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System Dynamics Simulation of Selected Composite Landfill Liners for Leachate Containment

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Abstract
The disposal of wastes through landfiling is becoming increasingly acceptable worldwide. Its attendant leachate pollution is however a source of concern to the 21st century environmental engineering researchers. This paper therefore focuses on the application of system dynamics modeling technique in simulating the breakthrough times of selected composite liners in order to determine their effectiveness in leachate containment. Four (4) composite liners were studied viz: High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE); Geotextile and Geonet; Geosynthetic Clay Liner (GCL) and Compacted Clay Liner (CCL); and Silt and Sand.
Governing equations coded in Visual Basic computer programming language based on the principles of system dynamics modeling was applied in the determination of retention abilities of the selected liners. Notable properties of the liners like Hydraulic Conductivity, Permeability, Porosity and Hydraulic Head were employed in model validation. Other inputs include the Thickness, Placement Slope and Insertion Depth of the liners. The interrelationship of the properties and breakthrough times was determined through simulation processes using STELLA 9.1.4 software.of the composite liners studied, HDPE-LDPE combination was found to be the most effective with the longest breakthrough time. The Geotextile-Geonet combination however has the highest leakage rate. The study therefore recommends the use HDPE-LDPE liner combination for use in landfill leachate retention.
Keywords: system dynamics, leachate, landfill, composite liner, breakthrough time

1. Introduction

The generation of solid waste has become an increasingly important global issue over the last decade due to escalating growth in the world population and large increase in waste production. This increase in solid waste generation poses numerous questions concerning the adequacy of conventional waste management systems and their environmental effects. Landfill disposal is the most common waste management method worldwide, and new methods are required to reduce emissions from landfills. Landfills have served as ultimate waste receptors for municipal refuse, industrial residues; recycle discards and waste water sludge. Landfill continues to be the major disposal route for municipal solid waste. Wastes in landfill experience physical and biological changes resulting in solubilization or suspension of high concentrations of organic matter in landfills leachate.

Leachate is a liquid that has percolated through solid and has extracted, dissolve, and suspended material that may include potentially harmful materials. The type of solid waste, physical, chemical, and biological avidities that occur in the solid waste determines the quality of leachate. The quality of leachate seeping from the landfill is proportional to the build-up of leachate within the landfill, alternatively called leachate mound. Leachate can cause serious problems since it able to transport contaminating materials that may cause a contamination of solid, groundwater and surface water. Management of leachate is the key to eliminating potential landfill problems. This study is focused on the management of the leachate pollution arising from landfilling processes with the application of composite liners.

Liners contain various materials which vary in thickness and their ability to resist the penetration of water. Clay is used to protect the ground water from landfill contaminants, clay liners are constructed as a simple liner that is two to five feet thick. In composite and double liners, the compacted clay layers are usually between two – and five feet thick, depending on the characteristic of the underlying geology and the type of liner to be installed. Regulation specifies that the clay used can only allow water to penetrate at a rate of less than 1.2 inches per year. It should also be noted that the effectiveness of clay liners can be reduced by fractures induced by freeze – than cycles, drying out, and the presence of some chemicals. The efficiency of clay liners is impaired if they are allowed to dry out during placement. In addition, clays compacted at low moisture contents are less effective barriers to contaminants than clays compacted at higher moisture contents.

Liners that are made of a single type of clay perform better than liners constructed using several different types. Geomembranes are also called flexible membrane liners (FML). These liners are constructed from various plastic materials, including polyvinyl chloride (PVC) and high – density polyethylene HDPE. This material is strong, resistant to most chemicals and is considered to be impermeable to water. Therefore, HDPE minimizes the transfer of leachate from the landfill to the environment. A Geonet is a plastic net – like drainage blanket which may be used in land landfill in place of sand or gravel for the leachate collection layer. Sand and gravel are usually used due to cost consideration, and because geonets are more susceptible to clogging by small particles. Geo-textiles are used in landfill liners to prevent the movement small soil and refuse particles into the leachate collection layers and to protect particles to reduce dogging in the leachate collection system. Geo-synthetic clay liner consists of a thin clay liner (4 to 6 mm) between two layers of a geo-textile.

There are various models employed for the prediction or forecasting of solid waste generation. Traditional Forecasting Method is based on the demographic and socio-economic factors on a per-capita basis. The per-capita coefficients may be taken as fixed over time or they may be projected to change with time. Grossman *et. al.* (1974) extended such considerations by including the effects of population, income level, and the dwelling unit size. System dynamics modeling is new approach for the prediction of municipal solid waste generation in an urban area based on a set of limited samples. System dynamic is an approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. System dynamics is quite different from other approaches used in studying complex system because it used the feedback loops. Stocks and flows. Most computer simulation applications using system dynamics models rely on the use of the software Stella®, in which the mechanisms of system dynamic can be handled by a user-friendly interface.

System dynamics modeling has been used to address practically every sort of feedback system, including business systems (Sterman 2000), ecological systems (Grant *et al,* 1997), social-economic systems (Forrester 1969, 1971; Meadows 1973), agricultural systems (Qu and Barney 1999; Saysel *et al.* 2002), and environmental systems (Vizaya and Mohapatra 1991, 1993; Vezjak *et al*. 1998; Ford 1999, Wood and Shelly 1999; Abbott and Stanley 1999; Deaton and Winebrake 2000; Guo *et al.* 2001). System dynamics offer a flexible way for building a variety of simulation models from casual loops or stock and flow. The dynamic relationships between the elements, including variables, parameters and their linkages, can be created onto the interface using user-friendly visual tools.

This work aims at studying the applicability of landfill liners in leachate containment using the System dynamics approach. The specific objectives are to study the application of some selected landfill liners in composite forms; to determine the effectiveness of these combined liners; to apply the system dynamics modeling in solving landfill leachate pollution problems by minimizing leachate migration into the groundwater; and to make appropriate recommendations. Findings from the study would properly guide the policy makers on the selection of landfill liner materials. It would therefore aid the mitigation of leachate pollution in groundwater resources.

2. Methodology

The method employed during the course of this project is the system dynamics modeling. In this study, four (4) main combinations of liners were considered. These combinations are assumed to be composite liners. They include: Geosynthetic clay liner (GCL) and Compacted clay liner (CCL); Geotextile and Geo-Net; High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE); and Sand and silt.

2.1 The governing equations used for this simulation:

(i) Breakthrough time (t) of liners

Liners were characterized using breakthrough time. This is the time taken for leachate to penetrate a liner before contaminating the underground water. The breakthrough time (t) of liners was predicted from the following equation (Kadlec and Knight 1996)

$$t = d^2\alpha / k(d + h) \qquad (1)$$

where,

d = thickness of the liner (m)
α = effective porosity
k = coefficient of permeability (m/s)
h = hydraulic head (m)

(ii) Leakage rate through liners, qi

The leakage rate through the liners, q_i as given by Kadlec and Knight (1996) is determined from:

$$qi = kl\,[1 + \frac{y\cos\emptyset}{d}] \qquad (2)$$

where,

kl = the saturated vertical hydraulic conductivity of the liner (m/s)
d = liner thickness (m)
Ø = the liner slope (measured in angles)
y = the leachate depth over liner (m)

The system dynamics simulation tool employed is Stella® in conjunction with the Visual Basic programming language (VB).

2.2 Mapping and Modeling

The Stock and Flow diagrams support the common language of Systems Thinking and provide insight into how systems work. Enhanced stock types enable discrete and continuous processes with support for queues, ovens, and enhanced conveyors. Causal Loop Diagrams present overall causal relationships. Built-in functions facilitate mathematical, statistical, and logical operations. Figure 1 shows the Stella flow diagram of the model.

2.3 Simulation and Analysis

The standard values of various parameters employed in the simulation of each liner are:

(i) Geosynthetic Clay Liner (GCL)

Hydraulic conductivity = 1.0 x 10^{-1}1m/s
Thickness = 3mm
Permeability = 1.0 x 10^{-5}m/s
Slope = 24^0
Hydraulic head (h) = 0.3m
Leachate depth (y) = 1m
Porosity = 0.6 = 60%

(Shackelford *et al.* 1999)

(ii) Compacted Clay Liner (CCL)

Hydraulic conductivity = 1.0 x 10^{-9}m/s
Thickness = 0.9m = 900mm
Permeability = 1.0 x 10^{-7}m/s
Porosity = 0.37 = 37%
Slope = 18.4^0
Hydraulic head (h) = 1m
Leachate depth (y) = 1.5m

(Shackelford *et al.* 1999)

(iii) Silt

Hydraulic conductivity = 1.0 x 10^{-6}m/s
Thickness = 0.6m
Permeability = 0.25 = 25%
Porosity = 1.5 X10^{-3}m/s
Slope = 35^0
Hydraulic head (h) = 1.5m
Leachate depth (y) = 3m

(Horner *et al*. 1994)

(iv) Sand

Hydraulic conductivity = 1.9 x 10^{-3}m/s
Thickness = 0.6m
Permeability = 0.39 = 39%
Porosity = 1.1 X10^{-1}m/s
Slope = 34^0
Hydraulic head (h) = 1.5m
Leachate depth (y) = 3m

(New Jersey Department of Agriculture 1999)

(v) High density polyethylene (HDPE)

Hydraulic conductivity = 1.0 x 10^{-7}m/s
Thickness = 1.5m
Permeability = 0.47 = 47%
Porosity = 4.22 X10^{-3}m/s
Slope = 45^0
Hydraulic head (h) = 1.3m
Leachate depth (y) = 6m

(Eith and Koerner 1996)

(vi) Low density polyethylene (LDPE)

Hydraulic conductivity = 1.0 x 10^{-14}m/s
Thickness = 1mm
Permeability = 0.21 = 21%
Porosity = 1 X10^{-9}m/s
Slope = 42^0

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Hydraulic head (h) = 3.65m
Leachate depth (y) = 7.5m

(Eith and Koerner 1996)

(vii) Geonet

Hydraulic conductivity = 1.0 x 10^1m/s
Thickness = 5.1m
Permeability = 0.8 = 80%
Porosity = 1.0 X10^{-4}m/s
Slope = 40^0
Hydraulic head (h) = 0.3m
Leachate depth (y) = 0.6m

(Giroud and Bonaparte 1989)

(viii) Geotextiles

Hydraulic conductivity = 1.0 x 10^{-10}m/s
Thickness = 7mm
Permeability = 0.7 = 70%
Porosity = 1.0 X10^{-5}m/s
Slope = 30^0
Hydraulic head (h) = 2.7m
Leachate depth (y) = 0.6m

(Giroud and Bonaparte 1989)

3. Results and Discussion

Various liner combinations (composite liners) are possible from the eight liners considered during the course of this work. The reason for these combinations is to evaluate whether a single liner would be better than the combined ones and to evaluate the best of the 12 liners in terms of higher breakthrough time and lower leakage rate.

The summary of the simulation carried out on the various landfill liners and the four (4) possible combinations are presented in Figures 2 and 3 below with each liner's breakthrough time (t) and the leakage rate (qi).

12:33 12/01/2011 Table 1 (Untitled Table)

Linear Slop	Leakage Rate	Breakthrough Time	Breakthrough Time in Days	Linear Slope
73	-5.096512e-003	43.46	5.030664e-004	73.00
74	3.533173e-003	43.46	5.030664e-004	74.00
75	0.010662	43.46	5.030664e-004	75.00
76	9.736269e-003	43.46	5.030664e-004	76.00
77	1.606582e-003	43.46	5.030664e-004	77.00
78	-6.252418e-003	43.46	5.030664e-004	78.00
79	-6.615204e-003	43.46	5.030664e-004	79.00
80	8.517692e-004	43.46	5.030664e-004	80.00
81	9.283400e-003	43.46	5.030664e-004	81.00
82	0.010928	43.46	5.030664e-004	82.00
83	4.272879e-003	43.46	5.030664e-004	83.00
84	-4.562623e-003	43.46	5.030664e-004	84.00
85	-7.455500e-003	43.46	5.030664e-004	85.00
86	-1.746054e-003	43.46	5.030664e-004	86.00
87	7.316477e-003	43.46	5.030664e-004	87.00
88	0.011400	43.46	5.030664e-004	88.00
89	6.750233e-003	43.46	5.030664e-004	89.00
Final	-2.357940e-003	43.46	5.030664e-004	90.00

Figure 2: Results of the simulated leakage rates and breakthrough times

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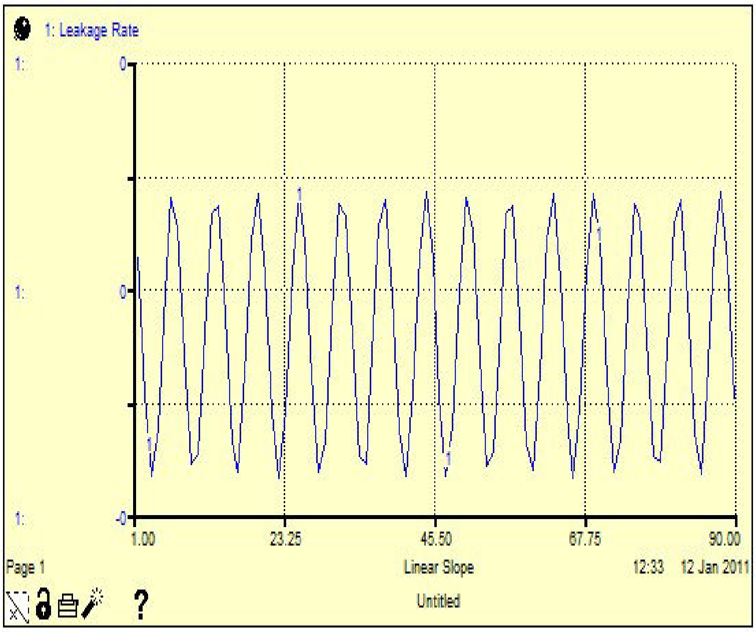

Figure 3: Results based on the varied linear slopes

The Simulation results for each of the eight (8) liners including the four possible combinations which are:-

1) Geo-synthetic clay liner and compacted clay liner
2) Silt and sand
3) HDPE and LDPE, and
4) Geotextile and Geonet

Thus, the values obtained from the simulation, for the
(1) Breakthrough time (t) and (2) Leakage rate (qi) for all the liners are discussed below:

(a) Geosynthetic Clay Liner (GCL)
Breakthrough time, t = 1.78 second
t = 2.062706 x 10^{-5} days
Leakage rate, qi: 1.423930 x $10^{-9}m^3/s$ at 24^0 (angle)

(b) Compacted Clay Liner (CCL)
Breakthrough time, t = 1,577,368.42 seconds
t = 18.26days
Leakage rate, qi: 2.100528 x $10^{-9}m^3/s$ at 18.4^0 (angle)

(c) Silt
Breakthrough time, t = 42.86 seconds
t = 4.960317x10^{-4}days
Leakage rate, qi: 3.518461x $10^{-6}m^3/s$ at 35^0 (angle)

(d) Sand
Breakthrough time, t = 0.61 seconds
t = 7.034632x10^{-6}days
Leakage rate, qi: 6.161418 x $10^{-3}m^3/s$

(e) High Density Polyethylene (HDPE)
Breakthrough time, t = 1,925,412 seconds
t = 22.28days
Leakage rate, qi: 2.102288 x $10^{-4}m^3/s$ at 45^0 (angle)

(f) Low Density Polyethylene (LDPE)
Breakthrough time, t = 57.52 seconds
t = 6.657232x10^{-4}days
Leakage rate, qi: 2.998890x$10^{-11}m^3/s$ at 42^0 (angle)

(g) Geonet
Breakthrough time, t = 0.68 seconds
t = 7.893587x10^{-6}days

Leakage rate, qi: 774.633014m^3/s at 40^0 (angle)

(h) Geotextile

Breakthrough time, t = 1.27 seconds
t = 1.466534x10^{-5}days

Leakage rate, qi: 1.422155 x $10^{-9}$$m^3$/s at 30^0 (angle)

(i) Combination of GCL and CCL

Breakthrough time, t = 1,577,370.20 seconds
t = 18.256600days

Leakage rate, qi: 9.899266 x $10^{-10}$$m^3$/s at 42^0 (average angle for the two liners) .

(j) Combination of Silt and Sand

Breakthrough time, t = 43.46 seconds
t = 5.030664 x 10^{-4}days

Leakage rate, qi = 6.688594x$10^{-10}$$m^3$/s at 35^0 (average angel for the tow liners)

(k) Combination of HDPE and LDPE

Breakthrough time, t = 1,925,469.87seconds
t = 22.285531days

Leakage rate, qi = 4.000374 x $10^{-4}$$m^3$/s at 44^0 (average angle for the two liners).

(l) Combination of Geotextile and Geo-net

Breakthrough time, t = 1.95 seconds
t = 2.225593 x 10^{-5}days

Leakage rate, qi = 1,053.1673m^3/s at 35^0 (average angle for the two liners).

For single liners, from the simulation results it was observed that High Density Polyethylene (HDPE) has the highest breakthrough time, t which is approximately 22.28 days. This implies that it is going to take High Density Polyethylene liner a maximum of 22.28 days to fail and leachate could then pass through to pollute the groundwater. Also, the simulation shows that Geonet membrane or liner has the highest leakage rate, qi which is approximately 774.633014 m^3/s. Thus, leachate will pass through the Geonet at a rate of 774.633014 m^3 per second. This is in line with earlier research findings on landfill liners (Forrester 1987; Barlas 1996; Ojoawo 2009; Ojoawo and Adegbola 2012). For composite liners however, the combination of HDPE and LDPE has the highest breakthrough time, t which is a maximum of 22.285532 days. This means, it will take the combination of these two liners a maximum of 22.285531days to fail. Meanwhile, the combination of Geotextile and Geonet have the highest leakage rate of 1,053.1673 m^3/s.

4. Conclusion

The study concludes that the High Density Polyethylene (HDPE) is the single most preferred of all the liners with the highest breakthrough time (*t*) of 22.28 days. Also that Geonet (GN) is the least effective liner with the highest leakage rate of 774.633014 m^3/s. In the composite study, the combination of HDPE and LDPE liners proved as the best containment against leachate pollution while Geotextile-Geonet combination has the highest leakage rate, making it to be the worst choice. The study therefore recommends HDPE for use as single liner and HDPE-LDPE combination for composite use in landfill leachate containments against underground water pollution. Geotextile-Geonet composite liner is however recommended for use as drainage layers.

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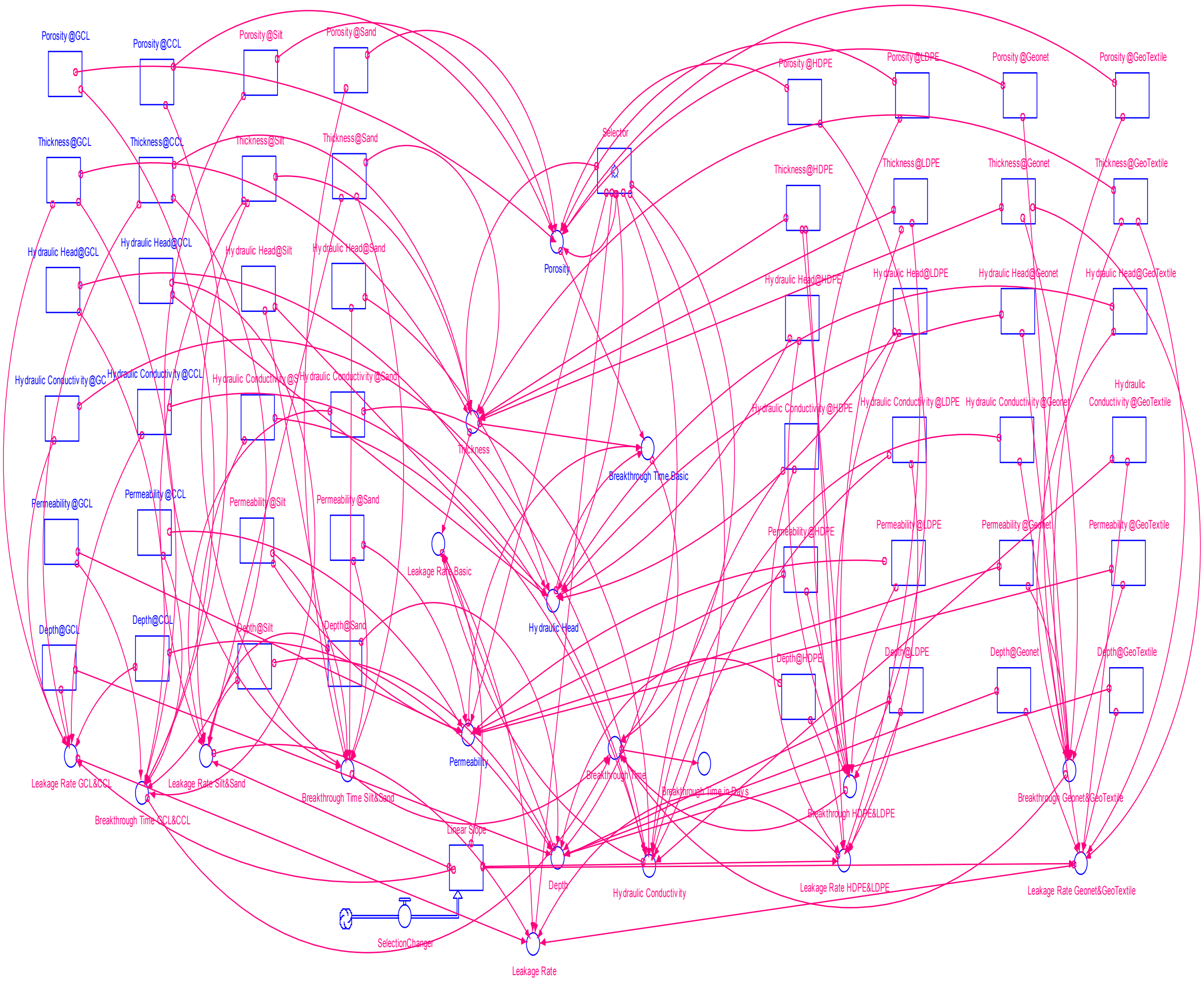

Figure 1: The Stella flow diagram of the system

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