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Influence of Different Mining Damage Types on Soil Erodibility in Coal Mining Areas of Northern Shaanxi in the Middle Reaches of the Yellow River in China

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Abstract: The middle reaches of the Yellow River basin are not only rich in coal resources in China, but are also a typical experimental field for studying the law and mechanism of soil erosion caused by coal mining in the area. Grasping the differences in soil's physical and chemical properties caused by different types of mining damage and then analyzing the differences in soil erosion is conducive to achieving ecological environmental protection and high-quality development in coal mining areas, thus improving soil and water conservation efficiency and saving costs. In this study, we took the typical loess subsidence slope of Ningtiaota mine field in the northern Shaanxi coal mining area as the research object, collected the soil samples at different slope positions, and measured the soil mechanical composition and organic matter mass fraction using an MS2000 laser particle size analyzer and a total organic carbon analyzer, respectively. Based on the EPIC model, the soil erodibility K value was further calculated, the spatial variation characteristics of the soil's mechanical composition and organic matter mass fraction were analyzed, and the soil erosion effect under different mining damage types was interpreted. The results are as follows: ① The subsidence of loess slope and the development of mining ground fissures will reduce the clay mass fraction and increase the sand mass fraction in the shallow soil on the slope. The clay mass fraction of the whole slope will decrease by 4.50–30.30%, and the soil sand mass fraction will increase by 6.83–23.67%. The shallow soil at the top and middle of the slope has obvious sandy characteristics, and the amount of sandy soil in the crack area of the same slope is obviously higher than that in the non-crack area. Slope position is the main reason to control the shallow soil sand on the slope of loess subsidence in the northern Shaanxi coal mining area. ② The subsidence of loess slope and the development of mining ground fissures will lead to a decrease in organic matter mass fraction in shallow soil in different amounts. The decrease in organic matter mass fraction in the whole slope is 12.68–35.46%, and the decrease in organic matter mass fraction in shallow soil at the top and middle of the slope is significant, and the loss of organic matter in the crack area of the same slope is obviously higher than that in the non-crack area. The greater the width of the mining ground fissures and the smaller the horizontal distance from ground fissures, the more organic matter mass fraction in shallow soil will decrease. Mining ground fissures are the main factors when it comes to controlling the loss of organic matter in the shallow soil on the loess subsidence slope in northern Shaanxi coal mining area. ③ The negative correlation coefficients of shallow soil erodibility K value with the soil clay mass fraction and organic matter mass fraction all exceeded 0.6, a significant level, and there is a high degree of consistency in the change characteristics of the slope scale. The subsidence of the loess slope and the development of the mining ground fissures will have the effect of improving the erodibility of shallow soil in all parts of the slope. The erodibility of shallow soil at the top and middle of the slope increases significantly, and the erodibility of shallow soil in the crack area of the same slope is obviously higher than that in the non-crack area. The larger the width of the mining ground fissures and the smaller the horizontal distance from the ground fissures, the higher the erodibility of the surrounding shallow soil. After calculation, it was found that the maximum boundary of the mining ground fissures developed on the loess subsidence

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slope in northern Shaanxi coal mining area to improve the erodibility of the surrounding shallow soil was 115 cm, and the main action range was concentrated within 90 cm. These research results can provide a scientific basis for accurate prevention and control of the soil erosion effect of mining subsidence in loess coal mining in the area of northern Shaanxi, thus saving costs.

Keywords: mining ground fissures; mining subsidence; soil erodibility; coal mine area; soil organic matter

1. Introduction

In recent years, the strategic shift of China's energy production center to the west has become increasingly obvious, especially in the middle reaches of the Yellow River, which have become the key place for coal production [1,2]. However, the ecological environment in the middle reaches of the Yellow River is fragile, water resources are scarce, and natural soil erosion is serious. The large-scale exploitation of coal resources has lead to a series of mining damage problems in mining areas, such as surface deformation, water resource depletion, soil quality degradation, vegetation degradation, etc., which has eventually lead to, and aggravated, soil erosion in mining areas. This has resulted in a sharp contradiction between efficient coal mining and ecological environment protection. In October 2021, the Central Committee of the Communist Party of China and the State Council issued [3] the Outline of the Yellow River Basin Ecological Protection and High-quality Development Plan, which emphasized that any activity performed in the middle reaches of the Yellow River should "pay special attention to soil and water conservation". Therefore, solving the problem of soil erosion in coal mining areas has become one of the keys to ecological protection and high-quality development in the middle reaches of the Yellow River.

At present, the effects of soil erosion in coal mining areas are mainly concentrated in two aspects: the estimation of soil erosion on a large spatial scale and the law of soil erosion in waste soil, slag, and coal gangue accumulation areas on a small spatial scale. For example, Li Zhu et al. [4] predicted that the No. 1 open-pit coal mine in Shengli mining area of Xilin Gol League, Inner Mongolia may cause 3.18×10^5 t of soil erosion and 3.09×10^5 t of new soil erosion within the prediction period. Fuyan Chen et al. [5] used remote sensing and GIS technology to estimate the amount of soil erosion in the northern Shaanxi coal mining area on a large spatial scale, and evaluated the ecological environment quality of the mining area as an important parameter. Wenlong Liu et al. [6] used ASTERGDEM data, Landsat/TM images, and ArcGIS as the processing platform to evaluate the soil and water loss in Xinzhou mining area, and found that about 20% of the soil and water loss in Xinzhou mining area was serious. Jianming Li et al. [7] found that the total amount of newly increased erosion of waste soil and slag was $2.25^6 31.59$ times that of the original ground. They accomplished this through simulated rainfall experiments in the field and they reached the conclusion that the mining area needs to do a good job in protecting the waste soil and slag accumulation in order to slow down its serious soil erosion. Kayet N [8] estimated the coal gangue accumulation area in Kiruburu and Meghahatuburu coal mines by using the revised universal soil loss equation (RUSLE) and SCS-CN method, and found that the soil loss is closely related to runoff and rainfall. However, at present, there are few reports at home and abroad on the changes of soil's physical and chemical properties caused by different types of surface damage due to mining, which in turn leads to soil erosion.

Soil erodibility, as one of the important parameters for describing and quantitatively analyzing soil erosion, has been regarded by domestic and foreign scholars as an important starting point for studying the law and mechanism of soil erosion in recent decades, which is generally expressed by K value [9]. At present, there are mainly EPIC model [10], Shirazi model [11], Torri model [12], Nome, and modified Nome's equation in the world. In this paper, aiming at the changes of soil mechanical composition and organic matter content in

Ningtiaota coal mine, EPIC model is adopted to further calculate soil erodibility, and the effect of soil erosion in coal mining areas under different mining damages is studied, so as to provide scientific basis for accurate prevention and control of soil erosion, ecological environment protection, and high-quality development in coal mining areas in the middle reaches of the Yellow River.

Overview of Research Area

The research area is located in Ningtiaota mine field in northern Shaanxi coal mining area, with geographical coordinates of 110°09′29.515″–110°16′23.355″ east longitude and 38°57′24.238″–39°07′57.126″ north latitude, belonging to Sunjiacha Town and Majiata Township, Shenmu County. This mine field is located in the north of Loess Plateau in northern Shaanxi, at the southeast edge of Mu Us Desert. The whole terrain is high in northwest and southwest, and low in the middle, with the highest elevation being 1364.40 m, the lowest elevation being 942.2 m, and an average elevation of about 1200 m. Within the scope of the mine field, it is mainly divided into two geomorphic types: sandy grass beach, and loess hilly and gully [13]. This area is a typical semi-arid continental climate in the middle temperate zone, with four hot and cold seasons, wide temperature difference between day and night, drought and little rain, and large evaporation. It belongs to Kuye River Basin, the first tributary of the Yellow River. The soil types are mainly aeolian sandy soil, chestnut soil, and loessial soil. The vegetation types are typical zonal grassland vegetation, and its representative formations are Leymus chinensis and Caragana-Artemisia taxa. The coal-bearing strata in the Ningtiaota mine field are the middle Jurassic Yan'an Formation, in which the current main coal seams are 2^{-2} and 5^{-2}. The mining field covers an area of 119.77 m^2. The longwall comprehensive mechanized mining method is adopted in the main coal seam, and all caving method is adopted in the roof management, so that the surface subsidence is obvious, and the subsidence coefficient is generally around 0.7. At the same time, the mining ground fissures are intensively developed at the edge and inside of the subsidence area, and their widths are mostly 0.2–0.6 m. There are various types of soil erosion in the Ningtiaota mine field in northern Shaanxi, mainly hydraulic erosion. The allowable soil loss in the loess plateau of northwest China is 1000 t/(km^2 a), which is 1479.70 t/(km^2 a) [14] in soil erosion modulus before mining, and over 5000 t/(km^2 a) [15] in soil erosion modulus after mining. The degree of soil erosion in the mining area has evolved from low intensity to high intensity, and is the focus of soil erosion in Shaanxi Province. In addition, there are all types of mining damage in the mining area of Ningtiaota, including subsidence slope and ground fissure, therefore this paper chooses the Ningtiaota mine field in the northern Shaanxi mining area of China to carry out the work. The location map of Ningtiaota mine field and its soil erosion status is shown in Figure 1 below.

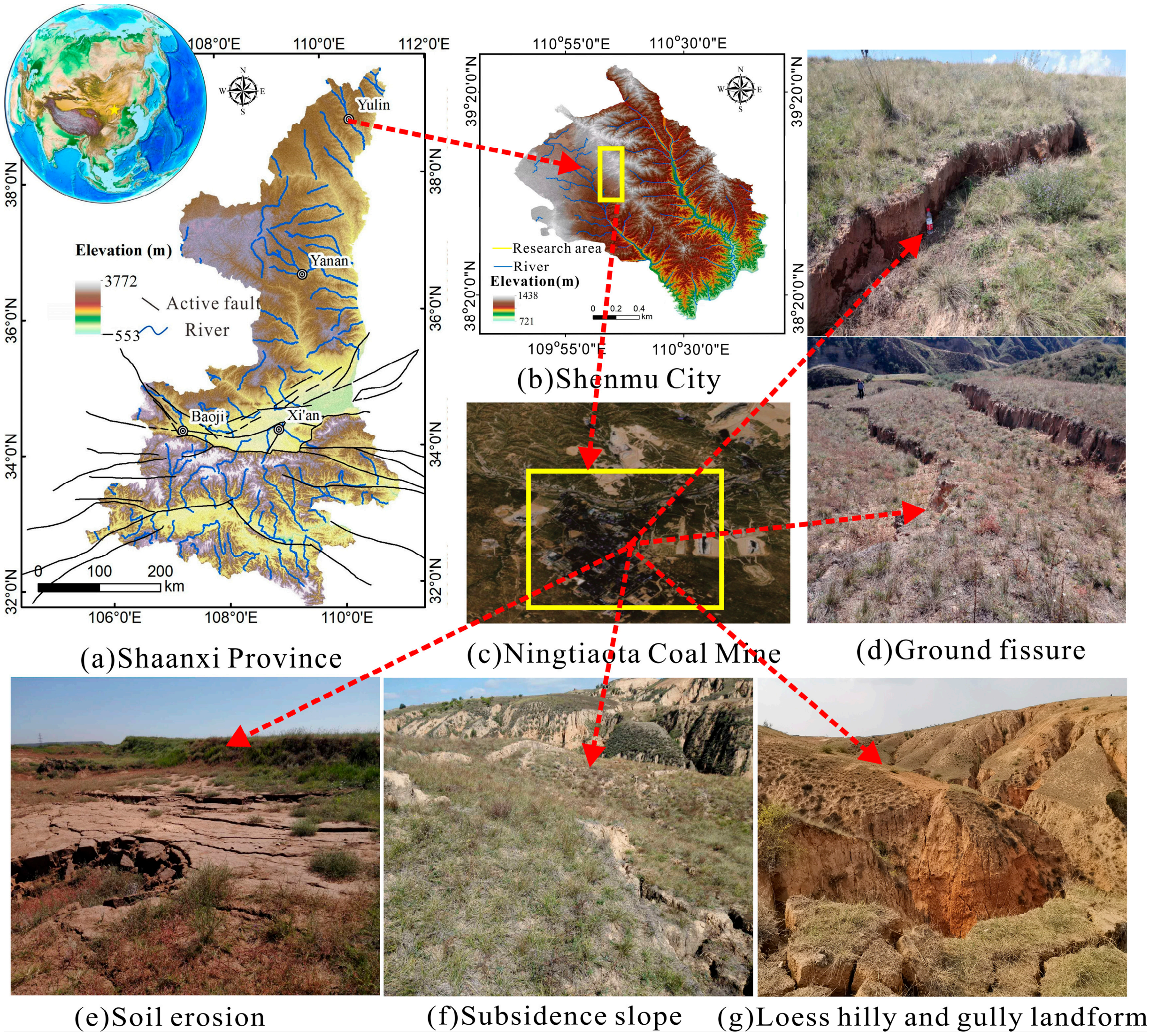


Figure 1. Geographical location of Ningtiaota mine field and map of soil erosion in mining area.

2. Materials and Methods

2.1. Sample Collection

First, we select the typical loess slope in the coal mining subsidence area in the north wing of the Ningtiaota mine field for sampling. The center coordinates of the sampling area are 110.38° E and 39.09° N. The area is a typical loess gully landform, with an average slope of 22° and an average slope length of 80 m. The slope type is uniform. There are many groups of arc-shaped mining ground fissures on the slope, with an average interval of 10 m, and the formation time is about 3 months. The sampling time selected is in June (the non-rainy season in the study area), so as to eliminate the influence of rainfall, temperature, and vegetation on soil erosion as much as possible. The upper 10 m of subsidence slope is divided into the top, the middle 30 m into the middle, and the lower 10 m into the foot. Among them, the development width of cracks at the top of the slope is 40–60 cm, that at the middle of the slope is 20–40 cm, and that at the foot of the slope is 0–20 cm. On each slope, the 1 m range on both sides of the ground fissures, caused by mining, is divided into fissured areas, and the rest are divided into non-fissured areas. According to the research progress of predecessors, mining ground fissures can cause changes in soil's physical and chemical properties, such as water content [15] and porosity [16], thus affecting the formation of soil erodibility K value. The farther away from the ground fissure, the smaller the change of soil porosity, and the weaker the influence on soil erodibility

K [17], therefore, this paper chooses the horizontal distance from the ground fissure as the independent variable to predict the soil erodibility K.

Next, according to the above characteristics and zoning results, a sampling scheme is designed (As shown in Figures 2 and 3 and Table 1). First, three loess subsidence slopes with the same tendency, similar shape and similar position are randomly selected as sampling targets. For each subsidence slope, soil samples in the cracked and non-cracked areas at the top, middle, and foot of the slope are collected, respectively. Second, three ground fissures with similar widths are randomly selected in the fissure area of each part. Three sampling sections are arranged on each ground fissure at equal intervals of 10–15 m, and four sampling points with horizontal distances of 20, 40, 60 and 80 cm are arranged on each sampling section along the normal direction of the fissure. Each sampling point collects soil to vertical depths of 0–10 cm and 10–20 cm layers with a soil drill, and mixes the soil with corresponding horizontal distances and vertical depths on the three sections of each ground fissure, then puts them into a sampling bag. Third, three 1 m × 1 m sampling squares are randomly arranged in the non-cracked area of each slope, and the soil with a vertical depth of 0–10 cm and 10–20 cm are collected by a five-point sampling method. The soil with a vertical depth corresponding to the five sampling points of each square is mixed, put into sampling bags, and marked with numbers. Fourth, the loess slope with similar slope, slope length, slope type, and slope direction is selected as the control in the undeveloped area 500 m away to the northwest of the sampling working face. The selected control area belongs to the same panel and is adjacent to the research area, and the background values of the research area and the control area in topography, soil, vegetation and other aspects are highly consistent, with minimal spatial heterogeneity. Soil sampling is carried out according to the collection method of non-crack areas on the subsidence slope. The samples are put into the sampling bag, marked with numbers, and a total of 288 soil samples are collected. The collected soil samples are taken back to the laboratory, laid flat, and placed in the indoor ventilated shade to be naturally dried until the quality has no obvious change. After removing litter, gravel, and other sundries, the soil samples are measured.

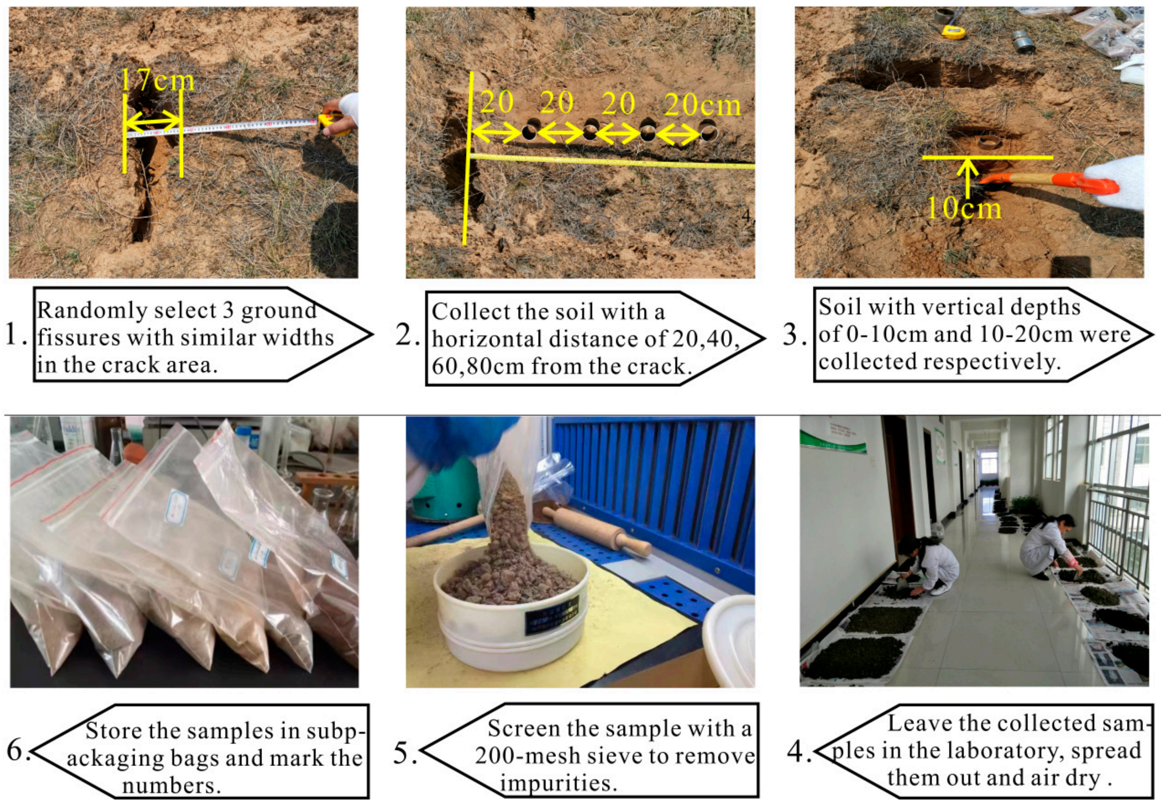


Figure 2. Field sampling flow chart.

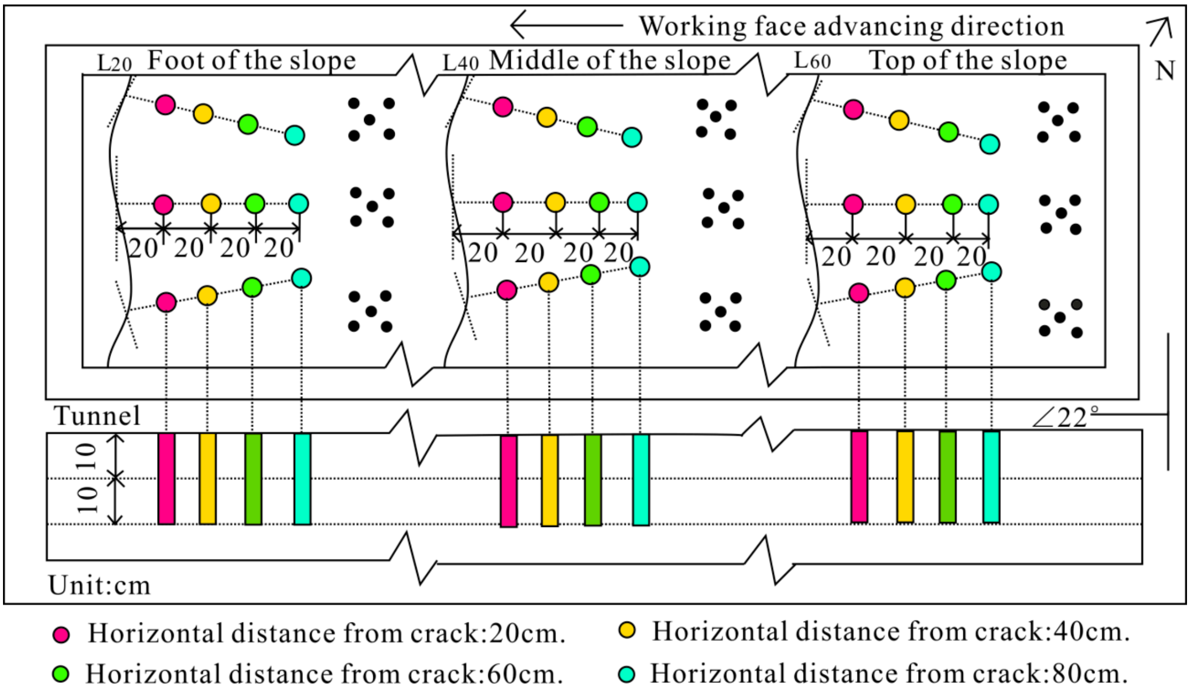


Figure 3. Sampling diagram.

Table 1. Field zoning acquisition method.

Position	Depth/cm	Horizontal Distance/cm	Position	Depth/cm	Method of Sampling
Crack area	0–10	20 40 60 80	Non-crack area	0–10	Five-point sampling
	10–20	20 40 60 80		10–20	

2.2. Experimental Method

Next, the mechanical composition of soil is determined by a laser diffraction method and the laser particle size analyzer (MS2000), and the content of the soil's organic matter is determined by a combustion oxidation-non-dispersive infrared absorption method and a total organic carbon analyzer (Vario TOC). The specific parameters are shown in Table 2 below. The indexes of each group of soil samples are measured three times in parallel.

Table 2. Instrument photos and parameters.

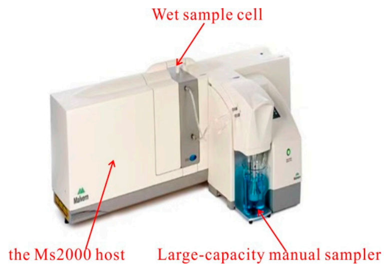
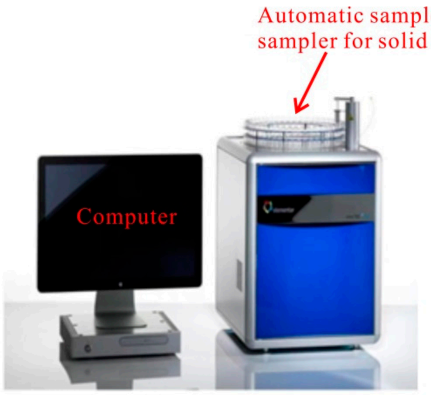
Instrumentation	Specification	Photograph
Laser particle size analyzer MS2000 (type: MS2000, British Malvern company. Marvin City, England.)	Granularity test range: 0.02–2000 µm. Scanning speed: 1000 Times/second.	

Table 2. *Cont.*

Instrumentation	Specification	Photograph
Total organic carbon analyzer (type: Vario TOC, Elementar company, Hannau, Germany)	Detection principle: NDIR. Measuring range: 60,000 ppm Repeatability: <1.5%. Detection limit: 2 ppb.	

3. Experimental Result

3.1. Soil Mechanical Composition

Soil mechanical composition is one of the most basic and important physical properties of soil, and it strongly affects the soil's physical and chemical properties such as pore structure, water-holding property and fertility level, and also has an important influence on soil anti-erosion ability. The soil mechanical composition of different parts of the loess subsidence slope in the study area, such as the top, middle, and toe of the slope, and the vertical depths of the crack area and non-crack area of each part are 0–10 cm and 10–20 cm. The data are shown in Table 3. According to the measurement results of the soil mechanical composition, the corresponding triangular map of soil texture is drawn, as shown in Figure 4.

As can be seen from Table 3 and Figure 4, the subsidence of the surface slope and the development of ground fissures caused by mining will not change the surrounding soil types (within 20 cm of vertical depth), but will have the effect of reducing the mass fraction of soil clay and increasing the mass fraction of sand. Specifically:

(1) The types of soil mechanical composition in the cracked and non-cracked areas on any subsidence slope are consistent with those in the control group, all of which are silty loam, which is consistent with the research results of Li Li [18] and Meng Hongqi [19].

(2) Compared with the control group, the clay mass fraction of 0–10 cm soil at the top, middle, and foot of the slope (the average value of cracked and non-cracked areas, the same below) decreased by 19.42% ($p < 0.05$), 10.99% ($p < 0.05$), and 4.46%, and that of 10–20 cm soil decreased by 30.11% ($p < 0.05$), 22.28% ($p < 0.05$) and 7.88%, respectively. The sand mass fraction of 0–10 cm soil at the top, middle, and foot of the slope increased by 11.34% ($p < 0.05$), 10.99% ($p < 0.05$) and 6.83%, respectively, and that of 10–20 cm soil increased by 25.38% ($p < 0.05$), 17.63% ($p < 0.05$) and 11.35% ($p < 0.05$), respectively. It can be seen that: ① The clay mass fraction of the soil at the top and middle of the slope decreased significantly, but the sand mass fraction increased significantly, and the change range increased with the increase in the vertical depth of the soil, showing obvious sanding characteristics. ② The characteristics of soil mechanical composition at the foot of the slope did not change obviously.

(3) Compared with the control group, the clay mass fraction of 0–10 cm soil in the crack area and non-crack area at the top of the slope decreased by 22.32% ($p < 0.05$) and 7.78%, and that of 10–20 cm soil decreased by 32.99% ($p < 0.05$) and 19.51% ($p < 0.05$). The clay mass fraction of 0–10 cm soil in the cracked and non-cracked areas of the middle slope decreased by 12.25% ($p < 0.05$) and 5.96%, respectively, and that of 10–20 cm soil decreased by 23.61% ($p < 0.05$) and 16.98% ($p < 0.05$), respectively. At the foot of the slope, the clay mass fraction of 0–10 cm soil in the crack area decreased

by 6.15%, while that in the non-crack area increased by 2.31%, and that of 10–20 cm soil in the crack area and a non-crack area decreased by 9.18% and 2.70%, respectively. At the top of the slope, the sand mass fraction of 0–10 cm soil in the cracked and non-cracked areas increased by 11.88% ($p < 0.05$) and 9.16%, respectively, and that of 10–20 cm soil increased by 27.32% ($p < 0.05$) and 17.62% ($p < 0.05$), respectively. The sand mass fraction of 0–10 cm soil in the cracked and non-cracked areas of the middle slope increased by 11.34% ($p < 0.05$) and 9.56%, respectively, and that of 10–20 cm soil increased by 18.06% ($p < 0.05$) and 15.87% ($p < 0.05$), respectively. At the foot of the slope, the sand mass fraction of 0–10 cm soil in cracked and non-cracked areas increased by 7.82% and 2.86%, respectively, and that 10–20 cm soil increased by 11.93% ($p < 0.05$) and 9.05%, respectively. It can be seen that: ① The clay mass fraction of the shallow soil in the crack area at the top and middle of the slope decreased significantly, but the sand mass fraction increased significantly, and the change range increased with the increase in the vertical depth of the soil, showing obvious sandification characteristics. ② The changes of clay mass fraction decreasing and sand mass fraction increasing in the shallow soil in the non-cracked area at the top and middle of the slope are concentrated in the 10–20 cm soil layer. ③ The mechanical composition characteristics of the shallow soil in the cracked and non-cracked areas at the foot of the slope have no obvious overall changes. ④ The sandy degree of shallow soil in the cracked area of the same slope is obviously higher than that in the non-cracked area.

Table 3. Determination results of soil mechanical composition and organic matter in different slope positions in northern Shaanxi coal mining area.

Slope Position	Crack Width (cm)	Soil Depth (cm)	Horizontal Distance (cm)	Sand (%)	Particle (%)	Cosmid (%)	Organic Matter (g/kg)
Top of slope	40–60	0–10	20	32.3	61.5	6.2	1.2
			40	31.8	61.9	6.3	1.4
			60	31.1	62.5	6.4	1.9
			80	31.9	61.3	6.8	2.1
		10–20	20	30.3	63.5	6.2	1.4
			40	29.8	63.9	6.3	1.5
			60	29.4	63.9	6.7	1.9
			80	29.6	63.5	6.9	2.9
	Non-crack area	0–10	/	30.7	61.7	7.6	2.3
		10–20	/	27.5	64.6	7.9	2.9
	CK	0–10	/	28.2	63.6	8.2	2.7
		10–20	/	23.4	66.8	9.8	3.3
Middle of slope	20–40	0–10	20	29.2	63.7	7.1	1.3
			40	29.1	63.6	7.3	1.6
			60	29.2	63.3	7.5	2.0
			80	29.4	63.0	7.6	2.1
		10–20	20	29.6	63.0	7.4	1.5
			40	29.1	63.5	7.4	1.8
			60	28.9	63.4	7.7	2.5
			80	28.2	63.6	8.2	3.1
	Non-crack area	0–10	/	28.7	63.4	7.9	2.1
		10–20	/	28.4	63.2	8.4	3.2
	CK	0–10	/	26.3	65.3	8.4	2.5
		10–20	/	24.5	65.4	10.1	3.3

Table 3. *Cont.*

Slope Position	Crack Width (cm)	Soil Depth (cm)	Horizontal Distance (cm)	Sand (%)	Particle (%)	Cosmid (%)	Organic Matter (g/kg)
Foot of slope	0–20	0–10	20	27.9	63.9	8.2	1.9
			40	27.4	64.2	8.4	2.5
			60	27.4	63.9	8.7	2.9
			80	27.3	63.8	8.9	3.0
		10–20	20	28.0	63.3	8.7	2.0
			40	27.2	64.1	8.7	2.6
			60	27.2	64.0	8.8	3.1
			80	27.0	64.1	8.9	3.5
	Non-crack area	0–10	/	26.2	64.5	9.3	3.5
		10–20	/	26.6	64.0	9.4	4.0
	CK	0–10	/	25.5	65.4	9.1	3.1
		10–20	/	24.5	65.9	9.6	3.8

(4) Compared with the control group, the clay mass fraction of 0–10 cm soil layer at the top of the slope, which is 20, 40, 60, and 80 cm away from the ground fissures with a width of 40–60 cm, decreased by 25.03% ($p < 0.05$), 23.09% ($p < 0.05$), 22.11% ($p < 0.05$) and 19.08% ($p < 0.05$) in turn, and the mass fraction of soil sand increased by 14.81% ($p < 0.05$), 12.68% ($p < 0.05$), 10.55% ($p < 0.05$) and 9.48% in turn. The clay mass fraction of 10–20 cm soil decreased by 35.96% ($p < 0.05$) and 35.44% ($p < 0.05$), 31.87% ($p < 0.05$), 28.70% ($p < 0.05$) in turn, and the mass fraction of soil sand increased by 29.47% ($p < 0.05$), 27.50% ($p < 0.05$), 25.83% ($p < 0.05$) and 26.48% ($p < 0.05$) in turn. The clay mass fraction of 0–10 cm soil layer with the horizontal distance of 20, 40, 60 and 80 cm from the mining ground fissure with the width of 20–40 cm on the middle slope decreased by 15.50% ($p < 0.05$), 13.47% ($p < 0.05$), 10.49% ($p < 0.05$) and 9.54%, and the soil sand mass fraction increased by 11.28% ($p < 0.05$), 10.93% ($p < 0.05$), 11.35% ($p < 0.05$) and 11.81% ($p < 0.05$), in turn. The clay mass fraction in 10–20 cm soil layer decreased by 26.32% ($p < 0.05$), 26.22% ($p < 0.05$), 23.73% ($p < 0.05$) and 18.17% ($p < 0.05$), in turn, and the sand mass fraction increased by 20.56% ($p < 0.05$), 18.60% ($p < 0.05$), 17.99% ($p < 0.05$), 15.10% ($p < 0.05$), in turn. The clay mass fraction of the 0–10 cm soil layer with horizontal distance of 20, 40, 60, and 80 cm from 0–20 cm wide ground fissures at the foot of the slope decreased by 9.77%, 7.57%, 4.39%, and 2.85%, in turn, and the sand mass fraction of soil increased by 9.45%, 7.49%, 7.33%, and 7.02%. The clay mass fraction in 10–20 cm soil layer decreased by 10.17%, 9.75%, 9.03% and 7.78%, while the sand mass fraction increased by 14.74% ($p < 0.05$), 11.22% ($p < 0.05$), 11.13% ($p < 0.05$), and 10.64% ($p < 0.05$). It can be seen that: ① The wider the width of the ground fissures developed on the subsidence slope, the more obvious the effect of reducing the clay mass fraction and increasing the sand mass fraction of the surrounding shallow soil. ② The smaller the horizontal distance from the ground fissures and the greater the vertical depth of the soil, the greater the decrease in clay mass fraction and the increase in sand mass fraction in the shallow soil, and the more serious the degree of sandification. ③ The effect of mining ground fissures on reducing clay mass fraction and increasing sand mass fraction in the surrounding shallow soil is more obvious in the vertical direction.

(5) According to the above analysis, the decrease in soil clay mass fraction and the increase in sand mass fraction are ranked as follows: crack area at the top of slope > crack area at the middle of slope > non-crack area at the top of slope > non-crack area at the middle of slope > crack area at the foot of slope > con-crack area at the foot of slope.

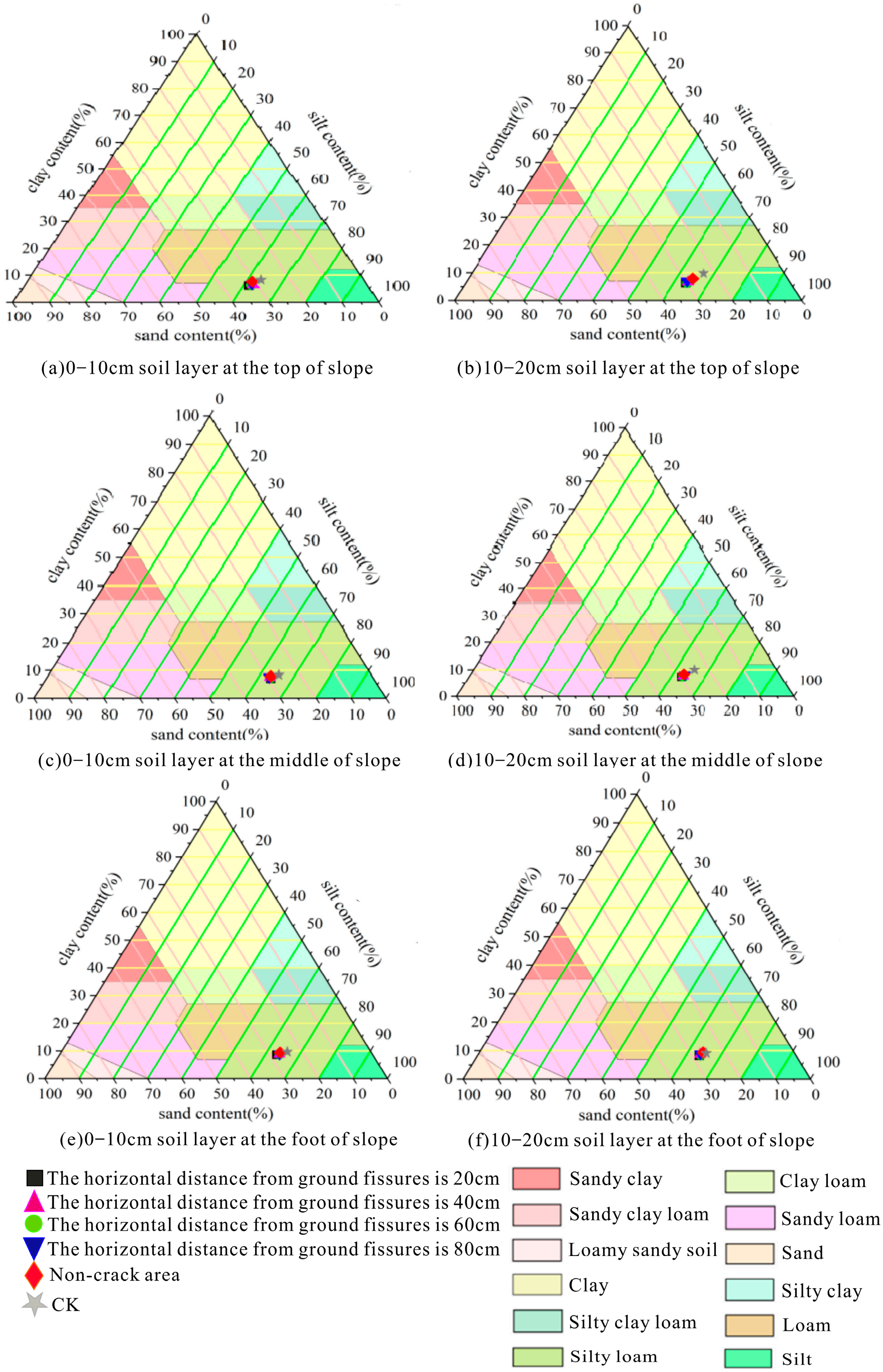


Figure 4. Triangular map of soil texture in different parts.

3.2. Soil Organic Matter

Soil organic matter can improve soil's physical properties, enhance soil's water-holding capacity, and form a good soil structure with a stable organic-inorganic complex, thus improving soil erosion resistance. The mass fraction of soil organic matter in different parts of the loess subsidence slope in the study area, such as the top, middle, and toe of the slope, and the vertical depths of the crack area and non-crack area of each part are 0–10 cm and 10–20 cm. The results are shown in Table 3. According to the determination results of soil organic matter mass fraction, the corresponding soil organic matter comparison map is drawn, as shown in Figure 5.

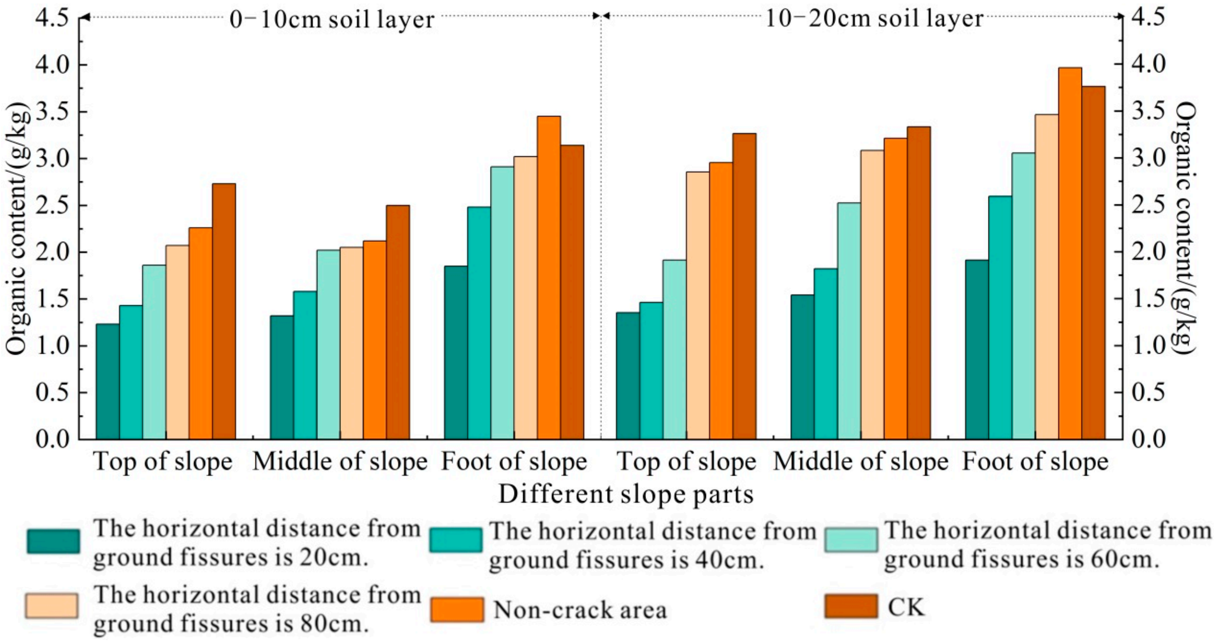


Figure 5. Comparison chart of soil organic matter mass fraction in different parts.

As can be seen from Table 3 and Figure 5, it can be seen that the subsidence of the surface slope and the development of ground fissures will have the effect of reducing the organic matter mass fraction of the surrounding shallow soil (within 20 cm vertical depth). Specifically:

(1) The mass fraction of organic matter in the shallow soil in the cracked area and the non-cracked area at the top and middle of any slope decreased, while the mass fraction of organic matter in the non-cracked area at the foot of the slope increased slightly, which is the same as the research results of Cheng Jingxia et al. [20].

(2) Compared with the control group, the soil organic matter mass fraction of 0–10 cm at the top, middle, and foot of the slope (the average of the cracked area and the non-cracked area, the same below) decreased by 35.16% ($p < 0.05$), 27.28% ($p < 0.05$) and 12.68% ($p < 0.05$), respectively, and that of 10–20 cm soil decreased by 35.46% ($p < 0.05$), 26.91% ($p < 0.05$) and 20.37% ($p < 0.05$). It can be seen that: ① The mass fraction of organic matter in shallow soil on the subsidence slope decreased in different degrees, and it is different with different slope positions. The descending order of organic matter mass fraction in the shallow soil of different slope parts is as follows: the top of the slope > the middle of the slope > the foot of the slope. ② The decrease in organic matter mass fraction in shallow soil on each slope increases with the increase in soil vertical depth.

(3) Compared with the control group, the soil organic matter mass fraction of 0–10 cm in the crack area and non-crack area at the top of the slope decreased by 39.65% ($p < 0.05$) and 17.22% ($p < 0.05$), respectively, and that of 10–20 cm soil decreased by 41.95% ($p < 0.05$) and 9.51%, respectively. The soil organic matter mass fraction of 0–10 cm

in the cracked area and non-cracked area of the middle slope decreased by 30.30% ($p < 0.05$) and 15.20% ($p < 0.05$), respectively, and that of 10–20 cm soil decreased by 32.73% ($p < 0.05$) and 3.60%, respectively. At the foot of the slope, the mass fraction of soil organic matter in the 0–10 cm crack area decreased by 18.31% ($p < 0.05$), while that in 0–10 cm non-crack area increased by 9.87%; that in 10–20 cm crack area decreased by 26.80% ($p < 0.05$) and that in a non-crack area increased by 5.32%. It can be seen that: ① The mass fraction of organic matter in shallow soil in the crack area at the top, middle, and foot of the slope decreased significantly, and the change rate increased with the increase in soil vertical depth. ② The mass fraction of organic matter in shallow soil in the non-cracked area at the top and middle of the slope also decreases, but the decrease is smaller than that in the cracked area, and it decreases with the increase in soil vertical depth. ③ The mass fraction of organic matter in the shallow soil in the non-fractured area at the toe of the slope increased instead of decreasing, and it is mainly concentrated in the 0–10 cm soil layer. ④ The loss degree of organic matter in shallow soil in the fractured area of the same slope is obviously higher than that in the non-fractured area.

(4) Compared with the control group, the soil organic matter mass fraction of 0–10 cm soil layer at the top of the slope, which is 20, 40, 60, and 80 cm away from the ground fissures with a width of 40–60 cm, decreased by 54.95% ($p < 0.05$), 47.62% ($p < 0.05$), 31.87% ($p < 0.05$), and 24.18% ($p < 0.05$), and the mass fraction of soil organic matter in 10–20 cm soil layer decreased by 58.59% ($p < 0.05$), 55.21% ($p < 0.05$), 41.41% ($p < 0.05$), and 12.58% ($p < 0.05$). The mass fraction of soil organic matter in 0–10 cm soil layer with horizontal distance of 20, 40, 60, and 80 cm from the mining ground fissures with width of 20–40 cm on the middle slope decreased by 47.20% ($p < 0.05$), 36.80% ($p < 0.05$), 19.20% ($p < 0.05$), and 18.00% ($p < 0.05$), and the mass fraction of soil organic matter in 10–20 cm soil layer decreased by 53.75% ($p < 0.05$), 45.35% ($p < 0.05$), 24.32% ($p < 0.05$) and 7.51%. The mass fraction of soil organic matter in 0–10 cm soil layer with horizontal distance of 20, 40, 60, and 80 cm from 0–20 cm mining ground fissures at the foot of slope decreased by 41.08% ($p < 0.05$), 21.02% ($p < 0.05$), 7.32%, and 3.82%, and 10–20 cm decreased by 49.20% ($p < 0.05$), 31.12% ($p < 0.05$), 18.88% ($p < 0.05$), and 7.98%, in turn. It can be seen that: ① On the subsidence slope, the larger the width of the ground fissures, the more obvious the effect of reducing the organic matter mass fraction of the surrounding shallow soil. ② The smaller the horizontal distance from the mining ground fissure and the greater the vertical depth of the soil, the greater the decrease in the organic matter mass fraction in the shallow soil. ③ The effect of mining ground fissures to reduce the organic matter mass fraction in the surrounding shallow soil is more obvious in the horizontal direction.

(5) According to the above analysis, the descending order of soil organic matter mass fraction is as follows: crack area at the top of slope > crack area at the middle of slope > crack area at the foot of slope > non-crack area at the top of slope > non-crack area at the middle of slope > non-crack area at the foot of slope.

3.3. Soil Erodibility

Soil erodibility K value is a quantitative index that objectively reflects the difficulty of soil erosion from the perspective of internal factors. When the value exceeds 0.3, it is regarded as high erodibility. The K value of soil erodibility is calculated by the EPIC model, such as formulas (1)–(3). See Table 4 for the soil erodibility K value calculated according to Table 3, and we drew the corresponding contrast map of soil erodibility K value according to the calculation results, as shown in Figure 6.

$$\begin{aligned} K_{EPIC} = &\left\{0.2 + 0.3\exp\left[-0.0256S_a\left(1-\frac{S_i}{100}\right)\right]\right\} \times \left(\frac{S_i}{C_i+S_i}\right)^{0.3} \\ &\times \left(1.0 - \frac{0.25C}{C+\exp(3.72-2.95C)}\right) \times \left(1.0 - \frac{0.71S_{n1}}{S_{n1}+\exp(-5.51+22.9S_{n1})}\right) \end{aligned} \quad (1)$$

$$S_{n1} = 1 - \frac{S_a}{100} \tag{2}$$

$$C = 0.58 S_{om} \tag{3}$$

Table 4. Calculation results of soil erodibility K value in different slope parts and different vertical depths.

Slope Position	Crack Width (cm)	Soil Depth (cm)	Horizontal Distance (cm)	Soil Erodibility K Value
Top of slope	40–60	0–10	20	0.3937
			40	0.3889
			60	0.3706
			80	0.3566
		10–20	20	0.3975
			40	0.3950
			60	0.3730
			80	0.3273
	Non-crack area	0–10	/	0.3460
		10–20	/	0.3284
	CK	0–10	/	0.3319
		10–20	/	0.3292
Middle of slope	20–40	0–10	20	0.3997
			40	0.3892
			60	0.3647
			80	0.3624
		10–20	20	0.3889
			40	0.3768
			60	0.3392
			80	0.3223
	Non-crack area	0–10	/	0.3595
		10–20	/	0.3191
	CK	0–10	/	0.3465
		10–20	/	0.3243
Foot of slope	0–20	0–10	20	0.3767
			40	0.3436
			60	0.3275
			80	0.3247
		10–20	20	0.3715
			40	0.3388
			60	0.3247
			80	0.3185
	Non-crack area	0–10	/	0.3198
		10–20	/	0.3150
	CK	0–10	/	0.3269
		10–20	/	0.3216

In the formula, K_{EPIC} is the soil erodibility factor, Mg·ha·h/(ha·MJ·mm); S_a is soil sand mass fraction, %; S_i is the mass fraction of soil silt, %; C_i is soil clay mass fraction, %; C is the soil organic carbon mass fraction, %; S_{om} is the mass fraction of soil organic matter, %.

The EPIC model is a continuous and systematic dynamic model for comprehensive evaluation of soil erodibility. Because it is suitable for the study of soil erodibility in different regions of China, it is included in the Handbook of Mathematical Models of Resources and Environment edited by the Institute of Geographical Sciences and Resources, Chinese Academy of Sciences, and has been widely used by many scholars [21], and it includes the ground fissures in the loess mining area of northern Shaanxi. For example, Shuangming Wang [16], Liqian Gao [22] and others all used this model to estimate the soil erodibility K value around the mining area and ground fissures in northern Shaanxi and verified the applicability of this model in this area.

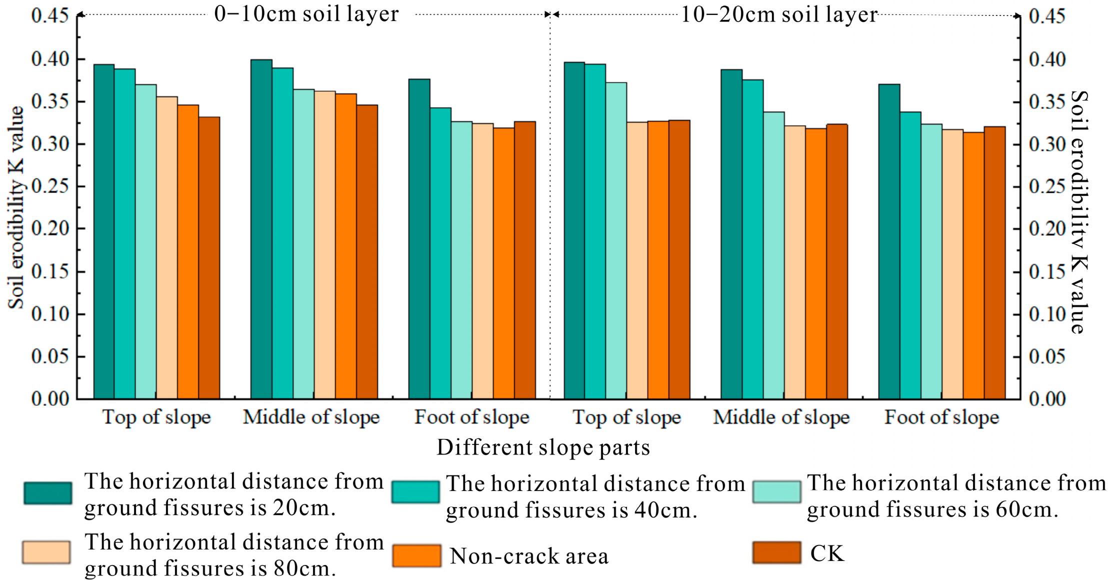


Figure 6. Comparison chart of soil erodibility in different parts.

As can be seen from Table 4 and Figure 6, the subsidence of the surface slope and the development of ground fissures caused by mining will have the effect of increasing the soil erodibility K value of the surrounding shallow soil (within 20 cm of vertical depth). Specifically:

(1) The soil erodibility K value in the crack area and non-crack area at the top and middle of any slope increased, while the soil erodibility K value in the non-crack area at the foot of the slope decreased.

(2) Compared with the control group, the soil erodibility K value of 0–10 cm at the top, middle, and foot of the slope (the average value of cracked and non-cracked areas, the same below) increased by 11.83% ($p < 0.05$), 8.25% and 3.54%, respectively, and the soil erodibility K value of 10–20 cm increased by 10.64% ($p < 0.05$), 7.70% and 3.76%, in turn. It can be seen that: ① Soil erodibility K value on the subsidence slope has increased in different degrees, showing the characteristics of the shallow soil erodibility on the whole slope, and that it varies with the slope parts. The increasing order of soil erodibility K value from big to small is as follows: the top of the slope > the middle of the slope > the foot of the slope. ② Subsidence enlarges the difference of soil erodibility between 0–10 cm and 10–20 cm at the top and middle of the slope, and the difference of soil erodibility between the two layers at the top of the slope enlarges by 159%, which is the most obvious, while the change at the foot of the slope is not significant.

(3) Compared with the control group, the soil erodibility K value of 0–10 cm in the crack area and non-crack area at the top of the slope increased by 13.72% ($p < 0.05$) and 4.25%, respectively, and that of 10–20 cm soil increased by 13.37% ($p < 0.05$) and −0.24%, respectively. The soil erodibility K value of 0–10 cm in the cracked area and non-cracked area of the middle slope increased by 9.38% and 3.75%, respectively, and that of 10–20 cm soil increased by 10.02% ($p < 0.05$) and −1.60%, respectively. At the foot of the slope, the soil erodibility K value of 0–10 cm in the cracked area and non-cracked area increased by 4.96% and −2.17%, respectively, and that of 10–20 cm soil increased by 5.22% and −2.05%, respectively. It can be seen that: ① The soil erodibility K value in any part of the crack area increases in different degrees, showing obvious characteristics of soil erodibility, and the increase rate decreases with the increase in soil vertical depth. ② The soil erodibility K value in the non-cracked area at the top and middle of the slope also increased, but the increase is obviously smaller than that in the cracked area. The soil erodibility K value in the non-cracked area at

the foot of the slope does not increase, but decreases, showing a certain anti-corrosion strengthening characteristic. ③ The erosion degree of shallow soil in the cracked area of the same slope is obviously higher than that in the non-cracked area.

(4) Compared with the control group, the soil erodibility K value of the 0–10 cm soil layer at the top of the slope, with horizontal distance of 20, 40, 60, and 80 cm from the 40–60 cm wide ground fissures, increased by 18.62% ($p < 0.05$), 17.17% ($p < 0.05$), 11.66% ($p < 0.05$), and 7.44%. The soil erodibility K value of the 10–20 cm soil layer with horizontal distance of 20 cm, 40 cm, 60 cm, and 80 cm from ground fissure increased by 20.75% ($p < 0.05$), 19.99% ($p < 0.05$), 13.30% ($p < 0.05$), and −0.58% in turn. The soil erodibility K value of the 0–10 cm soil layer with the horizontal distance of 20, 40, 60, and 80 cm from the mining ground fissure with the width of 20–40 cm on the middle slope increased by 15.35% ($p < 0.05$), 12.32% ($p < 0.05$), 5.25%, and 4.59%, and that of 10–20 cm soil increased by 19.92% ($p < 0.05$), 16.19% ($p < 0.05$), 4.59% and −0.62% in turn. The soil erodibility K value of the horizontal distance of 20, 40, 60, and 80 cm from the mining ground fissures with a width of 0–20 cm at the foot of the slope increased by 15.23% ($p < 0.05$), 5.11%, 0.18% and −0.67%, in turn, and the horizontal distance of 10–20 cm soil layer from the ground fissures increased by 15.52% ($p < 0.05$), 5.35%, 0.96% and −0.96%, in turn. It can be seen that: ① On the subsidence slope, the larger the width of the ground fissures, the more obvious the effect of increasing the soil erodibility K value. ② The smaller the horizontal distance from mining ground fissures and the greater the vertical depth of soil, the greater the increase in soil erodibility K value and the more serious the soil erodibility. ③ The effect of mining ground fissures increasing the soil erodibility K value of the surrounding shallow soil is more obvious in the horizontal direction.

(5) According to the above analysis, the increasing order of soil erodibility is as follows: crack area at the top of slope > crack area at the middle of slope > crack area at the foot of slope > non-crack area at the top of slope > non-crack area at the middle of slope > non-crack area at the foot of slope.

(6) According to the data in Table 4 and Figure 6, the scatter diagram of soil erodibility K value at different horizontal distances around ground fissures in different slope parts is drawn, and the relationship between soil erodibility K value and horizontal distance is marked on the diagram, as shown in Figure 7. It can be seen from Figure 7 that for the ground fissures with a width of 40–60 cm, when the horizontal distance exceeds 115.00 cm and 85.17 cm, respectively, the effect of increasing the soil erodibility K value of the surrounding 0–10 cm and 10–20 cm soil layers by mining ground fissures basically disappears.; For the ground fissures with a width of 20–40 cm, when the horizontal distance exceeds 95.14 cm and 76.58 cm, respectively, the effect of increasing the soil erodibility K value of the surrounding 0–10 cm and 10–20 cm soil layers by mining ground fissures basically disappears. For the ground fissures with a width of 0–20 cm, when the horizontal distance exceeds 65.89 cm and 66.78 cm, respectively, the effect of increasing the soil erodibility K value of the surrounding 0–10 cm and 10–20 cm soil layers by mining ground fissures basically disappears.

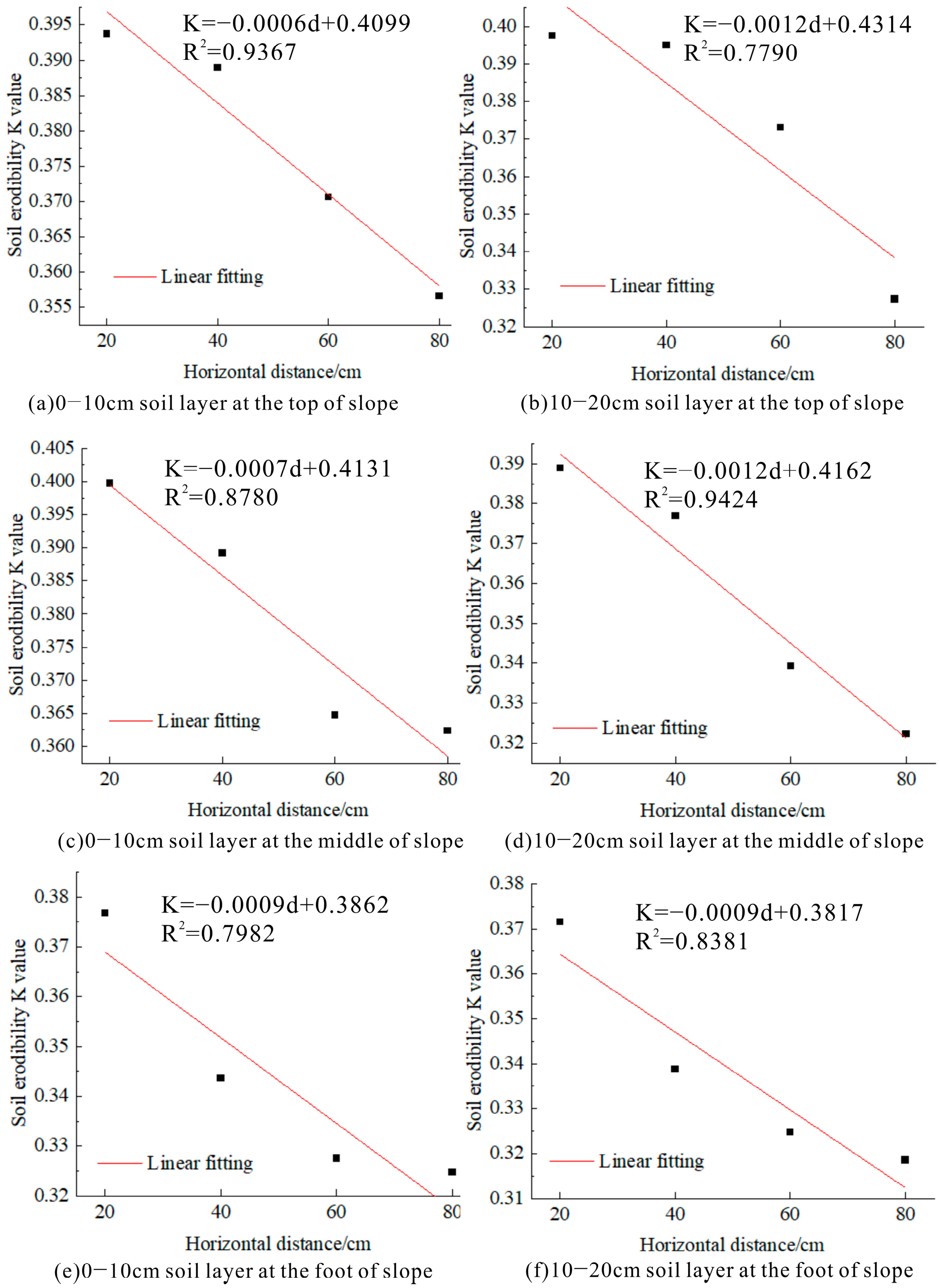


Figure 7. The corresponding relationship between K value of soil erodibility and horizontal distance in different crack areas.

4. Discussion

The above research results are basically consistent with those of Zhao Ling et al. [23], but there are some differences, which are mainly caused by the different topography, subsidence characteristics, and types of the research object areas. For the mining areas in eastern China, the terrain is flat and the undulation is even. Under this condition, the surface deformation continuity in the coal mining subsidence area is good, and the surface cracks develop sparsely and shallowly, and can often receive the water and soil flowing into the depression in the surrounding area, with the characteristics of “collecting water” and “gathering soil”. Although subsidence destroys the original morphology and physical and chemical characteristics of soil, which leads to the intensification of soil erosion on the subsidence slope, the eroded sediment collects in many directions in the subsidence area, and the kinetic energy of surface runoff generated by rainfall in the flat area is small; the kinetic energy of runoff buffered by cracks distributed in the subsidence area is further reduced, and the erosion ability is weakened. To sum up, it may have the effect of soil and water conservation. For the western mining area where the study area of this paper is located, the terrain is steep and ravines are crisscrossing. Under these conditions, the continuity of surface deformation in the coal mining subsidence area is poor, and the surface cracks develop densely and deeply (even connecting the underground goaf), therefore, it is generally difficult for it to become a water and soil enrichment area for the surrounding area, with the erosion characteristics of “running water” and “losing soil”. The eroded soil in the loess slope inside the subsidence area and in a certain range outside it will either migrate along the loess slope in the subsidence area until it enters the surrounding surface runoff and run off, or migrate downwards along the cracks on the loess slope in the subsidence area. Therefore, the soil erodibility K value will increase under the influence of the steep subsidence of loess slope, which is not conducive to soil and water conservation.

There is a high degree of consistency between the spatial variation characteristics of the soil’s mechanical composition and organic matter around the subsidence slope, ground fissures, and the spatial variation characteristics of soil erodibility K value. According to the correlation test, the correlation coefficients between the soil erodibility K value at the top, middle, and foot of the slope and soil clay mass fraction are −0.783, −0.758 and −0.722, in turn, all reaching extremely significant negative correlation levels ($p < 0.01$). The correlation coefficients between the average soil erodibility K value at the top, middle, and foot of the slope and soil organic matter mass fraction are −0.973, −0.986 and −0.932 in turn, all reaching extremely significant negative correlation levels ($p < 0.01$); The correlation coefficients of soil erodibility K value in the crack area of subsidence slope with clay content and organic matter mass fraction are −0.715 and −0.987, respectively, all reaching extremely significant negative correlation levels ($p < 0.01$). The correlation coefficients of soil erodibility K value, clay mass fraction, and organic matter mass fraction around the non-cracked area on the subsidence slope are −0.629 and −0.924, respectively, all reaching significant negative correlation levels ($p < 0.05$). The reason is that the top, middle, and foot of the loess slope shows different movement and deformation characteristics under the same mining subsidence process and influence, which in turn has different influences on the physical, chemical and biological characteristics of shallow soil and the surface vegetation, resulting in obvious differences in soil erodibility of different slope parts. Specifically:

In the process of mining subsidence, the top part of the loess subsidence slope does not only sink vertically and move horizontally towards the coal mine gulf, but also tends to produce additional deformation such as a loss layer sliding along the slope [24], so that the “stretching effect” of shallow soil at the top part of the slope is very obvious and it is easy to induce larger width (generally more than 40 cm) mining ground cracks. The strong tensile deformation and the development of large-width ground fissures have a significant impact on the mechanical composition characteristics, organic matter mass fraction, and soil erodibility of the shallow soil at the top of the slope. First, the original porosity characteristics of the shallow soil at the top of the slope are significantly changed, and the porosity is obviously increased, especially in the wide-width cracks and the nearby soil. Studies have shown that mining ground fissures can increase the porosity of the surrounding soil by 24% [25]. This not only provides more channels for the convection and diffusion of soil air and the migration and infiltration of soil water, but also increases the velocity, flow rate, and influence range of airflow and loam flow in soil pores, so that under the same wind and water erosion conditions, small-sized particles such as soil clay tend to gather in the middle and foot of the slope [26] or migrate to the deep soil along the cracks. In addition, increasing soil porosity also provides more ways for some of the soil's organic matter to be lost with surface runoff infiltration. Second, the contact area between the shallow soil and the air at the top of the slope is greatly increased, resulting in a sharp increase in the evaporation of soil water, a significant increase in the decomposition rate of the soil's organic matter, and a significant decrease in the water content and organic matter mass fraction of shallow soil. Previous research results show that mining ground fissures can reduce the surrounding soil water content by 60% [27] and the soil organic matter mass fraction by 33–38% [24]. The decrease in soil water content obviously increases the concentration of soil solution and produces an "aggregation and sedimentation effect", which promotes the polymerization of small soil particles into large ones, while the decrease in the soil's organic matter, especially humus content, significantly weakens its cementing effect on soil aggregates and micro-aggregates, resulting in the separation and loss of small soil particles [28]. All these will lead to the further decrease in clay mass fraction in the shallow soil at the top of the slope. Third, the natural characteristics of the roots of plants such as herbs and shrubs at the top of the slope are seriously damaged, resulting in mechanical strain or breaking of the horizontal roots of plants, and even causing some roots to dry up and die when exposed to the air [29,30]. The strong tensile action and the development of wide cracks make the pores of the shallow soil at the top of the slope significantly increase, which leads to the obvious decline of the soil's ability to hold water and fertilizer, which seriously weakens the activity and soil-fixing function of plant roots, resulting in the destruction and disintegration of the original "root-soil complex" structure in the soil, then resulting in the loss of a large number of scattered small particles. In addition, the strong tensile action and the development of large-width ground fissures greatly increased the intrusion intensity of external gas and heat into the shallow soil at the top of the slope, resulting in significant changes in soil water, fertilizer, gas and heat, which in turn caused some soil microorganisms to stop breeding or even die because they could not adapt to the change of living environment. Previous studies have shown that the ground fissures caused a sharp decrease in the number of bacteria, fungi and actinomycetes in the soil by 28.8–70.2% [31]. The decrease in the number of soil microorganisms leads to the weakening of their physical entanglement and chemical bonding to soil particles, which in turn reduces the stability of soil aggregates formed by microorganisms and increases the supply and loss of soil erosive substances, mainly small-sized particles, under the dissipation of water and air [32]. Therefore, under the same process and influence of mining subsidence, the tense action at the top of the slope is the strongest, the width of the ground fissures is the largest, the physical, chemical, and biological characteristics of the shallow soil change most obviously, and the vegetation damage is also the most serious. Previous studies have shown [26] that the damage degree of plant roots and the decrease degree of soil organic matter and microorganisms caused by mining ground fissures mainly depend on the width of fissures, that is, the larger the fissure width, the more serious the damage degree of plant roots, and the more significant the decrease in soil organic matter mass fraction and microorganism quantity [33]. This may be the reason why the sandy degree, fertility dilution degree, and soil erodibility of the shallow soil at the top of the slope are higher than those at the middle and foot of the slope, and the crack area at the top of the slope is the highest. See Figure 8 for the differences of soil organic matter, moisture and microorganisms between the surface vegetation in the crack area and the non-crack area.

In the process of mining subsidence, the middle part of the loess subsidence slope not only moves significantly horizontally, but also increases the slope, so that the "steepening effect" of shallow soil in the middle part of the slope is obvious. Influenced by the heterogeneity of the shallow soil on the slope, the middle part of the slope is prone to mining ground fissures of medium width (generally between 20 cm and 40 cm) in the process of steepening. The obvious "whole horizontal movement superimposed and steepening effect" and the development of middle width ground fissures have different influences on the mechanical composition characteristics, organic matter mass fraction, and soil erodibility of the shallow soil in the middle part of the slope from those at the top of the slope. First, the movement and deformation in the middle part of the slope will also change the original porosity characteristics of shallow soil, increase soil porosity, reduce soil water content and organic matter mass fraction, damage soil microbial activity [34] and surface vegetation, and then lead to the loss of small particles such as soil clay. Its mechanism is basically the same as that in the top part of the slope, so we will not repeat it here, but its impact on all aspects is obviously smaller than that in the top part of the slope, so, in the change range of clay, sand, and organic matter mass fraction in the shallow soil in the middle part of the slope. Second, the increase in slope not only makes the same intensity of surface wind or surface runoff have a stronger erosion effect, so that the possibility and quantity of small-sized particles and organic matter in shallow soil in the middle of the slope tend to migrate along the slope greatly increase, but also leads to the loosening of slope soil under the action of gravity, the increase in water and fertilizer loss, and the deterioration of the habitat of slope vegetation [35], thus reducing the biomass of vegetation and its protection and interception function for soil particles and organic matter and promoting the loss of soil small-sized particles. Third, the increase in slope will also increase the effect of supplying small particles and organic matter in the shallow soil at the top of the slope to the middle part of the slope, which will slow down the quality decline and loss of the shallow soil in the middle part of the slope to some extent. Therefore, under the same mining subsidence process and influence, the steepening effect in the middle part of the slope is obvious, the width of the ground fissures caused by mining is large, and the shallow soil characteristics and vegetation changes seriously. This may be the reason why the sandy degree, fertility dilution degree, and soil erodibility degree of shallow soil in the middle part of the slope are obviously lower than those in the middle part of the slope, but obviously higher than those at the foot of the slope.

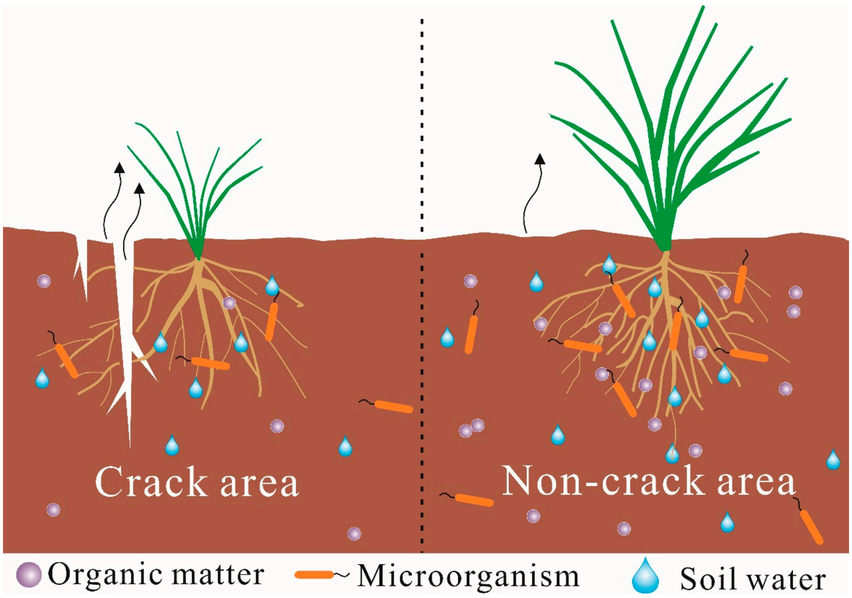


Figure 8. Schematic diagram of plant roots in crack area and non-crack area.

In the process of mining subsidence, the slope toe of the loess subsidence slope is squeezed by the valley soil and the subsidence movement towards the opposite slope, resulting in the phenomenon that the horizontal displacement decreases or even that the surface rises. As a result, the "squeezing effect" of the shallow soil at the slope toe is obvious, which not only makes the slope toe form an accumulating body, but also induces the occurrence of small width (generally less than 20 cm) mining ground cracks. The obvious squeezing action and the development of small-width mining ground fissures have different effects on the mechanical composition characteristics, organic matter mass fraction, and soil erodibility of the shallow soil at the foot of the slope from those at the top and middle of the slope. Although, the movement and deformation at the foot of the slope, especially in the crack area, will also cause some damage to soil characteristics and vegetation, and then have a negative impact on soil erodibility [36]. However, small soil particles and organic matter lost at the top and middle of the slope tend to migrate to the foot of the slope in large quantities [37], so that the mechanical composition characteristics of the shallow soil at the foot of the slope before mining have not changed significantly, and the soil organic matter mass fraction and soil erodibility K values have improved locally, and greatly offset the negative effect of mining subsidence on the quality decline and erosion of the shallow soil at the foot of the slope. Therefore, under the same mining subsidence process and influence, the squeezing effect at the foot of the slope is obvious, the width of the ground fissures is small, and the shallow soil characteristics and vegetation change little. This may be the reason why the shallow soil at the foot of the slope has the lowest degree of sanding, fertility dilution, and soil erodibility, and the local features of fertility enrichment and erosion resistance enhancement.

5. Conclusions

(1) The subsidence of the loess slope and the development of mining ground fissures in the coal mining area of northern Shaanxi will not change the texture type of shallow soil on the slope, but will have the effect of reducing clay mass fraction and increasing sand mass fraction. This effect makes the shallow soil at the top and middle of the loess subsidence slope have obvious sandy characteristics, and the sandy degree of the shallow soil in the crack area of the same slope is obviously higher than that in the non-crack area. The greater the width of the mining ground fissure, the higher the degree of sand formation in the surrounding shallow soil, and the degree of sand formation in the shallow soil in the fissure area is negatively correlated with the horizontal distance from the mining ground fissure. The degree of soil sanding on the subsidence slope is in descending order as follows: crack area at the top of slope > crack area at the middle of slope > non-crack area at the top of slope > non-crack area at the middle of slope > crack area at the foot of slope > non-crack area at the foot of slope. Slope position is the main reason to control the shallow soil sand on the slope of loess subsidence in northern Shaanxi coal mining area.

(2) The subsidence of loess slope surface and the development of mining ground fissures in northern Shaanxi coal mining area will lead to the effect that the mass fraction of shallow soil organic matter in all parts of the slope surface will decrease in different degrees, and the decline of shallow soil organic matter in the top and middle parts of the slope is large, and so the loss of shallow soil organic matter in the fractured area of the same slope surface is higher than that in the non-fractured area. The greater the width of the mining ground fissure developed on the subsidence slope, the higher the organic matter loss of the surrounding shallow soil, and the organic matter loss of the shallow soil in the crack area is negatively correlated with the horizontal distance from the mining ground fissure. The descending order of soil fertility dilution degree on the subsidence slope is as follows: crack area at the top of slope > cracked area at the middle of slope > crack area at the foot of slope > non-crack area at the top of slope > non-crack area at the middle of slope > non-crack area at the foot of slope. Mining ground fissures is the first main reason to control the loss of organic matter in shallow soil on the loess subsidence slope in northern Shaanxi coal mining area.

(3) The shallow soil erodibility K value of the loess subsidence slope in northern Shaanxi coal mining area is highly consistent with soil clay mass fraction and organic matter mass fraction in slope scale variation characteristics, and the negative correlation coefficients are all over 0.6, reaching a significant level. The subsidence of loess slope surface and the development of mining ground fissures will have the effect of improving the erodibility of shallow soil in all parts of slope surface, and the erodibility of shallow soil in the top and middle parts of slope surface will increase significantly; the erodibility of shallow soil in the crack area of the same slope surface is obviously higher than that in the non-crack area. The greater the width of the

ground fissures developed on the subsidence slope, the higher the erodibility of the surrounding shallow soil, and the erodibility of the shallow soil in the crack area is negatively correlated with the horizontal distance from the ground fissures. Based on the position of the subsidence slope and the development of mining ground fissures, the division and order of shallow soil erodibility on the loess subsidence slope in northern Shaanxi coal mining area are highly consistent with the loss of organic matter in shallow soil. Based on the principle of linear regression, it has been found that the maximum boundary of shallow soil erodibility around the loess subsidence slope developed by mining ground fissures in northern Shaanxi coal mining area is 115 cm, and the main action range is within 90 cm. Different soil erosion effects caused by different types of mining damage and their main scope of action can provide scientific basis for accurate prevention and control of soil erosion effects caused by mining subsidence in the loess coal mining areas in northern Shaanxi, improve soil and water conservation efficiency, and save costs.

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