Retention of Free Liquids in Landfills Undergoing Vertical Expansion

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Abstract: This paper presents the results of an evaluation of the potential release of liquids stored within a waste mass undergoing compression due to a landfill vertical expansion. The mechanism of free liquid generation is initially evaluated and data interpretation methods are developed to estimate the maximum allowable waste thickness that a landfill could reach without releasing liquids stored within the waste. The proposed conceptual framework of free liquid generation is used to evaluate the environmental implications of the vertical expansion of an unlined case history landfill located in southern California. The moisture content of waste in southern California landfills is generally below field capacity. However, if the waste is compressed, its available moisture-holding capacity will decrease and its moisture content may eventually reach field capacity. Additional compression beyond this point will squeeze liquid from the waste. Laboratory testing and field characterization programs were undertaken to evaluate the field capacity, the in-situ moisture distribution, and the unit weight profiles of the waste in the case history landfill. These experimental data were used to evaluate the ability of the landfill to continue to retain moisture after continued waste placement. The evaluation indicated that the moisture content of the waste will not reach its field capacity for the proposed final grading of the case history landfill and, therefore, that the liquids should remain within the waste mass after the vertical expansion.

INTRODUCTION

The potential of a landfill to impact ground water is generally evaluated using water balance or water budget techniques in which the generation of free liquid (water output) is estimated using precipitation information (water input) and either measured or estimated hydraulic properties. In this approach, the hydraulic properties of the municipal solid waste (MSW) and cover soil remain constant during the analysis. The focus of the present paper is on the evaluation of the potential generation of free liquid in landfills undergoing vertical expansion. Different from conventional water balance analyses, free liquid could be generated in this scenario due to a decrease in the available moisture-holding capacity of the waste, which is induced by reduction of the voids within the waste rather than by infiltration of water into the system.

The field capacity of waste is the quantity of water per unit volume that can be held within the refuse against the pull of gravity. Consequently, free liquid will be generated when the amount of moisture within the waste exceeds the field capacity. The moisture content of waste in arid climates, such as in southern California, is generally below field capacity. However, if the waste is compressed, its available moisture-holding capacity will decrease and the moisture content of the waste may eventually reach its field capacity. Further compression beyond this point will generate free liquid.

The current paper indicates (1) an analytical evaluation of the effect of confinement on the field capacity and in-situ moisture content of waste, as well as an evaluation of the mechanism of free liquid generation that could be triggered due to a landfill vertical expansion; (2) a presentation and discussion of experimental results obtained from laboratory testing and field characterization programs undertaken to quantify the field capacity, the in-situ moisture distribution, and the unit weight profiles of the waste in a southern California landfill; and (3) a case history, which presents the results of an investigation performed to assess the ability of the existing waste in an unlined landfill undergoing vertical expansion to retain moisture and, consequently, to avoid any impact in the ground water. The methods and information presented herein allow estimation of the maximum allowable waste thickness (H_{max}) that a landfill can reach without releasing liquids initially stored within the waste mass.

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FIELD CAPACITY OF MSW

Field capacity is the moisture content that a porous material (e.g., waste or soil cover) will store within its pores by capillary stress. Veihmeyer and Hendrickson (1931) introduced the field capacity concept and defined it as ''the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased.'' For practical purposes, this definition implies that if a quantity of water is added to a porous material already at its field capacity, an equal quantity will drain out of it to restore moisture equilibrium.

Moisture retention parameters and relevant volumetric phase relationships for a porous material are illustrated in Fig. 1. Besides field capacity, other moisture retention parameters are the wilting point (lowest moisture content that can be achieved

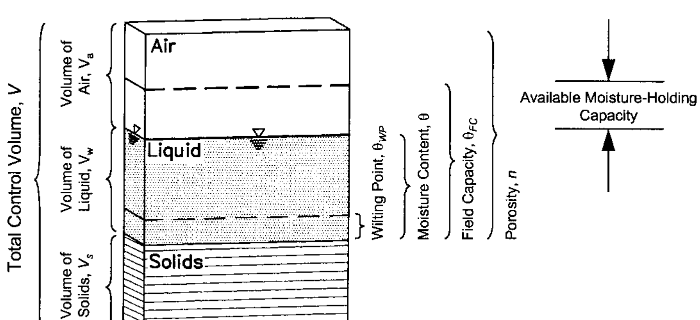

FIG. 1. Volumetric Phase Relationships and Moisture Retention Parameters in Porous Material

by plant transpiration) and the porosity (ratio between volume of voids and total control volume, $n = V_v/V$). Always less than 1.0 and greater than or equal to the field capacity, the porosity corresponds to the volumetric moisture content when the porous material is at saturation. The in-situ volumetric moisture content θ is the ratio between the volume of liquid and the total control volume ($\theta = V_w/V$), and it typically ranges between the field capacity and the wilting point of the porous material. For an in-situ moisture content θ, the additional moisture that the porous material can retain before free liquid is generated may be defined as the available moisture-holding capacity (i.e., the difference between the field capacity and the in-situ moisture content).

The moisture retention parameters and phase relationships in Fig. 1 are expressed using volumetric relationships. The use of volumetric relationships is the state of practice in agronomy and soil physics, and volumetric relationships have been used in the hydrologic performance evaluation of landfills model (Schroeder et al. 1994). In geotechnical applications, however, the moisture content is commonly reported using gravimetric relationships. The gravimetric moisture content, w, is defined as the ratio between the weight of water W_w and the weight of solids W_s in a control volume ($w = W_w/W_s$).

Useful relationships between gravimetric and volumetric moisture contents (and moisture retention properties) that will be used in the data analyses presented in this paper are as follows:

$$\theta = \gamma_d/\gamma_w \cdot w \quad (1)$$

$$\theta = \frac{\gamma_t}{\gamma_w} \cdot \frac{w}{1 + w} \quad (2)$$

$$\theta = (1 - n) \cdot G_s \cdot w \quad (3)$$

where γ_d = bulk dry unit weight of the porous material; γ_w = unit weight of water; γ_t = total (wet) unit weight of the porous material; and G_s = specific gravity of the solids.

The results of water balance analyses in MSW landfills are sensitive to the field capacity value selected for the waste. However, moisture retention properties of MSW are among the water balance components that are most difficult to define or estimate. This is probably a consequence of the inherent difficulty of laboratory testing of MSW, the lack of standardization in reported experimental results, and the dependence of moisture retention properties on the composition and the unit weight of the waste. McBean et al. (1995) reported typical (volumetric) values of 55% for field capacity and 17% for the wilting point of MSW.

There is only limited information on the effect of confinement on the field capacity of waste. Blight et al. (1992) implemented a testing program to investigate this issue. As part of this experimental program, waste samples were inundated with water, allowed to drain for 24 h, and finally compressed under increasing overburden pressures at which field capacity was measured. Reported gravimetric field capacity values from this laboratory program ranged from 225% for fresh waste at low confining pressures to approximately 55% for older wastes compressed to a unit weight of approximately 10 kN/m^3. Typical gravimetric field capacity values measured by Blight et al. (1992) as part of the field characterization of three landfills located in semi arid areas of South Africa ranged from 125% to 150%.

Experimental results were also reported by Fungaroli and Steiner (1979), who indicated that the volumetric field capacity increases with the unit weight of the waste material (i.e., with the reduction of the voids within the waste). The reported test results showed, for example, that milling of waste increases the volumetric field capacity. For unmilled waste, the field capacity and unit weight were reported to fit the following relationship:

$$\theta_{FC} = 21.7 \ln \gamma_t - 5.4 \quad (4)$$

where θ_{FC} = volumetric field capacity (%); and γ_t = total (wet) unit weight of the waste (kN/m^3). For a waste unit weight of 13.5 kN/m^3, the prior relationship yields a volumetric field capacity of 51%. Field capacity values estimated using (4) are consistent with the values obtained experimentally for the waste in the case history landfill described in the present paper.

IN-SITU MOISTURE DISTRIBUTION WITHIN MSW LANDFILLS

Evaluation of the available moisture-holding capacity of MSW requires adequate in-situ characterization with depth of the waste moisture distribution within the landfill. Moisture content in landfills is highly dependent on several interrelated factors, including waste composition, weather conditions, landfill operating procedures, presence of leachate and/or gas collection systems, and closure sequence of the landfill. Results from landfill field investigation programs have shown that the amount of moisture within the waste varies greatly with location and depth. It is common, for example, for waste material to show saturated or partly saturated intraparticle voids and dry interparticle voids (Landva and Clark 1990). Boring logs at the Operating Industries Inc. landfill in southern California have often shown intervals of saturated waste separated by comparatively large intervals of dry waste (''Waste'' 1996). Moreover, poor correlation was often observed between the elevations of saturated zones in borings of this landfill located less than 30 m apart. This pattern of multiple perched liquid zones with little apparent lateral connectivity suggests that liquid occurs in isolated waste cells within the landfill. These isolated liquid zones may exist because of localized disposal of liquid wastes and/or the use of relatively low-hydraulic conductivity soils as daily covers.

For the purposes of characterizing the amount and distribution of liquids within an MSW landfill, mechanisms of moisture retention within the waste mass can then be classified as (Fig. 2):

1. Moisture within the waste particles (i.e., within intraparticle voids)
2. Moisture between particles (i.e., within interparticle voids), held by capillary stresses
3. Moisture between particles, retained by low-hydraulic conductivity layers

Moisture retained within the waste by mechanisms 1 and 2 should be less than the field capacity of the waste. However, moisture accumulated above layers of low-hydraulic conductivity (mechanism 3) often leads to areas within the landfill where moisture is above field capacity of the waste.

There is limited information regarding in-situ distribution of moisture with depth in MSW landfills. In-situ gravimetric moisture content values in excess of 100% have been reported

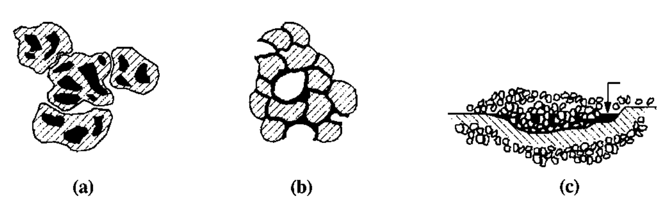

FIG. 2. Mechanisms of Moisture Retention in Waste Mass: (a) within Particles (Intraparticle Voids); (b) between Particles, Retained by Capillary Forces (Interparticle Voids); (c) between Particles, Retained by Low Hydraulic Conductivity Layers

by Blight et al. (1992) for South African landfills located in arid regions. Measurements at the Pioneer Crossing Landfill in Pennsylvania (Gabr and Valero 1995) showed a trend of increasing gravimetric moisture content with depth, with values ranging from 30% near the surface to 150% at a depth of 20 m. However, the opposite trend of gravimetric moisture content with depth was reported for the Ano Liossa Landfill in Greece (Coumoulos et al. 1995), with values exceeding 150% at shallow depths and moisture contents of approximately 50% at a depth of 30 m. Results presented in the present paper from a field characterization program undertaken at a southern California landfill provide much needed additional information on the distribution of moisture within MSW landfills.

MECHANISM OF FREE LIQUID GENERATION DUE TO LANDFILL VERTICAL EXPANSION

The flow of moisture within MSW landfills is generally evaluated using mass conservation principles by water balance techniques. The water balance used for prediction of free liquid in landfills is generally stated as

$$\text{Infiltration} - \text{evapotranspiration} = \text{change in liquid storage} + \text{liquid extraction} + \text{free liquid} \quad (5)$$

Infiltration is the difference between precipitation and surface water runoff. Evapotranspiration accounts for moisture loss by surface evaporation and plant transpiration. Change in liquid storage is the change in moisture either stored by capillary stresses within the waste and intermediate cover layers, or in transit under downward (gravity) or upward (evapotranspirative) flow gradients. Liquid extraction is the removal of moisture by liquid and gas extraction systems and by biodegradation processes within the waste. Finally, the free liquid (i.e., the unknown in the water balance equation) is the liquid exiting at or collected from the base of the landfill. Eq. (5) is generally applied to cases in which it is reasonable to assume that waste properties will remain unchanged and, consequently, that free liquid generation will be governed by the amount of liquid infiltration into the system. The focus of the present paper, however, is on the evaluation of a scenario in which waste properties do change and the generation of free liquid is caused by variations in the retention capacity of the waste. In the situation under investigation, the waste mass undergoes compression and the infiltration, evapotranspiration, and liquid extraction components of the water balance problem can be neglected. Consequently, (5) in this case is reduced to:

$$\text{Change in liquid storage} + \text{free liquid} = 0 \quad (6)$$

Change in liquid storage of waste undergoing compression may occur not only due to a change in the void space within the landfill, but, possibly, also due to a change in the field capacity of the waste due to the increased confinement.

The available moisture-holding capacity of waste will decrease as the waste is compressed during a landfill vertical expansion. Some studies have been performed on the effect of compression of MSW on landfill settlements (Sowers 1968, 1973; Edil et al. 1990; Othman et al. 1995). However, there is only limited information on the effect of compression of MSW on the moisture retention properties (Fungaroli and Steiner 1979; Blight et al. 1992). Field and laboratory data generated for the case history landfill provide insight into the effect of confinement on the field capacity of waste materials.

Fig. 3(a) shows a schematic representation of three different stages during the vertical expansion of a landfill. The three stages correspond to cases in which the waste thickness (H) is respectively below, equal to, or above the maximum allowable waste thickness (H_{max}). H_{max} represents the total thickness of waste below which liquid stored within the landfill is not released as free liquid due to compression of the waste. Fig. 3(b) shows volumetric phase diagrams illustrating the decrease in available moisture-holding capacity and subsequent generation of free liquid at different stages during a landfill vertical expansion. The phase diagrams shown in Fig. 3(b) correspond to a waste control volume located toward the base of the landfill, where the confining pressures are the highest and, consequently, where free liquid will first be generated. If the waste thickness H is below H_{max} (stage I), the waste has an available moisture-holding capacity quantified as the difference between the volumetric field capacity at this stage ($\theta_{FC,\mathrm{I}}$) and the in-situ volumetric moisture content (θ_{I}). As the waste mass undergoes compression, a change in the initial control volume will result in a decrease in porosity, landfill settlements, and a decrease in the available moisture-holding capacity. However, if the waste thickness remains below H_{max}, the moisture content will be below the field capacity, and free liquid will not be generated. Once the waste thickness reaches H_{max} (stage II), the available moisture-holding capacity is zero; i.e., the volumetric field capacity ($\theta_{FC,\mathrm{II}}$) equals the in-situ volumetric moisture content (θ_{II}). Any additional compression beyond this point, induced by a vertical expansion by which the waste thickness exceeds H_{max} (stage III), will release liquid initially stored within the waste.

The following assumptions are considered regarding the mechanism of free liquid generation depicted in Fig. 3:

- Moisture retention mechanisms are induced only by capillary stresses. Field capacity accounts only for moisture retained within waste particles [Fig. 2(a)] and between particles due to capillary stresses [Fig. 2(b)]. Consequently, moisture stored within the waste mass due to the presence of low-hydraulic conductivity layers [Fig. 2(c)] is not considered. This neglected moisture-holding mechanism represents an additional, unquantified capacity of the waste to hold moisture. This is a conservative assumption when evaluating the generation of free liquid due to a landfill vertical expansion.
- The field capacity measured at laboratory scale is representative of field scale values. That is, generation of free liquid will not occur at the base of a landfill unless the waste field capacity measured at a laboratory scale is reached in the field. It has been reported, however, that free liquids may migrate, or short-circuit, by specific routes through the waste in voids or channels through which water can flow without advancing a uniform, downward wetted front (Blight et al. 1992; Zeiss and Major 1993). The result would be that infiltration water flows downward unevenly, reaching the bottom of the landfill as free liquid before the landfill is at field capacity. This uneven flow is generally not accounted for by water balance models, in which the existence of a main wetting front (i.e., a plug flow condition) is assumed. As the potential generation of free liquid due to a landfill vertical expansion is evaluated at the base of the landfill, the impact in this analysis of assuming homogeneous waste properties is not as relevant as in water balance evaluations in which homogeneous conditions are assumed within the entire landfill.
- Changes with time of the in-situ moisture and moisture retention properties of the waste are only due to increased confinement. As indicated by (6), liquid extraction mechanisms are not considered part of the water balance analysis presented herein. Consequently, reduction of moisture within the landfill with time due to liquid and/or gas extraction is neglected. This represents additional conservatism when evaluating the potential generation of free

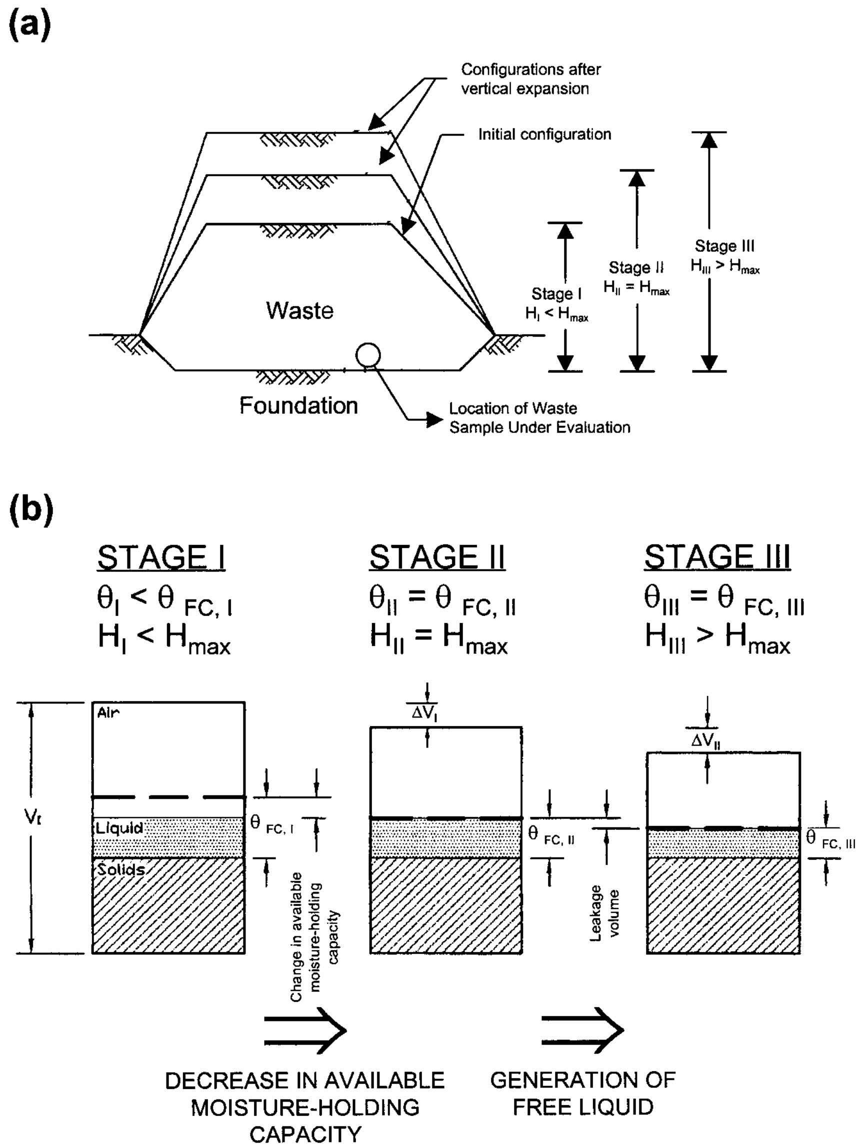

FIG. 3. Generation of Free Liquid due to Waste Compression: (a) Schematic Landfill Vertical Expansion; (b) Phase Relationships for Waste Control Volume Located at Base of Landfill

liquid due to a landfill vertical expansion. Also, degradation of the waste is a time-dependent process that not only reduces the waste moisture with time, but may also change the waste moisture retention properties (e.g., field capacity). Since evaluation of free liquid generation is made at the time of the landfill, where the waste is older, the impact of waste degradation is probably less significant.

The available moisture-holding capacity of the waste (i.e., the difference between field capacity and in-situ moisture content) decreases with increasing compression, independent of whether moisture is expressed using volumetric or gravimetric relationships. However, it should be noted that the trends of in-situ moisture content and field capacity with increasing confinement (or depth) depend on whether volumetric or gravimetric relationships are used in establishing these trends. Because volumetric moisture content θ is defined in terms of the total control volume V, which decreases when the waste undergoes compression, the volumetric moisture content of the waste increases with increasing confinement. If liquids are not squeezed out of the waste mass, the final volumetric moisture content θ_f after compression can be related to the initial volumetric moisture θ_i as follows:

TABLE 1. Mechanism of Free Liquid Generation due to Waste Compression

(1)	Stage I (2)	Stage II (3)	Stage III (4)
Waste thickness, H	$<H_{max}$	$=H_{max}$	$>H_{max}$
Free liquid generated?	No	No	Yes
Porosity, n	n_I	$n_{II} < n_I$[a]	$n_{III} < n_{II}$[b]
Gravimetric moisture, w	w_I	$w_{II} = w_I$[c]	$w_{III} < w_{II}$[d]
Volumetric moisture, θ	θ_I	$\theta_{II} > \theta_I$[e]	θ_{III} > or < θ_{II}[f]

[a] $n_{II} = n_I - \Delta n_I$, where $\Delta n_I = \Delta V_I / V_I$ is the change in porosity from stage I to stage II.
[b] $n_{III} = n_{II} - \Delta n_{II}$, where $\Delta n_{II} = \Delta V_{II} / V_{II}$ is the change in porosity from stage II to stage III.
[c] The ratio W_w/W_s remains constant from stage I to stage II.
[d] $w_{III} = w_{II} - \Delta w_{FC,II}$, where $\Delta w_{FC,II}$ is the change in gravimetric field capacity from stage II to stage III.
[e] $\theta_{II} = \theta_I/(1 - \Delta n_I)$.
[f] $\theta_{III} = (\theta_{II} - \Delta\theta_{FC,II})/(1 - \Delta n_{II})$, where $\Delta\theta_{FC,II}$ is the change in volumetric field capacity from stage II to stage III.

$$\theta_f = \theta_i/(1 - \Delta n) \qquad (7)$$

where Δn = change in porosity. Eq. (7) applies for the case in which compression occurs from stage 1 to stage 2, as illustrated in Fig. 3(b). If liquids are squeezed out of the waste mass, as in the compression from stage 2 to stage 3, the final moisture θ_f will be below the value estimated by using (7).

On the other hand, since the gravimetric moisture content is defined in terms of the weight of solids W_s, which remains constant while the waste undergoes compression, the gravimetric moisture content of the waste does not change due to compression of the waste if free liquid is not generated. Instead, generation of free liquid due to compression of the waste will result in a reduction of the gravimetric moisture content. Table 1 summarizes relevant information regarding the moisture condition of a waste sample during the different stages in the landfill vertical expansion illustrated in Fig. 3.

CASE HISTORY LANDFILL: FIELD AND LABORATORY INVESTIGATION

General Description of Landfill

A case history is presented herein involving evaluation of the potential generation of free liquid due to a planned vertical expansion of an existing unlined landfill. The evaluation considers the mechanism of free liquid generation described previously and uses site-specific field capacity, in-situ moisture content, and total unit weight measurements of the waste material. The case history landfill is located in the San Gabriel Valley in Los Angeles County, California. The climate at the site is semiarid, with yearly evapotranspiration greatly exceeding the average annual precipitation. As shown in Fig. 4, the landfill is divided into two zones: Zone I, which is unlined and accepts MSW; and Zone II, which is underlain by a multicomponent liner system and accepts inert waste. Liquids, sludges, or hazardous wastes have not been accepted at the landfill.

The topography of the site is the result of excavations from sand and gravel mining and landfill operations. The washing of the excavated materials during mining operations produced silt with comparatively low-hydraulic conductivity that has been hydraulically deposited in a series of ponds at the bottom of the excavation. The bottom 8–20 m of the landfill up to an elevation of 108 m (msl) is inert waste such as construction and demolition debris. Nonhazardous MSW has been deposited from an elevation of 108 m to a current maximum elevation of 168 m. As part of a vertical expansion plan, waste would be placed in Zone I of the landfill to final contours at a maximum elevation of 177 m. The waste has been placed in layers forming cells separated by daily cover soils, which are generally imported soil or silt from the on-site silt sediment ponds. Liquid and gas extraction wells are currently in operation at the landfill. The performance of the landfill is monitored by a series of ground water monitoring wells and gas monitoring probes.

To characterize the geotechnical properties of the waste material at the site, laboratory testing and field characterization programs were implemented. As part of the field program, waste samples were recovered during the drilling and installation of 20 new gas extraction wells into the landfill. Fig. 4 shows the locations of the gas extraction wells from which waste material was sampled. In-situ unit weight measurements of the waste were performed during the drilling of two of the deeper gas extraction wells. Characterization tests were also performed on the waste recovered from these borings. The tests included measurement of moisture content, composition, and field capacity of the waste. Additionally, spectral analysis of surface wave (SASW) surveys (Kavazanjian et al. 1996) were performed at the landfill to measure the shear wave velocity and estimate the total unit weight profiles.

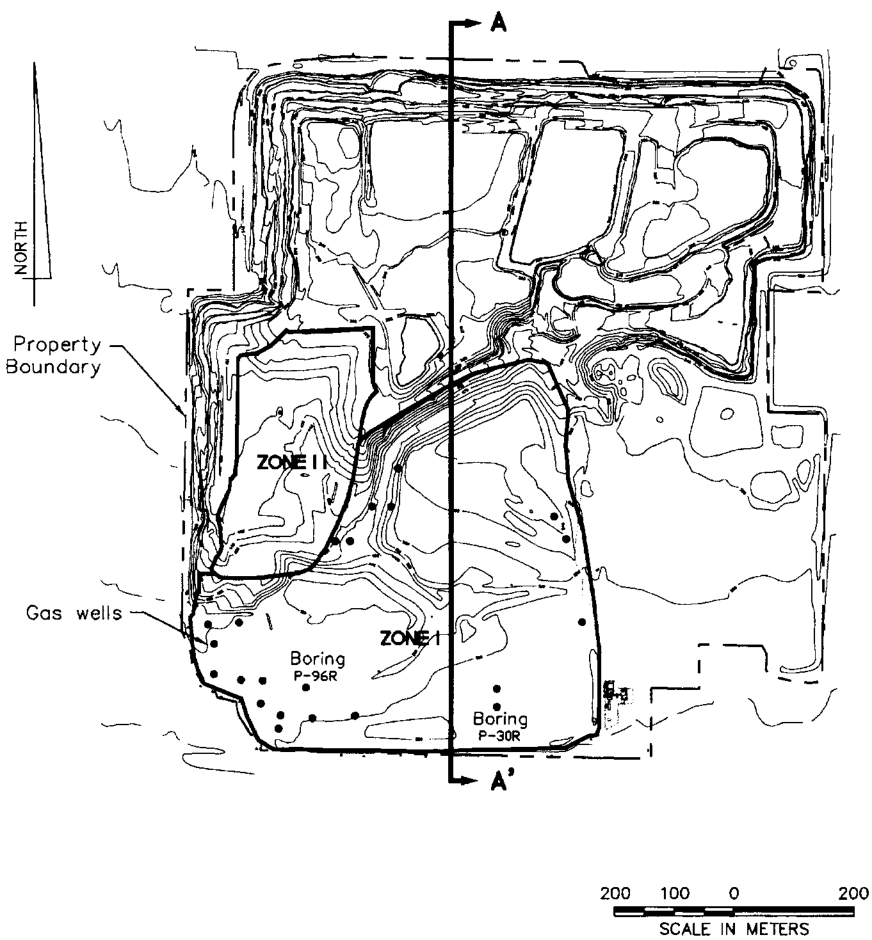

FIG. 4. Southern California Landfill

Moisture Characterization of Waste

Eighty samples of waste were collected from borings used to install new gas extraction wells. Over 56% of the waste material in Zone I is soil, which is a higher percentage than historically reported for MSW. Newspapers from as early as 1975 were recovered during drilling operations and were still legible. Isolated and localized areas of saturated waste, generally the result of the low-hydraulic conductivity soil layers from daily cover, were observed during the field investigation. Liquid did not appear to flow downward when it encountered low-hydraulic conductivity daily covers, as the waste immediately below daily cover layers showed gravimetric moisture content values as low as 3.5%. Boring logs compiled during installation of the gas extraction wells showed that the waste material is mainly soil, household waste, green waste, and inert waste. Measured waste temperatures ranged from 22°C to 62°C.

The gravimetric moisture content of the waste samples was determined by weighing the waste specimens before and after oven drying using an oven temperature of approximately 85°C. Two sizes of waste samples were tested: bucket samples weighing approximately 222 N (50 lb) and glass jar samples weighing approximately 13 N (3 lb). The moisture content was measured for 51 bucket samples and 27 glass jar samples. Waste samples were obtained at various depths during the drilling of the gas wells. Gravimetric waste moisture content measurements obtained from both bucket and glass jar samples are shown in Fig. 5. The gravimetric moisture content results, which average 28%, do not show a significantly increasing trend with depth. As will be discussed, an increasing trend of moisture with depth can be observed if moisture content results are expressed using volumetric relationships.

The waste samples from the case history landfill showed a heterogeneous nature, as is generally reported for MSW from other landfills. Accordingly, the moisture content results obtained from glass jar samples showed larger scatter than those obtained from bucket samples.

Field Capacity Characterization of Waste

A laboratory testing program was implemented during the course of this investigation to evaluate the moisture retention properties of the waste. Field capacity tests were performed using waste samples obtained during drilling of one of the gas extraction wells (boring P-30R). Each test was performed at a vertical confining stress representative of the depth at which the waste sample was collected, up to a depth of 60 m.

Laboratory field capacity specimens were prepared by compacting five lifts of waste into a 450 mm diameter cell. Each lift was compacted to approximately 50 mm thick layers, so the total sample height was 250 mm at the beginning of the test. A top loading platen was placed on the waste and a seating pressure of 34.5 kPa was added to the sample. After displacements of the waste specimen equilibrated, the top platen was loaded incrementally to final vertical confining stresses of 207, 414, 620, and 827 kPa. Once displacements of the waste specimen equilibrated under the final vertical confining stress, water was slowly induced from the bottom of the test specimen until free water was observed on the top. Following a soaking period of 20–48 h, the waste specimen was allowed to drain by gravity. Drainage continued until the vertical displacement rate and the liquid drainage rate became less than 0.38 mm/d and 35 mL/d, respectively. Final gauge readings were used for calculation of the final height and bulk unit weight of the specimens. The view of a waste specimen after testing is shown in Fig. 6. The specimen was dismantled after the test and the final gravimetric moisture content of the waste was determined. This value corresponds to the gravimetric field capacity at the vertical confining stress used in the test.

The laboratory test results for the waste field capacity are presented in Table 2. The confining pressures used in the tests are indicated as equivalent depths within the waste mass, and range from 15 m to 60 m (assuming a unit weight of 13.5 kN/m^3 for the waste). The measured gravimetric field capacity ranged from 60.2% to 40.5%, with an average value of 50.6%. The volumetric field capacity of the waste specimens was estimated from (1) using the measured dry unit weight and gravimetric field capacity values. The average volumetric field capacity is approximately 50%, which is consistent with field capacity values reported in the literature for MSW (Blight et al. 1992; McBean et al. 1995).

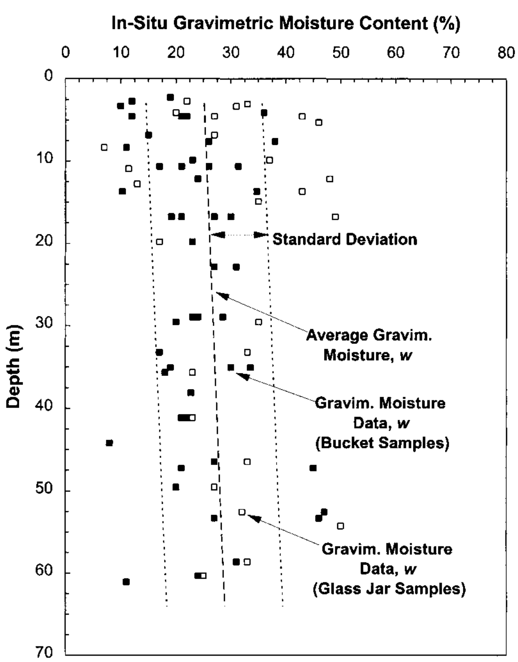

FIG. 5. In-Situ Gravimetric Moisture Content of Waste Material

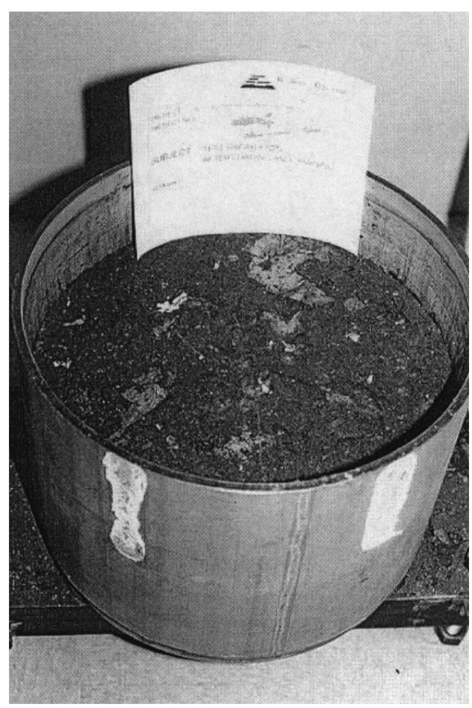

FIG. 6. Waste Sample after Laboratory Field Capacity Testing

TABLE 2. Field Capacity Laboratory Results

Confining pressure (kPa) (1)	Equivalent depth (m) (2)	Gravimetric field capacity (%) (3)	Dry unit weight (kN/m^3) (4)	Volumetric field capacity (%) (5)	Porosity (%) (6)
206.8	15.2	60.2	8.6	53.0	61.7
413.7	30.5	50.2	9.3	47.4	59.0
620.5	45.7	51.6	9.7	51.0	57.0
827.4	61.0	40.5	11.6	47.8	48.6

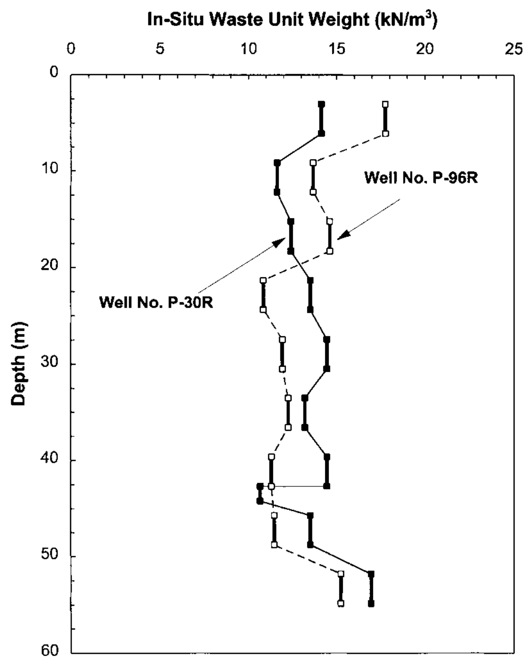

FIG. 7. Field Measurement Results of Waste Total Unit Weight

Unit Weight Characterization of Waste

A field investigation program that included direct field measurements and SASW surveys characterized the total unit weight profile for the waste in the case history landfill. The procedure used for direct field measurement of the total unit weight was adapted from the ASTM standard procedure for evaluating the unit weight of soil in situ by the sand-cone method. Total unit weight measurements were performed on waste samples obtained from two large diameter borings advanced into the landfill for installation of gas extraction wells (borings P-30R and P-96R, shown in Fig. 4). Total unit weight measurements correspond to the average unit weight of the waste material obtained in boring segments approximately 3 m long, which were situated in increments of, approximately, every 6 m. Fig. 7 shows the waste total unit weight profiles obtained for the waste material from the two borings. The waste total unit weight obtained from field direct measurements ranges approximately from 10 kN/m^3 to 15 kN/m^3 between 8 m and 50 m below the landfill surface. The upper 3 m and the bottom 3 m of both borings showed higher total unit weight values.

Total unit weight values obtained from these two borings were used to calibrate the profiles derived from the SASW surveys performed at the landfill. A relationship between shear wave velocity, overburden pressure, and total unit weight was developed and used to predict unit weight versus depth for each of the six SASW lines on waste (Kavazanjian et al. 1996). The SASW survey allowed characterization of the total unit weight profiles over a broader area than did the in-situ measurements at two boring locations. Moreover, the consistency of the results obtained from the SASW survey program

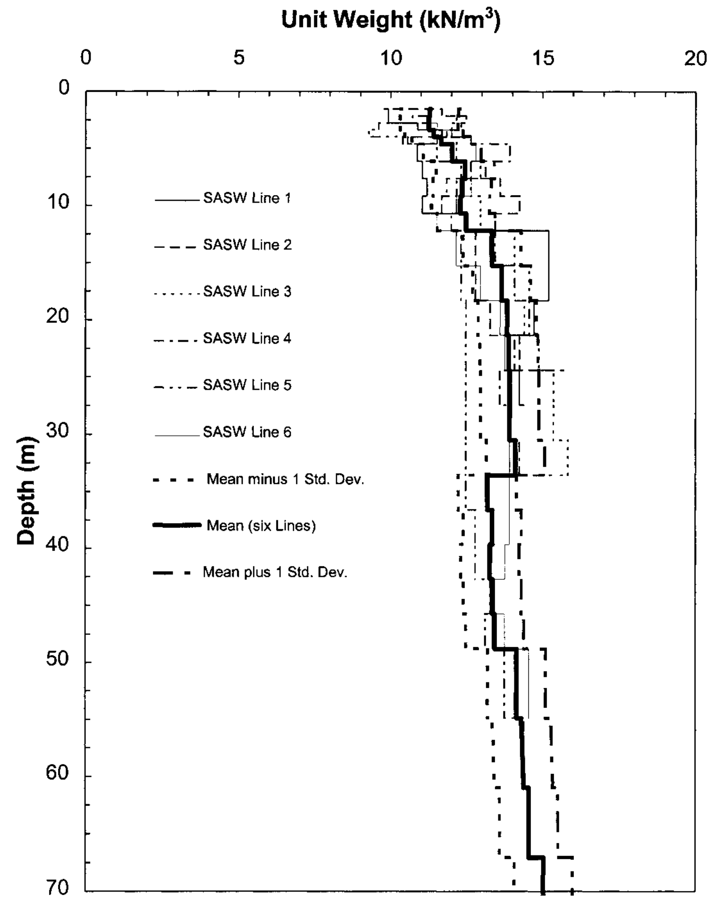

FIG. 8. Unit Weight Profiles from Six SASW Lines at Case History Landfill

at different depths and along the different lines provided confidence regarding the representativity of the samples collected for field capacity testing. Fig. 8 shows the total unit weight profiles obtained at the six SASW lines surveyed for this investigation. SASW lines 5 and 6 are in the vicinity of borings P-96R and P-30R, respectively, where direct measurements of total unit weight were obtained. These six total unit weight profiles were averaged to develop a consolidated mean profile. The mean as well as the mean plus and minus one standard deviation unit weight profiles are indicated in the figure. The averaged profile of total unit weight was used in this investigation to estimate the volumetric moisture content of the waste using gravimetric moisture content measurements.

CASE HISTORY LANDFILL: DATA INTERPRETATION FOR ASSESSMENT OF MAXIMUM VERTICAL EXPANSION

Interpretation of Field Capacity and Compressibility Data

Use of volumetric moisture relationships (instead of gravimetric ones) allows comparison of the in-situ moisture of the

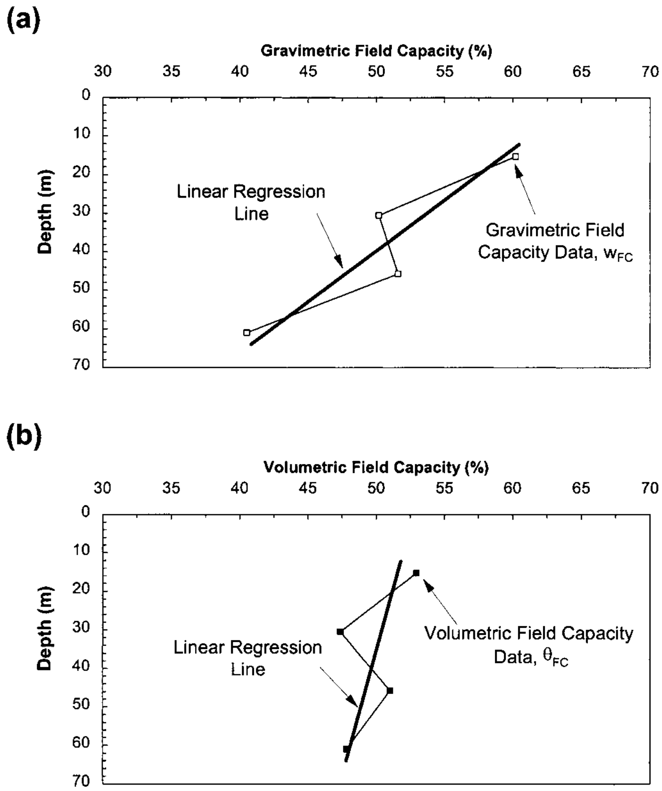

FIG. 9. Field Capacity of Waste As Function of Depth: (a) Expressed Using Gravimetric Relationships; (b) Expressed Using Volumetric Relationships

waste not only with its field capacity, but also with its porosity (i.e., the volumetric moisture at saturation). Field capacity test results, presented both as gravimetric and volumetric moisture contents, are shown in Fig. 9. Although field capacity values show a decreasing trend with depth (or confining pressure) when expressed using gravimetric relationships, volumetric field capacity values are approximately constant with depth, at least for the range of confining pressures considered in the laboratory testing program.

For the purposes of the analyses presented herein, linear relationships were defined to fit the field capacity data points (Fig. 9). The regression lines of field capacity versus depth, determined by the least-squares method, are as follows:

$$w_{FC} = 65.05 - 0.3786d \quad (8)$$

$$\theta_{FC} = 52.74 - 0.0771d \quad (9)$$

where w_{FC} and θ_{FC} = gravimetric and volumetric field capacity values (in %), respectively; and d = depth below the waste surface (in m). While the gravimetric field capacity of the waste in the case history landfill decreases from approximately 60% near the surface of the waste to approximately 40% at a depth of 60 m, the volumetric field capacity is approximately constant with depth, averaging 50%.

The laboratory testing program undertaken to determine the field capacity of the waste also provided information on the compressibility of the waste material. The porosity n of the waste was estimated as a function of the confining pressure. The porosity n of the waste was determined as a function of the confining pressure using the measured unit weight of the specimens and the estimated specific gravity of the solids. A specific gravity value of 2.3 was defined based on the composition of the waste material. Porosity values estimated for the specimens tested during the laboratory testing program are indicated in Table 2.

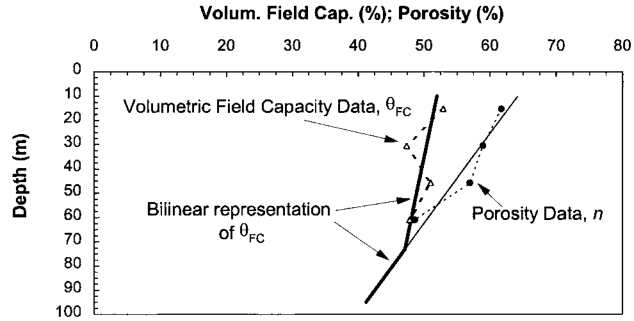

FIG. 10. Volumetric Field Capacity and Porosity

A linear regression analysis of the porosity data points yields the following correlation:

$$n = 66.9 - 0.271d \quad (10)$$

where n is expressed in percent and d in meters. The average porosity obtained for the waste material is 57%, and decreases from approximately 62% near the surface to approximately 49% at 60 m from the surface.

Fig. 10 shows the linear regression trends with depth obtained for the volumetric field capacity θ_{FC} and for the porosity n of the waste. The experimental results show that the volumetric field capacity approaches the porosity line at depth. The linear representation of θ_{FC} meets the line representing the porosity n at a depth of 73.2 m. As the volumetric field capacity cannot exceed the porosity, the volumetric field capacity of the waste is defined by the bilinear representation shown in Fig. 10 for the purposes of this investigation. According to this representation, the volumetric field capacity equals the porosity of the waste at comparatively high confining pressures.

The representation of the compressibility of the waste, expressed by (10) as a linear decrease in porosity with depth, is equivalent to a linear decrease in void ratio of the waste ($e = V_v/V_s$) with overburden pressure (σ_v in kPa) as follows:

$$e = 1.86 - 0.00102\sigma_v \quad (11)$$

where the slope of the void ratio–overburden pressure relationship for the waste of the case history landfill (0.00102 kPa^{-1}) is the coefficient of compressibility, a_v.

The use of a linear relationship to characterize the porosity versus depth in this investigation (Fig. 10) implies that a constant a_v coefficient is adopted to model the waste compressibility. The compression index C_c, defined as the change in void ratio per logarithmic cycle of overburden pressure, is other parameter commonly used in geotechnical practice to represent the compressibility of the waste. For the waste tested herein, over the range of confining pressures of interest, the estimated compression index is $C_c = 0.986$. This value is in the upper end of reported compression index values for waste materials (Fassett et al. 1994). The use of a constant a_v for the waste in this analysis overpredicts void ratio changes for the range of confining stresses of interest compared to the assumption of a constant C_c, and thus provides a conservative basis for the evaluation of the maximum allowable waste thickness.

Interpretation of In-Situ Moisture Content Data for Estimation of H_{max}

The approach used to estimate the maximum allowable waste thickness, H_{max}, involves a three-step procedure.

1. Establishing a correlation between the volumetric field capacity of the waste with depth (or overburden pressure)
2. Establishing a correlation between the in-situ volumetric moisture content of the waste with depth (or overburden pressure)

3. Determining the depth (or overburden pressure) at which the in-situ moisture content of the waste reaches its field capacity, based on the correlations defined in steps 1 and 2. This depth is H_{max}.

A correlation of the volumetric field capacity with depth (step 1) was already established by the bilinear representation shown in Fig. 10. Correlations of the in-situ volumetric moisture content with depth (step 2) can be defined using available data for the waste material in the case history landfill. However, different volumetric moisture content correlations (a total of four) could be established in this investigation considering different sets of available data. These correlations were obtained by combining the following two selections of available information:

- Type of data (and phase relationships) selected to define the correlations. A correlation for the in-situ volumetric moisture content with depth can be defined using the gravimetric moisture content measurements and phase relationships that use either the compressibility data from the laboratory testing program or the total unit weight data from the field characterization program.
- Size of the samples selected to define the correlations. Bucket samples and glass jar samples weighing 222 N and 13 N, respectively, were collected in the field investigation program to characterize the waste moisture content. A correlation for the in-situ volumetric moisture content can be defined using in-situ gravimetric moisture content measurements from the more representative bucket samples only or moisture measurements obtained from all available samples (bucket and glass jar samples).

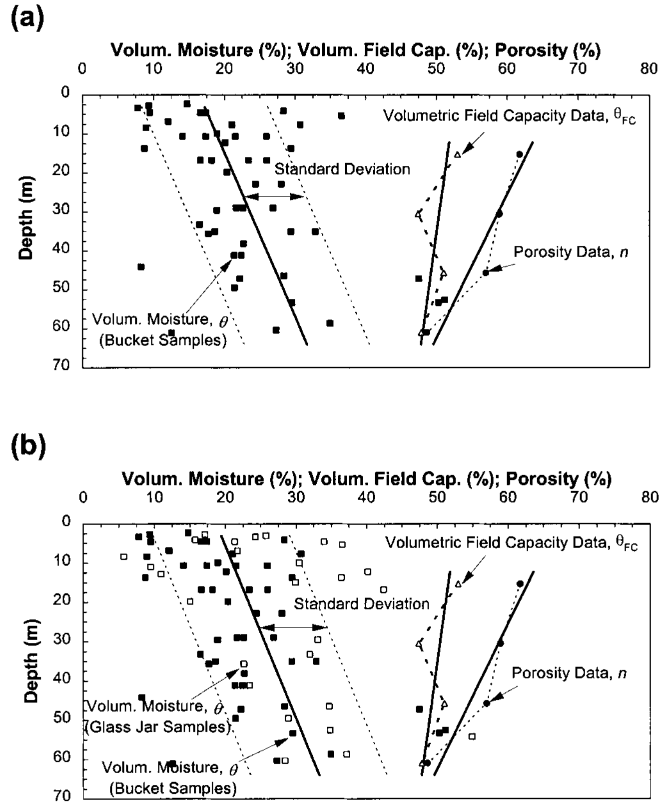

FIG. 11(a, b). Evaluation of H_{max}: (a) Analysis 1, Using Bucket Samples Only and Laboratory Compressibility Data; (b) Analysis 2, Using All Samples and Laboratory Compressibility Data

Phase relationship in Eq. (3) was used to determine the in-situ volumetric moisture content of the waste samples, using gravimetric moisture content w measurements and the porosity n defined by the linear relationship in (10). Fig. 11(a) shows the distribution with depth of the in-situ volumetric moisture content obtained by using only the bucket waste samples (analysis 1). The volumetric field capacity θ_{FC} and the porosity n obtained from laboratory testing are also indicated. The figure shows that the moisture content of the waste is below the field capacity and, consequently, that the waste material in the landfill is currently not releasing liquid. A least-squares linear regression using measurements from bucket samples yields the following linear relationship for the in-situ volumetric moisture content:

$$\theta_{\text{Analysis 1}} = 16.48 + 0.2373d \qquad (12)$$

where θ is expressed in percent and d in meters. Although the in-situ gravimetric moisture content w showed an approximately constant value with depth (Fig. 5), the volumetric moisture content θ shows an increasing trend with depth. The in-situ gravimetric moisture content averages 28%, while the foregoing linear regression shows in-situ volumetric moisture content increasing from approximately 20% near the surface to approximately 30% at 60 m below the surface.

The maximum allowable waste thickness, H_{max}, was estimated from the intersection of the linear representation of the in-situ volumetric moisture defined by (12) with the bilinear representation for the volumetric field capacity shown in Fig. 10. The calculated H_{max} in this analysis is 99 m. Summary information on this analysis (analysis 1) is presented in Table 3.

A second analysis (analysis 2) was performed in a similar manner as the previous one, but used gravimetric moisture measurements from both bucket and glass jar samples collected in the field to define the volumetric moisture content correlation. Fig. 11(b) shows the in-situ volumetric moisture values estimated using the bucket and glass jar samples, along with the θ_{FC} and n relationships. Although the in-situ volumetric moisture data show a larger scatter than in Fig. 11(a), where only bucket samples are used, the correlation obtained using bucket and glass jar samples is similar to the one obtained using only the bucket samples. The estimated H_{max} value in this analysis is 97 m, which, for practical purposes, is the same as the value obtained in the previous analysis. Summary information on this case is presented in Table 3 (analysis 2).

The in-situ volumetric moisture content θ of the collected samples was also estimated using the gravimetric moisture content w and the total unit weight γ_t profiles obtained from field measurements, instead of the porosity n values obtained from laboratory measurements. Phase relationship Eq. (2) was used in this case. The mean waste unit weight profile obtained from the SASW survey at increasing depths (Fig. 8) was used to define the correlation of volumetric moisture content versus depth. In-situ volumetric moisture contents estimated using this approach and gravimetric moisture measured only from bucket waste samples are presented in Fig. 11(c) and Table 3 (analysis 3). The volumetric field capacity θ_{FC} and the porosity results are also indicated in the figure. The maximum allowable waste thickness, H_{max}, calculated in this analysis is 108 m. This value, estimated considering field unit weight data, compares well (within a 9% difference) with the result obtained in analysis 1, which used laboratory compressibility data. The consistency of these results provides confidence in the assumptions considered in the analyses, and in the soundness of field and laboratory data collected for this investigation.

Analysis 4 was performed in a similar manner as in analysis 3, but used the waste samples collected in the field, using both bucket and glass jar samples to define the correlation of volumetric moisture content with depth. Fig. 11(d) and Table 3

TABLE 3. Summary of Analyses Performed to Estimate H_{max}

Analysis (1)	Phase relationship selected to define correlation (2)	Size of samples selected to define correlation (3)	Volumetric Moisture Content (%)[a] Intercept a[b] (4)	Slope b[c] (5)	Standard deviation (6)	H_{max} (m) (7)
1	Porosity from lab measurements	Bucket samples	16.48	0.2373	8.88	99
2	Porosity from lab measurements	Bucket and glass jar samples	18.73	0.2271	9.65	97
3	Unit weight from field measurements	Bucket samples	21.71	0.1471	8.00	108
4	Unit weight from field measurements	Bucket and glass jar samples	23.61	0.1397	8.78	105

[a] $\theta = b \cdot d + a$, where θ = volumetric moisture content (in %) and d = depth (in m).
[b] Intercept n of linear regression of volumetric moisture versus depth.
[c] Slope m of linear regression of volumetric moisture versus depth.

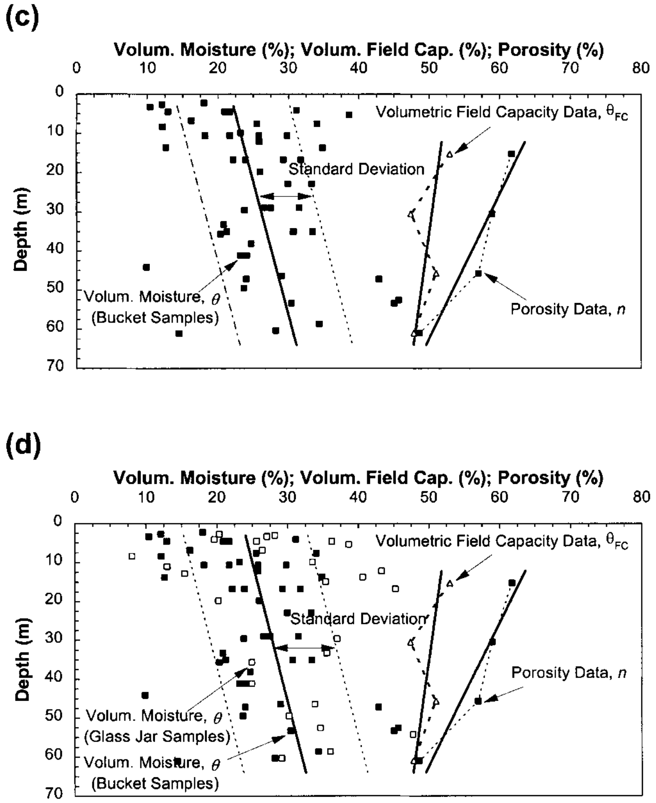

FIG. 11(c,d). Evaluation of H_{max}: (c) Analysis 3, Using Bucket Samples Only and Field Unit Weight Data; (d) Analysis 4, Using All Samples and Field Unit Weight Data

(analysis 4) present the in-situ volumetric moisture correlation obtained in this case, along with the θ_{FC} and n relationships. As previously observed for analysis 2, although a larger scatter is obtained when using both bucket and glass jar samples than when using bucket samples only, the correlations obtained in both cases are similar. The estimated H_{max} in this analysis is 105 m, which is similar (within 8%) to the result obtained in analysis 2 using laboratory compressibility data.

CASE HISTORY LANDFILL: IMPLICATION OF RESULTS

Current Facility Performance

A comparison between in-situ volumetric moisture content and field capacity profiles for the waste in the case history landfill indicates that liquids stored within the landfill are not being squeezed out of the waste. This is shown in Figs. 11(a)–(d), which compare the distribution of the in-situ moisture with the field capacity, considering different approaches for determination of in-situ volumetric moisture. While the average in-situ volumetric moisture content for the upper 60 m of waste is approximately 25% (estimated using the linear relationship for θ defined in analysis 3), the average field capacity value is on the order of 50%. Consequently, the average available moisture-holding capacity for the upper 60 m is approximately 25%. This available moisture-holding capacity indicates that the landfill could take approximately twice as much moisture as it now contains without leaking (if the assumption regarding representativity between field capacity at laboratory and field scales holds true). This comparison provides confidence that liquids within the landfill in its current configuration are stored within the waste and do not leak from the landfill. This available moisture-holding capacity impacts favorably the water balance analyses that evaluate the effect of liquids that might infiltrate into the landfill before the vertical expansion or final closure.

Future Facility Performance

The relevance of the results to future facility performance refers to the implications of a landfill vertical expansion on the available moisture-holding capacity of the existing waste. The maximum current thickness of the waste material in the Zone I area of the landfill is approximately 60 m, while the maximum waste thickness will be 69 m after the planned vertical expansion, 9 m above the current maximum waste thickness. The results of the analyses presented herein indicate that H_{max} ranges between 99 m and 108 m. This range of results for H_{max} was obtained after considering four different approaches to define the correlation of in-situ volumetric moisture content with depth.

The analyses performed using moisture content measurements from bucket samples are considered more representative than the analyses performed using measurements from the bucket and glass jar samples (see standard deviations in Table 3). Moreover, the analyses performed using phase relationships that consider total unit weight values are deemed more representative than those performed using phase relationships that consider porosity values. This is because total unit weight results were obtained from field measurements and, consequently, may better reflect the heterogeneity of the waste mass than porosity results obtained from laboratory measurements. Moreover, standard deviations for volumetric moisture content correlations are lower when using total unit weight than when using porosity relationships. Consequently, analysis 3, which used bucket samples and unit weight profiles to estimate the in-situ volumetric moisture, is considered to provide the most accurate value of H_{max} (108 m). The lowest H_{max} value obtained from the different analyses (97 m in analysis 2) may, however, be considered a conservative estimate. Nevertheless, for practical purposes, H_{max} results obtained considering the different assumptions did not differ significantly from each other.

The analyses presented herein are conservative, since they neglect the potential decrease with time of the moisture within the waste mass. Moisture content within the existing waste mass should decrease with time as a consequence of operation

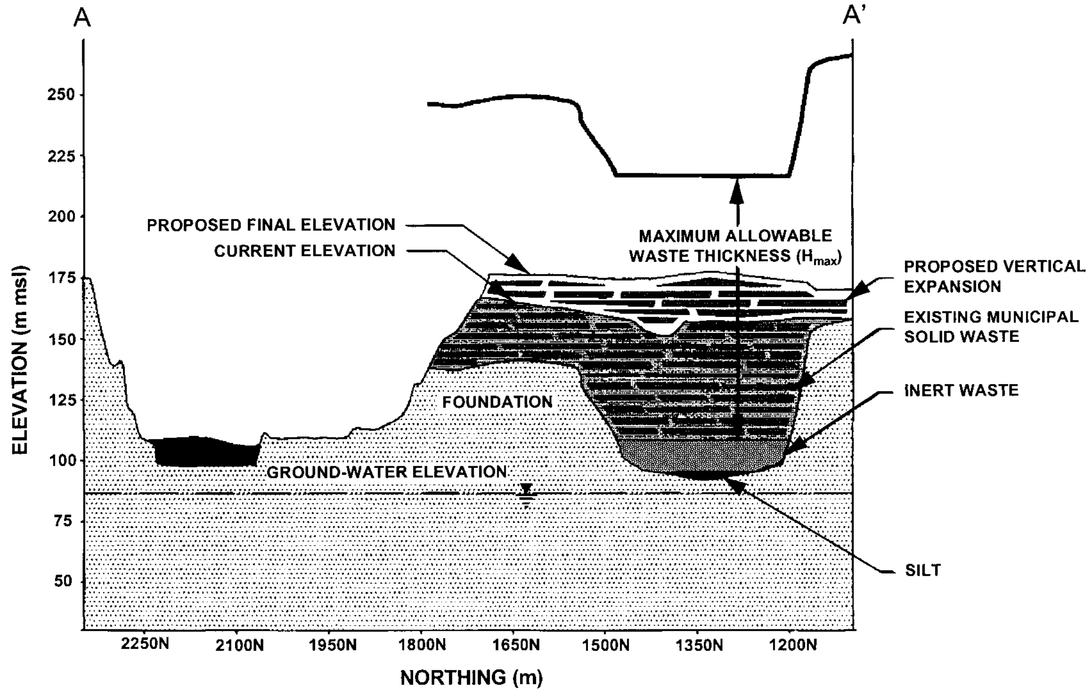

FIG. 12. Cross Section of Southern California Landfill Showing H_{max}

of the liquid and gas extraction wells implemented in the landfill. Consequently, H_{max} will actually increase as the moisture within the existing waste mass decreases with time. Considering an estimated H_{max} value of 108 m and the base of the municipal waste at an elevation of 108 m (msl), the final landfill elevation should remain under 216 m (msl) in order to prevent squeezing of waste liquids. This maximum allowable elevation is well above the anticipated maximum planned elevation of 177 m.

Fig. 12 shows cross section A-A′ drawn along a north-south line of the landfill (see Fig. 4 for the location of the cross section). The cross section shows the elevations of waste material corresponding to the 1994 grading, as well as the final planned elevation after the landfill vertical expansion. The estimated H_{max} of 108 m is also indicated in the figure, which illustrates that additional waste can be safely placed up to the planned final elevations at the case history landfill. Consequently, the vertical expansion does not present the potential for squeezing of landfill liquids out of the existing waste.

CONCLUSIONS

The potential generation of free liquid in landfills undergoing vertical expansion was evaluated in the present paper. As the available moisture-holding capacity of the waste decreases due to the increased confinement induced by the vertical expansion, the in-situ moisture content may eventually reach the field capacity of the waste. Additional compression beyond this point will squeeze liquid from the landfill. This conceptual framework of free liquid generation was proposed and used to evaluate the environmental implications of the vertical expansion of a case history landfill located in southern California. Laboratory testing and field characterization programs were undertaken to evaluate the field capacity, the in-situ moisture content distribution, and total unit weight profiles of the waste material. The results of this investigation can be summarized as follows:

- A methodology for evaluation of the potential generation of free liquid in a landfill undergoing vertical expansion was formulated, which involves an evaluation of the profiles of in-situ volumetric moisture, volumetric field capacity, and compressibility of the waste.
- Use of volumetric or gravimetric relationships for the moisture content and retention properties of the waste may lead to different trends with depth. The in-situ gravimetric moisture content of the waste in the case history landfill was approximately constant with depth, while the in-situ volumetric moisture showed an increasing trend. On the other hand, the volumetric field capacity of the waste was approximately constant with depth, while the gravimetric field capacity showed a decreasing trend.
- The in-situ volumetric moisture content of the waste in the case history landfill ranged from approximately 20% near the surface to approximately 30% at 60 m from the surface (the gravimetric moisture content was approximately constant with depth, averaging 28%).
- Laboratory testing of waste samples from the case history landfill yielded an approximately constant volumetric field capacity with depth, which averaged 50% (the gravimetric field capacity ranged from approximately 60% near the surface to approximately 40% at 60 m from the surface).
- The porosity of the waste in the case history landfill, obtained from laboratory testing, ranged from approximately 65% near the surface to approximately 50% at 60 m from the surface.
- The in-situ moisture content of the waste in the case history landfill is below field capacity, indicating that liquids currently stored within the waste mass cannot migrate from the unlined landfill by gravity gradients only.
- Analyses performed using different approaches for the determination of volumetric moisture content correlations rendered similar values of maximum allowable waste thickness, H_{max}, for the case history landfill. H_{max} represents the maximum waste thickness beyond which placement of additional waste may squeeze liquid out of the existing waste.
- The proposed final grading plan for the case history landfill after vertical expansion would result in a maximum waste thickness below the estimated H_{max}. Consequently, despite a decrease in the available moisture-holding ca-

pacity of the waste, landfill liquids should remain stored within the waste after the vertical expansion.

ACKNOWLEDGMENTS

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APPENDIX II. NOTATION

The following symbols are used in this paper:

a_v = coefficient of compressibility (kPa^{-1});
C_c = compression index (dimensionless);
d = depth (m);
e = void ratio (dimensionless);
G_s = specific gravity of solids (dimensionless);
H = waste thickness (m);
H_{max} = maximum allowable waste thickness (m);
n = porosity (%);
n_I, n_{II}, n_{III} = porosity at stages I, II, and III (Fig. 3) (%);
V = total control volume (m^3);
V_s = volume of solids (m^3);
V_v = volume of voids (m^3);
V_w = volume of water (m^3);
W_s = weight of solids (N);
W_w = weight of water (N);
w = gravimetric moisture content (%);
w_{FC} = gravimetric field capacity (%);
w_I, w_{II}, w_{III} = gravimetric moisture content at stages I, II, and III (Fig. 3) (%);
γ_d = dry unit weight of waste or soil (kN/m^3);
γ_t = total (wet) unit weight of waste or soil (kN/m^3);
γ_w = unit weight of water (kN/m^3);
Δn = change in porosity (%);
Δw_{FC} = change in gravimetric field capacity (%);
$\Delta\theta_{FC}$ = change in volumetric field capacity (%);
θ = volumetric moisture content (%);
θ_{FC} = volumetric field capacity (%);
θ_{WP} = wilting point (%);
$\theta_I, \theta_{II}, \theta_{III}$ = volumetric moisture content at stages I, II, and III (Fig. 3) (%); and
σ_v = vertical stress (kPa).