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IMPACT OF THE WATER TABLE FLUCTUATIONS ON THE APPARENT THICKNESS OF LIGHT NON-AQUEOUS PHASE LIQUIDS

Wpływ wałk poziomu zwierciadła wody podziemnej na miąższość pozorną lekkich cieczy organicznych

Abstract: The light non-aqueous phase liquids (LNAPLs) percolating into the subsurface from damaged underground storage tanks, pipelines, cisterns and from the unsealed landfills present a threat to soil and groundwater. If a layer of LNAPL floats on the groundwater table the initial step of remediation should be its recovery. In order to a proper design of LNAPL recovery an assessment of the mobile LNAPL volume is required. This volume can be determined on the base of a thickness of LNAPL layer in the porous medium (the actual thickness) or on the base of LNAPL specific volume. Then the LNAPL actual thickness and specific volume are estimated on the base of the LNAPL thickness measured in the monitoring well (the apparent thickness). Unfortunately, the actual LNAPL thickness is always different from the apparent LNAPL thickness. This difference depends on the properties of soil and the amount and properties of LNAPL. Additional factors influencing significantly the difference between apparent and actual thicknesses are the fluctuations of the water table level (the hydraulic head fluctuations).

The major objectives of this study became to investigate the impact of hydraulic head fluctuations on the measured apparent and actual LNAPL thicknesses. Obtained results show that when the hydraulic head diminishes, the apparent thickness of LNAPL increases and the actual thickness decreases. Instead, when the hydraulic head again rises, the apparent thickness decreases, and the actual thickness increases. When the hydraulic head rises considerably it can take place that the free product don’t be present in the observation well. The results affirm that hydraulic head fluctuations complicate considerably the estimation of the actual thickness and the mobile volume of LNAPL on the base of the apparent LNAPL thickness measured in the observation well.

Keywords: LNAPL, actual thickness, apparent thickness, hydraulic head, groundwater table fluctuations

The light non-aqueous phase liquids (LNAPL) percolate into the subsurface from damaged underground storage tanks, pipelines and cisterns [1]. A certain amount of hydrocarbons accesses the water environment with the leachates infiltrating from the

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unsealed landfills [2] and during the coal deposits exploitation [3]. In the case of the LNAPL spill its migration comprise three steps [1, 4]: (1) vertical infiltration through the vadose zone that goes ahead due to the forces of gravity and capillarity, (2) horizontal spread of LNAPL on the groundwater table and displacing of the capillary fringe; dissolving of some soluble constituents into the groundwater (3) stabilization of the lateral spread of free product and migration of the plume of dissolved contaminants in the direction of the hydraulic gradient. After stabilization, due to the water table level fluctuations can eventuate the vertical movement of the LNAPL lens [5]. At this stage both free product and residual phase are source of the soil and groundwater contamination with soluble constituents [6]. Water percolating through the residual LNAPL due to precipitation infiltration or water table elevation changes dissolves soluble constituents resulting in a dissolved phase contaminant plume [6]. Even polycyclic aromatic hydrocarbons (PAHs) that are poorly soluble in water, can under certain conditions be leached out from the contaminated soil and pose a potential threat to groundwater [7]. It should be emphasized that as a result of the long-standing infiltration of LNAPL through the layer of cohesive soils it can come to the change of their original properties and to the worsening of their isolating ability [8]. Thus, in the case of oil pollution there is a necessity of the remediation and reclamation of both soil and groundwater with use of the properly attuned techniques [4]. Sites that need the remediation are characterized not only by morphologic changes but also by the disturbance of biological processes and the contamination with toxic substances [9]. It should be emphasized that reclamation of the degraded lands entails not only the land clearance, but also the need to the revitalization of their physical, chemical and biological properties [10]. If the LNAPL layer floats on the groundwater table the initial remediation step should be its recovery [11]. In order to a proper design of LNAPL recovery there is required an assessment of the mobile LNAPL volume [12] that can be determined on the base of the LNAPL thickness measured in the wells bored in several points of the contaminated area [13]. However, the LNAPL thickness measured in the observation well (the apparent thickness) is always different from the LNAPL layer thickness in the porous medium (the actual thickness) [14–17]. This difference depends on the properties of soil and the amount and properties of LNAPL [16]. Additional factors influencing the difference between apparent and actual thicknesses are the fluctuations of the water table level (hydraulic head fluctuations) and rate of these fluctuations [18–20].

When the hydraulic head changes the LNAPL lens moves up and down leading up to the increase of the volume of soil contaminated with LNAPL [18, 19]. During the descent of the water table level the LNAPL lens moves down leading up to the increase of the vertical extent of the interval of porous medium contaminated with LNAPL. Then, during the rising of the water table level a part of LNAPL lens moves up, but significant amount of it is trapped as a residual phase below the water table. This phenomenon has an impact on the decrease of the free product volume and the concurrent increase of the residual contamination zone [19]. Instead, during the descent of the water table level that follows the previous hydraulic head rise a part of LNAPL remains in the soil under the capillary fringe as adsorbed or residual phase, but a part of
LNAPL drops trapped previously below the water table is released. This results in the re-increase of the mobile LNAPL volume and thus the apparent thickness [19]. During the water table fluctuations changes the relationship between apparent and actual thicknesses and it can lead up to the imprecise estimation of the actual LNAPL thickness in the geological formation [18–20].

In the case of fluctuating water table very great influence on the relationship between apparent and actual thicknesses has the movement of free product and water between the well and geological formation. This is very often neglected at the estimation of the actual LNAPL thickness [18, 19]. If the hydraulic head in the geological formation rises, LNAPL drains from the well and flows into the adjacent formation. However the repletion of LNAPL recharges back into the well due to the pressure difference until the equilibrium is reached [18, 19]. However the apparent LNAPL thickness is in this case smaller than its equilibrium value. The faster the water table level rises, the smaller the apparent LNAPL thickness will be. If the hydraulic head in the aquifer falls, LNAPL flows into the monitoring well. Then the repletion of LNAPL drains back into the soil. In this case the apparent LNAPL thickness is larger than its equilibrium value. The faster the water table level falls, the larger the apparent LNAPL thickness will be [18, 19].

Water table fluctuations complicate the estimation of the actual LNAPL thickness and volume. When hydraulic head varies, the LNAPL volume estimates on the base of the apparent thickness may be significantly different from the actual LNAPL volume in the geological formation [18–20].

The focus of the experiments described in this article was to investigate the impact of hydraulic head fluctuations on the measured apparent and actual LNAPL thicknesses on the groundwater table in the case of sandy, homogeneous soil.

Materials and methods

The experiments were performed with use of sandy soil with effective grain size $d_{10} = 0.33$ mm, Hazen’s uniformity coefficient $U = 2.03$ and hydraulic conductivity (at $10^\circ$C) $k_{10} = 4.2 \cdot 10^1$ m · d$^{-1}$. As LNAPL was used the rapeseed oil with the density $\rho = 918$ kg · m$^{-3}$ and the dynamical viscosity coefficient $\mu = 0.07$ kg · m$^{-1}$ · s$^{-1}$ (at the temperature of $20^\circ$C).

The experiments were carried out in 10 cm diameter Plexiglas column with inbuilt filter-tube used as monitoring well (with diameter of 3.5 cm) (Fig. 1).

In the experimental column was also inbuilt the 3 cm diameter equalizing column with perforated bottom used to the changing of the water table elevations during the experiments. The column was packed with the soil sample. The perforated tube for injection of LNAPL was located into the soil (see Fig. 1). Then the experimental column was filled with water until the water table reached the assumed elevation (below the outfall of perforated tube). After 3 days about 600 cm$^3$ of LNAPL was injected to the column directly above the capillary fringe zone. LNAPL was stained with the dye – Sudan III for better visibility of the liquid in the column. After next 4 days, the apparent and actual LNAPL thicknesses were measured in the well and in the soil. The actual
thickness was in this case the distance between the top and the bottom of LNAPL layer in the soil – the interval of porous medium containing LNAPL. Then the hydraulic head was lowered a few centimeters and after next 3–4 days the apparent and actual LNAPL thicknesses were measured. These procedures were repeated several times, until the LNAPL-water interface in the well has reached the well bottom. Then the hydraulic head was raised a few centimeters and after 3–4 days the apparent and actual thicknesses were measured. These procedures were repeated several times, until the air-LNAPL interface in the soil reached the top of soil sample. The top of the experimental column was protected against LNAPL evaporation by the cover. Experiments were performed at the temperature of about 20 °C.

**Results and discussion**

Fig. 2 shows the changes of the vertical placements of the LNAPL layers in the observation well and in the soil brought about the groundwater table fluctuations.

Results show that the actual LNAPL thickness diminishes for the falling water table level and increases when the hydraulic head rises. When the hydraulic head has the lowest elevation (measurement 9) the actual thickness diminishes to the zero value. In the case of measurements 6–10 the elevation of LNAPL layer in the observation well is so low that the LNAPL layers in the well and in the soil lost their connectedness.
Fig. 2. The changes of the vertical placements of the LNAPL layers in the observation well and in the soil.

Fig. 3 shows the impact of the water table fluctuations on the changes of the actual and apparent thickness values.

The obtained results show that when the hydraulic head falls the apparent thickness of LNAPL rises and the actual thickness noticeably diminishes. At some point (measurement 9) the actual thickness has diminished to the zero value. Note that the maximal value of apparent thickness was obtained in the case of 7th measurement, ergo prior to the minimal values of the hydraulic head and of the actual thickness. During further abatement of the water table level (measurements 8 and 9) it was noticed very inconsiderable decrease of the apparent thickness and the considerable decrease of the actual thickness, until the disappearance of the LNAPL layer in the soil (measurement 9).

Instead when the hydraulic head rises the apparent thickness diminishes and the actual thickness increases. At some point (measurement 17) the apparent thickness has diminished to zero value. In this case whole volume of LNAPL has drained from the well into the adjacent formation.

The obtained results show noticeably that during the experiment was observed the increase of the vertical extent of the residual contamination zone.
Fig. 4 shows the relationships between the apparent and actual thicknesses during the groundwater table fluctuations.

![Graph showing relationships between apparent and actual thicknesses](image)

The results show that the graphs for falling and rising groundwater table level aren’t coincident. It suggests the existence of the hysteresis phenomenon in the geologic formation LNAPL-, water- and air saturation during decrease and increase of the groundwater table.

The obtained results show that the water table fluctuations significantly complicate the estimation of the actual LNAPL thickness on the groundwater table on the base of the measured apparent LNAPL thickness. Results confirm that most available methods for estimation of the actual LNAPL thickness should be used only at the hydraulic equilibrium conditions. In the case of significant abatement of the hydraulic head the use of the apparent thickness for the estimation of the actual thickness may give the punitive results. Then in the case of the considerable hydraulic head rise the actual thickness estimated on the base of the apparent thickness can be largely understated. In an extreme case it may come to the disappearance of the LNAPL layer in the well, although LNAPL will be present in the soil.

The results confirm that it is very important or the hydraulic head change is the effect of the fall or rise of the water table level. The proper estimation of the actual LNAPL thickness in the geologic formation requires the study of the history of the hydraulic head changes in the contaminated site.

The diameters of the experimental column and the observation well have an effect on the experiment results. Very important was the relationship of the area of the soil cross section to the well cross section area. In the field conditions the well diameter cannot play so important role.

**Conclusions**

1. The results show that the water table fluctuations complicate significantly the estimation of the actual LNAPL thickness and volume on the base of the apparent thickness measured in the observation well.
2. When the hydraulic head falls the apparent thickness of LNAPL rises and the actual thickness diminishes.

3. When the hydraulic head rises the apparent thickness diminishes and the actual thickness increases. In the case of the rising water table level there can occur the situation in that the free product don’t be present in the observation well.

4. The graphs showing the relationships between apparent and actual thicknesses for falling and rising groundwater table level aren’t coincident. It can suggest on the hysteresis phenomenon.

5. During the experiment was observed an increase of the vertical extent of the residual contamination zone.

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References

WPŁYW WAHAŃ POZIOMU ZWIERCIADŁA WODY PODZIEMNEJ NA MIĄJSZOŚĆ POZORNĄ LEKKICH CIECZY ORGANICZNYCH

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Streszczenie: Lekkie cieczki organiczne (LNAPL) infiltrujące do środowiska gruntowo-wodnego z uszkodzonych zbiorników magazynujących paliwa, rurociągów, cystern itp., a także z nieuszkodzonych składowisk odpadów komunalnych stanowią bardzo poważne zagrożenie dla środowiska wodno-gruntowego. W przypadku pojawienia się LNAPL na zwierciadle wody podziemnej pierwszy etap remediacji powinno stanowić jej sczerpanie. W celu odpowiedniego zaprojektowania operacji sczerpywania niezbędna jest znajomość objętości mobilnej LNAPL, którą ustala się na podstawie miąższości zanieczyszczonej strefy gruntu (miąższości rzeczywistej) lub na podstawie tzw. objętości jednostkowej LNAPL w ośrodku porowatym. Miąższość rzeczywistą i objętość jednostkową wolnego produktu oblicza się na podstawie miąższości LNAPL zmierzonej w studni obserwacyjnej (tzw. miąższości pozornej). Jednak miąższość pozorna zawsze różni się od miąższości rzeczywistej, a różnica między nimi zależy od właściwości gruntu, jak również od właściwości i ilości LNAPL. Dodatkowym czynnikiem, który wpływa na różnicę między miąższością pozoną i rzeczywistą, są wahania poziomu zwierciadła wody podziemnej. Celem badań prowadzonych w ramach niniejszej pracy jest ustalenie wpływu zmian wysokości hydraulicznej na zmierzone wartości miąższości pozornej i rzeczywistej LNAPL na zwierciadle wody podziemnej. Otrzymane wyniki wskazują, że w przypadku obniżania się wysokości hydraulicznej miąższość pozorna wzrasta, natomiast miąższość rzeczywista maleje. Z kolei, w przypadku ponownego podwyższania poziomu zwierciadła wody podziemnej miąższość pozorna maleje, podczas gdy miąższość rzeczywista wzrasta. Przy znacznym podwyższeniu poziomu zwierciadła wody podziemnej może dojść do sytuacji, w której następuje całkowity zanik warstwy LNAPL w studni obserwacyjnej, mimo obecności wolnego produktu w ośrodku wodno-gruntowym. Uzyskane wyniki potwierdzają, że wahania wysokości hydraulicznej w znacznym stopniu komplikują ustalanie rzeczywistej miąższości oraz objętości mobilnej LNAPL w ośrodku porowatym na podstawie miąższości pozornej zmierzonej w studni obserwacyjnej.

Słowa kluczowe: LNAPL, miąższość rzeczywista, miąższość pozorna, wysokość hydrauliczna, wahania zwierciadła wody podziemnej