

A Basic Investigation into the Hydro-physical Properties of Emplaced Waste Lifts in a MSW Landfill

¹Olayiwola A. Oni PhD and ²Emmanuel Okunade PhD

¹ Prowork Ltd. 13 Newman Street, Southampton, UK.

²Department of Civil Engineering, University of Ado Ekiti, Nigeria, West Africa.

Abstract: A quasi-holistic investigation involving the simulation of hydro-physical properties of emplaced waste lifts at White's pit landfill, Poole, UK using the Hydrologic Evaluation of Landfill Performance (HELP) computer model and empirical models was undertaken. These joint models, calibrated using site characteristics obtained from laboratory tests and field measurements, unlike conventional ones, considered the impact of sequential infill of waste. Cone penetration tests (CPT) were preliminarily undertaken to determine the in situ properties of the waste fills. The data obtained from the CPT tests, however, only indicated the densification of emplaced waste with depth, without the depiction or quantification of any definite properties, which would have allowed parallel comparison with the modelled properties of waste lifts. The simulated results showed a temporal increase in field capacity and a reduction in porosity and saturated hydraulic conductivity of each emplaced waste lift, varying according to composition and thickness, and quantity of further refuse infill. The results showed the most significant rate of change during the period of sequential refuse placement, with the volumetric moisture content of each emplaced lift increasing owing principally to compression by the overlying burden. Consequently, the quantity and formation of leachate is increased with the depth of landfill. However, a delayed period of three years in leachate formation with a threefold reduction of drained leachate resulted from inconsideration of sequential infill in the leachate routing of the landfill.

Key words: investigation; waste lift; volumetric moisture; simulation; hydrologic evaluation of landfill performance (HELP); leachate

INTRODUCTION

Whatever the method of landfilling, municipal solid waste (MSW) is placed in thin layers and compacted until the desired height is reached for a day. Typically, a minimum of 15cm daily soil cover is put on the emplaced waste at the end of the day to minimise rainfall infiltration and to act as barrier to disease vectors. It also prevents odours, fires, and blowing of litter. The daily sequence of refuse infill is repeated until the design elevation of the landfill is reached, followed by the final placement of a top liner system. While waste landfilling is not instantaneous, but takes place over a considerable period of time, the majority of site investigations undertaken on the properties of waste landfills are commonly undertaken on completed landfills (Gee, 1981; Blakey, 1982; Blight *et al.*, 1992). Among the likely reasons for this trend is the evermore-stringent practice regulation, which makes data collection in operating landfills very difficult. Furthermore, the time required for complete continuous data is often long, while there is not yet a universal reliable instrumentation for data acquisition. Similarly, computer simulation studies on the temporal characteristics of emplaced waste during the operative life of the landfill are uncommon. The heterogeneity of waste components and the complexity involved in accurate predictions of the environmental factors that influence waste behaviour might contribute to unavailability of universally accepted models to estimate the geotechnical and hydraulic properties of refuse lifts with time.

The volume of leached water produced in refuse fills is among the principal concerns of landfill operators, and is influenced by factors that include, precipitation, evapotranspiration, surface runoff, moisture storage and microbial degradation. These factors are mutually dependent and usually vary within sites, and from site to site. For instance, the moisture storage of refuse significantly influences gas production, while uneven water storage between cells may cause both clogging and differential settlement in landfills, (Charles and Burland, 1982).

Corresponding Author: Olayiwola A. Oni PhD, Consultant, Prowork Ltd. 13 Newman Street, Southampton, UK.
E-Mail: onilayi@googlemail.com

The moisture stored in waste lifts is influenced by physical properties, comprising density, field capacity, porosity, height or thickness, and hydraulic conductivity (Powrie and Beaven, 1999). Generally, accurate prediction of the volume and quality of leachate is a highly complex and difficult task owing to the uncertainties involved in determining some of the terms of the water balance equation (Farquhar, 1989; Parsons, 1995). Often, the volume of leachate contributed by microbial degradation is ignored in the water balance method used at a landfill site. The micro-modelling of the temporal and spatial distribution of moisture in Landfills is also not exact with the existing models (El-Fadel *et al.*, 1997). Notwithstanding, any attempt to reasonably include even the macro-effects of the refuse infill period on the properties of emplaced waste lifts in computer modelling will improve the estimation of moisture volumes, which is required when evaluating alternative landfill designs, and also, in retroactive evaluation of old landfills.

In this study, an investigation comprising field and laboratory tests was undertaken on the restored landfill at Whites' Pit, Poole, Dorset. The data obtained from these tests were used in a computer modelling of the hydro-physical properties of emplaced refuse lifts. The simulation has been undertaken taken into consideration the sequential filling of the refuse layers at the landfill. Prior to the tests, a site investigation to obtain topographical, geological, and refuse disposal practices at the site was undertaken. The field tests involved primarily pit tests and cone penetration tests. In addition, the runoff and evaporative depth in topsoil, required in the HELP model, were determined from field measurements. The laboratory tests comprised the determination of compression, dry density, drainable porosity, and the saturated hydraulic conductivity of representative refuse samples obtained from the landfill at different overburden stresses.

A retroactive modelling of the moisture stored in the waste lifts and leachate drained from the landfill from inception in 1986 to post-closure period in 1998 was undertaken with the Hydrologic Evaluation of Landfill Performance (HELP) computer model. The HELP model, which is based on the water balance method (WBM), is probably the most widely used model for moisture routing in MSW landfills (Farquhar, 1989; Blight *et al.*, 1992; Bleiker *et al.*, 1995). However, the model is based on constant parameters and therefore does not account for time-changing conditions in the physical fabrics of a waste fill. To compensate for this, empirical waste and soil models, derived from the site data (Oni, 2000) were included in the simulation technique used. It was believed that this comprehensive approach would provide simple but yet reliable modelling of the physical characteristics and moisture routing, typical of MSW landfill.

MATERIALS AND METHODS

The Study Landfill:

The landfill (Figure 1) is located at White's Pit, Canford Heath, Poole, UK. The site is underlain predominantly by 15m Broadstone clay of Poole Formation of the Palaeocene age (Freshney *et al.*, 1985). The pit, originally created from sand quarrying is bounded by 800 acres of the Canford Heath Site of Special Scientific Interest, one of the largest surviving fragments of lowland heath in the south of England. The site consists of an old landfill (1.88ha) that comprises a restored "dilute and disperse" area, and an inert area located in the northern part of the pit. The modern landfill, located at the southern part of the site consists of an active containment landfill area. Waste tipping took place in the biodegradable area between 1982 and 1989. Clay capping was completed in the early 1990. Inert soil is still being placed to the south of the inert area. The surface runoff from the landfill collects to a perimeter ditch that drains to a wastewater pond located at the eastern part of the site. Gas production wells and leachate-monitoring wells are located within and outside the restored part of the landfill. The gas exploited from the site is used to generate approximately 7000 kilowatts of electricity into the National Grid.

A preliminary investigation of the site was undertaken to obtain waste composition, phases of filling, topography, geology, and weather (Oni, 2000). A computer visualisation model, UNIMAP 2000 was used to produce a topographic map of the site (Figure 1).

Investigative Tests:

Field Tests:

Test pits could reasonably give more continuous visual information than conventional borings in soil/waste formations (Gifford *et al.*, 1990). However, test pits are usually located in the top zone of the landfill and cannot give significant information usually required across the depth of a deep waste fill. Such information, especially the impact of successive waste emplacement on the properties of emplaced layers is vital to the understanding formulation and validation of predictive models for landfills. Three conventional test pits measurements at the site were undertaken on fresh, 5yr and 14 yr old waste deposits respectively. The values of the density, porosity and field capacity of these tests are similar to the previous reported waste data (Gifford *et al.*, 1990).

Static Cone Penetration Tests:

Static cone penetration tests (CPT) were undertaken in October 1998 at sixteen locations at the site to obtain information on the emplaced waste beyond the 3m depth of the pit test. As CPT is most suited for fine-grained fills (Landva and Clark, 1990), these tests were carried out with allowance for drilling failures. The tests were undertaken with a 20-tonne capacity hydraulic penetrometer with both a 10cm² and 15 cm² two-channel electric friction cone capable of measuring cone resistance and local friction within the waste mass. The rate of penetration was kept constant at 20mm per second, except where penetration was in very dense or hard strata. Instantaneous and continuous graphical records of cone end resistance and local side friction could be monitored on a colour screen during the drilling. The tests were terminated at any location where a combination of the following conditions occurred:

- High load (determined according to degree of rebound of test string)
- High load on the cone tip (generally 90% of rated capacity or suspected eccentric loading)
- Excessive inclination of the cone and test string (3 degrees or rapid inclination in any stroke)

Of the sixteen test locations, only four (CPT 7, CPT 11, CPT 12, CPT 14) had successful drillings exceeding 7m depth. Apart from three other spots (CPT 1, CPT 2, CPT 4), where the penetrometer reached 6m, the CPT did not go beyond 3m depth. Nevertheless, the series of tests was considered a success, owing to the expected variety of sizes and textures of the waste placed at the site.

Evaporative Depth of the Topsoil:

Whereas the evaporative zone in operational landfills is mostly limited to the relatively small depth of daily cover, it extends to root depth in a vegetated surface, and accounts for major loss of incident rainfall. Field measurements of the soil water profile in the topsoil of the landfill were undertaken at four locations at the site (Figure 1), using a neutron probe. Prior to the measurements, the standard count of the neutron probe (R_w) was obtained from the mean of ten 64-sec counts, taken at the mid-point of water, in a drum, in the laboratory. In addition, four each of 1m and 2m aluminium access tubes of the probe were installed at each location. The probe was calibrated by establishing a relationship between its count rate and the volumetric water content of soil cores (samples) taken at 10cm intervals from one of the locations (NP2). The calibration equation is given as:

$$\theta = 0.838 \left(\frac{R}{R_w} \right) - 0.0235 \quad (1)$$

where θ is the volumetric water content, R , the field count rate of the neutron probe, and R_w , the standard count of the neutron probe.

Runoff Measurement:

The runoff coefficient is required for the water balance calculations of moisture routing in refuse fills. It has been well reported that the runoff from landfill surfaces is generally less than surface flows from traditional soil formations (Ettala, 1987; Qasim and Chiang, 1994) and therefore needs to be measured from site to site. Two 3mm steel plated V-notch weirs were installed along the eastern drainage ditch at the site (Figure 1). They were to complement each other in case of unforeseen breakdown or damage. The immediate downstream of each weir was filled with gravel to prevent erosion owing to the water jump from the crest of the weir. Prior to installation of the weirs, a 10m stretch of the drainage ditch at the area of installation was cleared of silt, debris, vegetation and obstructions that might have affected flow conditions required for standard installation of the weirs.. A water recorder was installed at approximately 1.2 m upstream of the upper weir (W2) to measure the head of water above the crest of the weir. A linear relationship was earlier established between vertical movement of the pen and the vertical movement of the float of the water recorder in the laboratory.

The equation of the weir, obtained by plotting the flow against the head of water above the weir crest, is given as:

$$Q = 1.4286H^{2.5} \quad (2)$$

where Q is the volumetric flow rate in m³/s, and H , the head of water above weir in m.

During the period of measurement, the channel and the entrance of the stilling well in the recorder were regularly cleared of silt. At regular intervals, manual measurements of the water head over the weir crest were also compared to the corresponding values, calculated from the horizontal movement of the pen in the recorder, to ensure workability of the equipment.

Laboratory Tests:

The refuse properties (field capacity, porosity, and absorption capacity) that are difficult to determine in situ could be obtained from cell tests on large representative samples of the refuse that are compacted to the in-situ density (Landva and Clark, 1990). The height, compressive strain, dry density, porosity, and the hydraulic conductivity of the refuse fill with and without cover soil, under incremental applied loads, were simulated in conventional test cells.

Each compression cell (Fig 2) consists of a Perspex cylinder, 240mm internal diameter, 230mm high, and 12mm thick. The base of the cylinder was sealed with the same Perspex plate. Directly on the base was 10mm of gravel of approximately 50mm thickness to provide uniform distribution of water into the refuse. A steel screen with 60% void area created by 8mm diameter holes was placed on the gravel, immediately beneath the waste sample. A similar screen bounded the sample at the top to prevent loss of fine particles during the flow of water in the cell. The waste-fill in the cell was compressed by a perforated 240mm-diameter Perspex platen (8mm holes), connected by a steel rod to metal weights. A layer of 20mm polystyrene cubes, placed in between the Perspex platen and the upper galvanised steel screen provided a uniformly distribution of vertically applied load to the waste. Four uniformly spaced ports were located on each of three levels of the cell. The ports on the lowest level were connected via a plastic manifold to an elevated constant head tank of water. The ports on the next level were connected to Pyrex standpipes while the topmost ports were channels for outflow of water.

The waste particles (Table 1) were reduced to a nominal size of 20 x 5mm, which was deemed compatible with the size of the test cells. Three types of refuse landfill practice were simulated in the cells. They were: (a) Test 1: Waste materials only; (b) Test 2: Waste materials with a cover material with a nominal thickness of 7.5% of the underlying refuse layer; and (c) Test 3: Waste materials with a cover material with a nominal thickness of 7.5% of the underlying refuse layer. In Test 1, the waste particles were uniformly placed and compacted in small volumes to a density of 250kg/m³ and height of 110mm. In Tests 2 and 3, the waste was placed to the same density but interbedded with the appropriate daily cover. The classification of the waste particles is recorded in Table 1.

Table 1: Composition of waste materials used in the permeability test

Waste material	Percent of bulk mass (%)		
	Test 1(No cover soil)	Test 2(7.5% cover soil)	Test 3(10% cover soil)
Paper	30.59	31.94	29.92
Cardboard	4.32	5.51	5.16
Plastic	3.7	2.95	2.77
Thin plastic	5.73	4.58	4.29
Textile	1.82	1.45	1.36
Glass	4.29	3.42	3.21
Food waste	12.48	4.37	4.1
Ferrous Metals	4.55	2.83	2.65
Non Ferrous metals	1.49	1.19	1.11
Combustible	6.43	5.13	4.81
Green/garden	16.32	9.84	9.22
Wood	0.61	0.49	0.46
Fines<10mm	0.78	6.15	5.76
Sand soil cover	6.89	20.15	25.18
Total	100	100	100

nd : not determined; na : not applicable

The waste fill in the cell was loaded in eight uniform increments of 1kPa. At each stress level, the waste was allowed to consolidate to less than 1% change in thickness, then slowly filled with water, and subsequently drained to obtain its effective porosity. Immediately, the waste was re-saturated, and the saturating flow of water continued until the height of water in each standpipe was stable, following by the measurement of the change in water head and volumetric flow rate in the waste fill. The sample was then drained prior to another cycle of operation. Two replicates of each waste sample were tested.

Simulation of Hydro-physical Parameters:

A back simulation of the physical properties and moisture stored in the infill area G of the restored biodegradable landfill at White’s Pit (Figure 1) was undertaken from 1986 to 1998. The models and the technique involved are described in the following sections.

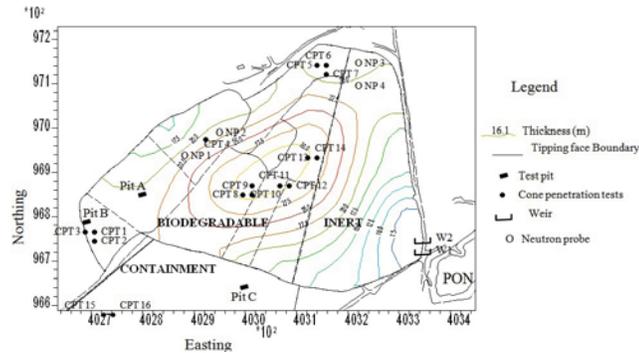


Fig. 1: The tipping phases, waste thickness, and locations for test pits and cone penetration tests at the site (Oni, 2000).

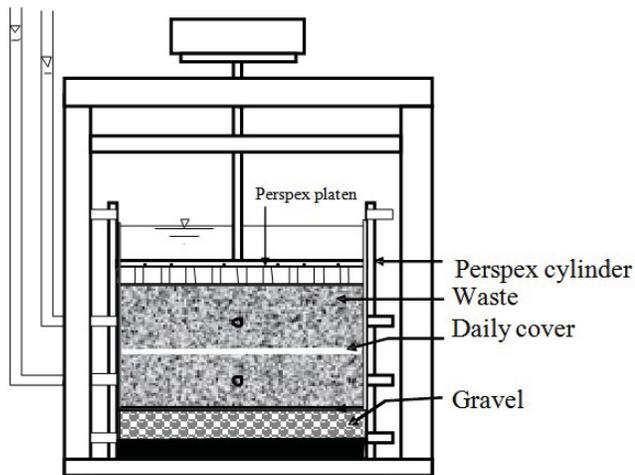


Fig. 2: Schematics of the test cell

Simulation Models:

Empirical Models:

An empirical model is quite useful in determining the characteristics of a material or process under various conditions, though it may not be universally applicable. Equations of the trend lines fitted to the test data enabled the prediction of porosity and hydraulic conductivity of emplaced waste lifts at various dry densities. Data from the waste samples incorporating 7.5% cover soil was used, being representative of the landfill practice at White’s Pit. The model for the field capacity at various dry densities could not be formulated from the test data but was derived from the data reported by Powrie and Beaven (1999), which have similar waste characteristics (Oni, 2000). The data derived from tests on painstakingly packed waste columns in cells were deemed to be more conservative than field values and thus suitable for modelling real waste characteristics. The equations are:

$$HC = 6 \times 10^{14} \rho_{dry}^{-7} \tag{3}$$

$$n = 2 \times 10^6 \rho_{dry}^{-195} \tag{4}$$

$$FC = 14.82 \rho_{dry}^{0.18} \tag{5}$$

where:

n = effective porosity of a waste lift in %; HC = hydraulic conductivity of a waste lift in m/s
 FC = field capacity of a waste lift in %; ρ_{dry} = dry density of a waste lift in kg/m^3

The determinant parameter in equations (3-5), dry density, was calculated from the vertical compression of waste lifts, which was also computed using empirical models derived from the temporal elevation data of the site Dorset County Council, (1997). Notwithstanding their simplicity, these settlement models were preferred to other models (Watt and Charles, 1999) due to their compatibility with the simulation technique. The equations are:

$$S_p = 0.3 H_i \log \frac{\sigma'}{\sigma} \tag{6}$$

$$S_s = 0.09 H_i \log \frac{t}{t_p} \tag{7}$$

where:

S_p, S_s = primary and secondary settlement occurring in the current refuse lift respectively

H_i = initial thickness of the current refuse lift

σ' = existing applied vertical stress acting at the mid-level of the refuse lift

σ = previous applied vertical stress acting at the mid-level of the refuse lift

t = present time or period at which settlement is desired

t_p = starting time or period at which secondary settlement is desired. t_p is usually taken as one month.

The HELP Model:

The HELP computer program, developed by the U.S Army Engineer Waterways Experiment Station (WES), Vicksburg, is a hydrological model of water movement across, into, through and out of landfills. The model utilises weather, soil and design data, and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and vertical leakage through soil, geomembrane or composite liner systems. It has the ability to model entire landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and composite liners incorporating synthetic geomembrane liners. The HELP model is well documented (Schroeder *et al.*, 1994).

The Simulation Process:

Major Assumptions: Reasonable assumptions, considered in the analysis to simplify the simulation process owing to the complexity of the nature of waste and site conditions, were:

- The simulated area of waste infill was considered a waste column, consisting of individual lifts of waste.
- A refuse lift comprises composite layers of refuse and intermediate cover materials placed in a single year.
- Each additional refuse lift was placed, only when the previous emplaced lift had been completely laid on the fill area.
- Each further placement of refuse was considered as additional imposed load on each emplaced refuse lift.
- Loss of waste mass due to biodegradation was insignificant during the period
- Waste compression due only to the self-weight of each waste lift is negligible.
- The only input of water was precipitation
- The net horizontal inflow of water into the refuse column was zero.
- The pore pressure in the emplaced refuse layers was considered to be negligible during the infill period.

- There was spatial uniformity in the climatic and landfill conditions on site.
- There was spatial uniformity in compaction, composition, compression, and hydraulic and geotechnical properties of each refuse lift during placement.
- Any leachate mound would drain from the sand drainage layer overlying the basal Broadstone clay liner.

Description: The procedure used in the computer simulation is best illustrated by a flow diagram (Figure 3). The process starts by inputting the essential hydro-physical data of the waste, weather data, and general site data into HELP 3.0 model to calculate the moisture volume in the lift placed in year 1 (lift 1) at the end of the year. The thickness, porosity, field capacity, and hydraulic conductivity of the lift 1 at the end of year remain as the initial, as the only overburden in year 1 is self-weight. Upon assimilation of moisture in lift 1 during year 1, the bulk wet density of lift 1 will increase, and is calculated for the end of year 1 as follows (Schroeder *et al.*, 1994).

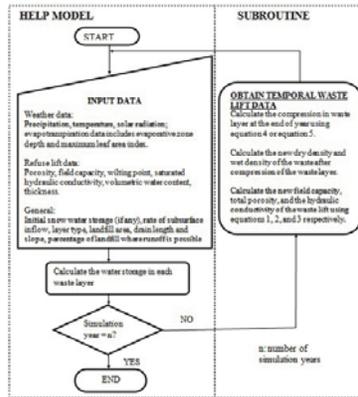


Fig. 3: Flow chart for the simulation of physical parameters and moisture stored in infill area G, White's Pit landfill.

$$\rho_{wet} = \rho_{dry} \left(1 + \left(\frac{\theta \rho_w}{\rho_{dry}} \right) \right) \quad (8)$$

where:

ρ_{wet} = wet bulk density of the waste lift; ρ_{dry} = dry bulk density of the waste lift
 ρ_w = density of water; q = volumetric moisture content of the waste lift

Following the placement of a new waste lift (lift 2) onto lift 1 in the second year, the moisture volumes in lifts 1 and 2 are calculated with the HELP program using the initial waste properties of both lifts at the start of year 2. The initial waste properties of waste lift 1 at the start of year 2 are the properties of the lift at the end of year 1, while the initial waste properties of lift 2 are the same as for lift 1 in year 1. The new thickness of lift 1, owing to its compression from the overburden, is calculated using equation 5. The total overburden stresses on lift 1 in year 2 include the stresses due to the overlying lift 2 and self-weight. By considering conservation of dry waste mass, the dry density of lift 1 at the end of year 2 is calculated as follows:

$$\rho_{1,2} = \rho_{1,1} \left(\frac{H_{1,1}}{H_{1,2}} \right) \quad (9)$$

where:

$\rho_{1,1}$ = dry density of lift 1 at end of year 1; $\rho_{1,2}$ = dry density of lift 1 at end of year 2
 $H_{1,1}$ = thickness of lift 1 at end of year 1; $H_{1,2}$ = thickness of lift 1 at end of year 2

The calculated dry density of lift 1 (post-compression) is then used to calculate the field capacity, porosity, and hydraulic conductivity of lift 1 at the end of year 2. The impact of the compression is also reflected in the moisture content of lift 1, earlier calculated with the initial properties using the HELP model. The real moisture content in lift 2 is thus:

$$\theta_{adj} = \theta_{HELP} \left(\frac{H_i}{H_f} \right) \quad (10)$$

where:

θ_{adj} = adjusted volumetric moisture content of lift 2 in year 2.

θ_{HELP} = initial volumetric moisture content of lift 2 obtained using HELP model in year 2

H_i = initial thickness of lift 2 in year 2.

H_f = final thickness of lift 2 in year 2.

The moisture volume in any lift cannot be greater than the total porosity. Equation (El-Fadel *et al.*, 1997), being based on conservation of moisture, may not be exact for the saturated zone of the landfill. However, the error in this case will be negligible, owing to the small temporal compression of the basal lifts, where saturation commonly occurs.

Adjustment for temporal changes in the hydro-physical properties of the waste lifts is done in sequence as above, up to the final clay capping. In the case of inactive filling, like in 1988 for fill area G, the additional overburden on the topmost lift during this year is considered as precipitation. During post-closure, the compression of the refuse lifts is calculated using equation 6, while all other procedures remain the same.

The characteristics of sandy loam given in the HELP manual (Schroeder *et al.*, 1994), were used for the topsoil of White's Pit. To account for the temporal vertical leakage of surface water through the top cover soil system, the properties of sandy clay (HELP no 10) were used instead of the top liner, stiff Broadstone clay. The use of the measured parameters on site (evaporative depth, runoff) and other pertinent data, including those obtained from site investigation in HELP, was to enhance the prediction results. Waste fills have double porosity and permeability, but the essential properties of waste were measured in one direction (vertical) in this study. Hudson (2005) stated that the saturated hydraulic conductivity in the horizontal direction (k_h) is twice that in the vertical direction (k_v) for a 20 year old deposit at low stresses. This ratio, $k_h:k_v$ increases to 5 at high stresses (~600kPa), and is 10 for fresh waste at an applied stress of 322 kPa. These values were obtained with the main flow of water in each direction. However, natural flow of water in refuse fills is powered by gravitational forces, downwards, in the vertical direction. Any lateral flow in waste is expected to be low, as hydraulic conductivity is influenced by the degree of wetness in the main direction of flow. The HELP model is developed for one-dimensional percolation in the waste and soil layers, but accurately computes the lateral flow occurring in the drainage bed. In addition, unsaturated hydraulic flow in the vadose zone of the waste fill is adequately computed in HELP.

RESULTS AND DISCUSSION

Cone Penetration Tests (CPT): The results of the most successful CPT (11) are depicted in Figure 4. The resistance to the penetration of the 20-tonne hydraulic penetrometer and the sleeve friction in the waste formation with depth at all the test points was not clearly defined. This is not surprising as the heterogeneity of waste implies that the cone would encounter various sizes and textures of waste particles randomly throughout the depth of drilling. The points of abrupt sharp changes in cone resistance (noises) were likely to be spots of cone contact with hard waste materials, and possibly, daily cover (slightly silty gravely sand). The random nature of the noises ruled out the possibility of them being solely spots of intermediate cover. However, if the noises are removed, then a general increase in the compactness of waste with depth is depicted, just as in soil formations.

As a characteristic rule in CPT, high cone resistance and low friction ratios signify the presence of coarse-grained soils, such as sands. Low cone resistance and high friction ratios characterize fine-grained soils, such as clays. Friction ratio (R_f), is the ratio of the sleeve friction to the cone resistance, expressed as a percentage. The analysis of the drill log, according to the recommendations of Robertson *et al.*(1986) showed that the behaviour of the waste fill with depth for CPT 11 was similar to soil characteristics that varying from sand to clay, with thin strips of organic soils. The same trend of soil behaviour was found for the waste fill at CPT

7 and CPT 12. However, the waste behaviour encountered at CPT 14 was slightly different, ranging from gravely sand to silt mixtures. As in typical MSW landfills, perched water appeared to be at 3m depths in CPT 11. However, both the measured dynamic and in situ pore pressures were near zero throughout the depth of the test areas.

Unfortunately, there was no distinct information gathered on the basic physical properties of the emplaced waste layers or lifts from the tests. However, the equivalent soil behaviour of the emplaced waste is characteristic of MSW fills, confirming the waste history, previously obtained from the site investigation. While the general information inferred was a general densification of the MSW fill with depth, perhaps the most pertinent information useful for the formulation of the simulation technique was the observed near-zero pore pressure of the entire area of cone penetration.

Moisture Profile of the Topsoil:

The mean evaporative zone of the vegetated topsoil at the site was obtained by comparing the moisture profile for the dry and wet periods in a year. The depth of the evaporative zone is the maximum depth from which water is extracted by evaporation, and the transpiration of plants. The rooting depths of grass may vary from 15cm to 120cm depending on the availability of moisture, soil type, plant density and species. The moisture volume with depth at one of the test points (NP 1) at various periods of the year is depicted in Figure 5. The profiles at other points were similar, as the same topsoil was used for restoring the landfill.

Distinct variation in the degree of saturation occurred between ground surface and a depth of 80cm. The maximum variation in the volumetric moisture in the vadose zone of the topsoil occurred during the extreme periods of wet and dry season during the measurements. Periods of measurement following a precipitation during the winter periods resulted in waterfronts, with a characteristic sharp increase in moisture volume, moving towards to the underlying clay liner. The slight increase in volumetric moisture between 80cm and 100cm was unlikely to be a water front, as it occurred during both wet and dry seasons. It would probably be caused by a soil strip of relatively high absorption, or any slight impediment to the downflow of water around the access probe at this depth. As the moisture content at 80cm and depths beyond 100cm appeared similar, the depth 80cm was chosen as the mean evaporative depth for the restored landfill. Neglecting all instrumentation errors, the mean field capacity of the topsoil was taken as 0.35. Considering the similarity in the moisture profile for the topsoil at both the inert and the biodegradable parts of the landfill, it was concluded that the impact of the biogas generated in the refuse fill on evaporation was negligible. Full exploitation of the biogas for electricity generation into the National Grid was implied.

Runoff:

The area contributing to the runoff was delineated using the elevation contours (Figure 1) that shed surface water into the stretch of drainage ditch along which the weir was installed, just before the pond at the site. The runoff, which is the ratio of the volume of runoff to the total precipitation received, was approximately 0.09 for a continuous period of measurement during the period of distinct wet and dry periods from September 10 - December 21, 1998.

It compares well with the runoff coefficients for sanitary landfills, (Qasim and Chiang, 1994), ranging from 0.07 to 0.2. Typical runoff coefficients used for drain designs with a similar surface lie within the range of 0.18 to 0.22.

The desiccation of clay liners owing to the uptake of moisture by the roots of landfill vegetation allow cracks to develop, and therefore encourages preferential channelling of water through the topsoil liners (Berger *et al.*, 1996). The thickness of the topsoil measured during the pit tests varied between 75cm to 100cm, the average being 85cm. The area of influence of moisture extraction by the plant roots is usually beyond the evaporative depth, which was 80cm at the site. Formation of macro-pores from cracks initiated by the plant roots is therefore expected at the site. The consequence is probably the relatively small runoff of precipitation measured at the site. Unless the topsoil liner is compacted or repaired, the cracks in the clay liner will increase with time, leading to less runoff of precipitation, and more moisture inflow into the mass waste. As in the evaporative process, there was no visible sign of any contribution to the formation or development of cave-ins on the ground surface by the biogas in the waste fill.

Experimental Data:

Without any universal models for waste mechanics, physical waste parameters will continue to be determined from soil mechanic equations, despite the fact that the unit weight of some waste particles is not constant (with varying applied stress). It may therefore be reasonable to view the calculated waste parameter as giving "typical" rather than "exact" values.

The trend of the physical properties of the waste tested in the conventional cells (Table 3) was similar to the values obtained from the drum test (Table 1) and reported data obtained from test cells (Chen and Chynoweth, 1995; Beaven and Powrie, 1995; Imam, 2003). The increase in the overburden stress resulted in a densification of the bulk waste of up to 80% conductivity of the waste, with and without intermediate soil cover, showed that, in addition to inter-granular voids, water was being transmitted through some of the absorbent particles of waste. This phenomenon has been demonstrated through numerical modelling of saturated hydraulic flow in refuse landfills (Powrie and Beaven, 1999). Among the factors responsible for the observed discrepancies in the measured data for waste fill, with and without intermediate layer, is the sifting of the soil particles into underlying waste layers, visually observed during the tests. For realistic results in tests on waste columns in cells, at least, an intermediate soil layer, representing the daily cover used in landfills should be included in the configuration of the column.

The experimental data compared fairly well with the data obtained from a large-scale Pitsea cell, 2m diameter by 3m high (Beaven, 2000), as it appeared to complement the latter at low stresses. The reduction of waste particles in proportion to cell size (Wall and Zeiss, 1995) and the similarity in the composition of the waste tested were suggested as the reason for this analogy. Accordingly, the characteristic equations derived from the plots to the test data appeared justified for use in the prediction of the behaviour of the waste at various overburden stresses.

Simulated Waste Characteristics and Practice Implications:

Physical Properties:

In the empirical models, derivations of the waste characteristics were indirectly based on unsaturated waste weights above the mid of each layer. The estimate at the saturated zone, commonly occurring at deep depths would therefore be a maximum, but these increased effects are likely to be counteracted by increased resistance due to pore water pressure at these depths. As the landfill was operated as a “dilute and disperse” facility, excess pore water pressure was likely to be insignificant with time, through leachate dissipation to the pores in the immediate environment, including transient rise in leachate level. The actual temporal depth of saturation is difficult to estimate, but will be influenced by the magnitude of additional overburden (if any), the rate of percolation and horizontal drainage, and volume of the pockets of entrapped biogases in the interstices.

Analysing the properties of individual lifts rather than the bulk of the refuse fill provided more detailed information, albeit cell heights would have been appropriate if the landfill were properly engineered and with no restriction in the HELP program. Owing to the unsteady rate of infill at the selected area used for the simulation, the thicknesses of the waste lifts used in the simulation were not the same. In some way, it allowed the impact of non-uniformity in the emplacement thickness of emplaced layers on waste characteristics to also be studied. Variability in the emplaced thickness of waste layers is likely to be common in old landfills, when no specific regulatory law was enacted.

Table 3: Average density, porosity, and saturated hydraulic conductivity of the waste at different applied stresses.

Applied vertical stress(kPa)	Dry density (kg/m ³)			Drainable porosity (%)			Saturated hydraulic conductivity (m/s)		
	T1	T2	T3	T1	T2	T3	T1	T2	T3
Initial	175	225	242	50.4	50.1	49.6	nd	nd	nd
1	200	247	263	44.4	45.6	45.7	3.6E-02	1.2E-03	4.7E-03
2	221	281	299	37.3	37.7	38.1	6.1E-03	4.0E-03	2.1E-03
3	234	295	315	34	34.1	34.1	5.E-036	3.3E-03	2.0E-03
4	255	316	335	28.1	30.2	31	2.5E-03	2.2E-03	1.4E-03
5	269	332	355	24.3	26.6	27.5	1.8E-03	1.2E-03	1.0E-03
6	291	353	379	21.2	23	23.1	1.4E-03	9.4E-04	7.8E-04
7	303	373	398	17.5	20.1	20.6	8.2E-04	7.0E-04	5.2E-04
8	314	389	417	16.2	17.2	17.5	6.5W-04	4.4E-04	4.0E-04

T1, T2, T3 – Tests 1, 2, 3 respectively. nd - not determined

As expected, the compactness of each lift increases with overburden, thus creating a temporal reduction in thickness, as cumulative infill increases with time (Figure 6). The general factors influencing the magnitude of settlement of completed (old) landfill are: (1) stress history; (2) fill height; (3) initial refuse density or void ratio; (4) the amount of degradable materials in the refuse; (5) leachate level; and (6) environmental factors (such as moisture content, temperature and gases present or generated within the landfill. For workability of the simulation technique, (3) and (4) are assumed constant, while the effects of (5) and (6) are considered minimal within the period of simulation (Watt and Charles, 1999).

The clay capping at the site progressed with the attainment of the design level of the top waste layer at each phase of tipping and was appropriately represented in the simulation. The profiles of the waste lifts and the layers of the cover soil system are the cumulative of heights of individual lift/layer above the basal clay liner. The summation of the varying settlements of the underlying waste lifts is particularly reflected in the surface profile of the Broadstone clay used as top liner. The temporal settlement of the clay cannot be due to the insignificant overburden of its overlying thin layer of topsoil. The total strain in the entire fill by 1998 was about 30%, with more than 50% of it accountable to the period up to the end of 1991, when the effects of daily tipping were predominant. This high compressibility is typical of MSW landfills. At the end of 1990, the strains in lifts 1, 2, and 3 were 14%, 8.3%, and 9% respectively. With the uniform placement conditions assumed for the site, the uneven thickness and overburden of the lifts were most likely responsible for this trend of strain in the waste lifts. In the experiments, irregular spatial settlement of the waste fill in the test cell was observed during the load increment. In a landfill site, irregular compression of underlying lifts will trigger spatial differential settlement of the top liner, which would assist or initiate cracks that commonly effect preferential inflow into the top-waste lift, as inferred in the runoff measurements.

The substantial quantity of absorbent materials in the refuse mass is demonstrated by an increase in the field capacity of each lift with increased overburden volume (Figure 7). Unlike soils, the water that can be retained under gravity is not limited to that controlled by capillary forces in the inter-granular pores. This extra water, retained within the soggy particles of the waste, makes the proportion of moisture retained under gravity to the bulk volume of each lift increase with compression, thus time. In effect, the porosity of the waste mass decreases, so does its saturated hydraulic conductivity.

The saturated hydraulic conductivity of the emplaced lifts decreased by one order following emplacement at the landfill site (Figure 8). This decrease was relatively rapid during the period of refuse infill. Being a dilute disperse site, the influence of the biodegradation on mass loss, and subsequent settlement of the lifts is expected to gradually continue with time. The low permeability of the basal lift provided relatively low saturated hydraulic conductivity, whose value should be used for designs requiring water transmission in the entire waste fill. The mean field capacity and hydraulic conductivity, calculated for the entire fill under prevailing conditions are shown by the dotted lines in Figures 7&8 respectively. Ordinarily, it will be expected to coincide with the values of lift 2. However, the irregular waste thickness of the lifts was responsible this disparity. In most cases, the degree of irregularity in the hydro-physical conditions of the lifts will increase with non-uniformity in waste placing conditions, and contrasting permeability of adjacent lifts will lead to temporary isolation or standing of water in the waste fill. For instance, if the placement arrangement in the landfill consists of an alternate very thick lift of waste (overburden) placed on a thin emplaced layer, then, there will be standing water on the less permeable thin lift, if its saturated hydraulic conductivity is less than the rate of leachate percolation. This was noticed in one of the drills (CPT1) in the cone penetration tests.

The validation of this simulation technique, which accounts for both vertical leakage and settlement, is supported by the similarity in simulated and parallel field data of Lift 3 in 1998. The simulated bulk wet density of top waste lift 3 is 1141.09 kg/m^3 , while the field density determined for the topmost refuse layer at the site from a pit test was 1198 kg/m^3 . In addition, the field capacity (46.5%), and total porosity (0.5260) of top waste lift compares well with measured values (44.9%, 0.631 respectively) obtained from the pit test.

Moisture and Leachate: The moisture routing of the real situation at the site including five other simulated cases, representing various scenarios of landfill conditions are described in this section, Comparing pairs of these scenarios allows the moisture conditions in various scenarios of landfilling to be studied. The scenarios are described as

- Case 1 - leakage and compression. This represents the real situation in the landfill, where the sequential filling of waste was considered (Figure 9).
- Case 2 - - leakage and no compression. This represents a scenario in which sequential filling of waste was not considered in the moisture routing of the landfill. The latter is based on evaluating landfill using the

water balance method only, which does not account for temporal changes in landfill features (Figure 9).

- Case 3 – No leakage with compression. This represents a situation in which there is no vertical leakage, as the integrity of the natural top liner is maintained with time (Figure 10) This situation is akin to the conditions expected in landfills operated on the principle of a “dry tomb
- Case 4 – No leakage and no compression. This as in Case 2 represents a situation in which Case 3 was simulated based only on the water balance method (Figures 10 & 11).
- Case 5 – Compression without cover. This represents a scenario in which the landfill lay bare, without any top liner. The scenario applies to old landfills that were abandoned, or refuse dumps in the developing countries (Figure 11).

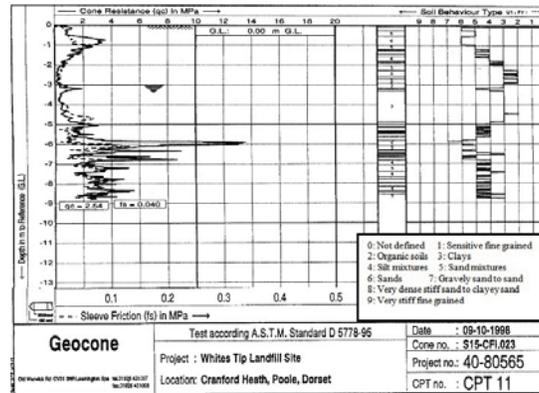


Fig. 4: Cone resistance, sleeve friction, and soil behaviour type at CPT 11 at White's Pit landfill.

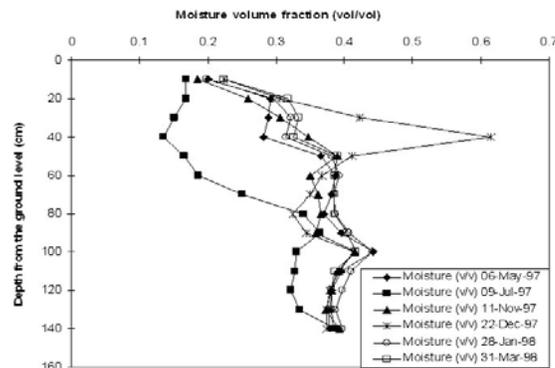


Fig. 5: Moisture profile at Point 1, White's pit landfill, Poole, UK.

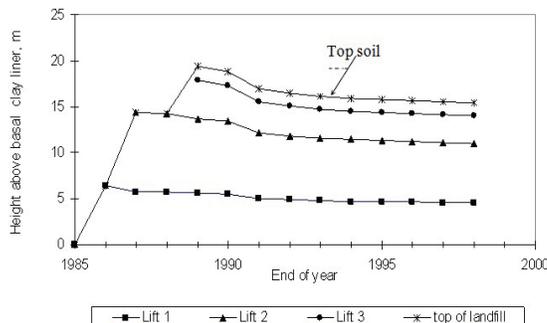


Fig. 6: Simulated profile of waste lifts and the cover soil system.

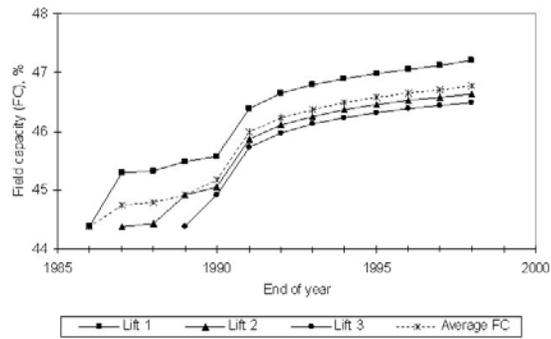


Fig. 7: Simulated field capacity of the waste lifts.

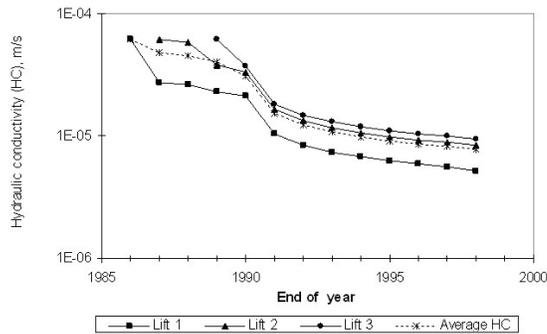


Fig. 8: Simulated saturated hydraulic conductivity of the waste lifts.

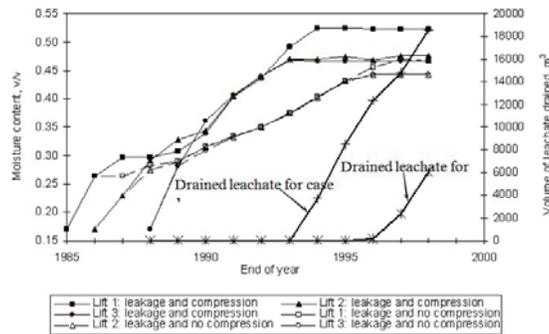


Fig. 9: Moisture in a refuse fill with leakage and compression, and leakage and no compression

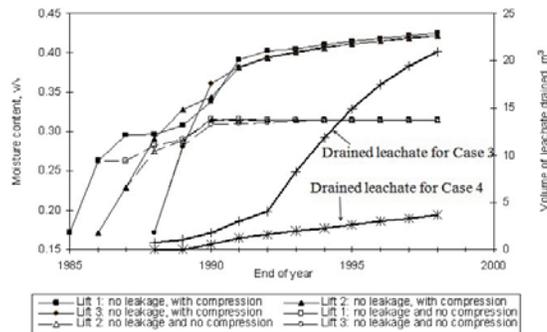


Fig. 10: Moisture in a refuse fill with no leakage but compression, and no leakage and no compression

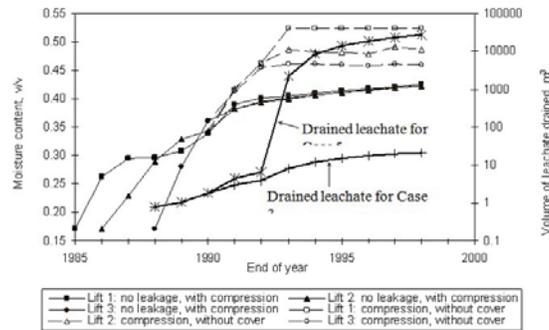


Fig. 11: Moisture in a refuse fill with no vertical leakage but compression, and no compression, without cover

The temporal moisture content in the waste lifts and the accumulated leachate in the entire landfill for cases 1 & 2 increased with time (Figure 9). The volume of drained leachate in the real landfill at White's pit (case 1) by 1998 is up to threefold of volume that would have obtained if the compression of the lifts were not considered in the modelling. By 1993, the compressed lifts 2 & 3 reached field capacity, and thus percolated moisture continued to accumulate in lift 1, until saturation was achieved in the next year. Following saturation, part of the percolated leachate was drained, while the rest built up in the overlying lift 2. Apparently, the volume of moisture required for saturation in if the lifts were assumed uncompressed was relative high. Despite having a relatively higher permeability, it took a longer time for the leachate to reach the basal drains. It took three extra years for waste in lifts 2 & 3 to reach field capacity, and the waste in lift 1 did not reach saturation prior to significant volumes of leachate being formed and drained, apparently due to its high permeability. Once the field capacity was reached in both the compressed and uncompressed lifts, the rate of basal drainage depended primarily on the rate of infiltration, and hence percolation, which is governed by permeabilities of the waste and intermediate cover soil. The trend (Figure 9) shows that the rate of water drained from the uncompressed lifts will become more significant with time. Nevertheless, modelling of moisture routing in waste fills without considering the compression of waste, which is significant during fill period, will seriously underestimate the start of leachate formation and therefore undermine efforts to operate a MSW waste facility in a safe way. Luckily, the natural attenuation of the emissions from the restored waste fill at White's Pit, owing to its location, to date prevented the detrimental effects from the old mode of operation at the landfill site.

At the end of 1998, the measured standing leachate level at tipping area G was 52.5m A.O.D, while the equivalent simulated level (for case 1) was approximately and 49m A.O.D, the basal Broadstone clay liner being 43m A.O.D. There is no data on the amount of actual leachate drained from the landfill to make a comprehensive comparison of the simulated and predicted values. However, the similarity in the standing levels of leachate once again suggests the suitability of the simulation technique used in the research

The moisture content in the lifts and the leachate drained in the landfill for cases 3 & 4 with time is depicted in Figure 10. Lifetime integrity of the top clay liner is probably impracticable, however, the complexity in the precise modelling of vertical leakage of clay liners may also encourage the omission of temporal vertical leakage by waste modellers. In both cases 1 & 2, the highest rate of increase in moisture in the lifts occurs during the waste infill period due to direct precipitation. The low permeability of the top barrier obviously resulted in relatively low moisture increase in the waste lifts during the post closure. Field capacity was not attained in either case; therefore the leachate percolated to the drains was as a result of transient vertical flows. Actually, the volume was insignificant, considering the size of the landfill. Yet, a distinct disparity still exists between the two different conditions. It shows that, even without significant moisture inflow into the landfill, the degree of saturation of the waste lifts subjected to compression will relatively increase. It further reiterates the importance of considering the temporal physical changes in waste lifts when modelling the essential hydro-behaviour of waste landfills.

Finally, two extreme cases of water inflow to the waste fill are considered (Figure 11). While both landfills are assumed to undergo compression when subjected to overburden, one of the fills has a cover liner with no temporal vertical leakage, while the other lay bare. In the uncapped fill, significant volumes of leachate formed barely two years after closure. In fact, the quantity of leachate produced was more than 1000-fold of the volume produced in a landfill without vertical leakage. This scenario indirectly portrays the disparity in the magnitude of environmental contamination being experienced by the West and Third World countries. As the

cost of aquifer pollution clear-up is very expensive, efforts should be made to legally regulate the landfill of waste in the developing countries, if the United Nation goals on child deaths owing to unsafe water are to be met.

In all the various scenarios, insignificant volumes of leachate were drained prior to attainment of field capacity in the waste lifts. These are transient vertical flows from the mid-point flow calculations used in HELP, which is based on vertical flow continuity of concurrent incoming and outgoing percolation processes in a waste segment. Significant flow volumes before the attainment of theoretical field capacity will occur if there are differential pathways in the waste mass. Such leachate flows to the basal drain have been reported in various field measurements (Blight *et al.*, 1992; Bengtsson *et al.*, 1994).

The distinction between the moisture and leachate volumes of the various scenarios illustrated above (Figures 9-11) shows the high sensitivity of the HELP model to variations in the permeabilities of waste and soil layers used in its modelling. However, the sensitivity of the HELP model to variation in the type of vegetation was found to be insignificant.

Conclusion:

A quasi-holistic method to investigating the basic hydro-physical processes in MSW fills has been found to be very effective, especially for the period of waste infill, considering the complex nature of waste. The use of refuse lifts in the analysis, despite being limited in number, enabled better understanding of the temporal variations within the depths of landfill.

Overburden owing to sequential landfill of refuse compressed the emplaced lifts, which consequently reduced permeability and increased the field capacity in varying degrees, with the rate of change decreasing with further filling. The magnitude of the settlement of the top liner, being an accrual of the compression of underlying lifts, is susceptible to both temporal and spatial deformations of the underlying lifts. Non-uniformity in the placement conditions of refuse might result in very contrasting hydro- characteristics in adjacent layers, leading to hydraulic isolation of parts of the landfill, as found at a depth of 3m below the ground level at White's Pit.

The rainfall leakage into the refuse during post-closure can be simply accounted for in the modelling of moisture conditions in waste fill by factoring down the original permeability of the top liner. Notwithstanding the absence of vertical leakage of moisture into the refuse during post-closure, secondary compression of refuse lifts would increase its volumetric moisture content (degree of saturation).

If the consequence of waste infill were not considered in the modelling of moisture routing, a grave underestimation of drainage volumes of leachate and time of occurrence at a landfill would ensue. Similarity in the predicted and measured moisture conditions of the study fill has shown that appropriate use of simple macro models, derived from site data, in conjunction with an established hydrological model such as HELP, can yield results that reasonably characterise the behaviour of a waste fill. The simulation method can be used for moisture and leachate predictions in designs or alternative plans of integrated waste systems. Further, the technique will be most useful for risk assessment of old landfills and refuse dumps that have waste history. However, the usefulness of CPT in field investigations of waste was found to be limited.

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