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ARTICLE

石油污染对土壤水分特性的影响

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摘 要：陕北是石油工业的发祥地，在石油大规模开采运输过程中，不可避免会造成石油的泄露倾洒，从而对土壤和地下水造成一定程度的污染。为了探讨陕北地区石油污染对土壤水分特性的影响，以 3 种不同土质土壤（塿土、黄绵土和风沙土）为研究对象，开展了 3 种土壤在 4 个不同污染梯度（0.5%、1%、2% 和 4%）下的土壤润湿性试验和饱和导水率实验，同时以清洁土壤作为对照。结果表明：当土壤受石油污染时，会引起其润湿性发生变化，产生一定程度的斥水性，该变化在风沙土上表现尤为明显；石油污染使 3 种土壤的饱和导水率均随着污染浓度的增大而呈现下降趋势，饱和导水率虽有降低，但是对于同一土质的土壤来说，均在一个数量级内。

关键词：石油污染；土壤水分；土壤润湿性；饱和导水率

Effects of oil pollution on soil moisture

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Abstract: ***Background, aim, and scope*** Northern Shaanxi is the birthplace of the oil industry. In the process of large-scale exploitation of oil, it will inevitably lead to leakage of oil spill, which causes a certain degree of pollution of soil and groundwater. In order to investigate the effect of oil pollution on soil water characteristics in northern Shaanxi, we conducted this study. ***Materials and methods*** In this study three different soils (Lou soil, Loessial soil and Aeolian sandy soil) were tested for soil wettability and saturated hydraulic conductivity at four different pollution gradients (0.5%, 1%, 2% and 4%), with clean soil as a control. ***Results*** Soil moisture of Lou soil, Loessial soil and Aeolian sandy soil infiltrated quickly at 0% and 0.5% oil contaminated concentration,

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wetting grade 0, no water repellent. The Lou soil began to show slight water repellency at 4% oil treatment. Starting from 2% oil content, the water repellency of Loessial soil was enhanced. At 1% oil content, the Aeolian sandy soil exhibit strong water repellency and extreme water repellency at 4% oil content. The effect of oil pollution on soil wettability is: Aeolian sandy soil, Loessial soil and Lou soil. The oil pollution has a significant effect on the saturated hydraulic conductivity of the three soils. The saturated hydraulic conductivity of the Lou soil and Loessial soil was on the order of 10^{-5}, the Aeolian sandy soil was on the order of 10^{-3}. At the same pollution concentration, the saturated hydraulic conductivity of Loessial soil is larger than that of Lou soil. The effect of pollution concentration on the saturated hydraulic conductivity of three soils was significant at low oil content. With the increase of oil content, the trend of saturated hydraulic conductivity decreased gradually, and this effect was more significant in Aeolian sandy soil. ***Discussion*** Clean soil usually has a certain degree of hydrophilicity, but when the soil is contaminated by oil organic matter, the surface wettability may change from the hydrophilic surface into a hydrophobic surface, resulting in varying degrees of water repellency, causing the soil water holding capacity reduced. After the oil pollutes the soil, the residual oil in the soil contains a lot of polar molecules. In the case where the soil is relatively dry or the moisture content is very low, the polar molecules will have the characteristics of oil wetting on the surface, which will cause the soil hydrodynamic characteristics to change greatly. The change of soil hydrodynamic characteristics will seriously affect the *in situ* treatment of petroleum contaminated soil. Our study showed that oil pollution has a significant effect on soil wettability, which has the greatest effect on the wettability of sandy soil and the smallest soil. The content of clay particles and hydrophilic components in the sandy soil is low, so the hydrophobic oil pollutants can greatly weaken the soil surface tension and increase the soil contact angle. Soil water transports, surface water to groundwater recharge, the migration of pollutants are closely related to soil permeability. We found that with the increase of oil content, the saturated hydraulic conductivity of sandy soil gradually decreased and the decreasing trend gradient was gentle. The possible reason for the slowdown in the saturated hydraulic conductivity of sandy soil is that the oil pollution causes the soil surface to produce some hydrophobicity, reduces the resistance of water infiltration, and relieves the trend of decreasing the saturated hydraulic conductivity. On the one hand, oil pollution of the soil will plug the soil moisture migration channel, on the other hand will make the soil surface to produce a certain degree of hydrophobicity to reduce the water migration resistance, these two areas together, causing soil permeability changes. ***Conclusions*** Oil pollution has a significant effect on soil water characteristics. When the soil is polluted by oil, it caused the wettability to change, resulting in a certain degree of water repellency. This change is particularly evident in sandy soils. The oil pollution of the three soils showed a decreasing trend with the increase of the pollution concentration. Although the saturated hydraulic conductivity of oil-contaminated soil was reduced, it does not produce an order of magnitude transition over an order of magnitude for the soil of the same soil. ***Recommendations and perspectives*** The oil industry is of great significance to the development of the national economy, but the problem of soil and water pollution caused by it cannot be neglected. It is very important to study the influence of oil pollution on soil water characteristics in northern Shaanxi. It should be further studied to further clarify the influence of oil pollution on soil hydrodynamic characteristics, so as to provide theoretical basis for oil pollution remediation.

Key words: oil pollution; soil water; soil wettability; saturated hydraulic conductivity

水是人类赖以生存的宝贵资源，随着经济和科技水平的快速发展，人类对自然环境的影响也与日俱增，在生产和生活中，会产生各种类型的污染物，以不同方式进入到地下水 - 土环境中，对土壤和地下水产生不同程度的污染威胁。石油是人类宝贵的自然资源，随着世界经济的飞速发展，对石油需求量逐渐增多，在石油大规模开采运输过程中，不可避免会造成石油的泄露倾洒，从而

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对土壤和地下水造成一定程度的污染。石油污染土壤后会堵塞土壤孔隙，影响土壤的通气透水性（程金香等，2004）；引起土壤养分状况发生改变，使碳氮比和碳磷比失调（陆秀君等，2003）；引起土壤微生物群落等发生变化，破坏土壤微生态环境。石油污染浓度高时还会导致油品下渗，从而污染地下水。

现阶段石油污染土壤相关研究主要集中在石油污染对植物生长（李小利等，2007；时腾飞等，2013）、土壤理化性质的影响（贾建丽等，2009；张晓阳等，2013），石油污染生态风险评价（刘志全等，2006；刘五星等，2007），石油污染生物修复等方面（顾传辉和陈桂珠，2000；毛丽华等，2006；祁迎春等，2015），关于石油污染对土壤水分特性的影响方面的研究较少。李小飞等（2015）开展了柴油污染对土壤水分特征曲线的研究，童玲等（2011）开展了柴油污染土壤中毛细水上升规律研究，郑西来等（2011）开展了柴油和机油污染多孔介质的水动力特性研究。这些研究多是针对石油提取物所开展，而原油对土壤水分特性影响方面的研究较少。土壤润湿性和渗透性与土壤水分入渗、地表径流的产生、水土流失等存在着密切关系，还会影响污染物在土壤中的迁移转化，以及土壤对污染物的吸附等。研究土壤润湿性和渗透性对于农业管理、水循环、环境保护等具有重要意义。陕北榆林和延安地区石油储量丰富，被誉为中国石油工业的发祥地，大规模的石油开采和运输难免会对土壤、地下水等产生危害。开展陕北地区石油污染对土壤水分特性的影响意义重大。不同种类土壤润湿性及渗透性差别很大，本研究以陕北采油区的黄绵土和风沙土为研究对象，以关中地区的塿土作为参比，人为设置不同石油污染浓度，讨论不同污染浓度对 3 种不同土质土壤水分特性的影响，为陕北地区石油污染土壤修复治理提供理论依据。

1 材料与方法

1.1 实验材料与制备

供试土壤分别取自陕西省延安市、榆林市和渭南市，采集未受污染地块的耕作层土壤，样品经自然风干、除杂、研碎、过 2 mm 筛后备用。供试土壤的机械组成采用 MS2000 型激光粒度仪测定，结果见表 1。试验石油取自延安油田，为油井开采的原油。试验采用人工配置的理想均质石油污染土壤作为研究对象，称取相同质量的土壤样品，按照质量含油率分别为 0.5%、1%、2%、4% 共 4 个污染梯度称取原油加入土壤中充分拌匀，备用，同时以清洁土壤作为对照。

表 1 供试土壤机械组成
Tab.1 Soil mechanical composition

土壤类型 Soil type	取样地 Sampling ground	粒级分数 /%			土壤质地 Soil texture
		黏粒 Clay <2 μm	粉粒 Silt 2—50 μm	砂粒 Sand 50—2000 μm	
塿土 Lou soil	渭南 Weinan	22.12	65.66	12.22	粉壤土 Silty loam
黄绵土 Loessial soil	延安 Yanan	10.28	71.44	18.28	粉壤土 Silty loam
风沙土 Aeolian sandy soil	榆林 Yulin	2.69	13.14	84.17	壤砂土 Loam sandy soil

1.2 实验方法

1.2.1 润湿性的测定

采用滴水穿透时间法（WDPT）（Letey，1969；吴延磊等，2007），分别对 3 种不同土质土壤在不同污染程度时的润湿性进行分析。分别取干燥样品 80 g 置于干净的玻璃培养皿中，轻轻将土样表面抹平，用滴定管将蒸馏水滴到土样表面，测定水滴渗入不同处理样品所需时间，根据水滴入渗时间的不同来表示其表面的润湿程度，时间越长则越难入渗，疏水性越强，润湿性也就越差，每处理重复 10 次。实验采用 Dekker 和 Jungerius 类标准（Dekker and Jungerius，1990；Dekker et al，2006）将表面斥水性分为 5 个等级，如表 2 所示。

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表 2　WDPT 斥水性分类标准
Tab.2　WDPT water repellency classification standards

水滴入渗时间 Water droplet infiltration time/s	等级 Grade	斥水性 Water repellent
<5	0 级　0 level	无　No
5—60	1 级　1 level	轻微　Slight
61—600	2 级　2 level	强烈　Strong
601—3600	3 级　3 level	严重　Serious
>3600	4 级　4 level	极度　Extreme

1.2.2　饱和导水率测定

采用 DIK-4012 四点式土壤透水性测定仪测定不同处理土壤饱和导水率。实验前将供试土壤按预设容重（1.40 g·cm^{-3}）填装仪器环刀，充分饱和后，间隔一定时间测定透水量，根据透水量计算得到土壤饱和导水率，每处理重复 6 次。

2　结果与分析

2.1　石油污染对土壤润湿性的影响

3 种土壤在不同石油污染程度的润湿性试验结果如表 3 所示，通过对比不同石油污染浓度土壤的滴水入渗试验结果可知，3 种土壤在 0% 和 0.5% 含油率条件下水分均能快速入渗，入渗时间均小于 5 s，润湿等级为 0 级，无斥水性；塿土在 4% 含油率处理下开始呈现轻微的斥水性；黄绵土从 2% 含油率开始斥水性增强，2% 含油率土壤为轻微斥水，4% 含油率呈现强烈的斥水性；风沙土在 1% 含油率时即表现为强烈的斥水性，2% 含油率为严重斥水，4% 为极度斥水。石油污染对土壤润湿性的影响从大到小依次为：风沙土、黄绵土、塿土。由此可见，当土壤受石油污染时，会引起其润湿性能发生变化，产生一定程度的斥水性，该变化在风沙土上表现尤为明显。

表 3　润湿性试验结果
Tab.3　Wetting test results

土壤类型 Soil type	污染浓度 Oil pollution concentration	水滴入渗时间 Water droplet infiltration time/s	等级 Grade	斥水性 Water repellent
塿土 Lou soil	0%	<5	0 级　0 level	无　No
	0.5%	<5	0 级　0 level	无　No
	1%	<5	0 级　0 level	无　No
	2%	<5	0 级　0 level	无　No
	4%	5—60	1 级　1 level	轻微　Slight
黄绵土 Loessial soil	0%	<5	0 级　0 level	无　No
	0.5%	<5	0 级　0 level	无　No
	1%	<5	0 级　0 level	无　No
	2%	5—60	1 级　1 level	轻微　Slight
	4%	61—600	2 级　2 level	强烈　Strong
风沙土 Aeolian sandy soil	0%	<5	0 级　0 level	无　No
	0.5%	<5	0 级　0 level	无　No
	1%	61—600	2 级　2 level	强烈　Strong
	2%	601—3600	3 级　3 level	严重　Serious
	4%	>3600	4 级　4 level	极度　Extreme

2.2　石油污染对土壤饱和导水率的影响

土壤饱和导水率是土壤重要的物理性质之一，了解土壤在不同污染程度下的饱和导水率直接表征了石油污染对土壤水分入渗能力的影响。3 种土壤的饱和导水率随含油率变化趋势见图 1。图中可见，石油污染对 3 种土壤的饱和导水率均有显著影响，饱和导水率均随着污染程度的加剧而呈现下降趋势，饱和导水率虽有降低，但是对于同一土质的土壤来说，均在一个数量级内，没有产生量级跃迁。塿土和黄绵土的饱和导水率均在 10^{-5} 数量级，同一污染浓度，黄绵土的饱和导水率大于塿土，风沙土的饱和导水率在 10^{-3} 数量级。污染浓度对于 3 种

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土壤饱和导水率的影响表现在较低含油率时较为显著，随着含油率的增加，饱和导水率下降趋势逐渐变缓，这种影响在风沙土上表现更为显著。以 1% 含油率的砂土饱和导水率为基准，当土壤含油率从 0% 变化到 1% 时，土壤饱和导水率平均变化率为 0.16 $cm\cdot s^{-1}$，含油率从 1% 升高到 4% 时，饱和导水率平均变化率仅为 0.02 $cm\cdot s^{-1}$。

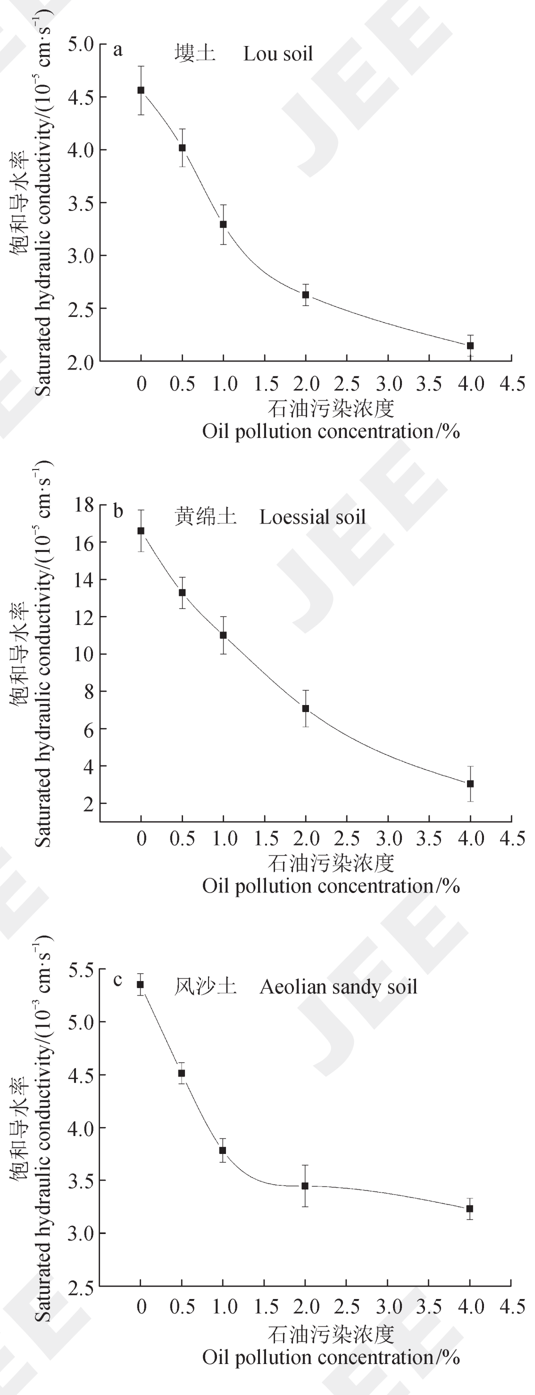

图 1 不同污染程度下的土壤饱和导水率

Fig.1 Soil saturated hydraulic conductivity of the tested soils under different pollution degree

3 讨论

3.1 石油污染对土壤润湿性的影响

洁净土壤通常具有一定程度的亲水性，但当土壤被油类有机物污染后，表面润湿性可能会发生变化，由亲水性表面转变为疏水性表面，产生不同程度的斥水性，从而引起土壤持水能力的降低。石油污染土壤后，土壤中残留油分含有大量的极性分子，在土壤比较干燥或者水分含量很低的情况下，会使其表面具有油润湿性的特征，导致土壤水动力特性发生很大变化，从而严重影响石油污染土壤原位治理技术。

本研究表明，石油污染对土壤润湿性产生显著影响，表现为对风沙土润湿性的影响最大，塿土最小。风沙土粘粒含量少，亲水性组分含量较低，故而疏水性的石油污染物能极大地减弱土壤表面张力，增大土壤接触角。李小飞等(2015)研究表明，当柴油渗入到石英砂中，较低含量的柴油就会引起其润湿性能发生较大的改变，产生明显的斥水性。梁春（2011）研究表明 ，轻微机油污染即可导致石英砂和粗砂产生强烈的斥水性，且随着机油污染程度的提高，斥水性急剧提高。柴油和机油均为石油提取组分，故二者引起石英砂斥水性的改变和本文石油在风沙土上的研究结果有一定的相似性。后续应进一步深化开展石油污染对土壤润湿性的作用机制，进一步明确石油污染对土壤水动力特性的影响。

3.2 石油污染对土壤渗透性的影响

土壤中水分运输和物质运移、地表水向地下水的补给、污染物的迁移等都和土壤渗透性密切相关（李梅，2008）。石油污染土壤后势必对土壤的渗透性能产生一定程度的影响，从而影响土壤水分运移与物质交换。石油污染对塿土、黄绵土和风沙土的饱和导水率均有显著影响，随着污染程度的加剧，饱和导水率均呈下降趋势，饱和导水率虽有降低，但是对于同一土质的土壤来说，没有产生量级跃迁。同一污染浓度下的饱和导水率均表现为风沙土最大，黄绵土次之，塿土最小，这可能是因为土壤质地和结构与导水率有直接关系，砂质土壤通常比细质土壤具有更高的饱和导水率（黄昌勇，1999），同时 Khamehchiyan et al（2007）研究也表明，土壤饱和导水率与土壤颗粒大小成正比，与含油率成反比。

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本文研究发现随着含油率的增加，风沙土饱和导水率逐渐减小，减小趋势渐变平缓，这与李梅等（2009）在砂土上的研究结果一致。可能原因是石油污染后在土壤表面产生一定的疏水性，减小了水分下渗的阻力，缓解了饱和导水率下降的趋势。本文风沙土饱和导水率均在 10^{-3} 数量级，但是童玲（2008）研究发现清洁砂和 1% 含油率砂土饱和导水率均在 10^{-3} 数量级，原油含量增加至 2% 时，饱和导水率发生了量级改变，数量级为 10^{-4}。这与两者研究对象机械组成不同有着直接的关系。石油污染土壤后一方面会堵塞土壤水分运移通道，一方面会使土壤表面产生一定的疏水性减小水分运移阻力，这两方面共同作用，引起土壤渗透性能发生改变。

4　结论

（1）石油污染能够改变土壤的表面润湿性，对风沙土润湿性的影响最大，塿土的影响最小。对于风沙土来说，较低含量石油污染就会造成土壤产生较强的斥水现象。

（2）石油污染对塿土、黄绵土和风沙土的饱和导水率均有显著影响，饱和导水率均随着污染程度的加剧而呈现下降趋势，饱和导水率虽有降低，但是对于同一土质的土壤来说，均在一个数量级内。随着含油率的增加，风沙土饱和导水率逐渐减小，减小趋势渐变平缓。

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