Influence of Lead Pollution on Cohesive Soil Erodibility using Jet Erosion Tests

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Abstract

Recent researches were investigated the high concentrations of Lead in Baghdad soils due to the emissions from Leaded fuel of cars, generators, and the industrials. These high concentrations in addition to their impact on human health may impact on the landscape and streambanks and may cause significant issues on soil erodibility. The erosion rate of cohesive soil was usually estimated using two alternative models, excess shear stress model which is depended on two major soil parameters: the critical shear stress, τ_c, and the erodibility coefficient, k_d, and Wilson model which is depended on two mechanistic soil parameters: b_0 and b_1. A new miniature version of Jet Erosion Test ("mini" JET) was performed to derive both model parameters. The objective of this study was to investigate the influence of Lead pollution on cohesive soil erodibility using "mini" JET under controlled laboratory setups to predict soil erodibility. In order to observe the Lead contamination on soil erodibility, soil samples were mixed with different quantities of Lead concertation and the samples were packed at ASTM standard mold on two different bulk densities. Results show that the Lead pollution increased soil erodibility when the concentration of Lead increased. An inverse relationship between excess shear stress parameters k_d and τ_c was observed as well as between Wilson model parameters b_0 and b_1. The Wilson model parameters were closely resembled the empirical excess shear stress parameters with benefit that Wilson model parameters are mechanistic parameters.

Keywords: Lead pollution, soil pollution, erodibility, Jet Erosion Test, sediment detachment

1. Introduction

Baghdad City is considered one of the most important and biggest industrialized city in Iraq due to the development and increasing in the population, as a result of increasing in car usages and industrial factories. These increasing in car numbers led to increasing in Lead concentration because the Iraqi oil ministry still adding the tetra alkyl Lead additive as an anti-Knocking agent. For instant, the Lead concentration in Al-Dora region (South of Baghdad, on the banks of the Tigris River) were high (about 846 μg/g) due to the Lead additives in Al-Dora fuel production plant (Sahib, 2005). As well as to using of Leaded fertilizers in the agricultural lands of Al- Dora region which is located on the Tigris river which is led to the contamination of Tigris riverbanks. Additionally, the Lead contamination of Al-Waziryah region (North east of Baghdad) is up to 25069.6 μg/g due to the presence of Babil car batteries factory (Rahi et al., 2014). This factory used old techniques and had no emission control devices and they had no water treatment plants on the waste water discharges. Therefore, some Baghdad regions are considered very high in Lead contamination risks.

The Lead emissions in the atmosphere is often deposited on the soil surface and correlated with its particulate depending on its characteristics and the conditions of the surrounding media. Lead may be correlated with soil particles into strong chemical bonds and it would be immobile, or Lead may penetrated into the soil through the rainfall and irrigation. When the Lead penetrated into the soil, it would be correlated with the organic compounds, carbonates, and sulfate in the presence of the reaction conditions. All these Lead emissions can be deposited into soil, absorbed by soil, and correlated with the soil in chemical bonds. These bonds may weaken the soil structure and will definitely influence on soil erodibility.

Normally, the soil erodibility is predicted using different models. The excess shear stress model (linear model) is widely used to estimate the erosion rate of cohesive soil based on two empirical parameters: erodibility coefficient, k_d, and critical shear stress, τ_c (Partheniades, 1965; Hanson, 1990a, 1990b; Al-Madhhachi et al.,

2013a, 2013b; Daly et al., 2015). Additionally, an alternative nonlinear model with more mechanistic parameters was developed (Wilson model). The Wilson model was developed by Wilson (1993a, 1993b) to describe the detachment of single or aggregate soil particles depending on two mechanistic dimensional soil parameters: b_0 and b_1. Several studies measure the erodibility of soils using different techniques; Large flumes (Hanson, 1990a; Hanson and Cook, 2004), small flumes (Briaud et al., 2001), laboratory hole erosion test (Wan & Fell, 2004), and a jet erosion test (Hanson, 1990b; Hanson & Cook, 2004; Al-Madhhachi et al., 2013a, 2013b, 2014a, 2014b), which is the focused of this study.

There are two versions of JET devices, the original JET (Hanson, 1990b) and the new miniature version of JET referred as "mini" JET (Simon et al., 2010; Al-Madhhachi et al., 2013a, 2013b). The "mini" JET is smaller, lighter, and required less water compared to original JET. It is easy to handle and setup in the field as well as in the laboratory. Al-Madhhachi et al. (2013a) provided equivalent erodibility parameters of "mini" JET with original JET under controlled laboratory setup. Al-Madhhachi et al. (2013b) verified the used of both original and "mini" JETs with flume experiments by deriving both excess shear stress model and Wilson model parameters. Additionally to widely usage of "mini" JET in the laboratory sitting, Daly et al. (2015) used the "mini" JET in the field at the streambanks across the Illinois River watershed in Oklahoma to derive the erodibility parameters and to investigate its variability or uniformity of these parameters at a river basin scale, the relationships between the derived parameters and the soil texture, and the possibility to predict the k_d-τ_c relationship.

Several researchers (Hanson, 2001; Wynn and Mostaghimi, 2006; Hanson and Hunt, 2007; Wynn et al., 2008; Regazzoni et al., 2008; Sang et al., 2015) have studied the influence of soil properties on soil erodibility, such as soil texture, soil moisture, bulk density, soil compaction, soil chemical, and vegetation. No studies or researches till now studied the influence of Lead pollution on the soil erodibility. This research is investigated the erodibility in cohesive soil materials that influenced by Lead pollution using "mini" JETs. The objective of this study was to investigate the influence of Lead pollution on soil erodibility using "mini" JET under controlled laboratory setups and comparing the analysis results of excess shear stress model and Wilson model.

2. Materials and Methods

2.1 Analysis Method

Two alternatives models were presented in this study to derive the erodibility parameters: the linear model (excess shear stress) and nonlinear model (Wilson model). The excess shear stress model is the most commonly used model depends on two empirical parameters (k_d and τ_c) and it is expressed as (Partheniades, 1965; Hanson, 1990a, 1990b):

$$\varepsilon_r = k_d \left(\tau - \tau_c \right)^a \tag{1}$$

where ε_r is the detachment rate (cm/s), τ is the average hydraulic boundary shear stress (Pa), and a is an empirical exponent assumed to be unity according to Hanson (1990a, 1990b) and Al-Madhhachi et al. (2013a, 2013b).

Presently, there are three approaches in analyzing data from JETs to estimate the erodibility parameters of the excess shear stress equation. The most popular method of analysis, called Blaisdell's solution (BL), was developed by Hanson and Cook (1997, 2004). The solution method was based on principles of fluid diffusion presented by Stein and Nett (1997) and a hyperbolic function modeling the depth progression of the scour hole developed by Blaisdell et al. (1981). The equilibrium depth, J_e, is defined as the maximum depth of the scour hole beyond which the water jet cannot erode further. This solution method predetermines the τ_c parameter based on J_e of scour hole as predicted by the Blaisdell's function as following (Hanson and Cook, 2004):

$$\tau_c = \tau_o \left(\frac{J_p}{J_e} \right)^2 \tag{2}$$

where $\tau_o = C_f \rho_w U_o^2$ is the maximum shear stress due to the jet velocity at the nozzle (Pa); $C_f = 0.00416$ is the coefficient of friction; ρ_w is water density (kg/m³); $U_o = C\sqrt{2gh}$ is the velocity of jet at the orifice (cm/s); C is discharge coefficient (ranged from 0.6 to 0.8 for "mini" JET according to Al-Madhhachi et al., 2013a); h is the pressure head (cm); $J_p = C_d d_o$ is the potential core length from jet origin (cm); d_o is the nozzle diameter (cm); and $C_d = 6.3$ is the diffusion constant. The k_d is then determined by solving for the least squared deviation between the observed scour time and predicted time of the following equation (Hanson and Cook, 1997):

$$T^* - T_p^* = -J^* + 0.5\ln\left(\frac{1+J^*}{1-J^*}\right) + J_p^* - 0.5\ln\left(\frac{1+J_p^*}{1-J_p^*}\right) \tag{3}$$

where $T^* = t / T_r$ is the dimensional time, t is the time of a scour depth measurement, $T_r = J_e /(k_d \tau_c)$ is the reference time according to Stein and Nett (1997), $J^* = J/J_e$; J is the scour depth (cm), and $J_p^* = J_p /J_e$.

Alternative solution methods to Blaisdell's solution have been suggested recently (Simon et al., 2010; Daly et al., 2013). One of these solution methods is called scour depth solution (SD). This method simultaneously searches for k_d and τ_c which provide the best fit of observed JET data on the scour depth versus time curve predicted by the excess shear stress equation (Eq. 1). The other approach was presented by Simon et al. (2010), and referred to as iterative solution (IT). This method is initialized using the values of erodibility parameters determined by Blaisdell's solution. The scour hole is assumed to reach the equilibrium depth at the end of each test. An upper bound on τ_c is fixed using this equilibrium depth. Then the values of k_d and τ_c which minimize the root mean square deviation between the observed scour time and predicted time is searched for iteratively. Finally, the parameters of the excess shear stress model were estimated using these three different solution techniques (BL, SD, and IT) for JET data using Spreadsheet Tool, Version 2.1.1 that developed by Daly et al. (2013).

The general framework for predicting the erosion rate in the Wilson model is based on dislodging and stabilizing forces and associated moment lengths for particle detachment as originally developed by Wilson (1993a, 1993b). The original framework of the Wilson model (Wilson, 1993a, 1993b) was developed for open channel environment. Al-Madhhachi et al. (2013b) incorporated the hydraulics of JET in Wilson model and demonstrated that the parameters of Wilson model can also be determined from the experimental data obtained from the JETs. Al-Madhhachi et al. (2013b) introduced the Wilson model for JET environment as following:

$$\varepsilon_r = b_0 \sqrt{\tau}\left[1 - \exp\left\{-\exp\left(3 - \frac{b_1}{\tau}\right)\right\}\right] \tag{4a}$$

$$b_0 = \rho_s \frac{k_r}{K_e} \sqrt{\frac{K_n}{k_{dd}(\rho_s - \rho_w)}} \tag{4b}$$

$$b_1 = \left(\frac{\pi}{e_v \sqrt{6}}\right)\frac{k_r (K_{ls} + f_c)}{K_o} g(\rho_s - \rho_w)d \tag{4c}$$

where b_0 has dimensions of $(M/L^3)^{0.5}$, and b_1 has dimensions of F/L^2; ρ_s is particle density; k_r (= k_v/k_a = 2/3) is the geometry ratio for a spherical particle; k_v (= $\pi/6$) is the volume constant of a sphere particle; k_a (=$\pi/4$) is the area constant of a spherical particle; K_e is the exposure of lower particle parameter; K_n is a combination of particle and fluid factors; k_{dd} is the detachment distance parameter equal to 2 according to Einstein (1950); e_v is the coefficient of variation, equal to 0.35 according to Einstein and El-Samni (1949); K_{ls} is the dimensionless parameter that depends on particle size, its orientation within the bed, and slope; K_o is the flow velocity parameter for JET; and f_c is the dimensionless parameter based on cohesion.

The parameters (b_0 and b_1) of the Wilson model were also determined using the spreadsheet tool described by Al-Madhhachi et al. (2013b). The observed particle detachment rate data is fit to equation (4a) by minimizing the sum of squared differences between the observed and modeled scour depth. Hence, the parameters of the model can be determined statistically from observed JET data similar to the linear model.

2.2 Soil Characteristics and Experimental Procedures

In this study the soil samples were acquired from Al-Rashdia region, Northern Baghdad. All physical and chemical tests were performed according to ASTM standards as shown in Table (1). Also to investigate the influence of Lead pollution on soil erodibility, a Lead powder (manufactured by the British Drug House, BDH England) was added to the soil samples as micro gram to each gram (μg/g) to obtain the desired concentrations. The "mini" JET device (Figure 1) was used to derive both excess shear stress model and Wilson model parameters. The description, dimension, and functions of this device were defined in Al-Madhhachi et al. (2013a). In this study, the "mini" JET was calibrated according to Al-Madhhachi et al. (2013a) and the coefficient discharge (*C*) was found to be 0.65.

The unpolluted soils were air dried and passed through the U.S. Sieve No. 4 (4.75 mm). Then, mixed with different quantities of water to achieve the desired water content, and left for 24 hr in a closed bucket to allow

for moisture equilibrium. Then, soil moisture content of the samples was determined. Lead powder was added to the dry unpolluted soil and mixed well for 2 to 5 min to distribute evenly between soil particles. Then, the above procedure was repeated for polluted soil. In order to investigate the influence of Lead pollution on soil erodibility, the soil samples were packed on two different bulk densities. The samples were first prepared by packing the soil in a standard mold (101.6 mm in diameter and 116.4 mm in height) at standard bulk density (25 blow per layer, three layers for each sample) to achieve standard bulk density of (1.7 Mg/m^3) near the optimum water content (17.5) using a manual rammer (30.5 cm in height, 50.8 mm in diameter, and 2.49 kg in weight) according to ASTM Standard, D698. Other soil samples were packed at uniform bulk density of 1.4Mg/m^3 near the optimum water content of 20%. Then, the top of soil specimen was trimmed and dry density was determined for each soil sample. After that, the soil samples were tested using "mini" JETs by placing the soil specimen in the center of the submergence tank directly below the jet nozzle (Figure 1), adjusting the head tank at the desired constant head (63 cm for all experiments) and connecting the hoses (including water source) to the JET device.

Table 1. Properties of the soils for testing "mini" JET device.

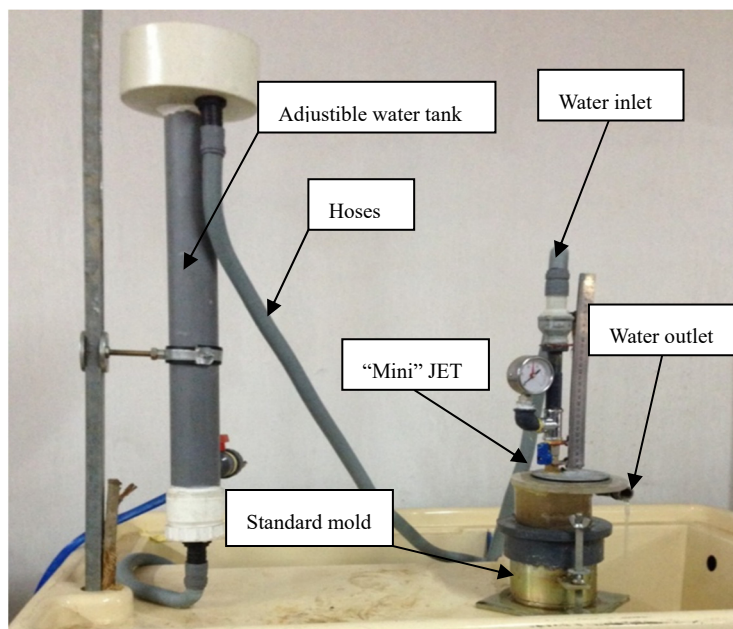| Site	USCS classification	Soil texture				Standard Compaction			Organic content (%)	PH
		Sand (%)	Silt (%)	Clay (%)	Plasticity Index	Maximum Density	Optimum water content (%)			
Al-Rashdia, North Baghdad	Lean Clay	2.0	62	36	25.5	1.7	17.5		8.8	8.7

Figure 1. Laboratory setup of the "mini" JET device

Before turning on the water, the height of the jet nozzle was determined by taking the depth gauge readings at the nozzle and the soil specimen surface at time zero. Then, the nozzle was rotated away from impinging on the soil specimen while depth gauge readings were taken. Following depth gauge readings, the water source was opened to fill the head tank. Then, the jet valve was opened to fill the submergence tank. After filling the submergence tank with water, an initial reading of water head was acquired from the top of the adjustable head tank to the water surface at the submergence tank. This reading was held constant during the test. The nozzle was then rotated to impinge directly on the soil specimen surface to start the test and the time was recorded. The readings of the scour bed were taken using the depth gauge at different time intervals. Usually, the first reading was acquired after 30 s while subsequent readings were acquired each 1 to 10 min interval with a maximum test

period of 120 minutes. The tests were repeated twice for each water bulk density. Finally, the "mini" JET data were analyzed to derive erodibility parameters for excess shear stress model and Wilson model as explained previously.

3. Results and Discussion

3.1 Influence of Lead Pollution on the Observed Data

Lead influenced the observed scour depth measurement of the "mini" JET experiments. Higher erosion rates were observed with higher Lead concentrations. Figure (2) show increasing in erosion rates with increasing the Lead concentration at 1.7 g/cm^3 and 1.4 g/cm^3 bulk densities. There are two reasons for increasing the erodibility due to increasing in the Lead concentration. The first explanation is a physical reason: due to the high density of Lead particles. When increasing the Lead concentration, the mass and the number of Lead particles that penetrate the soil particles increased. The second explanation is a chemical reason. SAAMI (1996) proposed that Pb^0 oxidized to Pb^{2+} and the Lead particles have the ability to the adsorption or ion exchange with the soil particles (Cuber, 2000). The adsorption occurs between cation (Lead particles) and anion (soil particles and organic material).This adsorption correlation weakens the cohesive forces between soil particles. Also, it can be observed that the bulk density had a significant role on the erosion rates, the soil at 1.4 g/cm^3 had less resistance to erosion and more influenced by Lead than 1.7 g/cm^3 bulk density.
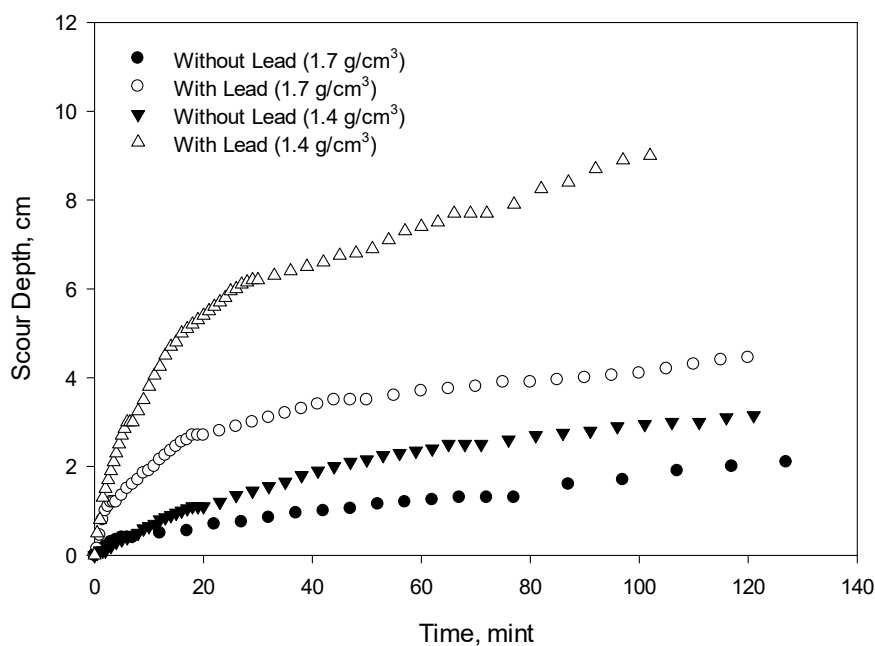

Figure 2. Influence of Lead concertation on the observed scour depth for two different bulk densities: 1.4 g/cm^3 and 1.7 g/cm^3

3.2 Influence of Lead Pollution on Linear Model

The excess shear stress parameters (k_d and τ_c) were derived from JET data using three solution techniques: Blaisdell solution (BL), scour depth (SD), and iterative solution (IT). The erodibility coefficient from BL, $k_{d\text{-}BL}$, was clearly influenced by Lead pollution as observed in Figure 3a. Even higher $k_{d\text{-}BL}$ values were observed with low bulk density (1.4 g/cm^3). From this Figure, it is obvious that the erodibility increased when the Lead concentration increased while the critical shear stress, $\tau_{c\text{-}BL}$, was decreased when Lead concertation increased. Similar to BL technique, SD solution of the excess shear stress parameters have the same behavior to BL technique but with different magnitude. The $k_{d\text{-}SD}$ increased as Lead concertation increased and the $\tau_{c\text{-}SD}$ decreased as Lead concertation increased (Figures 3c and 3d). In addition, the results of IT solution technique were close to the BL solution technique and the Lead concentrations had the same influence on its parameters (Figures 3e and 3f).

3.3 Influence of Lead Pollution on Non-Linear Model Parameters

The derived parameters of Wilson model (b_0 and b_1) at 1.7 g/cm^3 and 1.4 g/cm^3 are shown in Figures 4a and 4b. Similar to excess shear stress parameters, the b_0 increased as Lead concertation decreased while b_1 decreased. This effect is due to the factors that the mechanistic parameters of b_0 and b_1 depend on soil properties and hydraulic parameters. The parameter b_0 as shown in equation (4b) depends on the soil properties such as particle shape, density, orientation (which influences, k_r) and soil cohesion (which influences, K_e). Therefore, the increasing in b_0 parameter with increasing the concentration of Lead are due to the facts that b_0 inversely proportional with the soil cohesion and Lead particles were weaken the bonds between the soil particles (decreasing, K_e). Also, according to equation (4c), b_1 directly proportional with soil cohesion (f_c) so the decreased in b_1 parameter with increasing in the concentration of Lead are due to this directly proportional and because Lead particles were weaken the bonds between the soil particles (decreasing f_c); therefore, b_1 decreased. The mechanistic parameters (b_0 and b_1) explained the physical behavior of empirical parameters of excess shear stress parameters (k_d and τ_c). Previous studies (Al-Madhhachi et al., 2013b, 2014a, 2014b; Daly et al., 2013, 2015) as well as to this study show that the parameter b_0 has same behavior to k_d but with different magnitude and the parameter b_1 has same behavior to τ_c but with different magnitude.
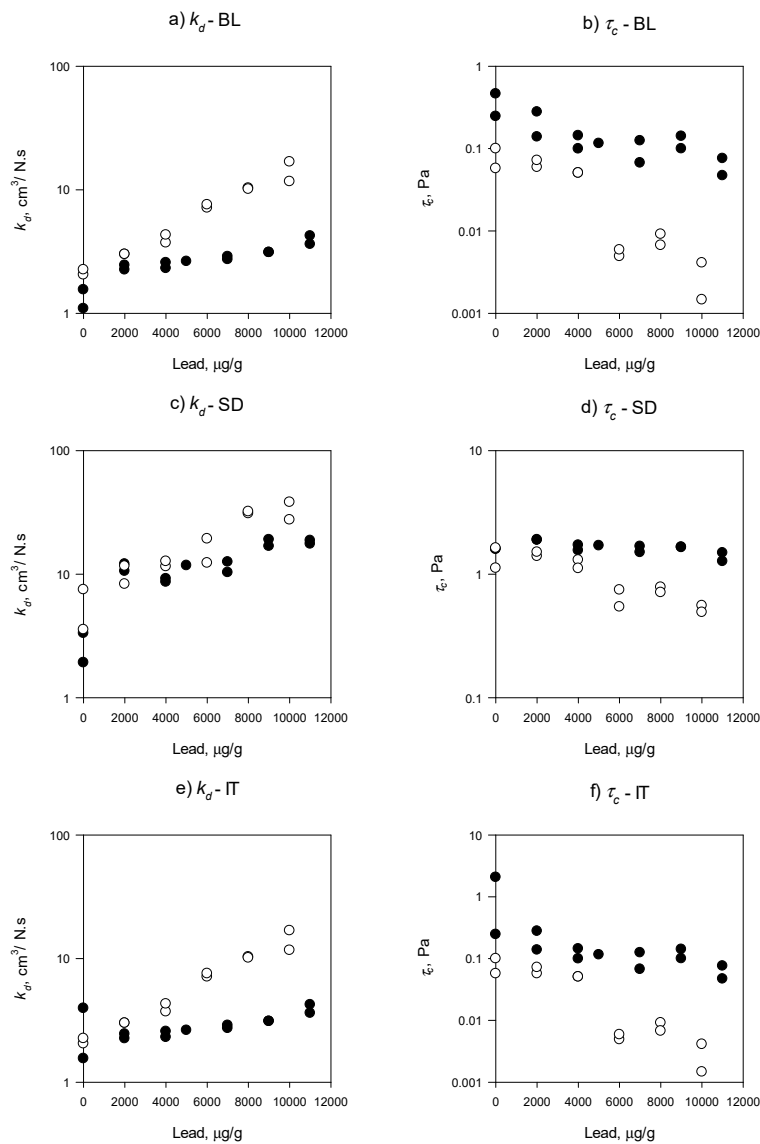

Figure 3. Influence of Lead pollution on excess shear stress parameters for three different techniques: (a) k_d – BL, (b) τ_c – BL, (c) k_d – SD, (d) τ_c – SD, (e) k_d – IT, and (f) τ_c – IT. Note that sold symbols are for 1.7 g/cm^3 bulk density and empty circle symbols are for 1.4 g/cm^3 bulk density
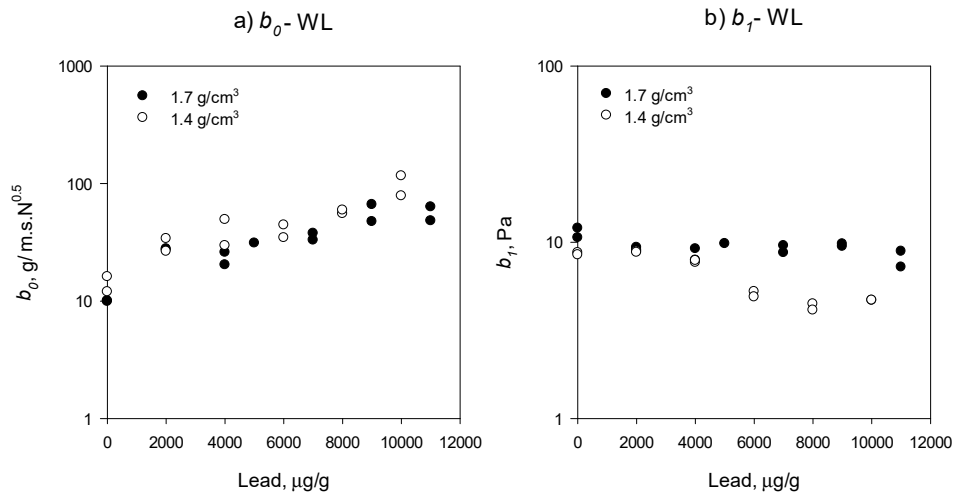
Figure 4. Influence of Lead pollution on Wilson model parameters: (a) b_0 – WL and (b) b_1 – WL. Note that sold symbols are for 1.7 g/cm^3 bulk density and empty circle symbols are for 1.4 g/cm^3 bulk density

3.4 Linear and Non-Linear Models Comparison

A Comparison between the models were performed to evaluate those models depending on the relationship of time versus observed scour depth from the "mini" JET experiments and the predicted scour depth from each model versus time at 1.7 g/cm^3 and 1.4 g/cm^3 bulk densities as shown in Figures 5a and 5b, respectively. Wilson model (WL) and scour depth solution (SD) technique fitted very close to the observed scour depth data. Blaisdell solution (BL) and Iterative solution (IT) techniques were identical and lower than the observed scour depth. That gave an indication that the performance of SD solution and WL were more consistent than BL and IT solution techniques because the Wilson Model (WL) and SD based on same procedure concept to derive the model parameters that based on minimizing the sum of squared differences between the observed and modeled scour depth data.
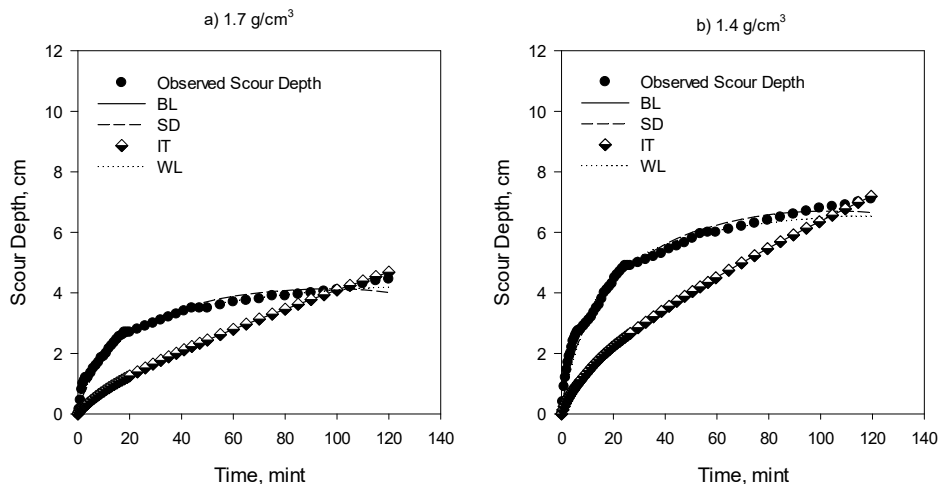

Figure 5. Comparison between the observed and predicted scour depths using excess shear stress model solutions (BL, SD, and IT) and Wilson model (WL) for two different bulk densities: (a) 1.7 g/cm^3 and (b) 1.4 g/cm^3

From the deriving the model parameters of linear model, an inverse relationship between τ_c and k_d was observed from the three techniques: BL, SD, and IT. This inverse relationship for the three linear techniques was compared with the pervious relationships of Hanson and Simon, (2001) and Al-Madhhachi et al., (2013a) (Figure 6). A power law relationship estimated k_d as a function of τ_c with an R^2 of 0.95, 0.50, and 0.78 for the BL, SD and IT solution techniques, respectively: $k_{d-BL} = 1.00\tau_c^{-0.43}$, $k_{d-SD} = 14.44\tau_c^{-0.90}$, and $k_{d-IT} = 1.50\tau_c^{-0.32}$. Similar to

the pervious study of Daly et al. (2015), the relationship between Wilson model parameters b_0 and b_1 was observed in a similar fashion of k_d-τ_c relationship by an inverse power law relationship as shown in Figure 7.
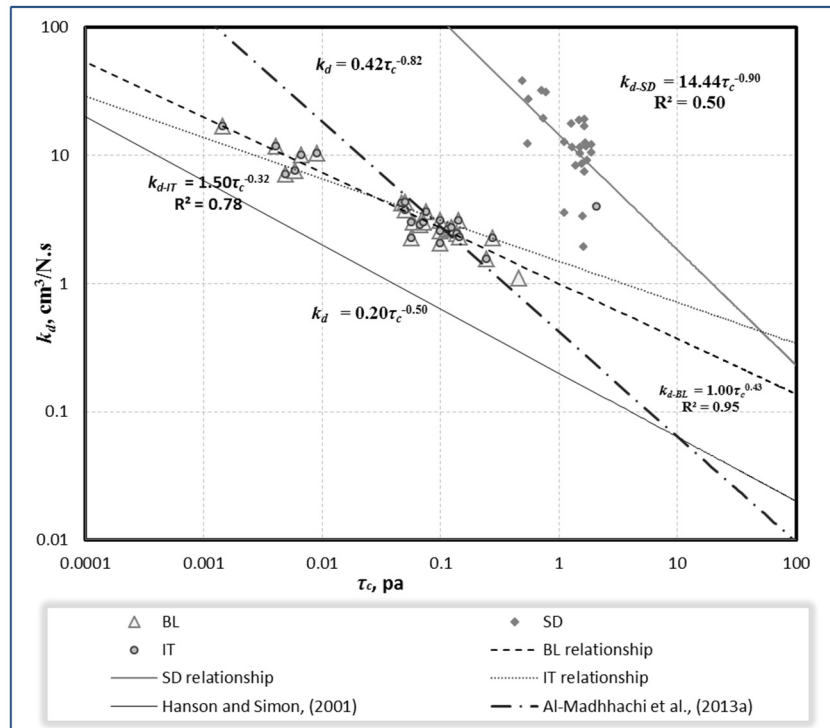

Figure 6. Relationship between k_d and τ_c for BL, SD, and IT solutions of excess shear stress model and comparison with previously proposed relationships by Hanson and Simon (2001) and Al-Madhhachi et al. (2013a)
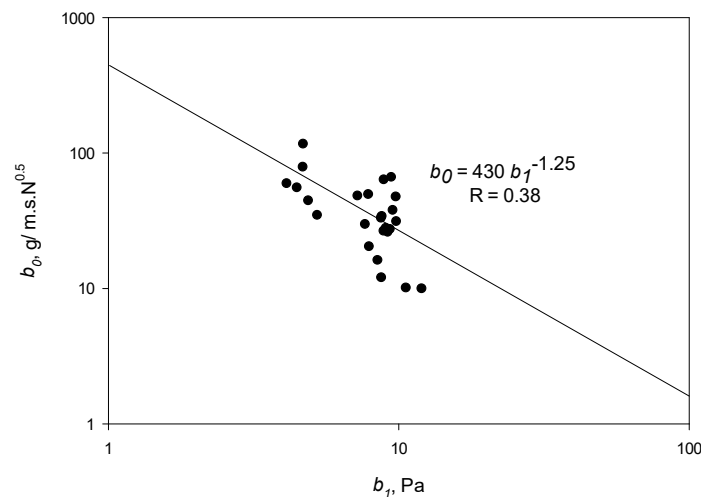

Figure 7. Relationship between Wilson model parameters b_0 and b_1

A relationship of k_d versus b_0 and τ_c versus b_1 for each solution technique were developed in order to investigate the model parameter relationships (Figure 8). When using the parameters derived with BL solution technique, a relationship was observed between b_0 and k_d with $R^2= 0.65$ and between b_1 and τ_c with $R^2= 0.89$ as shown in Figures (8a) and (8b), respectively. For parameters derived with SD solution technique, the b_0-k_d relationship was observed with $R^2=0.87$ and b_1-τ_c relationship with $R^2=0.82$, as shown in Figure (8c) and (8d), respectively. For the parameter derived with IT solution technique, the b_0-k_d relationship was observed with $R^2=0.50$ and b_1-τ_c

relationship with $R^2=0.86$, as shown in Figure (8e) and (8f). Therefore, the mechanistic parameters b_0 and b_1 were resembled empirical parameters k_d and τ_c, for all three solution techniques, but with different magnitudes. Note that the parameters of Wilson model were derived in a similar technique as SD solution technique for the excess shear stress parameters. This is similar to the previous observations by Al-Madhhachi et al. (2013b) and Daley et al. (2015) due to both Wilson model and SD technique based on same solution concept.
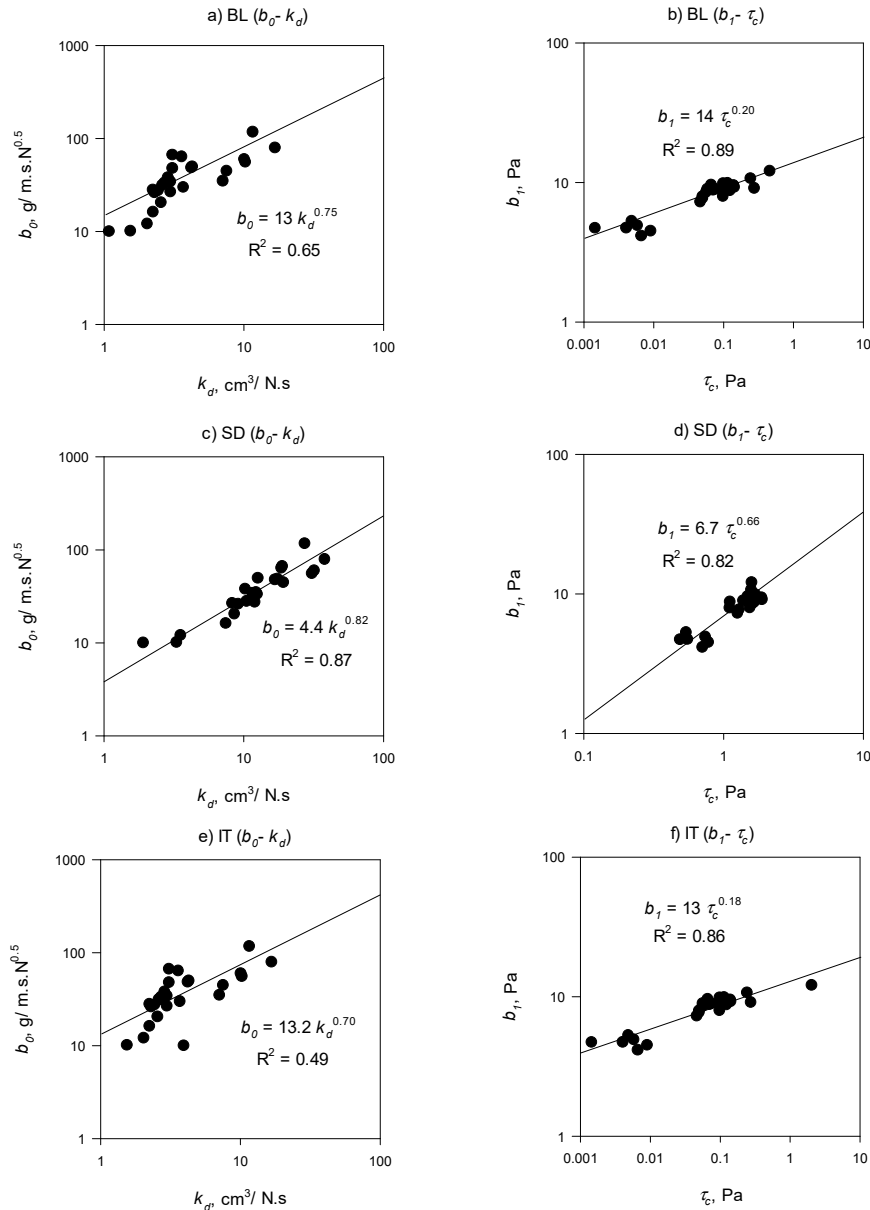

Figure 8. Relationship between Wilson model parameters and excess shear stress parameters for three different techniques: (a) BL ($b_0 - k_d$), (b) BL ($b_1 - \tau_c$), (c) SD ($b_0 - k_d$), (d) SD ($b_1 - \tau_c$), (e) IT ($b_0 - k_d$), and (f) IT ($b_1 - \tau_c$)

4. Summary and Conclusions

Twenty-five tests were performed using "mini" JET device to investigate the influence of Lead pollution on cohesive soil erodibility and compared the analysis results of both excess shear stress (linear model) and Wilson model (nonlinear model). The results showed that the Lead pollution influence significantly on soil erodibility by accelerating the soil scouring as Lead concertation increased. The data of the "mini" JETs were analyzed with the linear model using three techniques (BL, SD, and IT solutions). The erodibility coefficient, k_d, increased when Lead concentration increased while the critical shear stress, τ_c, decreased as Lead concertation increased for all three techniques. The variation in the bulk density had an important role on the soil erodibility and the

Lead pollution had more influence on the soil of 1.4 g/cm^3 bulk density than the soil of 1.7 g/cm^3 bulk density. The Lead concertation had similar effect on Wilson model parameters (b_0 and b_1) as excess shear stress parameters (k_d and τ_c). The Wilson model explained the reason of increasing the erodibility due to increasing in the Lead concentration. The Wilson parameters (b_0 and b_1) depend on the soil properties such as particle shape, density, orientation and soil cohesion. Therefore, the increasing in the concentration of Lead caused to the weakening of the cohesion forces and led to increased b_0 (b_0 inversely proportional with the soil cohesion) and decreasing b_1. Similar to previous studies, inverse relationships of k_d-τ_c as well as to b_0-b_1 were observed which agreed with the previous research observations. The results of comparing excess shear stress model with Wilson model had showed that both b_0 and b_1 have similar behavior relative to Lead contamination to k_d and τ_c, respectively, but with different magnitude. The performance of SD technique and WL model were more consistent than BL and IT solution techniques. The mechanistic parameters (b_0 and b_1) were resembled empirical parameters (k_d and τ_c) for all three solution techniques, but with different magnitudes.

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