Numerical simulation of the law of leachate movement in landfill of a mountain city

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Abstract: There are a lot of mountain cities in western China. A large number of landfills in mountain cities in western China were constructed before the 1990s. Where these landfills are not adapted to modern needs, the landfills will be closed and renovated. The law of leachate transport must be studied in order to close and remediate them successfully. This paper provides a study of the Qilongcun landfill in Chongqing city in western China. The Qilongcun landfill is typical of those in mountain cities. The law of leachate transport in the landfill reflects the law of leachate transport for all mountain cities. The geological model was generalized for the Qilongcun landfill and a mathematical model was established. Then, the simulated density of leachate was compared with the actual density and the mathematical model was identified and adjusted. The correct mathematical model had been acquired when the simulated density of leachate approximates the actual density of leachate. The variation of leachate density was numerically simulated for inside and outside, northward, southward and both sides of the landfill, and the law of leachate transport was analyzed. The law is that the leachates move rapidly along faults and in the Quaternary strata and influx to low-lying land on the southward side of the landfill. The law supplies a basis to close and remediate other landfills of mountain city in western China.

Résumé: Il y a beaucoup de villes de montagne en Chine occidentale. Un grand nombre d'enfouissements des déchets dans des villes de montagne en Chine occidentale a été construit avant les années 1990. Où ces enfouissements des déchets ne sont pas adaptés aux besoins modernes, les enfouissements des déchets seront fermés en haut et rénovés. La loi de transport de leachate doit être étudiée pour fermer en haut et les reobtenir par médiation avec succès. Le papier fournit une étude de l'enfouissement des déchets Qilongcun dans la ville Chongqing en Chine occidentale. L'enfouissement des déchets Qilongcun est typique de ceux dans des villes de montagne. La loi de transport de leachate dans l'enfouissement des déchets Qilongcun reflète la loi de transport de leachate pour toutes les villes de montagne. Le modèle géologique a été généralisé pour l'enfouissement des déchets Qilongcun et un modèle mathématique a été établi. Puis, la densité simulée de leachate a été comparée avec la densité réelle et le modèle mathématique a été identifié et ajusté. Le modèle mathématique juste avait été acquis quand la densité simulée de leachate se rapproche à la densité réelle de leachate. La variation de densité leachate a été numériquement simulée pour l'intérieur et extérieur, vers le nord, vers le sud et les deux côtés de l'enfouissement des déchets et la loi de transport de leachate a été analysée. La loi est que le leachates se déplace le long des fautes et le mouvement rapidement dans la strate Q et l'afflux dans la cavité sur le côté vers le sud de l'enfouissement des déchets. La loi fournit une base pour fermer en haut et reobtenir par médiation d'autres enfouissements des déchets de ville de montagne en Chine occidentale.

Keywords: landfill, environmental geology, leachate, pollution, numerical models, diffusion.

INTRODUCTION

The handling of domestic refuse is often restricted by the development of the urban economy. The economy of most mountain cities in westward of China has been underdeveloped in the past, so most of the refuse was simply dumped and buried on the outskirts of cities. The leachate infiltrates through soil due to the lack of any capping on the top of the site and lack of any means to prevent leakage at its bottom. Furthermore, with the rapid development of these cities, urban areas including residences are being constructed closer and closer to the landfill. As a result, they are no longer adapted to current needs and so will be closed and remediated.

Studies on landfill remediation of plain cities are under way but so far there is practically no report on studies of mountain cities. The remediation measures of plain city landfills cannot be applied to those from mountain cities as the two differ in topographic and geological conditions. Landfills of mountain cities tend to be in valleys and hydrology characterised by fracture flow.

Chongqing, a typical mountain city in China, urbanized and developed rapidly in recent years. The landfills which cannot meet present needs will be closed and renovated. Compared with landfills of plain cities, the geological conditions of landfills in Chongqing city are complicated, inhomogeneous and anisotropic with weathered joints and faults (Wang, Liu &Wang et al, 2001). The leachate easily permeates into the groundwater through the faults and joints, contaminating the groundwater. The groundwater is an important resource for water supply of nearby residents of villages and towns and landfill pollution constitutes a serious threat to human health (Lui, Sun, Jiang & Zhang et al.2002.). It is an urgent task to close and remediate the landfill. However, while the top and periphery of landfills can be sealed, the bottom cannot. As a result of technological limitations, the atmospheric precipitation, surface water and some heavy-metal contamination still replenish landfills (Lei, Qing & Yang, 1993). Leachate therefore pollutes the groundwater and geological environment through the bottom of landfills (Smith, Rowe & Booker, 1993). In order to close and remediate them successfully, it is necessary to study the law of leachate movement. Among the 9 landfills in Chongqing cities, the topographic and geological conditions of Qilongcun landfill are the most typical of mountain cities. The law of leachate movement in Qilongcun landfill can reflect that of mountain cities. The study on the law of leachate movement in Qilongcun landfill can serve as a guidance to renovate landfill of Qilongcun and other landfills in Chongqing, and even in other mountain cities in western China.

HYDROGEOLOGICAL CONDITION OF THE LANDFILL

Most of the landfills in Chongqing are located in valleys. The strata are sandstone, mudstone and limestone. They are inhomogeneous and anisotropic with jointing. The groundwater is porewater and fracture water. Most of the aquifer is unconfined.

The Qilongcun landfill was built in 1986. The Qilongcun landfill covers an area of 50 000 m^2. The amount of waste handled is about 0.00347 kg/s. The total amount of waste handled is about 2 200 000 kg. The regional slope is from north to south. The obliquity is 200. The groundwater flows from north to south in the landfill. There are mudstones and deposits of the Quaternary Period (Q), and sandstone of Jurassic (J) age. The groundwater consists of porewater in unconsolidated deposits and of fracture water in weathered bedrocks. There is a precipitous two-meter-high sandstone cliff with few fractures in the east of landfill. The seepage is feeble, and the stratum is confining. Three faults, namely F1, F2, and F3 form a "Y" shape (Fig.1). There are also joints around faults. The top of landfill has no capping to prevent permeation, so the landfill is replenished by precipitation. The leachate flows into the gully, which is in south of the landfill. There is no establishment to prevent leakage. The leachate permeates to the exterior of the landfill, making the exterior and interior of the landfill as a whole. The research areas include the landfill and areas 300 m away from it.

As there is no shroud over top of the landfill to prevent the precipitation replenishment, the top of landfill is flux of Neumann boundary. The influx is precipitation, and the efflux is evaporation. The gully is Dirichlet boundary. There is no establishment to prevent leakage at the bottom of the landfill, so the bottom is flux of Neumann boundary.

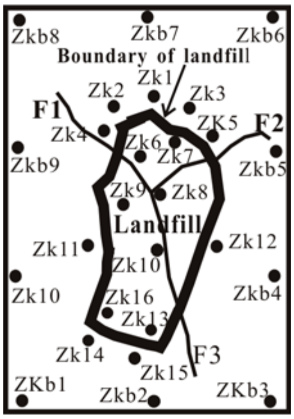


Figure 1. The sketch map of the research area.

ESTABLISHMENT AND CALCULATION

At present, there is no model for fracture flow. Hence, the equivalent pore media was adapted to study on leachate movement. The study of leachate movement involves the calculation of the flow equation, convection and dispersion equation of contamination (Faust, 1985). The three-dimensional flow equation is expressed as equation (1) (Wang, Zhou & Gong, 2000).

$$\frac{\partial}{\partial x}(k_{xx}\times m\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(k_{yy}\times m\frac{\partial H}{\partial y})+\frac{\partial}{\partial z}(k_{zz}\times m\frac{\partial H}{\partial z})+\varepsilon=\mu\frac{\partial H}{\partial t} \qquad (x,y,z)\in\Omega \tag{1}$$

where H is the hydraulic head in m, Kxx, Kyy are values of conductivity through the unit volume along the x, y coordinate axes in m/s, ε is a volumetric flux per unit volume in m^3/s, μ is the storage coefficient, m is aquifer thickness in m, μ is storativity; Ω is field of seepage; and n is the outside normal direction of seepage boundary.

The convection and dispersion equation of contamination expressed as (2).

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}(D_{xx}\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(D_{yy}\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(D_{zz}\frac{\partial C}{\partial z})-\frac{\partial \upsilon_x c}{\partial x}-\frac{\partial \upsilon_y c}{\partial y}-\frac{\partial \upsilon_z c}{\partial z}+\frac{q_s}{\theta}C_s+\frac{\rho_b}{\theta}\frac{\partial\bar{c}}{\partial t}-\lambda(C+\frac{\rho_b}{\theta}\bar{c}) \tag{2}$$

Equation (2) can change to (3).

$$R\frac{\partial}{\partial t}=\frac{\partial}{\partial x}(D_{xx}\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(D_{yy}\frac{\partial C}{\partial y})-\frac{\partial}{\partial z}(D_{zz}\frac{\partial C}{\partial z})-\frac{\partial \upsilon_x c}{\partial x}+\frac{\partial \upsilon_y c}{\partial y}+\frac{\partial \upsilon_z c}{\partial z}+\frac{q_s}{\theta}C_s-\lambda(C+\frac{\rho_b}{\theta}\overline{C}) \tag{3}$$

where R is independent of the concentration field, $R=1+\frac{\rho_b}{\theta}\frac{\partial \overline{c}}{\partial c}$; ρ_b is density of soil mg/L. θ is the porosity of the porous medium; C is the solute concentration in mg/L; C_S is concentration of influx or efflux in mg/m, D_{xx}, D_{yy}, D_{zz} is diffusion coefficient in m^2/s; υ_x, υ_y, υ_z are velocities of groundwater flow in m/s. $\upsilon=-\frac{k}{\theta}\frac{\partial H}{\partial x}$; λ typically represents radioactive decay of both the free and adsorption solute in s^{-1}; t is time in s; $\overline{c}$ is concentration of pollution in the medium of containing water or moisture in mg/L.

The start conditions are initial hydraulic head and initial concentration condition that expressed as equation (4) (Mecarthy & Zachara, 1989).

$$H\big|_{t=0}=H_0(x,y,z)\ \ (x,y,z)\in\Omega \qquad C\,|_{c=0}=C_0(x,y,z)\ \ (x,y,z)\in\Omega \tag{4}$$

The first boundaries, varying head and Dirichlet boundary expressed as (5)

$$H\big|_{B_1}=H_1(x,y,z,t)\ \ t>0 \qquad C\,|_{B_1}=C_1\ (x,y,z,t)\ \ t>0 \tag{5}$$

The second boundaries, constant head and flux of Neumann boundary expressed as (6) and (8).

$$\left[K_{xx}\frac{\partial H}{\partial x}\cos(\vec{n},\ x)+K_{yy}\frac{\partial H}{\partial y}\cos(\vec{n},\ y)+K_{zz}\frac{\partial H}{\partial z}\cos(\vec{n},\ z)\right]\Bigg|_{B_2}=q(x,\ y,\ z,\ t) \tag{6}$$

$$\left[-\upsilon c+\vec{D}\tfrac{\partial C}{\partial n}\right]_{B_2}=p(x,y,z,t) \tag{7}$$

$$\vec{K}\tfrac{\partial H}{\partial \vec{n}}\Big|_{B_2}=q(x,y,z,t); \qquad \left[\upsilon c+\vec{D}\frac{\partial c}{\partial \vec{n}}\right]_{B_1}=p(x,y,z,\mathrm{t}) \tag{8}$$

where $\vec{K}$ is tensor of conductivity; $\vec{D}$ is tensor of dispersion coefficient. $q(x,y,z,t)$, $p(x,y,z,t)$ is flux of flow and flux contamination through aquifer boundaries in m^3. n is the outside normal direction of seepage boundary. $\cos(\vec{n},\ x)$, $\cos(\vec{n},\ y)$, $\cos(\vec{n},\ y)$ is cosine of the outside normal direction of seepage boundary.

The three-dimensional flow equation (1), the convection and dispersion equation of contamination (2) or (3), the start condition (4), Boundaries condition (6) to (8), they form of the leachete movement mathematical model.

Penman adopted the finite-difference, disperse three-dimensional flow equation (1), and then acquire finite-difference formula of geothermal water seepage in the cell (i, j, k). If all the flows are finished at the same time, the finish time is t. Then acquire finite-difference formula; it is expressed as equation (9).

$$\begin{aligned}&CR_{i,j-\frac{1}{2},k}(h^m{}_{i,j-1,k}-h^m{}_{i,j,k})+CR_{i,j+\frac{1}{2},k}(h^m{}_{i,j-1,k}-h^m{}_{i,j,k})+CR_{i-\frac{1}{2},j,k}(h^m{}_{i-1,j,k}-h^m{}_{i,j,k})\\&+CR_{i+\frac{1}{2},j,k}(h^m{}_{i+1,j,k}-h^m{}_{i,j,k})+CR_{i,j,k-\frac{1}{2}}(h^m{}_{i,j,k-1}-h^m{}_{i,j,k})+CR_{i,j,k+\frac{1}{2}}(h^m{}_{i,j,k+1}-h^m{}_{i,j,k})\\&+P_{i,j,k}h^m{}_{i,j,k}+Q_{i,j,k}=\mu_{i,j,k}(\Delta r_i\Delta l_j\Delta V_K).(h^m{}_{i,j,k}-h^m{}_{i,j,k})/(t_m-t_{m-1})\end{aligned} \tag{9}$$

where CR is hydraulic conductivity of border upon cells in m^3/s^{-1}. P is a constant related to the exterior source, Q is a volumetric flux per unit volume and represents internal sources of water in m^3/s^{-1}; t is finish time in m.

The H was calculated by equation (8), so thevelocity was acquired by calculation H. Then the equation (3) was adopted finite-difference to calculate the density of contamination. This is the principle of the leachate movement mathematical model.

DISCRETING RESEARCH AND IDENTIFICATION OF THE MATHEMATICAL MODEL

The research area includes the landfill and areas 300m away from it. The thickness is about 112.5 m from the landfill's surface to bottom, where there is no jointing or faulting. Hence, the thickness of the research area is 112.5 m. The area studied is divided into 3 layers, 60 rows, 46 columns, and 8280 cells. The area is divided into four parameter areas according to experiments and aquifer characteristics. The faults are the first partition, the waste is the second partition, sandstone is the third partition, and mudstones and unconsolidated deposits the fourth partition. The landfill is to be remediated, so the area lacks monitored data. The landfill COD was monitored around ZK7 and ZK9 after landfilling for 8 years. On the basis of the mathematical model established using the parameters of experiment, the leachate movement be simulation to calibrate the model (Iaco, Green & Maurer et al, 2003).

As the landfill lacks monitored data, there are few points where the simulated density was contrasted with the actual density. There exist several points to monitor water level, but only ZK16 well has been monitored for any length of long time. In order to successfully identify the mathematical model, the simulated COD density was compared with the actual density, and the simulated water level and the actual water level, then the parameters were adjusted up or down by 0.05 and 0.1. The model was modified. An appropriate mathematical model had been acquired when the simulated density and water level approximated the actual density and water level (Figure 2 & Figure 3). See Table 1 for the main parameters.

C ALCULATION THE TOTAL REPLENSHMENT OF THE MODEL

The top of landfill is flux of Neumann boundary. Rainfall is about 1081.6 mm/a in Chongqing (Yin, Wang, & Zhang, 2002). The filter coefficient is about 0.5 in the landfill, and is about 0.15 on the exterior of landfill. So the replenishment of atmospheric precipitation is 0.000 856 m^3/s within the landfill and 0.000 257 m^3/s on the exterior of the landfill of the research area. The total replenishment of atmospheric precipitation is 0.001 113 m^3/s. The moisture content of waste is about 0.06 in Chongqing (Yin, Wang, & Zhang, 2002), and the total amount of waste handled is about 2 200 000 kg, so the yield of leachate is 0.001 520 m^3/s.

The water consumed by decomposed degradation. The gases of landfill are CO_2 and CH_4, the percentage of CH_4 being about 50. The gases come from decomposing organic compounds. The yield of water consumed by decomposed water is about 0.000 499 m^3/s through calculation. The vapour water is about 0.000 160 m^3/s.

So the total replenishment of the model is 0.001 974 m^3/s in the research area.

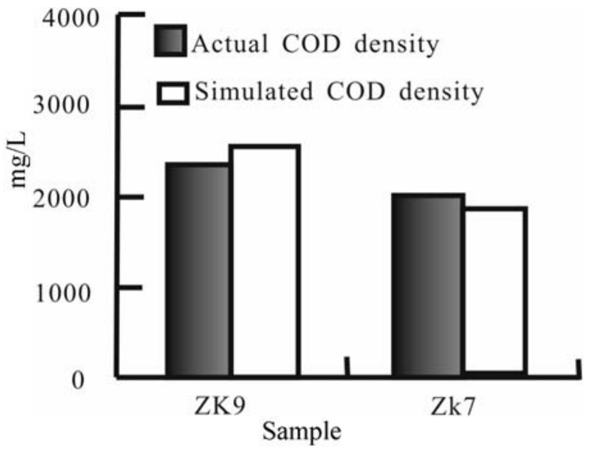


Figure 2. Comparison of simulated COD density with actual COD density.

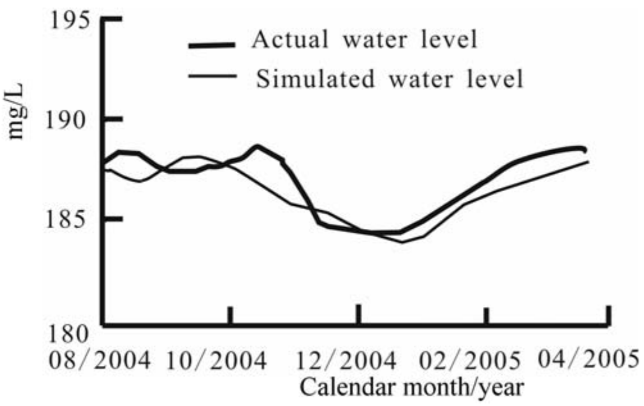


Figure 3. Comparison of simulated water level with actual water level.

Table 1. The main simulation parameters

The zones of parameters	Coefficient of permeability (m/s)	Storativity	Longitudinal dispersion coefficient (m)	Porosity (%)
Areas of faulting	3.2×10^{-3}	0.25	0.112	25.2
Areas of refuse	3.2×10^{-4}	0.25	1.2	27.5
Areas of sandstone and sandstone	9.49×10^{-7}	0.20	0.1	23
Areas of Q deposit	5.2×10^{-6}	0.21	0.1	21

NUMERICAL SIMULATION OF THE LAW OF LEACHATE MOVEMENT IN LANDFILL

Because the research area is heterogeneous and anisotropic, the law of leachate movement is different in different parts (Aristodemou, Thomas-betts, 2000). For example, the variation law contamination density (such as BOD, COD, P, and N) is different in different time. So the contamination density variation law reflects the character of leachate movement. In order to analyze the law of leachate movement, the COD density variation law is studied with respect to the interior, exterior and periphery of the landfill.

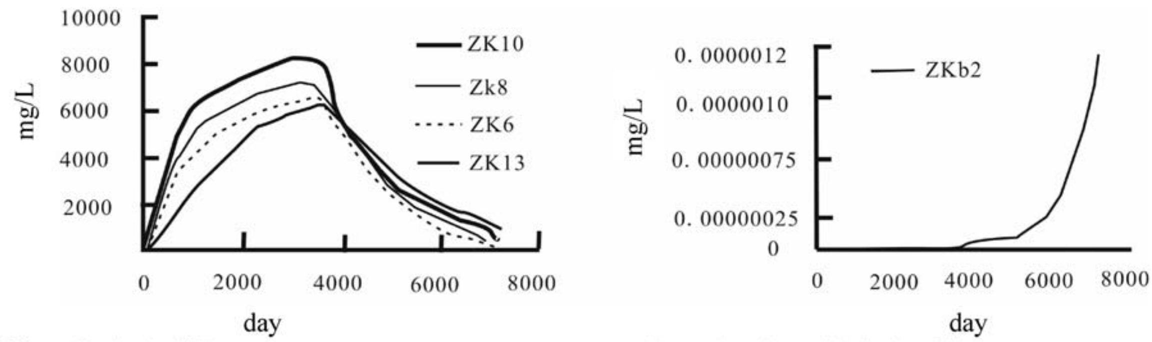
Interior of the landfill

The three faults meet at the ZK8 well in the north of the landfill. ZK10 well is close to the fault F3 in the middle of landfill. There is no fault near ZK13 well, which is at the south end of landfill. Density variations are shown in Figure.4. The law of COD density variation of ZK8 is similar to that of ZK10 and ZK13. The density has increased during the 10 years of waste disposal. The density is maximal in the tenth year of the waste disposal, and the density gradually decreases after that. The COD density of ZK6 and ZK10 is higher than that of ZK13, because the conductivity of faults is so high that the leachate rapidly flows into faults, leading to the increase of the COD density of ZK6 and ZK10 well. The COD density of ZK10 is higher than that of ZK13 because the topography of landfill is valley, with north higher than south. Besides, the faults become channels for the leachate movement and the leachate flows into ZK10. As a result, the density and the pollution of ZK10 are higher than that of ZK8.

The variable characteristics of leachate density show that the leachate movement was influenced by faulting and topography. The faults serves as the conduit for leachate movement and accelerate movement. The leachate moves downwards, so the pollution in the low-elevation area is greater than that of the high-elevation area.

Exterior of the landfill

There are 10 wells for density observation in the research zone 300–450m away from the periphery of the landfill (Fig.1). Their density variations are similar. Among them, the topography of ZKB2 well, which is at the middle of south research periphery, is relatively low and the leachate flows into it, so its density variation is the highest (refer to Fig.4 for the COD density variations of ZKB2 well). The density variation of the 10 wells shows that the leachate density in the research zone 200m away from the periphery of the landfill is low and the pollution is not serious.



(a) Inside the landfill (b) In B2 well outside the landfill

Figure 4. The COD density variation of leachate in the interior and exterior of landfill.

Periphery of the landfill

On the north boundary of the landfill, there are no faults near ZK1, ZK2 and ZK3 wells, so the leachate movement is not affected by faulting. The groundwater flows from north to south, the north of the landfill is at the upper reach of the groundwater, and the pollution source centralizes in the middle of landfill. So the contamination of leachate moves by dispersion. The process of dispersion is slow (see Fig.5a for the density variations of ZK1, ZK2 and ZK3 wells). Fig 5a shows that the density is relatively low on the north boundary of landfill. The density of ZK2 and ZK3 wells is approximately zero. ZK1 well is located between ZK2 and ZK3 well, and it is close to the landfill. The leachate COD density of ZK1 well is conversely higher than that of ZK2 and ZK3 wells. Their maximum density is lower than 500 mg/l.

On the south boundary of landfill, the density variations of ZK14 and ZK15 wells are shown in Fig.5b. The density is maximal in the tenth year of the waste disposal. The density is about 3 500–5 000 mg/l. ZK15 well is located in the gully and is close to F1 fault. The gully and fault serve as the conduit for the leachate movement, so the COD density of ZK15 increases or decreases more quickly than that of ZK14 well, and the maximum value of ZK15 is higher than that of ZK14.

Fig 6 shows the leachate density variations of wells on the south and north boundaries of the landfill. The leachate COD densities of ZK14 and ZK15 wells on the south boundary are higher than those of ZK1, ZK2 and ZK3 on the north boundary. This indicates that the leachate flows towards the south of the landfill.

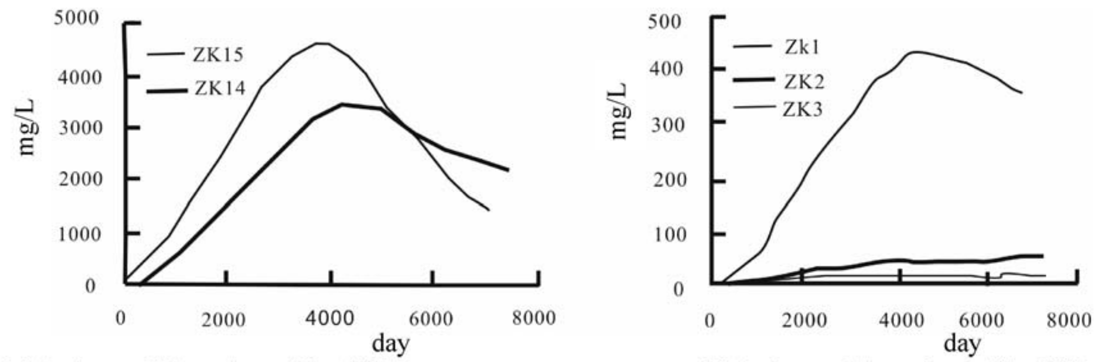
On both sides of the landfill, there are 4 wells for density observation. Two of them, ZK4 and ZK10, are in the east of the landfill and the other two, ZK5 and ZK11, in the west. ZK4 and ZK5 are of the same latitude, as are ZK10 and ZK11.

The variations of leachate COD density in ZK4 and ZK5 wells are shown in Fig. 6. Fig. 6 and Fig. 5 b show that the law of leachate COD density variation of ZK4 and ZK5 is similar to that of ZK1 well. The elevation of ZK5 well is higher than that of ZK4, so the COD density of ZK4 is higher than that of ZK5 well. The ZK4maximum density is 300 mg/L.

Fig. 6 shows the leachate COD density variation of ZK11 and ZK12 wells. The figure shows that the density of ZK4 and ZK5 wells is higher than that of ZK11 and ZK12 because ZK4 and ZK5 are in the unconsolidated sediment, while the ZK11 is in the mudstone and the ZK12 in sandstone. Mudstone and sandstone conductivities are smaller. These show that the conductivities of rock influence the leachate movement and the degree of pollution.

The law of leachate movement

The variation of leachate density was studied with respect to the interior, exterior and periphery of the landfill. The COD densities of the wells are highest in the interior of landfill, with a maximum density of about 7500 mg/L. The maximum density is 4500 mg/L around the southern boundary of landfill. From the middle to the north of the boundary, the maximum density is 450 mg/L. Unconsolidated sediments on both sides of the northern part of the landfill have a maximum density of 300 mg/L. Mudstone and sandstone on the both sides of the middle-south of landfill have a maximum density of 25 mg/L. Finally, the minimum COD densities are seen around the periphery of research area. There is little pollution 300–450m away from the landfill.



(a) In the south boundary of landfill.
(b) In the north boundary of landfill.

Figure 5. The COD density variation of leachate in the north and south boundary of landfill.

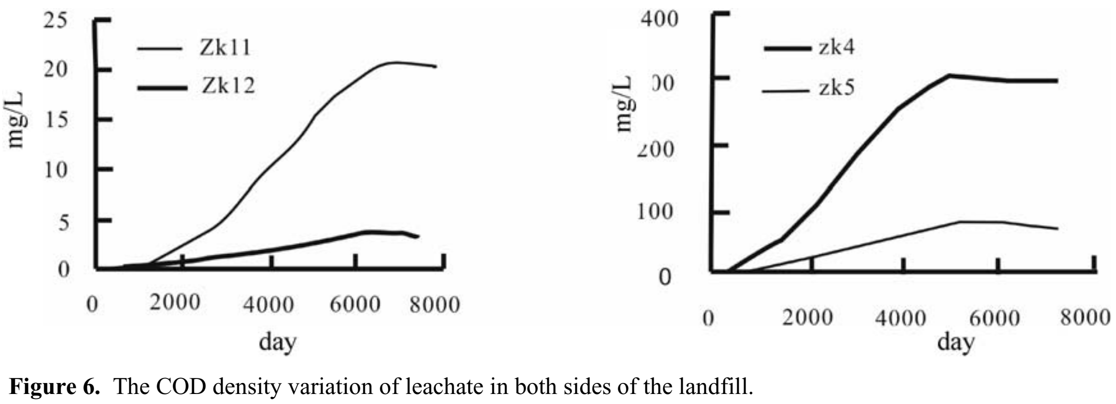


Figure 6. The COD density variation of leachate in both sides of the landfill.

CONCLUSIONS

The Qilongcun landfill is typical of landfill of mountain cities. The law of leachate transport in the Qilongcun landfill reflects the law of leachate transport for most mountain cities. Four laws of leachate movement in the mountain cities were drawn from the study on leachate transport in the Qilongcun landfill. The 4 laws are as follows: firstly, the wells closer to the landfill have higher leachate density and more serious pollution, the maximum COD density is about 7500 mg/L in the interior of landfill and about 450 mg/L around the boundary of landfill. Secondly, the faults and joints serve as conduits for the leachate movement, so the density is high in the faults. Within the fault, the ZK10 maximum COD density extends to more than 7000 mg/L. Thirdly, the higher the rock conductivities, and the faster the movement of the leachate, the maximum COD density is about 300 mg/L in the unconsolidated sediment. Finally, the density of wells at higher elevation is lower than that of wells at lower elevation, the contamination density in the lower elevation on the north of the landfill is higher than in the interior.

The law of leachate movement shows that seepage must be prevented in the fault zones and unconsolidated deposits. The leachate flows into the lower-elevation area, so it is important to build a cistern to contain the leachate, and then pump leachate out of the cistern. The barrel-drains are supposed to be constructed to drain water around the landfill and to reduce the replenishment of precipitation. That way, the yield of leachate can be reduced and the pollution controlled. If these measures are taken, the landfill may be remediated effectively.

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