METHODOLOGY FOR ASSESSING
MUNICIPAL SOLID WASTE USING A LARGE-DIAMETER BOREHOLE

by

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METHODOLOGY FOR ASSESSING MUNICIPAL SOLID WASTE

USING A LARGE-DIAMETER BOREHOLE

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Municipal solid waste (MSW) landfills are permanent repositories of society's non-hazardous wastes. Landfill facilities are becoming harder to site, resulting in increasing pressure to maximize the use of available airspace. Increasingly, this results in developing additional airspace by way of vertical expansion. This expansion imparts greater stress on the landfill mass and the containment infrastructure.

The engineer's understanding of the geotechnical properties of MSW has been limited to sampling of relatively shallow test pits and reconstitution of disturbed MSW samples in the laboratory. Deeper assessment using small diameter borings is difficult and produces poor low volume samples for ex-situ testing. Some researchers have synthesized MSW with obvious limitations. Landfill failures have provided opportunities for back calculation of MSW properties including shear strength, but these estimates are based on limited understanding of unit weight and moisture content with depth.

The recent trend for the harvesting of methane produced by the anaerobic degradation of MSW has resulted in the need for nearly full-depth, large-diameter, landfill gas collection wells. Prior to completion, these boreholes provide excellent opportunities for directly observing and measuring the condition of MSW in its buried, variably degraded state at depths that are far greater than previously accessible.

The large diameter MSW gas well borehole assessment methodology presented in this paper is shown to be an efficient and valuable means for characterizing MSW. This means that the cost of the assessment is relatively low as the drilling costs are negligible

and therefore limited to the cost of labor to sample and perform field observation and laboratory testing. The assessment methodology, which includes scaled full coverage photography and videography, allows precise analysis of a number of geotechnical properties such as wet and dry unit weight, moisture content, specific gravity, void ratio, % saturation of MSW and buried soil layers throughout the depth of the borehole. Further, MSW constituents and biologic degradation can be measured. The orientation / alignment of tensile reinforcement within the waste mass is readily observable. Zones of perched leachate and the effects of mechanical creep on borehole diameter can also be measured.

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Table of Contents

List of Appendices

1. Introduction

The modern landfill has evolved throughout recorded history from a place considered by society as the closest earthly representation of Hell to wit: Gahanna[1] in biblical Old Testament writings that referred to unquenchable fires, etc., to the present "civilized" and most common method of dealing with the discarded refuse of society. This method is now commonly referred to as "land disposal" when it is restricted by modern regulation to the final processing of "solid" waste by way of relatively shallow burial vaults in native soil[2]. These burial vaults are also commonly known as landfills. The most common type of landfill that handles the refuse from the surrounding communities has been dubbed the municipal solid waste (MSW) landfill.

'Solid wastes comprise all the wastes arising from human and animal activities that are normally solid and that are discarded as useless or unwanted. The term solid waste is all-inclusive, that encompasses the heterogeneous mass of throwaways from the urban community as well as the more homogeneous accumulation of agricultural, industrial, and mineral wastes.'[3] Solid wastes disposed of in modern US MSW landfills are classified as non-hazardous in nature and contain relatively small amounts of hazardous wastes, which are allowed by regulation through a limited number of exemptions. Through an evolving plethora of environmental regulations promulgated at the federal, state, and community level, these land-based disposal units are intended to be protective of human health and the environment. Modern MSW landfills therefore have become sophisticated engineering containment structures designed to provide a permanent repository of discarded, societal, non-hazardous waste that will not adversely impact the local environment or populace.

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[1] II Kings 23:10, *The Holy Bible - Old Testament*

[2] Qian X, Koerner, R.M., Gray, H.G., *Geotechnical Aspects of Landfill Design and Construction*, Prentice Hall, 2002, pp. 717, pg. 1.

[3] Tchobanoglous, G., Theisen, H., Vigil, S., *Integrated Solid Waste Management - Engineering Principles and Management Issues*, McGraw Hill, 1993, Page 3, pp. 978.

It is useful here to spend some time describing the composition of the modern landfill. Typically, modern municipal solid wastes are derived from an orderly collection, and transfer process that may or may not be voluntary, and may or may not include refuse sorting and volume reduction. These recycling mechanisms are designed to reduce the quantity of waste that is ultimately land disposed. Once the refuse is delivered to the landfill facility, it is deposited into a containment cell which typically consists of some type of multi-faceted, relatively impermeable barrier described as a composite primary or base liner sequence (primary liner). This liner is designed to severely limit the migration of waste constituents into the adjoining soil and groundwater regimes. The collected MSW is deposited at a receiving area (working face) where it is mechanically compacted and covered daily by some form of vector and atmospheric isolating soil or artificial material. Ultimately when the landfill cell is completely filled, it is closed by the construction of an upper containment barrier sequence known as a "final cover sometimes referred to as a cap". The final cover, like the primary liner, consists of multi-faceted, relatively impermeable barrier sequence which is designed to impede the introduction of surface borne moisture, vermin and vectors, while at the same time allowing for the conveyance (and in some cases collection, treatment and/or processing) of gases generated by the biological degradation of the encapsulated waste mass.

The engineered containment and related control components identified above are described briefly below:

- Primary (bottom or lateral / side slope) liner sequence – typically consists of a re-compacted clay layer (RCL), a geosynthetic clay layer (GCL), a geomembrane or flexible membrane liner (FML), and/or a combination, thereof. The purpose of the primary liner is to create a barrier against advective and diffusive flow of waste leachate and gas to the adjoining environment. The layer further physically segregates the waste and its active components (gas and leachate) from the surrounding environment.

- Leachate collection and recovery system – This system is a layer sequence overlying the primary liner, which consists of a high permeability layer and collection

conveyance. This system may be a granular layer overlain with some type of filter material, fine-grained soil or geotextile, or a geosynthetic drainage layer (GDL) or a combination thereof.

- Gas collection and control system (GCCS) – Typically, overlies the waste mass, (but may be embedded within it) and is installed for the purpose of conveying landfill gas through the cover containment envelope to the atmosphere or gas collection system. The GCCS sometimes consists of a near surface high permeability layer that is used to intercept gas which is vented to the surface, but most often the system is simply a series of horizontal or vertical extraction wells that are tied into surface manifolds for the purpose of safely conveying the landfill gas through the cover liner to flares or processing facilities. Landfills with sufficient waste mass to justify the beneficial use of landfill gas may elect to capture and convey the landfill gas to a processing facility (flare, or waste to energy plant). When US landfills reach sufficient size, they are required by regulation to mitigate potential adverse impact to the atmosphere with the installation and operation of a GCCS.

- Final cover sequence – The purpose of this system is to segregate the buried waste mass from the atmosphere and the surrounding environment. It further impedes and/or controls the flow of gas and leachate to the environment while simultaneously blocking infiltrating moisture. This cover has the additional function of creating a vector and varmint invasion barrier, and the preservation of the cover by controlling erosion of the uppermost surface, and in most cases, establishes a vegetative support, rooting zone. The final cover typically consists of an RCL, GCL, FML and erosion protection / insulating surface layer.

One of the fundamental requirements for creating a permanent land-based waste disposal / containment structure is to 'demonstrate… that engineering measures have been incorporated into the facility's design to ensure that the integrity of the

containment systems of a solid waste disposal area will not be disrupted'.[4] The task of establishing the 'stability' of the MSW landfill resides largely within the realm of modern geotechnical engineering. The demonstration of stability involves the evaluation of potential unstable areas related to the foundation of the landfill and the mechanical behavior of the landfill waste mass and containment structures themselves. This analysis involves estimating the impact of the waste mass on itself, containment structures, and adjoining environment relative to bearing capacity, total and differential settlement, and the slope stability.

While evaluation of the foundational stability via an analysis of bearing capacity and settlement are useful and important efforts, they are seldom the critical factors for determining the efficacy of the structure. In particular, bearing capacity, settlement, and subsidence at the base of the landfill cell are almost never issues except for special circumstances such as the design of a waste overlay over a former landfill cell or some other buried anomaly. Conversely, settlement of the cover surface is almost always significant, but it can be accommodated by a robust design, suitable surface preparation, and periodic and routine post closure maintenance. Usually, the most pertinent geotechnical analyses are for the global and laminar slope stability of the waste mass and the enveloping containment sequences under static and seismic loading.

The containment envelop of a modern landfill of modest height (100 ft. to 150 ft. by today's standards) represents less than 5% of the total mass of the landfill. The engineering properties and behavior of the containment envelope can be measured and evaluated with relative ease, and are therefore not the subject of this study. The waste mass itself is the remaining 95% by weight. Before the design engineer can begin to evaluate the stability of a waste mass and the encompassing containment envelop, they must have a reasonable understanding of the geotechnical index properties of the waste mass itself. These basic index properties include waste constituent composition, wet

[4] Nebraska Department of Environmental Quality, "Title 132 Integrated Solid Waste Management Regulations", Chapter 3, Criteria for MSW Disposal Areas, Para 002.07

and dry unit weight, moisture content, specific gravity, void ratio, field capacity and % saturation in addition to consolidation and strength properties of the buried MSW and soil layers.

Statement of the Problem

With the constant pressure to more efficiently use existing landfill volume (aka., 'air space') due to the continuing problems and uncertainties involved in siting and developing new facilities, existing land disposal and recycling facilities across the country find that after optimizing operations to most efficiently use their current permitted airspace, it is often preferable to increase the landfill capacity by vertical expansion when lateral expansion is no longer possible. This has resulted in significant steepening of landfill side slopes and the overall height of waste fill. Where forty years ago landfill side slopes were routinely 5H to 10H to 1V, now landfills are being designed with side slopes in the 2H to 3H to 1V range or steeper with the occasional but increasingly more frequent use of innovative toe buttress structures, such as mechanically stabilized earth (MSE) walls. Forty years ago, many MSW landfills were trench fills that were terminated at or near the original land surface. Now, even medium-sized communities have landfills that are designed to rise above the surrounding land surface hundreds of feet.

As a result of the continued vertical expansion of older landfills, the stresses imparted on the underlying and/or abutting foundation soils, the waste containment envelope and waste mass itself have increased considerably. While the entire landfill profile typically has to be "re-engineered" when these modifications are proposed, the designer is usually constrained with the existing physical layout of components, such as low (or no) buttressing toe walls, or outwardly sloping base (primary) liners that tend to decrease overall stability. Except for the considerable difficulty of siting a new landfill that results from the public's 'Not in My Back Yard' (NIMBY) sentiment, the design of 'green field' sites (from scratch) is often far simpler than retrofitting existing facilities to

accommodate steeper and taller waste masses. Regardless of whether the design involves a green field or retrofitted site, the significance of understanding the in-situ geotechnical index properties of MSW (as noted earlier) is of increasing importance.

The geotechnical engineer has at his (or her) disposal many tests and now an increasing choice of software to assist in understanding and predicting the behavior of the foundational soils and the natural and synthetic materials used to support and contain the modern MSW landfill. Our knowledge of the behavior and interaction of the 'engineered' materials employed in constructing the containment envelope has advanced considerably in the past 30 years. However as noted above, the "engineered" materials used to construct the containment envelope typically constitute less than 5% of the total mass of the structure. The remaining 95% is of course the waste itself, and our understanding of the engineering properties of MSW is still relatively limited.

At present today, there has been only limited success in measuring the 'undisturbed' geotechnical index properties of MSW, including shear strength and compressibility. The primary thrust of waste property research has occurred by way of studying the behavior of the waste mass in aggregate, by back calculation, or indirectly by re-constructing or synthesizing 'representative' waste in the laboratory. Considering that the prospect that landfills and the associated internal loads will likely continue to increase with time, and that there is a trend toward increasing the biologic decomposition processes of solid waste by adding great quantities of water, the geotechnical professional is in great need of improving understanding of the in-situ properties of MSW. This research is timely in that it provides a means to assess the waste mass with far greater accuracy to greater depths than have been previously achievable.

Research Objectives

The overall objective of this research was to assess the potential for quantifying important geotechnical properties of MSW through the use of large diameter boreholes that are drilled for installation of wells used to collect and control landfill gas. The intent of this research was to develop a means to directly observe borehole conditions and measure general geotechnical index properties, such as wet and dry unit weight, moisture content, field capacity, void ratio, degree of saturation, waste composition and degree of bio-degradation. Once observed and measured, these parameters can then be correlated to burial depth and vertical total stress. Developing an understanding of these properties based on direct observation of the waste profile exposed on the borehole wall is a potential critical development in improving understanding of the relationships between the diverse constituents in MSW (classification) and the behavior of the waste mass insitu over time from initial placement to its ultimate disposition as a chemically and mechanically stable mass. The utility of quantifying and characterizing the waste mass and correlating its properties to mechanical behavior is of fundamental importance to the design engineer.

Dixon 2006[5] proposed a MSW classification system for evaluation of the mechanical properties of waste and then later developed correlation between the classification system and mechanical behavior using synthetic waste in Dixon 2008[6]. Dixon 2006[7] also explored the variability of geosynthetic-to-geosynthetic and geosynthetic-to-soil interface shear strengths reported in recent international literature to estimate the reliability of factors-of-safety and the probability-of-failure of MSW landfills. As an extension of Dixon's research, it may be possible using the techniques proposed herein

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[5] Dixon, N., and Langer, U., "Development of a MSW classification system for evaluation of mechanical properties", Waste Management Journal, 26 (2006) pp. 220-232.

[6] Dixon, N., Langer, U. and Gotteland, P., "Classification and Mechanical Behavior Relationships for Municipal Solid Waste: Study Using Synthetic Wastes", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Jan 2008, pp. 79-89.

[7] Dixon, N., Jones, D.R., Fowmes, G.J., "Interface shear strength variability and its use in reliability-based landfill stability analysis", Geosynthetics International, 13, No. 1, 2006, 1-14.pp. 1-13.

to access large diameter boreholes to perhaps ultimately measure geotechnical index properties as well as to better quantify existing internal waste mass stress. The geotechnical index properties obtained from the methodologies described and measured in this paper could be most useful in advancing the Dixon's 2006[8] approach to the reliability of MSW shear strength and compressibility measurements when developing landfill design parameters in the future.

Landva 1990[9], Daniel 1993[10], Mehta 2002[11], Dixon 2006[12], Dixon 2008[13] have all formulated systems for describing and predicting the mechanical and biological behavior of MSW. While the ultimate future goal of borehole access and assessment may be to develop information on the shear strength and compressibility of MSW. The immediate goal of this research is to develop predictive relationships for efficient placement of solid waste based on more easily measured chemical and mechanical waste properties such as unit weight, moisture content, and waste composition. These in turn can be used to predict the long term behavior of MSW as proposed by Dixon and others.

While the strength of MSW has been the subject of investigation for a number of years as reported by Sharma and Lewis 1994[14] dating back to 1975, the difficulties in characterizing mechanical behavior and strength are underscored by the fact that MSW

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[8] Ibid, Dixon, 2006 on MSW Classification
[9] Landva, A.O. and Clark, J.I., "Geotechnics of Waste Fill", Geotechnics of Waste Fill – Theory and Practice, ASTM STP 1070, American Society for Testing and Materials, Philadelphia, 1990. Pp. 86-103.
[10] Daniel, D.E., Geotechnical Practice for Waste Disposal, Chapman & Hall, London, 1993, ISBN 0 412 35170 6
[11] Mehta, R., Barlaz, M., Yazdani, R., Augenstein, D., Bryars, M. and Sinderson, L., "Refuse Decomposition in the Presence and Absence of Leachate Recirculation", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Mar 2002, pp. 228-236.
[12] Dixon, N., and Langer, U., "Development of a MSW classification system for evaluation of mechanical properties", Waste Management Journal, 26 (2006) pp. 220-232.
[13] Dixon, N., Langer, U. and Gotteland, P., "Classification and Mechanical Behavior Relationships for Municipal Solid Waste: Study Using Synthetic Wastes", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Jan 2008, pp. 79-89.
[14] Sharma, H.D., and Sangeeta, P.L., *Waste Containment Systems, Waste Stabilization, and Landfills: Design and Evaluation*, John Wiley & Sons, Inc., New York, NY, 1994, pp. 588, pg. 65.

is a heterogeneous mixture of materials and disparate processes (e.g., its composition, constituents, and collection and disposition methods). Describing MSW is difficult, and precisely predicting its behavior is an even more complex and frustrating endeavor.

As with any geotechnical material, the behavior of MSW can be better estimated with more complete understanding of its engineering properties. It is therefore useful to begin by defining pertinent geotechnical engineering index properties, (definitions adapted after Spangler, (1960)[15] and typical values as reported by Sharma 1994):

W_d = dry weight of the waste (MSW) mass

W_w = wet weight of the MSW mass

W_m = weight of the liquid phase of the MWS

MC = m = moisture content, in % (dry weight basis) = (W_w/W_d) 100 = from 15% to 40%

γ_d = dry unit weight

γ_m = wet unit weight = ranges from 20 to 84 pcf depending on compaction, method of dry density measurement, composition of waste, and whether it was shredded, baled or 'un-processed". If specific information on γ_w is not available, range of 60 to 70 pcf is typically used in an engineering evaluation either for old degraded and settled waste or for very well compacted fresh waste. [16]

γ_w = unit weight of water = 62.4 pcf

V_s = volume of the assortment of solid particles

V_e = volume of the void spaces

V_a = volume of the air voids

V_m = volume of the liquid phase filled voids

V = total volume of the MSW mass = $V_s + V_e = V_s + V_a + V_m$

n = porosity (or total porosity), in % = (V_e/V) 100 = 67%

e = void ratio = V_e/V_s = 2

[15] Spangler, M.G., *Soil Engineering*, 2nd Ed", International Textbook Co., Scranton, PA, 1960, pp. 483.
[16] Ibid, Sharma 1994

G = Specific Gravity (G_{MSW} = Specific Gravity of municipal solid waste)

FC = Field Capacity = the volumetric moisture content after a prolonged period of gravity drainage. = (V_{m*}/V) 100 = 22.4%

where V_{m*} is the volumetric moisture content. Note this is equivalent to a moisture content of about 28.9% if computed on a dry weight basis.

According to Sharma 1994[17], "strength and compressibility of MSW are important engineering considerations because these characteristics are required for landfill stability and settlement analyses. Due to variability in municipal refuse, reliance on conventional laboratory results is not prudent. Various laboratory and field tests have been reported in literature… In general, strength and compressibility characteristics of MSW are not yet well understood and need further evaluation. No useful information is yet available on the stress-strain behavior of landfill behavior."

Compressibility of waste is estimated using various methods that have been proposed by different researchers over the past thirty years. Sharma 1990[18] suggests that the compressibility of waste and the associated total settlement is a result of primary and secondary settlement. Primary settlement is reported to be principally mechanical compression in nature. It is further assumed to have fully occurred prior to the placement of the following waste increment, with little or no pore pressure buildup. The amount of primary settlement is dependent on the degree of initial compaction, composition, and environmental conditions. Secondary compression is defined as being due to decomposition and creep processes which may take up to 50 years after completion of the waste fill.

Sharma proposes several methods of estimating total (primary + secondary) compression, namely the Sowers Model, the Gibson and Lo Model, and the Power Creep Law. The Sowers Model indicates that the MSW behaves similar to peat. The remaining

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[17] Ibid

[18] Ibid

methods are reported to yield settlement predictions that range from 2% to 20%, and 0% to 14% of actual settlements for Gibson and Lo and Power Creep, respectively. Several studies have been performed over the years that propose some form of primary and secondary compression as described above, McDougall 2007[19], Sharma 2007[20], Ling 1998[21], Watts 1999[22], and Morris 1990[23].

Landva 2000[24] advances the concept of landfill total settlement being divided into immediate, instant and delayed compression. Immediate compression is described as occurring when the waste lift is compacted in place and is disregarded. Instant compression is taken from Bjerrum's 1967[25] hypothetical model for marine clays that results from the short-term mechanism corresponding to primary compression. The corresponding measure of this behavior is the coefficient of primary consolidation (C_{ce}), which is the slope of a plot of vertical strain versus the logarithm of time. Delayed compression is also described by Bjerrum's as 'secondary compression and is a result of plastic creep, raveling and corrosion, oxidation, and combustion, either separately or in combination. It also includes the long-term component of distortion, bending, crushing and reorientation of particles due to decomposition'. Here the corresponding measurement is the coefficient of secondary consolidation (C_{se}). Landva 2000[26] reports the range of C_{ce} in their limited study as being 0.17 – 0.24. Twelve other studies were summarized and a C_{ce} range of 0.08 to 0.5 was reported. The range C_{se} in the Landva

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[19] McDougall, J., "A hydro-bio-mechanical model for settlement and other behavior in landfilled waste", Computers and Geotechnics, 34 (2007) pp. 229-246.
[20] Sharma, H.D., De, A., "Municipal Solid Waste Landfill Settlement: Post Closure Perspectives", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Jun 2007, pp. 619-629.
[21] Ling, H.I., Leshcinsky, D., Mohri, Y., Kawabata, T., "Estimation of Municipal Solid Waste Landfill Settlement", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Jan 1998, pp. 21-28.
[22] Watts, K.S., Charles, J.A., "Settlement characteristics of landfill wastes", Proceedings of the Institution of Civil Engineers, Geotechnical Engineering, 1999, 137, Oct., pp. 225-233. Paper 11836.
[23] Morris, D.V., and Woods, C.E., "Settlement and Engineering Considerations in Landfill and Final Cover Design", *Geotechnics of Waste Fills – Theory and Practice, ASTM STP 1070*. Landva, A., and Knowles, G.D., Editors, American Society for Testing and Materials, Philadelphia, 1990, pp. 9-21.
[24] Landva, A.O., Valsangkar, A.J., and Pelkey, S.G., "Lateral Earth Pressure at Rest and Compressibility on Municipal Solid Waste", Canadian Geotechnical Journal, Vol. 37: pp. 1157-1165, 2000.
[25] Bjerrum, L., "Engineering geology of Norwegian normally consolidated marine clays as related to settlement of buildings. 7th Rankine Lecture. Norwegian Geotechnical Institute, Publication No. 71, 1967.
[26] Ibid, Landva, 2000.

study discussed here was 0.01 to 0.016. The above referenced summary of prior research indicated a C_{se} range of 0.0005 to 0.08. The Landva 2000 study reported compositional variations in particle size, limited constituents, and material entombment age, but no inferences were drawn using these basic classifications.

More recently, Hossain 2003[27] proposed and reported on compression indices where C_c was defined as the primary compression index and secondary compression was divided into a creep index ($C_{\alpha i}$) and biological index (C_{Bi}). The researchers relate these compression parameters to a bio-degradation ratio (C+H/L) where C, H, and L are the concentration of cellulose, hemicellulose, and lignin, respectively. A lower ratio value corresponds to a greater degree of biodegradation. Here again, the compression index is the plot of vertical strain versus the logarithm of time. C_c ranged from 0.16 to 0.37 and correlated inversely with the degradation ratio. $C_{\alpha i}$ ranged from 0.015 to 0.03 and C_{Bi} ranged from 0.09 to 0.05. Insufficient data was available for the researchers to develop a numeric correlation between the degradation ratio and the various compression indices, except that the authors did recommend that the compression indices should be applied to each waste layer in a landfill to estimate settlement rather than continuing the practice of applying a single value of C_c to the entire waste mass. The means by which this recommendation was to be employed was not discussed.

Most recently, Bareither 2012[28] refined the MSW compressibility methodology by asserting that MSW settlement consists of three phases: immediate compression, mechanical creep and bio-compression. The authors state that immediate (primary in prior research noted above) compression and mechanical creep are abiotic processes while bio-compression is a combination of abiotic mechanical creep coupled with biotic decomposition. Bio-compression depends on organic content, moisture content, and

[27] Hossain, M.S., Gabr, M.A., Barlaz, M.A., “Relationship of Compressibility Parameters to Municipal Solid Waste Decomposition”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Dec 2003, pp. 1151-1159.

[28] Bareither, C.A., Benson, C.H., Edil, T.B., and Barlaz, M.A., “Abiotic and Biotic Compression of Municipal Solid Waste”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Aug 2012, pp. 877-888.

temperature. In the Bareither (2012) study, MSW was analyzed for moisture content, C, H, and L, volatile solids (VS) and biochemical methane potential (BMP). The study looks at the variation in time-dependent compression ratios (mechanical compression ratio = $C'_{\alpha m}$ and bio-compression ratio = $C'_{Bm)}$ compared to abiotic and biotic processes, and it ultimately suggests that time-dependent compression strain (ε_{td}) can be predicted using a three part formula that takes into account the estimation of transition times from immediate compression to mechanical creep, from mechanical creep to bio-compression and the time to complete bio-compression. While Bareither's observations were elucidating as to the process by which compression might occur in the waste mass it does not appear to have immediate application to the design practitioner. Bareither 2012[29] expands on the understanding, measurement, and prediction of primary compression using 7.7 ft. diameter by 26.4 ft. tall lysimeter designed to measure MSW settlement. The study then uses the first order rate equation (FORE) procedure presented by Handy 2002[30] to predict the end-of-immediate compression strain (ε_{EOI}) for MSW.

The study of compression mechanisms in MSW continues to evolve, but as yet there is currently no way to accurately predict MSW landfill settlement. Park 2002[31] summarizes the current thinking on the subject with the conclusion that; 'If long-term settlements were estimated for the design of the cover systems for long-term maintenance for fresh MSW landfills in which decomposition conditions are not favorable and hence the decomposition of organic solids has not yet occurred, a considerable underestimation might be obtained. Then, any structure built on the landfill site could be damaged by excessive long-term compression as a result of

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[29] Bareither, C.A., Benson, C.H., Edil, T.B., and Barlaz, M.A., "Compression Behavior of Municipal Solid Waste Immediate Compression", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Sept 2012, pp. 1047-1062.
[30] Handy, R.L., "First-Order Rate Equations in Geotechnical Engineering", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 2002, 128(5), pp. 416-425.
[31] Park, H.I., Lee, S.R., and Do, N.Y., "Evaluation of Decomposition Effect on Long-Term Settlement Prediction for Fresh Municipal Solid Waste Landfills", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Feb 2002, pp. 107-118.

decomposition.' There appears to be considerable work yet to be done regarding the accurate prediction of MSW settlement. Perhaps the large diameter MSW borehole will provide an opportunity to measure mechanical compression indices in-situ. Correlation with biologic degradation data would be useful in refining the magnitude of settlement yet to occur in a MSW profile.

The ultimate object of this study focuses on developing strategies to measure the in-situ long-term geotechnical properties of MSW.

Prior studies that have developed in-situ properties of MSW have involved the exhumation of waste using test pits where the volume of the test pit is measured and the contents weighed and classified. Test pit methods limited the study of waste properties to relatively shallow waste burial depths. Testing was primarily focused on classification of waste constituents as well as unit weight and moisture content properties related to the follow on disturbed testing of MSW in various shear strength test devices.

MSW has been studied at depth using conventional, relatively small, borehole diameters (< 12 inches in diameter), where down hole geophysics was performed on the waste mass. The completion of small diameter boreholes to significant depths is extremely difficult given the random and frequent presence of waste obstructions that often end with auger refusal or drill stem breakage forcing borehole abandonment and relocation. Extraction of undisturbed samples using these methods has not been feasible. As a result, conventional geotechnical drilling and sampling of MSW to significant depths has typically provided only marginally useful information. Given these obstacles, the study of MSW at depth has been limited.

The opportunity for accessing MSW at depth comes from the solid waste industry's relatively recent and increasingly frequent harvesting of methane gas generated as a

natural by-product of the degradation of landfill waste. This opportunity arises from the need to install gas collection and control system (GCCS) wells. These GCCS wells typically range in diameter from 30 to 48 inches (0.76 to 1.22 m), and they can be installed to depths of hundreds of feet. This paper describes an experimental methodology that has been developed to characterize the general physical, chemical and geotechnical index properties of the MSW encountered in the GCCS well boreholes.

These GCCS boreholes are typically drilled with large, truck or track-mounted, rotary-type, drill rigs employing large diameter bucket augers. Waste depths in modern MSW landfills can range up to several hundred feet. A GCCS well typically penetrates up to 90% of the waste depth. The objective being to penetrate the waste profile sufficiently to control and capture landfill gas without jeopardizing the integrity of the primary liner system. The frequent and regular need for GCCS borings represents a low cost opportunity to gain access that would otherwise be very expensive, if the borehole were to be completed solely for the purpose of geotechnical characterization.

The assessment strategy proposed in this study takes advantage of the need to complete the boring, and the only impact on the GCCS installation is a temporary delay in the well fabrication. The drill rig typically relocates to the next well and continues the project effort, while the borehole of interest is subjected to the in-situ testing program. Thereafter, the construction crew simply returns to the borehole at their convenience to complete the well. In effect, there is no additional cost to the GCCS project installation for adding the proposed in-situ testing program if the testing can be performed before the crew has finished the remaining well installations.

The procedure employed to evaluate the condition of MSW cuttings that are extracted from the boring operation, and observe and record the condition of the borehole is the MSW Borehole Assessment (MBA).