DOI: 10.2428/ecea.2012.19(07)078 ECOL CHEM ENG A. 2012;19(7):787-794

Iwona DESKA[1] and Anna TKACZYŃSKA[1]

EMPIRICAL MODEL FOR ESTIMATING THE ACTUAL LNAPL THICKNESS BASED ON THE HYDRAULIC CONDUCTIVITY

MODEL EMPIRYCZNY DO WYZNACZANIA RZECZYWISTEJ MIĄŻSZOŚCI LNAPL KORZYSTAJĄCY ZE WSPÓŁCZYNNIKA FILTRACJI

Abstract: The actual thickness of lighter-than-water non-aqueous phase liquid (LNAPL) on the groundwater table is always different from the apparent thickness (measured in the monitoring well). There are several methods developed for estimating the actual LNAPL thickness on the base of the apparent thickness, but the results obtained with different formulas are inconsistent and (in many cases) very imprecise. The obtained results of laboratory investigations indicate that the appropriate model for estimating the actual thickness of light non-aqueous phase liquid should include the properties of soil and LNAPL. The investigations confirmed that the hydraulic conductivity is very important parameter in the case of homogeneous soils.

On the base of the results the empirical model was developed. This model includes the hydraulic conductivity of soil and the density and dynamical viscosity of LNAPL. The results of the verification of developed model indicate that the calculated values corresponded in many cases with the values obtained during laboratory investigations.

Keywords: LNAPL, actual thickness, apparent thickness, hydraulic conductivity, empirical model

The main sources of soil and groundwater contamination with *lighter-than-water non-aqueous phase liquids* (LNAPL) are surface spills from cisterns and leakages from underground storage tanks and pipelines. If the layer of LNAPL floats on the groundwater table the initial remediation step should be its recovery [1–3]. A proper design of recovery requires an assessment of the contamination plume volume on the base of the LNAPL thickness measured in specified points of the contaminated area [1]. Unfortunately, the thickness of LNAPL on the groundwater table (the actual thickness) is different from the thickness observed in the well (the apparent thickness) [4–6] and this difference depends on the properties of soil, and the properties and amounts of the free product floating on the groundwater table [7–9]. The results obtained with different

[1] Institute of Environmental Engineering, Czestochowa University of Technology, ul. Brzeźnicka 60A, 42–200 Częstochowa, Poland, phone: +48 34 325 09 17, email: ideska@is.pcz.czest.pl

formulas for estimating the actual thickness are inconsistent, and in many cases inaccurate [4, 5, 10, 11]. The results of laboratory investigations indicate that the appropriate model for estimating the actual LNAPL thickness should include the properties of both: soil and LNAPL [7, 10].

This paper presents the developed empirical model for estimating the actual LNAPL thickness on the groundwater table. The model is based on the properties of soil (hydraulic conductivity) and properties of LNAPL (dynamical viscosity).

Materials and methods

Laboratory experiments were conducted in Plexiglas columns with filter-tubes as monitoring wells (Fig. 1) with use of six model soils and six types of LNAPL. The properties of soils and LNAPLs are given in Tables 1 and 2.

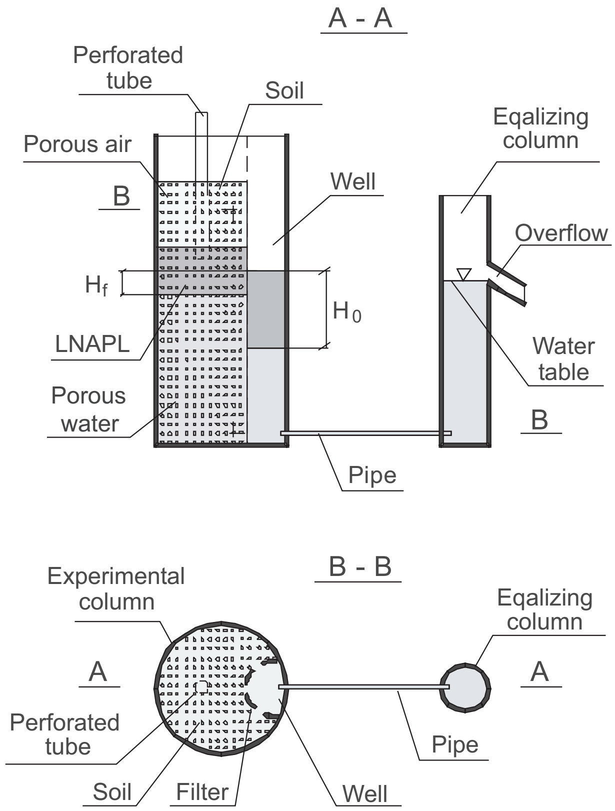

Fig. 1. The experimental columns with filter-tubes connected with equalizing columns

The experimental columns were packed with the soil samples (soils 1–6) and filled with tap water until the water table reached the assumed elevation. After 3–4 days 50 cm^3

Table 1

Properties of soils used in the experiments

Soil	Type of soil	Soil grain size [mm]	Medium soil grain size [mm]	Hydraulic conductivity at 10 ^{o}C k [m/d]
1	fine sand	0.1–0.25	0.175	$1.0 \cdot 10^1$
2	medium sand	0.25–0.315	0.2825	$2.3 \cdot 10^1$
3	medium sand	0.315–0.5	0.4075	$7.1 \cdot 10^1$
4	coarse sand	0.5–0.63	0.565	$1.1 \cdot 10^2$
5	coarse sand	0.63–0.8	0.715	$1.5 \cdot 10^2$
6	coarse sand	0.8–1.0	0.9	$2.3 \cdot 10^2$

Table 2

Properties of LNAPLs used in the experiments (at temperature of 20 ^{o}C)

LNAPL	Notation	Type of LNAPL	Density ρ_o [kg/m^3]	Dynamic viscosity η_o [kg/m · s]
LNAPL 1	L1	Petroleum	820	$1.8 \cdot 10^{-3}$
LNAPL 2	L2	Rape oil	918	0.072
LNAPL 3	L3	Mineral oil "Lotos"	880	0.30
LNAPL 4	L4	Semi-synthetic oil "Orlen"	872	0.22
LNAPL 5	L5	Synthetic oil "Lotos"	855	0.18
LNAPL 6	L6	Synthetic oil "Orlen"	871	0.19

of diverse LNAPLs, coloured with the pigment – Sudan III, were injected above the capillary fringe zone. After subsequent 3–4 days, the apparent and actual LNAPL thicknesses were measured in the well and in soil. This procedure was repeated at least 10 times. The actual thickness was the distance between LNAPL-water interface in the soil and air-LNAPL interface in the well (without the capillary fringe of LNAPL in the soil). The columns were hydraulically connected with equalizing columns which aim was to keep the water table constant during experiments. The styropore covers protected the top of columns.

Results and discussion

On the base of the experiments for each composition of soil and LNAPL the graphs and trend lines were plotted which present the relationships between apparent and actual thickness [9]. Results and high values of the determination coefficients (R^2) for linear functions show that these relationships have the linear character. Then were fixed the values of apparent thicknesses corresponding to the actual thicknesses of 5, 10 and 15 cm (for each composition of soil and LNAPL). On the base of these results the graphs were plotted which show the influence of the hydraulic conductivity of soil in 10 °C (k) on the difference between apparent and actual thicknesses ($\Delta H = H_0 - H_f$) for three selected actual thicknesses: 5, 10 and 15 cm (Fig. 2). The results indicate that the difference between apparent and actual thicknesses increases with the decrease of the hydraulic conductivity of soil. This relationship has the logarithmic character. It can be confirmed by high values of the determination coefficients derived for logarithmic functions. These high values suggest the functional relationship.

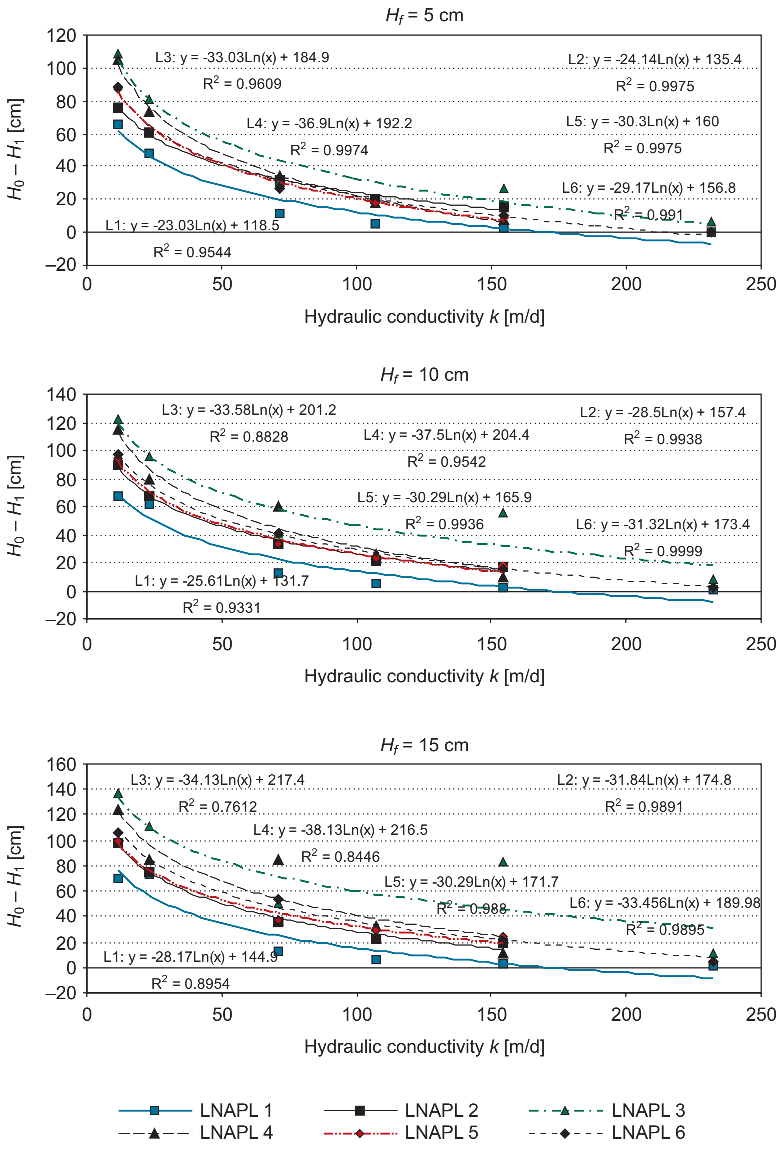

Fig. 2. The influence of the hydraulic conductivity on the difference between apparent and actual thickness

On the base of the results presented in the Fig. 2 the empirical model was developed that describes the relationship between apparent and actual LNAPL thicknesses (Equation 1). Model is based on the hydraulic conductivity and the dynamic viscosity of LNAPL. The actual LNAPL thickness can be derived from equation:

$$H_f = H_0 - (\omega\eta_o + \varphi)\ln k - \chi\eta_o - \xi \tag{1}$$

where: H_f – actual LNAPL thickness [cm],
H_0 – apparent LNAPL thickness [cm],
k – hydraulic conductivity in 10 °C [m/d],
η_o – dynamic viscosity of LNAPL [kg · m^{-1} · s^{-1}],
ω, φ, χ and ξ – factors depending on actual LNAPL thickness [-].

Factors ω, φ, χ and ξ can be calculated from the equations 2–5:

$$\omega = 1.989 H_{fe} - 52.006 \tag{2}$$

$$\varphi = -0.6445 H_{fe} - 19.457 \tag{3}$$

$$\chi = -0.878 H_{fe} + 247.29 \tag{4}$$

$$\xi = 2.932 H_{fe} + 104.29 \tag{5}$$

where: H_{fe} – initial estimated actual LNAPL thickness [cm].

Use of proposed model requires initial estimation of actual thickness (H_{fe}) to determine the proper values of factors ω, φ, χ and ξ. The calculation should be repeated until the calculated actual thickness is equal to the initial estimated value.

Figure 3 presents the verification of the model. The relationships between apparent and actual thicknesses obtained from the model (the curves) were compared with the experimental data (point graphs). The results indicate that the values calculated from the developed model corresponded in many cases to the experimental data. In the case of soil 1 the best results were obtained for LNAPLs 1, 2 and 6. In the case of soil 2 the model curves are similar to the experimental graphs for all LNAPLs. The best fits are also reached for the compositions: soil 3 – LNAPL 4; soil 4 – LNAPLs 2, 4, 5; soil 5 – LNAPLs 1, 5, 6 and for soil 6 – LNAPL 6. Only for a few compositions of soils and LNAPLs the results derived from the developed model differ from the experimental data. The most unfavorable results were obtained for the compositions: LNAPL 1 – soils 3, 4, 6 and LNAPL 4 – soil 5. The relationships between apparent and actual thicknesses drawn on the base of the proposed model have the linear character. Further studies aimed at the improvement of the model should include the check of the importance of the hydraulic conductivity in the case of the heterogeneous soils. The experiments should also include the examination of the influence of other parameters *eg* the equivalent diameter and the coefficient of uniformity.

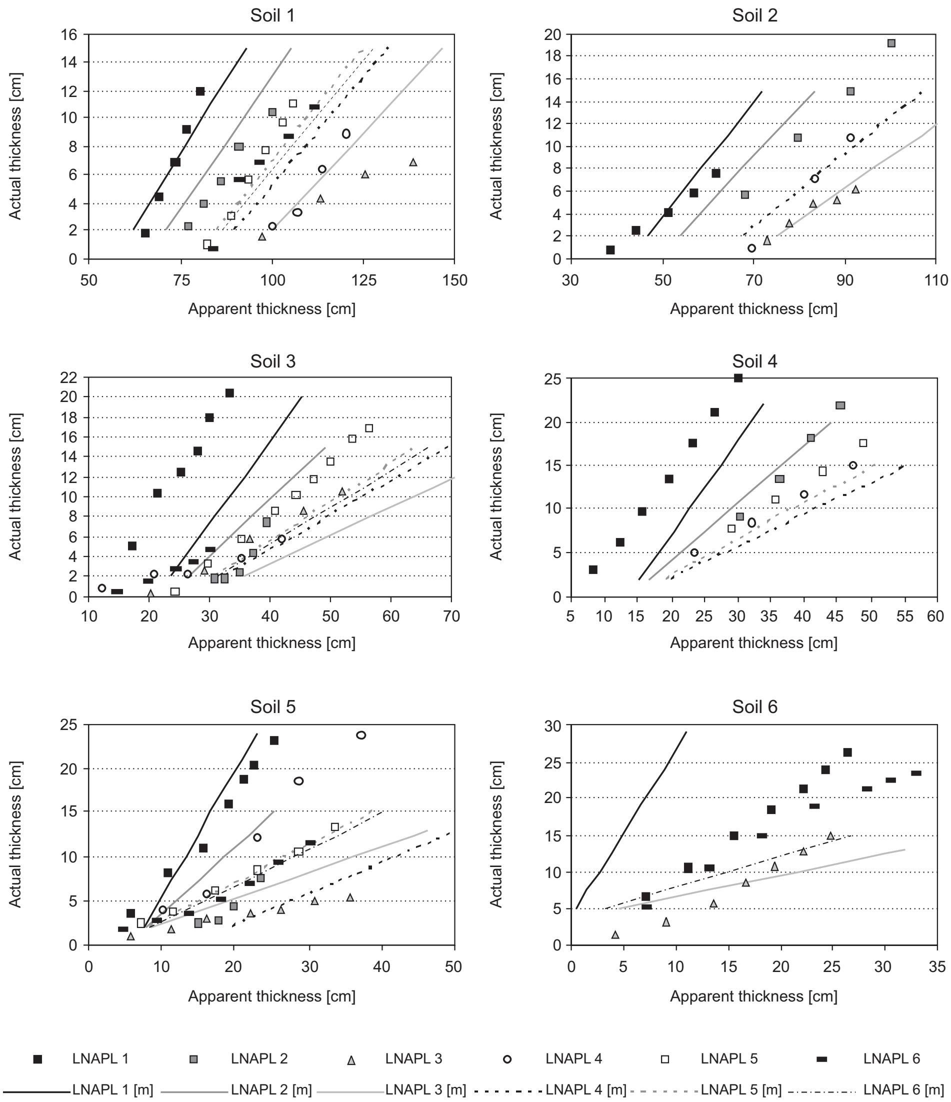

Fig. 3. The verification of the developed model on the base of laboratory investigations

Conclusions

1. The difference between apparent and actual thicknesses increases with the decrease of the hydraulic conductivity of soil. This relationship has a logarithmic character.

2. The appropriate model for estimating the actual LNAPL thickness on the groundwater table should include the properties of both: soil and LNAPL.

3. The values of actual LNAPL thickness calculated from the developed model are in many cases consistent with the results of the laboratory investigations. The best results were obtained in the case of the fine-grained soils.

4. Further studies aimed at the improvement of the proposed empirical model should include the laboratory experiments with the use of heterogeneous soils to check the importance of the hydraulic conductivity in this case and to study the influence of other parameters of soils *eg* the equivalent diameter and the coefficient of uniformity.

Acknowledgements

This work was financially supported by BS-401/302/08/R.

References

[1] Cooper GS, Peralta RC, Kaluarachchi JJ. Optimizing separate phase light hydrocarbon recovery from contaminated unconfined aquifers. Adv Water Resour. 1998;21:339-350. DOI: 10.1016/S0309-1708(97)00005-5.

[2] Cooper GS, Peralta RC, Kaluarachchi JJ. Stepwise pumping approach to improve free phase light hydrocarbon recovery from unconfined aquifer. J Contam Hydrol. 1995;18:141-159. DOI: 10.1016/0169-7722(94)00047-L.

[3] Hernández-Espriú A, Martinez-Santos P, Sánchez-León E, Marin LE. Free-product plume distribution and recovery modeling prediction in a diesel-contaminated volcanic aquifer. Phys Chem Earth. 2012;37-39:43-51. DOI: 10.1016/j.pce.2010.12.007.

[4] Lenhard RJ, Parker JC. Estimation of free hydrocarbon volume from fluid levels in monitoring wells. Ground Water. 1990;28(1):57-67. DOI: 10.1111/j.1745-6584.1990.tb02229.x.

[5] EPA: How to effectively recover free product at leaking underground storage tank sites. A guide for state regulators. (EPA 510-R-96-001); 1996.

[6] De Pastrovich TL, Baradat Y, Barthel Y, Chiarelli A, Fussell DR. Protection of groundwater from oil pollution. CONCAWE, Report 3/79. Den Haag, Netherlands; 1979; 62 pp.

[7] Deska I, Malina G. Estimation of actual free product thickness on the groundwater table based on soil and LNAPL properties. Proceedings of ECOpole. 2008;2(2):303-308.

[8] Deska I, Malina G, Radło A. Wpływ uziarnienia gruntu oraz cech paliwa na różnicę między miąższością pozorną i rzeczywistą LNAPL na zwierciadle wody podziemnej. Inż Ochr Środow. 2003;6(2):203-220.

[9] Golder Associates Ltd. Report on guidance on assessment of light non-aqueous phase liquid mobility for site classification purposes in British Columbia. Report Submitted to BC Ministry of Environment, October 9, 208, 45 pp (no 08-1436-0016).

[10] Deska I, Malina G. Laboratory verification of models for estimation of LNAPL actual thickness on the groundwater table. Proc 14th Central European Conference ECOpole'05. Duszniki Zdrój-Hradec Kralove; 2005;55-59.

[11] Dippenaar MA, Sole MD, Van Rooy JL, Du Toit GJ, Reynecke JL. Determining actual LNAPL plume thickness: review and case study in a fractured aquifer. Bull Eng Geol Environ. 2005;64:347-360. DOI: 10.1007/s10064-005-0278-5.

MODEL EMPIRYCZNY DO WYZNACZANIA RZECZYWISTEJ MIĄŻSZOŚCI LNAPL KORZYSTAJĄCY ZE WSPÓŁCZYNNIKA FILTRACJI

Instytut Inżynierii Środowiska
Politechnika Częstochowska

Abstrakt: Rzeczywista miąższość lekkiej cieczy organicznej (LNAPL) na zwierciadle wody podziemnej zawsze różni się od miąższości zmierzonej w studni (tzw. miąższości pozornej), a różnica między nimi jest zależna od właściwości gruntu i LNAPL oraz od ilości cieczy organicznej na zwierciadle wody. Metody stosowane obecnie do ustalania rzeczywistej miąższości LNAPL na podstawie zmierzonej miąższości pozornej pozwalają na uzyskiwanie wyników bardzo rozbieżnych i w większości przypadków nieprecyzyjnych. Metody te są bardzo uproszczone, uwzględniają zbyt małą liczbę parametrów (jedynie właściwości gruntów lub jedynie właściwości LNAPL). Poza tym, poprawne ustalenie wartości niektórych parametrów uwzględnionych w metodach jest bardzo trudne, zarówno w warunkach laboratoryjnych, jak i terenowych.

Na podstawie uzyskanych wyników badań laboratoryjnych ustalono, że poprawnie opracowany model obliczania rzeczywistej miąższości LNAPL powinien uwzględniać zarówno właściwości gruntu, jak i LNAPL. Ustalono, że w przypadku gruntów jednorodnych, bardzo równomiernie uziarnionych, jednym z ważniejszych parametrów jest współczynnik filtracji. Na podstawie analizy kluczowych parametrów wpływających na zależność między miąższością pozorną i rzeczywistą opracowano model empiryczny uwzględniający współczynnik filtracji gruntu oraz współczynnik lepkości dynamicznej LNAPL. Weryfikacja modelu potwierdziła, że w większości przypadków jego zastosowanie pozwoliło na uzyskanie wyników zbliżonych do ustalonych w warunkach laboratoryjnych.

Słowa kluczowe: LNAPL, miąższość rzeczywista, miąższość pozorna, współczynnik filtracji, model empiryczny