011; Yu et al., 2015). These research showed that spatial structure of the original landform was partially or completely destroyed by mining, which significantly changed some soil properties, including soil organic carbon, total nitrogen, soil bulk density (BD), saturated hydraulic conductivity (K_s) and water content (Shukla et al., 2004; Wang et al., 2015c). On the other hand, land rehabilitation can remediate the impacted ecological ecosystem, including biodiversity restoration, soil moisture and nutrient improvement (Akala and Lal, 2000; Barnhisel and Hower, 1997). However, the studies on the changes and spatial variability in soil hydraulic characteristics in subsided areas resulting from underground coalmining activities are insufficient, especially BD, K_s, FC, SDR, soil moisture retention curve (SMRC) and pore size distribution (PSD). The mechanism and driving forces of effects of subsidence on soil hydraulic characteristics were unclear, and the recovery of functions of soil water storage and transport in rehabilitated land on the Loess Plateau area have not been fully examined.

The effects on soil hydraulic properties from subsidence cracks are complex. In previous studies, the methods of simple correlation analysis and multiple regression analysis have been widely used to analyze the effects of some explanatory variables on a response variable (Xu et al., 2015; Zhang et al., 2015b). Although these methods could make a quantitative analysis, they cannot reflect the complex relationship among explanatory variables. Path analysis can reflect the direct effect of explanatory variables on response variables and the indirect effect which is not directly affected on response variable by one explanatory variable but can change it by affecting another variable (Emdad et al., 2013; Ye et al., 2014). At present, path analysis has been increasingly utilized to define the best criteria for selection in biological, agronomic and ecological studies (Z. Chen et al., 2014; C. Chen et al., 2014).

In a word, soil hydraulic properties were seriously affected and ecological environment is fragile in the subsided lands of Loess Plateau area; moreover, soil hydraulic properties play a crucial role in land rehabilitation and ecological restoration. Therefore, the objectives of this study were (i) to assess the variability of soil hydraulic properties in unmined land, subsided land and rehabilitated land of the Loess Plateau, (ii) to analyze the effects of land subsidence and rehabilitation on soil hydraulic properties, and (iii) to evaluate the direct and indirect effects of cracks from subsidence on soil hydraulic properties using path analysis.

2. Materials and methods

2.1. Study area

The study area is in the Pingshuo Coalmine in Shanxi Province of China. It is located along the border of the Shanxi Province, Shaanxi and Inner Mongolia in the east Loess Plateau, with geographical coordinates of 112°11′ to 113°30′E, 39°23′ to 39°37′N (Fig. 1). The climate of the study area is typical temperate arid to semi-arid continental monsoon climate, winters are cold with less rain and summers are hot with frequent rain (Wang et al., 2015c). Average annual temperature is 6.3 °C, the highest temperature difference up to 61.8 °C, the frost-free period is about 115 to 130 days. The average annual rainfall is approximately 450 mm, the average annual evaporation, however, is 5 times more than the rainfall.

The specific study sites were the unmined, subsided and rehabilitated lands in the 3rd Underground Coalmine of Anjialing mine area. One unmined plot, two subsided plots and one rehabilitated plot were selected to conduct this study. The size of each plot was 100 m × 100 m. There were 13 subsidence cracks with width range of 0.1 to 3.5 m in subsided plotI (SPI). There were 8 subsidence cracks in subsided plotII (SPII), and crack width varied from 0.1 to 5.5 m. Soil type was Kastanozems according to World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Herbaceous vegetation occupied in the two subsidence plots.

The unmined plot (UMP) and rehabilitated plot (RHP) were very close to the subsided plots. Land rehabilitation was carried out in June 2012 in RHP. After 20 cm surface soils were stripped, the cracks were filled using local soils; then the subsided lands were consolidated into horizontal terrace and stripped surface soils were covered. The vegetation was restored naturally in RHP. In UMP and RHP, the only vegetation type also was herbaceous. The topography in the unmined and rehabilitated plots was also similar with those of two subsided plots. The overview of four plots is represented in Fig. 2, and the details are shown in Table 1.

2.2. Sample collection and analysis

The sampling network was designed on a grid of 25 m × 25 m in each 1 hm^2 plot, and there were total 64 sampling points in four plots (UMP, SPI, SPII and RHP). Each sampling point was fixed in the center of the grid, and soil profiles were excavated in July 2015. Two soil core samples with 50 mm in height and 50.2 mm in diameter were collected using cutting rings at the depths of 0–20, 20–40, 40–60 and 60–80 cm at each sampling point. One soil core sample was used to determine the BD and K_s, and one soil core sample was used to determine soil moisture retention curve (SMRC). Moreover, one clod with an approximate size of 5 cm × 5 cm × 5 cm was collected to determine the soil disintegration rate (SDR). The disturbed soils were air-dried in laboratory, then clods were broken using a gavel to pass through a 2-mm sieve. Coordinates of each sample point were recorded using a GPS.

Soil BD was determined using a cutting ring method (Ussiri et al., 2006). SDR was determined using Jiang method (Jiang et al., 1995), and K_s was determined using a variable head method (Wang et al., 2015c).

Soil moisture retention curves were determined using a high speed freezing centrifuge - CR22G II (Hitachi, Japan). The centrifugal time and rotational speed were set after soils tested in cutting rings were saturated for approximately 14 h. The soils tested were centrifuged for 60 or 90 min at speeds of 970, 1670, 2160, 2730, 3050, 5290, 6820, 8630, 8830 and 10,800 r min^{-1}, respectively. The corresponding matrix suction values were 102, 306, 510, 816, 1020, 3060, 5100, 8160, 10,200 and 15,300 cm H_2O, respectively. The samples were weighed after the water content was stabilized in each rotational speed. After centrifugation, all samples were placed into an oven to dry to a constant weight at 105 °C. The water contents of different soil suction values were then calculated. The Van Genuchten model was used to construct the soil moisture retention curve based on the Lsqcurvefit function using MATLAB 7.0 (Mathworks, USA). The Van Genuchten equation is

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{1 + [1 + (-\alpha h)^n]^m} \quad (1)$$

where, θ is volumetric soil water content in $cm^3 \cdot cm^{-3}$, h is soil water pressure head in cm, θ_r is residual volumetric soil water content in $cm^3 \cdot cm^{-3}$, θ_s is volumetric soil water content at zero pressure head in $cm^3 \cdot cm^{-3}$, and α (cm^{-1}), n and m are positive fitting parameters ($\alpha > 0, n > 1, m = 1 - \frac{1}{n}$). The value of h at the inflection point (h_p) of the curve given by Eq. (1) is (van Genuchten, 1980)

$$-h_p = \frac{1}{\alpha} m^{1-m} \quad (2)$$

The corresponding pore diameter d (assuming cylindrical pores) at h_p is given by the expression (Kargas et al., 2016)

$$d = \frac{4\alpha\sigma\cos(\gamma)}{\rho g m^{1-m}} \quad (3)$$

where, σ is surface tension coefficient of water in $N \cdot m^{-1}$, γ is solid-water contact angle, usually assumed to be zero, ρ is water density in