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Protecting groundwater from leachate contamination: design of drainage system at Sa Kaeo Landfill, Thailand

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ABSTRACT

This study focuses on the design of a drainage layer at the Sa Kaeo Landfill, Thailand, to effectively isolate its leachate. The leachate thickness build-up in the granular layer of the primary leachate collection and removal system (PLCRS) as well as the geocomposite layer of the secondary leachate collection and removal system (SLCRS) was calculated from the measured values of apparent permeability of gravels and transmissivity of geocomposite, and compression and creep factors of geonet at site-specific boundary conditions. To evaluate the efficiency of granular and geosynthetic drainage materials in terms of leachate isolation, hydraulic safety factors were calculated for four landfill lives (i.e. for 1, 2, 10, and 100 years). The results show that the hydraulic safety factor decreases with a decrease in slope angle, increase in landfill life, and increase in drainage length. The safety factor of the PLCRS for landfill life of 100 years under Module 1 (with a drainage length of 138 m) is 29.0 and 2.2 in coarse and fine gravels (commercial size of 1.905 and 0.318 cm) respectively. This safety factor corresponds to the slope gradient of 0.01 at the worst case of leachate production (when all rainfall enters into the drainage system as leachate). Under Module 2 (with a drainage length of 183 m) the safety factor reduced by 22–25% in comparison with that of Module 1. Similarly, the safety factor of the SLCRS drastically decreases from 50.4 to 0.8 at a leachate leakage rate of 10% of the maximum rainfall when the landfill life is increased from 1 to 100 years. However, the leachate thickness in the PLRS and SLCRS is less than their saturated thickness in both modules. Hence it is concluded that Module 1 is relatively more efficient than Module 2 at lower slope gradients (i.e. 0.01).

INTRODUCTION

The increase in world's population and living standards has led to an increased emphasis on the implementation of technical improvements in the construction of containment facilities for hazardous and non-hazardous solid waste in order to mitigate its environmental impact (Holtz et al. 1997). The precipitation or other moisture that infiltrates through the waste in a landfill can mix with liquids that are already present in the waste and leach chemical compounds from the solid waste, forming the leachate. If the landfill is poorly developed, the leachate can escape from the landfill containment system and pollute groundwater. This problem has raised the necessity to introduce liner systems for interception and removal of the leachate. As a result, the need of engineered waste containment and lining system was realised and consequently environmental and related agencies focused on researches and activities to enact legislation. Therefore, this technology has changed from relatively slow evolution prior to 1980 to a technological revolution in the past years (Holtz et al. 1997; Koerner 1998).

The drainage layers in a liner system are classified as primary and secondary (Koerner 1998; Giroud et al. 2000a). The primary leachate collection and removal system (PLCRS) normally consists of granular materials. The secondary leachate collection and removal system (SLCRS) of a waste containment facility, also called the leak detection layer, usually consists of a geonet located between two geomembranes with a geosynthetic clay liner. The ultimate flow capacity of a geonet is reduced by a series of factors such as the creep of geosynthetics, intrusion of adjacent geosynthetic and construction materials into the pore space of the geonet, and due to biological, particulate, and chemical clogging. The properties of granular drainage materials vary less than those of geosynthetics except clogging. Despite these problems, geosynthetic materials are often used in the SLCRS especially to get early warning of leakage because of their low water retention capacity. Additionally, its factory-controlled properties and a small thickness make geosynthetic materials a successful candidate in the selection of landfill drainage materials.

The domestic industries generate a significant portion (70–80%) of total hazardous waste in Thailand. Hence there is an urgent need of engineered hazardous waste landfill sites. Since these wastes are mostly derived from diverse types of manufacturing industries, the composition and toxicity of waste vary widely. The type and estimated volume of hazardous waste produced in Thailand are given in Table 1 (PCD 1992; JICA 1992).

This research was undertaken to design an efficient yet safe drainage system in the Sa Kaeo Landfill. To achieve this goal, we measured the transmissivity of the geonet, apparent hydraulic conductivity of gravels, and time-dependent creep of the geonet. These measured data along with other estimated values were analysed to calculate the leachate thickness build-up to identify an efficient structure and its suitability based on the hydraulic safety factor.

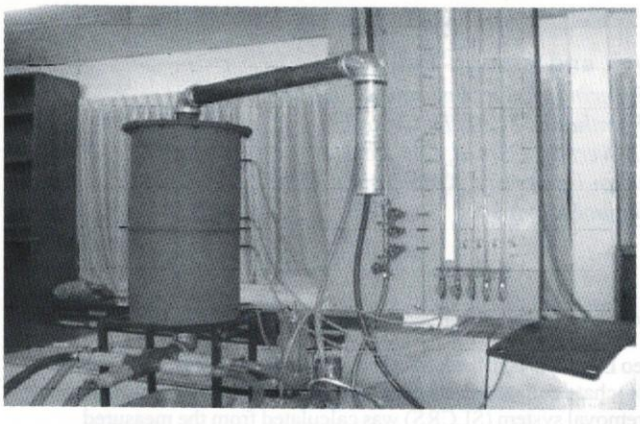

Fig. 1a: Permeameter to measure apparent permeability of gravels

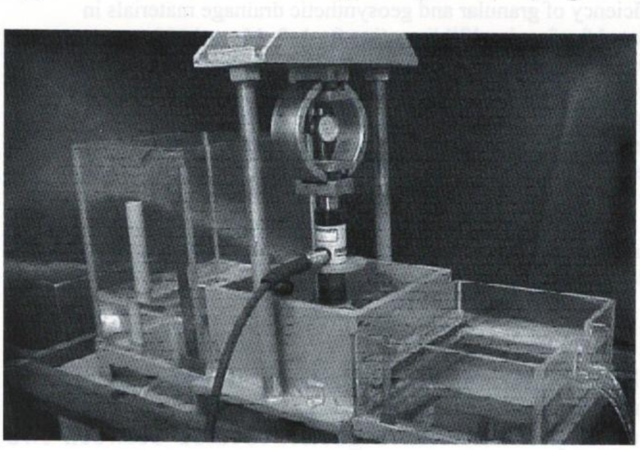

Fig 1b. Transmissivity testing equipment

TESTING MATERIALS AND THEIR PROPERTIES

The testing materials included the geonet (GNT 750, from Tenax SpA), geosynthetic clay liner (Bentomat ST, from CETCO Lining Technology), geotextile (TS006, from Polyfelt), and geomembrane (Huitex HD-150, from InAsia). Each of the geosynthetic material was cut and later trimmed to fit snugly to the base of the transmissivity apparatus (Fig. 1a) and layered as designed for the Sa Kaeo Landfill design (Figs. 2a,b). The geonet for the creep testing was similarly cut to fit into the base of a modified oedometer.

The compacted clay liner (CCL) used in the Sa Kao Landfill was borrowed from the construction site. The optimum moisture content of the soil corresponding to a maximum dry density of 1.596 gm/cm^3 was found to be 23.4% following the standard Proctor compaction method under ASTM D 698-91. The water content was chosen as 2% wet of optimum for the analysis. Based on the desired degree of compaction, the amount of soil required to attain a 25 mm thickness was calculated and compacted in a transmissivity apparatus. It was then cured for three days before testing into the drainage system.

TRANSMISSIVITY AND APPARENT PERMEABILITY

A permeameter cell for gravel (Fig. 1a) and a constant-flow (transmissivity) apparatus for geosynthetic materials (Fig. 1b) were designed and constructed at the Asian Institute of Technology, Thailand, to meet ASTM D2434-68 and

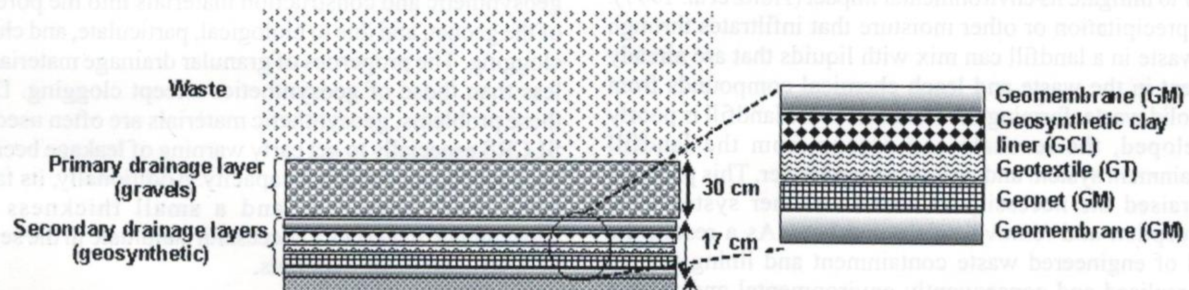

Fig. 2a: Typical profile of the hazardous unit of the Sa Kao Landfill. The primary drainage profile consisted of the gravels, the top of which was covered with geotextile. The secondary drainage layer consists of GM–GCL–GT–GN–GM–CCL profile (as shown in exploded view). The roller compacted clay liner (CCL) lies below that of the secondary drainage system

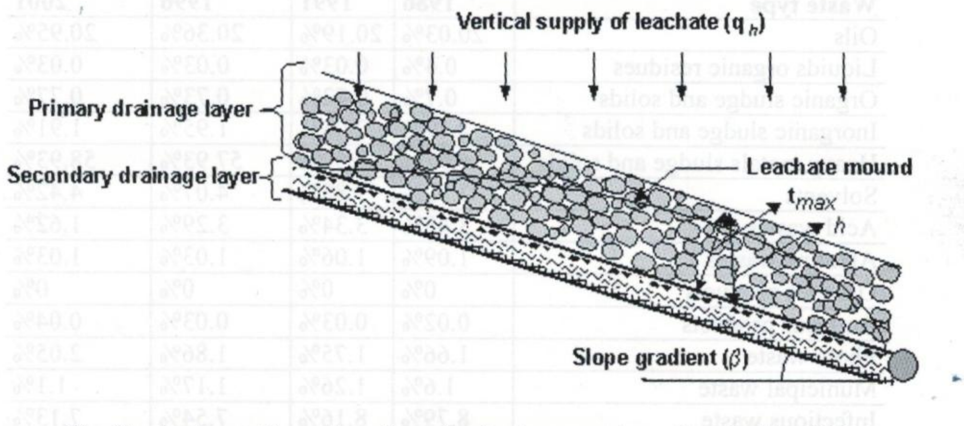

Fig. 2b: A schematic section along the drainage system of typical landfill

ASTM D4716-00 standards respectively. Extensive transmissivity tests were carried out on various configurations of the geosynthetic materials with a variety of boundary conditions (Jaisi et al. 2005). This research is focused on landfill design aspect choosing the best combination of geosynthetic and granular material for the purpose of leachate collection and removal in the PLCRS and SLCRS. The vertical profile of the best combination of the granular and geosynthetic materials for the Sa Kaeo Landfill drainage system is shown in Fig. 2a.

The flow rate (*q*) at each value of the hydraulic head (*h*) was measured and was later converted to apparent permeability (or transmissivity) using Darcy law as follows:

$$q = k_p iA = k_p\left(\frac{h}{L}\right)(wt) \qquad (1)$$

$$k_p t = \theta = \left(\frac{q}{w}\right)\left(\frac{L}{h}\right) \qquad (2)$$

where *kp* is the in-plane hydraulic conductivity, *t* and *w* are the thickness and width of the material respectively, and *L* is the length of geosynthetics. For the apparent permeability of gravels, only the first equation is sufficient.

The long-term-in-soil flow capacity of drainage materials is less than this laboratory-measured flow capacity due to the different mechanisms that reduce the flow capacity in the field. Therefore, the long-term-in-soil hydraulic conductivity (k_{LTIS}) of gravels is calculated from the laboratory-measured hydraulic conductivity ($k_{measured}$) by taking into account the effect of physical (RF_{PC}), chemical (RF_{CC}), and biological (RF_{BC}) clogging as follows (Giroud et al. 2000a).

$$k_{LTIS} = \left[\frac{k_{measured}}{\prod RF}\right] = \left[\frac{k_{measured}}{RF_{PC}\times RF_{CC}\times RF_{BC}}\right] \qquad (3)$$

There are several other factors that contribute to reduce the laboratory-measured transmissivity ($q_{measured}$). Therefore the long-term-in-soil transmissivity of the geosynthetics (q_{LTIS}) is calculated by incorporating reduction factors, besides those used in granular materials, due to immediate compression (RF_{IMCO}) and intrusion (RF_{IMIN}), long-term creep (RF_{CR}) and intrusion (RF_{IN}) of transmissive core, and chemical degradation (RF_{CD}) as follows (Giroud et al. 2000a).

$$\theta_{LTIS} = \left[\frac{\theta_{measured}}{\prod RF}\right] = \left[\frac{\theta_{measured}}{RF_{IMCO}\times RF_{IMNI}\times RF_{CR}\times RF_{IN}\times RF_{CD}\times RF_{PC}\times RF_{CC}\times RF_{BC}}\right] \qquad (4)$$

Geonet creep and reduction factors

The geonet creep was measured for an instantaneous thickness reduction due to instantaneous compression, and a long-term thickness reduction due to creep (Giroud et al. 2000b). The virgin thickness (t_{virgin}) of geonet before application of any compressive stress was measured according to ASTM D5199-91 (which measures the thickness at a normal pressure of 20 kPa) before creep testing. The immediate compression thickness (t_{IMCO}) immediately after the application of stress and creep thickness (t_{CR}) after the end of time period was calculated from the oedometer creep test (Cancelli et al. 1987). The tests were conducted dry (at the laboratory temperature and humidity).

The compression reduction factor (RF_{CO}) due to thickness reduction (resulting from immediate compression and some creep) between t_{virgin} and t_{CO} is

$$RF_{CO} = \left[\frac{n_{virgin}}{t_{CO}/t_{virgin} - (1-n_{virgin})}\right]^3 \qquad (5)$$

where n_{virgin} is the initial porosity of geosynthetics. The suggested time at which t_{CO} is measured is often 100 hours (Giroud et al. 2000b) and the time required for obtaining a

Table 1: Composition of hazardous waste produced in Thailand

Waste type	1986	1991	1996	2001
Oils	20.03%	20.19%	20.36%	20.95%
Liquids organic residues	0.4%	0.03%	0.03%	0.03%
Organic sludge and solids	0.7%	0.72%	0.73%	0.77%
Inorganic sludge and solids	2.19%	2.06%	1.95%	1.91%
Heavy metals sludge and solids	56.92%	57.52%	57.93%	58.93%
Solvents	3.72%	3.88%	4.07%	4.42%
Acid wastes	3.48%	3.34%	3.29%	1.62%
Alkaline wastes	1.09%	1.06%	1.03%	1.03%
Off spec products	0%	0%	0%	0%
Aqueous products	0.02%	0.03%	0.03%	0.04%
Photo waste	1.66%	1.75%	1.86%	2.05%
Municipal waste	1.6%	1.26%	1.17%	1.1%
Infectious waste	8.79%	8.16%	7.54%	7.13%
Total waste (tons/year)	**531,154**	**932,638**	**1,634,104**	**2,813,980**

Table 2a: Different reduction factors of granular and geosynthetic drainage at different normal stress and hydraulic gradient

Transmissive core material		Pressure kPa	Reduction factors								
			RF_{IMCO}	RF_{IMIN}	RF_{CR}	RF_{IN}	RF_{CD}	RF_{PC}	RF_{CC}	RF_{BC}	$IIRF$
Geonet		50	1	1	1:11	1.15	1.1	1.1	1.2	1.15	2.132
		100	1	1	1.19	1.25	1.25	1.25	1.5	1.35	4.725
		200	1	1	1.17	1.4	1.5	1.5	2.5	1.75	16.183
Gravels	Coarse	50	NA	NA	NA	NA	NA	1	1.25	1.1	1.375
		100	NA	NA	NA	NA	NA	1.25	1.75	1.25	2.734
		200	NA	NA	NA	NA	NA	1.5	2	1.35	4.050
	Fine	50	NA	NA	NA	NA	NA	1.15	1.3	1.2	1.794
		100	NA	NA	NA	NA	NA	1.25	1.55	1.3	2.519
		200	NA	NA	NA	NA	NA	1.55	1.82	1.75	4.937

Table 2b: Long-term-in-soil hydraulic conductivity and transmissivity of gravel and geocomposite respectively derived from reduction factors

Transmissive core material		Pressure kPa	Measured Transmissivity ($q_{measured}$) $m^3/s\text{-}m$					Long-term-in-soil Transmissivity (q_{LTIS})$m^3/s\text{-}m$				
			I = 0.005	I = 0.01	I = 0.015	I = 0.02	I = 0.03	I = 0.005	I = 0.01	I = 0.015	I = 0.02	I = 0.03
Geonet		50	1.22E-02	8.55E-03	8.13E-03	6.41E-03	6.14E-03	5.72E-03	4.01E-03	3.81E-03	3.01E-03	2.88E-03
		100	1.10E-02	8.05E-03	7.06E-03	6.08E-03	5.58E-03	2.34E-03	1.70E-03	1.49E-03	1.29E-03	1.18E-03
		200	8.20E-03	6.22E-03	5.39E-03	4.56E-03	3.72E-03	5.07E-04	3.85E-04	3.33E-04	2.81E-04	2.30E-04
Gravel	Coarse	50	7.25E-01	5.81E-01	4.83E-01	3.25E-01	2.55E-01	5.27E-01	4.23E-01	3.51E-01	2.36E-01	1.85E-01
		100	7.25E-01	5.81E-01	4.83E-01	3.25E-01	2.55E-01	2.65E-01	2.13E-01	1.76E-01	1.19E-01	9.31E-02
		200	7.25E-01	5.81E-01	4.83E-01	3.25E-01	2.55E-01	1.79E-01	1.44E-01	1.19E-01	8.01E-02	6.28E-02
	Fine	50	1.14E-01	1.11E-01	1.09E-01	1.08E-01	1.02E-01	6.36E-02	6.21E-02	6.08E-02	6.03E-02	5.71E-02
		100	1.14E-01	1.11E-01	1.09E-01	1.08E-01	1.02E-01	4.53E-02	4.42E-02	4.33E-02	4.30E-02	4.07E-02
		200	1.14E-01	1.11E-01	1.09E-01	1.08E-01	1.02E-01	2.31E-02	2.26E-02	2.21E-02	2.19E-02	2.08E-02

satisfactory value of creep reduction factor (RF_{CR}) is 10,000 hours (Holtz et al. 1997). In this experiment, we calculated RF_{CO} from the thickness retained in 1,000 hours, and creep from 4,430 hrs of loading. The creep reduction factor was calculated from the remaining thickness (t_{CR}) based on measured or extrapolated data after the creep occurred as follows.

$$RF_{CR} = \left[\frac{\left(t_{co} / t_{virgin} \right) - \left(1 - n_{vergin} \right)}{\left(t_{CR} / t_{virgin} \right) - \left(1 - n_{virgin} \right)} \right]^{3} \qquad (6)$$

The reduction factors employed in (3) and (4), but not calculated in this research were selected based on the guidance for the selection of reduction factors (Richardson et al. 2000; Richardson and Zhao 1998; Zhao and Montanelli 2000). The reduction factor for the landfill life of 1 year is shown in Table 2a.

Calculation of maximum leachate thickness on liner

Using the values of long-term-in-soil transmissivity and long-term-in-soil apparent permeability obtained after employing the necessary reduction factor for the given landfill life (Table 2b), we calculated the leachate thickness or head build-up on the liner using the following three methods.

Giroud's numerical approximation

The geometry of liquid collection layer is characterised by its thickness (t), slope angle (β), and slope length (L) (Fig. 2b). The thickness of liquid varies along the length of the liquid collection layer and has a maximum value, t_{max}, at a certain horizontal distance from the top of the liquid collection layer (Rowe 2000). The approximation of t_{max} under steady flow conditions (Giroud and Houlihan 1995) is defined as

$$t_{max} = \frac{L}{2 \times Cos\beta} \left[1 - 0.12 \exp\left\{ - \left[\log\left(\frac{8(q_h/k)}{5\tan^2\beta} \right)^{\frac{5}{8}} \right]^2 \right\} \right] \left[\left(\frac{4 \times q_h}{k \times Tan^2\beta} + 1 \right)^{\frac{1}{2}} - 1 \right] \qquad (7)$$

where L is the horizontal projection of the length of the leachate collection and removal system, qh is the rate of vertical liquid supply. Similarly, k is the hydraulic conductivity of the drainage layer, which has a slope angle of β.

McEnroe's exact solution

McEnroe's (1993) equations are based on free drainage conditions so that there is no backwater effect over the barrier layer. The equations are defined separately for the following three cases.

Case I: When slope or transmissivity capacity of the drainage layer controls the mounding height [$R > 1/4$ (*i.e.* $q_h / k\sin^2\beta > 1/4$)]

$$h_{max} = LS(R - RS + R^2S^2)^{1/2} \exp\left[\frac{1}{B}\tan^{-1}\left(\frac{2RS-1}{B} \right) - \frac{1}{B}\tan^{-1}\left(\frac{2R-1}{B} \right) \right] \qquad (8a)$$

Case II: When a balance exists between the design rate of fluid supply and the slope or transmissivity capacity of the drainage layer [$R = 1/4$ (*i.e.* $q_h / k\sin^2\beta = 1/4$)]

$$h_{max} = LS\frac{R(1-2RS)}{1-2R} \exp\left[\left(\frac{2R(S-1)}{(1-2RS)(1-2R))} \right) \right] \qquad (8b)$$

Case III: When the design rate of fluid supply controls the mounding height [$R < 1/4$ (*i.e.* $q_h / k\sin^2\beta < 1/4$)]

$$h_{max} = LS(R - RS + R^2S^2)^{\frac{1}{2}} \left[\left(\frac{(1-A-2R)(1+A-2RS)}{(1+A-2R)(1+A+2RS)} \right)^{\frac{1}{2A}} \right] \qquad (8C)$$

where h_{max} is the maximum head over the liner, which can be converted to a maximum thickness based on the slope angle (b) of the liner. The values of constants A and B *are* $(1\text{-}4R)^{1/2}$ and $(4R\text{-}1)^{1/2}$ respectively. Most of the instances in the Sa Kao Landfill lie under Case III.

USEPA equations

Moore (1980, 1983) developed a series of equations for estimating the liquid head over a sloping barrier in various technical documents of the United States Environmental Protection Agency (USEPA). The maximum height of leachate obtained from this method is

$$h_{max} = L\left(\frac{q_h}{k} \right)^{\frac{1}{2}} \left[\left(k\frac{S^2}{q_h} \right) + 1 - \left(k\frac{S}{q_h} \right) \left[S^2 + \frac{q_h}{k} \right]^{\frac{1}{2}} \right] \qquad (9)$$

The leachate thickness was calculated from each of these three methods and the results are compared and discussed below.

Design rate of liquid supply

The actual measurement of the vertical supply of leachate coming into the drainage layer (q_h) was not possible during the design phase of the landfill. Therefore the database of the Phitsanulok Landfill situated about 350 km NW of the site (Manandhar 2000), calculations from HELP (Hydrological Evaluation of Landfill Performance) program (Schroeder et al. 1994), and the actual database collected from similarly designed landfill situated in similar hydrological regimes (Othman et al. 1998) were used. The HELP model was used to approximate the rate of leachate generation in terms of the percentage of rainfall entering into the leachate collection layer. These input data were employed to analyse the leachate thickness build-up in the landfill liner and hydraulic safety factor for the given liner configuration in the Sa Kaeo Landfill. For this purpose, a 30-year rainfall cycle was analysed and the maximum rainfall was utilised in the calculations.

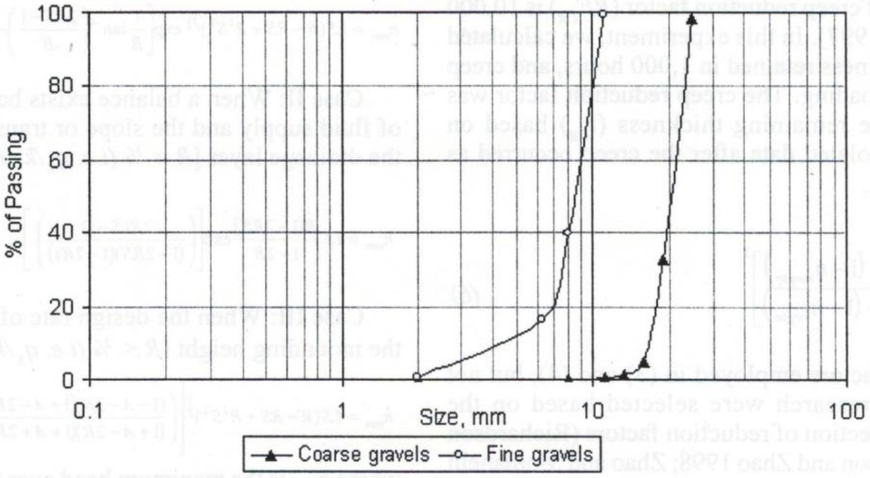

Fig. 3: Grain size distribution of two types of commercial gravels used in the testing as candidates for the primary drainage materials

Analysis of data

Two gravel beds: one for the primary leachate collection layer (coarse gravel: commercial size of 1.905 cm) and the other for the sand blanket (fine gravel: commercial size of 0.318 cm) in the Sa Kaeo Landfill were studied. Their grain size analysis (Fig. 3) under ASTM D 422-63 (1990) yielded a uniformity coefficient (*CU*) and a coefficient of curvature (*CC*) of 1.24 and 0.96 for the coarse gravel and 1.46 and 2.05 for the fine gravel respectively.

RESULTS AND DISCUSSION

From the several configurations of secondary drainage profiles, an optimum configuration was selected based on the laboratory testing of flow rate and the landfill design alternatives for the Sa Kao Landfill. The selected profile consisted of (from top to bottom): geomembrane (GM)–geosynthetic clay liner (GCL)–geotextile (GT)–geonet (GN)–geomembrane (GM)–compacted clay liner (CCL) (Fig. 2a). The transmissivity of this configuration was measured under different normal stresses and hydraulic gradients.

To take into account the variable landfill waste load, effect of daily cover, and the level of waste compared to the ground level, the analysis was divided into four major phases of landfill: Year 1 (active construction and the waste placement), Year 2 (when the landfill waste level is at least equal to that of the ground level), Year 10 (stable phase of landfill), Year 100 (landfill after top closure, post use of landfill). In each case, q_{LTIS} and k_{LTIS} were calculated and used to identify the leachate thickness. Finally the hydraulic safety factor for each hydraulic gradient and design alternative was calculated from the retained thickness of drainage layer and the thickness of leachate under consideration.

Apparent permeability of gravels

The measured permeability value of gravels (Table 2b) is not a constant quantity. For the coarse gravel, it decreases with increasing hydraulic gradient. But for the fine gravel, it remained almost constant for a range of gradients. The calculation of the Reynolds number suggested that a turbulent flow in the coarse gravel was expected for a hydraulic gradient ranging from 0.003 to 0.03, but in the fine gravel the flow remained within a laminar to transitional region for a hydraulic gradient varying from 0.003 to 0.08.

TRANSMISSIVITY AND TRANSMISSIVITY REDUCTION FACTORS

The plot of transmissivity versus hydraulic gradient at various normal compressive stresses for the geocomposite configuration of GM–GCL–GT–GN–GM–CCL showed a decrease in transmissivity with an increase in normal stress and hydraulic gradient, as expected (Fig. 4). The decrease was drastic in the stress range over 200 kPa. At a given hydraulic gradient, only a minor amount (10–16%) of flow rate was retained at a 400 kPa normal stress as compared to that at a 50 kPa normal stress. The tests carried out at various hydraulic gradients yielded comparable transmissivity trends. Hence, this transmissivity reduction may be attributed to the deformation of auxiliary planes of geonet resulting in the intrusion of geotextiles and a possible stand-layover reducing the size of flow channel. It suggested that the application of this geonet configuration was ineffective in the areas where large normal stresses are anticipated.

COMPRESSION AND CREEP REDUCTION FACTOR

The creep test showed that the thickness reduction was prominent even immediately after the application of the load.

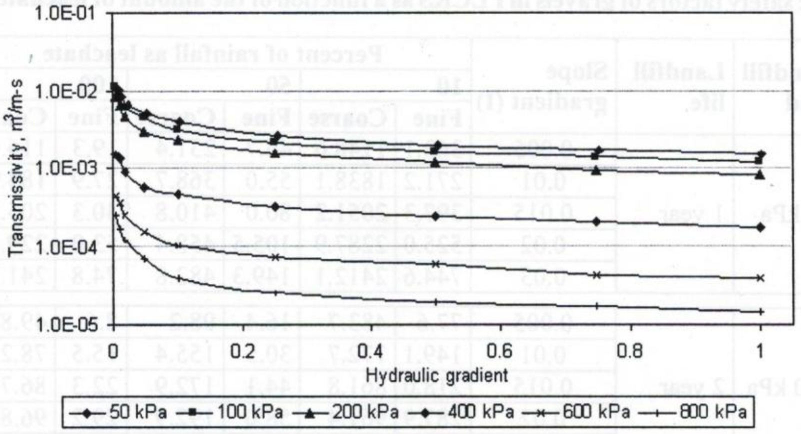

Fig. 4: Transmissivity of GM-GCL-GT-GN-CCL-profile under different hydraulic head and normal stress conditions

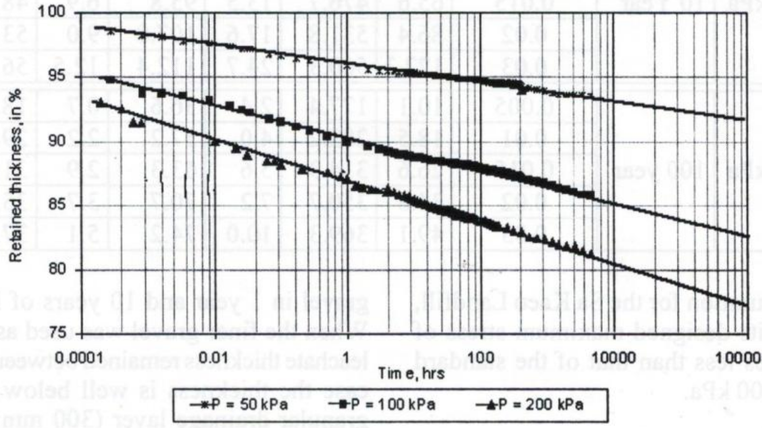

Fig. 5: Creep of geonet (GN): the central transmissive core of the secondary drainage system.

The retained thickness at 1 hour of creep test was 95.8, 90.5, and 87.6% of the virgin thickness at a normal stress of 50, 100, and 200 kPa respectively (Fig. 5). This behaviour is consistent with a higher decrease in transmissivity (Fig. 3). The thickness reduction factor increased from 1.21 to 2.43 when the stress was increased from 50 to 400 kPa. The factor reached 9.60 at a stress level of 800 kPa. But the creep reduction factor (RF_{CR}) was comparatively much lower than its compression reduction factors (RF_{CO}) suggesting a higher immediate reduction in thickness. The maximum creep reduction factor obtained was only 1.28. The measured and calculated reduction factors for a landfill life of 1 year are shown in Table 2a.

DESIGN OF LANDFILL DRAINAGE

The two important requirements regarding the allowable flow rate of a geonet are its efficient performance of regulatory and functional roles. To quantify these properties of both granular and geocomposite configurations, they were subjected to testing following the USEPA standard, and observed whether they retain the leachate thickness below the design thickness of landfill liner to ensure the proper functioning of the system (Koerner 1998).

The industrial hazardous waste cell of the Sa Kaeo Landfill, Thailand, had initially considered two design alternatives based on a single slope but with different drainage lengths: Module 1 (a length of 138 m) and Module 2 (183 m). Therefore the present analysis was based on the comparison of the two modules at different slope angles.

REGULATORY ROLE

The USEPA standard suggests a codified minimum transmissivity value of 3×10^{-5} m³/s-m. The long-term-in-soil hydraulic conductivity (k_{LTIS}) values of gravels are far more efficient in their capacity to transmit leachate than the minimum value suggested by the USEPA. Similarly, the long-term-in-soil transmissivity (q_{LTIS}) value of geocomposite,

Table 3 Hydraulic safety factors of gravels in PLCRS as a function of the amount of leachate and landfill life

Landfill load	Landfill life	Slope gradient (I)	Percent of rainfall as leachate					
			10		50		100	
			Fine	Coarse	Fine	Coarse	Fine	Coar
50 kPa	1 year	0.005	363.1	1148.6	46.7	231.4	19.3	116.6
		0.01	271.2	1838.1	55.0	368.7	27.9	184.9
		0.015	397.3	2051.2	80.0	410.8	40.3	205.7
		0.02	525.0	2287.9	105.5	458.4	53.0	229.6
		0.03	744.6	2412.1	149.3	482.8	74.8	241.7
100 kPa	2 year	0.005	77.6	483.7	16.4	98.2	8.6	49.8
		0.01	149.1	772.7	30.5	155.4	15.5	78.2
		0.015	218.0	861.8	44.1	172.9	22.3	86.7
		0.02	287.9	961.4	58.0	192.9	29.2	96.8
		0.03	408.2	1013.2	82.0	203.0	41.2	101.7
200 kPa	10 Year	0.005	24.0	268.3	5.4	54.9	2.9	28.0
		0.01	45.1	427.7	9.5	86.3	5.0	43.6
		0.015	65.6	476.7	13.5	95.8	6.9	48.1
		0.02	86.4	531.8	17.6	107.0	9.0	53.8
		0.03	122.3	560.3	24.7	112.4	12.5	56.4
200 kPa	100 year	0.005	10.1	177.4	2.4	36.6	0.7	18.8
		0.01	18.5	282.2	4.0	57.2	2.2	29.0
		0.015	26.6	314.3	5.6	63.3	2.9	31.9
		0.02	34.8	350.7	7.2	70.7	3.7	35.6
		0.03	49.1	369.3	10.0	74.2	5.1	37.3

which is an optimal configuration for the Sa Kaeo Landfill, satisfied the standard for its designed maximum stress of 200 kPa. Its value becomes less than that of the standard only at a stress level of ≥ 600 kPa.

FUNCTIONAL ROLE

Primary leachate collection and removal system (PLCRS)

The maximum thickness of leachate into the primary liner was calculated utilising McEnroe's exact method (1993), modified Giroud numerical method (1995), and Moore's method (1983) (Giroud et al. 2000). The results showed that the leachate thicknesses calculated from the first two methods were equal (with a difference of <0.5%), but the Moore's method (1983) greatly underestimated the thickness (Fig. 6). Since the validity of Moore's equation has been questioned (Giroud et al. 2000a), we have compared the results from the first two methods only.

Fig. 7 shows the comparison of leachate thickness build-up under Module 1 in both gravel types for two landfill lives of 1 and 10 years. The ranges of leachate entering into the PLCRS are then expressed in terms of the per cent of rainfall at Sa Kaeo. The results show that the leachate thickness decreases with increasing slope angle (i.e. hydraulic gradient). Assuming the worst-case scenario where all of the rainfall enters into the drainage system as leachate, the leachate thickness remains within 3 and 11 mm in the coarse gravel in 1 year and 10 years of landfill life respectively. When the finer gravel was used as a drainage material, the leachate thickness remained between 16 and 101 mm. In either case the thickness is well below the design thickness of granular drainage layer (300 mm). A comparison of each alternative was made based on the hydraulic safety factors (Table 3). The results show that the safety factor increases with an increase in slope angle. The safety factor at the lowest slope angle (I = 0.005) is 19 and 116 in the fine and coarse gravels respectively for a landfill life of 1 year. The safety factor decreases in successive years due to the greater reduction factors in the long-term hydraulic conductivity (k_{LTIS}).

The thickness of leachate on the primarily liner is more in Module 2 than in Module 1 because of its longer travel distance for the leachate before entering into the toe drains or manhole. The hydraulic safety factor in Module 2 decreases by 22–25% as compared to that in Module 1. Even in this case the safety factor is sufficiently large to allow for efficient drainage even of some storm water. This result shows that though both design alternatives are adequate Module 1 is relatively more efficient. This analysis indicates that the hydraulic safety factor decreases with a decrease in slope angle, increase in landfill life, and increase in drainage length. However, the role of each variable has to be judged based on the consumption of landfill space and the cost of materials required for construction at higher slope angles.

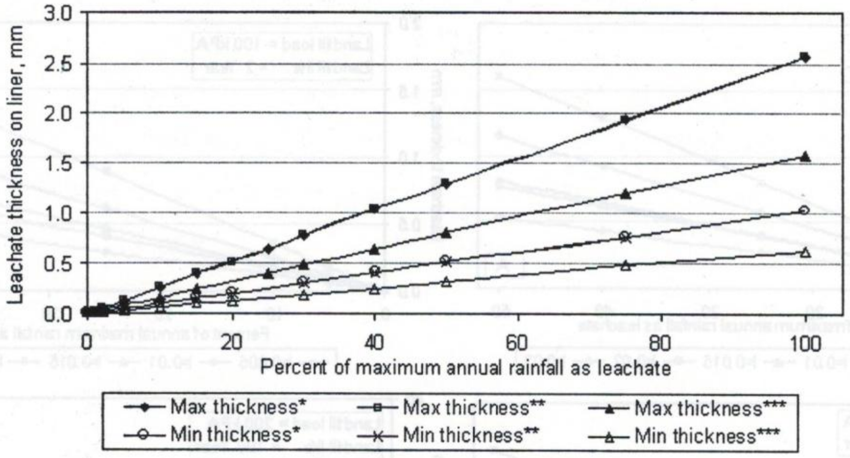

Fig . 6: Comparison of leachate thickness build-up using three methods: * MeEnroe Method (1993), ** Giroud Method (1995) , * Moore Method(1983). The maximum thickness corresponds to the month of highest rainfall (April) and minimum thickness refers to the month of minimum rainfall (December) at Sa Kaeo.**

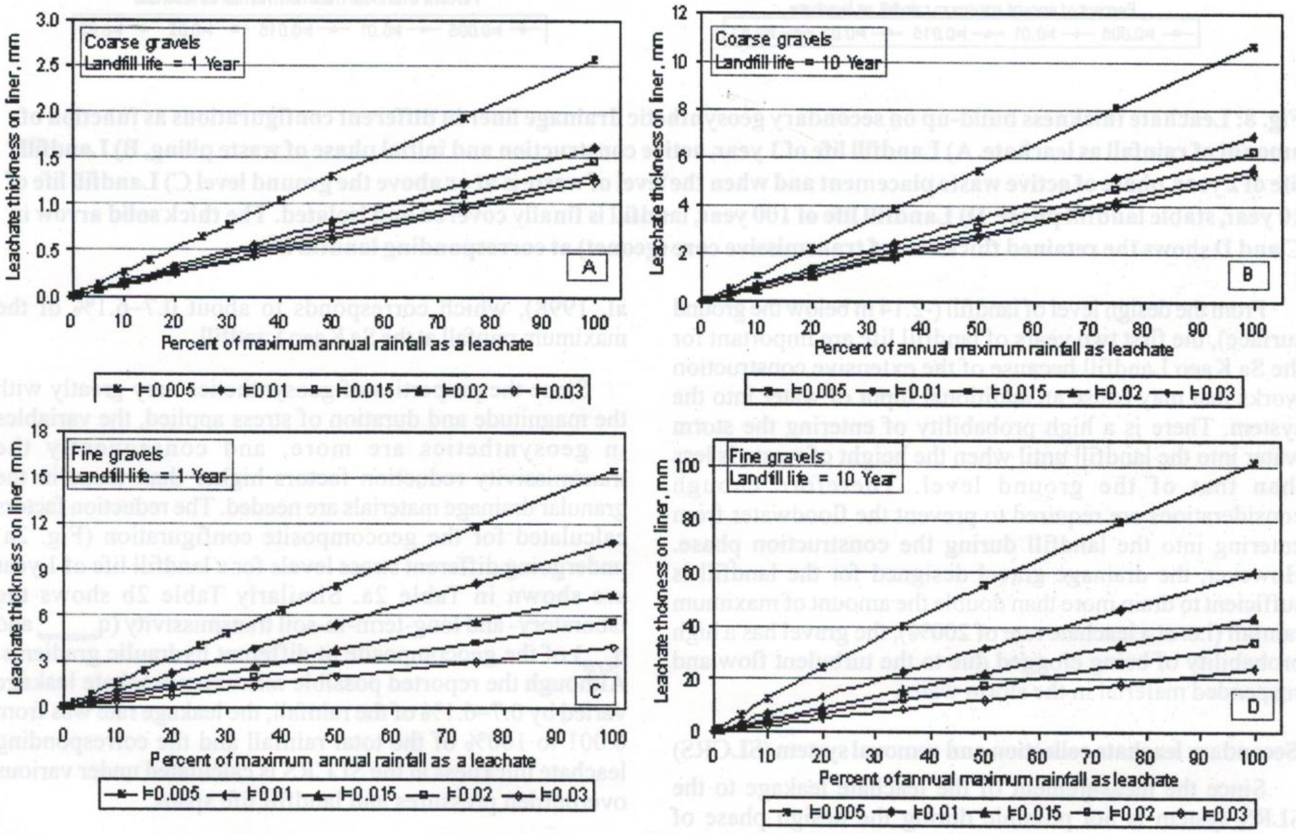

Fig. 7: Leachate thickness build-up on primary granular drainage liner in different configurations as function of amount of rainfall as leachate. A) Coarse gravels with landfill life of 1 year, B) Coarse gravels with landfill life of 10 year C) Fine gravels with landfill life of 1 year D) Fine gravels with landfill life of 10 year.

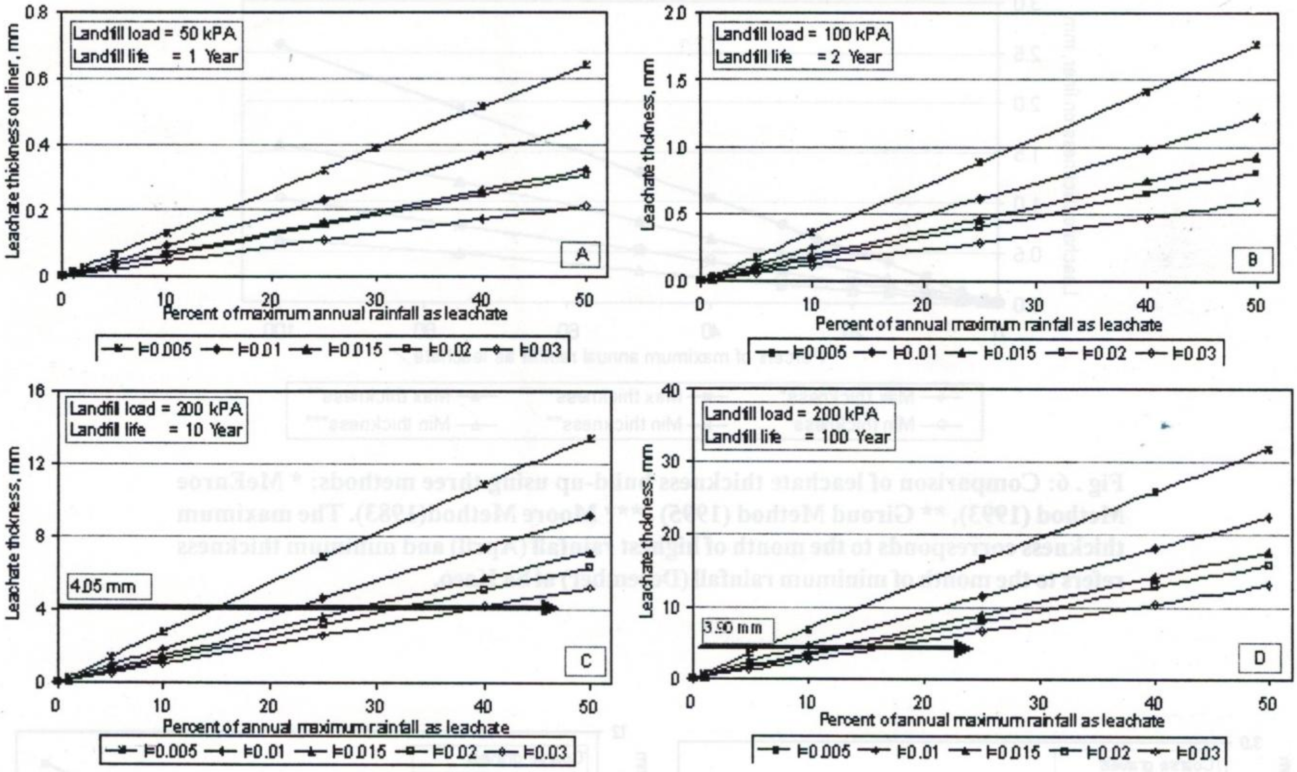

Fig. 8: Leachate thickness build-up on secondary geosynthetic drainage liner in different configurations as function of amount of rainfall as leachate. A) Landfill life of 1 year, active construction and initial phase of waste piling, B) Landfill life of 2 year, phase of active waste placement and when the level of waste is at or above the ground level C) Landfill life of 10 year, stable landfill phase D) Landfill life of 100 year, landfill is finally covered and isolated. The thick solid arrow in C and D shows the retained thickness of transmissive core (geonet) at corresponding landfill life.

From the design level of landfill (-2.14 m below the ground surface), the first two years of landfill life are important for the Sa Kaeo Landfill because of the extensive construction works that may cause an additional input of water into the system. There is a high probability of entering the storm water into the landfill until when the height of waste is less than that of the ground level. Therefore enough considerations are required to prevent the floodwater from entering into the landfill during the construction phase. However, the drainage gravel designed for the landfill is sufficient to drain more than double the amount of maximum rainfall (i.e. at a leachate rate of 200%), the gravel has a high probability of being clogged due to the turbulent flow and suspended material in the storm water.

Secondary leachate collection and removal system (SLCRS)

Since the measurement of the leachate leakage to the SLRS system is not possible during the design phase of landfill, the values from literature and case studies of similar landfills under similar SLCRS configurations are taken for the analysis. According to a compiled case study report, the maximum leachate leakage into the secondary drainage layer is found to be in the order of $3x10^{-10}$ to $3x10^{-9}$ m/s (Othman et al. 1998), which corresponds to about 0.7–6.1% of the maximum rainfall at the Sa Kaeo Landfill.

Since the properties of geosynthetics vary greatly with the magnitude and duration of stress applied, the variables in geosynthetics are more, and consequently the transmissivity reduction factors higher than those in the granular drainage materials are needed. The reduction factors calculated for the geocomposite configuration (Fig. 2a) undergoing different stress levels for a landfill life of 1 year are shown in Table 2a. Similarly Table 2b shows the laboratory- and long-term-in-soil transmissivity ($q_{measured}$ and q_{LTIS}) of the geocomposite at different hydraulic gradients. Although the reported possible maximum leachate leakage varied by 0.7–6.1% of the rainfall, the leakage rate was from 0.001 to 100% of the total rainfall and the corresponding leachate thickness at the SLCRS is calculated under various overburden pressures and landfill life spans.

The leachate thickness build-up shows that the thickness of leachate for a landfill life of 1 year is less than 1 mm in all slope angles considered (Fig. 8a) for the leachate leakage at 50% of the rainfall. The leachate thickness is low when the slope angle is increased. For a landfill life of 2 year, the

Table 4: Hydraulic safety factors of geocomposite in SLCRS as a function of the amount of leachate and landfill life

Landfill load	Landfill life	Slope gradient (I)	Percent of rainfall as leachate							
			0.01	0.1	1	5	10	25	40	100
50 kPa	1 year	0.005	35921.6	3593.2	359.4	71.9	36.0	14.4	9.0	3.6
		0.01	50183.0	5037.3	503.8	100.8	50.4	20.2	12.6	5.1
		0.015	70830.6	7185.5	718.4	143.7	143.7	28.8	18.0	7.2
		0.02	75193.8	7558.5	755.9	151.2	75.6	30.3	18.9	7.6
		0.03	113966.5	10870.5	1085.8	217.2	108.6	43.4	27.2	10.9
100 kPa	2 year	0.005	11876.1	1187.7	118.8	23.8	11.9	4.8	3.0	
		0.01	17300.7	1730.8	173.1	34.6	17.3	6.9	4.3	
		0.015	22799.1	2278.6	45.6	45.6	22.8	9.1	5.7	
		0.02	26068.4	2614.7	261.5	52.3	26.2	10.5	6.5	
		0.03	36074.8	3596.6	359.7	71.9	36.0	14.4	9.0	
200 kPa	10 Year	0.005	1381.8	138.2	13.9	2.8	1.4			
		0.01	2096.6	209.7	21.0	4.2	2.1			
		0.015	2723.0	272.3	27.2	5.5	2.7			
		0.02	3068.0	306.8	30.7	6.1	3.1			
		0.03	3758.2	375.8	37.6	7.5	3.8			
200 kPa	100 year	0.005	542.3	54.3	5.5	1.1	0.6			
		0.01	822.7	82.3	8.2	1.7	0.8			
		0.015	1068.5	106.9	10.7	2.1	1.1			
		0.02	1203.9	120.4	12.1	2.4	1.2			
		0.03	1474.8	147.5	14.8	3.0	1.5			

leachate thickness reaches 1.8 mm at a slope angle of 0.005, and 0.6 mm at a slope angle of 0.03 respectively (Fig. 8b) for the leachate leakage at 50% of the rainfall. The leachate thickness in the realistic values of leachate leakage (≤10%) was less than 0.4 mm. This low leachate thickness in early two years of landfill life results in higher hydraulic safety factors (Table 4). Assuming a safety factor of 5 acceptable at an early phases of the landfill life, the geocomposite is capable of removing the leachate which is as high as 100% of the rainfall at a slope angle of ≥0.01 for the landfill life of 1 year. Similarly for a life of 2 years, the geocomposite can drain the leachate as high as 40% of the rainfall at a slope angle of ≥0.015, and 20% at a slope angle of <0.015.

The leachate thickness is excessively higher at the later phases of landfill because of the several factors that degrade the transmissive core (geonet) of the geocomposite resulting in the decrease in transmissivity. The retained thickness of transmissive core also decreases with time due to the creep (Fig. 5). The leachate thickness build-up in 10 years of landfill life becomes equal to the retained thickness of transmissive core (4.05 mm) at leachate leakage of 15% and 38% of the maximum rainfall at a slope angle of 0.005 and 0.03 respectively (Fig. 8c). Similarly, this value reduces to a leachate leakage of 5 and 14% of the maximum rainfall at the ultimate landfill life (100 years) at a slope angle of 0.005 and 0.03 respectively (Fig. 8d). When the design Module 2 is used, an additional increase in the leachate thickness of 18–27% in each case of the leachate thickness is expected.

Based on the above calculation and discussion, the optimal design of landfill will be either to chose Module 1 with a low slope angle (as low as 0.01) or to choose Module 2 with a large slope angle (≥0.02). Since Module 2 contains longer flow path, the possibilities of clogging will be higher.

Clogging of drainage materials and proper functioning of drainage system

Although the upper bound values of reduction factors for biological, particulate, and chemical clogging suggested by Giroud et al. (2000a), and Zanzinger and Gartung (1999) were employed to calculate the long-term-in-soil hydraulic conductivity and transmissivity, the degree of clogging cannot be ascertained at the design phase of any landfill. The field and laboratory analysis of particulate clogging in geosynthetics (Xiao and Reddi 2000; Koerner et al. 1993), chemical and biological clogging (Koerner and Koerner 1992), and chemical degradation (Kay et al. 2004) of existing landfills have shown that the degree of clogging is site-specific. Therefore the following two possible ways to ascertain the proper functioning of both granular and geosynthetic drainage layers in the Sa Kaeo Landfill are recommended.

1. A periodic measurement of the leachate (pumped from toe drains and manholes) leakage rate into the primary and secondary drainage layers will help to identify the amount of leachate entering into the system. This information can

easily be converted into the per cent of rainfall to reckon the hydraulic safety factor for the given amount of leachate.

2. Periodic sampling of drainage materials for accessing the degree of clogging (physical, chemical, and biological) and comparing the observed values with the estimated ones (during the design phase) will help to trace any significant differences. If the clogging is found to be severe to hamper the acceptable flow of leachate, suitable methods of flushing and injecting oxygen to allow aerobic degradation or antibacterial chemicals to dissolve biofilms may be used.

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