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Vertical migration of leachate pollutants in clayey soils beneath an uncontrolled landfill at Huainan, China: A field and theoretical investigation

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HIGHLIGHTS

- Leachate transport in uncontrolled landfill bottom soils was investigated.
- Chloride migrated into the natural clayey soils to a depth of 9 m after 17 years.
- Migration depth of sodium and COD was 3–4 m.
- Advection and dispersion are more important than molecular diffusion at this site.
- Layered advection–dispersion model was used to evaluate the parameters of interest.

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ABSTRACT

To assess the extent of leachate migration, continuous samples of clayey soils (about 9 m) were obtained beneath a 17-year old uncontrolled landfill in southeastern China. The soil samples were sub sectioned and analyzed to determine the concentrations of chloride, sodium and COD in the pore water. Total nitrogen and soil organic matter content of the soil samples were also determined. Leachate-derived chloride was detected in the clayey soil to a maximum depth of 9 m. Sodium and COD were found to migrate into the soils to depths of 3–4 m due to the attenuation of solutes by the soil organic matter and clay minerals at the shallow soils. The estimated migration depths for the chloride are 3 m in the case of pure diffusion. Advection and mechanical dispersion were found to be more important than molecular diffusion for this site with an 8 m high leachate mound. By comparing the results obtained by the mathematical modeling for layered advection–dispersion problem with the measured concentration profiles, the ranges of the effective diffusion coefficient, retardation factor and dispersivity of the soils were estimated. Better fits are obtained by employing an artificial effective interface about 1 m above the observed interface. The clayey soils showed a relatively high attenuation capacity for COD with the estimated retardation factor of 5.

1. Introduction

More than 90% of municipal solid wastes (MSW) are disposed in landfills in China. Among these landfills, about 40% are uncontrolled landfills without any construction of bottom liner system and leachate collection system (Du et al., 2009). Landfill leachate may be characterized by four groups of pollutants: dissolved organic matter, inorganic macro-components, heavy metals, and xenobiotic organic compounds (Huang et al., 2009; Varank et al., 2011). The resultant pollutant plume from the leachate and its transport into the soil beneath the landfill site should be evaluated to determine whether it poses a threat to the immediate surroundings. The potential pollution caused by the leachate is the result of several factors, including the release of volatile fatty acids, chlorinated and non-chlorinated organic compounds and heavy metal ions into the environment, all of which are toxic to living organisms (Regadío et al., 2012).

Low-permeability soils are frequently used at waste disposal sites as a means of minimizing the convective flux of contaminants (Guyonnet et al., 2001; Mitchell, 2009; Foose, 2010). Field investigation, laboratory testing and numerical modeling are generally used to investigate the migration of landfill leachate in clayey soils (Rowe et al., 2004; Du et al., 2005; Chai et al., 2009). Many works have been done on leachate-derived contaminant migration through soils by laboratory column diffusion test (Khandelwal et al., 1998; Cuevas et al., 2012),

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advection–diffusion test (Rowe and Badv, 1996; Machado Sturmer et al., 2008) and adsorption test (Barone et al., 1989; Du and Hayashi, 2006; Pivato and Raga, 2006). Chalermyanont et al. (2009) carried out a series of physical and chemical tests of batch adsorption, column, hydraulic conductivity, etc. to evaluate the heavy metal sorption capacity, chemical compatibility of hydraulic conductivity, and transport parameters of the soils. The soil materials were then evaluated for potential use as landfill liner. Hyun et al. (2011) investigated the adsorptive behavior of fluoride using two model mineral sorbents (e.g., montmorillonite and kaolinite) during the seepage process. They found that the thickness of the liner and seepage rate through the liner layer should be primary factors in determining the efficacy of F^- removal from SPL-induced leachate. The Arkose sandstone–bentonite compacted mixtures were prepared and compared to evaluate their use as an isolation material in underground waste disposal (Ruiz et al. 2012). Experiments on synthetic landfill leachate migration through the specimens were carried out. Simulations of long-term diffusion transport and geochemical processes in an ideal landfill were also performed in their study. De Soto et al. (2012) investigated the diffusion of a synthetic urban landfill leachate through compacted natural illitic clays and evaluated the role of reactive accessory minerals (carbonates and gypsum) in the geochemical behavior of major soluble ions. Ghosh et al. (2012, 2013) investigated the feasibility of using a fine-grained soil as a suitable landfill liner material for the effective containment of chromium in the sludge leachate. Several series of laboratory permeability, adsorption, and column tests were conducted using soil without and with selected additives (rice husk, bentonite, and fly ash) to determine permeability and adsorption and transport of chromium in the soil.

Analytical and numerical methods are developed for leachate contaminant transport through the soils beneath and around the landfill site (Munro et al., 1997; Smith et al., 2004; Foose, 2010). However, examples of filed investigation on leachate migration in natural clay deposits are rather scarce in the literature, partly because barrier exhumations are very expensive once tens of meters of waste are in place, and partly because most research on contaminant migration has been devoted to plumes in non-cohesive soil deposits since these impact immediately on local groundwater resources (Rowe et al., 2004).

Several researchers have reported the field investigation of migration of contaminants through clayey soils (Goodall and Quigley, 1977; Crooks and Quigley, 1984; Quigley and Rowe, 1986; Johnson et al., 1989; King et al., 1993; Kugler et al., 2002; Lake and Rowe, 2005). In most cases, the leachate level within the studied landfills is always kept below a specific height (e.g., a height of 30 cm as regulated by USEPA) (USEPA, 1993). Concentration-gradient derived diffusion is always the dominant mechanism controlling leachate contaminant migration into the low hydraulic conductivity ($<1\times10^{-9}$ m/s) clayey soils. However, at present, hundreds of open dumps or uncontrolled landfills in China are generally lacking effective facilities for water management and leachate control (Chen and Zhan, 2007; Xie et al., 2009). The leachate mound within the landfills as well as the leachate generation rate is quite high, particularly in humid regions (e.g., Southeast China) (Zhan et al., 2008; Xie et al., 2009, 2010, 2011; Zhang and Qiu, 2010). The filed investigation of the leachate contaminant transport in the underlying soils beneath these landfill sites is particularly scarce.

The main objective of this paper is to: (1) investigate how deep the leachate-derived contaminants had penetrated into the natural clayey soils after 17 years of landfill operation; (2) estimate the range of transport parameters by calibrating field data with a mathematical model and determine the mechanism controlling solute transport in the natural clayey soils at this site. The work presented here represented the qualitative transport modeling for the natural clayey soils. The results may also provide a guide for choosing a mathematical model to investigate contaminant transport through the soils.

2. Materials and methods

2.1. Site description

The Huainan landfill is located about 5 km southeast of Anhui province in China (see Fig. 1). The landfill site is 6 km away from the Huaihe River. The topography of the landfill site is high in the south and low in the north with a gradient of 0.4%. Regional ground-water flow underneath the landfill site is generally in a south to north direction that reflects the regional topography. The west part of the landfill was selected for field investigation. It has a surface area of about 3 ha and began accepting municipal solid waste (MSW) since the year 1990. The height of the landfill was 15 m when the field investigation was carried out in 2007. Leachate level in the west part of the landfill site was 8 m. Fig. 2 shows the cross section of the landfill. Neither liner system nor leachate collection system was constructed for the landfill. The MSW is directly founded on the natural soils.

2.2. Soil sampling

Site investigation was carried out in July 2007. Seven boreholes (BH1 to BH7) were drilled to the bottom of the clayey soil layers and continuous soil samples were obtained (see Fig. 2). BH1 and BH2 were located inside the landfill and penetrated to a depth of 9 m below the ground surface. The distance between BH1 and BH2 was 10 m. The up-gradient (i.e. up groundwater flow gradient) borehole BH7 was located outside of the landfill (about 100 m away from the leachate ditch) to provide background concentrations of the contaminants.

Steel pipe casing was installed to the two boreholes (BH1 and BH2) in order to avoid collapse of boreholes. The casing was also used to prevent soil samples from being contaminated by the leachate. Each borehole sampling was continuous from the bottom of the waste, through the waste/clay interface, and to depths into the old clay layer. When the samples were taken from the surface, they were removed from the sampler and cleaned to remove any residues. A total of 110 soil samples (20 cm each) were obtained and 48 of the soil samples were taken to the laboratory for analyses. All soil samples were sealed and put in a container with a temperature below 4 °C. Before the preprocessing of the studied soil samples, 400 g of soil was cut from every subsection of the soil sample. The soil samples were air dried, pulverized, and passed through a 60 μm-mesh sieve. The water content for each sample was measured by oven-drying method. The dried soil samples were then mixed thoroughly. It is believed that the samples were of high quality and can be representative of the in situ condition.

The soil profile consists of a surface layer of 1–2 m plowed earth underlain by a 2–4 m clayey silt layer. Below the clayey silt layer is a 5–8 m old clay layer. Bedrock is located deeper than 9 m. The color of the soil deepens with the depth from yellow to green gray. The physical properties of the soil samples are shown in Table 1. The average porosity of the soils underlying the waste is about 0.4. The shallow plowed earth has a high water content of about 30%. The water content decreases (≤25%) as the depth increases to the clayey silt layer. The hydraulic conductivity of the plowed earth, the clayey silt layer, and the old clay are measured to be 3.0×10^{-5}, $5.0–8.0 \times 10^{-6}$, and 3.0×10^{-7} cm/s, respectively. Leachate level was measured and four leachate samples were obtained 24 h after the boreholes were drilled. The pH value was determined in a 1:5 soil:deionized water slurry (Xie et al., 2009). The soils were slightly acidic with pH values of 6.4 and 6.2 for BH1 and BH2, respectively. X-ray diffraction analyses of the soil samples indicated that the main clay minerals of the soil samples were kaolinite (90%), illite (7%) and montmorillonite (3%). The cation exchange capacity of the <74 μm fraction is ~10 meq/100 g. The high content of total nitrogen and ammonia nitrogen (>0.4%) in the shallow soils (2 m) at the landfill site indicated that there may be a strong effect of human activities.