Environ Geol (2005) 47: 795–803
DOI 10.1007/s00254-004-1207-9

ORIGINAL ARTICLE

İ. Met
H. Akgün

Composite landfill liner design with Ankara clay, Turkey

Received: 5 August 2004
Accepted: 2 November 2004

İ. Met
Ziraat Bankası Genel Müdürlüğü,
Tandoğan, Ankara

H. Akgün (✉)
Faculty of Engineering, Department
of Geological Engineering, Middle East
Technical University, Ankara, 06531,
Turkey
E-mail: hakgun@metu.edu.tr
Tel.: +90-312-2105727
Fax: +90-312-2101263

Abstract This study presents an overview of the geotechnical properties of the clayey soils, referred to as “Ankara clay”, at two sites of the Ankara region in an attempt to design a landfill profile composed of a high density polyethylene (HDPE) geomembrane/clay composite liner through the Hydrologic Evaluation of Landfill Performance (HELP) model and the Water Balance Method. The geotechnical properties of the landfill layers along with the water balance factors (i.e., evapotranspiration, precipitation, temperature, etc.) were assessed to determine the height of the water-saturated zone in the refuse above the composite liner for landfill design. The cumulative expected leakage rates through the composite liner constructed with compacted Ankara clay were related quantitatively to the cumulative average leachate head. The results of this investigation show that the leakage rates through the composite liner are within tolerable limits.

Keywords Ankara clay · Composite liner · Compacted clay · HDPE geomembrane · Expected leakage rate · Turkey

Introduction

Ankara is the second largest city in Turkey with a population of about 3 million and a mean daily waste generation of about 0.59 kg/person. To fulfill the landfilling needs of Ankara, the Ankara Metropolitan Municipal Authority developed a sanitary landfill project at Sincan-Çadırtepe (Fig. 1) with an estimated total waste capacity of 57,523,125 m^3 and a life span of approximately 20 years (Met 1999; Met and Akgün 1998; Met et al. 2005). However, as the new landfill site has a limited capacity, the Ankara Metropolitan Municipal Authority is planning to construct and operate new alternative landfill sites in the near future which require the design of landfill profiles composed of compacted clay/HDPE geomembrane composite liners (Fig. 1).

Ankara may be considered to be a major source of clay liners, as clay-bearing Upper Miocene–Pliocene deposits are found commonly within the Ankara city limits. These deposits, referred to as “Ankara clay” by Birand (1963); Çokça (1991, 2000); Ordemir et al. (1965) and Met et al. (2005) are rich in clay minerals, which makes these deposits desirable materials for landfill liners. The objective of this study is to present an overview of the geotechnical properties of the clayey soils at the Karakusunlar and Gölbası sites of the Ankara region; and to design a landfill profile composed of an HDPE geomembrane/clay composite liner through the Hydrologic Evaluation of Landfill Performance (HELP) model and the Water Balance Method.

Geology of the Ankara basin

Koçyiğit and Türkmenoğlu (1991) named the basin fill of Ankara as Yalıncak formation, which has its type locality in the ruins of Yalıncak village, and studied the geological and mineralogical characteristics of the clay-bearing soils, referred to "Ankara clay", at this type locality (Fig. 2). The Yalıncak formation at this type locality consists mainly of three different lithofacies: from bottom to top, the debris flow conglomerate, braided-plain conglomerate and sandstone and clay-bearing finer clastics of flood-plain origin. The term "Ankara clay" refers only to the finer red clastics contained on the upper half of the Yalıncak formation. The clay mineral assemblage contained in these red mudstones and siltstones is dominated mainly by smectite, illite, chlorite and kaolinite. The composition of the sand and gravel sized particles reflect a similar composition to that of the underlying graywacke and limestone bedrocks. According to these observations, it was concluded that the graywackes and limestones are the sources of the inherited clay and non-clay mineral assemblages of these red clastics.

An overview of the geotechnical properties of Ankara clay

Met (1999) and Met et al. (2005) report the results of the geotechnical index, standard compaction and falling head permeability tests of three disturbed clayey soil specimens obtained from the Karakusunlar and Gölbası sites of the Ankara region. The soil particle size distribution, specific gravity of the solids and the Atterberg limits were determined according to ASTM standards (ASTM D422-63 (2002), D854-02 and D4318-00). The results of the index tests showed that the clayey soils varied in specific gravity ($2.69 \le G_s \le 2.74$), plasticity ($42.4 \le LL \le 53.6$ and $25.5 \le PI \le 34.8$), and particle size distribution ($63.8\% \le$ fines $\le 79.9\%$ and $44.2\% \le$ clay content $\le 61.5\%$). The soil samples had a mean specific gravity (G_s) ± one standard deviation of 2.72 ± 0.03, mean liquid limit (LL) of 47.6 ± 5.64, mean plastic limit (PL) of 16.8 ± 2.05 and mean plasticity in-

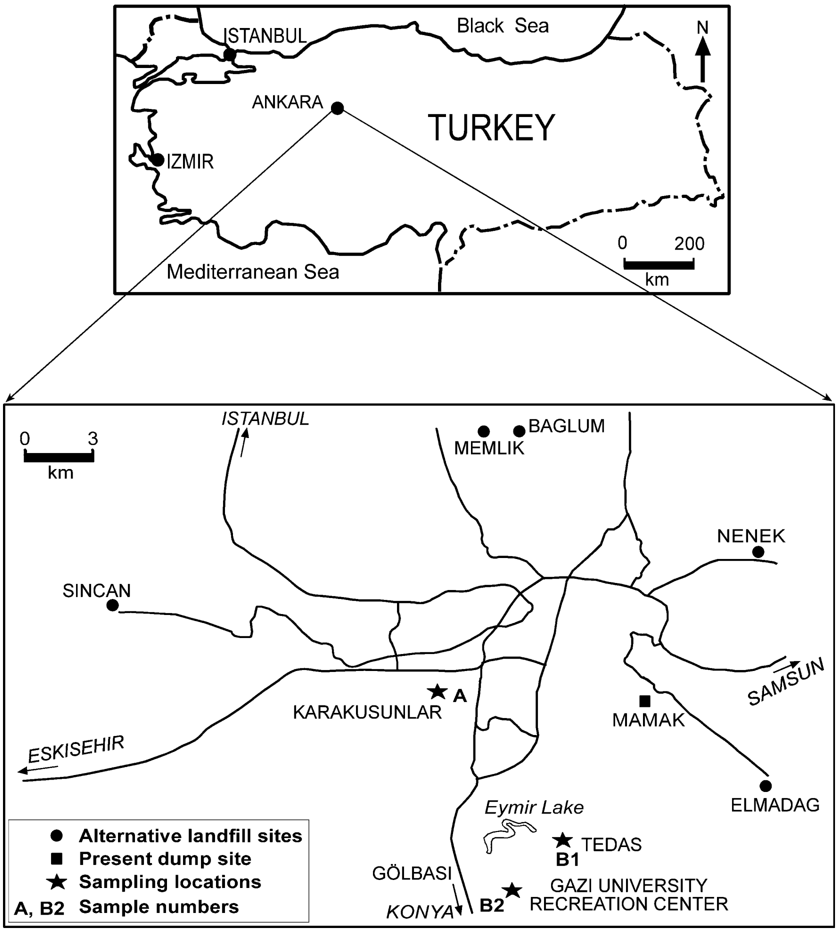

Fig. 1 Location map of the study area (Met 1999)

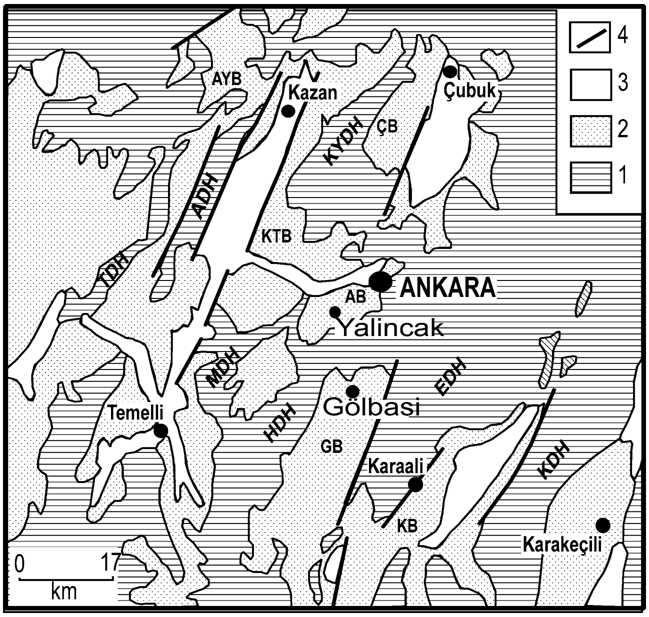

Fig. 2 Simplified geologic map of the Ankara Region. *1* Quaternary alluvial sediments, *2* late Miocene–Pliocene continental basin deposits and volcanics, *3* pre-late Miocene basement rocks, and *4* basin margin fault. Key to abbrevations: *AB* Ankara basin, *AYB* Ayas basin, ÇB Çubuk basin, *GB* Gölbası basin, *KB* Karaali basin, *KTB* Kazan-Temelli basin, *ADH* Abdülselamdağ highland, *EDH* Elmadağ highland, *HDH* Hacılardağ highland, *KDH* Küredağ highland, *KYDH*-Karyağdıdağ highland, *MDH*-Mesedağ highland, and *TDH*-Torludağ highland (Koçyiğit and Türkmenoğlu 1991)

dex (PI) of 30.8 ± 4.78. Three to thirteen index tests were performed for each group of tests. Using the unified soil classification system (USCS; ASTM D2487-00), the soil sample from Karakusunlar was classified as CH (fat clay with sand) and that from Gölbası as CL (sandy lean clay).

The results of the rigid-wall permeameter tests performed (ASTM D5856-95 (2002)) showed that the soil samples compacted at about 2–4% wet of the optimum moisture contents in accordance with ASTM D698-00 possessed a mean hydraulic conductivity of 2.12×10^{-10} m/s, which satisfied the regulatory requirement for a compacted clay liner (i.e., 1×10^{-9} m/s in the United States (USEPA 1993) and 1×10^{-8} m/s in Turkey (Resmi Gazete 1991).

Landfill profile design through the HELP model and the Water Balance Method

The HELP model, which is a quasi two-dimensional hydrologic computer model for conducting water balance analysis of landfills, cover systems and other solid waste containment system components was used to estimate the magnitude of the water-balance components and the height of the water-saturated refuse above the compacted clay/HDPE geomembrane composite liner (Schroeder et al. 1994). The HELP model computes sequential daily runoff, evapotranspiration and percolation from landfills to obtain daily, monthly and annual water balances. The hydrologic considerations include precipitation of any form, such as, surface evaporation, runoff, snowmelt, infiltration, vegetation, rooting depth, plant transpiration and soil evaporation. The program handles each of these considerations, often in a simplified manner, to estimate runoff, evapotranspiration, vertical drainage to liners and percolation through liners.

A landfill profile composed of a geomembrane/clay composite lining system to contain the waste was analyzed (Fig. 3). The profile is made up of three subprofiles containing a total of four layers in the following order. From top to bottom, one layer (topsoil) in the top subprofile, one layer (refuse) in the second profile, and two layers (HDPE geomembrane liner and compacted clay liner forming a composite lining system) in the bottom profile. This profile was created to satisfy the minimum requirements of the top and bottom subprofiles as suggested by Resmi Gazete (1991). The hydraulic conductivity of the compacted clay was taken to be equal to 2.12×10^{-10} m/s which represents a mean hydraulic conductivity value obtained from the soil sampling points (Fig. 1). The landfill area was taken to

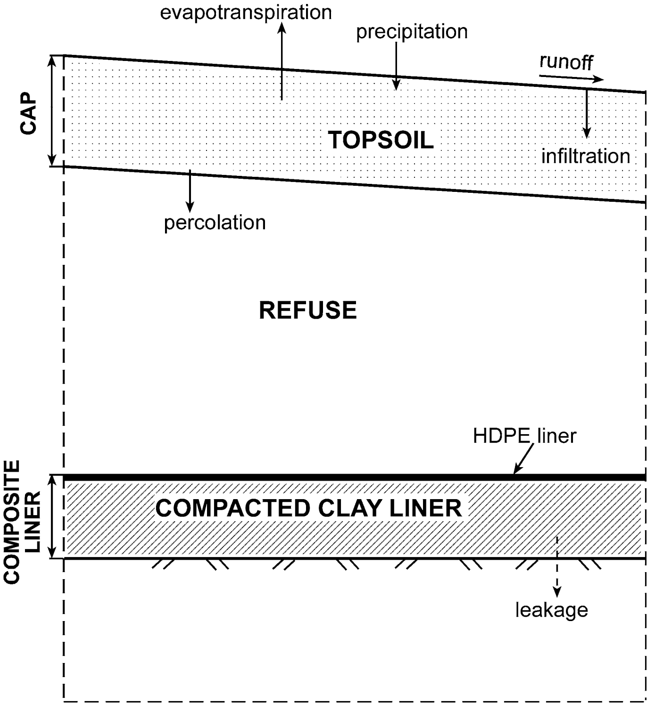

Fig. 3 Landfill profile composed of a HDPE geomembrane/compacted clay composite lining system

Table 1 Layer parameters used in the landfill profile presented by Fig. 3

Layer type	Thickness (m)	Porosity (vol/vol)	Hydraulic conductivity (m/s)
Vertical percolation layer (topsoil)[a]	1.0	0.475	1.7×10^{-7}
Vertical percolation layer (refuse)[a]	7.5	0.671	1.0×10^{-5}
Geomembrane liner[a]	0.002	0.000	4.0×10^{-15}
Barrier soil layer (compacted clay liner)[b]	0.6	0.462	2.12×10^{-10}

[a] Data from Schroeder et al. (1994)
[b] Data from Met (1999) and Met et al. (2005)

Table 3 The mean monthly temperature of Ankara between the years 1979 and 1998 (Met 1999)

Month	Mean monthly temperature (°C)
January	−0.1
February	0.5
March	4.4
April	10.4
May	14.5
June	17.6
July	20.5
August	20.4
September	16.9
October	11.5
November	5.2
December	1.8

be equal to 1 ha (10,000 m^2) and the thicknesses of the topsoil, refuse, compacted clay liner and geomembrane liner were selected as 1 m, 7.5 m, 0.6 m and 0.002 m, respectively. Table 1 is a tabulation of the layer parameters used in the HELP model.

The weather data required by the HELP model were classified into three groups: evapotranspiration, precipitation, and temperature data. The evapotranspiration data is composed of the evaporative zone depth, maximum leaf area index, dates starting and ending the growing season, normal average annual wind speed and normal average quarterly relative humidity. The evaporative zone depth is the maximum depth from which water may be removed by evapotranspiration. This value was taken as 0.91 m, as suggested by Schroeder et al. (1994) for clayey topsoils. The maximum leaf area index (LAI) is defined as the dimensionless ratio of the leaf area of actively transpiring vegetation to the nominal surface area of the land on which the vegetation is growing. In this study, LAI was taken as 2.0 assuming the presence of a fair stand of grass on the topsoil. The precipitation and temperature data of Ankara were provided by General Directorate of State Meteorological Works for the years 1979 through 1998 (Tables 2 and 3). In this analysis, it was assumed that the precipitation and temperature distribution between 1979 and 1998 is representative of the following 20 years.

Table 2 Precipitation data for Ankara for the years 1979 through 1998 (Met 1999)

Year	Precipitation (mm)
1979	512.5
1980	511.3
1981	482.1
1982	324.7
1983	606.7
1984	310.6
1985	478.1
1986	372.5
1987	494.6
1988	588.3
1989	467.0
1990	409.7
1991	412.8
1992	483.4
1993	400.4
1994	337.3
1995	425.7
1996	398.6
1997	480.1
1998	541.9

All the layer, design and weather data were used to evaluate the performance of the composite liner considered for a period of 20 years. Figure 4 gives a plot of the cumulative average leachate head acting on the composite liner as a function of time for the landfill profile presented by Fig. 3. The average cumulative leachate head acting on the composite liner increases from 42.41×10^{-3} m at the end of the first year to 7.29×10^{-1} m at the end of the 20th year.

The expected leakage rate per hectare through flaws in the geomembrane component of the composite liner (q_f) was calculated, on the assumption of good geomembrane–soil contact, by the following equation (Bonaparte et al. 1989, as quoted by Oweis and Khera 1998):

$$q_f = 0.877\, n_f\, k_s\, i_{av}\, \pi R^2 \tag{1}$$

$$R = 0.26\, a_o^{0.05}\, h^{0.45}\, k_s^{-0.13} \tag{1a}$$

$$i_{av} = 1 + \frac{h}{2h_s \ln(R/r_o)} \tag{1b}$$

where n_f is the number of flaws in the geomembrane per hectare (10,000 m^2), k_s is the hydraulic conductivity of the compacted soil component of the composite liner (m/s), i_{av} is the average hydraulic gradient on the wetted area of the compacted soil layer (m/m), R is the radius of the interfacial flow around a geomembrane flaw (m), a_o

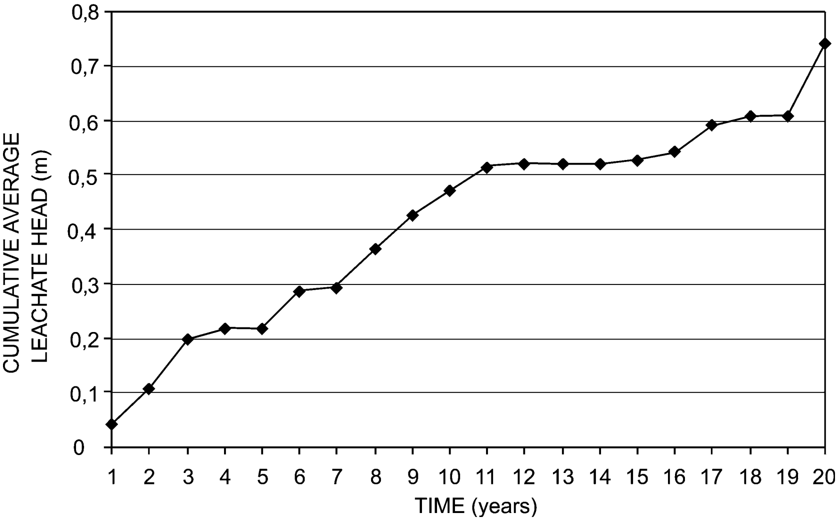

Fig. 4 Cumulative average leachate head acting on the composite liner as a function of time

is the geomembrane flaw area (m^2), h is the hydraulic head acting on the geomembrane (m), h_s is the thickness of the compacted soil (m), and r_o is the radius of the geomembrane flaw (m).

Flaws in geomembrane can range in size from pinholes that generally result from manufacturing errors to larger defects resulting from seaming errors, abrasion and punctures occurring during liner installation. Giroud and Bonaparte (1989a,1989b) define pinhole flaws to be smaller than the thickness of the geomembrane typically having a diameter of 1 mm and defects with a typical diameter of 11.28 mm or a cross-sectional area of 100 mm^2. The frequency of pinholes and defects may be considered as one and ten per hectare, respectively, for a reasonably conservative approach.

Figure 5 gives a plot of the cumulative expected leakage rate per hectare through flaws in the geomembrane component of the composite liner as a function of time for the landfill profile presented by Fig. 3. A good geomembrane-compacted clay contact was assumed. The cumulative expected leakage rates through the pinhole and defects as well as both are plotted in Fig. 5 assuming geomembrane pinhole and defect densities of one and ten per hectare, and pinhole and defect diameters of 1 mm and 11.28 mm, respectively. The composite liner cumulative expected leakage rate through the pinhole, defects and both are equal to 5.9×10^{-3} m^3/ha, 9.6×10^{-2} m^3/ha and 0.102 m^3/ha, respectively, at the end of the first year. These values increase up to 8.2×10^{-2} m^3/ha, 1.37 m^3/ha and 1.45 m^3/ha at the end of the 20th year, which are all within tolerable limits.

The accuracy of the results obtained through the HELP model was verified by using the Water Balance Method, which is the most commonly used method for estimating the volume of leachate generated by landfill

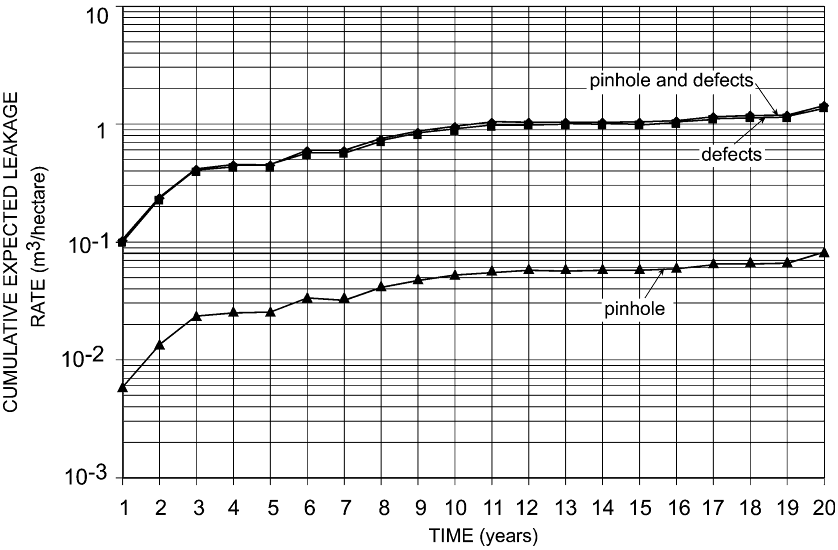

Fig. 5 Cumulative expected leakage rate per hectare through flaws in the geomembrane component of the composite liner as a function of time

Table 4 Runoff coefficients (C; Lu et al. 1985)

Area type	Flat slope < 2%	Rolling slope 2–10%	Hilly slope > 10%
Grassed	0.25	0.30	0.30
Earth	0.60	0.65	0.70
Cultivated			
(Clay)	0.50	0.55	0.60
(Loam)	0.25	0.30	0.35

wastes. The method assumes one-dimensional flow, conservation of mass and transmission characteristics of soil and refuse (Oweis and Khera 1998).

The basic equation in the Water Balance Method is given by Eq 2:

$$I = P - R_o \tag{2}$$

where I is the infiltration into the soil cover (mm), P is the precipitation (mm) and R_o is the surface runoff (mm). Figure 3 illustrates all these three parameters.

Precipitation (P) is estimated based on the average monthly values at the closest meteorological monitoring point(s). Surface runoff (R_o) on the other hand is estimated from an empirical equation as suggested by Lu et al. (1985):

$$R_o = CP \tag{3}$$

where C is the empirical runoff coefficient that depends on the type of surface, vegetation and slope as presented by Table 4.

Evapotranspiration (PET) may be computed from the Thornthwaite equation:

$$\mathrm{PET} = 16\left[\frac{10t}{\mathrm{TE}}\right]^{\mathrm{a}} \quad \text{for } t > 0°\mathrm{C} \tag{4a}$$

$$\mathrm{PET} = 0 \quad \text{for } t \leqslant 0°\mathrm{C} \tag{4b}$$

where PET (mm) is the unadjusted potential evapotranspiration for a standard 12-h day, t is the mean monthly temperature (°C), TE is the temperature efficiency index calculated by Eq 5 and "a" is a constant calculated by Eq 7:

$$\mathrm{TE} = \sum_{i=1}^{12} I_t \tag{5}$$

where I_t is a monthly value of the heat index computed from Eqs 6a and b as follows:

$$I_t = \left(\frac{t}{5}\right)^{1.514} \quad \text{for } t > 0°\mathrm{C} \tag{6a}$$

$$I_t = 0 \quad \text{for } t \leqslant 0°\mathrm{C} \tag{6b}$$

The constant "a" in Eq 4 is calculated by Eq 7:

$$a = 6.75 \times 10^{-7}(\mathrm{TE})^3 - 7.71 \times 10^{-5}(\mathrm{TE})^2 + 1.792 \times 10^{-2}(\mathrm{TE}) + 0.49239 \tag{7}$$

As PET is standardized for 12 h of daylight per day, it needs to be adjusted for unequal day and night durations. Adjusted evapotranspiration (AdjPET; mm) is obtained by Eq 8:

$$\mathrm{AdjPET} = (\mathrm{AdjFAC})(\mathrm{PET}) \tag{8}$$

where AdjFAC is the adjustment factor for potential evapotranspiration. Table 5 gives a tabulation of AdjFAC values for various latitudes according to Chow (1964).

If the annual (I − PET) is positive, the moisture retention, S_t, available for evapotranspiration is characterized by the following equation:

$$\mathrm{S_t} = (\mathrm{FC} - \mathrm{WP})c_t \tag{9}$$

where FC is the field capacity, WP is the wilting point and c_t is the root penetration distance, which is limited by the soil cover thickness. If (I − AdjPET) is negative, the soil moisture retention will be less.

The soil moisture retention (S_t) after potential evapotranspiration has occurred may be estimated from Table 6 (Thornthwaite and Mather 1957). The deficiencies are summed up on a running basis. A sum of zero is assigned to the last month having a positive value of (I − AdjPET) because at the end of the wet season the soil moisture is at field capacity. For negative months,

Table 5 Adjustment factors (AdjFAC) for potential evapotranspiration (PET) (Chow 1964)

Latitude	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0	1.04	0.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
10	1.00	0.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	0.98	0.99
20	0.95	0.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	0.93	0.94
30	0.90	0.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	0.98	0.89	0.88
35	0.87	0.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03	0.97	0.86	0.85
40	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81
45	0.80	0.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04	0.94	0.79	0.75
50	0.74	0.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	0.92	0.76	0.70

Table 6 Soil moisture retention (S_t) after potential evapotranspiration has occurred[a]

Σ NEG (I − PET)[b]	S_t (mm)[c]					
	25	50	75	100	125	150
0	25	50	75	100	125	150
10	16	41	65	90	115	140
20	10	33	57	81	106	131
30	7	27	50	74	98	122
40	4	21	43	66	90	114
50	3	17	38	60	83	107
60	2	14	33	54	76	100
70	1	11	28	49	70	93
80	1	9	25	44	65	87
90	1	7	22	40	60	82
100		6	19	36	55	76
150		2	10	22	37	54
200		1	5	13	24	39
250			2	8	16	28
300			1	5	11	20
350			1	3	7	14
400				2	5	10
450				1	3	7
500				1	2	5
600					1	3
700						1
800						1

[a] From Thornthwaite and Mather (1957)

[b] Σ NEG(I − PET) is lack of infiltration water needed for vegetation

[c] S_t is the soil moisture storage at field capacity

Table 6 is used to estimate the moisture retention. After the dry period when (I − Adj PET) becomes positive, the retention is equal to that for the previous month plus (I − AdjPET) for that month; however, the value can not exceed S_t. Where a positive (I − Adj PET) occurs between two negative values, retention is calculated by direct addition of (I − AdjPET) to the previous retention.

The actual loss due to evapotranspiration (AET; mm) is given by Oweis and Khera (1998):

$$\mathrm{AET} = \mathrm{AdjPET} \quad \text{(for wet months)} \tag{10a}$$

$$\mathrm{AET} = I - |\mathrm{d}S_t| \quad \text{(for dry months)} \tag{10b}$$

where d S_t is the change in the moisture storage in the cover.

The portion of the infiltration that will percolate into the landfill is then calculated by:

$$\mathrm{PERC} = I - (\mathrm{AET}) - \mathrm{d}S_t \quad \text{for } \mathrm{d}S_t \geqslant 0 \tag{11a}$$

$$\mathrm{PERC} = 0 \quad \text{for } \mathrm{d}S_t < 0 \tag{11b}$$

where PERC is the percolation amount and AET is the evapotranspiration, which depends on the adjusted potential evapotranspiration (AdjPET) and the change in moisture storage in the cover (d S_t).

Table 7 gives an example calculation of percolation through a 1-m thick vertical percolation layer of the

Table 7 Determination of percolation through the 1-m thick vertical percolation layer of the cap cover system by the Water Balance Method

	January	February	March	April	May	June	July	August	September	October	November	December	Annual total
Temperature (°C)	−0.40	0.00	5.80	12.20	17.00	22.10	24.90	23.90	19.70	13.20	8.50	1.30	
I_t (Eqs. 6a and b)	0.00	0.00	1.25	3.86	6.38	9.49	11.37	10.68	7.97	4.35	2.23	0.13	57.71
PET (Eqs. 4a and b)	0.00	0.00	16.11	45.62	72.57	104.77	123.80	116.90	89.20	50.93	27.51	1.99	649.40
AdjFAC (Table 5)	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81	
AdjPET (Eq. 8)	0.00	0.00	16.60	50.63	89.99	130.96	157.23	137.94	92.77	48.89	22.83	1.61	749.45
P (mm)	74.93	54.36	124.71	70.36	81.53	112.52	52.83	97.28	118.87	49.02	20.57	102.62	959.60
C (Table 4)	0.55	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	
R_o (mm) (Eq. 3)	41.21	16.31	37.41	21.11	24.46	33.76	15.85	29.18	35.66	14.71	6.17	30.79	306.62
I (Eq. 2)	33.72	38.05	87.30	49.25	57.07	78.76	36.98	68.10	83.21	34.31	14.40	71.83	652.98
I-(AdjPET)	33.72	38.05	70.70	−1.38	−32.92	−52.20	−120.25	−69.84	−9.56	−14.58	−8.43	70.22	−96.47
Σ NEG (I-AdjPET)			0.00	−1.38	−34.30	−86.50	−206.75	−276.59	−286.15	−300.73	−309.16		
S_t (Table 6)	83.00	83.00	83.00	81.00	52.00	25.00	6.00	2.00	1.00	1.00	1.00	71.22	
dS_t	0.00	0.00	0.00	−2.00	−29.00	−27.00	−19.00	−4.00	−1.00	0.00	0.00	70.22	
AET (mm) (Eqs. 10a, b)	0.00	0.00	16.60	51.25	86.07	105.76	55.98	72.10	84.21	34.31	14.40	1.61	522.29
PERC (mm) (Eqs. 11a, b)	33.72	38.05	70.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	142.47

soil (cap) cover system of the landfill profile given by Fig. 3 through the Water Balance Method. The cap cover of the landfill that is located at a latitude of 40° constitutes of loamy soil with a field capacity of 0.108 (vol/vol) and a wilting point of 0.025 (vol/vol). The annual percolation amount (PERC) is calculated to be equal to 142.47 mm, which is about only 0.44% lower than that of 143.10 mm calculated by the HELP model. Peyton and Schroeder (1988) performed long-term simulations ranging between periods of 1–8 years at 17 landfill cells in six different sites in the United States using the HELP model. They correlated the field data from landfill sites with the results computed by the HELP model. In their studies, the HELP model overestimated the runoff by about 25% and underestimated evapotranspiration by approximately 10%. Hence, a 0.44% difference obtained between the Water Balance Method and the HELP model suggests that computations made by the HELP model are within tolerable limits and that the HELP model leads to accurate results for the landfill profile considered herein.

Summary and conclusions

The clayey levels of the Upper Pliocene deposits of the Ankara basin, referred to as "Ankara clay", is considered as a source for compacted clay liners due to their low coefficients of permeability and widespread distributions throughout Ankara. This study presents an overview of the geotechnical properties of the clayey soils, referred to as "Ankara clay", at two sites of the Ankara region in an attempt to design a landfill profile composed of a HDPE geomembrane/clay composite liner through the HELP model and the Water Balance Method. The cumulative expected leakage rates through the composite liner constructed with compacted Ankara clay were determined as a function of the cumulative average leachate head. The average cumulative leachate head acting on the composite liner, as calculated by the HELP model, increases from 42.41×10^{-3} m at the end of the first year to 7.29×10^{-1} m at the end of the 20th year. The cumulative expected leakage rate through flaws of the composite liner is calculated to be equal to 0.102 m^3/ha at the end of the first year and 1.45 m^3/ha at the end of the 20th year, which is within tolerable limits.

Acknowledgments This work is supported by the Middle East Technical University (METU) Research Fund Project No. AFP-97-03-09-01. Thanks are due to Dr. A. P. Önen and Mr. Ö. Aktürk of the Middle East Technical University, Department of Geological Engineering, Ankara, Turkey for their kind assistance in drafting the illustrations in this manuscript.

References

ASTM D422-63 (2002) Standard test methods for particle-size analysis of soils. Annual Book of ASTM Standards, Section 4, Vol. 04.08, Soil and Rock; Building Stones. ASTM, Philadelphia

ASTM D698-00 Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)). Annual Book of ASTM Standards, Section 4, Vol. 04.08, Soil and Rock; Building Stones. ASTM, Philadelphia

ASTM D854-02 Standard test methods for specific gravity of soils. Annual Book of ASTM Standards, Section 4, Vol. 04.08, Soil and Rock; Building Stones. ASTM, Philadelphia

ASTM D2487-00 Standard classification of soils for engineering purposes (Unified Soil Classification System). Annual Book of ASTM Standards, Section 4, Vol. 04.08, Soil and Rock; Building Stones. ASTM, Philadelphia

ASTM D4318-00 Standard test methods for liquid limit, plasticity limit, and plasticity index of soils. Annual Book of ASTM Standards, Section 4, Vol. 04.08, Soil and Rock; Building Stones. ASTM, Philadelphia

ASTM D5856-95 (2002) Standard test method for measurement of hydraulic conductivity of porous material using a rigid wall, compaction mold permeameter. Annual Book of ASTM Standards, Section 4, Vol. 04.08, Soil and Rock; Building Stones, ASTM, Philadelphia

Birand AA (1963) Study characteristics of Ankara clays showing swelling properties. MSc Thesis, Middle East Technical University, Department of Civil Engineering, Ankara, pp 39 (unpublished)

Bonaparte R, Giroud JP, Gross BA (1989) Rates of leakage through landfill liners. In: Proceedings of Geosynthetics'89 Conference, Vol. 1, San Diego, Industrial Fabrics Association International (IFAI), Minneapolis, pp 18–29

Chow TV (1964) Handbook of applied hydrology. McGraw-Hill, NY

Çokça E (1991) Swelling potential of expansive soils with a critical appraisal of the identification of swelling of Ankara soils by methylene blue tests. PhD Thesis, Middle East Technical University, Department of Civil Engineering, Ankara, pp 323 (unpublished)

Çokça E (2000) An overview of the 35 years of research on the volume change behavior of Ankara soils. Middle East Technical University, Department of Civil Engineering, Ankara, pp 35

Giroud JP, Bonaparte R (1989a) Leakage through liners constructed with geomembranes—Part 1. Geomembrane liners. Geotextiles Geomembr 8:27–67

Giroud JP, Bonaparte R (1989b) Leakage through liners constructed with geomembranes—Part 2. Composite liners. Geotextiles Geomembr 8:71–111

Koçyiğit A, Türkmenoğlu AG (1991) Geology and mineralogy of the so-called "Ankara clay" formation: a geologic approach to the "Ankara clay" problem. In: Zor M (ed) Vth national clay symposium, Eskisehir Anadolu University, pp 87–101 (in Turkish)

Lu JCS, Eichenenberger B, Stearns RJ (1985) Leachate from municipal landfills. Noyes Publications, Park Ridge

Met İ (1999) Engineering geological assessment of clayey soils in Ankara for being utilized as compacted clay liners. MSc Thesis, Middle East Technical University, Department of Geological Engineering, Ankara, Turkey, pp 151

Met İ, Akgün H (1998) Utilization of Ankara clay as a compacted clay liner. In: third international turkish geology symposium abstracts, Middle East Technical University, Ankara, Turkey, p 46

Met İ, Akgün H, Türkmenoğlu AG (2005) Environmental geological and geotechnical investigations related to the potential use of Ankara clay as a compacted landfill liner material, Turkey. Environ Geol 47(2):225–236

Ordemir I, Alyanak I, Birand AA (1965) Report on Ankara clay. Middle East Technical University, Engineering Faculty, Ankara, No. 12, 27 pp

Oweis IS, Khera RP (1998) Geotechnology of waste management, 2nd edn. PWS Publishing Company, Boston

Peyton L, Schroeder PR (1988) Field verification of HELP model for landfills. J Environ Eng 114:247–267

Resmi Gazete (1991) Solid waste control regulation. Resmi Gazete, pp 4–19 (in Turkish)

Schroeder PR, Dozier TS, Zappi PA, McEnroe BM, Sjostrom JW, Peyton RL (1994) The Hydrologic Evaluation of Landfill Performance (HELP) model, Engineering documentation for version 3. Risk Reduction Engineering Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, Report No. EPA/600/R-94/168b, pp 116

Thornthwaite CW, Mather JR (1957) Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology, Laboratory of Climatology, Drexel Institute of Technology, Centerton, Pennsylvania

USEPA (1993) Criteria for municipal solid waste landfills (MSWLF Criteria), 40 CFR, Part 258, Cincinnati, Ohio