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ДОСЛІДЖЕННЯ ЗАБРУДНЕННЯ ГЕОЛОГІЧНОГО СЕРЕДОВИЩА АВІАЦІЙНИМ ГАСОМ У РАЙОНІ АЕРОПОРТУ “БОРИСПІЛЬ” З ВИКОРИСТАННЯМ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ

RESEARCH OF SUBSURFACE CONTAMINATION WITH GASOLINE WITHIN BORYSPIL AIRPORT USING MATHEMATICAL MODELLING

(Матеріал друкується мовою оригіналу)

Забруднення геологічного середовища нафтопродуктами на території складу ПММ аеропорту “Бориспіль” (Київська обл.) у вигляді лінзи авіаційного гасу вперше виявлено 1998 року. Попередні відновлювальні заходи не дали змоги повністю ліквідувати забруднення через те, що кількість ліквідаційних свердловин була недостатньою, щоб покрити всю територію забруднення, і відстані між свердловинами суттєво перевищували радіус впливу свердловин. Забруднення нафтопродуктами зберігається й загрожує довкіллю, що стало причиною проведення еколого-геологічних досліджень ІГН НАНУ. За даними моніторингу підтверджено наявність шару гасу майже в усіх ліквідаційних свердловинах. У ситуації, що склалася, треба вилучити мобільні нафтопродукти за допомогою відкачування.

Математично змодельовано роботу ліквідаційних свердловин на лінзі гасу для визначення їхнього оптимального розміщення. Для розрахунків використано програмне забезпечення API LNAPL. У першому модельному експерименті задавали табличні значення α – параметра, що характеризує розмір пор, і β – параметра, що характеризує розподілення пор. Результати моделювання мали попередній характер, тож отримані відстані між свердловинами виявилися дещо завищеними. Для достовірніших результатів уточнено фільтраційні характеристики ґрунту завдяки проведенню лабораторних досліджень. Визначено залежності тиску від насиченості $p(\theta)$ для зразків ґрунту, відібраних на території аеропорту “Бориспіль”; і за допомогою програми RETC розраховано значення параметрів α і β . У другому модельному експерименті визначено оптимальні відстані між ліквідаційними свердловинами на ділянках із середньою потужністю авіаційного гасу 0,7 та 0,5 м.

Ключові слова: авіаційний гас, підземні води, математичне моделювання, ліквідаційні свердловини, забруднення геологічного середовища.

Subsurface contamination with gasoline has occurred within Boryspil airport (Kyiv region) for long period. Previous remedial actions including pumping of gasoline and contaminated groundwater have not provided to remove contamination completely. The monitoring data confirmed the presence of a gasoline layer in most monitoring wells. Using mathematical modelling, we imitated the operation of pumping wells to determine their optimal location. API LNAPL program was applied for calculations. In order to obtain more reliable results, soil hydraulic characteristics were specified by laboratory experiments. A pressure-saturation relation, $p(\theta)$ was determined for soil samples taken from Boryspil region, and then the values of α and β parameters describing pore size and distribution were calculated using RETC program. Optimal distances were calculated between pumping wells at two contaminated sites with a gasoline layer of 0,7 and 0,5 m, respectively.

Keywords: gasoline, groundwater, mathematical modeling, pumping wells, subsurface contamination.

Introduction

Environmental and geological research carried out by Groundwater Protection Department of the Institute of Geological Sciences of the NASU within airfield territories showed that, as a rule, the unsaturated soils and groundwater are contaminated with petroleum products [2, 10, 11, 13, 14]. Due to spills and leakages petroleum products enter the subsurface and reaching a water table form mobile lenses. During remedial actions it is the first priority to remove mobile petroleum products from aquifers to limit their migration in the subsurface [1, 9]. Mathematical modelling can also be used to design recovery systems [3, 17].

Subsurface contamination with gasoline has occurred within Boryspil airport (Kyiv region) for long period. Previous remedial actions including pumping of gasoline and contaminated groundwater have not provided to remove contamination completely. Sub-

surface contamination with gasoline continues and poses a threat to the environment, which caused the ecological and geological research conducted by Groundwater Protection Department. The monitoring data confirmed the presence of a gasoline layer in most monitoring wells. Using mathematical modelling, we imitated the operation of pumping wells to determine their optimal location.

This research was carried out in the frame of the budget theme “Scientific fundamentals of the liquidation of subsurface contamination with light petroleum products” and the contract for “Monitoring groundwater at the area contaminated with petroleum products within Boryspil airport” with LLC scientific production center INGEOCOM.

Ecological and geological research at the contaminated area Geological and hydrogeological conditions of the study area

In geomorphological aspect, the study area belongs to the second terrace above the flood plain of the Dnieper River. The relief of the area is flat with absolute elevation marks of 116–118 m.

The upper part of the geological section contaminated with petroleum products consists of the layered Quaternary sedimentary deposits that occur horizontally and are stratigraphically sustained by extension. The soil-vegetation layer is represented by recent eluvial formations (eIV), the thickness of which reaches 1,1 m. It is underlain by the upper Quaternary atmogenic and dealluvial deposits (vdIII) represented by loess-type pale yellow macroporous sandy loam with a thickness of 1,0–1,5 m. The Upper Quaternary alluvial deposits (aIII), the upper part of which is represented by sand and sandy loam up to a depth of 5,5–6,0 m, lie below. This layer is underlain by the Upper Quaternary alluvial sands of the second terrace above the flood plain of the Dnieper River (aIII) that are fine-grained yellow-gray, and clay iron water-saturated at the top of the layer. Within the scope of this study the sands were drilled to a depth of 0.8 m from their top but these sands are assumed to occur up to a depth of 50 m.

A groundwater aquifer is contained in alluvial sandy and sandy-loam deposits (aIII). Groundwater table depths are from 1,5 to 4,2 m. The recharge of the aquifer is due to the infiltration of precipitation as well as overflow from the underlying confined aquifers and river waters during the spring flood. The groundwater table declines in the east direction with a slope of 0,0018. The groundwater aquifer is not protected from entering contaminants from surface sources, an example of which is subsurface contamination with petroleum products due to the functioning of a fuel storage within Boryspil airport.

Background

Subsurface contamination with gasoline within Boryspil airport, Kyiv region was found in 1998. A source of contamination is a fuel storage. Due to leakages gasoline entered the unsaturated zone consisting of permeable loessial and alluvial sandy loam and sand. Then gasoline moved vertically and formed a lens on a groundwater table, the area of which was 4,2 hectares and a thickness reached up to 1,2 m. A total gasoline volume accumulated in the subsurface was 1 725 m³ [4]. Based on the results of exploratory works, urgent remedial actions were required to localize and remove contamination.

In 1999–2000 the project of gasoline recovery system was developed to avoid contamination spreading out of the fuel storage area. Within the framework of the project 42 pumping wells were

drilled, and about 30 000 m³ of contaminated water and 341 m³ of mobile gasoline were recovered and cleaned.

However, these remedial works did not provided to remove contamination completely. This is because a number of recovery wells was not sufficient to cover all contaminated area and distances between wells considerably exceeded a range radius of wells. Therefore, although remedial actions were realized, subsurface contamination with gasoline continues and poses a threat to the environment.

Recent field research

Groundwater protection department has carried out environmental and hydrogeological monitoring at the contaminated area (the region of Boryspil airport) since 2011. Monitoring wells drilled to a depth from 1 to 17 m upstream and perpendicularly to a groundwater flow provide to observe areal groundwater contamination. A stage sound system, which is unique in Ukraine, was installed to observe groundwater contamination to depth. Totally, four sounds were installed in saturated zone at different depth.

Monitoring works consist of:

- soil sampling to determine gasoline contents during well drilling;
- periodical measurements of groundwater and mobile gasoline levels in monitoring wells (once in a quarter) and measurements of a gasoline layer in pumping wells;
- groundwater sampling in monitoring wells, sounds and artesian wells to determine chemical water composition and dissolved hydrocarbon contents.

Today, the monitoring data have confirmed the presence of a gasoline layer in most monitoring wells. Figure 1 shows a lens of gasoline on a water table by monitoring data. In this situation, it is necessary to recover gasoline by pumping using mathematical modeling to determine optimal location of pumping wells within a gasoline lens.

Mathematical modelling of gasoline recovering

Theoretical study and methodology

Oil, water and air contents above the water table are calculated depending on a water table depth and an oil thickness in a well. Calculations are based on the theory of vertical equilibrium of oil thickness in an observation well with the environment [5, 7].

Fig. 1. Subsurface contamination with gasoline by monitoring data

Capillary head h_{ow} is calculated by a nominal design point position relative to “oil-water” level (Z_{ow}) and capillary head h_{ao} is relative to “air-oil” level (Z_{ao}) using the following equations:

$$h_{ow} = (1 - \rho_{ro})Z_{ow}; \quad h_{ao} = (1 - \rho_{ro})Z_{ao}, \quad (1)$$

where $\rho_{ro} = \rho_o/\rho_w$; ρ_o, ρ_w – oil and water densities.

Volume oil and water contents are calculated by capillary heads using van Genuchten function [15]:

1) effective water saturation (θ_w):

$$\bar{\theta}_w = \left[1 + (\alpha_{ow} h_{ow})^{n_{ow}} \right]^{-m}, \quad (2)$$

where α_{ow}, n_{ow} – parameters of $h_{ow}(\theta_w)$ relation; $m = 1 - 1/n_{ow}$;

2) volume water content (θ_w) is:

$$\theta_w = \bar{\theta}_w (\theta_s - \theta_{wr}) + \theta_{wr}, \quad (3)$$

where θ_s – total fluid saturation; θ_{wr} – irreducible saturation;

3) effective liquid saturation ($\bar{\theta}_{o+w}$):

$$\bar{\theta}_{o+w} = \left[1 + (\alpha_{ao} h_{ao})^{n_{ao}} \right]^{-m}, \quad (4)$$

where α_{ao}, n_{ao} – parameters of $h_{ao}(\theta_w)$ relation;

$$\theta_{o+w} = \bar{\theta}_{o+w} (\theta_s - \theta_{wr}) + \theta_{wr}. \quad (5)$$

In the saturation zone (within a mobile oil lens) $\theta_{o+w} = \theta_s$.

4) Within a mobile oil lens ($Z_{ao} - Z_{ow}$):

$$\theta_o = \theta_s - \theta_w. \quad (6)$$

5) In the capillary zone above “air-oil” interface (Z_{ao}):

$$\theta_o = \theta_{o+w} - \theta_w. \quad (7)$$

6) Oil volume along a vertical profile is:

$$V_o = \int_0^{\text{surf}} \theta_o dz. \quad (8)$$

Relative permeability (k_r), effective permeability (K_{eff}) and conductivity (T_{eff}) are calculated based on [8, 12]:

$$k_{ro} = (\bar{\theta}_o)^{0.5} \left[\left(1 - \bar{\theta}_w^{1/m} \right)^m - \left(1 - \bar{\theta}_{o+w}^{1/m} \right)^m \right]; \quad (9)$$

$$k_{rw} = (\bar{\theta}_w)^{0.5} \left[1 - \left(1 - \bar{\theta}_w^{1/m} \right)^m \right]; \quad (10)$$

$$k_{ra} = (1 - \bar{\theta}_{o+w})^{0.5} \left(1 - \bar{\theta}_{o+w}^{1/m} \right)^{2m}; \quad (11)$$

$$K_{\text{eff}} = k_r K_i, \quad (12)$$

where K_i – hydraulic conductivity of fluid, i:

$$K_i = \frac{K \rho g}{\mu}, \quad (13)$$

where K – soil permeability; (μ – dynamic viscosity; g – gravitational acceleration).

$$T_{\text{eff}} = \frac{K \rho g}{\mu} \int_0^{z_0} k_{ro}. \quad (14)$$

Specific rates are calculated downstream fluid flow ($f = w, o, a$) according to Darcy's law:

$$q_f = \frac{k_{rf} K_{ij}}{\mu_f} \left[\frac{\partial P_f}{\partial x_i} + \rho_f g \frac{\partial z}{\partial x_j} \right], \quad (15)$$

where K_{ij} – tensor of soil permeability; P_f – fluid pressure.

The modified equations are used to calculate oil pumping in

different conditions [3]. The following equations are used to calculate simultaneous oil and water pumping:

$$Q_o = \frac{2 \rho_{ro} b_o k_{ro} Q_w}{\mu_{ro} b_w \left(1 + \sqrt{1 - \frac{Q_w}{\pi K_w b_w^2} \ln \frac{r_i}{r_w}} \right)}. \quad (1)$$

$$Q_w = \frac{(b_w^2 - h_{ow}^2) \pi K_w}{\ln \frac{r_i}{r_w}}, \quad (2)$$

where Q_o and Q_w – oil and water flow rates, m^3/day ; b_w – a distance from a filter bottom to a piezometric head, m ; h_{ow} – a distance from a filter bottom to an oil-water interface, m ; K_w – water hydraulic conductivity, m/day ; $\mu_{ro} = \mu_o/\mu_w$ (μ_o and μ_w – oil and water viscosity, cp ; r_i – a radius of influence, m ; r_w – a well radius, m .

The statement of computing experiments

Using mathematical modelling, we imitated the operation of wells pumping gasoline and water simultaneously. API LNAPL program [6] was applied for calculations.

A mobile oil lens on a water table consists of gasoline with a density of $0.815 \text{ g}/\text{cm}^3$, viscosity of 1.82 cp and surface tension $\sigma_{ao} = 27.4 \text{ dyne}/\text{cm}$ at oil-air interface and $\sigma_{ow} = 13 \text{ dyne}/\text{cm}$ at oil-water interface. Hydraulic conductivity of the aquifer was determined by the recovery of water and gasoline levels after pumping. According to the calculations, hydraulic conductivity for water (K_w) is $1 \text{ m}/\text{day}$. Porosity determined experimentally at the field scale is 0.44 .

At the map of groundwater contamination with gasoline within a fuel storage (Boryspil airport) two sites were distinguished where the thickness of a gasoline lens was the highest (see fig. 2):

1) in a southwestern part of the contaminated zone, dimensions of which were approximately $100 \times 100 \text{ m}$ and the thickness of a gasoline lens was 0.50 – 0.88 m , and

2) in a northeastern part of the contaminated zone, dimensions of which were approximately $200 \times 100 \text{ m}$ and the thickness of a gasoline lens was 0.40 – 0.65 m .

An averaged thickness of a gasoline lens was accepted to be 0.7 m at the first site and 0.5 m at the second site, respectively.

In the first computing experiment we imitated the operation of pumping wells located at a distance of $25, 20$ and 15 m from each other at both contaminated sites to determine optimal location of wells. Respectively, the fragments of sites, $50 \times 50, 40 \times 40$ and $30 \times 30 \text{ m}$ were examined. Typical values of α and β parameters were specified (α is a parameter describing a pore size and β is a parameter describing pore distribution). Therefore, the results of modeling can be considered as tentative and must be adjusted. The obtained distances between wells were rather longer than it is required.

In order to obtain more reliable results, soil hydraulic characteristics must be specified by laboratory experiments. We determined a pressure-saturation relation, $p(\theta)$ for soil samples taken from Boryspil region. Then α and β parameter values were calculated using RETC program [16].

In the second computing experiment the obtained α and β parameter values were used, which resulted in reduction of modeling distances between wells.

We imitated the operation of wells located at a distance of $20, 15$ and 12 m from each other at the site where a gasoline layer was 0.7 m , and at a distance of $15, 12$ and 10 m from each other at the site where a gasoline layer was 0.5 m . Table shows the results of the second modeling experiment.

* Subscripts indicate: “o” – oil, “w” – water; “a” – air.

Figure 2. The map of groundwater contamination with gasoline within Borispil airport by monitoring data

The results of modelling showed that the effectiveness of the recovery well network depends on a maximal gasoline rate, a specific recovered gasoline volume, minimal residual gasoline volume, and time of pumping. Based on this, pumping wells should be located by 30×30 m grid at the site where a gasoline layer is 0,7 m, and by 24×24 m or 20×20 m grid at the site where a gasoline layer is 0,5 m.

This calculation procedure can be applied for other similar objects where unsaturated soils and groundwater are contaminated with petroleum products, and remedial actions, particularly, recovery of petroleum products by pumping are required.

Further research should include development of a two-layer (oil and water) model to imitate movement of a gasoline lens on a water table and gasoline recovery. This model supplemented with recent monitoring data will enable to estimate effectiveness of recovery wells and correctly plan remedial actions to prevent from spreading of a gasoline lens out of the fuel storage area.

Conclusion

Subsurface contamination with gasoline has occurred within the fuel storage of Boryspil airport since 1998. Previous remedial

works did not provided to remove contamination completely because a number of recovery wells was not sufficient to cover all contaminated area and distances between wells considerably exceeded a range radius of wells.

Ecological and geological research were carried out at the contaminated site. According to monitoring data, the presence of a gasoline layer is observed in most wells. It is necessary to recover gasoline by pumping using mathematical modelling to determine optimal location of pumping wells within a gasoline lens.

Using API LNAPL program, the operation of pumping wells was imitated at two contaminated sites with a gasoline layer of 0,7 and 0,5 m, respectively. In the first modeling experiment obtained distances between wells were rather longer than it is required and must be adjusted. In order to obtain more reliable results, soil hydraulic characteristics were specified by laboratory experiments. A pressure-saturation relation, $p(\theta)$ was determined for soil samples taken from Boryspil region, and then the values of α and β parameters describing pore size and distribution were calculated using RETC program.

Table. The results of modeling of the operation of pumping wells at two sites contaminated with gasoline

Gasoline layer, m	0,7	0,7	0,7	0,5	0,5	0,5
Distance between wells, m	20	15	12	15	12	10
Site area, m	40×40	30×30	24×24	30×30	24×24	20×20
Initial gasoline volume, m ³	224	126	81	90	58	40
Time of pumping, years	8	5	3	5	3,5	2
Gasoline rate, m ³ /day	0,24–0,01	0,24–0,01	0,24–0,01	0,15–0,01	0,15–0,01	0,15–0,01
Total recovered gasoline volume, m ³	196	111	75	75	48	33
Specific recovered gasoline volume, m ³	0,12	0,127	0,13	0,07	0,083	0,083
Residual gasoline thickness, m	0,19	0,17	0,17	0,19	0,17	0,17
Residual gasoline volume, m ³	28	12	6	15	10	7
Residual gasoline volume per 1 m ² , m ³	0,017	0,001	0,001	0,017	0,017	0,017
A filter length, m (below a gasoline-water interface)	1,2 (0,5)	1,2 (0,5)	1,2 (0,5)	1,0 (0,5)	1,0 (0,5)	1,0 (0,5)
Water rate, m ³ /day	0,74	0,8	0,86	0,51	0,55	0,58

Note. Hydraulic conductivity, K is 1 m/day, total porosity is 0,44; residual water saturation is 0,24; field residual gasoline saturation is 0,2; $\alpha=4,3$; $\beta=1,206$, a well radius is 450 mm.

The results of modelling showed that the effectiveness of the recovery well network depends on a maximal gasoline rate, a specific recovered gasoline volume, minimal residual gasoline volume, and time of pumping. Based on this, pumping wells should be located by 30×30 m grid at the site where a gasoline layer is 0,7 m, and by 24×24 m or 20×20 m grid at the site where a gasoline layer is 0,5 m.

Further research should include development of two-layer (oil and water) model to imitate movement of a gasoline lens on a water table and gasoline recovery. This model supplemented with recent monitoring data will enable to estimate effectiveness of recovery wells and correctly plan remedial actions to prevent from spreading of a gasoline lens out of the fuel storage area.

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Світлої пам'яті Анатолія Васильовича ЛУЩИКА

30 березня 2020 року відійшов у вічність видатний український гідрогеолог, доктор геолого-мінералогічних наук, професор Анатолій Васильович Лущик.

Анатолій Васильович народився 15 жовтня 1933 року в м. Новгороді-Сіверському Чернігівської області. Після закінчення 1962 року Дніпропетровського гірничого інституту працював у Забайкальському науково-дослідному інституті Міністерства геології СРСР у м. Читі (РФ).

Уся подальша трудова й наукова діяльність Анатолія Васильовича була пов'язана з Кримським півостровом. Упродовж 1965–1975 років він працював у Виробничому геологічному об'єднанні "Кримгеологія", а з 1975 року по 2012 рік – у Кримському відділенні Українського державного геологорозвідувального інституту (УкрДГРІ, до 1999 року – Інститут мінеральних ресурсів).

Наукова діяльність Анатолія Васильовича була пов'язана з надзвичайно актуальними для України, зокрема й для Криму, питаннями вивчення й прогнозування небезпечних геологічних процесів. Він обіймав посади завідувача лабораторії селей та інженерно-геологічних досліджень, завідувача лабораторії гідрогеодинаміки, завідувача відділу прогнозування геодинамічних процесів, головного наукового співробітника інституту.

Анатолій Васильович успішно поєднував роботу в УкрДГРІ з викладацькою діяльністю: був професором кафедри інженерної геології та безпеки життєдіяльності Національної академії природоохоронного й курортного будівництва, талановитим педагогом, який виховав не одне покоління інженерів і науковців.

Головними напрямками наукових інтересів А. В. Лущика були інженерна геологія, інженерна екологія, прогнозування виникнення та активізації сучасних небезпечних екзогенних геологічних процесів і обумовлених ними надзвичайних ситуацій, прогнозування підготовки землетрусів, пошуки і розвідка родовищ підземних вод. А. В. Лущик є автором понад 250 наукових публікацій, у т. ч. шість колективних монографій. Анатолій Васильович зробив вагомий внесок у розвиток екологічної геології України і плідно співпрацював з колегами-геологами в Словаччині та КНР.

Наукова діяльність Анатолія Васильовича отримала високу оцінку геологічної та наукової спільноти ("Почесний розвідник надр" (1995 р.), медаль В. І. Лучицького (2003 р.), "Заслужений діяч науки і техніки Автономної Республіки Крим" (2006 р.), медаль Л. І. Лутугіна (2008 р.), Державна премія України у галузі науки і техніки (2010 р.).

Анатолій Васильович прожив життя гідно і чесно, залишивши по собі плоди своїх добрих і потрібних справ.

Ми пам'ятатимемо Анатолія Васильовича не лише як авторитетного вченого, а і як добру, життєрадісну людину, до якої завжди можна було звернутися за порадою. Його вирізняло поєднання високої інтелігентності, толерантності, доброзичливості, всебічності інтересів, любові до людей і рідної природи.

Світла пам'ять про Анатолія Васильовича Лущика, ученого й людину, назавжди залишиться в серцях усіх, хто його знав. Нехай Господь дарує Анатолію Васильовичу вічне життя в Царстві Небесному.

Друзі та колеги