

Risk assessment from the oil waste disposal in deep wells

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Abstract

In this paper we present the risk assessment analysis of oil waste disposal in deep wells. Oil waste disposal is analyzed in the oil field Žutica (Croatia) at an injection depth of around 2000 m. The risk assessment analysis is based on the flow and transport of injected oil waste using stochastic Monte-Carlo numerical simulations through a heterogeneous injection zone, which consists of low permeable marl and high permeable sandstone zones. The injection zone is bounded by low permeable marl zones, which decrease vertical spreading of the injected oil waste and considerably reduce risk. Risk assessment is defined by exceeding risk, which is the probability that injected oil waste passes through the selected cross section or important surface aquifers. Results show that exceeding risk is a very low or practically negligible, $p_r=10^{-3}$ for period $t=100$ year at depth of $Z=1850$ m and $p_r=10^{-47}$ for period $t=10000$ year at depth of $Z=500$ m (surface aquifers), which confirms the safety and reliability of the presented oil waste disposal methodology.

Keywords: risk assessment, oil waste disposal, flow and transport analysis, subsurface hydrology, Monte-Carlo simulations, exceeding risk, heterogeneity.

1 Introduction

The exploration of hydrocarbons in the Republic of Croatia started some 100 years ago, and significant oil and gas reserves have been discovered. More than 4,300 exploration and production wells were drilled into onshore and offshore sedimentary deposits. In the 1990s, Croatia initiated a program for disposing of



the oil waste generated in the process of exploring, drilling, producing, refining, and distributing of hydrocarbons—by deep-well injection into dry exploration or depleted production wells. Deep injection technology enables not only the disposal of waste generated by the oil industry, but also the waste generated in other industries—such as the food, chemical, leather, and pharmaceutical industries. Through deep injection disposal, waste may be permanently and safely isolated into geologically appropriate media. The overall waste disposal cost and the possibility of heavy metals polluting potable water are thereby reduced.

Apart from disposal technology, there is a very important segment of flow and transport analysis needed in order for disposal methodology to be reliable and safe [1, 3, 5]. Reliability of the disposal methodology is defined with the concept of risk exceedance, i.e. probability that injected oil waste passes through the selected cross section (e.g., shallow subsurface aquifers). The objective of the disposal methodology is to reduce the exceeding risk and safely remove oil waste “from our neighborhood” without endangering other water and human resources.

In this paper we present risk assessment analysis of the oil waste disposal in the deep wells of the Žutica oil field. Risk assessment analysis is based on flow and transport of injected oil waste using the stochastic Monte-Carlo numerical simulations and detailed geostatistical analysis of the subsurface heterogeneity structure. We will present flow and transport analysis as well as risk assessment for different time periods and cross sections.

2 Computational setup

Figure 1 shows a map of the north part of the Žutica oil field in Croatia. There is an abundance of appropriate deep wells for injection. We have analyzed the injection well Žu-273 in the middle sector of the field. Geological stratification can be roughly presented as follows: first 500 m dominate gravel and sand layers with clay sublayers (surface aquifers important for water supply), from 500 to 1000 m dominate sand and sandstone layers with clay sublayers, while for deeper layers there is exchange of sandstone and marl sublayers. Deep geological sandstone and marl sublayers around depth of 2000 m are used in the past for oil production. Nowadays, these practically isolated sublayers are appropriate for deep oil waste injection. In the deep well Žu-273 there are three open holes at 1976–1985 (m), 1994–2021 (m) and 2038–2055 (m). Porosity is assumed constant with average value of 0.15, while conductivity field is considered as isotropic and heterogeneous explained through the detailed geostatistical analysis in the next section. Oil waste is specially prepared as fluid with small suspended particles (colloids) which has a density of $1006 - 1020 \text{ kg/m}^3$. Injection period is 20 years with an average daily amount of 30 m^3 .

Flow computational domain has a dimension of $2000 \times 2000 \times 350 \text{ m}$ around the injection well in a horizontal plane and from 1850 to 2200 m in the vertical direction. Top and bottom parts of the domain consist of low permeable marl sublayers. Domain is divided to 68921 cells. Each cell or block has dimension of



50×50×8.5 m. The transport analysis considers injection mass as collection of 190000 particles with uniform mass using the Monte-Carlo approach and 100 conditional realizations of the heterogeneous geologic media.

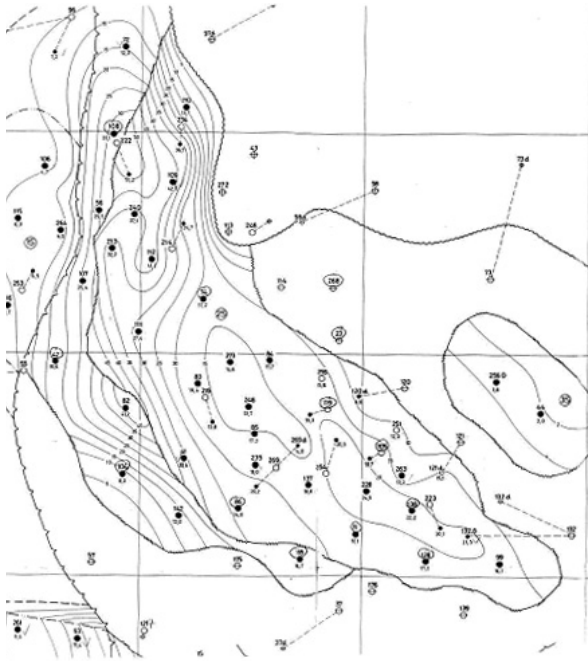


Figure 1: Map of the Žutica oil field (Croatia).

3 Flow and transport analysis

3.1 Geostatistical analysis

Geostatistical analysis is needed in order to describe heterogeneity of the injection domain, which is the main input for the flow and transport model. It is particularly important to incorporate all available hard and soft data or direct measurements for obtaining the best possible prediction of the hydraulic conductivity distribution. In the injection zone there are a relatively large number of direct or hard laboratory core measurements, especially for the sandstone zones, but soft data are important for detailed description of the conductivity field due to their amount, quality and different support scales. Large amount of useful surrogate data are available in the form of the geophysical measurements of the spontaneous potential and resistivity or field injectivity tests. All these measurements enable categorization of the low (marl) and high (sandstone) permeability zones where direct hard data are not available. Suitable methodology for analyzing soft data in the form of the categorical variables (0 –

sandstone, 1 – marl) is provided by indicator kriging (GSLIB, [4], program SISIM). Soft measurements show that sandstone and marl zones occupy 75 and 25% of the injection area, respectively. Figure 2a shows indicator 3-D map for one typical conditional realization where measurements are exactly satisfied, but in other blocks stochastic simulations are used to generate sandstone or marl zones, according to the prescribed proportion. Note that for the flow and transport of the injected oil waste, detection of the connected high permeable sandstone zones are particularly important.

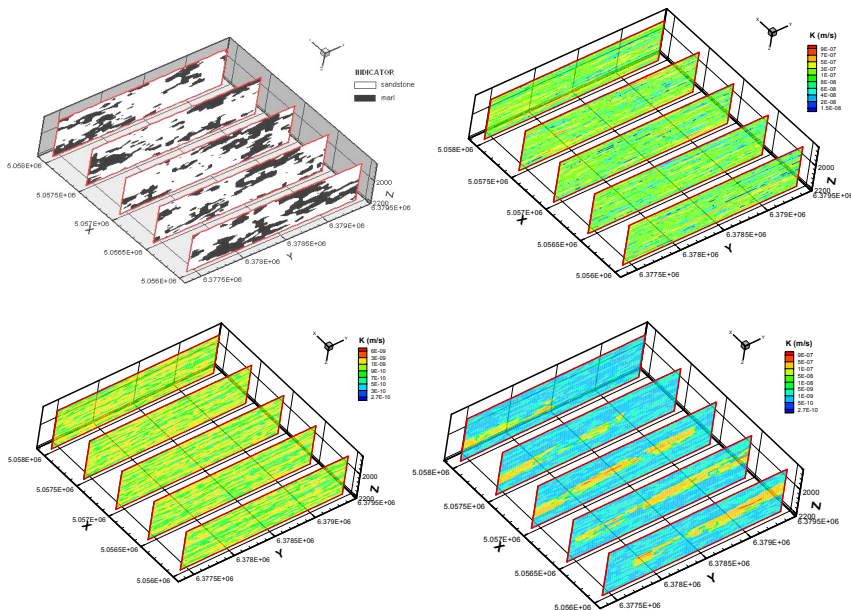


Figure 2: Geostatistical analysis in one typical conditional realization: a) upper left, indicator map of marl and sandstone cells using soft data, b) upper right, map of sandstone using hard data, c) lower left, map of marl using hard data and d) lower right, final map of marl and sandstone cells using soft and hard data.

Figure 2b presents one typical conditional realization of the sandstone using only hard data (GSLIB, [4], program SGSIM). Heterogeneity is a relatively small, while conductivity fluctuations are occurred over the one order of magnitude. Figure 2c shows one typical unconditional realization of the marl, because hard data are too sparse in the low permeable zones. We know that mean value of the marl zones is at least two orders of magnitude lower than sandstone zones and they are relatively homogeneous. Figure 2d shows final geostatistical conductivity map, which is obtained by merging all three presented particular maps (Figure 2a-c) in each realization. The top and bottom parts of the injection zone consist of low permeable marl zones, which practically isolate injected oil

waste. Note that despite relatively homogenous sandstone and marl zones, the complete injection zone is highly heterogeneous porous formation with different low and highly permeable zones. In this way, we were able to use hard as well as all existed soft data in our geostatistical analysis.

3.2 Flow problem

In this paper 3-D steady flow problem is modeled using the software package Modflow (1996):

$$\frac{\partial}{\partial x} \left(K(x, y, z) \frac{\partial H(x, y)}{\partial x} \right) + \frac{\partial}{\partial y} \left(K(x, y, z) \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left(K(x, y, z) \frac{\partial H}{\partial z} \right) - q = 0 \quad (1)$$

where K is conductivity (L/T) and H is piezometric head (L). Initial conditions are constant over the whole domain ($H=2000$ m). Boundary conditions on top and bottom side of the domain are no-flow Neumann conditions, while other vertical sides consist of constant Dirichlet conditions ($H=2000$ m). Moreover, constant boundary conditions are imposed in the injection deep well through open holes ($H=3282$ m). Figure 3 shows piezometric field in one chosen realization. Contrary to the conductivity field, piezometric fields do not differ significantly over the different realizations because piezometric head is mainly determined by injection boundary conditions rather than conductivity heterogeneity. Finally, in each realization the velocity field is obtained through Darcy Law using the conductivity and piezometric head field.

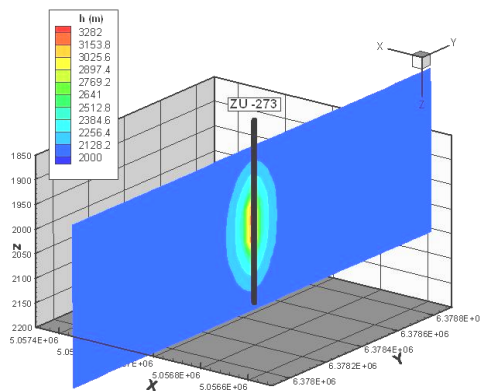


Figure 3: Piezometric head field in one typical conditional realization.

3.3 Transport

Conventional finite element and difference methods require very fine discretization in order to accurately solve transport advection-dispersion equation (ADE) and satisfy grid Peclet number in order to eliminate numerical

dispersion and/or oscillations. The robust alternative is given by the particle tracking method which solves the ADE by tracking the large number of distinct particles that are distributed within the source area or injection deep well [7]. Without loss of generality, each particle is initially associated with a uniform mass. The sum of all particles gives the total mass of the contaminant source. Particles are then spread by random steps which consist of the advective and dispersive part according to the given steady velocity field in the each realization [6–8]. Hence, it is possible to calculate displacement and travel time for each particle and arbitrary control plane or concentration field for particular discretization. Since we consider only advective transport influenced by heterogeneity and neglecting pore-scale dispersion, random walk method is transformed to its dispersion-free form, i.e. particle-tracking algorithm.

Figure 4a and b shows displacement and concentration field, respectively, in one chosen realization at $t=100$ year. Both fields are mainly influenced by heterogeneity patterns and connected highly permeable sandstone zones.

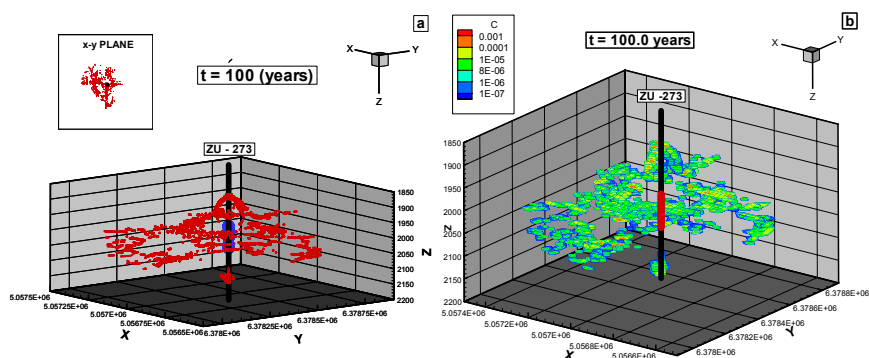


Figure 4: (a) Particle displacement field, and (b) concentration field in one typical conditional realization at $t=100$ year.

3.4 Monte-Carlo ensemble statistics

Displacement, travel time and concentration ensemble transport results are calculated over all 100 conditional realizations. Monte-Carlo statistics are the main input to the risk assessment, especially displacement statistics, which show horizontal and vertical spreading of the injected oil waste plume. Figure 5a shows horizontal displacement statistics for three distances or control planes (CP) from the injection well, 100, 300 and 500 m, respectively. Mean value of the mass fraction is 50% for the first control plane, less than 10% for the second plane and practically zero for the third control plane at 500 m from the injection well. It means that radius of the injection influence is less than 500 m for $t=100$ year. The standard deviation is not too large (less than 10% and 5% for the first and second CP, respectively) due to using all possible hard and soft data.

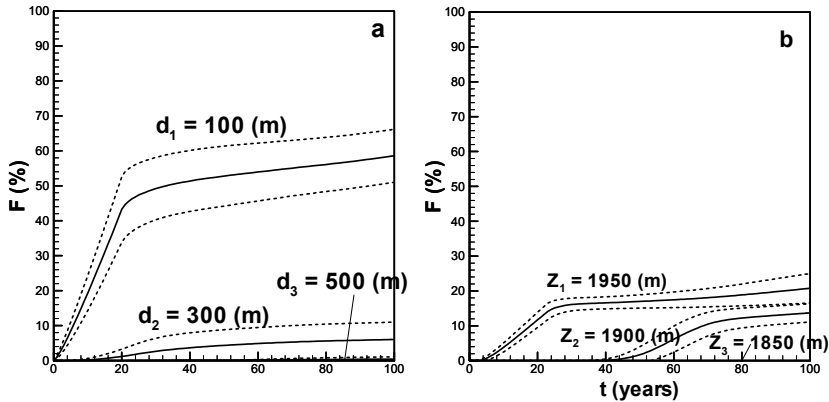


Figure 5: Displacement statistics: (a) mass fraction that passes through three different horizontal distances from the injection well (b) mass fraction that passes through three different horizontal cross-sections.

More important for the risk assessment is the analysis of the vertical spreading of the injected oil waste plume. Figure 5b shows mass fraction of the injected oil waste that passes through three selected cross sections above the open holes. In the first 100 years for the injection time of 20 year, very small mass fraction will pass through the third cross section ($Z=1850$ m) around 150 m above the open holes. For 50 and 100 m above the open holes, only mean value of 20% and 13% will pass toward the shallow aquifers. Once again, standard deviation is a relatively small which implies our strong ability to predict considered injection process without significant amount of the uncertainty. Detailed presented numerical model can serve as a basis for extrapolation flow and transport analysis to the time period of 10000 years.

4 Risk assessment

The risk associated with the potential failure of a system is the result of the combined effects of inherent randomness of various uncertainties involved in the analyses [1]. Risk of an engineering system can be defined as the probability that load “L” on the system exceeding the resistance “R” of the system:

$$p_r = P(L > R) \quad (2)$$

in which $P(L > R)$ denotes the risk probability. Generally, risk calculation requires the knowledge of the joint pdf of L and R:

$$p_r = \int_{r_1}^{r_2} \left[\int_r^{l_2} f_{R,L}(r,l) dl \right] dr \quad (3)$$

If we assume that L and R present independent events, risk is defined by:

$$p_r = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} f_L(l) dl \right] g_R(r) dr \quad (4)$$

For the oil waste disposal system the risk in (4) can be interpreted as an exceeding risk that load, i.e. vertical spreading of the injected oil waste exceeds resistance, i.e. vertical position of the aquifer for water supply or some other limit in the upper horizontal zones. In this paper we will present exceeding risk for different vertical position of the shallow aquifer.

Firstly, we choose cross-section at $Z=1850$ m which is 150 m above the injection open holes and it is also the boundary of the detailed numerical flow model described in sections 2 and 3. The risk exceedance is evaluated up to $t=100$ year and from equation (4) is $p_r=10^{-3}$.

In general, especially in the radioactive waste disposal, the exceeding risk is usually considered for a longer time period, i.e., $t=10000$ years and resistance is placed at the level of shallow aquifers which are or will be utilized for water supply in agriculture and industry. In the presented example, the hydrogeological reports defined shallow aquifers at the depth of 500 m. We use presented flow and transport Monte-Carlo results as initial conditions for long-term analytical calculation [2] of the vertical plume spreading toward the shallow aquifers. Figure 6 shows that multiple marl layers between injection zone and shallow aquifers considerably decrease vertical plume spreading and therefore

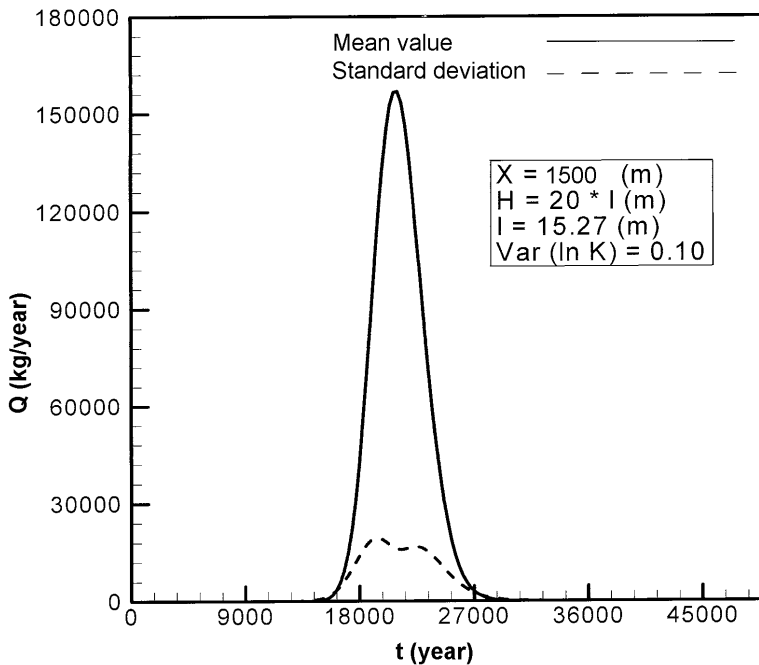


Figure 6: Long-term transport, in the vertical direction, from the injection zone to the shallow aquifers.

significantly reduce the risk exceedance. Mean breakthrough curve from the Figure 6 can be regarded as a load function and using again equation (4), exceeding risk is $p_r=10^{-47}$ which confirms that the proposed oil waste disposal in this case could be appropriate and safe.

5 Conclusions

In this paper we present risk assessment analysis for the oil waste disposal in the deep wells of the Žutica oil field (Croatia) at an injection depth of around 2000 m. The injection zone is described using geostatistical methods consisting of low permeable marl and high permeable sandstone zones. Flow and transport analysis of injected oil waste is considered using the stochastic Monte-Carlo approach. The exceeding risk is defined as a probability that injected oil waste passes through selected cross section or shallow aquifers. The results show that the exceeding risk of $p_r=10^{-47}$ is a very low or practically negligible for period $t=10000$ years, at shallow depth of $Z=500$ m which confirms safety and reliability of the presented oil waste disposal for this case. For a deeper control plane, $Z=1850$ m, and shorter time period ($t=100$ year), $p_r=10^{-3}$ indicating a certain level of risk which should be considered before making decisions. Note that additional processes like unsteady velocity field involving the chemical reactions together with the influence of the local dispersion are not considered in this case although they will be on safe side creating additional vertical spreading of the oil waste plume and could considerably reduce the exceeding risk.

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