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Evaluation of a buried vertical well leachate recirculation system for municipal solid waste landfills

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Abstract

Vertical liquids addition systems have been used at municipal landfills as a leachate management method and to enhance biostabilization of waste. Drawbacks of these systems include a limitation on pressurized injection and the occurrence of seepage. A novel vertical well system that employed buried wells constructed below a lift of compacted waste was operated for 153 days at a landfill in Florida, USA. The system included 54 wells installed in six clusters of nine wells connected with a horizontally-oriented manifold system. A cumulative volume of 8430 m^3 of leachate was added intermittently into the well clusters over the duration of the project with no incidence of surface seeps. Achievable average flow rates ranged from 9.3×10^{-4} m^3 s^{-1} to 14.2×10^{-4} m^3 s^{-1}, which was similar to or greater than flow rates achieved in a previous study using traditional vertical wells at the same landfill site. The results demonstrated that pressurized liquids addition in vertical wells at municipal solid waste landfills can be achieved while avoiding typical operational and maintenance issues associated with seeps.

Keywords

Landfill, solid waste, leachate, vertical well, recirculation, seeps

Introduction

A variety of techniques can be employed to introduce liquids into landfilled municipal solid waste (MSW), which is a practice that can have a host of benefits including low-cost leachate disposal, more rapid stabilization of waste compared to landfills that do not recirculate liquids, and reduced leachate strength (Townsend et al., 2015). A commonly-employed liquids addition method is the use of constructed vertical wells within the waste mass (Benson et al., 2007; Jain et al., 2005a; Kadambala et al., 2011; Khire and Mukherjee, 2007). Previous investigations using vertical wells that terminate above the waste surface have shown that while substantial volumes of liquid can be added over time, these wells require a great deal of operation and maintenance (Jain et al., 2005a). Observed issues have included (i) surface seeps around the injection wells when liquids are added at a hydrostatic head above the surface of the landfill, (ii) air intrusion into the gas collection system when large numbers of vertical wells penetrate the surface, thus reducing gas collection system efficiency, and (iii) differential settlement in the vicinity of the wells (Jain et al., 2014).

This paper reports results of research conducted at the New River Regional Landfill (NRRL) in Union County, Florida, where an area of the site was retrofitted with vertical wells that employed a novel design and construction method. The system consisted of vertical wells that were covered with a layer of compacted MSW so that liquids could be added to the vertical wells via a horizontally-connected manifold under pressure without concern of surface seeps, and so that wells could accommodate anticipated settlement (see Supplementary Figure S-1 online for a conceptual view). The performance of the system in terms of achievable flow rates and pressures as a function of depth are presented and compared to results obtained in previous studies (Jain et al., 2010).

Material and methods

Site description

The landfill site consists of six lined landfill cells (Cells 1–6) with mixed MSW, construction and demolition debris, and commercial waste totaling more than 30 ha – a more detailed

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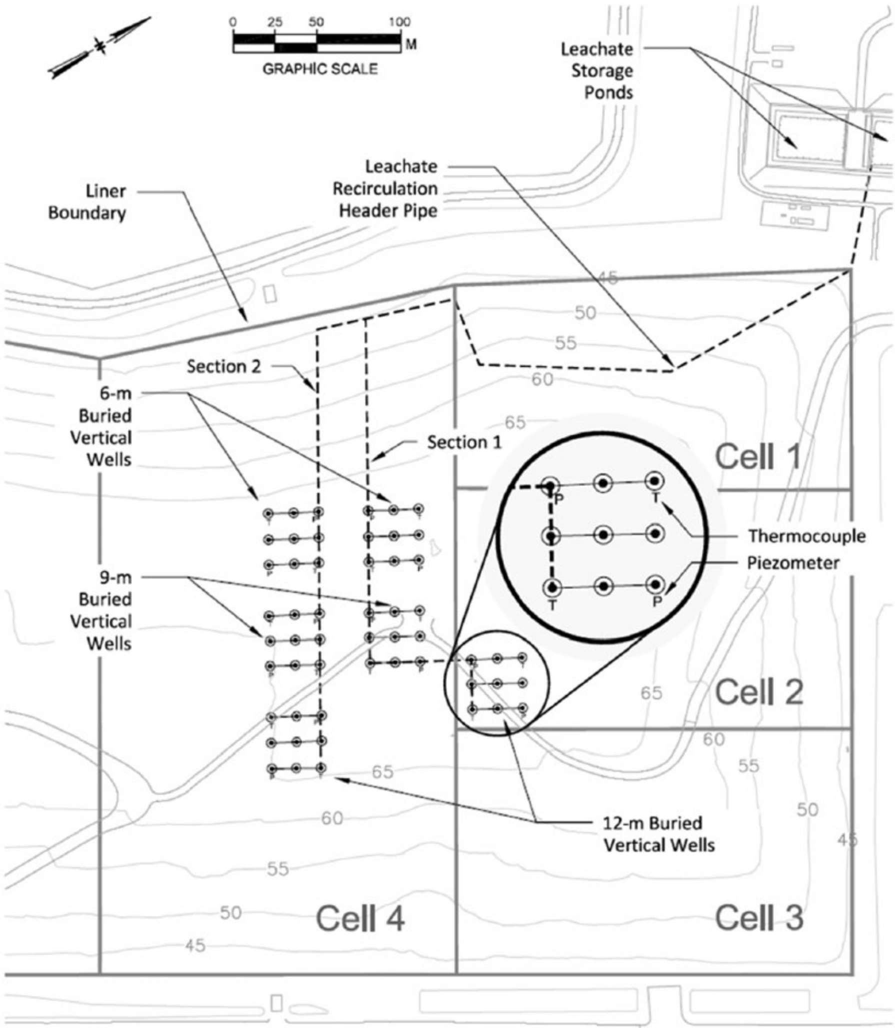

Figure 1. Plan view of the buried vertical well clusters in Cell 4 and part of Cell 2 at the experimental site.

description of the site is presented elsewhere (Jain et al., 2005b). The buried vertical well system was built in Cell 4 and part of Cell 2 as shown in Figure 1, which are approximately 7.8 and 3.6 ha, respectively. Both cells were built with a double bottom liner system (i.e. a primary liner system underlain by a leak detection system, underlain by another liner) with independently-plumbed leachate collection systems. The average depth of waste in the experimental area was approximately 21 m and the in-place density of the landfilled waste was approximated to be 710 kg m^{-3}. A clayey-sandy soil mined onsite was used as daily cover. The maximum daily leachate addition volume in Cell 4 and Cell 2, which was established during site permitting with the state (Florida) based on a criterion to limit liquid head on the bottom liner to less than 0.3 m, was 122 m^3 and 132.6 m^3, respectively.

Concept of buried vertical well clusters

Clusters of buried vertical wells were designed with several objectives in mind. First, it was hypothesized that leachate or other liquids could be added at pressures greater than the length of the well without causing visible surface seepage, owing to the presence of the overlying waste layer. Adding liquid at greater pressures would thus enable a larger amount of liquid to be added in a short time compared to only relying upon gravity to distribute liquids into the landfill. Second, the termination of the wells beneath the surface and subsequent tie-in to a horizontal manifold would further decrease the likelihood of seepage issues because of the reduction in surface penetrations (compared to vertical wells that terminate above the landfill surface). Third, an identified advantage of this construction method included the opportunity to add more waste on top, thus providing more operator flexibility by avoiding the need to vertically extend wells or otherwise work around a series of surface penetrations.

Experimental setup and construction

The experimental setup consisted of six clusters of buried vertical wells located 30 m apart, except for one cluster that was located 23 m away from the adjacent cluster, as shown in Figure 1. The six clusters were grouped into two sections (Section I and Section II). Each section had three clusters with depths of 6, 9, and 12 m, respectively, as shown in Figure 2. Each cluster had nine vertical wells spaced 15 m apart, which were all connected to a single lateral leachate recirculation line via a high density

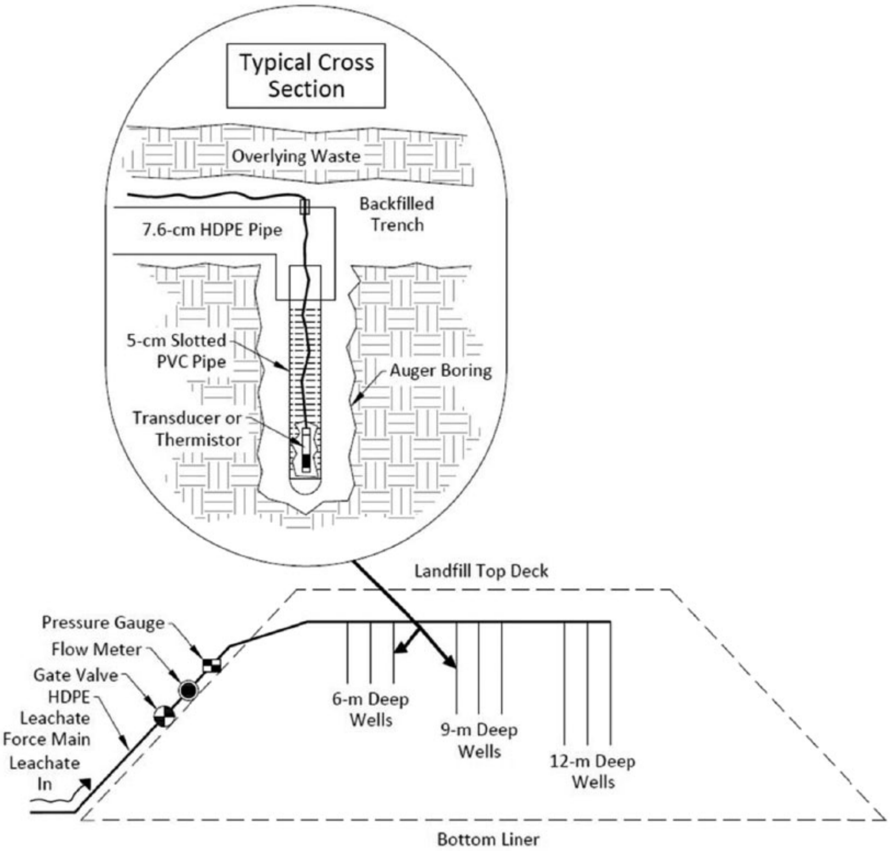

Figure 2. Cross-section view of the buried vertical well clusters in Cell 4 at the experimental site.

polyethylene (HDPE) pipe manifold system. These six lateral leachate recirculation lines extended to the side slope (which was three horizontal to one vertical) of the landfill and were connected to the main leachate recirculation system of the landfill, as shown in Figure 1. The first well in a cluster is defined as the well closest to the lateral leachate recirculation line; the last well in a cluster is defined as the well farthest from the lateral leachate recirculation line.

Two vibrating wire (VW) piezometers (Model 4500 S, Geokon Inc.) placed on the bottom of the first and last well (Figure 1) were used to measure the pressure and temperature of the leachate injected into the buried vertical well clusters. Two T-type thermocouple wires (PVC/PVC Ripcord, Type T, # 24 AWG, Nanmac Corporation) placed on the bottom of two other wells (Figure 1) were used to measure temperature in different locations of the cluster. A total of 12 VW piezometers and 12 thermocouple wires were connected from the well clusters to a Campbell Scientific (CR10X) data logger using two multiplexers. Multilogger software (Canary system) was used to program the CR10X data logger to measure and record data at regular intervals. The frequency of data collection was initially set at every hour and was then reset to every 10 minutes just before leachate was recirculated in the clusters for the first time. The multilogger software converted the pressure measured in digits into units of pressure by using the equations provided in the unit's calibration sheets.

A pressure transducer, pressure gauge, flow meter, and globe valve were attached to the six lateral leachate recirculation lines on the side slope of the landfill (Figure 2). The leachate injection pressure was measured using a 0–20 mA pressure transducer (GE Druck Inc., Connecticut, USA) and read using a loop calibrator (UPS II, GE Druck Inc.). A 0–30 lbf/in^2 (0–0.21 MPa) Omega pressure gauge was also used to monitor leachate injection pressure. The flow rate and cumulative volume of leachate injected in the clusters were measured using SeaMetrics IP80 flowmeters (Controls Warehouse, Ocala, FL). Globe valves were used to control the flow rate of leachate injected in each cluster.

Construction of the experimental setup began in mid-2006. The clusters were installed inside a 0.75–1 m deep trench using a hydraulic excavator (Caterpillar 385C L Series). A solid-stem open-flight auger with a diameter of 11.5 cm attached to the drilling rig was used to drill the boreholes. A 7.6 cm diameter HDPE pipe was inserted inside the well temporarily after drilling to avoid collapse of the borehole. Thereafter, a 5 cm diameter slotted PVC pipe was inserted into the borehole through the HDPE pipe. A cap was placed on the HDPE pipe and the drilling rig was moved to the next well location until all the wells in a cluster were drilled. A manifold assembly was fabricated to connect all the wells in a cluster to a lateral leachate injection line using 7.6 cm diameter standard dimension ratio (SDR) 17 HDPE pipes. The temporary pipes were then removed from the wells and their respective

Table 1. Field injection test results of buried vertical well clusters.

Section	Depth of well cluster (m)	Screen length (m)	Total volume of leachate added (m^3)	Total hours of operation (h)	Average flow rate (× 10^{-4} m^3 s^{-1})	Average leachate injection pressure (m)	Average hydrostatic head at the bottom of the first vertical well in a cluster (m)
I	12	10.7	2389.39	960	6.91	6.13 ± 3.1	7.33 ± 4.69
I	9	7.6	2295.1	957	6.66	6.13 ± 3.4	6.01 ± 4.93
I	6	4.6	1806.44	802	6.26	6.39 ± 4.2	4.94 ± 3.69
II	12	10.7	1462.35	556	7.31	7.54 ± 3.15	2.79 ± 2.28
II	9	7.6	362.404	101	9.97	1.58 ± 3.75	-[a]
II	6	4.6	115.326	147	2.18	5.2 ± 3.5	1.68 ± 1.28

[a]Leakage of leachate along the lateral line precluded substantial pressure measurements, thus no data are reported here.

manifold assemblies were placed inside the wells. The manifold assembly extended 1.4 m deep in all the vertical wells. The screen lengths of the 6, 9, and 12 m deep wells were 4.6, 7.6, and 10.7 m, respectively. These manifold assemblies were connected to the lateral leachate recirculation line (SDR-17 HDPE, 7.6 cm diameter), which extended to the side slope of the landfill. This lateral leachate recirculation line was then connected to the main leachate recirculation system of the landfill using a fixed flow rate pump.

The VW piezometers and thermocouple wires were placed inside the bottom of the vertical wells by drilling a 2.5 cm hole on top of the vertical well manifold assembly. The VW piezometers and the thermocouple wires were then dropped through the hole in their respective wells until they reached the bottom of the well. The hole was then plugged using an epoxy resin. The VW piezometer and thermocouple wires were extended all the way to the side slope of the landfill and connected to the data logger. Once construction was complete, one additional 3 m thick lift of waste was placed on top of the clusters and compacted using the landfill's waste handling equipment.

System operation and monitoring

Leachate was recirculated in each of the six clusters over a period of 153 days. The leachate recirculated came from leachate generated from all cells, and on a very limited basis (<10% of all injected liquid volume) groundwater was used for supplemental liquids addition when an insufficient quantity of leachate was available. Leachate recirculation and associated monitoring occurred for the first 105 days during the operating hours of the facility (8:00 a.m. to 5:00 p.m.). Following this initial period, the system transitioned to nearly continuous operation (24 hours per day, seven days per week with the exception of occasional cessation of operation for maintenance) for the remaining 48 days. The data logger was programmed to record leachate injection pressure using the 12 VW piezometers and temperature from the 12 thermocouples continuously. The time of operation, cumulative flow rate, flow rate, and leachate recirculation pressure were recorded manually every hour during operating hours for each of the six clusters during the entire leachate recirculation period.

The leachate injection pressure was calculated by subtracting the pressure due to the elevation difference between the top of a vertical well in a cluster and its corresponding pressure gauge in the lateral leachate line and the frictional loss due to pipe flow. A total of 80–120 m^3 of leachate was added per day in each of the clusters. The leachate injection pressures were maintained at 4–8 m of water column. The flow rates were maintained at 3×10^{-4} m^3 s^{-1} to 9×10^{-4} m^3 s^{-1} per cluster to avoid exceeding the permitted leachate injection limit.

Results and discussion

Overall performance

A cumulative volume of 8431 m^3 of leachate was recirculated over a period of 153 days. Table 1 shows the well depth, screen length, cumulative volume of leachate injected, total hours of operation, average flow rate, average leachate injection pressure, and average hydrostatic head at the bottom of the first well in all six clusters. A total of 1400–2300 m^3 of leachate was added per cluster in four clusters. However, only 115 and 362 m^3 of leachate was added in the remaining two clusters. Impacts potentially caused by waste heterogeneity or potential kinking of pipe were observed in the 6 m deep cluster well in Section II, which achieved an average flow rate that was 65% less than the 6 m deep cluster well in Section I even though the operating pressures of both cluster wells was effectively the same. In addition, leakage in the lateral recirculation line was observed in the 9 m deep cluster in Section II – likely attributable to an opening at pipe joints – as soon as leachate injection was started, which necessitated shutdown of this cluster. Limited leakage was also observed at the 6 m and 12 m depth wells, which necessitated occasional shutdown and thus reduced operational time as shown in Table 1.

The results shown in Table 1 indicate that the leachate recirculated in the clusters of Section I had an average flow rate of 6.26 to 6.91×10^{-4} m^3 s^{-1} at a lateral injection pressure of 6.13–6.39 m. The average flow rates of recirculated leachate increased slightly with the depth of the clusters at a similar operating pressure. The surface of Cell 4 was frequently monitored for seeps – no seeps were observed on the landfill surface or the side slope during the recirculation period; however, the lateral leachate

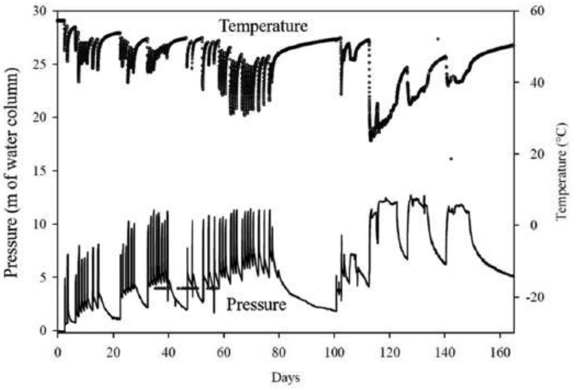

Figure 3. Change in pressure and temperature at the bottom of the first vertical well of a 6 m deep vertical well cluster over time.

recirculation lines on the side slope of the landfill occasionally showed minor leakage at pipe joints during the operational period. This was attributed to the relatively thin wall of the HDPE pipe that was used. The surface of Cell 2 was not monitored as rigorously as Cell 4 since Cell 2 had an exposed geomembrane cap, but occasional inspections suggested that limited or no seepage was occurring in this area.

Three out of 12 thermocouples and eight out of 12 VW piezometers that were placed in the cluster and buried in the landfill showed evidence of sensor failure, which was attributed to the choice to bury the sensors directly in the waste without any protective covering. This phenomenon has been observed previously with sensors placed in situ at MSW landfills (Jonnalagadda et al., 2010; Kadambala et al., 2011; Kumar et al., 2009; Larson et al., 2012).

Performance of a typical buried vertical well cluster

A 6 m deep cluster from Section I was chosen to illustrate the performance of a typical buried vertical well cluster. A cumulative volume of 1806 m^3 of leachate was added during 802 hours of intermittent leachate injection over 153 days (Table 1). The average flow rate of leachate recirculated in this cluster was 6.26 $\times 10^{-4}$ m^3 s^{-1} at an average leachate injection pressure of 6.39 m.

Figure 3 presents the change in hydrostatic head and temperature at the bottom of the first vertical well of a 6 m deep vertical well cluster over time. The results show that the leachate injection pressure increased sharply following initiation of recirculation and was maintained at a level equal to or greater than the screen length for the duration of operation (see Supplementary Figure S-2 online for more detail on the initial pressure and temperature following initiation of recirculation).

Figure 4 presents the change in hydrostatic head in the first and last vertical wells of the cluster during leachate recirculation over time. The results indicate that the pressure in the last well was significantly lower than in the first well. Moreover, the liquid level in the last well was less than the length of screen for the first 125 days of operation. This suggests that greater leachate injection pressures were achieved in wells closer to the leachate

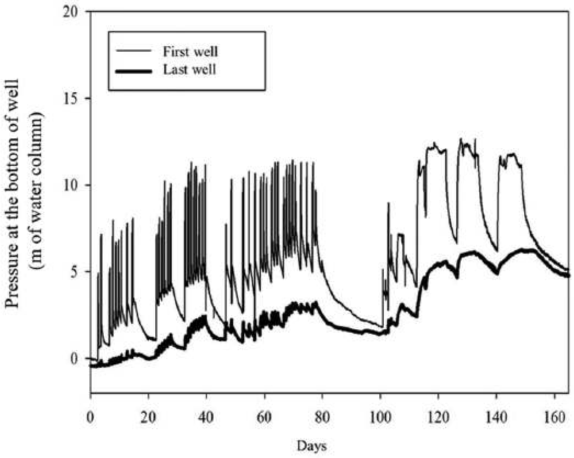

Figure 4. Change in pressure at the bottom of the first and last vertical wells in a 6 m deep vertical well cluster due to the leachate recirculation over time.

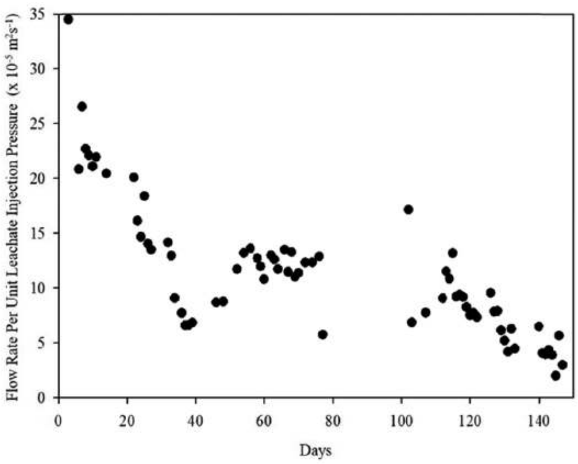

Figure 5. Change in flow rate per unit leachate injection pressure over time.

recirculation header line, and that the influence of landfill gas pressure may have initially limited the ability to inject leachate at higher pressures in wells more distant from the leachate recirculation header line. Additionally, not all of the screen length in the individual vertical wells might have been utilized during the initial operation period.

Figure 5 presents the change in flow rate per unit of leachate injection pressure head over time. The figure shows a decrease in the flow rate over time – this was attributed to a reduction in the hydraulic gradient as more liquids were added. As more liquid is added, the zone surrounding the well is impacted by liquids addition increases, thus increasing the flow path length that leachate must travel.

Comparison of two buried vertical well clusters constructed at the same depth

The operational data for vertical well clusters at the 12 m depth from Section I and Section II were compared to assess respective performance. Leachate was recirculated intermittently over 80 days in both of the clusters and operated at a similar leachate injection pressure of 6–7 m. A total of 1100 m^3 (average flow rate 14.8×10^{-4} m^3 s^{-1}) of leachate was added in the Section I cluster, while 730 m^3 (average flow rate 8.6×10^{-4} m^3 s^{-1}) of leachate was added in the Section II cluster. Figure 6 presents the change in flow rate of leachate added at various leachate injection pressures between 12 m deep clusters of Section I and Section II. The lower achievable flow rate in the Section II clusters was likely caused by pipe deformation from the overburden and compaction of waste on top of the lateral pipe.

Impact of well depth on the performance of the vertical well clusters

Vertical well clusters of different depths were compared to assess the impact of depth on the performance of clusters. Three Section I clusters of different depths were compared after injecting 1000 m^3 of leachate to examine the achievable flow rate for each cluster depth. Table 2 provides the well depths, screen length, hours of operation, average flow rate, average leachate injection pressure, and flow rates per unit screen length for the clusters. The average flow rate varied substantially from 9.3×10^{-4} to 14.2×10^{-4} m^3 s^{-1} with a clear difference in flow rate between the 6 m and 9 m depth wells; however, no substantial difference was observed when comparing the 9 m and 12 m depth clusters. This result suggests that the additional screen length allowed the 9 m deep clusters to achieve higher flow rates, but lower permeability of waste in the deeper sections of waste likely prevented significant additional liquid to be added at the 12 m depth. Jain et al. (2005b, 2006) observed substantially lower permeability in deeper waste sections due to waste overburden, presence of liquid, and presence of landfill gas.

Leachate was injected at various pressures, and the corresponding flow rate was measured to understand the impact of depth on the performance of the clusters in detail. Figure 7 indicates that the flow rates of injected leachate did not vary significantly with the well depth of the clusters at various leachate injection pressures. For example, at a leachate injection pressure of 5 m, the flow rates were 10.5×10^{-4} and 11.5×10^{-4} m^3 s^{-1} for 6 m and 12 m deep vertical well clusters, respectively. This can be attributed to the wells not yet reaching steady state flow conditions.

Comparison of field test results of buried vertical wells with conventional vertical wells

Table 3 presents the field test results of the buried vertical well clusters compared to the field test results of conventional vertical wells operated at the same site (Jain et al., 2005a). The average leachate flow rate per unit screen length of the clusters was almost the same or greater compared to the conventional vertical wells. The flow rate per unit screen length of the clusters was lower than the 6 m deep vertical well but higher than the 16.2 m and 18 m deep vertical wells. The higher flow rate

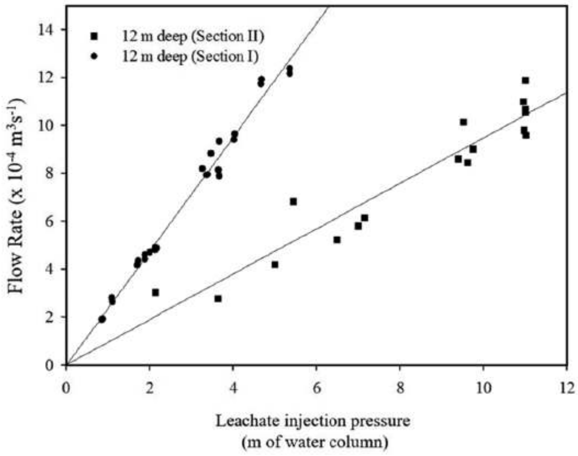

Figure 6. Change in flow rate of leachate added at various leachate injection pressures (in m of water column (w.c.)) between 12 m deep vertical well clusters of Section I and Section II.

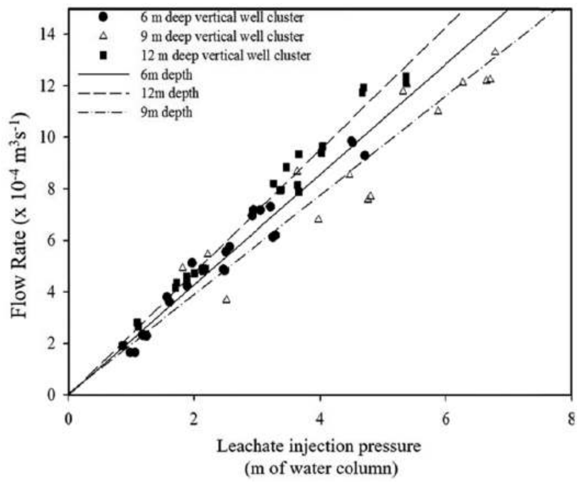

Figure 7. Change in flow rate at various leachate injection pressures in 6, 9, and 12 m deep vertical well clusters.

Table 2. Comparison of field test results of buried vertical well clusters with different depths.

Type of vertical well	Well depth (m)	Screen length (m)	Total volume injected (m^3)	Time of injection (h)	Average flow rate ($\times 10^{-4}$ m^3 s^{-1})	Average leachate injection pressure (m)	Flow rate per unit screen length ($\times 10^{-5}$ m^3 s^{-1} m^{-2})
Vertical well cluster	6	4.6	1068.7	317.9	9.3	6.39 ± 4.2	2.2
Vertical well cluster	9	7.6	1051.9	205.7	14.2	6.13 ± 3.4	2.1
Vertical well cluster	12	10.7	1022.7	186.7	15.2	6.13 ± 3.1	1.6

Table 3. Comparison of field test results of conventional vertical wells (Jain et al., 2010) and buried vertical well clusters (this study).

Type of vertical well	Well depth from surface of the landfill (m)	Screen length (m)	Total volume injected (m^3)	Time of injection (h)	Average flow rate per vertical well ($\times 10^{-4}$ m^3 s^{-1})	Flow rate per unit screen length ($\times 10^{-5}$ m^2 s^{-1})
Conventional vertical well	6.1	3.05	118	313	1.0	3.3
	16.2	6.1	151	364	1.1	1.8
	18	6.1	97	364	0.7	1.1
Buried vertical well cluster	11	4.6	1068.7	317.9	1.0	2.2
	14	7.6	1051.9	205.7	1.6	2.1
	17	10.7	1022.7	186.7	1.7	1.6

in the 6 m deep vertical well might be due to the lower permeability of waste in the shallow sections of the landfill. Additionally, not all of the screen length in the individual vertical wells of the cluster might have been utilized during the initial period of leachate recirculation.

Conclusion

A cumulative volume of 8431 m^3 of leachate was recirculated intermittently into buried vertical well clusters for 153 days without causing any surface seeps on the landfill. Five of the six buried vertical well clusters had comparable performance to one another, while one of the clusters indicated pipe failure within the waste mass that prevented the recirculation at higher flow rates. The average flow rate ranged from 9.3×10^{-4} to 14.2×10^{-4} m^3 s^{-1}, with higher flow rates achieved in the 9 m deep clusters compared to the 6 m deep clusters but similar achievable flow rates were observed in the 9 m deep and 12 m deep clusters. Operation at these pressures showed that the full utilization of the entire screen length was not achieved until approximately 100 days of leachate recirculation, which was attributed to the presence of landfill gas within the well system – eventually; leachate was evenly distributed into all wells.

The average leachate flow rate per unit screen length of the buried vertical well clusters was almost the same or higher compared to conventional vertical wells (Jain et al., 2010) but without surface seeps. The construction cost and time for the buried system is expected to be comparable to conventional vertical wells because drilling and vertical pipe and backfill material costs (likely the most expensive element) are the same for equivalent constructed depths. Limited operational issues were observed (e.g., pipe deformation and minor leaks at joints) which was primarily attributed to the use of a thinner-walled HDPE lateral pipe. The employment of a thicker-walled pipe (e.g., SDR 11) in future designs would reduce differential movement on the surface and thus reduce the likelihood of leakage.

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