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Equipment pressure applied to geomembrane in composite liner system

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ABSTRACT: This technical paper presents the results of a test pad at an operating municipal solid waste landfill that measured pressures applied to the primary geomembrane in the double composite liner system used at the site. The pressures were measured with two pressure cells placed on top of the geomembrane and covered with varying thicknesses of sandy structural fill and rounded stone, i.e. a leachate collection and removal layer stone. The pressures were applied by two types of dozers to investigate the magnitude of applied pressures and the effect of equipment on the applied pressure. In general, the results show increased pressure with decreasing cover layer thickness, increasing speed, and turning over of the pressure cells. The data can be used to estimate the minimum layer thickness to limit the pressure applied to an underlying geomembrane to a tolerable value, e.g. 41.4 kPa, and prevent geomembrane damage or puncture during construction.

KEYWORDS: Geosynthetics, Geomembranes, Puncture, Applied pressure, Drainage layer, Leak location

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1. INTRODUCTION

The versatility of a dozer crawler has made it an important piece of equipment at most landfill sites. In particular, a dozer is usually used to place the leachate collection and removal layer (LCRL) above the primary geomembrane in a composite liner system and the select structural fill or leak detection layer (LDL) below the primary geomembrane in a double composite liner system. This can be problematic, because a dozer can easily damage a geomembrane during material placement, since the placed soil makes it difficult to locate a defect in a geomembrane. This is undesirable, because increased leakage could be detected in the underlying LDL in a double composite liner system, or in a monitoring well outside the liner system. Either type of detection may require expensive remedial actions: therefore it is important to ensure that a dozer does not damage the geomembrane during soil placement. Even if the defect is located with a leak location survey, there will be some additional cost in removing the soil layer, repairing the geomembrane, and re-placing the soil layer.

This technical paper presents the results of a test pad at an operating landfill used to measure the pressures applied to the primary geomembrane in a double composite liner system, and to determine whether the two dozers used to place the covering soil damaged the liner. The pressures applied were measured with two pressure cells placed on top of the geomembrane and covered with varying thicknesses of sandy structural fill and rounded stone to simulate a LCRL or the LDL. After each dozer had operated on the geomembrane, a leak location survey was

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performed to ensure that the geomembrane was not damaged by the equipment or, if it was, that the geomembrane was repaired before the next piece of equipment operated on it.

The main objectives of the study areas follows.

- Determine the ground pressure applied by the two dozers.
- Determine the ground pressure applied through various thicknesses of soil material.
- Determine the minimum allowable thickness of cover soil for the two dozers tested.

The test pad was constructed as part of the Phase V expansion of Clinton County Landfill, located in Schuyler Falls, Clinton County, New York, USA. Schuyler Falls is approximately 8.5 km west of the City of Plattsburgh on County Route 31 (Sand Road) in the Town of Schuyler Falls, NY. It is also about 385 km northeast of Syracuse, NY, and about 50 km west from Burlington, Vermont. The total property at the site encompasses approximately 178.2 ha. Categories of waste acceptable for disposal at the landfill include solid waste generated by households, commercial establishments, and industries. Construction and demolition debris, petroleum-contaminated soil, and any residues and bypass wastes from recycling, incineration or other waste-processing technologies are also accepted at the site (Barton & Loguidice 2007).

To comply with 6 NYCRR Part 360 Solid Waste Management Facilities Regulations Section 360-2.13, effective November 1999 (NYSDEC 1999), a double composite liner system was installed in the Phase V expansion. It consists of the following components, from top to bottom:

1. The primary LCRL, consisting of a 0.3 m thick layer of 75 mm minus rounded stone with an in-place hydraulic conductivity of 0.01 m/s, overlain by a 0.45 m thick layer of processed tires.
2. A 814 g/m^2 cushion nonwoven geotextile over the primary geomembrane as a cushion to protect the geomembrane from puncture.
3. A primary 1.5 mm thick double-sided textured high-density polyethylene (HDPE) geomembrane.
4. A reinforced geosynthetic clay liner instead of a 0.15 m thick compacted low-permeability soil liner.
5. A 0.3 m thick layer of sandy structural fill installed only on the landfill floor (slopes less than 10%), and consisting of onsite fill screened to 25 mm minus material.
6. A double-sided drainage composite on the landfill floor (slopes less than 10%) and side slopes.
7. A secondary 1.5 mm thick double-sided textured HDPE geomembrane.
8. A secondary 0.6 m thick compacted low-permeability soil liner with a vertical, saturated hydraulic conductivity of less than or equal to 1.0×10^{-9} m/s and a maximum particle size passing the 25.4 mm sieve.

2. TEST PAD DESIGN

2.1. Test pad materials and components

The test pad is located across the access road from the Unlined Landfill and the Phase V Expansion. The test pad is 13.4 m by 27.8 m, and Figure 1 shows the generalized cross-section and each component.

The geotextile was placed below the primary LCRL

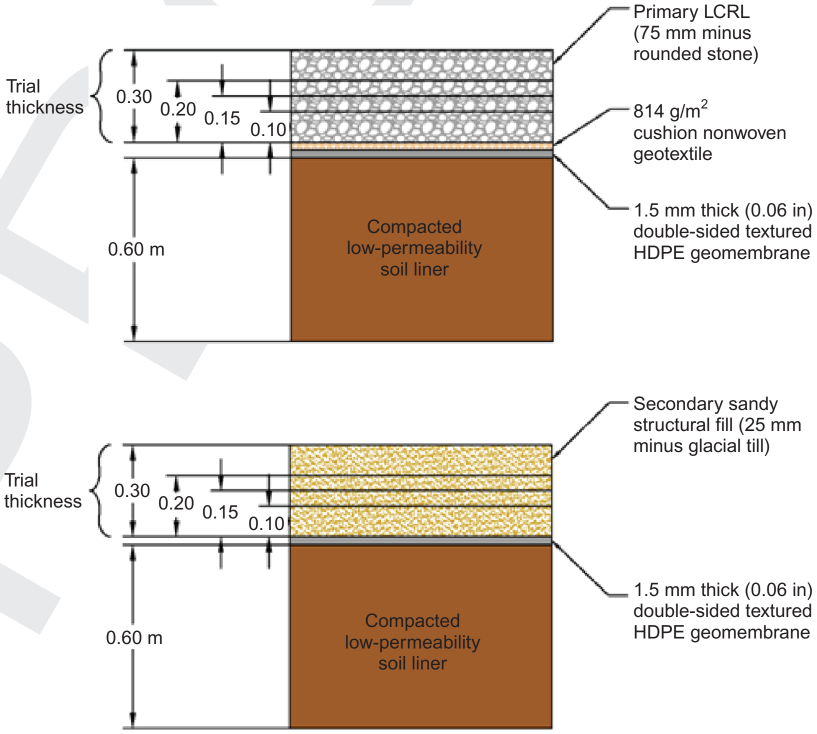

Figure 1. Test pad cross-section with leachate collection and removal layer configuration and sandy structural fill, and tested layer thicknesses (in meters)

(rounded stone) but not the secondary sandy structural fill. The HDPE geomembrane was constructed using two widths of about 7.2 m wide HDPE geomembrane that simulates the primary and secondary geomembranes in the Phase V expansion. The compacted low-permeability soil liner has a vertical, saturated hydraulic conductivity less than or equal to 1.0×10^{-9} m/s and a maximum particle size passing the 25 mm sieve.

The grain-size distribution curves for the LCRL and structural fill used in the test pad are shown in Figure 2.

2.2. Test pad construction

Pressures were applied to the pressure cells on top of the geomembrane by two types of dozers to investigate the effect of equipment on the applied pressure and geomembrane damage. The term ‘applied pressure’ is used throughout this paper to refer to the pressure exerted on the geomembrane as measured by the pressure cells. Two pressure cells were placed on top of the geomembrane. One pressure cell was located near the center of the sandy structural fill portion of the test pad and the other near the center of the LCRL portion. Prior to placement of the sandy structural fill and nonwoven cushion geotextile on the LCRL portion of the tests, the cells were leveled on top of the geomembrane with some fine bedding sand. In addition, the 0.60 m thick compacted low-permeability soil liner was constructed and inspected to provide a stiff surface on which to place the pressure cell, to avoid tilting of the cell. The location of each place was documented using a Trimble R6 GPS equipment prior to placement of the structural fill and LCRL so the dozer operators would know where to pass over during the testing. The Trimble R6 unit has a horizontal accuracy of ±10 mm (Trimble 2009). The pressure cells used were 3515 Geokon earth pressure cells. Each pressure cell is a 200–400 kPa semiconductor strain gage earth pressure cell with 0–5 V DC output, and a maximum allowable pressure of 400 kPa. The pressure cells are composed of two thick back cells so that they will not deflect locally under point loads transferred from granular materials (Geokon 2007). These cells will over-register the soil pressure by less than 5%, and have successfully been used for measurement of traffic-induced pressures on roadway subgrades, airport runways and railroad tracks (Geokon 2009). Additional information and sketches can be found in the load cell instruction manual (http://www.geokon.com/products/manuals/3500_Earth_Pressure_Cells.pdf).

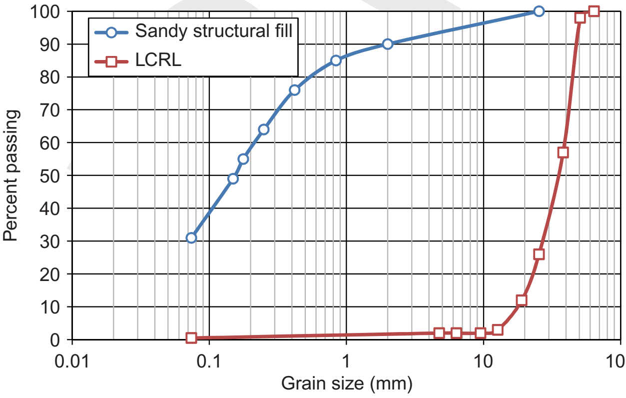

Figure 2. Grain-size distributions for leachate collection and removal layer and sandy structural fill

The dozers selected for the testing were a John Deere 764 high-speed dozer (HSD) and a Caterpillar D6H low ground pressure dozer (D6H), and are shown in Figure 3. The HSD is a new dozer that can move up to 25.8 km/h, has an articulated frame to reduce turning induced stresses, uses four rubber tracks instead of two steel tracks, and applies a ground pressure of about 40.6 kPa. The D6H has a continuous body, and two steel tracks with grousers, and applies a ground pressure of about 37.9 kPa. The ground pressures listed above are based on the dozer weights and dimensions shown in Table 1, which were measured at the site.

The actual ground pressure of 40.6 kPa of the HSD varies from the published ground pressure for it of 46.0 kPa. The published ground pressure must be calculated using ISO-6747 (1998), which requires the measurement to be used only for the track footprint on the centerline between the track idlers. Each of the four

(a)

(b)

Figure 3. HSD and D6H used in testing

Table 1. Dozer weights and dimensions

Parameter	764 HSD	D6H
Weight (kg)	17 034	23 027
Track width (mm)	610	914
Track length: mm	1676	3277
Number of tracks	4	2

rubber tracks of the HSD has a measured length of 1676 mm, as noted in Table 1, as compared with the calculated length of 1343 mm according to ISO-6747 (1998). The actual length of each track of 1,676 mm is used for the calculations herein.

The testing consisted of the following steps after placement and leak location testing of the geomembrane, which are discussed below.

1. Spread a 0.30 m thickness of secondary sandy structural fill on one-half of the test pad with no cushion geotextile, and a 0.30 m thickness of primary LCRL (rounded stone) on the other half of the test pad with a 814 g/m^2 cushion nonwoven geotextile using the 764 HSD (see Figure 4).
2. Measure the pressure applied by the HSD below a 0.30 m lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning over the pressure cells.
3. Conduct a leak location survey.
4. Measure the pressures applied by the D6H below a 0.30 m lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning.
5. Conduct a leak location survey.
6. Remove a 0.10 m thickness of structural fill and LCRL material with the HSD for a remaining thickness of 0.20 m over the entire test pad.
7. Measure the pressures applied by the HSD below a 0.20 m lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning over the pressure cells.
8. Conduct a leak location survey.
9. Measure the pressures applied by the D6H below a 0.20 m thick lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning over the pressure cells.
10. Conduct a leak location survey.
11. Remove a 0.05 m thickness of structural fill and LCRL material with the HSD for a remaining thickness of 0.15 m over the entire test pad.
12. Measure the pressures applied by the HSD below a 0.15 m lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning over the pressure cells.
13. Conduct a leak location survey.
14. Measure the pressures applied by the D6H below a 0.15 m lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning over the pressure cells.
15. Conduct a leak location survey.
16. Remove a 0.05 m thickness of structural fill and LCRL material with the HSD for a remaining thickness of 10 cm over the entire test pad.
17. Measure the pressures applied by the HSD below a 0.10 m lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning over the pressure cells.
18. Conduct a leak location survey.
19. Measure the pressures applied by the D6H below a 0.10 m lift at slow (5 km/h) and fast (10 km/h) speeds, and while stationary and turning over the pressure cells.
20. Conduct a leak location survey.

Figure 4. Test pad with HSD placing sandy structural fill on geomembrane

2.3. Leak location testing

The geomembrane was installed after smooth-wheel rolling the surface of the 0.60 m thick compacted low-permeability soil liner. The geomembrane was seamed using a DemTech split-wedge welder. The resulting split seam was air-channel tested, and passed the criterion used for the Phase V expansion geomembrane just across the access road. The air-channeled test criterion used is that the seam must hold a pressure of at least 172.4 kPa with a pressure loss no greater than 13.8 kPa over a 3 min period. The geomembrane was also inspected for holes and defects before the leak location testing described below was performed.

Leak location tests were conducted on the geomembrane after each dozer had operated on it to ensure that no defect was induced in the geomembrane and, if the geomembrane was damaged, which dozer caused the defect. The edges of the geomembrane were turned up by about 0.45 m to isolate the materials on the geomembrane from the earth surrounding the test pad.

The leak location tests used during the study are described in ASTM D 6747. The bare geomembrane was tested in general accordance with ASTM D 7002 prior to placement of any cover material, using the water puddle test to determine whether any leaks were induced during geomembrane placement and seaming. No leaks were found with the puddle test method. The leak location equipment was verified using a 1 mm hole in the geomembrane. The geomembrane is systematically scanned with overlapping coverage. When a leak is detected, it is located and marked for repair.

One of the two geomembrane panels used for the test pad was covered with secondary sandy structural fill (25 mm) and the other panel was covered with a 407 g/m^2 nonwoven geotextile and then 0.3 m of LCRL (75 mm minus rounded stone). Geomembrane leak location surveys were conducted on the sandy structural fill and rounded stone portions of the test pad using the method for geomembranes covered with earth materials (ASTM D 7007). Measurements with a 1 m dipole were made every

1 m on survey lines spaced 1.5 m apart across the long dimension of the test pad. In general, this electrical leak location method detects electrical paths through the liner caused by water or moisture in the leaks.

Leak location testing was performed for each lift thickness after the applied pressures for each dozer operating at 5 km/h and 10 km/h, and while stationary and turning, had been recorded. After all of the leak location tests, no defect was found in the geomembrane, even after dozer operation on a lift thickness of only 0.10 m. Therefore neither the HSD nor the D6H caused a leak in or puncture of the geomembrane during operation on only a 0.10 m thickness of sandy structural fill and LCRL rounded stone. Rarely is a dozer allowed to operate on a geomembrane with a soil cover of only 0.10 m, so using the minimum lift thickness of 0.10 m was deemed representative of a worst-case field scenario.

3. ANALYTICAL ELASTIC SOLUTION

The following theoretical elastic solution will serve as a comparison with the results obtained through this study. 1 The method presented by Giroud (1970) for the distribution of vertical stress increase with depth under a rectangular loaded area on an elastic soil of infinite depth is used in this analysis. For a point under the corner of the loaded rectangular area, the following expression is used:

$$\sigma_z = pK_0 \qquad (1)$$

where σ_z is the normal vertical stress at a given depth (z) from the stress applied at the surface; p is the uniform vertical stress applied at the surface; and K_0 is the depth influence factor (Giroud 1970).

The principle of superposition is used to determine the maximum load that corresponds to the center of the required loaded area, i.e. the average pressure exerted on the surface of the fill by a single dozer track. Using the ground pressures applied by each dozer mentioned previously (HSD applies 40.6 kPa and D6H applies 37.9 kPa of ground pressure) and the equation above, the following theoretical pressures applied on the geomembrane for each height of fill considered are summarized in its respective test section. Even though the HSD dozer applies a larger stress on the surface, thanks to its weight and track contact area, the size and geometry of the track allow a larger reduction in stress with increasing thickness than that computed for the D6H dozer (at 0.30 m lift thickness, the HSD dozer experienced a reduction on stress of 19%, whereas the D6H dozer showed only an 11% reduction of its exerted pressure). At a small fill thickness, the stress reduction is greater with the D6H dozer, but by only 3%. The contribution of adjacent tracks to the calculated ground pressure under a single track was calculated to be negligible.

4. RESULTS

4.1. Soil type

Figure 5 presents the recorded pressures applied under a 0.15 m thick layer of structural fill and a dozer speed of 5 km/h, referred to here as a 'slow' speed. The pressure cells recorded were adjusted/zeroed to account for only the pressure applied by the dozer, and not the overburden stress of the fill material. The maximum pressures applied during this test by the D6H and HSD dozers are indicated by the arrows. As the D6H dozer advances, the pressure along the length of the track is not uniform, and it increases until a maximum pressure is reached. This time lapse includes two separate passes. For the HSD dozer, owing to the smaller track length and the articulated body with two track sets, two distinctly separate surges in pressure are recorded for each dozer pass. The average applied pressure corresponds to the numerical average of maximum pressures measured during the test.

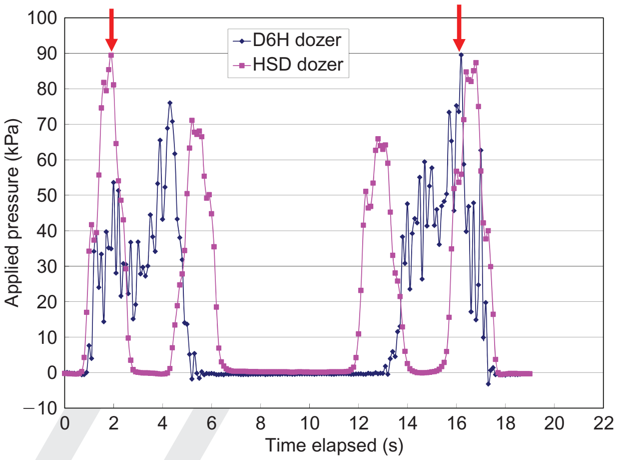

Figure 5. Applied pressures with 0.15 m thick sandy structural fill layer and slow dozer speed during one test. Arrows indicate maximum pressures applied by each dozer

Figure 6 presents the pressures applied under various LCRL thicknesses in the LCRL portion of the test pad. The four graphs shown in Figure 6 correspond to the following.

- HSD average applied pressure.
- HSD maximum pressure applied during test.
- D6H average applied pressure.
- D6H maximum pressure applied during test.

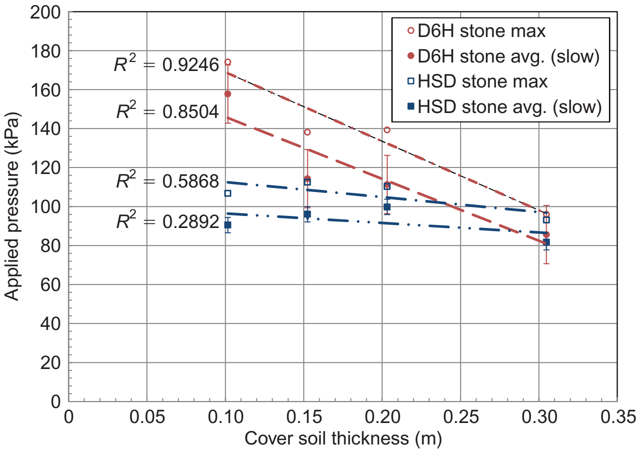

Figure 6. Applied pressures for varying LCRL thicknesses at slow dozer speed

The average applied pressures correspond to the average of the peak recordings obtained during each case. For these readings, the standard deviation of the average is provided. Except for a slightly anomalous reading for an LCRL thickness of 0.15 m, the D6H exhibited a higher average and maximum applied pressure than the HSD. The slightly anomalous reading for an LCRL thickness of 0.15 m is probably due to soil arching of the rounded stone above the pressure cell when a thickness of 0.05 m of rounded stone was removed to reduce the LCRL thickness from 0.20 m to 0.15 m. Soil arching is suspected because the maximum applied pressure decreased from about 160 kPa to about 139 kPa, even though the thickness of rounded stone decreased from 0.20 m to 0.15 m. Of course, it would be expected that the applied pressure would increase as the thickness of rounded stone decreased.

Figure 6 shows that the D6H exhibited a higher average and maximum applied pressure than the HSD. However, at a layer thickness of 0.30 m both dozers exhibit about the same pressures, even though the HSD exhibits a slightly higher ground pressure. Figure 6 also shows that the measured applied pressures exceed the calculated ground pressures for the two dozers (see Table 2). For example, the calculated ground pressure for the HSD is only 40.6 kPa, but the measured maximum applied pressures are around 113 kPa. The D6H exhibits a ground pressure of 37.9 kPa, but the maximum applied pressures range from to 174 kPa to 96 kPa. It is expected that the measured pressures will significantly exceed the calculated ground pressures as well as the theoretical elastic solution for both dozers, because the LCRL consists of rounded stone that applies concentrated point loads to the pressure cell.

Even though the HSD exhibits a higher calculated ground pressure (see Table 2), the lower pressure applied by the HSD is probably due to the rounded pads of the rubber tracks dissipating the applied pressure better than the thin steel grousers on the tracks of the D6H. In other words, the grousers probably force some of the rounded stones to impact on the pressure cell instead of dissipating the applied pressure. The grousers on the D6H are 0.92 m wide, 0.038 m high, and 0.019 m thick.

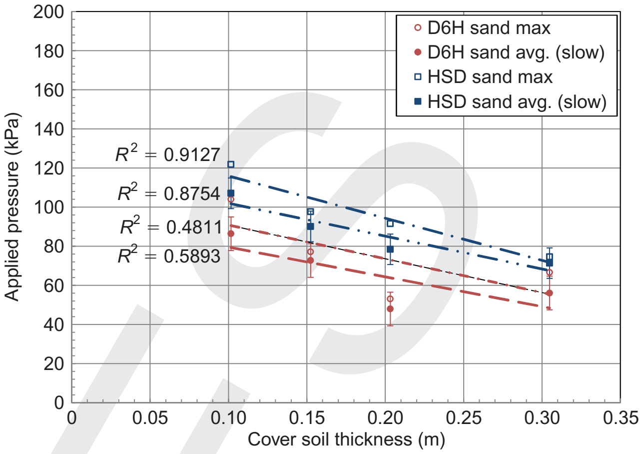

Figure 7. Applied pressures for varying sandy structural fill thicknesses at slow dozer speed

Figure 7 presents the pressures applied under various sandy structural fill thicknesses in the fill portion of the test pad. The measured pressures in Figure 7 show a better-defined trend than in Figure 6 because of the finer nature of the sandy structural fill, which did not result in concentrated point loads being applied to the pressure cells. The data show a logical trend of decreasing applied pressure with increasing structural fill thickness. In general, the applied pressure decreases from about 103 kPa to 69 kPa for layer thicknesses of 0.10–0.30 m. In contrast with the rounded stone, the HSD exhibited a higher pressure than the D6H in the sandy structural fill portion of the test pad.

Comparing Figures 6 and 7 shows that the sandy structural fill transferred a much lower pressure to the geomembrane than the LCRL stone. For example, the maximum pressures transferred by the sandy structural fill range from 86 kPa to 122 kPa at a slow speed of 5 km/h, whereas the maximum pressure exerted by the LCRL exceeds 90–174 kPa. This suggests that equipment ground pressures may be less important when a sandy material is being placed on a geomembrane than for a coarser-grained material.

As successive removal of cover material results in thinner cover above the geomembrane, at the same time this material can be considered more compact due the increased number of passes. However, the compactive

Table 2: Analytical elastic solution for uniformly loaded rectangular area

Fill thickness, z (m)	$2z/l$	K_0	$\sigma_T = 4\sigma_z$ (kPa)	Stress reduction (%)
HSD				
0.30	0.36	0.202	32.7	19%
0.20	0.24	0.228	37.0	9%
0.15	0.18	0.238	38.6	5%
0.10	0.12	0.248	40.3	1%
D6H				
0.30	0.19	0.224	36.3	11%
0.20	0.12	0.233	37.8	7%
0.15	0.09	0.237	38.5	5%
0.10	0.06	0.241	39.2	4%

[a] HSD: $l/2 = 0.84$ m; $b/2 = 0.305$ m; $b/l = 0.364$; $p = 40.6$ kPa.

[b] D6H: $l/2 = 1.64$ m; $b/2 = 0.457$ m; $b/l = 0.279$; $p = 37.9$ kPa.

effort decreased with depth. No discernible trend of increased compaction, i.e. less induced pressure, at the smaller soil thicknesses was evident.

4.2. Operating speed

Figure 8 presents the pressures applied under various LCRL thicknesses in the LCRL portion of the test pad with both dozers operating at a faster speed than the speed used to generate the data in Figure 6 (10 km/h instead of 5 km/h). The measured pressures for the LCRL are similar to those in Figure 6, with another apparently anomalous reading for an LCRL thickness of 0.15 m and the D6H dozer. This also confirms that some soil arching was occurring, because the LCRL was not changed between the slow and fast speed dozer tests, which occurred immediately after one another. Evidence of soil arching is the applied pressure decreasing with decreasing cover soil thickness. The mechanism of soil arching is described by Terzaghi (1943) as the relative movement within a soil mass that is opposed by a shearing resistance with the zone of contact between the yielding and stationary masses of the soil. Because the shearing resistance tends to keep the yielding mass in its original position, the pressure applied by the yielding potion is reduced but the applied pressure to the stationary increases, which is similar to a transfer of loading (Terzaghi 1943).

The D6H dozer exhibited higher average and maximum applied pressures than the HSD for the high speed, as also observed for the slower speed. The D6H pressures applied at a lift thickness of 0.10 m also appear anomalous, and are probably influenced by a stone or stones impacting on the pressure cell, because the pressures are significantly greater than those measured at the slower speed. Again, the pressures at a layer thickness of 0.30 m are similar for both dozers. Thus, at a layer thickness of 0.30 m, the initial difference in calculated ground pressure is negated by the soil thickness.

Comparing Figures 6 and 8 shows that the slower dozer speed exhibited a slightly higher pressure than the faster speed for both dozers for various LCRL thicknesses. For example, the D6H dozer exhibits a maximum pressure that slightly exceeds 172 kPa at a slow speed, whereas the maximum pressure exerted at a fast speed is slightly lower than 172 kPa. The pressures exerted by the HSD at a faster speed are also slightly lower, but still about 103 kPa.

Figure 9 presents the pressures applied under various sandy structural fill thicknesses in the test pad with both dozers operating at 10 km/h instead of 5 km/h, which was used to generate the data in Figure 7. The measured pressures in Figure 9 also show a better-defined trend than in Figure 8 because of the finer nature of the sandy structural fill, i.e. decreasing applied pressure with increasing structural fill thickness. In general, the applied pressure decreases from about 103 kPa to 62 kPa for layer thicknesses of 0.10–0.30 m, which is about the same as for the slow speed on the sandy structural fill (see Figure 7). In contrast to the rounded stone, the HSD and D6H exhibited similar pressures, even though the HSD has a higher calculated ground pressure (see Table 1).

Comparing Figures 7 and 9 shows that the slower dozer speed also exhibited a slightly higher pressure than the faster speed for both dozers for various sandy structural fill thicknesses. For example, the applied pressures range from 117 kPa to 69 kPa for the slow speed, and from 103 kPa to 62 kPa for the fast speed.

4.3. Lift thickness

Figures 5–9 show that, in general, the applied pressure decreases with increasing lift thickness. However, the applied pressure is higher for the LCRL than for the sandy structural fill, but decreases more quickly for the LCRL than for the sandy structural fill. The increase in pressure with decreasing lift thickness can be expressed by the following relationship for the HSD on the sandy structural fill because of the somewhat definable trend of the data:

$$P_{\mathrm{HSD}} = 132 - 201 H_{\mathrm{sand}} \tag{2}$$

where P_{HSD} is the pressure applied on the geomembrane by the HSD (kPa), and H_{sand} is the height of the sandy structural fill (m)

A similar relationship can be developed for the HSD on the LCRL because of the somewhat linear trend of the data:

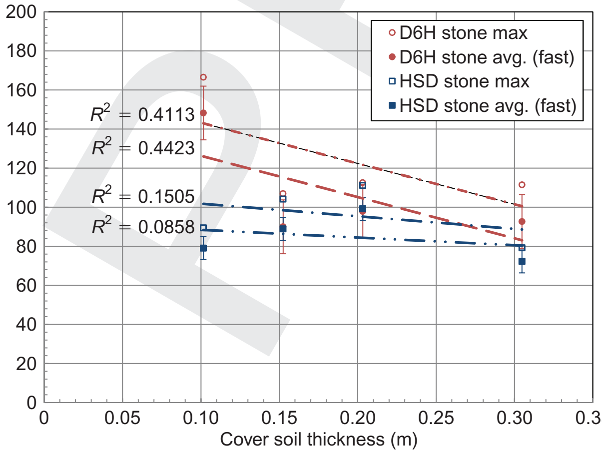

Figure 8. Applied pressures for varying LCRL thicknesses at fast dozer speed

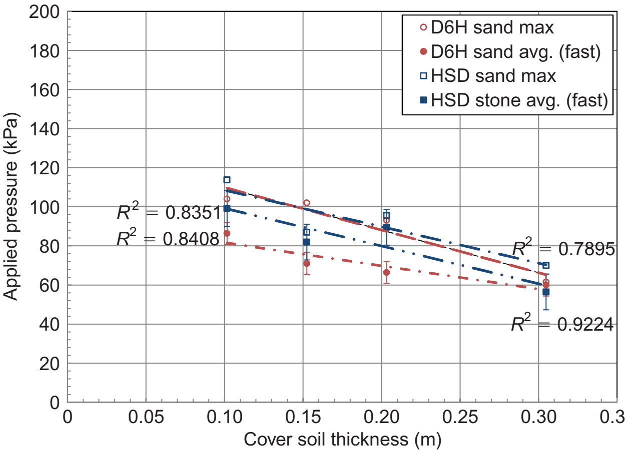

Figure 9. Applied pressures for varying sandy structural fill thicknesses at fast dozer speed

$$P_{\mathrm{HSD}} = 114 - 71\,H_{\mathrm{LCRL}} \quad (3)$$

where H_{LCRL} is the height of the LCRL (m).

These two relationships can be used to estimate the pressure applied by the HSD for sandy and coarse-grained soil layers of varying thickness.

The following relationship was developed for the pressure applied by the D6H on the sandy structural fill, and can be used to estimate the pressure applied by the D6H for a sandy soil layer.

$$P_{\mathrm{D6H}} = 120 - 195\,H_{\mathrm{sand}} \quad (4)$$

where P_{D6H} is the pressure applied on the geomembrane by the D6H (kPa).

A similar relationship can be developed for the D6H dozer on the LCRL because of the somewhat linear trend of the data:

$$P_{\mathrm{D6H}} = 187 - 290\,H_{\mathrm{LCRL}} \quad (5)$$

4.4. Operating activity

This section investigates the pressures applied by the two dozers while stationary above the pressure cells, and while turning above the pressure cells because of the different designs of the two dozers. In particular, the HSD is an articulated dozer with four rubber tracks that incorporate a bogey suspension system for the rollers, whereas the D6H is a monolithic body comprising two steel tracks with fixed rollers. As a result, when the D6H turns it causes more soil disturbance than the HSD. This occurs because of the larger contact area of a single track, i.e. 2.995 m^2 for the D6H dozer compared with 1.022 m^2 for the HSD dozer, as turning will inevitably cause the front and rear ends of the track to skid in opposite directions, even while implementing differential speeds of the two tracks (thus the name ‘skid steer’ for differential steering systems). This is an artifact of the dimensions of the track: the contact area of each D6H track is 293% of the contact area of a single HSD track, whereas the calculated ground pressures of the D6H are only 6.6% smaller than those of the HSD dozer. Therefore it was expected that the HSD would induce lower applied pressures than the D6H, as it would reduce disturbance by minimizing the skidding of the tracks because of the articulating capacity of the body and the reduction in the contact area of individual tracks.

Figures 10 and 11 show the applied pressures for stationary dozers (4–5 min) on rounded stone and sandy structural fill, respectively. The D6H exhibited some anomalous results on rounded stone, whereas the pressures are more consistent and somewhat lower for the HSD at a thickness 0.10 m. However, Figure 10 does show the D6H exerting a significantly higher pressure than the HSD at a thickness of 0.10 m. Otherwise, both dozers exert a pressure of around 80 kPa.

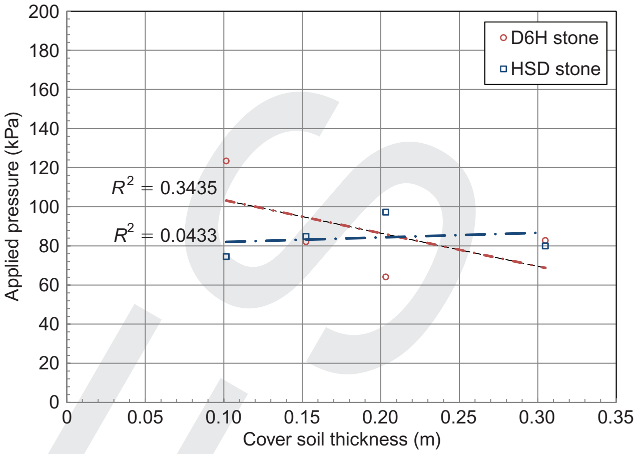

Figure 10. Applied pressures on rounded stone with stationary dozers

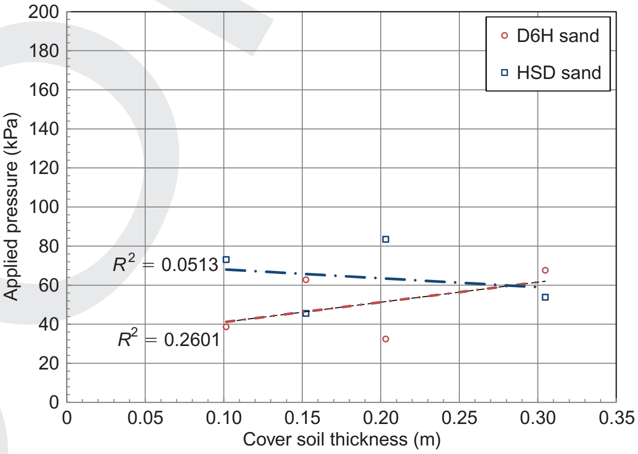

Figure 11. Applied stationary pressures on sandy structural fill

Surprisingly, the results in Figure 11 are more scattered for the sandy structural fill than for the rounded stone which differs from Figures 7 and 9 above, where the dozers were not stationary. The data in Figure 11 are confusing, but indicate that the HSD gives a higher applied pressure for thicknesses of 0.10 m and 0.20 m. The D6H data are suspect in Figure 11, because they suggest that the applied pressure decreases with a thinner cover soil thickness.

Figures 12 and 13 show the applied pressures for the two dozers turning over the pressure cells on rounded stone and sandy structural fill, respectively. Prior to this

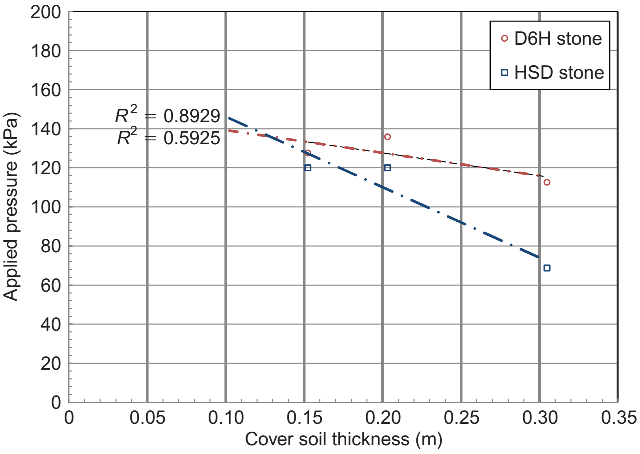

Figure 12. Applied pressures on round stone while dozers are turning

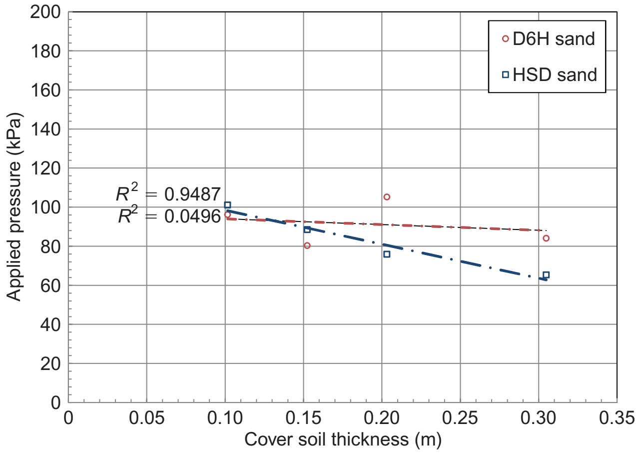

Figure 13. Applied pressures on sandy structural while dozers are turning

testing, the cells were located using GPS equipment, and the top of the sandy structural fill and rounded stone were spray-painted so that the dozer operator knew where to execute the turns to coincide with the pressure cells. Review of Figures 12 and 13 shows that testing was not conducted at a layer thickness of 0.10 m for the rounded stone as shown above, because it was anticipated that the turning operation on only 0.10 m of stone cover might damage the pressure cells. Geokon, manufacturer of the pressure cells, recommends a minimum cover thickness of 0.10 m to prevent or minimize damage to the cells.

Figure 12 shows that the D6H again exhibited higher applied pressures than the HSD, because it is expected that the reading at 0.15 m is probably due to soil arching. This reading was assumed anomalous because the applied pressure should increase with decreasing cover soil thickness, as observed at other D6H thicknesses, and for the HSD. Comparison of Figures 10 and 12 shows that turning above the pressure cell resulted in an increase in applied pressure of about 34 kPa over the stationary pressures.

Figure 13 also shows that the D6H again exhibited higher applied pressures than the HSD for turning on the sandy structural fill. However, two anomalous readings were obtained for the D6H at 0.10 m and 0.15 m, which is unexpected, because soil arching was not exhibited previously for the sandy structural fill. In general, the applied pressure should increase with decreasing layer thickness. The inconsistent nature of some of the data trends indicates some of the difficulties in measuring pressures applied by operating equipment. Finally, comparison of Figures 11 and 13 shows that turning above the pressure cell resulted in an increase in applied pressure of about 21–28 kPa over the stationary pressures on the sandy structural fill.

4.5. Equipment type and applied ground pressure

One of the objectives of the test pad was to compare the pressures applied by the D6H and HSD dozers to facilitate introduction of the HSD to landfill operations, because the D6H is widely viewed as an acceptable low-ground-pressure dozer for landfill operations. The D6H exhibited higher pressures than the HSD for the LCRL, even though the calculated ground pressure is higher (see Table 1), but similar pressures for the sandy structural fill (see Figures 3–9). The pressure applied by the D6H ranges from 172 kPa to 96 kPa, whereas the HSD applied pressures of 103–90 kPa for the LCRL. On the sandy structural fill portion both dozers exhibited similar pressures, in the range of 103–69 kPa.

Another conclusion from these data is that the HSD exhibited similar applied pressures, regardless of whether LCRL or sandy structural fill was being compacted. Thus the rounded pads of the rubber tracks appear to dissipate the applied pressure, regardless of the material being placed. In addition, the HSD did not exhibit a large decrease in applied pressure with increasing cover thickness as the D6H did, which suggests that the HSD can be used on thinner cover thicknesses than the D6H, even though it exhibits a slightly higher calculated ground pressure (see Table 1).

5. CONCLUSIONS

Figures 4–13 present the results obtained from the tests performed on both the sandy structural fill and LCRL materials. In general, the results show increased pressure with decreasing soil layer thickness, decreasing speed, and turning over the pressure cells. The data can be used to estimate the minimum layer thickness to limit the applied pressure to a tolerable value, e.g. 41 kPa, and prevent geomembrane damage or puncture. The pressure trends in these figures are not perfectly clear, which probably reflects the different soil types used above the geomembrane. However, the data are sufficient to achieve the main objectives of the study.

This technical paper presents the results of a test pad at an operating municipal solid waste landfill used to measure the pressures applied to the primary geomembrane in a double composite liner system. This is important to avoid puncturing or weakening of the geomembrane liner by equipment operating on top of the liner system. The applied pressures measured for the varying thicknesses of sandy structural fill and rounded stone were used to develop the following observations or conclusions.

- Pressures applied to the geomembrane are greater than calculated ground pressures and theoretical elastic solutions.
- Neither the HSD nor the D6H caused a leak or puncture of the geomembrane during operation on only a 0.10 m (4 in) thickness of sandy structural fill and LCRL rounded stone.
- The D6H exhibited a higher average and maximum applied pressure than the HSD for the rounded stone and similar pressure for the sandy structural fill, even though it has a lower calculated ground pressure.
- The HSD exhibits a higher calculated ground pressure (see Table 1), so the lower pressure applied by the HSD is probably due to the rounded pads of the rubber tracks dissipating the applied pressure

better than the thin steel grousers on the tracks of the D6H, especially for the LCRL rounded stone.
- The applied pressures exceed the calculated ground pressure by a factor of 2 to 5, depending on the layer thickness and material type.
- Pressures applied under various sandy structural fill thicknesses show a better-defined trend and lower applied pressure than the rounded stone. This suggests that equipment ground pressures may be less important when a sandy material is being placed on a geomembrane than on a coarser material.
- Faster dozer speed (10 km/h) generally induces a lower applied pressure than a slower dozer speed (5 km/h).
- Turning usually induces a higher applied pressure than stationary equipment.
- Mathematical relationships were developed to express the increase in pressure with decreasing lift thickness for the sandy structural fill and rounded stone, and for the two dozers tested.

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ABBREVIATIONS 3

D6H	Caterpillar D6H Low Ground Pressure Dozer
HDPE	high-density polyethylene
HSD	John Deere 764 High-Speed Dozer
LCRL	leachate collection and removal layer
LDL	leak detection layer

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