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

Jinman Wang\textsuperscript{a, b, x}, Ping Wang\textsuperscript{a}, Qian Qin\textsuperscript{a}, Hongdan Wang\textsuperscript{a}

\textsuperscript{a} College of Land Science and Technology, China University of Geosciences, 29 Xueyuanlu, Haidian District, 100083 Beijing, People’s Republic of China

\textsuperscript{b} Key Laboratory of Land Consolidation and Rehabilitation, Ministry of Land and Resources, 100035 Beijing, People’s Republic of China

\begin{abstract}
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.
\end{abstract}

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\textsuperscript{2} and is continually increasing at a rate of 130 km\textsuperscript{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

\textsuperscript{x} Corresponding author at: College of Land Science and Technology, China University of Geosciences, 29 Xueyuanlu, Haidian District, 100083 Beijing, People’s Republic of China.

E-mail address: wanghai@cugb.edu.cn (J. Wang).

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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 system, 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 plot I (SPI). There were 8 subsidence cracks in subsided plot II (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 hm² 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 desiccation 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 H₂O, 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 $L_{sc}$curvefit function using MATLAB 7.0 (Mathworks, USA). The Van Genuchten equation is

$$\theta = \theta_r + \left( \frac{1}{1 + (\alpha h)^{m}} \right)^{n}$$

(1)

where, $\theta$ is volumetric soil water content in cm³ cm⁻³, $h$ is soil water pressure head in cm, $\theta_r$ is residual volumetric soil water content in cm³ cm⁻³, $\alpha$ is volumetric soil water content at zero pressure head in 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 ($h_i$) of the curve given by Eq. (1) is (van Genuchten, 1980)

$$-h_i = \frac{1}{\alpha} m^{-1}$$

(2)

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

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

(3)

where, $\sigma$ is surface tension coefficient of water in N m⁻¹, $\gamma$ is solid-water contact angle, usually assumed to be zero, $\rho$ is water density in
Fig. 1. Schematic diagram of geographical location.

Fig. 2. Overview of study plots (a. UDP, b. SPI, c. SPII and d. RHP).

Table 1
The details of four study plots (UMP, SPI, SPII and RHP).

<table>
<thead>
<tr>
<th>Plot number</th>
<th>Coordinate X (E)</th>
<th>Y (N)</th>
<th>Crack Number</th>
<th>Width (m)</th>
<th>Vegetation Types</th>
<th>Coverage (%)</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMP</td>
<td>112°21'58&quot; – 112°22'2&quot;</td>
<td>39°31'46&quot; – 39°32'49&quot;</td>
<td>0</td>
<td>–</td>
<td>Herbaceous</td>
<td>35</td>
<td>Kastanozems</td>
</tr>
<tr>
<td>SPI</td>
<td>112°20'16&quot; – 112°20'20&quot;</td>
<td>39°33'53&quot; – 39°33'56&quot;</td>
<td>13</td>
<td>0.1–3.5</td>
<td>Herbaceous</td>
<td>41</td>
<td>Kastanozems</td>
</tr>
<tr>
<td>SPII</td>
<td>112°20'15&quot; – 112°20'19&quot;</td>
<td>39°33'56&quot; – 39°34'00&quot;</td>
<td>8</td>
<td>0.1–5.5</td>
<td>Herbaceous</td>
<td>27</td>
<td>Kastanozems</td>
</tr>
<tr>
<td>RHP</td>
<td>112°20'17&quot; – 112°20'21&quot;</td>
<td>39°33'49&quot; – 39°33'52&quot;</td>
<td>0</td>
<td>–</td>
<td>Herbaceous</td>
<td>30</td>
<td>Kastanozems</td>
</tr>
</tbody>
</table>
kg·m\(^{-3}\). \(g\) is the acceleration of gravity in m·s\(^{-2}\).

It may be mentioned that \(h_p\) separates in general, the relatively larger pores from the relatively smaller ones and there its changes may provide information on the pore space temporal changes.

Field capacity (FC) was determined based on the measured results of SMRC, and the soil water content under 300 cm H\(_2\)O pressure (30 kPa) was considered as FC (Duan et al., 2010).

2.3. Data analysis

All the measured data were analyzed using standard univariate statistics, and the mean, median, standard deviation (SD), standard error (SE), coefficient of variation (CV), minimum and maximum were calculated using the SPSS 19.0 software package (SPSS, Chicago, USA). Variability in soil hydraulic properties was presented by ranking the CV into three levels in this study, and which were low (< 15%), moderate (15%–35%) and high (> 35%) (Cassel and Nelson, 1985).

Significant differences of different hydraulic properties were analyzed using one-way ANOVA, and the differences were considered to be statistically significant at \(P < 0.05\). The correlation of different soil hydraulic properties was analyzed using Canoco 4.5 (Microcomputer Power, NY, USA) by constructing analysis array in four plots. The effects of subsidence cracks on soil hydraulic properties were analyzed quantitatively by path analysis.

2.4. Path analysis

Path analysis is a multiple variate statistical method, which was proposed by Sewall Wright in 1921, it examined the linear relationship between multiple independent variables \((X_1, X_2, ..., X_n, ..., X_n)\) and the response variable \((Y)\) (Bhan, 1973; Liu et al., 2003). The effects of land subsidence on soil hydraulic properties were analyzed using path analysis. In the study, BD, FC, Ks and SDR were selected as response variables. Moreover, we assumed that the crack nearest to sampling point has the greatest impact on the soil hydraulic properties of this sampling profile. Vegetation roots close to the crack may be pulled off during subsidence and the normal growth of vegetation was affected, which resulted in the changes in soil properties. Therefore, the distance between sampling point and edge of crack \((X_1)\), the width of crack \((X_2)\), the length of crack \((X_3)\) and vegetation coverage \((X_4)\) were selected as explanatory variables. \(X_1\) was independent on \(X_2, X_3\) and \(X_4\), and we assumed that there was no correlation between \(X_1\) and \(X_2, X_3, X_4\). Effect relationships among these variables are shown in Fig. 3. The regression equation between response variable \((Y)\) and explanatory variables \((X_1, X_2, X_3, X_4)\) was as follows (Xu et al., 2015):

\[
Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + O
\]  

(4)

where \(O\) is the error, \(r_{ij}\) are the correlation coefficients among these variables and \(r_{12} = r_{13} = r_{14} = 0, r_{23} = 0, r_{24} = 0, r_{34} = 0\).

After a series of transformations on Eq. (4), the equations of path coefficient and determination coefficient were as follows:

\[
\tilde{r}_0 = \tilde{p}_{0,1} + \sum r_{ij} \times \tilde{p}_{0,j}
\]  

(5)

\[
R^2 = (\sum \tilde{d}_{0,1} + \sum \tilde{d}_{0,j})
\]  

(6)

where \(\tilde{r}_0\) is the correlation coefficient between \(X_i\) and \(Y\), \(\tilde{p}_{0,1}\) is the direct effect coefficient on \(Y\) of \(X_0\), \(\tilde{r}_{ij}\) is the indirect effect coefficient of \(X_i\) via \(X_j\) on \(Y\), \(R^2\) is the determination coefficient of the explanatory variables \((X_1, X_2, X_3, X_4)\) on \(Y\), \(\tilde{d}_{0,j}\) is the determination coefficient of \(X_0\) on \(Y\), \(i = 1, 2, 3, 4\), \(j = 1, 2, 3, 4\) and \(i \neq j\).

All of the analyses were performed using the SPSS 19.0 software package (SPSS, Chicago, USA) and MATLAB 7.9 (Mathworks, Natick, MA, USA).

3. Results and discussion

3.1. Variability of soil hydraulic properties

Descriptive statistics, including mean, median, SD, SE, CV, minimum and maximum values, for soil hydraulic properties in the UMP, SPI, SPII and RHP are presented in Table 2. The medians of different soil hydraulic properties were very close to their means, and most medians were either equal to or less than the means for most soil hydraulic properties in unmined, subsided and rehabilitated plots. This result indicated that the outliers did not dominate the measures of central tendency in the distributions of soil hydraulic properties. BD in all plots showed a low variability, and FC exhibited a moderate variability. All of the CV values of Ks and SDR were > 35% and they had a high variability; whereas, it was an exception for SDR in UMP with a moderate variability. The orders of variability magnitudes of BD, FC, Ks and SDR were SPI > SPII > UMP > RHP, SPI > UMP > SPII > RHP, SPI > RHP > SPI > UMP and SPI > SPII > RHP > UMP. Except for Ks, the variability of soil hydraulic properties was highest in SPII, and the variability in RHP was less than that in subsided plots (SPI and SPII). This result indicated that land subsidence increased the variability of soil hydraulic properties; whereas, they became relatively uniform after land rehabilitation.

3.2. Variation in soil hydraulic properties

3.2.1. Soil bulk density

Mining subsidence changed the soil BD closely related to the transport of soil moisture and nutrient. The variations in BD among four plots at different soil depths are shown in Fig. 4. BD ranged from 1.29 to 1.49 g cm\(^{-3}\) across all soil depths and study sites. The BDs in SPI were higher than those of other plots at all depths \((P < 0.01)\). The BD in SPII increased by 10.4%, 4.4%, 4.4% and 5.8% compared with those in UMP at the depths of 0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm, respectively. For UMP, SPII and RHP, the order of magnitude of BD was SPII > RHP > UMP on the whole; however, there were no significant differences among these three plots \((P > 0.1)\). With increasing soil depth, BD increased in the unmined plot and decreased in rehabilitated plot; however, there wasn’t a clear trend for subsided plots.

During the formation of cracks, the soils in the non-crack zone were seriously condensed (Shu and Bhattacharyya, 1993); which resulted in an increase in BD. Because the crack in surface soil was wider than that in bottom soil, the increase of BD in surface soil was higher than that in bottom soil. Moreover, land subsidence also affected the development of plant roots. Roots play a critical role in the improvement of soil physical properties, which can increase soil porosity and infiltration and decrease soil bulk density (Josa et al., 2012). Therefore, the destruction of roots also could lead to an increase in BD. Moreover, the development of roots was closely linked with vegetation coverage. The
Moreover, land subsidence caused a decrease of reduction of the radii of mesopores ($1000 > d > 10 \mu m$, $h > 3 cm$). On the contrary, land rehabilitation led to an increase of macropores ($d > 300 cm$) and an increase of macroporosity ($d > 10 \mu m$, $h < -300 cm$). On the contrary, land rehabilitation led to an increase of macropores ($d > 300 cm$) and an increase of macroporosity ($d > 10 \mu m$, $h < -300 cm$).

Underground coalmining resulted in severe surface deformation and gave rise to a number of cracks, which led to the alteration of soil pore size. Soil pores play an important role in controlling the movement of water, nutrients and gas (McSweeney and Jansen, 1984). The size, shape and connectivity of the pores all affect the speed and efficiency of the migration of those substances (Frouz et al., 2008). In addition, soil pores help conserve water by increasing water infiltration rate and reducing soil erosion (Zhang et al., 2015a). Therefore, the alteration of soil pore size caused by underground coalmining led to the increase of the variability of soil hydraulic properties described in Section 3.1.

After land consolidation and crack filling, the evolution soil pore space and its pore size distribution were evolved after the rehabilitation. The soil pore conditions were effectively improved and then vegetation coverage was increased. After land rehabilitation, the distribution of soil porosity became uniform. Therefore, land rehabilitation resulted in the decrease of the variability of soil hydraulic properties.

### 3.2.2. Particle size distribution

The pore diameter $d$ at $h_p$ based on SMRC is presented in Table 3. The $d$ values varied between 123.72 and 171.29 $\mu m$ indicating the dominance of mesopores (Kargas et al., 2016; Luxmoore, 1981).

Moreover, land subsidence caused a decrease of $h_p$ in other words a reduction of the radii of mesopores ($1000 > d > 10 \mu m$, $-3 \leq h \leq -300 cm$) and an increase of micropores ($d < 10 \mu m$, $h < -300 cm$). On the contrary, land rehabilitation led to an increase of $h_p$, and it exhibited a reduction of the radii of mesopores ($1000 > d > 10 \mu m$, $-3 \leq h \leq -300 cm$) and an increase of macropores ($d > 1000 \mu m$, $h > -3 cm$).

Underground coalmining resulted in severe surface deformation and gave rise to a number of cracks, which led to the alteration of soil pore size.
reduced the soil water retention, which might have some relationships with the destruction of soil pore structure and plant roots. There was a significantly negative correlation between BD and soil water retention. Soil BD increased after land subsidence, and thus total soil porosity would decrease; which also resulted in a reduction in capillary porosity and a decrease in water retention. Moreover, the plant roots also can develop soil pore structure and increase the water retention (Rocha et al., 2010), the destruction of plant roots would inevitably lead to the decrease of soil water holding capacity. After land rehabilitation, land consolidation and soil tillage promoted the formation of soil aggregate, and soil aeration was improved and then soil retention capacity was effectively increased (Fig. 5).

3.2.4. Field capacity

The variations in FC in UMP, SPI, SPII and RHP are shown in Fig. 6. There were significant differences in FC among different plots, and all of the orders of magnitude of FC were RHP > UMP > SPII > SPI at any depth. FC in SPI was decreased by 10.06% and 12.51% compared with UMP and RHP, and the values were 4.15% and 6.75% in SPII. The difference in FC between RHP and UMP was not significant. These results indicated that land subsidence decreased FC at different depths, and land rehabilitation improved the hydraulic properties of subsided soils and increased soil FC. Except for the RHP, no significant differences in FC were represented at any depth in UMP, SPI and SPII (P > 0.1). The reasons of changes in FC were consistent with soil water retention characteristics.

3.2.5. Saturated hydraulic conductivity

Land subsidence had a great effect on Ks values, and the variations are shown in Fig. 7. The Ks in subsided lands were higher than those in unmined and rehabilitated lands, and they were the highest in the SPI at different depths. These results indicated that land subsidence increased Ks. On the whole, the Ks in different plots ranked as SPI > SPII > UMP > UHP. The Ks in SPI at 20–40 cm depth was the highest, and which was approximately 11 times that of UMP at the same depth. The effects of subsidence on Ks in SPII were less than those in SPI, but the change in trend of Ks with increasing depth was same as that in SPI. The significant difference in Ks between SPI and SPII might

Fig. 5. The variation in soil moisture retention curve in UMP, SPI, SPII and RHP (a. 0–20 cm; b. 20–40 cm; c. 40–60 cm; d. 60–80 cm).

Fig. 6. The variation in field capacity in UMP, SPI, SPII and RHP. Error bars represent standard error of means. For each soil depth, different capital letters indicate significant differences between depths (P < 0.05). For each plot, different lower-case letters indicate significant differences between plots (P < 0.05).

Fig. 7. The variation in saturated hydraulic conductivity in UMP, SPI, SPII and RHP.
be from the difference of magnitude of land subsidence. The number of subsided cracks in SPI was more than that in SPII, which might lead to a high $K_s$.

The subsided cracks would increase the effective water flow path and reduce the tortuosity of the path to promote the downward movement of the water and result in increasing the rate of infiltration (Tan et al., 2016). Therefore, land subsidence led to an increase in the saturated hydraulic conductivity. Moreover, land rehabilitation reduced the effective water flow path and increased the tortuosity of the path to resist the downward movement of the water and to result in decreasing the rate of infiltration (Tan et al., 2016; Felton, 1992). Therefore, land rehabilitation led to a decrease in the saturated hydraulic conductivity and made an improvement in the use efficiency of soil water.

### 3.2.6. Soil disintegration rate

The variations in SDR in UMP, SPI, SPII and RHP are shown in Fig. 8. The SDR among four plots differed significantly and varied at different depths, and the orders of magnitude were SPI > SPII > UMP > RHP, SPI II > SPI > RHP > UMP > SPI > SPI and SPI > RHP > UMP > SPI at the depths of 0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm, respectively. Overall, the SDR in subsided sites were higher than those in unmined and rehabilitated sites, except at the 40–60 cm and 60–80 cm depths in SPI and 40–60 cm depth in SPII. The SDR in UMP were close to those in RHP, and their change trends were consistent at the vertical direction. The SDR at the depth of 60–80 cm was the highest at all soil depths for different plots.

The more disintegrated soil particles, the easier it is to detect and concentrated flow erosion may increase (Shainberg et al., 1994). The increase in SDR was also from the changes in soil pores and plant roots. The SDR in surface soils increased after land subsidence, which would result in the increase of soil disintegration. Therefore, some measures should be taken to control soil erosion. With increasing soil depth, all of the SDR increased, which may be from the effects of vegetation. Water-stable aggregates are beneficial in erosion control. Plants play two main roles in the formation of soil aggregates. First, plant roots physically enmesh soil into aggregates (Degens, 1997). Refecting this, root length can relate positively to aggregate. Second, plants affect aggregate formation through organic residues that enter the soil and mix with mineral particles (Blankinship et al., 2016). In this study area, the main vegetation type is herbaceous, and the root is very short. In bottom soil depth, the density of root was low, which led to a high SDR. After land rehabilitation, with the improvement of soil pore structure and the promotion of plant root function, the SDR in surface depth also were decreased compared with those in subsided soils.

### 3.3. Correlation among the soil hydraulic properties

Matrix analysis of correlation of soil hydraulic properties is shown in Table 4. There was a significantly negative correlation between BD and FC in UMP, and the correlation coefficient were $-0.491$. Except for SPI, there was a significantly positive correlation between SDR and $K_s$ in UMP (0.309), SPII (0.584) and RHP (0.310). There were a negative correlation between FC and $K_s$ in UMP (0.309), SPII (0.584) and RHP (0.310). There were a negative correlation between BD and FC in UMP (0.309), SPII (0.584) and RHP (0.310). There were a negative correlation between BD and $K_s$ in SPI (0.356). These results showed that land subsidence had some effects on FC and $K_s$, and that land rehabilitation made an improvement on SDR and $K_s$.

### 3.4. The effects of subsided crack on soil hydraulic properties

Path analysis results of the effects on soil hydraulic properties of subsidence cracks are shown in Table 5. The explanatory variables ($X_1$, $X_2$, $X_3$ and $X_4$) were the main determinants of BD and FC, with high determination coefficient of 0.71 and 0.76, respectively. The effects of $X_2$ and $X_4$ on BD were clearer than those of other two variables, with the correlation coefficients of 0.55 and 0.80, respectively. The direct effect of $X_4$ on BD was the highest, with the effect coefficient of 0.76, which resulted in a high integrated path coefficient. Although the direct effect of $X_4$ on BD was low, there was a total indirect effect coefficient of 0.46, especially the effect from $X_4$ which resulted in a high integrated path coefficient. The direct effect of $X_4$ on FC was the highest and it had the effect coefficient of 0.70, followed by $X_2$ and $X_3$. Except for $X_4$ having an indirect effect coefficient of 0.30, the indirect effects from other variables were very low.

The determination coefficient of $K_s$ ($R^2 = 0.56$) were at medium level, indicating that there were other factors affecting $K_s$ except crack and vegetation coverage, including soil particle distribution, bulk density, soil organic matter and so on. The integrated path coefficients of $X_2$ on $K_s$ and $0.54$; this result indicated that the crack width and vegetation coverage had some effects on the $K_s$. The determination coefficient of SDR was relatively low ($R^2 = 0.14$), indicating that explanatory variables ($X_1$, $X_2$, $X_3$ and $X_4$) were not the main determinants of SDR in this model.

High direct effect coefficients of $X_4$ and indirect effects coefficients on BD, FC, Ks and SDR from $X_4$ were observed in the study, indicating that it was correct to select vegetation coverage as an explanatory variable in the path analysis.
Table 5

<table>
<thead>
<tr>
<th>Response variable</th>
<th>Explanatory variable</th>
<th>X1</th>
<th>X2</th>
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Note: X1 is the distance from the sampling point to the edge of crack; X2 is the width of crack; X3 is the length of crack; X4 is vegetation coverage.

4. Conclusions

This study analyzed the effects of land subsidence and rehabilitation on soil hydraulic properties in an underground coalmining area on the Loess Plateau of China. Land subsidence increased the variability of soil hydraulic properties, and they became relatively uniform after land rehabilitation. Land subsidence led to poor soil hydraulic properties, increasing BD, Ks, 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, Ks and SDR and increasing FC and soil macropores. The subsided cracks and vegetation had some effects on soil hydraulic properties, especially in BD; the crack width and vegetation coverage had a marked effect on BD.

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