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The Influence of Crude Oil on Mechanistic Detachment Rate Parameters

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Abstract: Iraqi soil contamination greatly influenced soil detachment. Previous researchers have not been able to predict the influence of crude oil soil contamination on either the mechanistic dimensional detachment parameter b_0 or the threshold parameter b_1 of the mechanistic detachment model (Wilson model). The aims of this research were (1) to investigate the influence of crude oil on deriving Wilson model parameters, b_0 and b_1, with two setups at different scales and different soil moisture contents and (2) to predict b_0 and b_1 in crude oil contaminated dry soils with varying levels of contamination. The "mini" JET apparatus was implemented under laboratory conditions for soil specimens packed at both a small (standard mold) and a large (in-situ soil box) scale. The results showed an inverse correlation between b_0 and water content for clean soil. No correlation between b_0 and soil moisture content was observed for contaminated soils. There was a huge reduction in the b_0 value as the contamination time increased compared to the clean soil. This was related to the role crude oil plays in soil stabilization. Crude oil contamination significantly increased lead contamination level while slightly increasing the pH and total organic carbon. The influence of crude oil on mechanistic soil detachment can be predicted with a priori JET experiments on soils without crude oil based on crude oil parameters.

Keywords: Wilson model; soil erodibility factors; crude oil; Jet Erosion Test; contaminated soil

1. Introduction

Estimating soil erodibility is a major challenge in water resource engineering due to the significant influence erosion has on water resource management. Several techniques have been developed to quantify soil erodibility both in the field and laboratory, highlighting the importance of quantifying soil erodibility [1–5]. The erodibility of polluted soils is a subject that has recently gained popularity with several researchers Abbas et al. [6], Al-Madhhachi and Hasan [7], Mutter et al. [8], Salah and Al-Madhhachi [9], and Shayannejad et al. [10] due to significant influence pollutants have on soil characteristics, the soil environment, and soil erodibility parameters. One of these pollutants is crude oil, recently investigated by Al-Madhhachi and Hasan [7].

The process of refining oil is the chief industry in Iraq, resulting in an incremental increase in environmental pollution by crude oil. Soil in Iraq is contaminated with crude oil because of continued accidental spillages and leakages. On average, 290 traffic accidents per year take place involving oil transport tankers on the Jordan Badia desert highway in Iraq [11]. Crude oil contamination occurs both naturally and accidentally. Accidental leakages or spills originate from storage tanks, transport pipelines, transport tankers, and ships. In Iraq, terror attacks on crude-oil-conveying pipelines and oil fields massively contribute to crude oil contamination [7]. This type of environmental contamination can adversely affect the landscape. Crude oil spillage has also resulted in increased levels of heavy metals in the soils surrounding oil refineries [12,13]. Salah and Al-Madhhachi [9] highlight the correlation between soil contamination by heavy metals and soil detachment. Therefore, investigation into the influence of crude oil spillage on soil erosion would be of great benefit. In addition, continuous reports of crude oil spills in Iraq have led to both soil and riverbank contamination. For example, on 16 April 2014, a bomb exploded under an oil pipeline near the Beiji city, northern Iraq, causing large quantities of crude oil to spill into the Tigris River [14]. This type of contamination could influence streambank erodibility through fluvial erosion.

Khanal et al. [5] and Al-Madhhachi [15] highlight the importance of predicting soil erodibility to quantify sediment loads. A variety of laboratory processes have been used to compute soil erodibility parameters such as flumes [3] and a Jet Erosion Test (JET) [16–20]. Empirical models can be used in the prediction of soil detachment. Such models include excess shear stress model, the bed bulk density model, and the turbulent burst erosion model. Cleaver and Yates [21] and Nearing [22] offered a turbulent burst erosion model to predict the erodibility of aggregates from the bed surface. The turbulent burst erosion model was proposed by Sharif and Atkinson [23] to develop a correlation for the distribution of aggregate size, as a function of the concept of self-similar growth of aggregates and bed-bulk density. The excess shear stress model is widely employed for estimating soil detachment. It is dependent upon two empirical soil parameters: the erodibility coefficient (k_d, m^3/N-s) and critical shear stress (τ_c, Pa), as well as the hydraulic shear stress (τ, Pa). Al-Madhhachi and Hasan [7] investigated the influence of crude oil contamination on the erodibility parameters, k_d and τ_c, at three different scales. They found a statistical difference in k_d and τ_c between polluted and unpolluted soil samples under dry soil conditions. However, no mechanistic anticipation can be provided by the excess shear stress model in the prediction of two soil parameters for any particular hydraulic setting, soil property, or additional pollutants such as crude oil. The mechanistic model is beneficial because it is able to mathematically predict soil erodibility due to pollutants (such as crude oil) without re-running JET experiments on polluted soils [24,25]. This study adopted mechanistic detachment parameters to predict contaminated soil erodibility by crude oil to overcome the difficulty in performing JET experiments in the field on soils or riverbanks contaminated with crude oil and affected by fluvial erosion.

Wilson [26,27] developed a non-linear mechanistic detachment model to examine the influence of soil and fluid features on the soil detachment rate. The Wilson model is based on two mechanistic soil parameters, b_0, the dimensional detachment parameter of the erosion model, and b_1, the dimensional threshold parameter of the erosion model. This mechanistic model can be applied to soil aggregates and is not limited to a single particle. This model can incorporate the effect of several factors, such as the orientation of soil materials, turbulence, seepage forces, roughness, and root effects [17,24,25,28]. The Wilson model can predict the detachment rate for both cohesive and non-cohesive soils, based on two mechanistic soil parameters, b_0 and b_1 [17,29,30]. Al-Madhhachi et al. [17] developed mathematical analysis techniques for the Wilson model parameters (b_0 and b_1) for two different cohesive soils using both flume and JET data. The flume experiments and JETs resulted in statistically equivalent derived values of mechanistic detachment parameters. Criswell et al. [29,30] utilized flume experiments to analyse soil detachment using the Wilson model and compare it to excess shear stress model on non-cohesive gravel to derive erodibility parameters. They observed a similar relationship between the Wilson model parameters (b_0 and b_1) with different amounts of k_d and τ_c. They also found that the fluvial erosion modelling of non-cohesive gravel was applicable to and dependent on the k_d-τ_c correlation. Criswell et al. [29,30] emphasised the need for awareness when calibrating the Wilson model to avoid unrealistic data beyond the range of the functional shear in the experiment.

Al-Madhhachi et al. [24] modified the Wilson model parameters by incorporating the impact of the seepage force on the soil detachment rates of cohesive soil. Al-Madhhachi et al. [24] observed a great, but non-uniform, impact of seepage force has on the derived Wilson parameters derived from both flume experiments and JETs. Al-Madhhachi et al. [25] combined seepage forces into the

Wilson model parameters, b_0 and b_1, to predict the erodibility of cohesive streambanks. They utilized laboratory "mini" JET apparatus and a seepage column to determine b_0 and b_1 for two different soils. The experimental arrangement was designed to imitate a streambed and a streambank when the JET device was placed vertically and horizontally, respectively. Similar to the study proposed by Al-Madhhachi et al. [24], seepage forces had a great impact on the Wilson model parameters for streambeds and streambanks [25].

Khanal et al. [5] examined the influence of the pressure head setting and time interval on the erodibility parameters of the nonlinear detachment model. They noticed a reduction in the value of b_0 at a longer time interval, with a head setting of 46 cm and 190 cm for both clay loam and sandy loam soils, while the value of b_1 declined at longer time intervals (at only 190 cm for clay loam soil). They highlighted the correlation between the head settings and time intervals and recommended a minimum initial time interval of 0.5 min at a high-pressure head. Khanal and Fox [28] conducted several JET experiments on bare and root-permeated soil samples to examine the influence of vegetation on soil detachment. They also predicted detachment parameters for both the linear model (k_d and τ_c) and the non-linear model (b_0 and b_1). They found a significant correlation between the two model parameters. A negative relationship between the erodibility coefficients of the two models and the root diameter was also observed, while no relationship was found between (b_1 and τ_c) and the root diameter.

Salah and Al-Madhhachi [9] and Mutter et al. [8] investigated the impact of soil contamination on soil erodibility. They found that soil contamination increased the soil detachment rate. Salah and Al-Madhhachi [9] observed a reduction in b_1 and an increase in b_0 as the lead concentration increased. This indicates instability in the contaminated soil compared to the clean soil. Mutter et al. [8] studied the influence of three stabilisers on soil erodibility parameters using "mini" JET. The use of the "mini" JET apparatus can be used to examine soil stability and reduce testing time [8]. Abbas et al. [6] studied the impact of different types of soil contamination by nitrate, phosphate, and phenol on soil erodibility parameters at different contamination times. They observed a reduction in τ_c values, while the value of k_d steadily increased as contamination time and/or contaminant concentration increased. Al-Madhhachi and Hasan [7] investigated the influence of crude oil contamination on erodibility parameters (k_d and τ_c) using three different in-situ scales at three different levels of soil moisture content. They found a statistical difference in k_d and τ_c between polluted and unpolluted soil samples at the dry side of the water content. No statistically significant differences of measured k_d and τ_c were observed across different in-situ scale ratios for polluted and unpolluted soils.

Previous studies have not been able to predict the Wilson model parameters from contaminated soils. In particular, the influence of crude oil contamination on the mechanistic detachment parameters, b_0 and b_1, is yet to be fully determined. The aims of this research were (1) to investigate the influence of crude oil on deriving Wilson model parameters (b_0 and b_1) at two different scale setups and at different levels of soil moisture content (dry, optimum, and wet soil moisture contents) and (2) to predict mechanistic detachment parameters, b_0 and b_1, in crude oil contaminated dry soils with varying levels of contamination, i.e., after 1st, 4th, and 8th day of soil preparations.

2. Materials and Methods

2.1. Mathematical Analysis of Erodibility Parameters in Persence of Crude Oil

Wilson [26] developed a non-linear model to estimate erosion rates, based on stabilizing and removing forces and associated moment lengths for particle displacement. The forces that act to remove soil particles in the presence of crude oil are presented in Figure 1. These forces include the weight of the soil particle (w_s), drag force (F_d), lift forces (F_L), the contact forces between adjacent soil particles ($F_{c1}, F_{c2}, \ldots, F_{cn}$), and the contact forces between adjacent soil particles and adjacent oil particles ($F_{o1}, F_{o2}, \ldots, F_{on}$). Particle detachment takes place if the resisting moment is less than the driving moment [26]. In this study, the Wilson model was modified to include the influence of oil contamination, based on the original framework developed by Wilson [26]. The detachment of soil particles is expected to occur if the drag force is higher than the cohesive force and weight, relative to the moment around point A, and can be defined with the introduction of the terms M_c and M_{co} as the following Equations (1)–(4):

$$F_d(l_3) + F_L(l_4) + w_s \sin(\alpha)(l_1) = w_s \cos(\alpha)(l_2) + M_c + M_{co} \tag{1}$$

$$w_s = g(\rho_s - \rho_w)k_v d^3 \tag{2}$$

$$M_c = \sum_{i=1}^{n_c} F_{ci}\bar{l}_i = \sum_{i=1}^{n_c} \sigma_{ci} a_i \bar{l}_i \tag{3}$$

$$M_{co} = \sum_{i=1}^{n_{co}} F_{coi}\bar{l}_i = \sum_{i=1}^{n_{co}} \sigma_{coi} a_i \bar{l}_i \tag{4}$$

in which M_c refers to the sum of moments of the frictional and cohesive forces, M_{co} is the sum of moments exerted by the frictional and cohesive forces on oil particles, n_c is the number of contact areas for soil particles, n_{co} is the number of contact areas for oil particles, F_{ci} is the contact forces between adjacent soil particles, F_{coi} is the contact forces between adjacent soil and oil particles, σ_{ci} is the soil particle to particle stress, σ_{coi} is the oil particle to soil particle stress, a_i is the contact area, $\bar{l}_i$ is the moment length for each contact force, α is the angle slope of channel, k_v is the volume constant of a spherical particle, ρ_w and ρ_s are water and soil particle densities, respectively, and d is the equivalent diameter of a soil particle.

Chepil [31] and Wilson [26] assumed a proportional correlation between (F_d) and (F_L) (i.e., $K_L/K_f = F_L/F_d$), in which K_f is the proportion of the projected area of the F_d and F_L forces, and K_L is the proportion of drag and lift coefficients along with that of the velocities [26]. Consequently, Equation (1) can be modified as the following Equations (5)–(8):

$$F_d = w_s(k_{ls} + f_c + f_{co}) \tag{5}$$

$$K_{ls} = \frac{\cos(\alpha)(l_2 - l_1 S)}{l_3 + l_4 \frac{K_L}{K_f}} \tag{6}$$

$$f_c = \frac{M_c}{w_s(l_3 + l_4 \frac{K_L}{K_f})} \tag{7}$$

$$f_{co} = \frac{M_{co}}{w_s(l_3 + l_4 \frac{K_L}{K_f})} \tag{8}$$

in which K_{ls} is a dimensionless parameter dependent on particle size, its orientation within the slope, and the bed; S $(= \tan\alpha)$ is channel slope; f_c is a dimensionless parameter based on soil cohesion; and f_{co} is a dimensionless parameter based on soil and oil cohesions. The values of f_{co} were derived and calibrated from tests on contaminated soils.

Adapting the mathematical approach proposed by Wilson [26] and Al-Madhhachi et al. [24,25], the time-averaged net force, F_n, acting in the direction of movement of the oil particles, was modified as the following Equation (9):

$$F_n = K_t \overline{F}_d - \mu_f w_s - \mu_o w_o \tag{9}$$

in which K_t is a factor of the cumulating instantaneous fluid forces, $\overline{F}_d$ is the time-averaged drag force, μ_f is the coefficient of friction, μ_o is the oil coefficient of cohesion between soil and oil particles as proposed in this study, $w_o = g(\rho_w - \rho_o)k_v {d_o}^3$ is the oil particle submerged weight, d_o is the oil particle diameter, and ρ_o is oil density. This study proposed that the oil particle diameter is equivalent to the soil particle diameter (d_o = d).

Wilson [26] assumed that the particle exchange time, t_e, was a function of the exit velocity ($V_e = F_n\, t_e/m$), in which m is the particle mass. Incorporating the definition of V_e and Equation (9), the exit velocity in the presence of crude oil can be expressed as the following Equation (10):

$$V_e = [\frac{K_t K_o k_a d^2 \tau}{(\rho_s - \rho_w) k_v d^3} - \frac{\mu_f g(\rho_s - \rho_w) k_v d^3}{(\rho_s - \rho_w) k_v d^3} - \frac{\mu_o g(\rho_w - \rho_o) k_v {d_o}^3}{(\rho_w - \rho_o) k_v {d_o}^3}] t_e \tag{10}$$

in which k_a is the area constant of a spherical particle and $k_r = k_v/k_a$ is the geometrical proportion for a spherical particle. Equation (10) can be simplified by introducing the fluid factor $K_n = (K_t\, K_o/k_r)$ and the Shields parameter (τ^*) to give as the following Equations (11)–(13):

$$V_e = [K_n \tau^* - \mu_f - \mu_o] g t_e \tag{11}$$

$$\tau^* = \frac{\tau}{g(\rho_s - \rho_w) d} \tag{12}$$

$$K_o = \frac{5.537 C_D K_f \exp[-200(\frac{z_d}{r})^2]}{C_f {c_d}^2} \tag{13}$$

in which K_o is the velocity JET parameter, as proposed by Al-Madhhachi et al. [17]; C_D is the drag coefficient; c_d is the diffusion constant of the jet; r is the jet radius; z_d is the height that the drag velocity is acting upon in the jet environment; and C_f is the coefficient of friction in the jet environment. In this study, the particle exchange time was predicted by incorporating the oil coefficient as the following Equation (14):

$$t_e = d\sqrt{\frac{k_{dd}}{gd(K_n \tau^* - \mu_o - \mu_f)}} \text{ if } [K_n \tau^* - \mu_o] > \mu_f \tag{14}$$

A probability framework for turbulent forces was developed by Wilson [26], similar to that developed by Einstein [32] and Partheniades [33]. Therefore, the soil erosion or soil detachment rate (ε_{ri}) in presence of oil particles is defined as the following Equations (15)–(17):

$$\varepsilon_{ri} = \Delta FF_i P \rho_s k_r \left(\frac{d}{K_e t_e}\right) \tag{15}$$

$$P = 1 - \exp[-\exp(-\mu_v)] \tag{16}$$

$$\mu_v = (\frac{\pi}{e_v \sqrt{6}})[\frac{k_r(K_{ls} + f_c + f_{co})}{K_o \tau^*} - (1 - \frac{1.365 e_v}{\pi})] \tag{17}$$

in which ΔFF_i is the fraction finer value for bed materials, P is the exceedance probability of drag force, K_e is the exposure of the lower particle parameter (i.e., additional time to eliminate neighbouring particles), μ_v is the upper limit of integration of exceedance probability distribution, and e_v is the coefficient of variations. Equation (15) could be further derived following the same procedure outlined by Wilson [26,27] and Al-Madhhachi et al. [24] to achieve the total detachment rate parameters of the Wilson model, including the influence of crude oil as the following Equations (18)–(21):

$$\varepsilon_r = b_0 \sqrt{\tau} \left[1 - \exp\{-\exp(3 - \frac{b_1}{\tau})\}\right] \tag{18}$$

$$b_0 = \rho_s \frac{k_r}{K_e} \sqrt{\frac{K_n - \mu_{or}}{k_{dd}(\rho_s - \rho_w)}} \tag{19}$$

$$b_1 = (\frac{\pi}{e_v \sqrt{6}}) \frac{k_r(k_{ls} + f_c + f_{co})}{K_o} g(\rho_b - \rho_w) d \tag{20}$$

$$\mu_{or} = \frac{\mu_o g d(\rho_s - \rho_w)}{\tau} = \frac{\mu_o}{\tau^*} \tag{21}$$

in which b_0 is the detachment parameter (g/m-s-N$^{0.5}$), b_1 is the threshold parameter (Pa), and μ_{or} is the oil coefficient ratio. It should be noted that τ^* decreases while μ_o increases as the soil erosion occurs.

Wilson [26,27] used a calibration procedure to empirically derive some parameters included in both the cohesive (f_c) and the exposure (K_e) parameters. This was due to there being little information available about these parameters at the time. Similarly, in this study, the crude oil parameters (f_{co} and μ_{or}) were developed and calibrated using tests on contaminated soils. Both parameters f_{co} and μ_{or} are functions of soil and oil particle cohesion and contamination time determined by the chemical-physical bonds between soil and oil particles. Based on experimental evidence in this study on soils that JETs were undertaken, the values of f_{co} and μ_{or} range from 81 to 140 and 18 to 23, respectively.

The definitions of the parameters in the Wilson model (Equations (18)–(21)), with their values, are reported in Table 1. In the absence of crude oil, the oil parameters can be neglected (i.e., μ_{or} = 0 and f_{co} = 0), and the developed model will match the set of equations suggested by Wilson [26,27]. The parameters b_0 and b_1 can be derived by employing curve-fitting techniques that reduce the errors of these functions in relation to measured erosion data obtained from JETs. Al-Madhhachi et al. [17] developed an Microsoft Excel spread sheet to derive parameters b_0 and b_1 using the solver routine in Microsoft Excel, which utilized the generalized reduced gradient method.

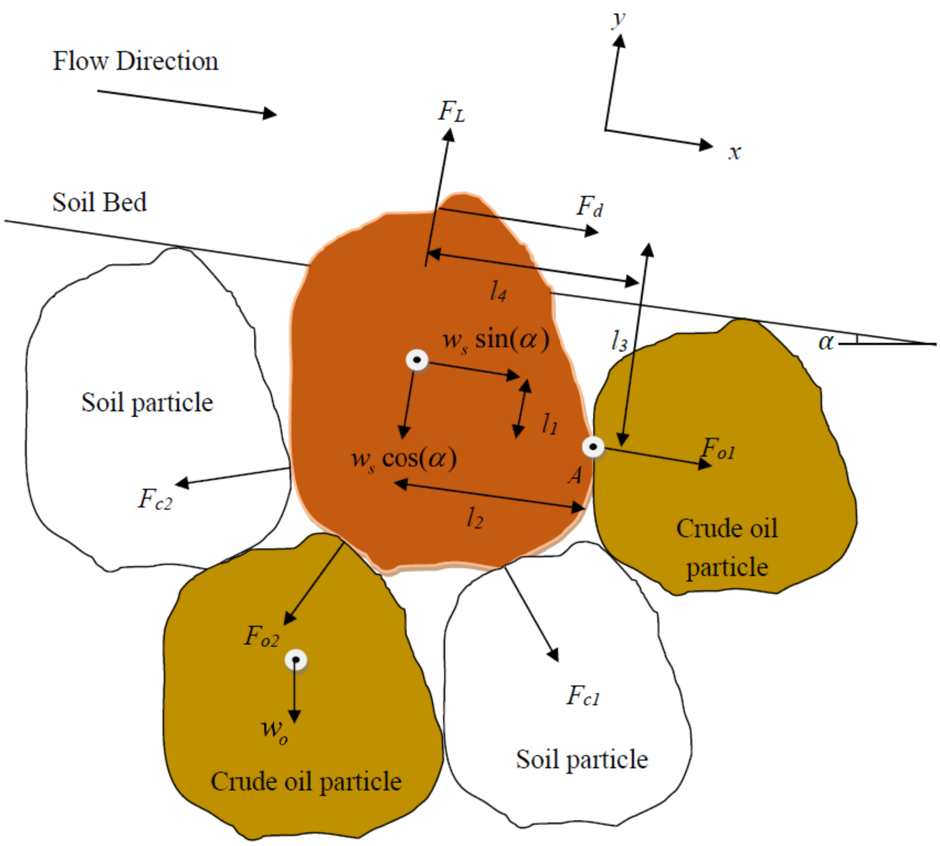

Figure 1. Forces and moment lengths in presence of crude oil particles acting on a single soil particle in JET environmental. Variables are defined in the text.

Table 1. Definition of parameters in the Wilson model obtained from soil contaminated with crude oil.

Symbols	Description	Value or Equation	Reference
C	Discharge jet coefficient	0.65	Mutter et al. [8]
C_D	Drag coefficient	0.2	Einstein and El-Samni [34]
c_d	Diffusion constant	6.3	Hanson and Cook [3]
C_f	Coefficient of friction	0.00416	Hanson and Cook [3]
d	Equivalent particle diameter equivalent to d_{50}	0.03 mm	Experiments in this study
d_o	Oil particle diameter	0.03 mm	Experiments in this study
e_v	Coefficient of variation	0.35	Einstein and El-Samni [34]
f_{co}	Dimensionless parameter based on soil and oil cohesions	Ranges from 81 to 140	Experiments in this study
h	Pressure head for JET	90 cm	Experiments in this study
J_i	Jet nozzle height	32 mm	Experiments in this study
J_p	Potential core of jet nozzle	$c_d\, d_o$	Hanson and Cook [3]
K_e	Exposure of lower particle parameter	Based on Wilson model parameter b_0	Experiments in this study
K_f	Ratio of projected area drag and lift forces	0.92 for equal radii of a spherical particle	Wilson [27]
K_L	Ratio of drag and lift coefficients along with the ratio of velocities	1	Wilson [27]
K_t	Factor of cumulating of instantaneous fluid forces	2.5	Chepil [31]
k_a	Area constant of a spherical particle	$\pi/4$ for the spherical particle	Wilson [27]
k_{dd}	Detachment distance parameter	2	Einstein [32]
k_r	Geometry ratio for a spherical particle	$k_v/k_a = 2/3$ for the spherical particle	Wilson [27]
k_v	Volume constant of a spherical particle	$\pi/6$ for the spherical particle	Wilson [27]
l_1	Moment length of gravity downslope	$0.86\, d/2$	Wilson [27]
l_3	Moment length of drag force	$1.18\, d/2$	Wilson [27]
r	Jet radius upon maximum jet velocity works	$0.13\, J_i$	Al-Madhhachi et al. [17]
U_o	Velocity of jet at the orifice	$C\sqrt{2gh}$	Hanson and Cook [3]
w_s	Submerged particle weight	$g(\rho_s - \rho_w)k_v d^3$	Wilson [26,27]
w_o	Submerged particle weight	$g(\rho_w - \rho_o)k_v {d_o}^3$	Proposed in this study
y_p	Pivot point a spherical particle	$d/2\sqrt{3} - d/2 - l_1$	Al-Madhhachi et al. [17]
z_d	Height that the drag velocity is acting upon	$l_3 + y_p$	Al-Madhhachi et al. [17]
μ_{or}	Crude oil coefficient ratio	Ranges from 18 to 23	Experiments in this study
ρ_s	Particle density	2.65 Mg/m^3	Freeze and Cherry [35]
ρ_o	Crude oil density	0.88 Mg/m^3	Al-Madhhachi and Hasan [7], Ibrahem et al. [36]
ρ_w	Water density	1 Mg/m^3	-

The erodibility of cohesive soils, affected by crude oil contamination, can be theoretically predicted based on observed JET data without crude oil. Mini JETs were undertaken with conditions without crude oil to derive b_{0w} and b_{1w} (in which b_{0w} and b_{1w} are the Wilson model parameters without the influence of crude oil). The b_{1w} can be converted to b_1 (including the crude oil term), and b_{0w} can be converted to b_0 (including the crude oil term) based on the measured crude oil parameters, at any time, without conducting new JETs. The parameters, b_0 and b_1, are mechanistically defined. Parameter b_1, based on Equation (20), can be rewritten as the following Equation (22):

$$b_1 = b_{1w} + \left(\frac{\pi}{e_v\sqrt{6}}\right)\frac{k_r f_{co}}{K_o} g(\rho_b - \rho_w)d \tag{22}$$

in which $b_{1w} = \left(\frac{\pi}{e_v\sqrt{6}}\right)\frac{k_r(K_{Is}+f_c)}{K_o} g(\rho_s - \rho_w)d$ is the Wilson model parameter derived from JET data without crude oil contamination (i.e., f_{co} = 0). The second term in Equation (22) can be mathematically found by using the terms given in Table 1.

In a similar fashion, the Wilson model parameter b_0 can also be predicted based on the observed properties of crude oil contaminated soil. The terms in Equation (19) can be mathematically defined using the values given in Table 1, combined the range of 18 to 23 found in this study for the crude oil coefficient ratio, and K_e, which can be predicted from observed JET data for soil without crude oil contamination, using the following Equation (23):

$$K_e = \rho_s \frac{k_r}{b_{0w}} \sqrt{\frac{K_n}{k_{dd}(\rho_s - \rho_w)}} \tag{23}$$

2.2. Materials and Experimental Procedure

The Taji region was selected as a case study for this research. The Taji region is located about 30 km northwest of Baghdad city (Figure 2). The study area was located between (33°35′40′′–33°28′42′′) N and (44°05′22′′–44°18′04′′) W. Figure 2 shows the crude oil pipe lines in Iraq, including the study area. The lean clay soil used in this study was acquired from the Taji region. The physical characteristics of the soil samples that were used are listed in Table 2 followed by their characteristics defined using the ASTM standard (ASTM, 2006). The crude oil was obtained from the Iraqi South Oil Company (Basrah, Iraq). Chemical and physical characteristics were found using its laboratory, the results of which are listed in Table 3. Chemical analysis of crude-oil-contaminated soil was performed by the Ministry of Science and Technology, the results of which are listed in Table 4.

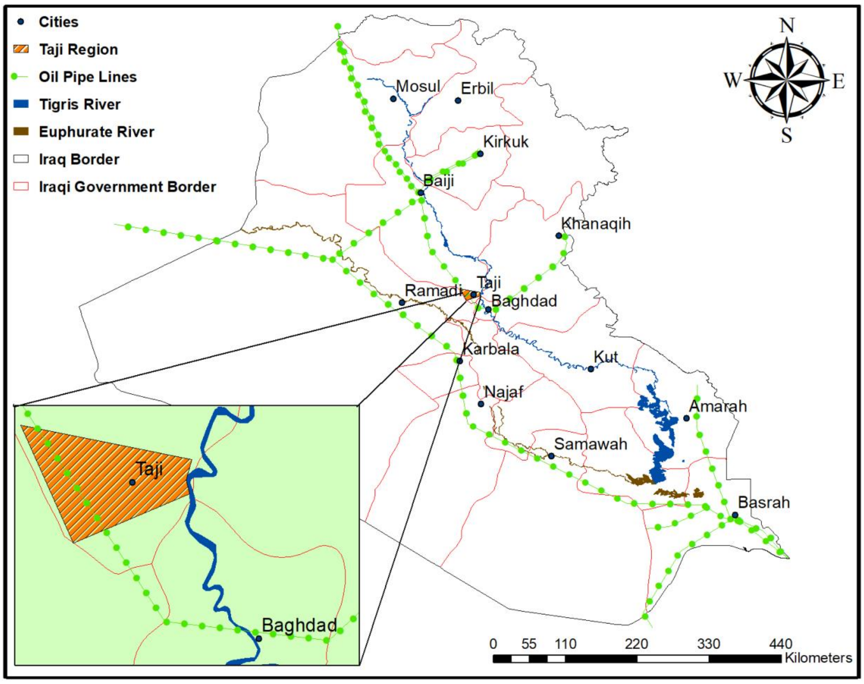

Figure 2. The location of the study area (Taji region) and crude oil pipelines in Iraq.

Table 2. Physical characteristics of soils used for the JETs.

		Soil Texture			Atterberg Limits			Standard Compaction	
Source	USCS classification	Sand (%)	Silt (%)	Clay (%)	Liquid limit	Plastic limit	Plasticity index	Maximum Density, g/cm^3	Optimum water content (%)
Al-Taji, northwest Baghdad	Lean Clay	15	55	30	38	26	14	1.88	16.00

Table 3. Physical and chemical characteristics of the crude oil used for the JETs.

American Petroleum Institute (API°) Density *	Kinematic Viscosity * at 40 °C, mm^2/s	Conradson Carbon Content *, %	Sulfur Content *, %	Vanadium Content *, ppm	Nickel Content *, ppm	Ash *, %
33.60	6.90	4.10	1.95	23.90	16.41	0.01

* Data were taken from Al-Madhhachi and Hasan [7] and Ibrahem et al. [36].

Table 4. Chemical characteristics of clean and crude oil contaminated soil after 1, 4, and 8 days of contamination.

Contamination Time, Days	pH	Electrical Conductivity (EC), ds/m	Pb_2, ppm	Total Organic Matter, %	Organic Carbon, %
0 (Clean soil)	7.14	23.78	46	1.27	0.74
1	7.18	17.40	89	1.50	0.87
4	7.31	19.50	102	1.56	0.91
8	7.81	19.80	135	1.69	0.98

The JET settings and operation followed the procedure laid out by Al-Madhhachi et al. [16,37]. Soil samples were first air dried and sieved through sieve number four. Then, the sieved samples were packed into small-scale (standard mold) and large-scale (in-situ soil box) setups at three different soil moisture contents: 10%, 16%, and 20%, respectively. This was to investigate the influence of crude oil contamination on deriving Wilson model parameters at two different scale setups and different soil moisture levels (Figure 3). The small-scale setup was an ASTM standard mold with 960 cm^3 in volume (Figure 3a). The large-scale setup was a soil box with 48,000 cm^3 in volume (Figure 3b). A standard bulk density was achieved by packing the soil into three layers using a manual rammer packed at three previously mentioned soil moisture levels. A similar technique was accomplished for the crude oil-contaminated soil. The packed contaminated soil was covered with 3 cm of crude oil and left for one day for each scale prior to JET testing. The next day, any excess oil was removed, and the JET experiments were performed.

Al-Madhhachi and Hasan [7] indicted that oil contamination influenced the erodibility of dry soil samples. Therefore, in this study, the influence of contamination time on contaminated soil was examined by implementing the JET device with the small-scale setup at dry soil moisture content (10%) to investigate the second objective of this study. The soil samples were covered with oil and left for 1st, 4th, and 8th days depending on the required contamination time prior to applying the JET. The procedure outlined by Khanal et al. [5] and Al-Madhhachi and Hasan [7] for collecting score depth vs. time was followed. A total of 48 "mini" JETs was performed for the clean and crude-oil-contaminated soils to achieve the objectives of this study. The Wilson model parameters (b_0 and b_1) were calculated using an Excel spread sheet that was developed by Al-Madhhachi et al. [17].

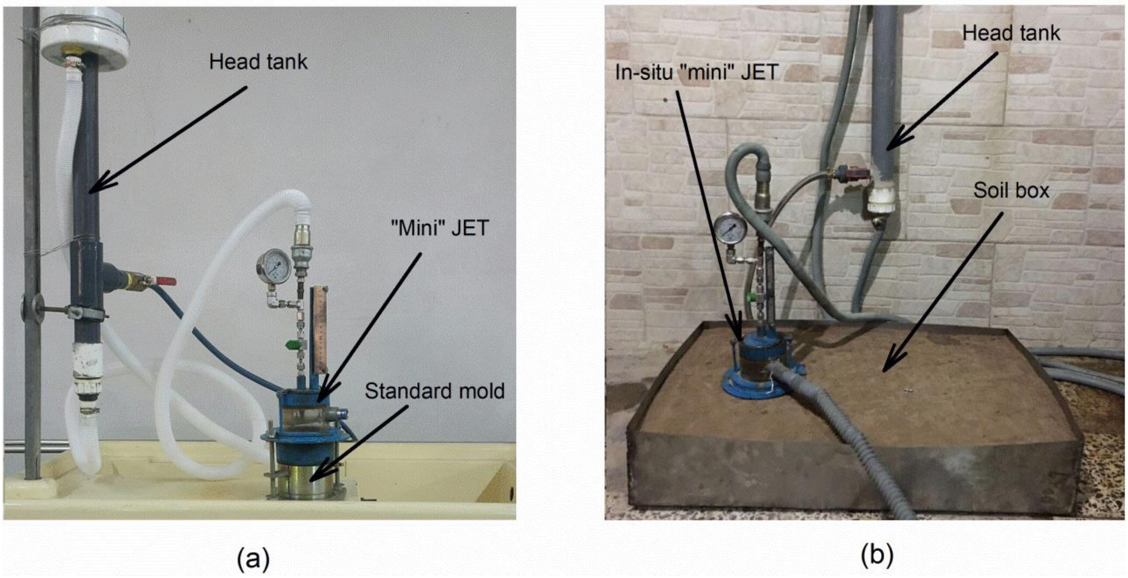

Figure 3. Jet Erosion Test (JET) device setup for (**a**) small-scale and (**b**) large-scale.

The Normalised Objective Function (*NOF*), which is the ratio of the standard deviation (*STD*) of differences between observed and predicted data to the overall mean (X_{av}) of the observed data, was calculated to quantify its suitability and to examine how well the Wilson model matched the observed data from the JET. Accordingly, the *NOF* is expressed as [24,25]

$$NOF = \frac{STD}{X_{av}} = \frac{\sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}}}{X_{av}} \tag{24}$$

in which O_i and P_i are the observed and predicted data, respectively, and N is the observation number.

The computed statistical differences in the Wilson model parameters were also investigated using the analysis of variance (ANOVA) technique between clean and crude oil contaminated soil after 1, 4, and 8 days of contamination. The median and the difference between the 25th and 75th percentiles (IQR) were described for b_0 and b_1. Pairwise comparison tests were undertaken for the mechanistic detachment parameters, which revealed a significant difference compared to ANOVA with a significance level of α = 0.05.

3. Results and Discussion

Crude oil spills on the soil's surface influence the Wilson model erodibility parameters that can be mathematically predicted from JET data. Such an influence is correlated to several factors that affect b_0 and b_1. The Wilson parameters are soil parameters, despite being driven by the flow-jet velocity parameter, which itself is driven by hydraulic conditions [17]. In the presence of crude oil, the parameter b_0 was influenced by μ_{or}, which was dependent on soil and oil cohesion (Equations (19) and (21)). It was also influenced by K_e, which depended on soil cohesion [14], while the parameter b_1 was influenced by f_{co}, which is the dimensionless parameter based on soil and oil cohesions, and f_c, which is the dimensionless parameter based on soil cohesion (Equation (20)).

Crude oil affected the observed scour-depth readings in the "mini" JET experiments. Examples for both the large-scale (in-situ soil box) and small-scale (standard mold) setups of scour depth data versus recording times at the dry side of packed contaminated soils are shown in Figure 4. Lower erosion rates were observed in both scale setups. The model was evaluated based on the Normalised Objective Function (*NOF*) using JET data for both scales (Figure 4). This was to examine how the Wilson model would fit the observed data. The *NOFs* were 0.09 and 0.22 for crude-oil-contaminated soil at small and large-scale setups, respectively (Figure 4). The *NOF* was 0.07 for clean soil at both scale setups. Consequentially, the Wilson model data fitted well the JET observed data.

For the small-scale setup, it can be observed from Figure 5a that the b_1 value slightly increased for both the clean and crude-oil-contaminated soil as the water content increased. Note that there was a slight increase for the contaminated soil compared to the clean soil. As expected, the b_0 value decreased as the water content increased for clean soil, while soil moisture content had no influence on b_0 for the oil-contaminated soil (Figure 5b). The presence of crude oil significantly influenced soil detachment at dry soil moisture content of 10%. Significant differences in b_0 values were observed between clean and contaminated soil at dry soil moisture content. The influence of crude oil on soil detachment was related to the water content when the soil was packed. This could be related to the variability of soil pores occupied with crude oil particles, as more pores are available with lower water content.

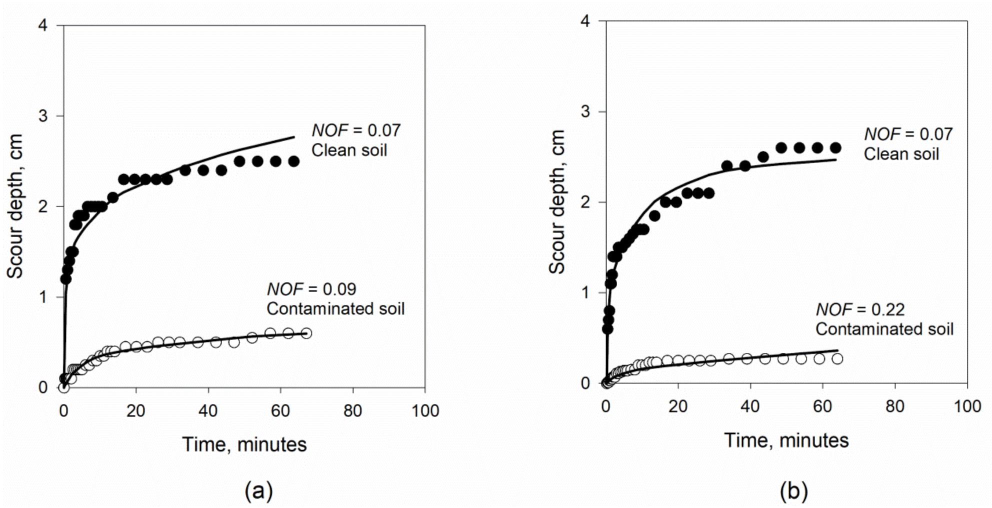

Figure 4. Wilson model evaluation using observed date for clean and oil contaminated soils at dry side for (**a**) small scale and (**b**) large scale. Note that empty circles represent the observed scour depth of contaminated soil by crude oil, solid circles represent the observed scour depth of clean soil, and solid lines represent predicted scour depth using the Wilson model.

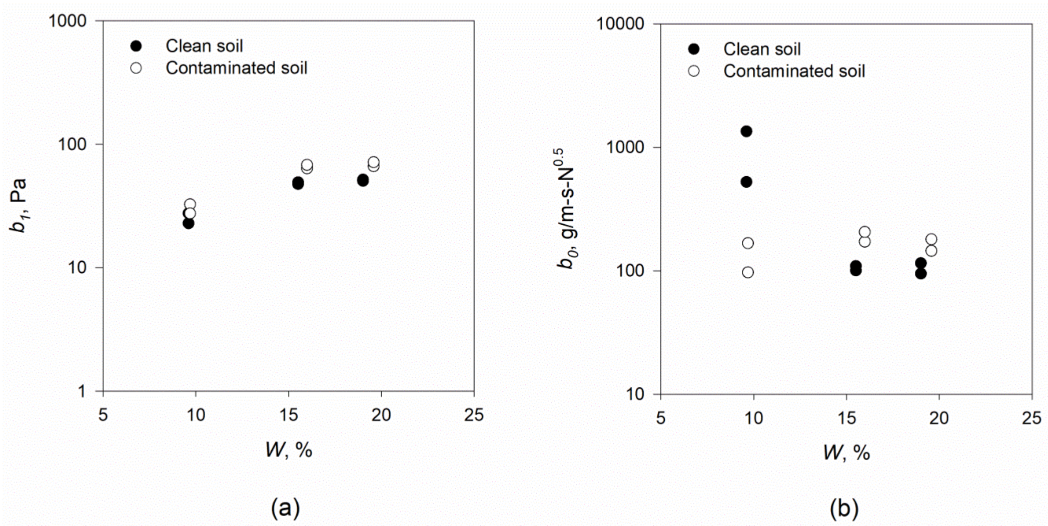

Figure 5. Derived b_1 and b_0 from the "mini" JET device for small scale at three different soil moisture contents for clean and crude oil contaminated soils: (**a**) parameter b_1 and (**b**) parameter b_0.

Figure 6 shows the influence crude oil contamination had on the Wilson parameters in the large-scale (in-situ soil box) setup. Similar to that found with small-scale setup, the b_1 value slightly increased for both clean and crude-oil-contaminated soil as the water content increased (Figure 6a). The b_0 value decreased as the water content increased for clean soil, while there was no influence of water content on b_0 for oil-contaminated soils (Figure 6b). Al-Madhhachi et al. [17] reported an inverse correlation between b_0 and water content when the soil was packed, due to the increase in K_e of parameter b_0 (Equation (19)). Similar observations were made in this study with clean soil. However, no correlations between b_0 and soil moisture content were observed for crude-oil-contaminated soils with either scale setups (Figures 5 and 6).

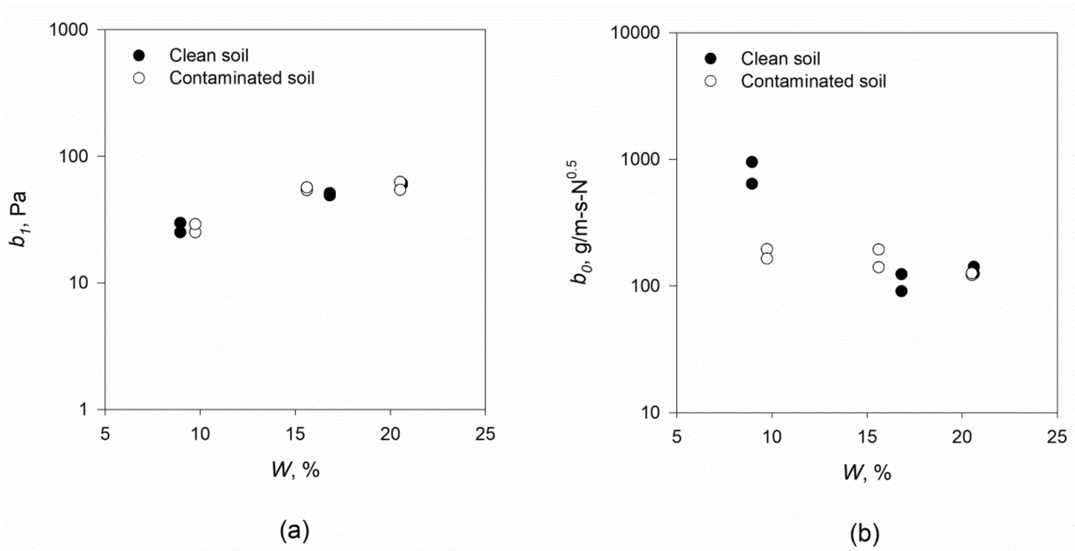

Figure 6. Derived b_1 and b_0 from the "mini" JET device for large scale at three different soil moisture contents for clean and crude oil contaminated soils: (**a**) parameter b_1 and (**b**) parameter b_0.

To investigate the influence of crude oil at dry moisture content in detail, Wilson parameters b_0 and b_1 were also derived from the JET data for clean and crude-oil-contaminated soils with the small-scale setup as an example at three different contamination times (1st, 4th, and 8th days) (Figure 7). There was no influence of the contamination times on the b_1 values for either of the clean or oil-contaminated soils (Figure 7a). ANOVA reported that there was no statistically significant difference between clean and contaminated soil for parameter b_1 (with $p > 0.05$), excluding the observed b_1 at 8 days of contamination (Table 5). Figure 7b indicates an inverse relationship between the b_0 value and contamination time for contaminated soils. A significant reduction in b_0 was found for crude-oil-contaminated dry soil as the contamination time increased in comparison to clean soil. This was due to the low soil moisture content and increased contamination time allowing more crude oil particles to occupy the soil pores. ANOVA confirmed that the results shown in Figure 7b have statistically significant differences between clean and contaminated soil for the observed b_0 parameter (with $p < 0.05$), excluding the observed b_0 on the first day of contamination (Table 5).

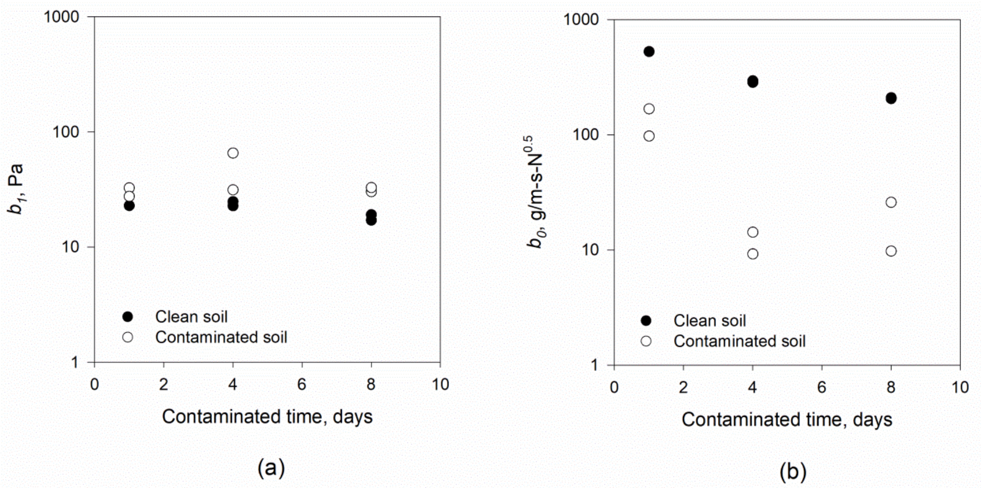

Figure 7. Comparison between clean soil and crude oil contaminated soil at different contaminated times (1st, 4th, and 8th) days of deriving Wilson model parameters of small scale setup at dry soil moisture content: (**a**) parameter b_1 and (**b**) parameter b_0.

Table 5. Crude oil parameters (f_{co} and μ_{or}) and the results of the Normality Test (Shapiro-Wilk) between clean and crude oil contaminated soils for the given Wilson model parameters after 1, 4, and 8 days of contamination.

			Median Values (IQR) [a] of Wilson Model Parameters					
			Clean Soil		Contaminated Soil			
Contamination Time, Days	f_{co}	μ_{or}	b_1, Pa	b_0, g/m-s-N$^{0.5}$	b_1, Pa	b_0, g/m-s-N$^{0.5}$	p-Value of b_1	p-Value of b_0
1	81.00	18.67	25.5 (4.7)	942.5 (827.2)	30.4 (5.2)	133.4 (70.7)	0.505	0.278
4	140.00	23.03	24.1 (2.0)	290.8 (10.0)	48.9 (34.3)	11.8 (5.1)	0.402	0.006
8	140.00	23.04	18.3 (2.0)	208.8 (4.0)	31.9 (2.6)	18.0 (16.3)	0.013	0.021

Note: p-values > 0.05 indicate that there is no statistically significant difference. [a] IQR = interquartile range, defined as the difference between the 25th and 75th percentiles.

Soil chemical characteristics were also influenced by the crude oil at different contamination times (Table 4). The soil pH level slightly increased as the contamination times increased. Wang et al. [38] found that crude oil contamination increases the pH level. The lead concentration (Pb^{2+}) significantly increased from 45.5 ppm to 135 ppm after eight days of oil contamination (Table 4). Total organic matter and organic carbon increased slightly from 1.27% to 1.69% and from 0.74% to 0.98%, respectively, as contamination times increased. Richardson et al. [39] investigated the influence of crude oil contamination on physiochemical characteristics of soil. Richardson et al. [39] observed elevated levels of lead and total organic carbon in contaminated soils. High levels of total organic carbons and lead confirmed severe soil hydrocarbon contamination. No significant differences were observed for EC and pH levels between clean and oil-contaminated soils [39]. Future research is needed to develop relationships between the crude oil parameters (f_{co} and μ_{or}) and soil chemical characteristics for different soil textures.

The predictive equations for b_0 and b_1 from the parameters without crude oil appropriately estimated the derived parameter values from JETs with small-scale setup and at different contamination times (see Figure 8). The Wilson parameters at zero contaminated time referred to values of b_1 and b_0 at clean soils (without contamination by crude oil). The *NOF* of prediction parameters versus observed data were 0.10 and 0.03 for b_1 and b_0, respectively. The prediction of b_1 was based on the dimensionless parameter, based on soil and oil cohesions f_{co}. The prediction of b_0 was based on the crude oil coefficient ratio μ_{or} and K_e. Table 5 shows that the parameters f_{co} and μ_{or} increased as contamination time increased until equilibrium was reached. These parameters are a function of soil and oil particle cohesion and contamination time based on the chemical-physical bonds between soil and oil particles. Additional research is needed to verify the values of f_{co} and μ_{or} for different soil textures at different contamination levels.

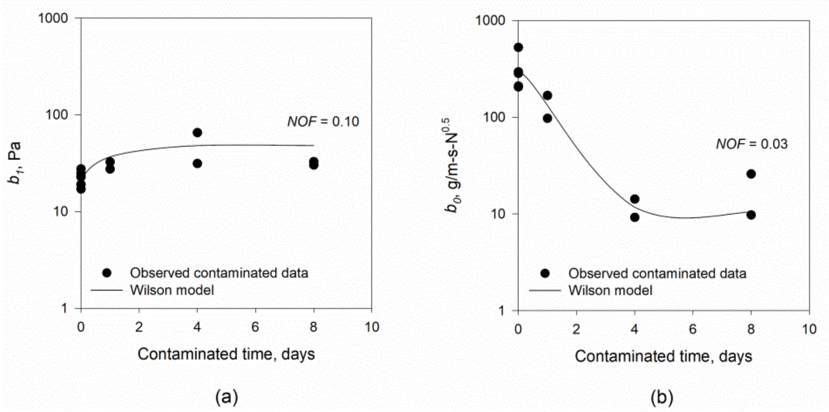

Figure 8. Predicting of Wilson model parameters (b_1 and b_0) of crude oil contaminated soil at different contaminated times (1, 4, and 8) days for small scale at dry soil moisture content: (**a**) parameter b_1 and (**b**) parameter b_0.

4. Summary and Conclusions

The influence of crude oil in relation to fluvial forces was incorporated into a fundamental detachment model (the Wilson model) to calculate the mechanistic detachment parameters, b_0 and b_1. A laboratory "mini" JET device was utilized to derive b_0 and b_1 for lean clay soils at different scale setups and packed at different soil moisture levels (10% to 20%) to investigate the influence of crude oil on deriving the Wilson model parameters. Another set of JET experiments was performed to investigate the influence of crude-oil-contaminated dry soil at different contamination times (1st, 4th, and 8th days). Crude oil decreased the observed scour depth measurements compared to the clean soils of the "mini" JET experiments. The parameter b_1 value slightly increased for both clean and crude-oil-contaminated soil as the water content increased. Significant differences in b_0 values were observed between clean and contaminated soil with dry soil moisture content. This was because the soil pores were occupied by crude oil particles at lower water content. No correlations between b_0 and the soil moisture content of contaminated soil were observed for both scale setups. No statistically significant differences were observed between clean and contaminated soil for b_1, excluding the observed b_1 at a high level of contamination. Statistically significant differences were found between clean and contaminated soil for the observed b_0 parameter, excluding the observed b_0 on low level of contamination. No significant differences were observed for soil pH levels, EC, organic matter, or carbon between the clean and oil-contaminated soils. The lead concentration significantly increased as the contamination times increased. The influence of crude oil on mechanistic soil erodibility parameters can be predicted with a priori JET experiment on clean soil based on crude oil parameters (f_{co} and μ_{or}). The Wilson model is beneficially a fundamentally erosion-based equation and thus benefits from being more mechanistic in comparison to other empirical erosion models.

Author Contributions: The performing experiments, providing required materials, and data/evidence collection have been performed by M.B.H. The data analysis, mathematical development of Wilson model, and methodology have been considered and hypothesized by A.-S.T.A.-M. The ideas, formulation of overarching research aims, and editing of the text have been performed by both authors.

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References

1. Briaud, J.L.; Ting, C.K.; Chen, H.C.; Han, S.W.; Kwak, K.W. Erosion function apparatus for scour rate predictions. *J. Geotech. Geoenviron. Eng.* **2001**, *127*, 105–113. [CrossRef]
2. Hanson, G.J. Surface erodibility of earthen channels at high stresses part ii-developing an in situ testing device. *Trans. ASAE* **1990**, *33*, 132–137. [CrossRef]
3. Hanson, G.J.; Cook, K.R. Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. *Appl. Eng. Agric.* **2004**, *20*, 455–462. [CrossRef]
4. Wan, C.F.; Fell, R. Laboratory tests on the rate of piping erosion of soils in embankment dams. *Geotech. Test. J.* **2004**, *27*, 295–303.
5. Khanal, A.; Fox, G.A.; Al-Madhhachi, A.T. Variability of erodibility parameters from laboratory mini jet erosion tests. *J. Hydrol. Eng.* **2016**, *21*, 04016030. [CrossRef]
6. Abbas, M.N.; Al-Madhhachi, A.T.; Esmael, S.A. Quantifying soil erodibility parameters due to wastewater chemicals. *Int. J. Hydrol. Sci. Technol.* **2018**, in press.
7. Al-Madhhachi, A.T.; Hasan, M.B. Influence of in-situ scaling on variability of polluted soil erodibility parameters. *Pollution* **2018**. [CrossRef]
8. Mutter, G.M.; Al-Madhhachi, A.T.; Rashed, R.R. Influence of soil stabilizing materials on lead polluted soils using jet erosion tests. *Int. J. Integr. Eng.* **2017**, *9*, 28–38.
9. Salah, M.M.; Al-Madhhachi, A.T. Influence of lead pollution on cohesive soil erodibility using jet erosion tests. *Environ. Nat. Resour. Res.* **2016**, *6*, 88–98. [CrossRef]
10. Shayannejad, M.; Ostad-Ali-Askari, K.; Ramesh, A.; Singh, V.P.; Eslamian, S. Wastewater and magnetized wastewater effects on soil erosion in furrow irrigation. *Int. J. Res. Stud. Agric. Sci.* **2017**, *3*, 1–14.
11. Quyum, A.; Achari, G.; Goodman, R.H. Effect of wetting and drying and dilution on moisture migration through oil contaminated hydrophobic soils. *Sci. Total Environ.* **2002**, *296*, 77–87. [CrossRef]
12. Tsai, T.T.; Kao, C.M. Treatment of petroleum-hydrocarbon contaminated soils using hydrogen peroxide oxidation catalyzed by waste basic oxygen furnace slag. *J. Hazard. Mater.* **2009**, *170*, 466–472. [CrossRef] [PubMed]
13. Anoliefo, G.O.; Vwioko, D.E. Effects of spent lubrication oil on the growth of Capsicum anumL and Hycopersiconesculentum Miller. *Environ. Pollut.* **1995**, *88*, 361–364. [CrossRef]
14. Tigris Oil Spill Pollutes Iraq Water Supplyitle of Site. Available online: https://www.oilandgasmiddleeast.com/article-12343-tigris-oil-spill-pollutes-iraq-water-supply (accessed on 24 April 2014).
15. Al-Madhhachi, A.T. Variability in soil erodibility parameters of tigris riverbanks using linear and non-linear models. *Nahrain J. Eng. Sci.* **2017**, *20*, 959–969.
16. Al-Madhhachi, A.T.; Hanson, G.J.; Fox, G.A.; Tyagi, A.K.; Bulut, R. Measuring soil erodibility using a laboratory "mini" jet. *Trans. ASABE* **2013**, *56*, 901–910.
17. Al-Madhhachi, A.T.; Hanson, G.J.; Fox, G.A.; Tyagi, A.K.; Bulut, R. Deriving parameters of a fundamental detachment model for cohesive soils from flume and jet erosion tests. *Trans. ASABE* **2013**, *56*, 489–504. [CrossRef]
18. Daly, E.R.; Fox, G.A.; Miller, R.B.; Al-Madhhachi, A.T. A scour depth approach for deriving erodibility parameters from jet erosion tests. *Trans. ASABE* **2013**, *56*, 1343–1351.
19. Daly, E.R.; Fox, G.A.; Al-Madhhachi, A.T.; Storm, D.E. Variability of fluvial erodibility parameters for streambanks on a watershed scale. *Geomorphology* **2015**, *231*, 281–291. [CrossRef]
20. Hanson, G.J.; Hunt, S.L. Lessons learned using laboratory jet method to measure soil erodibility of compacted soils. *Trans. ASABE* **2007**, *23*, 305–312.
21. Cleaver, J.W.; Yates, B. Mechanism of detachment of colloidal particles from a flat substrate in a turbulent flow. *J. Colloid Interface Sci.* **1973**, *44*, 464–474. [CrossRef]
22. Nearing, M.A. A probabilistic model of soil detachment by shallow turbulent flow. *Trans. ASAE* **1991**, *34*, 81–85. [CrossRef]
23. Sharif, A.R.; Atkinson, J.F. Model for surface erosion of cohesive soils. *J. Hydraul. Eng.* **2012**, *138*, 581–590. [CrossRef]

24. Al-Madhhachi, A.T.; Hanson, G.; Fox, G.; Tyagi, A.; Bulut, R. Mechanistic detachment rate model to predict soil erodibility due to fluvial and seepage forces. *J. Hydraul. Eng. ASCE* **2014**, *140*, 04014010. [CrossRef]
25. Al-Madhhachi, A.T.; Fox, G.A.; Hanson, G.J. Quantifying the erodibility of streambanks and hillslopes due to surface and subsurface forces. *Trans. ASABE* **2014**, *57*, 1057–1069.
26. Wilson, B.N. Development of a fundamentally based detachment model. *Trans. ASAE* **1993**, *36*, 1105–1114. [CrossRef]
27. Wilson, B.N. Evaluation of a fundamentally based detachment model. *Trans. ASAE* **1993**, *36*, 1115–1122. [CrossRef]
28. Khanal, A.; Fox, G.A. Detachment characteristics of root-permeated soils from laboratory jet erosion tests. *Ecol. Eng.* **2017**, *100*, 335–343. [CrossRef]
29. Criswell, D.T.; Fox, G.A.; Miller, R.B.; Daly, E.R.; Al-Madhhachi, A.T. Flume experiments to determine the erodibility of gravel streambank soils. In Proceedings of the American Society of Agricultural and Biological Engineers Annual International Meeting 2013, Kansas City, MO, USA, 21–24 July 2013.
30. Criswell, D.T.; Al-Madhhachi, A.T.; Fox, G.A.; Miller, R.B. Deriving erodibility parameters of a mechanistic detachment model for gravels. *Trans. ASABE* **2016**, *59*, 145–151.
31. Chepil, W. Equilibrium of soil grains at the threshold of movement by wind 1. *Soil Sci. Soc. Am. J.* **1959**, *23*, 422–428. [CrossRef]
32. Einstein, H.A. *The Bed-Load Function for Sediment Transportation in Open Channel Flows*; USDA Soil Conservation: Washington, DC, USA, 1950; Volume 1026.
33. Partheniades, E. Erosion and deposition of cohesive soils. *J. Hydraul. Div. ASCE* **1965**, *91*, 105–139.
34. Einstein, H.A.; El-Samni, E.-S.A. Hydrodynamic forces on a rough wall. *Rev. Mod. Phys.* **1949**, *21*, 520–524. [CrossRef]
35. Freeze, R.A.; Cherry, J.A. *Groundwater*; Prentice Hall: Upper Saddle River, NJ, USA, 1979.
36. Ibrahem, M.M.; Mohammed, A.A.; Jar-Allah, A.T. Kinetics of sulfur, vanadium and nickel removal from basra crude oil hydro treating. *Tikrit J. Eng. Sci.* **2010**, *17*, 1–14.
37. Al-Madhhachi, A.T.; Hanson, G.; Fox, G.; Tyagi, A.; Bulut, R. Measuring erodibility of cohesive soils using laboratory jet erosion tests. Presented at the World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability, Palm Springs, CA, USA, 22–26 May 2011; ASCE: Reston, VA, USA, 2011.
38. Wang, Y.; Feng, J.; Lin, Q.; Lyu, X.; Wang, X.; Wang, G. Effects of crude oil contamination on soil physical and chemical properties in momoge wetland of china. *Chin. Geogr. Sci.* **2013**, *23*, 708–715. [CrossRef]
39. Richardson, V.; Herath, G.; Kalpage, C.; Jinadasa, K. Physico-chemical characteristic of a petroleum contaminated soil from the spill site of jaffna district. In Proceedings of the 6th International Conference on Structural Engineering and Construction Management, Kandy, Sri Lanka, 11–13 December 2015.