

Analysis on contaminant migration through vertical barrier walls in a landfill in China

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Abstract Vertical barrier walls are often constructed to prevent contamination of ground water and soils by landfill leachate. The leachate water levels in landfills in southern China are generally high. Contaminants in such landfills may migrate through the vertical barrier walls and give rise to environmental problems. Qizishan landfill in Suzhou, China was taken as an example to investigate contaminant migration through the vertical barrier walls. Advection, diffusive and adsorption processes were considered in the analysis. Influences of permeability and depth of the barrier wall on contaminant migration were analyzed. The results show that it will be 13.5 years before breakthrough at 0.1% of the source concentration and 20.5 years before breakthrough at 10% of the source concentration. By and large, the contaminant has not passed through the barrier wall at present, and the contaminated zone is mainly located in the sandy clay layer near the earth dam, which is validated by testing on sampled soils. Hydraulic conductivity and depth of the barrier wall are critical to contaminant migration. Special attention need to be paid on them when building such a barrier wall. If bottom of the barrier wall is keyed into the aquitard and the hydraulic conductivity reaches 10^{-9} m/s, the time before breakthrough will be long enough to allow stabilization of the landfill. Pollution of the surroundings will be avoided, and therefore the requirement for contaminant control will be attained.

Keywords Landfill · Vertical barrier wall · High leachate water level · Contaminant migration · Breakthrough time

Introduction

The generation of municipal solid waste (MSW) has increased rapidly with economic development and urbanization in China. Land disposal of MSW has consequently become a common practice since the late 1980s in China. Now, there are more than 700 landfills in China. Unfortunately, most of these landfills are not sanitary landfills and were constructed under the earliest regulations for landfills (CJJ17-1988) by the Ministry of Construction, China. Generally, there are no engineered basal sealing systems in these landfills. Vertical barrier walls were often built for pollution prevention. There are also no effective leachate collection and drainage systems at the bottom of these landfills. To make things even worse, there are usually no stormwater/leachate separation systems on the surface of the landfills. As a result, leachate levels are generally high in these landfills, particularly in southern China where rainfall is plentiful. In such circumstances, contaminants in leachate may be transported through the vertical barrier wall, and the downstream area may be polluted.

A number of studies (Rowe et al. 1995; Foote et al. 1996; Katsumi et al. 2001; Sangam 2001; Merayyan 2001; Qian et al. 2002) have been carried out to investigate the contaminant migration through horizontal barriers, i.e., geomembranes and compacted clay liners at the bottom of a landfill. Though vertical barrier walls have been used for many years in landfills, only few literature references focusing on contaminant migration through vertical barrier walls are readily available. Anderson and Mesa (2006) studied the effectiveness of impermeable open barrier walls on hydraulic control of contaminants. The barrier walls that they studied were combined with extraction wells as components of pumping and treating systems. Analytic

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solutions were given considering only the advection process. Harte et al. (2006) simulated solute transport across low-permeability barrier walls using two numerical models, in which advective transport across the barrier was neglected. On the other hand, it was pointed by Philip (2001) that advective flux was the dominant contaminant transport process. Philips (2001) investigated contaminant transport through cement–bentonite slurry walls considering advection and diffusion. Performance of the slurry walls was investigated in detail, whereas contaminant transport process in the soil layers was not mentioned.

As leachate water levels are often high in landfills in China and vertical barrier walls are widely used to restrict pollution, it is of practical significance to investigate contaminant migration in such landfills and to evaluate the performance of a vertical barrier wall. A typical valley fill, the Qizishan landfill, is taken as an example to study the problem. Advection, dispersion and adsorption processes are considered in the analysis of contaminant migration. The result of the analysis is validated by tests on drilling samples. Influences of permeability and depth of the vertical barrier wall on contaminant migration were analyzed.

Site description

Qizishan landfill is representative of the landfills built in 1990s in China. It was regarded as a standard landfill by the Ministry of Construction, China. The landfill is located in a valley (Fig. 1) in Suzhou, where the average annual rainfall is 1036 mm. It began operating in 1993 and had a planned active life of 15 years. Now, the buried wastes reach a depth of more than 30 m. The landfill covers an area of 7.44 ha and has a capacity of $4.7 \times 10^6 \text{ m}^3$. In recent years, the landfill has received 1250–1660 ton/day of waste generated from Suzhou city. The (average) volumetric water content of the collected waste is about 40%. The wastes are dumped directly into the landfill with little compaction. There is an earth dam at the toe of the landfill

to maintain slope stability and at the same time, to allow burying more wastes. A leachate lagoon with a capacity of $20 \times 10^3 \text{ m}^3$ was built to hold leachate. There is a natural pool located 30 m downstream of the leachate lagoon. It has a capacity of $50 \times 10^3 \text{ m}^3$ and is used for sediment of surface runoff from the valley. There are no leachate collection and removal systems beneath the waste. Broken stones were put below the earth dam to form a drain for the leachate. The drain became fully clogged after several years of operation. Consequently, there has been a buildup of leachate in the landfill. Five monitoring wells (MW1 ~ MW5) shown in Fig. 1 were drilled in the buried area and piezometers were installed to monitor leachate water level. The results illustrate a leachate depth of about 20 ~ 30 m.

According to the engineering geological investigation, the landfill is underlain by sandy gravelly clay, with a thickness of 10 m and a permeability of $1.12 \times 10^{-6} \text{ m/s}$, followed by moderately weathered sandstone, with a thickness of 10 m and a permeability of $2 \times 10^{-6} \text{ m/s}$ and slightly weathered sandstone (aquicard), with a thickness more than 20 m and a permeability of $5 \times 10^{-9} \text{ m/s}$ (Fig. 2). The landfill has no horizontal basal liner systems. In order to prevent the migration of contaminants in leachate, a vertical grout curtain, i.e., a barrier wall was built downstream the leachate lagoon, with its base keyed into the slightly weathered sandstone (Fig. 2). The thickness of the vertical barrier wall is 1 m in the sandy gravelly clay and 3 m in the other two layers. In the initial scheme, the permeability of the barrier wall was designed to be not higher than 10^{-9} m/s , whereas it reached about 10^{-8} m/s after being constructed. Under high leachate head, contaminant may be transported through the soil strata and the vertical barrier wall, and therefore, the downstream areas may be polluted.

Governing equation

Mechanisms of contaminant migration in a porous medium include transport process and attenuation process. The two basic transport processes are advection and dispersion. Advection is the movement of the contaminant with the flowing water. Dispersion is the apparent mixing and spreading of the contaminant with the flow system. The mixing component, often called mechanical dispersion, arises from velocity variations in porous media. The spreading component, often called chemical diffusion, arises from chemical potential gradient. In many cases, the effects of mechanical dispersion cannot be separated from chemical diffusion and hence, the two terms are grouped into one parameter called the hydrodynamic dispersion coefficient. The process of adsorption is believed to be the

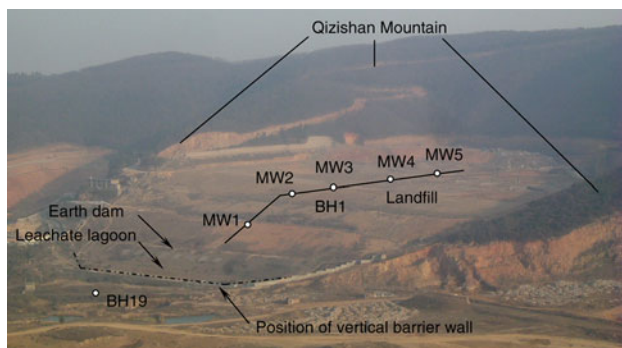
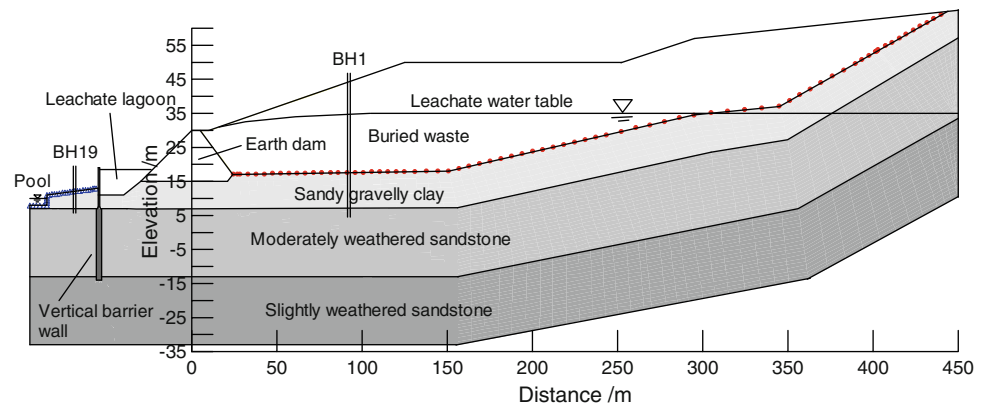


Fig. 1 Photograph of Qizishan landfill

Fig. 2 Numerical model of contamination migration



most important factor in attenuating the contaminant migration, which occurs between the contaminant and the soil particles.

The differential equation that describes contaminant migration is derived by applying the principle of mass balance to an element of a porous medium and considers the processes of advection, dispersion and adsorption. The following is the two-dimensional form of the equation:

$$\theta D \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) - V \left(\frac{\partial C}{\partial x} + \frac{\partial C}{\partial y} \right) = \theta R_d \frac{\partial C}{\partial t} \quad (1)$$

where θ , volumetric water content, note that θ equals porosity n when saturated; C , concentration (kg/m^3); D , hydrodynamic dispersion coefficient (m^2/s); V , Darcy velocity (m/s); R_d , retardation factor; x and y , orthogonal coordinates (m); t , time (s)

It can be seen that the first term on the left side of Eq. (1) represents the dispersion process, the second term represents the advection process and the right side of Eq. (1) represents the adsorption process. Retardation is considered to be:

$$R_d = 1 + \frac{\rho_d \partial S}{\theta \partial C} \quad (2)$$

where S is adsorption (kg/kg) and ρ_d is dry mass density of the porous medium (kg/m^3).

Contaminant migration analysis and field investigation

Soils below the landfill are assumed to be homogeneous and isotropic. Parameters of these soils are shown in Table 1.

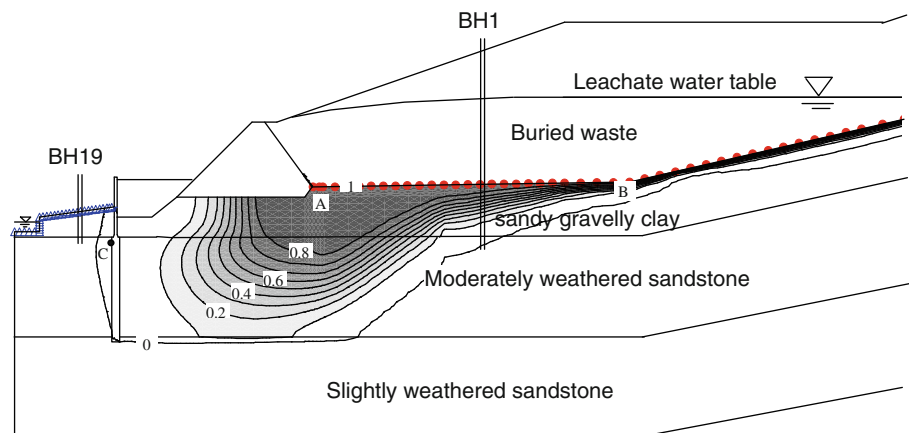
The retardation factor, R_d is assumed to be a constant for simplicity. This means a linear relationship between S and C . The value of R_d is referenced from a similar valley fill in Hangzhou, China. Dispersion coefficients of organic and inorganic contaminants in the soil layers are all assumed to be $2.0 \times 10^{-10} \text{ m}^2/\text{s}$ for simplicity. The permeability of the barrier wall was assumed 10^{-8} m/s .

The two-dimensional numerical model used to analyze the problem is shown in Fig. 2. The leachate water level is assumed to be steady in the analysis for simplicity, though it should be lower previously and higher in the following years. Preceding the contaminant migration analysis, a seepage analysis was carried out to obtain the flow field. In the seepage model, the boundary corresponding to the natural pool is defined as total head boundary according to the real water table there. The boundary between the natural pool and the leachate lagoon is defined as a review boundary to model the unconfined flow. Results of seepage analysis were used as input of the contamination migration model to consider the advection effect. In the contamination migration model, the initial concentration of all nodes is set to be zero. The boundary downstream the barrier wall is defined as free exit boundary with a constant concentration of zero. The boundary condition of the landfill bottom is considered to be a constant source concentration. It is noted that the relationship between contaminant concentration and the mass of adsorption is linear, so the proportion of dissolved contaminant to adsorbed mass remains unchanged. In addition, advection and diffusion do not change the quantity of contaminant in fluid, so the constant source concentration can be regarded as a relative one. For convenience, a relative concentration of 1 is used in this analysis.

Table 1 Transport parameters of the soils

Soil layer	Thickness m	k_s m/s	D m^2/s	n	R_d	ρ_d kg/m^3
Debris-containing silty clay	10	1.12×10^{-6}	2.0×10^{-10}	0.42	1.2	1.7×10^3
Moderately weathered sandstone	10	2.00×10^{-6}	2.0×10^{-10}	0.40	1.1	1.8×10^3
Light weathered sandstone	>20	5.00×10^{-9}	2.0×10^{-10}	0.36	1.05	1.8×10^3

Fig. 3 Contaminant migration after 15 years, $k_s = 10^{-8}$ m/s



Results show that the contaminant mainly exists in the fluid phase. For example, given a source concentration of 1 kg/m^3 , the total contaminant mass will be 785 kg after 15 years, with 722 kg in the fluid and 63 kg adsorbed on soils. The simulated relative concentration after 15 years, i.e., in the year 2008, is given in Fig. 3 at 0.1 intervals. It can be seen that the isoline of 0 concentration has passed the barrier wall. In other words, contaminant has migrated beyond the barrier wall at a relatively low concentration. Advection plays a key role in contaminant migration in view of the high leachate water level. It is known from the seepage theory that the nearer the position to the earth dam, the shorter the flow path and hence, the larger the flow velocity will be. For example, at point A (Fig. 3, near the earth dam), the flow velocity is 2.09×10^{-7} m/s, whereas at point B (Fig. 3, far from the earth dam), the flow velocity is only 7.18×10^{-10} m/s. So, the vertical extent of the pollution at point A is much larger than that at point B. The polluted area is mainly located near the earth dam, as shown in Fig. 3. As breakthrough time is concerned, it will be 13.5 years before breakthrough at 0.1% of the source concentration and 20.5 years before breakthrough at 10% of the source concentration. On the whole, contaminant has not migrated beyond the barrier wall on a large scale at present.

Field investigation was carried out to check whether soils below the landfill were polluted. Two boreholes, denoted as BH1 and BH19 in Fig. 2 and 3, were drilled and the sandy gravelly clay was sampled. Thickness of the sandy gravelly clay layer was 10 m in BH1 and 6 m in BH19, respectively. The sampled soil was eluted with water in laboratory to obtain an eluate of the adsorbed contaminant. The chemical oxygen demand (COD) concentration in the eluate was measured using the potassium dichromate method and chloride ion Cl^- concentration was measured by ion chromatography. The tested COD and Cl^- concentrations of samples in BH1 are high, especially the COD, which is higher than the warning pollution level

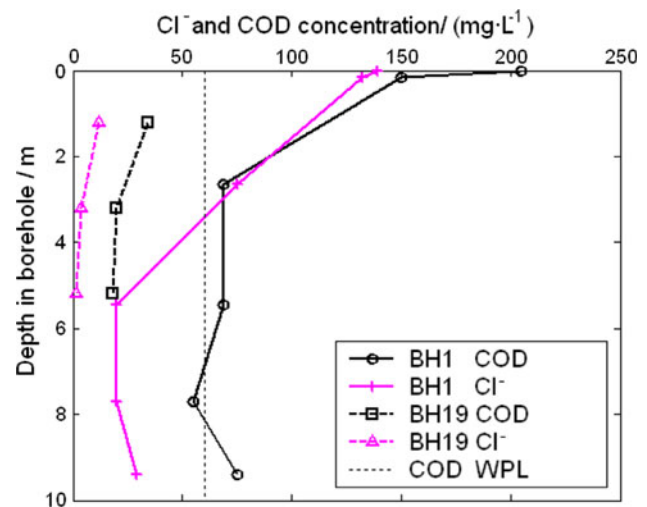


Fig. 4 Concentration of COD and Cl^- in BH1 and BH19

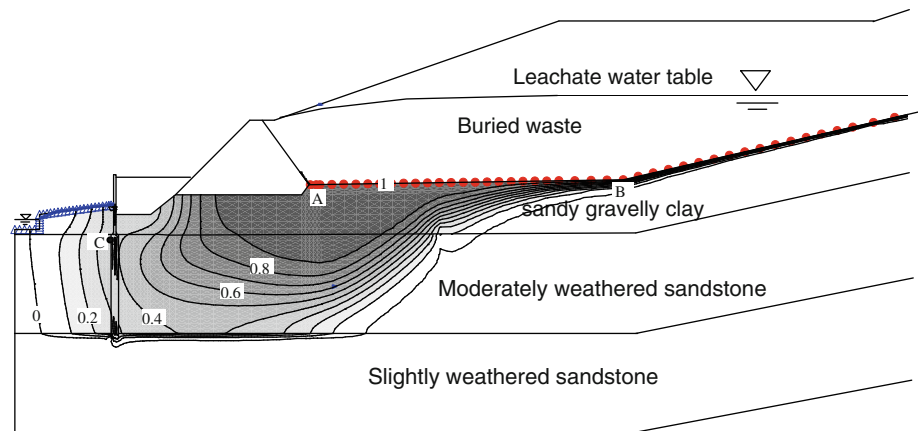
(WPL), as shown in Fig. 4. This illustrates that soils within the 10 m depths in BH1 were polluted. COD and Cl^- concentrations of samples in BH19 are relatively low and approximately close to their background concentration. This illustrates that soils here have not been polluted. The results of chemical analysis are consistent with results of numerical analysis described previously. Further monitoring is continuing to get more information on this landfill.

Analyses on permeability and depth of the vertical barrier wall

Analysis on permeability of vertical barrier wall

If hydraulic conductivity of the vertical barrier wall reaches 10^{-7} m/s, the increase in permeability will give rise to a larger flow velocity (Fig. 5). For example, at point A, the flow velocity is 4.31×10^{-7} m/s, two times larger than that corresponding to a 10^{-8} m/s hydraulic conductivity of

Fig. 5 Contaminant migration after 8 years, $k_s = 10^{-7}$ m/s



the barrier wall. As a result, the contaminant is transported faster by advection. The breakthrough times are calculated to be 3.8 years for 0.1% of the source concentration and 6.3 years for 10% of the source concentration. The simulated relative concentration after 8 years is given in Fig. 5 at 0.1 intervals.

If hydraulic conductivity of the barrier wall can satisfy the design requirement CJJ17-2004- China (ECPS-PRC 2004), i.e., if it attains a low hydraulic conductivity of 10^{-9} m/s, the decrease in permeability will induce a smaller flow velocity. For example, at point A, the flow velocity is 3.82×10^{-8} m/s, much smaller than in the case considered above. It will be 78.5 years before breakthrough at 0.1% of the source concentration and 125 years before breakthrough at 10% of the source concentration occurs. A point downstream the barrier wall (denoted as point C in Figs. 3 and 5) was examined. Variations of concentration at point C versus breakthrough time corresponding to different hydraulic conductivities of the barrier wall are shown in Fig. 6. It can be seen that the hydraulic conductivity has a great influence on the breakthrough time.

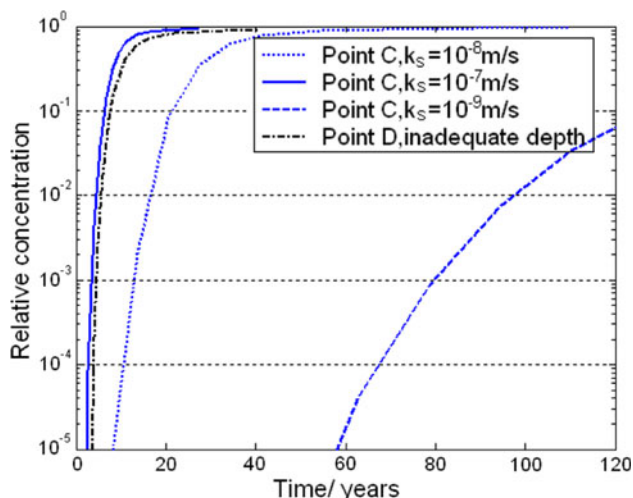


Fig. 6 Breakthrough curves corresponding to different hydraulic conductivity of barrier wall

Because the landfill itself can be regarded as a treatment system, the concentrations of COD and inorganic components of leachate will decrease to low levels when the landfill is covered for 20 years (VanGulck 2003). In other words, the landfill will approach stabilization and its polluting potential to the surroundings will be small at that time. Given the active life of 15 years, it is thought that pollution from the landfill will happen mainly in the first 35 years. The analysis shows that the barrier wall can prevent surroundings from being polluted for at least 78.5 years if the hydraulic conductivity attains 10^{-9} m/s. As the before mentioned stabilization time is concerned, it is concluded that the barrier wall can satisfy the requirement for contaminant control.

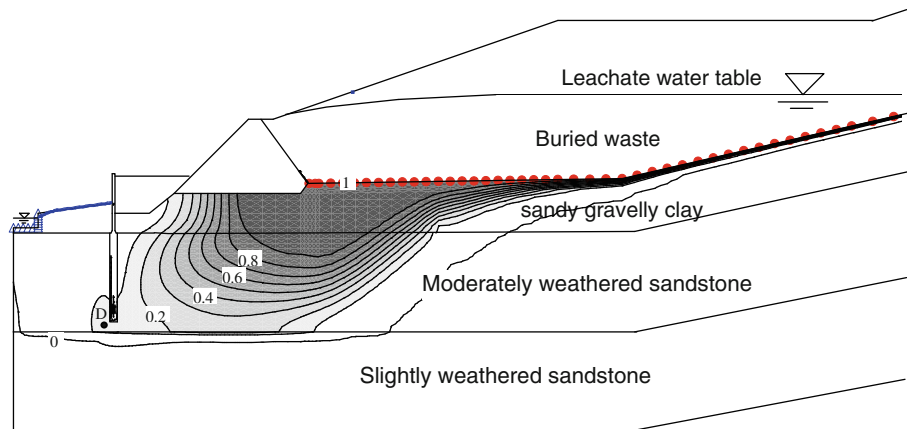
Analysis on depth of vertical barrier wall

Here, it is assumed that the vertical barrier wall was not keyed into the aquitard, i.e., the slightly weathered sandstone. A 2-m space between the barrier wall and the aquitard is used in the analysis. Whether the hydraulic conductivity of the vertical barrier wall is 10^{-8} m/s or 10^{-9} m/s, the breakthrough time for 10% of the source concentration is calculated to be about 7.7 years. Therefore, whether the vertical barrier wall is keyed into the aquitard or not is crucial to contaminant migration. The simulated relative concentration after 8 years is given in Fig. 7 at 0.1 intervals for $k_s = 10^{-8}$ m/s. It can be seen that breakthrough occurred under the barrier wall. Variation of contaminant concentration at point D is also shown in Fig. 6.

Conclusions

A typical landfill with a high leachate level is taken as an example in this study. Advection, dispersion and adsorption processes are considered in the analysis of contaminant migration through the vertical barrier wall. The results

Fig. 7 Contaminant moves under the barrier wall when its depth is inadequate



of numerical analysis show that it takes 13.5 years for the breakthrough of the barrier wall at 0.1% source concentration and 20.5 years for the breakthrough at 10% source concentration. The contamination is mainly restricted to the sandy clay layer near the earth dam, which is validated by testing on soil samples obtained from boreholes. Further analysis shows that hydraulic conductivity and depth of the barrier wall has great influences on the contaminant migration. It is important to attain the design requirements when building such a barrier wall. If the bottom of the barrier wall is keyed into the aquitard and the hydraulic conductivity is no higher than 10^{-9} m/s, the breakthrough time will be long enough to enable stabilization of waste within the landfill. Pollution of the surroundings will be avoided and therefore, the barrier wall will satisfy the requirement for contaminant control.

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References

- Anderson EI, Mesa E (2006) The effects of vertical barrier walls on the hydraulic control of contaminated groundwater. *Adv Water Resour* 29:89–98
- ECPS-PRC (Editorial Committee of Professional Standards of People's Republic of China) (2004) Regulations on sanitary landfill of municipal solid waste (CJJ17-2004). China Architecture and Building Press, Beijing (in Chinese)
- Foose GJ, Benson CH, Edit TB (1996) Evaluating the effectiveness of landfill liners. In: Proceedings 2nd international conference on environmental geotechnics. A.A. Balkema, Rotterdam, pp 217–221
- Harte PT, Konikow LF, Hornberger GZ (2006) Simulation of solute transport across low-permeability barrier walls. *J Contam Hydrol* 85(3):247–270
- Katsumi T, Benson CH, Foose GJ, Kamon M (2001) Performance-based design of landfill liners. *Eng Geol* 60:139–148
- Merayyan SM (2001) Evaluation of the unsaturated hydraulic functions of compacted landfill clay liners: impact on the predicted leakage rate. The Graduate School of Wayne State University, Detroit
- Philip LK (2001) An investigation into contaminant transport process through single-phase cement-bentonite slurry walls. *Eng Geol* 60(1–4):209–221
- Qian XD, Koerner RM, Gray DH (2002) Geotechnical aspects of landfill design and construction. Prentice-Hall, Inc, New Jersey, pp 131–179
- Rowe RK, Quigley RM, Brooker JR (1995) Clay barrier systems for waste disposal facilities [M]. Chapman & Hall, London
- Sangam HP (2001) Performance of HDPE geomembrane liners in landfill applications. Department of Civil and Environmental Engineering, in the University of Western Ontario, Ontario, pp 1–236
- VanGulck JF (2003) Biodegradation and clogging in gravel size material. Queen's University, Kingston, pp 20–28