Prediction of the contamination track in Al-Najaf city soil using numerical modelling

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Abstract. Leachate generated from Municipal Solid Waste (MSW) may drain into groundwater aquifers as a consequence of rainfall, transmitted to the conterminous river system through groundwater flow and contaminate the environment. Iraq, because of the lack of accurate data and the high cost of measurement, accurate assessment of leachate generation levels has often been considered a problem. The production of leachate connects into many factors, such as the data of meteorological, levels of waste production, and requirements of design landfill, the large differences in these factors indicate that leachate modelling processes are complicated. The purpose of this paper is to predict the movement of various contaminants in landfill soil in Al Najaf city to predict the behaviour and distribution of landfill pollution in order to properly understand the distribution of contamination in these soil, to control it and to prevent groundwater contamination to predict the depth of leachate from landfill using numerical model by SEEP/W, and CTRAN/W packages from GeoStudio 2012 Software.

1. Introduction
In the last decades, the rapid growth of urban center and the progress of industrialization has resulted in the production of a great amount of industrial solid refuse, a big portion of it ends up in the engineered landfills [1]. Soil contamination is one of the most critical issues in environmental engineering that affects human health and living organisms directly and indirectly; generally, any alteration in soil properties and its element with an unusual increase or decrease in concentration affecting human health, engineering facilities, groundwater and agricultural land is called soil pollution [2].

Landfills are semi-natural terrestrial ecosystems rebuilding on lands terrains debased by waste disposal, or its typical waste disposal facilities in urban areas [3,4]. During the stabilization of waste in a specific landfill for a period of time it produces a liquid substance which is called leachate [5], it may contain significant quantities of organic matter (biodegradable, but also refractory to biodegradation) where wet-type components consist of an essential group, heavy metals, ammonia-nitrogen, inorganic salts, and chlorinated organics. [6], Municipal solid waste (MSW) is containing a high percentage of liquid and soluble components because discarded waste consists fundamentally of organic materials, involves the residual of fruit, vegetables, and food [7]. The leachate under landfill sites are passing easily through the soil layers, this process has an effect on the engineering properties of soils such as swelling and compressibility of soil, the shear strength, and the chemical properties of soils [8].
Gypseous soils are mainly the topsoil in Iraq and mostly in an unsaturated state [9,10]. Wetting progress in such soil (unsaturated gypseous) caused a reduction in the strength of the soil and increasing in its deformation [11-15].

In the Najaf governorate, solid waste management is one of the major problems faced by the local administration, and it’s one of the reasons for the political dispute in the governorate because of the holiness of the city, and the increase in solid waste generation [16]. Iraqi municipal solid waste density $(C) = 0.45 \text{t/m}^3$ [16].

The leachate may infiltration to groundwater aquifers due to rainfalls propagation in the near river system by groundwater flow and contaminate the environment; this process does not stop even after the landfill activities have stopped receiving solid waste. So, it is very necessary to stay monitoring and assessing the surroundings of decommissioned landfill sites [17]. Estimating the amount of leachate is essential in waste management and treatment of leachate systems upon discharge to the surrounding environment [18]. Millions of people all over the world depend a drinking water supply on groundwater as the major source of drinkable, groundwater contamination as the main source of potable water supply is of environmental and health concern, because of the side effects of landfill leachate penetration into the groundwater [19].

The recent paper investigates the depth and width of the contamination pulp due to the leachate from landfill in Al-Najaf city soil.

2. Methodology and materials

2.1. Material
The studied area is located in AL-Najaf Governorate in the middle of Iraq [10]. The samples used was taken from Al-Furat district (32°01’14.8” N 44°21’08.2”E) from a depth up to 2m. The initial soil tests are conducted to determine influential soil properties like maximum and minimum density, soil particle distribution, coefficient of permeability and other tests which are clarified in Table 1 and summarizes the properties of the soil for the selected sample in AL-Najaf Governorate.

2.2. Capillary rise
The authors have been made a series of capillary rise experiments on different soil samples [20]. They stated that the capillary rise in the selected site is 350mm at density 1.65 gm/cm$^3$.

2.3. Coefficient of permeability
The permeability coefficient of sandy soil plays a key role in the landfill numerical analysis process. The permeability of sand soil is tested by using a constant head test. The constant head permeability tests were carried out on the sandy soil (from the selected site) remoulded specimens; the tests were replicated at four relative densities of 40%, 60%, 80%, and 100% to assess the effect of density on soil permeability as illustrates in Table 2.

2.4. Numerical Modelling
The GeoStudio 2012 package of SEEP/W and CTRAN/W was used for numerical modelling. SEEP/W is a finite element software tool for predicting groundwater leakage and excess water pressure dissipation in porous materials. In addition to steady- saturated flow, SEEP / W can model both saturated and unsaturated flow.

CTRAN/W is a finite element software tool used to model the movement of pollutants via porous materials such as sandy soils. CTRAN/W uses SEEP / W flow velocity to measure the emission of dissolved components in pore water [21,22].
Table 1. Properties of the soil in AL-Najaf governorate.

| Characteristics          | Value  |
|--------------------------|--------|
| Gravel, %                | 2.64   |
| Sand, %                  | 94.32  |
| Fine, %                  | 3.04   |
| $D_{10}$, mm             | 0.17   |
| $D_{30}$, mm             | 0.28   |
| $D_{60}$, mm             | 0.9    |
| Soil Classification System (USCS) | SP   |
| Field density, gm/cm$^3$ | 1.8142 |
| Field water content, %   | 3.05   |
| Max. dry density, gm/cm$^3$ | 1.77 |
| Optimum moisture content (OMC), % | 16   |
| Gypsum content, %        | 18.03  |

Table 2. Permeability coefficient of soil at various Relative densities.

| Relative Densities, % | Permeability, m/s |
|-----------------------|-------------------|
| 40                    | 0.000248          |
| 60                    | 0.000236          |
| 80                    | 0.000107          |
| 100                   | 0.000037          |

2.5. Methodology

To model the contaminant emission in sandy soil, the geometry used is 15 m in length × 5 m in depth. Groundwater table is at 3m below the surface of the soil, as shown in Fig. 1, where (D) is depth and (W) is width of the contamination. The value of diffusion coefficient for leachate is estimated $1 \times 10^{-9}$ m$^2$/sec [23] and the saturated water content of sand is estimated 0.41 m$^3$/m$^3$ [24]. The permeability Ratio ($k_y/k_x$) for sandy soil is taken 1 and 0.1 [25].

Matric suction is the difference between both pore air pressure ($U_a$), and pore water pressure ($U_w$). The relationship between soil water content and matric suction in sand soils is described by the soil-water characteristic curve (SWCC) [26]. SWCC is a graphical illustration of the mathematical relation between matric suction of a soil ($U_a-U_w$) and water content (volumetric or gravimetric). The data of curve is obtaining from GeoStudio program and re-plotted in Excel, as shown in Fig. 2.

Figure 1. The geometry of the domain.
Figure 2. Soil-Water Characteristic Curve (SWCC).

The investigated parameters are the solid waste density (C) (25 kg/m$^3$, 100 kg/m$^3$, 250 kg/m$^3$, and 450 kg/m$^3$), the soil relative density (40%, 60%, 80%, and 100%) and the anisotropic (k$_y$/k$_x$) (1 and 0.1), the track (depth (D) and width (W)) of the contamination is predicted and plotted for the different studied parameters. Table 3 shows the information that used in the numerical modelling. Figure 3 shows the contaminant's penetration into the soil and the pollutant's propagation when it reaches to capillary level and groundwater level during the time.

Table 3. Input data in the numerical modelling.

| Parameter                     | Value    |
|-------------------------------|----------|
| Water level, m                | 3        |
| Capillary Rise, mm            | 350      |
| Longitudinal Dispersivity, m  | 2        |
| Transverse Dispersivity, m    | 1        |
| Dry density, gm/cm$^3$        | 1.77     |
| Length of model, m            | 15       |
| Width of model, m             | 5        |
| Diffusion, m$^2$/sec          | $10^{-9}$|

Figure 3. Contaminant’s penetration into the soil during the time.
3. Results and Discussion

3.1. Effect of the density of the solid waste
In this study, we have studied how the contamination depth is affected in sandy soil at four values of the permeability, which are 0.000248, 0.000236, 0.000107, and 0.000037 all in m/s at two values of permeability ratio \((k_y/k_x)\). Figure 4 shows the increasing contamination depth overtime at four permeability values and at \((k_y/k_x) =1\). The behavior of the increased contamination depth in these figures show that the contamination reaches a specific depth at different values of time, i.e. it needs more time for \(k= 0.000037\) than for \(k= 0.000248\). This is similar to the case in real-life where the contamination depth reduces by decreasing the permeability coefficient and increases by increasing the permeability coefficient.

Figure 4. Depth of contamination vs time for the specified concentrations \(C\) and \(k_y/k_x=1\)

Figure 5 illustrate increasing the width of the contamination horizontally with respect to the originally proposed width of the applied contamination area, which is taken to be 2 m. At low values, the width of the contamination increases very slightly and reaches moderated values at relatively high values of the time. It is clear from Figures that the progress of the contamination width for 40% and 60% relative density approximately coincided and we can notice a sensible change at 80% and 100% relative density.

Prediction of the horizontal diffusion is very important for some applications and infrastructures that can be affected by changing the composition of the subsoil of these infrastructures. As we have mentioned before, the leachate consists mostly of organic materials that can cause swelling over time, and this can cause damage to the neighbour infrastructures.
Figure 5. Width of the contamination vs time for the specified concentrations C and \( k_y/k_x = 1 \)

3.2. Effect of Anisotropic (\( k_y/k_x = 0.1 \))

Figure 6 reveal the penetration depth of the contamination at permeability coefficients of 0.000248, 0.000236, 0.000107, and 0.000037 all in m/s at ratio \( (k_y/k_x) = 0.1 \). The behavior of the penetration still as the same as what we have noticed at ratio \( (k_y/k_x) = 1 \) but with significantly large amounts of time to reach its destination at the corresponding depth at \( (k_y/k_x) = 1 \). For example, the depth of 2.5 m at concentration 25 kg/m\(^3\) and permeability 0.000037 can be reached at elapsed time 5200 seconds when \( k_y/k_x = 1 \) while the elapsed time will be 56000 seconds to reach this depth when \( k_y/k_x = 0.1 \). The ratio 0.1 means that \( k_y \) is 10 times greater than \( k_x \), and this causes that the majority of the contamination material diffuses horizontally at the unit of time.

Figure 7 illustrate how the width of the contamination diffused horizontally with respect to the assumed width of the applied contamination area at permeability coefficients of 0.000248, 0.000236, 0.000107, and 0.000037 all in m/s at ratio \( (k_y/k_x) = 0.1 \). At low amounts of time, the width of the contamination increases slightly as we have noticed when \( (k_y/k_x) = 1 \) and reaches high values at high values of elapsed time. The required time to reach a specific horizontal distance at \( (k_y/k_x) = 0.1 \) needs more time than what is required at \( (k_y/k_x) = 1 \). Also, we can only notice the difference in horizontal emission for 80% and 100% relative density while the diffusions at 40% and 60% relative densities are very close to each other.
Figure 6. Depth of contamination vs. time for the specified concentrations C and $k_y/k_x = 0.1$

Figure 7. Width of the contamination vs. time for the specified concentrations C and $k_y/k_x = 0.1$
3.3. Tracking of the Contamination

The contamination reaches the zone of the capillary rise at depth 2.65m at time $T_c$. Table 4 illustrates the relationship among relative densities of the soils, different concentrations, and the elapsed time for the contamination material to reach the underground water at the zone of the capillary rise. The duration time is very important to be estimated contamination emission because they present the dangerous time period at which the pollution can occurs. We note that the contamination reach the capillary zone and groundwater table at time ($T_c$) has increased due to the assumption that the soil is Anisotropic, i.e. the permeability in the vertical and horizontal direction, which increases the time of contamination emission and spreading to the soil. Figure 8 illustrates the ratio of the width of contamination (WC) to the depth of penetration (DC) when the contamination reaches to capillary rise zone (WC/DC Ratio). There is a decreasing trend in the WC/DC ratios but with limited range (1.6-1.7)

| RD, %  | C, kg/m$^3$ | $T_c$, min. | $k_y/k_x = 0.1$ | $k_y/k_x = 1$ |
|--------|------------|-------------|----------------|----------------|
| 40     | 25         | 119.17      | 17.2           |                |
| 60     | 25         | 158.33      | 17.8           |                |
| 80     | 25         | 350         | 40             |                |
| 100    | 25         | 1116.67     | 115.5          |                |
| 40     | 100        | 205.33      | 20.83          |                |
| 60     | 100        | 213.33      | 21.67          |                |
| 80     | 100        | 466.67      | 45.83          |                |
| 100    | 100        | 1333.33     | 133.33         |                |
| 40     | 250        | 250         | 25             |                |
| 60     | 250        | 266.67      | 25.84          |                |
| 80     | 250        | 566.67      | 56.67          |                |
| 100    | 250        | 1666.67     | 158.33         |                |
| 40     | 450        | 319.17      | 33.33          |                |
| 60     | 450        | 358.33      | 35             |                |
| 80     | 450        | 750         | 77             |                |
| 100    | 450        | 2175        | 218.17         |                |

**Table 4.** Elapsed time for the contamination to reach the capillary rise zone.

![Figure 8](image-url)  
**Figure 8.** The relation between the $W_C/D_C$ Ratio and Leachate Density (C).
4. Conclusion

1- The time of contaminant penetration into the soil and reaching it to groundwater level in coarse-grained soils such as sandy soil decreases with decreasing relative soil density, so, reducing the Relative soil density, the soil permeability ratio increased and, as a consequence, the contaminant penetration rate increased.

2- For sandy soils, the level of capillary rise increases by increasing the relative density of the soil, while the rise in the relative density of the soil, the void becomes smaller, and water deposits for capillary paths and smaller cavities of the soil, as a wetting fluid, so the level of capillary increases.

3- Soil and fluid properties such as permeability, volumetric water content, void ratio, relative soil density, and permeability ratio \((ky/kx)\), longitudinal and transverse dispersion coefficients, and pollutant diffusion coefficient significantly influence on the trend and pattern of contaminant emissions in soil depths.

4- In the Anisotropic soil, the time of pollutant penetration into the soil reaches the groundwater level is increased due to the permeability in the vertical and horizontal direction, so the pollutant needs more time to emission in the soil.

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Acknowledgment
The authors would like to acknowledge the staff of the soil laboratory at the Faculty of Engineering at the University of Kufa in Najaf-Iraq. Also, we would like to acknowledge Dr. Madarász Tamás and Dr. Hasan Eteraf at the University of Miskolc - Faculty of earth science in Hungary for their help and facilities.