SOLVING THE LANDFILL PUZZLE

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ABSTRACT

Landfill design engineers, working for owners and operators, are continually searching for the most appropriate density, shear strength and compressibility parameters to estimate site life, maintain stability, and provide for safe and efficient operations. While published literature on waste composition, density and shear strength are numerous, the wide ranges in published values make it necessary for engineers to perform site testing or other studies to establish reasonable site specific parameters.

This paper offers an overview of what goes on inside a landfill which should help explain why the wide range in waste parameters exists. For example, is an appropriate effective density of waste used in predicting lifespan and stability at 900, 1200, or 1500 pounds per cubic yard? And, based on the effective density, what friction angle and cohesion values should be used in stability modeling? It should be evident, as we look at solving the landfill puzzle, that the answer may be that all three values are possible within the same landfill mass, and the shear strengths will vary at depth, but another landfill mass may be completely different.

It should become clear that landfills are essentially large puzzles, but the better we understand the internal workings of landfills, the better answers and solutions we can provide as landfill engineers.

INTRODUCTION

Let's start with a view of a modern municipal solid waste (MSW) landfill depicted in Figure 1. Typically, modern landfills are lined on the bottom with some combination of native low permeability soil or possibly a manufactured, geosynthetic clay liner (GCL), a flexible geomembrane such as high density polyethylene (HDPE), and a high permeability drainage layer consisting of gravel or manufactured drainage layer to collect and transmit. The exterior slopes of a modern waste mass may be as steep as 3 horizontal to 1 vertical (3:1) and the overall waste depth of up to 200 feet are typical. This configuration represents many landfills around the United States.

We will consider the engineering properties of waste within our example landfill in a way that you may not have done before. We will look at effective density first, then waste shear strengths. We are not going to reveal any magic numbers that will solve all of your landfill problems, but we will show concepts and ways of looking at landfills that help us to understand how things work inside. Practical applications using waste effective density and shear strength to solve age-old engineering problems will be discussed. We even have some suggestions for design and engineering aides that will help you to solve your Landfill Puzzle.

EFFECTIVE DENSITY OF WASTE

What if you are asked the question, "What is the effective density of the waste in your landfill?" How would you answer? Let's discuss the traditional answer and then look at some not-so-traditional ways to answer.

Traditional Approaches and Methods

At the outset, it is important to define terms. In this case, the term effective density means the mass per volume of the waste as it exists in the field. By this definition, the value includes the waste itself plus daily cover soil that may have been used, and represents the value that one would obtain if a sample could be taken from the waste mass and measured. In this case, effective density is more than just the amount of waste (tons) that can be packed into a cubic yard, which is more of a utilization factor.

To answer the density question, most engineers would be inclined to go to a reliable literature source or reference, compare those values with their experience, assuming that knowledge exists, and factor in previous site information. In some cases, engineers or operators may be motivated to answer the question by performing large scale field tests. Such tests have been performed at several sites and usually involve excavating waste and carefully measuring the dimensions of a large area, weighing the excavated waste and calculating the density directly. Where survey data exists and volume changes over specific time can be checked, engineers may compute density using tonnage records. However, such density values need to be adjusted for daily cover if they are used in stability modeling, but do not need such correction if they are used only for lifespan estimates.

Without performing such tests, or reviewing the literature, the question of effective density may be answered like this: "The effective density is 1,000 pounds per cubic yard (pcy), because that's how dense we can compact it." Or, we could say it is the same as we determined in our last waste cell, which was, say, 1,200 pcy. We might even say that we read a technical paper that says that they measured at a similar site and it was 1,450 pcy. These answers are familiar because we may have used them ourselves. So, given the variability in the numbers and methods for deriving the number, which density do we use to calculate how long our current landfill cell can operate until it is full and which do we use to measure stability?

Density Column Concept

Now, let's introduce waste depth into the question and see how it impacts the Landfill Puzzle. Figure 1 shows a landfill that has a waste thickness of 200 feet, which is on the upper end of the most landfill cells. Is the effective density of the waste on the top surface the same as 200 feet down? Most likely, it is not. How about in between at mid depth? Let's isolate a 1-foot-square vertical column of waste from the top to the bottom of the waste and refer to it as a "density column," Figure 2. This density column includes the lightest, on the top, to the heaviest effective density, on the bottom, based on the location or depth in the column. The effective density could range from 1,000 pcy to as much as 1,660 pcy. The greatest change in effective density occurs at less than 100 feet of waste depth. Actual waste densities have been measured at significantly higher levels approaching 2,700 pcy at depths greater than 100 feet. That's quite a range in weight. The age of waste is a major factor. Since we can only add waste to the top of the column, thinking in terms of an average density makes sense. The average is a whopping 1,660 pcy for a 200 foot thick cell. This means that for every cubic yard of waste placed on top of the 200 feet, you may be tempted to claim an effective density of 1,660 pcy for the new waste, even if it is compacted only to 1,000 pcy.

Table 1 shows estimated effective densities at 10, 50, 100, 150, and 200 feet of waste depth for an example landfill.

Table 1
EFFECTIVE DENSITIES
OF TYPICAL MSW

Waste Depth (ft)	Effective Density (pcf)	Normal Load (psf)	Density Column (pcy)
10	35	350	1,000
50	50	2,050	1,150
100	65	4,925	1,350
150	74	8,400	1,510
200	83	11,650	1,660

The authors have seen many occasions where landfill owners/operators assign 1,000 pcy to the effective density value because the waste is being placed on the surface of the landfill. They may believe that the waste cannot be mechanically compacted to a higher density. The implications of this belief is that the calculated cell/landfill life may be incorrect, which could have a significant economic effect on their operations. Hence the often repeated statement, "The landfill is going to close in X years over and over again," when in reality it might be much longer than X."

A technical paper was written and presented in 2001 that addresses issues related to effective density and filling rates ("Predicting Landfill Filling Rates, Ultimate Capacity, and Closure Dates", McCready and Stearns, 2001.) The paper offers methods of estimating these parameters based on observed and documented data. This paper presents values in tables and graphic form based on the density column concept.

WASTE SHEAR STRENGTH PROPERTIES

Another important landfill parameter is the shear strength of waste, which is derived from the internal friction angle and cohesion (or adhesion) These values are used to calculate factors of safety for both static and seismic condition of the waste masses. This analysis allows landfill engineers to set final exterior and interim interior slopes for the waste and to verify that a landfill meets regulatory requirements.

Published/Literature Values

Most landfill engineers utilize slope stability software programs to compute factors of safety for static and seismic stability of the waste mass. While soil parameters are relatively easy to estimate within reasonable ranges, and can be tested for in the laboratory, waste shear properties are far more difficult to predict. There is also much less information published on waste properties not only because of the costs involved in testing but also the wide variability from landfill to landfill. Landfill engineers may initially review literature for shear strength values that would be within ranges generally accepted by the waste industry. However, solving the puzzle of shear strength requires the engineer to ask how do we as landfill engineers go about picking the most appropriate value? And, does it make a difference anyway? Without question the waste shear strength properties are critical in any stability analysis, especially when the landfill design is marginally passing/acceptable.

Published values for waste shear strength include the following and its source:

	Ø-Degrees	Cohesion-psf
Solid Waste Association of North America (SWANA)	33	0
SCS Engineers	32	250
Environmental Protection Agency (EPA)	31	200
Caicedo et al. (2002)	23	1400
Eid et al. (2000)	42	520
Harris et al. (2006)	20-29	190-290
Kavazanjian et al. (1995)	0	500
Kavazanjian et al. (1995)	30	0
Landva and Clark (1990)	24-41	0-480
Mazzucato et al. (1999)	31	900
Vilar and Carvalho (2002)	29	820
Whithiam et al. (1995)	30	210
Zekkos et al. (2006)	36-41	0

As the numbers indicate, there are a number of values that are used in the Waste Industry. So which one is right/appropriate for your landfill or application?

Test Values

If we are not comfortable with published values, then why not test the strength of your waste? The short answer is that testing of waste using remolded samples is both expensive and difficult because the waste characteristics are likely changed during remolding of samples. Field or in-situ testing is possible but is also very expensive and the test results subject to the variability in waste. Nevertheless, testing of waste shear strength has been performed and is reported in recent papers such as "Compositional and Loading Rate Effects on the Shear Strength of Municipal Solid Waste", Zekkos, et al, 2007. The findings of the paper are that the rate of loading has a short term effect, but the strength values for normal loads are similar regardless of the rate of loading. The strength values of waste are of interest here. Using strength values expressed by internal friction values only based on a Mohr-Coloumb relationship, waste strength varies from 42 degrees for low normal loads to 31 degrees for high loads like those experienced at the bottom of a landfill with 200 feet of waste in place. Figure 3 shows back-calculated internal friction angles from MSW testing on waste from various landfills, Kavazanjian, E. (2001). Zero cohesion is assumed in the calculations. That's a wide range of variation; however, the variation is associated with the normal load on the waste at the time of testing. That suggests that there are different shear strengths for deep waste and shallow waste, and with variations at different locations across the site.

Strength Envelop

Let's look at how we can incorporate these strength values into useful information that we all can benefit from. Table 2 is an extension of Table 1. We have added the above parameters for internal friction at different normal loads associated with waste depth. To make the information even more useful, it is expressed in terms of internal friction angle and cohesion. Interestingly, the numbers look very familiar and similar to the published strength parameters previously referenced. The difference is that we now have associated that the strength parameters vary with normal loads and Table 2 provides a way to select the parameters based on depth of waste. This information has also been added to Figure 4. Both Table 2 and Figure 4 allow us to select waste shear strength parameters that apply to our site conditions.

Table 2
EFFECTIVE DENSITIES AND STRENGTHS OF TYPICAL MSW

Waste Depth (ft)	Effective Density (pcf)	Normal Load (psf)	Density Column (pcy)	Internal Friction Degrees	Internal Friction Degs/Cohesion
10	35	350	1,000	43	37 @ 50 psf
50	50	2,125	1,150	39	35 + 200 psf
100	65	4,925	1,350	34	33 + 100 psf
200	83	11,650	1,660	31	30 + 300 psf

PRACTICAL APPLICATIONS

A couple of examples of how the parts of the Landfill Puzzle can be used will show the advantages for every day applications.

Effective Density Example

The authors are the engineers of record for a landfill site that accepts MSW at an average rate of 650 tons per day (tpd). A new cell has been constructed that will have a waste height of approximately 100 feet and a capacity of 1,650,000 cubic yards (cy). What is the life of the cell?

OK, is the effective density 1,000 pcy or 1,660 pcy? In this case we can go to Table 1 and see that the average effective density for waste approximately 100 feet high is 1,350 pcy under the density column. We can now calculate the site life for the average disposal rate.

650 tpd

$$\text{Site Life} = \frac{1{,}350 \text{ pcy}}{2{,}000 \text{ ppt}} \times \frac{1{,}600{,}000 \text{ cy}}{650 \text{ tpd}} = 1{,}662 \text{ Days}$$

ppt = lbs per ton

The cell will have a life of 4.6 years. If we had assumed 1,000 pcy for the effective density, the life would have been 3.4 years and 5.6 years for 1,660 pcy. As you can see, there is a wide range of variation depending on our assumption of effective density. If you choose too high, you might find your cell filled before you have planned your next cell. That would be a real problem.

You might also need to make a mid-course change. Maybe your waste stream is increased in the middle of a cell life and you need to re-evaluate site life. Let's say that in the above example, you are 1/3 filled. What will the remaining site life be at 850 tpd?

850 tpd

$$\text{Site Life} = \frac{1{,}350 \text{ pcy}}{2{,}000 \text{ ppt}} \times \frac{2}{3} \times \frac{1{,}600{,}000 \text{ cy}}{850 \text{ tpd}} = 847 \text{ Days}$$

The remaining cell life will be 2.4 years. That's an easy and simple analysis, when you know the average effective density of the waste.

Waste Shear Strength Example

Our example for waste shear strength shows the effects of selecting the realistic values based on the depth of waste. You want to know the effect on the Factor of Safety (FS) for static and seismic stability if you pick an internal friction and cohesion at 10, 100, and 200 feet of waste. The local regulations require an FS of 1.5 for static stability. Our waste mass is 200 feet high with 3:1 final exterior slopes.

Let's go to Table 2 and look for the variation in shear resistance for the three different depths. The equations used to compute the static FS are linear; therefore, we can determine the effects of varied shear strength using ratios of the shear resistance calculated from Table 2.

Depth (ft)	Ø (deg)	Cohesion (psf)	Shear Resistance (psf)	Factor of Safety
10 Feet				
10	**37**	**50**	**325**	**1.5**
100	33	100	325	1.5
200	30	300	500	2.3
100 Feet				
10	37	50	3,800	1.7
100	**33**	**100**	**3,300**	**1.5**
200	30	300	3,100	1.4
200 Feet				
10	37	50	8,800	1.9
100	33	100	7,700	1.7
200	**30**	**300**	**7,000**	**1.5**

The FS column shows that the selection of the strength parameters does have an effect at all depths. The more accurately we can select the strength parameters, the more realistic our results.

CONCLUSIONS

The physical properties of waste vary throughout a waste mass and are likely to change over time as the waste decomposes and as new waste is placed over old waste. The best we can do as landfill engineers is to utilize available information on waste shear strength values from published studies, adjust the values for our specific site conditions, and then perform testing if warranted to refine the values. This paper has attempted to show a simplified process so that representative parameters can be determined relatively easy and with a degree of confidence. Further testing and evaluations are suggested to confirm and broaden the concepts offered in this paper.

We hope that this paper has shed new light on solving the often perplexing Landfill Puzzle.

ACKNOWLEDGEMENTS

The authors acknowledge the contributions of Robert Isenberg as peer reviewer of this paper. His knowledge and experience in the field of landfill engineering were valuable in balancing the presented concepts with traditional industry practices.

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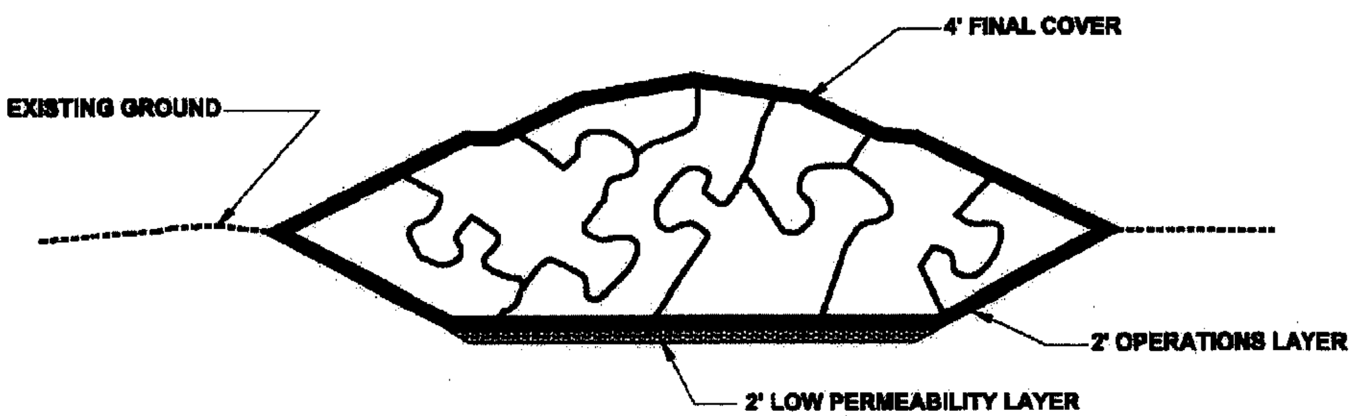
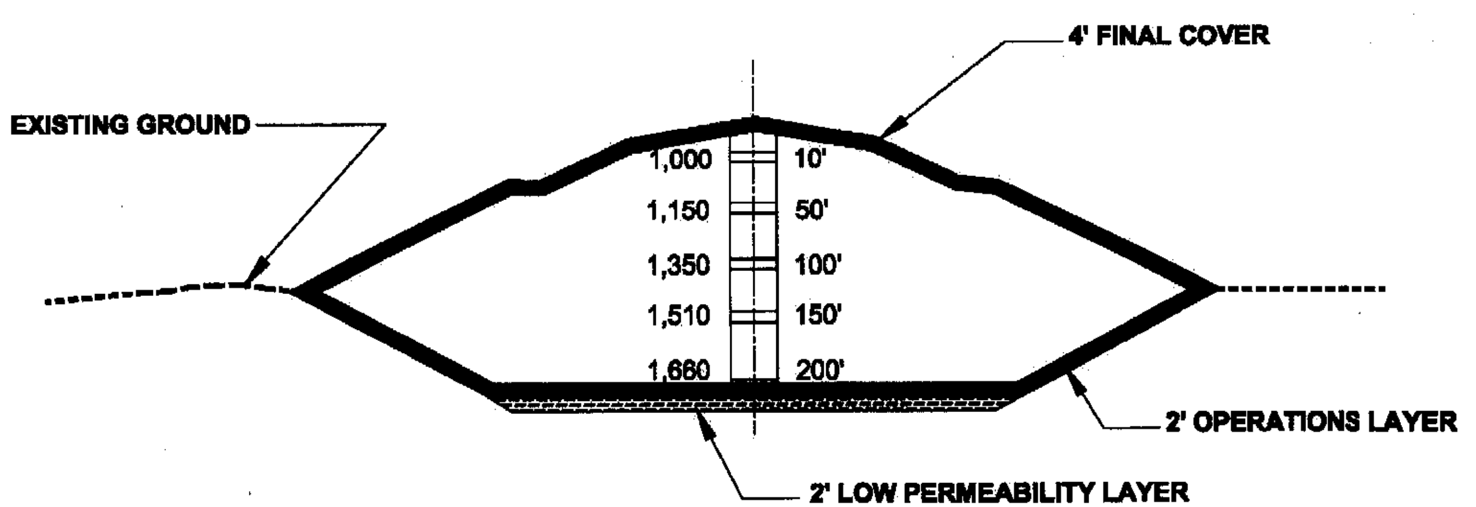
LANDFILL CROSS SECTION
FIGURE 1



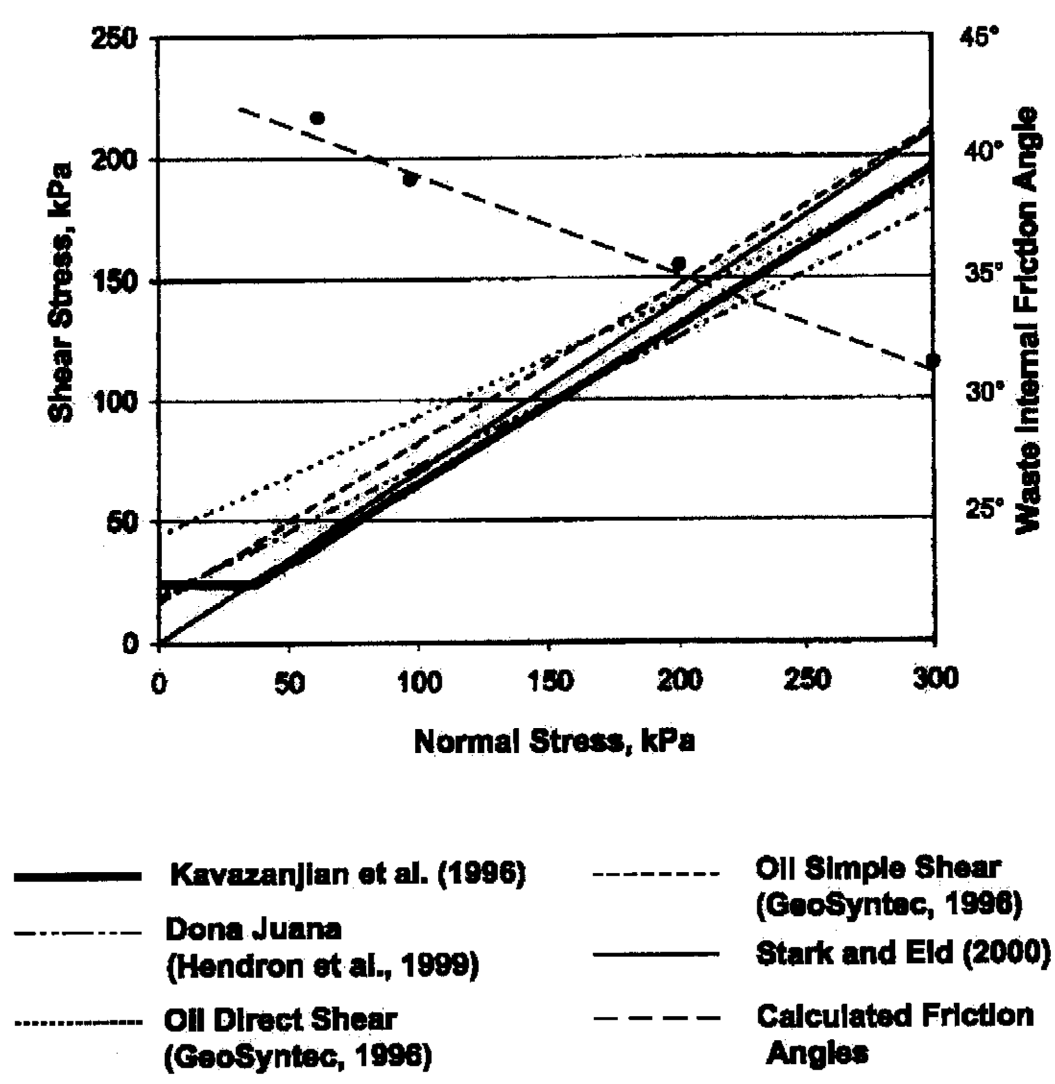
DENSITY COLUMN

FIGURE 2



CALCULATED FRICTION ANGLES

FIGURE 3



FRICTION ANGLES

FIGURE 4