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DETERMINATION OF RETARDATION FACTOR AND HYDRODYNAMIC DISPERSION COEFFICIENT OF Ni^{2+} , Zn^{2+} , Cd^{2+} , AND Pb^{2+} IN UNSATURATED ZONE USING INFILTRATION COLUMNS OF UNCONSOLIDATED AND UNDISTURBED SOILS

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Abstract: This paper presents the in-door experimental results of an investigation in determining the retardation factor (R) and hydrodynamic dispersion coefficient (D) of the Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} during the seepage along unsaturated zone using infiltration columns packed with undisturbed soil cores. The lithology of soil in the infiltration columns composed of sand collected in the vicinity of Tien Thanh landfill, Binh Thuan province, clayey sand from Phu Dien commune, Bac Tu Liem district, Hanoi, and clay from Man Xa commune, Yen Phong district, Bac Ninh province. A 0.1 M CaCl_2 solution containing 45 mg L^{-1} of each Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} ion was used to supply the infiltration columns. Continuing flow rates were controlled at 0.55, 0.59, and 0.65 cm min^{-1} for sand, clayey sand, and clay, respectively. The Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} concentrations from the seepage solution were analyzed using inductive couple plasma mass spectrometry (ICP-MS) method. The data obtained were used to build breakthrough curves for each cation. The STANMOD program was used to fit the experimental breakthrough curves with those of a transport model that describes the movement of the ions along the soil columns from which the values of R and D were derived. Results of the investigation revealed that the R values of Ni^{2+} , Zn^{2+} , and Cd^{2+} in all the three soils types vary from 2.8 to 6.5, and the D values in sandy and clayey sand soils vary from 3×10^{-2} to $7 \times 10^{-2} \text{ m}^2/\text{day}$, for clayey soil from Man Xa commune the D values for the three ions were found to be varied from 0.16 to 0.41 m^2/day . The values of R for Pb^{2+} in all the three soil types was found to be from 12 to 18 times and the D was 15 times higher than that for the zinc, nickel and cadmium ions, irrespective of the organic matter content in soils. It was supposed that the goethite in soils could play a role controlling the migration of ion Pb^{2+} . The mechanism of the process could be not only simple adsorption-desorption of Pb^{2+} on the surface soils particles but Pb^{2+} ions can also participate in ion exchange with the active sites of H^+ of the mineral making the adsorption and dispersion of the ion along the soil layers to be low down.

Keywords: Retardation factor; Hydrodynamic dispersion coefficient; Unsaturated zone; Heavy metal ions.

1. INTRODUCTION

Groundwater pollution is currently a major public concern worldwide. Pollution sources are found in dumps containing toxic substances, hazardous waste landfills, domestic waste landfills, and industrial wastewater (Depountis, 2000). Waste that

contains harmful substances threaten human health and the environment. Hazardous chemical migration from the surface into groundwater aquifers through unsaturated zone soil layers has the potential to degrade groundwater quality and harm the ecological environment. This leads to an urgent requirement for the management of polluted lands to ensure groundwater quality for sustainable development. The development of precisely simulating models to forecast the

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movement and dispersion of contaminants infiltrating with water through the soil layer, is a crucial task for the restoration of groundwater pollution areas.

Simulating the hydraulic phenomena in soils is a challenging problem because of the complex structure, heterogeneous soils, and aspects related to the movement of water flow in the soils. Therefore, there are a lot of efforts in research to understand and simplify modeling procedures. For instance, some simplified models describe small scale concepts for physical processes (Bozic et al., 2009; Celia and Boluloutas, 1990; Foo and Hameed, 2009; Gyliene et al., 2009; Javadi et al., 2006; Li et al., 1999; Vomvoris and Gelhar, 1990) or biological effects in the movement of water within the unsaturated zone (Barry et al., 2002; Nezhad and Javadi, 2010; Schäfer et al., 1998). These models characterized the influence of the infiltration flow to the process of pollution movement along with the infiltration flow within the unsaturated soil layer.

Due to the heterogeneous characteristics of the lithology and soil particle size as well as the chemical compositions of the soils, etc., the movement process of pollutants in the soil is one of the biggest challenges in modeling. However, this is a mission that one must, as most possible, realistically describe and evaluate the

uncertainties and potential fluctuations of the hydraulic parameters in soil in order to have the most reliable predictions. The hydraulic parameters in this case are retardation factor (R) and hydrodynamic coefficients (D). The retardation factor characterizes the adsorption-desorption of pollutants on the surface of soil particles that makes the speed of solutes movement along the soil profile to be lower than that of water flow. The hydrodynamic coefficient (D) reflects the dispersion process of pollutants during the infiltration of water along the soil layers. The values of both R and D are the inputs for models used to describe the process of pollution transport along the soil layer with a seepage water flow. Both R and D parameters can be determined experimentally in the laboratory using disturbed and undisturbed soil columns as well as directly in the field with an undisturbed soil layer.

This study aims to determine the R and D values of the seepage process of Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} ions in unsaturated, unconsolidated soil layers using infiltration columns in the laboratory. The data obtained can be used in modelling the process of contaminants transport from a point source presented in several soil types with different mechanical properties.

2. EXPERIMENTAL METHODS

2.1. Equipment and instruments

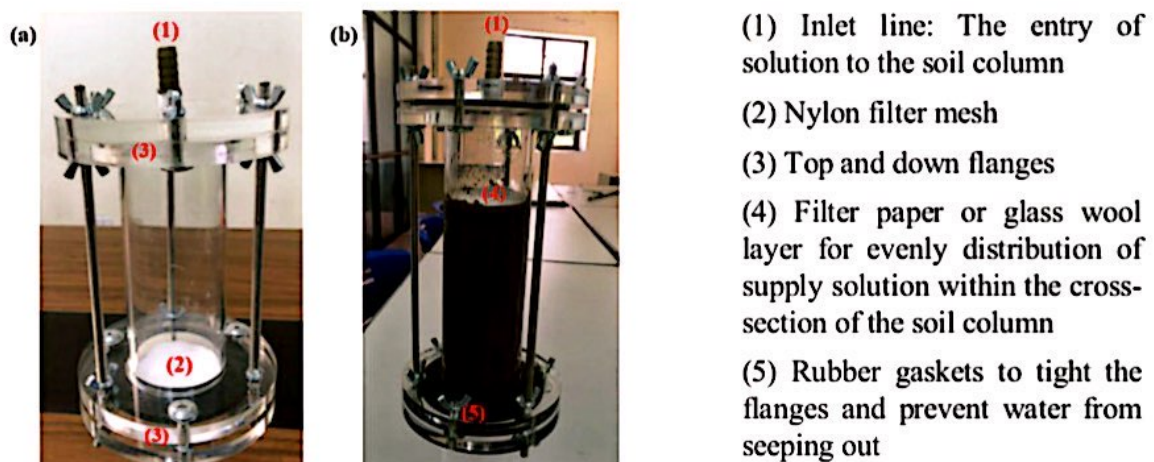
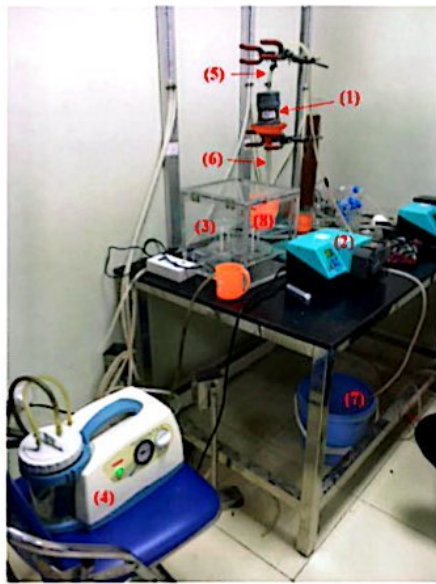


Fig.1: An infiltration column used in this study: (a) an empty column, (b) an infiltration column of undisturbed soil core of a certain height after assembling

An assembly of the infiltration column system and accompanying instruments used in these

experiments are presented in Figs. 1a, b, and Fig. 2.



- (1) Infiltration column packed with an undisturbed clay soil core
- (2) Peristaltic pump to supply permeable flow
- (3) Vacuum chamber for accommodation of a cup for collecting infiltrated solution samples (This part is used only case of clay and clayey sand soils)
- (4) Vacuum pump
- (5) Inlet line
- (6) Outlet line
- (7) Container with recharge infiltration solution
- (8) A cup for collecting infiltrated solution samples

Fig. 2: An assembly of a infiltration column system for determining R and D parameters (e.g., for clay soil collected in Man Xa commune, Yen Phong district, Bac Ninh province)

Three different types of subsurface soil were used for these experiments. The first type, clayey sand soil, was gathered at Phu Minh commune, Phu Dien ward, Hanoi. The second type is clay soil collected in Man Xa commune, Yen Phong district, Bac Ninh province. The third soil

column is sand that was taken in the vicinity of the Tien Thanh landfill, Binh Thuan province. The heights of the infiltration columns for sandy, clayey sandy, and clay soils were 35, 15, and 10 cm, respectively. Several physical parameters of these three soil types are presented in Table 1.

Table 1: Some physical characteristics of three different soil types used in this study

Physical parameters of soils	Sand ^(a)	Clay ^(a)	Clayey sand ^(b)
Bulk density, ρ_B (g/cm ³)	1.51	1.74	1.68
Particle density, ρ_P (g/cm ³)	2.64	2.44	2.35
Soil porosity, θ	0.43	0.355	0.285
Humidity, %	6.0	26.5	15.6
pH _{KCl}	6.5	5.3	5.9
Mechanical composition: sand:mud:limon (%)	95.2:4.8: < 0.05	28.0:33.2:38.8	-
Organic matter content, %	0.3±0.1	3.0±0.5	2.3±0.3

Data provided by (a) Center of Analysis, CODECO Company; (b) Section of Isotope Hydrology, INST; and (-) not analysis

Nickel chloride (NiCl₂), cadmium nitrate (Cd(NO₃)), zinc chloride (ZnCl₂), and lead acetate (Pb(CH₃COO)₂) (PA grade, Merck, Germany) were used in this study. The infiltration solution

containing Ni²⁺, Zn²⁺, Cd²⁺, and Pb²⁺ ions with initial concentrations of 45 mg/L each was prepared in 0.1 M CaCl₂ solution, a solution of an ionic strength equivalent to soil water

(ASTM, 2016). Water used for preparing the solution was distilled. The experiment was conducted following the sequences.

Through the inlet line ((5) Fig. 2), the peristaltic pump ((2), Fig. 2) delivers the solution containing metal ions from the container ((7) Fig. 2) to the infiltration column (Fig. 2). The velocities of seepage flow were maintained at 0.55, 0.59, and 0.65 cm min⁻¹ for clay (from Man Xa), clayey sand (from Phu Minh), and sand (from Tien Thanh), respectively. The soil cores in the columns were subsurface and undisturbed with heights of 10, 15 and 35 cm, respectively, and the internal diameter (ID) is 5 cm.

A vacuum was established by the vacuum pump ((4) Fig. 2) at the bottom of the clay and clayey sand infiltration column systems to achieve the desired flow rate (Fig. 2); however, a vacuum is not applied for the sand soil column. The samples of seepage solution were collected into the collecting cup ((8) Fig. 2) accommodated in the vacuum chamber ((3) Fig. 2) at a time interval of 20-minute each. The collected samples were then subject to the analysis for concentrations of metal ions at time t (C_t) using inductively coupled plasma mass spectrometry (ICP-MS, Switzerland) of the Institute of Nuclear Science and Technology (INST). The limit of detection (LOD) of the equipment was certified by the equipment supplier to be as low as 1 ppb (1 μ g/L). The precision of the results was determined by triplicate analysis of the same sample and it was as good as $\pm 5\%$. The accuracy of the results was proven by the analysis of the respective standard solutions supplied by the ICP MS equipment supplier. The deviation of results derived by the INST Lab compared with the certified values of concentration of respective constituents was not higher $\pm 7\%$.

2.2. Data processing, D and R calculation

The breakthrough curve of individual metal ions was obtained based on the relationship between the relative concentration (c_e) and the relative void volume of the infiltration column (T). The c_e and T were determined by the formulas (1) and (2):

$$c_e = C_t/C_0 \quad (1)$$

where C_t and C_0 are the concentration of individual ions in seepage solution from the column at time t and the initial time ($t = 0$), respectively.

$$T = \vartheta \times \frac{t}{L} \quad (2)$$

where ϑ is the seepage velocity, cm min⁻¹; t is the seepage time, minute; and L is the height of the infiltration column, cm.

In practice, the transport of substances within the infiltration column is a complex process due to the sizes of soil pores not being identical. There are macropores and micropores that make the front of the seepage flow to be not even. This phenomena is called as disequilibrium transport, meaning that the flow can exist in macropores as mobile phase and in micropores as in immobile phase (van Genuchten & Wierenga, 1976; Brusseau & Rao, 1990; Ray, et al., 1997; Schwartz, Juo, & McInnes, 2000; Lamy, Lassabatere, Bechet, & Andrieu, 2009). In this case the general CDE (Convective-Dispersive Equation) is well applicable for the solute transport with mobile phase, but dispersive equation is better applied for the transport with immobile phase (van Genuchten and Wierenga, 1976). With the concept of disequilibrium transport van Genuchten (1981) has improved the CDE to as follows (Eq. 3).

$$\beta R \frac{\partial C_1}{\partial t} + (1 - \beta) R \frac{\partial C_2}{\partial t} = \frac{1}{Pe} \frac{\partial^2 C_1}{\partial x^2} - \frac{\partial C_2}{\partial x} \quad (3)$$

where C_1 and C_2 are the concentrations of substances in the mobile and in the immobile phases, respectively; R is retardation factor and Pe is the Peclet number.

The solution of the Eq. (3) with initial and final boundary conditions $C(0, t) = C_0$, and $\frac{\partial C}{\partial x}(L, t) = 0$, respectively, like this study, was given as follows (van Genuchten, 1981):

$$c_e = G(T) \exp\left(-\frac{\omega T}{\beta R}\right) + \frac{\omega}{R} \int_0^T G(\tau) H(T, \tau) d\tau \quad (4)$$

The detailed description of β , ω symbols, function $G(T)$ in Eq. (4) can be found in the literature (Genuchten, 1981).

The function $G(\tau)$ of Eq. (4) is expressed in the form:

$$G(\tau) = \frac{1}{2} \operatorname{erfc}\left[\left(\frac{Pe}{4\beta R\tau}\right)^{1/2}(\beta R - \tau)\right] + \frac{1}{2} \exp(Pe) \operatorname{erfc}\left[\left(\frac{Pe}{4\beta R\tau}\right)^{1/2}(\beta R - \tau)\right] \quad (5)$$

Where erfc is error function.

Genuchten's group has developed the STANMOD computer program for fitting experimental points of the breakthrough curve, i.e. c_e vs. T , with theoretical function (Eq. 4) by adjusting the R and Pe values in expression (4). The iteration will be interrupted when the square root of the total error between the experimental data and the fitted data is minimal. These values of R and Pe are considered to be reality for the experimental conditions. With the known Pe value, the hydrodynamic dispersion coefficient (D) can be calculated using formula (6):

$$D = \vartheta \times \frac{L}{Pe} \quad (6)$$

3. RESULTS

3.1. Concentration breakthrough curves of Ni^{2+} , Zn^{2+} , Cd^{2+} and Pb^{2+} from the infiltrating columns with sandy soil from Tien Thanh landfill

Figure 3 a, b, c and d depicts the concentration breakthrough curves for Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} that were experimentally obtained in case of the use of sandy soil from Tien Thanh landfill, Binh Thuan province. In Fig. 3 the values of concentrations of respective ions were expressed in the c_e (Eq. 1) and the time was in the times of the void volumes of soil T that were replaced by the seepage flow (Eq. 2)

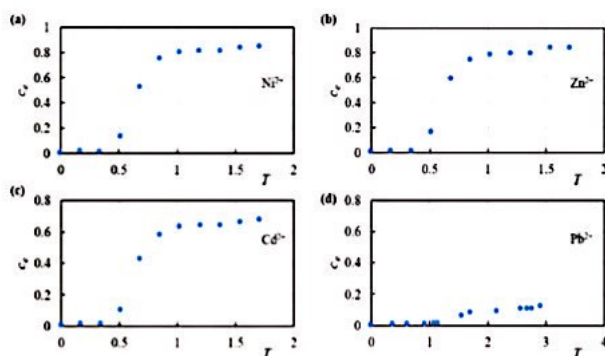


Fig. 3: Relative concentration breakthrough curve (c_e) (Eq. (1)) versus the relative void volumes of soil (T) (Eq. (2)). (a): Ni^{2+} , (b): Zn^{2+} , (c): Cd^{2+} , and (d): Pb^{2+}

To derive the values of R and D of the transport of ions, the model (Eq. 4) was used to fit the experimental data of c_e vs. T under disequilibrium conditions. The fitted curves were depicted by solid lines in Fig. 4a, b, c, and d for Ni^{2+} , Zn^{2+} , Cd^{2+} and Pb^{2+} , respectively.

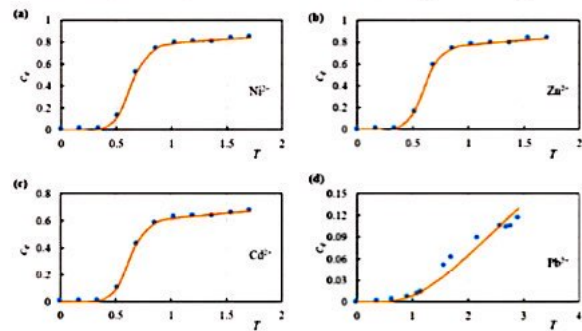


Fig. 4: Fitting concentration breakthrough curves (solid orange colour lines) with experimental data (blue points) of (a) Ni^{2+} , (b) Zn^{2+} , (c) Cd^{2+} , and (d) Pb^{2+} ion concentrations

3.2. Concentration breakthrough curves of Ni^{2+} , Zn^{2+} , Cd^{2+} and Pb^{2+} from the infiltrating columns with clayey soil from Man Xa commune

The experimental data obtained in case of the use of infiltration column with clayey soil from Man Xa commune and the fitting lines of c_e with T for Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} ions are presented in Fig. 5.

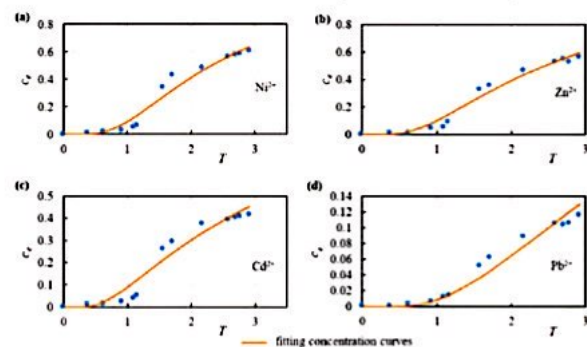


Fig. 5: Relative concentration (c_e) of (a) Ni^{2+} , (b) Zn^{2+} , (c) Cd^{2+} , and (d) Pb^{2+} ions in the seepage solution vs. the relative porosity (T) from clayey soil column and the fitting concentration curves of the experimental data

The similar approach of the experiment was applied for the clayey sand soil column. It was revealed that the equilibrium state in this case was reached when the T value is 2.3, which is in between the T values of Tien Thanh sandy soil (1.5) and Man Xa clay soil (3.0). The graphs describing the dependence between c_e and T for the sandy clay soil from Phu Minh field are not presented here.

3.3. The values of R and D derived for the three soil types

Following the STANMOD execution, the R and Pe values from expression (4) that match the experimental ce value are presented in Table 2. Based on the Pe value, the D values are calculated according to formula (6), with the height of the infiltration column and the infiltration rate presented above.

Table 2: R , Pe , and D values obtained for Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} in this study

Ions	sand, in Tien Thanh, Binh Thuan				clayey sand, in Phu Minh, Bac Tu Liem, Hanoi				clay, in Man Xa, Yen Phong, Bac Ninh			
	R	Pe	θ cm/min	D , m ² /day	R	Pe	θ cm/min	D , m ² /day	R	Pe	θ cm/min	D , m ² /day
Ni^{2+}	2.82	49	0.65	$6.72 \cdot 10^{-2}$	3.15	44	0.59	$2.88 \cdot 10^{-2}$	2.86	4.07	0.55	0.157
Zn^{2+}	5.64	56	0.65	$5.89 \cdot 10^{-2}$	3.67	49	0.59	$2.58 \cdot 10^{-2}$	3.20	3.11	0.55	0.205
Cd^{2+}	6.51	53	0.65	$6.28 \cdot 10^{-2}$	3.16	44	0.59	$2.88 \cdot 10^{-2}$	5.27	1.54	0.55	0.414
Pb^{2+}	35.40	22	0.65	$14.85 \cdot 10^{-2}$	5.26	20	0.59	$6.38 \cdot 10^{-2}$	55.00	0.26	0.55	2.450

4. DISCUSSION

The breakthrough concentration curves show that the migration process of Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} ions through the sandy soil and clay soil columns is under an disequilibrium model (Figs. 3, 4, and 5). This implies that several types of pores exist in the soil columns, such as macropores, dual-pores, and micropores. As a result, it creates an immobile phase in the microscopic pores, and a mobile phase in the macroscopic pores of the soils. It is seen that the ion concentrations in the seepage water samples have a delay time from 0.4 to 1 compared to the T values for sand and clay, respectively, and are the inflection points of the cumulative concentration curves (Figs. 3, 4, and 5). Moreover, the results of fitting experimental data with two types of disequilibrium and equilibrium models indicate that the transport process of the studied metal ions also follows the disequilibrium transport model. It was found that the results of fitting experimental data using the equilibrium model give the value of the mean root square deviation difference between theoretical c_e and experimental c_e be larger than a thousand times compared to those

in the case of fitting by the disequilibrium model with the same R and D values.

De Godoy et al. (2017) also used an infiltration column and a disequilibrium displacement model to determine the hydrodynamic dispersion coefficient of Na^+ ions in sandy soil taken from Cabrália Paulista city, Sao Paulo state, in Brazil. Based on the Pe number obtained by fitting experimental data of an infiltration experiment of $NaCl$ solution through a sand column with an inner diameter of 1 cm and a height of 15 cm, this study determined the hydrodynamic dispersion coefficient (D) of $0.002 \text{ m}^2/\text{s}$ (approximately $1.728 \times 10^2 \text{ m}^2/\text{day}$).

Le and Weysure (2019) designed a sand tank with an electrical conductivity (EC) measurement system to experimentally determine the hydrodynamic dispersion coefficient for three types: coarse, medium, and fine sand soils taken from the Mekong River with a grain size $> 60 \text{ mm}$ of 77.3%, 44.4%, and 29.9%, respectively. The KCl solution was used as an indicator for this experiment to determine the EC parameter. The Convective-Dispersive Equation (CDE) equation with an expression of $R \cdot \frac{\partial c}{\partial t} = D \cdot \frac{\partial^2 c}{\partial x^2} - \theta \cdot \frac{\partial c}{\partial x}$ was applied for this

study. The results of this study showed that the D values of $0.523 \text{ m}^2/\text{day}$ were obtained for the coarse sand with a flow rate of $0.465 \text{ cm min}^{-1}$ and that values were $0.016 \text{ m}^2 \text{ day}^{-1}$ and $0.128 \text{ m}^2 \text{ day}^{-1}$ for the medium and fine sand at a flow rate of $0.222 \text{ cm min}^{-1}$ for the medium sand and $0.342 \text{ cm min}^{-1}$ for the fine sand (Le and Weysure, 2019).

Until now, the hydrodynamic dispersion coefficient of the transport process of heavy metal ions in soils, especially in undisturbed soil columns, has not been much studied yet. There were few experiment data on sandy soil with the Na^+ indicator from NaCl or K^+ indicator from KCl in which Na^+ and K^+ ions have very different adsorption properties than those of ions with higher valence, such as Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} . Therefore, this study did not get the data on the D coefficient of heavy metals in clay, and clayey sand soils for comparison. However, the D coefficient of sandy soil for Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} ions found in this study (Table 2) is 2-3 times higher than those found for K^+ ions of sandy soils from Le and Weysure (2019). This proves a fact that the D value depends not only on the type of soil but also on the type of ions moving with the permeate flow.

The obtained results show that the D coefficient of Pb^{2+} from sandy soil in Binh Thuan and clayey sandy soil in Bac Tu Liem is more than 2 times higher than the D coefficient of Ni^{2+} , Zn^{2+} , and Cd^{2+} ions (in Table 2). In the clay column (Man Xa), the D coefficient of Pb^{2+} is 16, 12, and 6 times higher than those of Ni^{2+} , Zn^{2+} , and Cd^{2+} , respectively. Moreover, results also show that there is a weak correlation observed between the D value of the studied ions and the organic content in the soil ($R^2 < 0.1$). This proves a fact that the D value of heavy metals does not depend much on the organic content in the soil, but it might depend mainly on the mineral composition of the soil. For example, in a research of Pb^{2+} adsorption on several different soil types in Brazil, Gomes (2001) shows that goethite (FeOOH) and soil pH are

the two important factors affecting the adsorption capacity of Pb^{2+} in soil. On the other hand, adsorption is also a factor that affects the dispersion of materials in soil. The adsorption results of Ni^{2+} , Zn^{2+} , Cd^{2+} , and Pb^{2+} ions in sandy soil in Tan Thanh (Binh Thuan province), in clayey sand in Phu Minh (Bac Tu Liem district) and clay soil in Man Xa (Bac Ninh province) also showed that among four metal ions studied, Pb^{2+} ion has the highest adsorption capacity (Dang et al., 2024). It was thought that beside the traditional electrostatic adsorption mechanism, ion Pb^{2+} appeared to be able to participate in the ion exchange process with H^+ group on the goethite. The ion exchange between Pb^{2+} and H^+ in FeOOH increases the retardation coefficient of Pb^{2+} in soil and increases the D coefficient. The average R -value of Pb^{2+} in the subsurface soil (0-30 cm) in Man Xa determined by the adsorption method is 14 that is 3 to 7 times higher than other ions. In this study the R -value of Pb^{2+} in the Man Xa clay column is 55, which is 10 to 18 times higher than those of Cd^{2+} , Zn^{2+} , and Ni^{2+} ions (Table 2). The difference in the R -value of Pb^{2+} in the same soil derived from the two studies is due to the distinct conditions of the two experiments. In this study, the adsorption has not reached equilibrium yet compared to that in the Dang et al. (2024). However, the values of R and D of Pb^{2+} in the three studied soils obtained from the two studies are the same trend that they are higher than the R and D values of Ni^{2+} , Zn^{2+} , and Cd^{2+} ions.

5. CONCLUSION

The experimental results of this study indicated that the retardation factor and hydrodynamic dispersion coefficients of Zn^{2+} , Ni^{2+} , Cd^{2+} , and Pb^{2+} ions are distinct for different soil types. There is not much difference between the R and D values of the three ions Zn^{2+} , Ni^{2+} , and Cd^{2+} in the same type of soil. However, the R and D values of Pb^{2+} in the same soil are higher from 1.5 to 17 times and 2 to 8

times, respectively, than those of the Ni^{2+} , Zn^{2+} , and Cd^{2+} ions, and these R and D values regardless of organic content in the soil. Mineral composition in soil, especially goethite, might be a factor influencing R and D values of Pb^{2+} ion in permeating flow. This is an issue that needs further research.

Acknowledgments

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REFERENCES

- [1] ASTM (2016). Standard Test Method for 24-h Batch-Type Measurement of Contaminant Sorption by Soils and Sediments, ASTM International, West Conshohocken, PA, 2016, www.astm.org. Accessed in September 2023
- [2] Barry D.A., Prommer H., Miller C.T., Engesgaard P., Brun A., Zheng C., (2002). Modeling of the fate of oxidizable organic contaminants in groundwater. *Advances in Water Resources* 25:945–983
- [3] Bozic D., Stankovic V., Gorgievski M., Bogdanovic G., Kovacevic R., (2009). Adsorption of heavy metal ions by sawdust of deciduous trees. *J. Hazardous Materials* 171:684–692
- [4] Celia M.A., Boluloutas E.T., (1990). A general mass-conservative numerical solution for the unsaturated flow equation. *Water Resources Research* 26:1483–1496
- [5] de Godoy V.A., Napa-García G.F., Zuquette L.V., (2017). Hydrodynamic dispersion of sodium by equilibrium and nonequilibrium methods through undisturbed sandy soil columns from the Adamantina Formation. *Acta Scientiarum. Technology*, 41: e35419. Doi: 10.4025/actascitechnol.v41i1.35419
- [6] Dang D.N., Vu T.H., Mai D.K., Nguyen V.K., Nguyen V.L., Tran V.L., Dao D. B., (2024). A batch Experiment for determining retardation factors of Ni, Zn, Cd, and Pb in an unsaturated zone of unconsolidated soil layers in Man Xa and Chau Khe communes, Bac Ninh province. *J. Mining and Earth Sci.*, DOI: 10.46326/JMES.202x.xyz
- [7] Depountis N., (2000). Geotechnical centrifuge modeling of capillary phenomena and contaminant migration in unsaturated soils. Ph.D. Dissertation, University of Cardiff, U.K., 2000.
- [8] Foo K.Y., Hameed B.H., (2009). An overview of landfill leachate treatment via activated carbon adsorption Process. *J. Hazardous Materials* 171:54–60. Freeze R. A., and Cherry J. A., 1979. *Groundwater*. Prentice Hall, Englewood Cliffs, NJ, 1979.
- [9] Gomes P.C., Fontes M.P.F, da Silva A.G., de S. Mendonça E, Netto A.R. (2001). Selectivity Sequence and Competitive Adsorption of Heavy Metals by Brazilian Soils. *Soil Sci Soc Am J.*, 65(4):1115–21. <https://doi.org/10.2136/sssaj2001.6541115x>
- [10] Gyliene O., Binkiene R., Butkiene R., (2009). Sorption of Cu(II) complexes with ligands tartrate, glycine and quadrol by chitosan. *J. Hazardous Materials* 171:133–139.
- [11] Javadi A.A., AL-Najjar M.M., Elkassas A.S.I., (2006). Numerical modeling of contaminant transport in unsaturated soil. *Proceeding of the 5th International Congress on Environmental Geotechnics*, Cardiff, U.K., pp.1177–1184.

- [12] Le A.T., Guido Wyseure, (2019). Using a physical model to determine the hydrodynamic dispersion coefficient of a solution through a horizontal sand column. VN J. Sci. Techol. Eng. 61: 14-22. Doi: 10.31276/VJSTE.61(1). 14-22
- [13] Li X., Cescotto S., Thomas H.R., (1999). Finite element method for contaminant transport in unsaturated soils. J. Hydrology Engineering 4:265–274
- [14] Nezhad M.M., Javadi A.A., (2010). Numerical Modelling of Contaminant Transport in Soils Including the Effect of Chemical Reactions. In modelling of Pollutants in Complex Environmental Systems, Hanrahan G (ed.). Volume II, ILM Publications: UK, pp. 311–335
- [15] Schäfer D., Schäfer W., Kinzelbach W., (1998). Simulation of reactive processes related to biodegradation in aquifers 1. Structure of the three-dimensional reactive transport model. J. Contaminant Hydrology 31:167–186.
- [16] van Genuchten M.Th., (1981). *Non-equilibrium transport parameters from miscible displacement experiments* (Research report no. 119). Riverside, CA: Salinity Laboratory, USDA, ARS.
- [17] Vomvoris E.G., Gelhar L.W., (1990). Stochastic analysis of the concentration variability in a three-dimensional heterogeneous aquifer. Water Resources Research 26:2591-2602.