Australian Journal of Basic and Applied Sciences, 8(7) May 2014, Pages: 207-214

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Prediction of Heavy Metal Contamination from Landfill: Lead and Chromium

[1]Mochamad Arief Budihardjo, [2]Amin Chegenizadeh and [3]Hamid Nikraz

[1]PhD candidate of the Department of Civil Engineering, Curtin University, Perth, Australia.
[2]Researcher at the Department of Civil Engineering, Curtin University, Perth, Australia.
[3]Professor and Head of Department of Civil Engineering, Curtin University, Perth, Australia.

ARTICLE INFO

Article history:
Received 25 January 2014
Received in revised form
8 April 2014
Accepted 20 April 2014
Available online 10 May 2014

Keywords:
Contaminant transport, Leachate, Lead, Chromium, Landfill

ABSTRACT

Leachate from unsorted solid waste landfill usually contains a variety of hazardous compounds including heavy metals such as lead (Pb) and chromium (Cr) which may contaminate soil and groundwater in the area surrounding the landfill. To minimize leachate contamination, there must be an impermeable liner beneath the landfill which functions as a leachate barrier. However, there is always the possibility for leachate to seep through the barrier and migrate to the soil and groundwater surrounding the landfill. It is useful for solid waste landfill management authorities to be able to predict the potential for leachate migration to the subsoil during landfill operations and after closure. This research aims to simulate the migration of heavy metal contaminants from a landfill area based on the initial Pb and Cr concentrations at the bottom of the landfill. This research also estimates the Pb and Cr concentration in soil at various depths beneath the landfill over 12 years. The concentrations of both Pb and Cr dropped significantly by more than 70% of their initial concentration when passing through the impermeable liner. Meanwhile, the predicted accumulated concentration of Pb and Cr in the subsoil seemed to increase slightly during the 12 years of the simulation. Results also indicated that the Pb and Cr concentrations in all landfill layers under the impermeable layer tend to increase significantly during the first five years of the simulation. Based on the initial concentrations, it was predicted that both of these contaminants could potentially contaminate groundwater surrounding the landfill.

To Cite This Article: Mochamad Arief Budihardjo, Amin Chegenizadeh., Hamid Nikraz., Prediction of Heavy Metal Contamination from Landfill: Lead and Chromium. ***Aust. J. Basic & Appl. Sci.,*** *8(7):207-214, 2014*

INTRODUCTION

Landfill is the final treatment for solid waste which is commonly practiced in some developing countries. Landfill is still the preferable choice due to the construction, investment and operational cost considerations (Hui *et al*., 2006 and Li *et al*., 2009). Landfill is generally a dumpsite constructed for final solid wastes disposal as depicted in Fig. 1. It is the cheapest and simplest method for the final treatment of solid wastes when adequate and appropriate landfill area is available (Supriyadi *et al*., 2000). There are two types of landfill method commonly implemented in developing countries. These are open controlled landfill and sanitary landfill. Sanitary landfill is more highly recommended for servicing large cities than controlled landfill. (Tchobanoglous and Theisen, 1993).

There has been also research on landfill systems conducted by Chow and Chai (2007) on acid precipitation effect in Taiwan on landfill management which showed how important could be landfill management and also the need of proper modelling on the landfill system. Another study concentrated on how the energy can be produced from landfill systems, as an example, Mambeli Barros *et al*. (2014) considered a study on biogas as a potential way to produce electricity energy.

However, landfill is also a threat to the environment because of the generation of leachate. Leachate generated by landfill may contain metal compounds (Salami *et al*., 2013). Although some metal compounds are useful to the soil as nitrates, others will contaminate and degrade the environment. The release of leachate containing heavy metals will contaminate the environment of the surrounding landfill (Mor *et al*., 2006).

Generally, leachate contains toxic substances such as heavy metals and various organic pollutants which are likely to contaminate soil and groundwater (Aziz *et al*., 2010). Previous researches have reported that the toxicity of heavy metals found in the landfill leachate is a cause for concern (Varank *et al*., 2011). Heavy metals

Corresponding Author: Mochamad Arief Budihardjo, PhD candidate of the Department of Civil Engineering, Curtin University, Perth, Australia
E-mail: m.budihardjo@postgrad.curtin.edu.au

commonly found in leachate include iron (Fe), cadmium (Cd), mercury (Hg), nickel (Ni), copper (Cu), zinc (Zn), lead (Pb), arsenic (As), and chromium (Cr) (Renou *et al*., 2008).

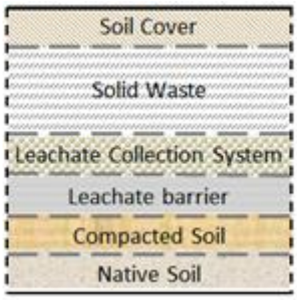

Fig. 1: Landfill illustration

Landfills are frequently equipped with a liner system consisting of gravel, geotextile, geomembrane and compacted soil. The liner system is installed to prevent any leachate migrating to the soil and groundwater around the landfill. However, even with a very low permeability liner such as geomembrane, there is still the potential for leakage of leachate through the liner. Shukla and Yin (2006) have stated that defects in the geomembrane can occur, due to the pressure of the leachate containing heavy metals which accumulates over a long period of time. This condition will promote leachate migration through the geomembrane, which is potentially harmful to the environment.

Prevention of potential leachate contamination from landfill will always be preferable to taking remedial action. Monitoring wells are commonly built in the area surrounding the landfill to monitor any instances of leachate migration from the landfill (McBean *et al*., 1995). However, leachate migration from landfill can also be predicted using simulation software which calculates leachate concentration at various soil depths based on the concentration at the top of the impermeable layer or from the leachate collection system (Schroeder, 1994). The result of the simulation can be used to take action to minimize further contamination.

Based on the previous research, this study focuses on lead (Pb) and chromium (Cr) migration. These two elements are commonly discovered out of leachate of the unsorted solid waste landfills in some developing countries. Pollute v.7 software will be used to simulate a one and a half dimensional contaminant transport. The software will also be employed to predict the changes in Pb and Cr concentration over 12 years.

MATERIALS AND METHODS

Liner Properties and Leachate Concentration:

A single landfill liner system consisting of a layer of protective gravel, leachate collection, geotextile, geomembrane and compacted soil was proposed for use in this simulation. This liner was chosen to represent a common liner system used for solid waste landfill in some developing countries. In this simulation, the composite landfill liner was laid down on two layers of native subsoil. The properties of the landfill liner components used in the simulation are presented in Table 1. The gravel thickness was set up at 0.7 m, the compacted soil at 0.9 m and two different types of subsoil at 2m and 4m. The thickness of the manufactured materials such as the geotextile and geomembrane were based upon the International Geosynthetics Society, (2006).

Table 1: Properties of Landfill Liner

Material	Dry Density (gr/cm3)	Permeability (m/s)	Porosity	Thickness (m)
Gravel	2.47	$1 \times 10^{-2} – 1$	0.35	0.7
Geotextile	0.5	0.65×10^{-1}	0.55-0.93	0.004
Geomembrane	0.94	$5 \times 10^{-13} – 5 \times 10^{-16}$	1	0.0015
Compacted Soil	1.1352	1.764×10^{-8}	0.57	0.9
Subsoil 1 (Native)	1.15	5.943×10^{-6}	0.51	2
Subsoil 2 (Native)	1.22	1.519×10^{-6}	0.56	4

In order to run the leachate migration simulation, the initial concentration of the monitored contaminant had to be determined. The initial concentrations of the contaminants were assumed to be the concentrations at the lowest area of the landfill (the concentration at the leachate pipe). The concentration of both lead and chromium concentration was set up at 0.93 mg/l (Table 2). This initial concentration was selected based on the concentration ranges for Pb and Cr stated by the European Commission (2002), which are 0.001–5 mg/l (Pb) and 0.02–1.5 mg/l (Cr). This value was much higher than the maximum limit for water quality standards.

Table 2: Initial Heavy Metal Concentration

Parameter	Initial concentration (mg/l)	Limit Class I (Water Quality Standards) (mg/l)
Lead	0.93	0.1
Chromium	0.93	0.1

Modelling Process:

The simulation was run using Pollute v.7 software which was purchased for the author by Curtin University, Western Australia. The model was developed based on a blank model, which allowed the variation and type of layer to be determined freely in accordance with the proposed setting. Pollute v.7 also provides default values that can be used when it is not possible to obtain a certain input. Pollute v.7 could be run directly after the primary and secondary data had been entered. The stages involved in the use of Pollute v.7 are shown in Table 3.

Table 3: Stages of execution

Stage	Option/Input/Output
Create the model	Blank model
General data input	Number of layers, maximum depth total layer depth and Darcy velocity
Layer data input	Number of sublayers, thickness, dry density, porosity, coefficient of hydrodynamic dispersion and distribution coefficient
Set up boundary conditions	Top boundary and bottom boundary
Run parameters	Concentration vs depth, concentration vs time, depth vs time

Calibration and Validation:

Calibration would usually be done in order to obtain precise simulation results for the value of the field data, after which model validation would be performed. The validation would normally be conducted to test whether the model reflected field conditions. Validation can be performed by three methods: the chi squared method, sum squared for errors and root square of errors. Since the results would not be compared to field conditions, the calibration and validation stages were not performed in this simulation.

Sensitivity Analysis:

Sensitivity analysis aims to determine the effect upon the preferred solution of making changes to input data or existing parameters. This is very useful for decision-making, since it is highly flexible and can be adapted to suit changing conditions and different situations (Malczewski, 1999). In this case, the sensitivity analysis was performed by trial and error in order to replace the default values for dry density, permeability and porosity. The chosen values should refer to previous theories while keeping the other parameters constant.

RESULTS AND DISCUSSION

Landfill liner:

The composition of the proposed landfill liner is depicted in Fig. 2. The initial Lead (Pb) and Chromium (Cr) concentrations were assumed to represent the concentrations at the lowest area of the landfill. In the simulation, the concentration of Pb and Cr in the gravel, geotextile, geomembrane, compacted soil and the subsoil were estimated. The developed model would be used to predict the Pb and Cr concentrations in every layer for 12 years.

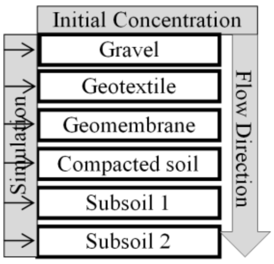

Fig. 2: Landfill Liner Composition

In a single liner landfill, the gravel layer functions to prevent solid waste from entering the leachate collection pipe and blocking the system. The geotextile layer is a protective layer preventing disruption to the geomembrane, and also works as a filter for the leachate. Meanwhile, the geomembrane with its very low hydraulic conductivity acts as the main leachate barrier material.

Lead (Pb) Simulation:

Figure 3 depicts the concentration of lead (Pb) over 12 years, showing that it dropped significantly after the geomembrane layer. In general, in every year of the simulation, the Pb concentration in each layer tended to rise. However, the most significant increase in Pb concentration occurred within the first five years, and particularly in the first year. Above the geomembrane layer, the initial concentration of Pb in the first year was 0.93 mg/l. The Pb concentration dropped to 0.25 mg/l in the compacted soil below the geomembrane and continued to decrease to 0.15 mg/l at the bottom of subsoil 2 (about 7 m below the impermeable layer).

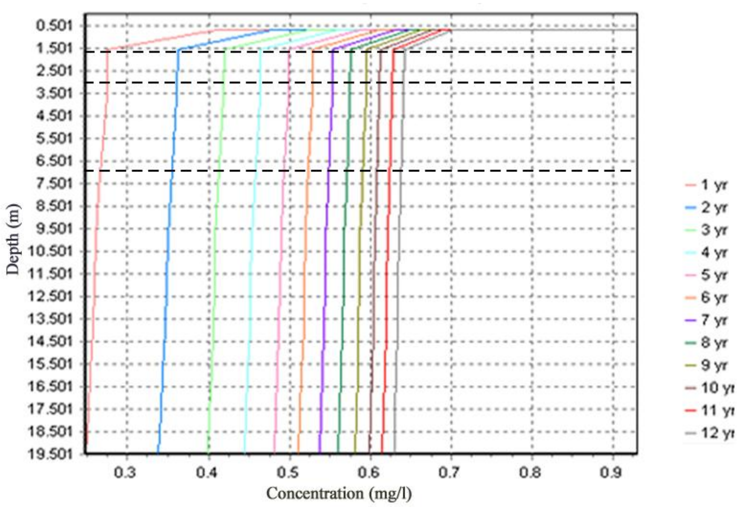

Fig. 3: Lead (Pb) Simulation

Figure 4 shows the changes in Pb concentration at various depths for each of the 12 years of the simulation. Considering that the Pb concentration at the lowest area of the landfill will be constant, the maximum concentration of Pb was found in the layer at 0.7055 m depth. In the first year, the Pb concentration at that point was 0.42 mg/l, increasing to about 0.67 mg/l after 12 years.

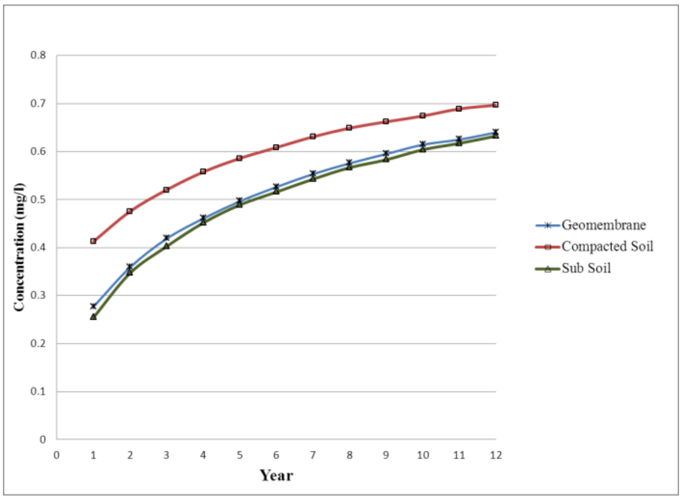

Fig. 4: Lead (Pb) Concentration at Various Depths over 12 Years

Chromium (Cr) Simulation:

The changes in chromium (Cr) concentration over 12 years are shown in Fig. 5. The patterns in Cr concentration are similar to those of Pb, dropping by about 70% after passing the geomembrane. Over the 12 years of the simulation, Cr concentration in the layer below the geomembrane increased to a maximum of 0.54 mg/l in year 12. Once again, the most significant increase in Cr concentration occurred in the first five years, going from 0.2 mg/l to 0.55 mg/l at a depth of 1.501 m.

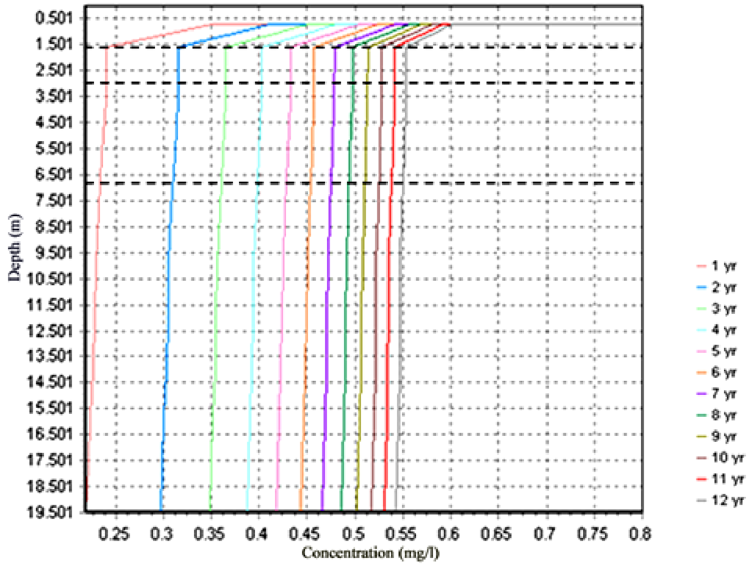

Fig. 5: Chromium (Cr) Simulation

Figure 6 shows the changes in Cr concentration at various depths over 12 years. Similarly to the results for Pb, the highest concentration of Cr occurred at a depth of 0.7055 m, starting at 0.36 mg/l in year 1 and then increasing slightly over the next 12 years and reaching a maximum of 0.57mg/l.

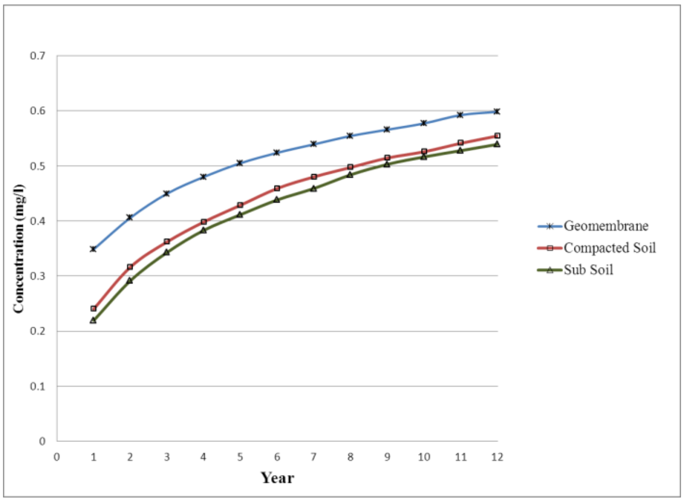

Fig. 6: Chromium (Cr) Concentration at Various Depths over 12 Years

Discussion:

Pb and Cr in the leachate moved towards the geotextile layer at a depth of 0.704 m. After passing through this layer, the Pb and Cr concentrations decreased as the leachate moved towards the subsoil. This decrease is caused by the geotextile which acts as a filter preventing soil particles and heavy metal contaminants being transported in the leachate (International Geosynthetics, Society, 2006). The geotextile used as a liner in landfill is non-woven and water permeable, so that leachate passes through while soil particles and Pb and Cr contaminants are filtered out.

The Pb and Cr remaining in the leachate after the filtration phase in the geotextile layer flows into the geomembrane layer at a depth of 0.7055 m. The geomembrane serves as an impermeable layer preventing any leakage of leachate generated from solid waste (International Geosynthetics Society, 2006). Nevertheless, geomembrane with permeability values of 0.5 x10- 11 m/s and 90% porosity has the potential to let the leachate pass through. There is a decreased concentration of Pb and Cr in the leachate that has passed through a layer of geotextile and geomembrane layer (Table 4).

Table 4: Concentration of Pb and Cr in Geomembrane (mg/l)

Year	Initial Concentration	Simulation Pb	Simulation Cr
1	0.930	0.4105	0.3513
2		0.4795	0.4114
3		0.5256	0.4513
4		0.5604	0.4813
5		0.5884	0.5053
6		0.6117	0.5253
7		0.6316	0.5423
8		0.649	0.5572
9		0.6643	0.5702
10		0.678	0.5819
11		0.6904	0.5924
12		0.7015	0.6019

The Pb and Cr in the leachate move from the geomembrane layer to compacted soil at a depth of 1.605 m. This layer has a low permeability value (k) so that the leachate will move through the layer with difficulty. There is therefore a slight decrease in the concentration of Pb and Cr in the leachate moving from the geomembrane to the compacted soil layer.

The concentration of Pb increases from the first to the twelfth year. However, the incremental rate of increase has declined over the years as shown by Fig. 7. This figure displays the Pb concentrations for two different locations with altered distance and depth in the landfill. Although the values are slightly different, the trend is the same for both points.

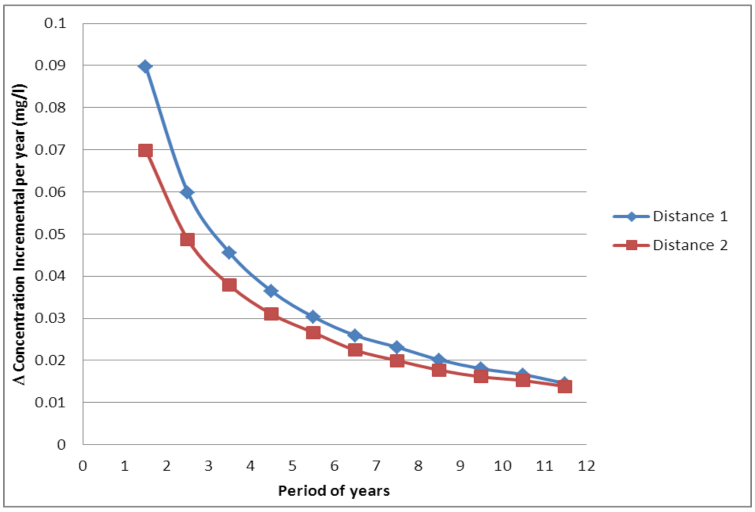

Fig. 7: The Declining Rate of Increase in Pb Concentration over 12 Years

Figure 8 shows the decline rate in Cr concentration in location 1 and 2. A similar simulation to the one for Pb was run to model the Cr concentration change in two different locations surrounding the landfill. A similar trend was observed, with the Cr concentration declining in both locations over the 12 years. The concentration of Pb and Cr in the subsoil will continue to increase from year to year until the subsoil reaches saturation point. After passing the saturation point, Pb and Cr transport in the soil will stop and this will lead to runoff. A similar downward trend has also been reported by Salami *et al*. (2013). The simulation results for Pb and Cr transport in landfill liner showed increasing concentration values (C) from the 1st to the 12th year.

Generally speaking, the concentration of Pb found in the leachate was greater than the concentration of Cr. Stegmann *et al*. (2005) have stated that the concentration of Pb in leachate landfill ranges from 0.001–5 mg/l, while the concentration of Cr is about 0.02–1.5 mg/l. The Cr content of metal waste dumped into landfill is lower than the Pb content (European Commission, 2002). Moreover, Cr in the leachate is more absorbable by plants. The more leachate filters into the subsoil, the higher the possibility of groundwater contamination would be, which in turn will lead to the contamination of shallow wells surrounding the landfill site. This is a serious problem in developing countries, since the majority of residents use water coming from shallow wells (dig wells) as their drinking water.

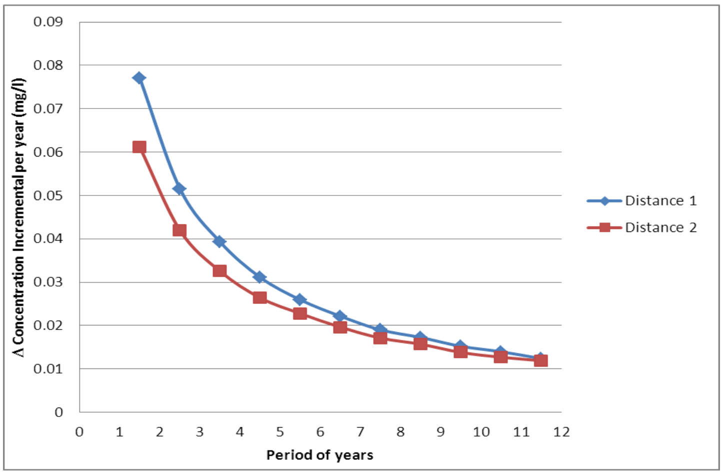

Fig. 8: The Declining Rate of Increase in Cr Concentration over 12 Years

Conclusion:

This study focused on the modelling of the heavy metal contamination in landfill systems. The simulation of lead (Pb) and chromium (Cr) transport in the leachate showed that the concentrations of Pb and Cr were increasing from year 1 to year 12. In the first subsoil, the concentrations of Pb were predicted to range from 0.2484 to 0.6298 mg/l, while concentration of the Pb in subsoil 2 was in between 0.1886 - 0.5078 mg/l. The Cr concentration in subsoil 1 was between 0.2191-0.5432 mg/l while in subsoil 2 varied from 0.1644 to 0.4392 mg/l. The concentration of both heavy metals tended to decrease more than 70% after passing the geomembrane. However, it was predicted that the Pb and Cr concentration in the subsoil would incline after a period of 12 years as a consequence of cumulative leachate seepage. Based on the initial concentrations, it was predicted that both of these contaminants could potentially contaminate groundwater surrounding the landfill.

ACKNOWLEDGEMENTS

The first author sincerely acknowledges the funding received from the Directorate General of Higher Education (DGHE), Ministry of National Education, Republic of Indonesia in the form of a scholarship for his PhD studies. He would also like to thank and acknowledge the Department of Environmental Engineering, Diponegoro University which provides extensive support during his PhD studies at Curtin University, Western Australia.

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