

Geoenvironmental Engineering

GSP 374

Honoring Rudolph Bonaparte

Selected Papers from Geo-EnvironMeet 2025
Louisville, Kentucky • March 2–5, 2025

EDITED BY

Susan E. Burns, Ph.D., P.E.
Dimitrios Zekkos, Ph.D., P.E.
Shaivan Shivaprakash, Ph.D.

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GEOENVIRONMENTAL ENGINEERING

HONORING RUDOLPH BONAPARTE

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The Geo-Institute
of the American Society of Civil Engineers

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Preface

This ASCE Geotechnical Special Publication (GSP) 374 has been prepared to honor Rudolph (Rudy) Bonaparte, Ph.D., P.E., F.ASCE, BC.GE, NAE in recognition of his outstanding contributions to the fields of geoenvironmental and geotechnical engineering. The publication follows the Special Session: *Honoring GeoLegend Rudy Bonaparte* held at the ASCE Geo-Institute Geotechnical Frontiers Conference in Louisville, KY, March 2025, which we co-organized with Dr. Beth Gross.

Dr. Bonaparte's visionary leadership in the field of geoenvironmental and geotechnical engineering has an enduring legacy in both research and practice, where he has been influential across a range of areas; most notably, the development of design guidelines for modern waste containment facilities. Throughout his career, Dr. Bonaparte has combined state of the art theory with the needs of practicing engineers to create and extend innovative solutions to the containment of a variety of challenging waste materials. His boundless energy has resulted in contributions to our field that are not only technical in nature but also have substantial personal impact. In addition to his technical skills, Dr. Bonaparte is renowned for his skills as a mentor and team builder, as he guided countless engineers and colleagues over the course of his career. We have benefited from his skills as friend and advisor, from his early days and continuing impact at UC Berkeley to his time as a leader in the consulting engineering community in Atlanta to the later stages of his career, where Dr. Bonaparte served as a popular Professor of the Practice at Georgia Tech, impacting students who studied Global Engineering Leadership. This GSP includes 15 invited papers by authors from both academia and geotechnical / geoenvironmental practice on topics that span the range of Dr. Bonaparte's professional contributions. These papers cover landfill design and construction, landfill monitoring including settlement and emissions (thermal, liquid, and gas), waste and waste containment, as well as topics of interest to geotechnical engineering practice.

As colleagues of Dr. Bonaparte, we are grateful for this opportunity to collaborate with him and express our gratitude for his exceptional contributions to our field. He is truly a GeoLegend, and we are inspired by his example of dedication to the highest standards of professionalism, his pioneering contributions in the field of waste containment, and his genuine warmth and good nature.

Susan Burns and Dimitrios Zekkos, 2025

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Acknowledgments

Rudolph Bonaparte, Ph.D., P.E., F.ASCE, BC.GE, NAE

Dr. Bonaparte received his B.S. degree in Civil Engineering from the University of Texas at Austin (1977), and M.S. (1978) and Ph.D. (1981) degrees in Geotechnical Engineering from the University of California, Berkeley where he was a National Science Foundation (NSF) Graduate Research Fellow. For the past 40 years, he has been with the firm Geosyntec Consultants, a firm that grew under his leadership from a handful of employees to thousands of employees worldwide. Amongst his professional contributions in his areas of research and practice, he was the lead author on five major U.S. Environmental Protection Agency (EPA) guidance and technical resource documents, with reports in the 1980s helping to establish the technical basis for the double-liner system requirements in EPA hazardous waste landfill and surface impoundment regulations contained in 40 CFR §264 and §265, and for the single-composite liner requirements for municipal solid waste (MSW) landfill contained in 40 CFR §258. In the 2000s, working with Professors David Daniel and Bob Koerner, and several Geosyntec colleagues, Dr. Bonaparte was lead author of the major EPA technical resource reports *Assessment and Recommendations for Improving the Performance of Waste Containment Systems* (2002) and *Technical Guidance for RCRA/CERCLA Final Cover Systems* (2004). In addition to these EPA reports, he is the author or co-author of more than 75 peer-reviewed technical papers, including the paper resulting from his 2018 ASCE Karl Terzaghi Lecture *Geotechnical Stability of Waste Fills – Lessons Learned and Continuing Challenges*. As a design engineer, Dr. Bonaparte has led major projects around the country involving MSW, hazardous waste, low-level radioactive waste, and coal combustion residual (CCR) landfills and surface impoundments. He has also worked on the remediation design of more than 15 EPA-designated contaminated Superfund sites and several EPA-designated contaminated waterway sediment mega-sites. For his accomplishments and contributions as a practicing professional, he was awarded the ASCE OPAL Lifetime Achievement Award in Design (2016) and the Georgia Society of Professional Engineers Lifetime Achievement in Engineering Award (2019). He was elected to the U.S. National Academy of Engineering (NAE) in 2007. He is also a recipient of the ASCE James R. Croes Medal and the International Geosynthetics Society IGS Award (1994). In 2021, he was selected by the ASCE Geo-Institute (GI) as a "GeoLegend." He has given dozens of invited lectures to universities, ASCE sections, and others. Between 2022-2024 he served (along with Jim Mitchell and Craig Benson) on the Blue-Ribbon Peer Review Panel for the ASCE GI *Manual of Geoenvironmental Practice.*

In addition to his professional practice, Dr. Bonaparte served as the President and CEO of Geosyntec for 20 years and as Chairman of the Board for 14 years. He is currently a Senior Principal in the firm. Since 2016, he has also served as a Professor-of-the-Practice in the CEE School at the Georgia Institute of Technology, developing and teaching a course on global engineering leadership.

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Rudy Bonaparte's Contribution to the Design and Construction of Landfill Liner Systems: A Commitment to Rationality

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ABSTRACT

Dr. Rudolph Bonaparte has made important contributions to a wide range of landfill design and construction issues over the past 35 years. These contributions have included the sources and magnitude of flows in leachate collections systems, the efficiency of composite liner systems in which a geomembrane is underlain by a low permeability soil layer or geosynthetic clay liner, interface shear strength, criteria for seismic design of landfills, the stability of cover systems employing GCLs, the allowable long-term strains on geomembrane liners, and design and construction of CERCLA hazardous and mixed waste landfills. These contributions, founded in the philosophy of "a commitment to rationality," have played an essential role in the formulation of recommendations and guidelines for environmentally protective and cost-effective landfill liner and cover system design and remain the basis for many of the design procedures and regulatory standards used in practice today.

INTRODUCTION

Over the past 35 years, working with his Geosyntec co-workers and other professional colleagues, Dr. Rudolph Bonaparte has created an impressive legacy with respect to design and construction of modern municipal solid waste (MSW) and hazardous waste landfill systems. This legacy has been founded in the philosophy of "a commitment to rationality," relying on logic and evidence to interpret data and observations in the formulation of recommendations and guidelines for environmentally protective and cost-effective landfill liner and cover systems. Dr. Bonaparte's contributions have been both direct, through his own research and publications, and indirect, through his facilitation of innovations by Geosyntec Consultants, the firm he led for over 30 years.

Dr. Bonaparte's contributions addressed a wide range of landfill design and constructions issues, including the sources and magnitude of flows in leachate collections systems, the efficiency of composite liner systems in which a geomembrane is underlain by a low permeability soil layer or geosynthetic clay liner (GCL), interface shear strength, seismic design criteria for MSW landfills, the stability of cover systems that employ GCLs, the allowable long term strains on geomembrane liners, and design and construction of CERCLA hazardous and mixed waste landfills. These contributions were essential in the development of modern landfill design methodology for compliance with federal Environmental Protection Agency (USEPA) "Subtitle D" Resource Conservation and Recovery Act (RCRA) requirements for municipal solid waste (MSW) landfills in Title 40 of the Code of Federal Regulations, part 258 (40CFR258) (referred to herein as simply Subtitle D), as well as interpretation of the Subtitle C requirements for hazardous waste landfills in 40CFR264. Dr. Bonaparte's contributions have been long lasting, as the rationale used to establish these recommendations as well as many of the

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recommendations themselves remain the basis for design procedures and regulatory standards in place today.

LANDFILL LINER LEAKAGE

One of the first, and most lasting, contributions to landfill design made by Dr. Bonaparte is his work on leakage through landfill liner systems. A two-part paper on "Leakage through Liners Constructed with Geomembranes (Parts I and II)," co-authored with Dr. J.P. Giroud (Giroud and Bonaparte 1989a, 1989b), provided the framework for all of the liner leakage evaluations used in practice today. Giroud and Bonaparte did posit the oft-repeated statement that "all liners leak" in these papers. However, they conditioned this statement by noting that, while it is accurate, we must qualify it by asking "… but how much?" They further demonstrated that, for a well-designed composite liner system consisting of a geomembrane underlain by a low permeability soil layer and constructed with rigorous construction quality assurance (CQA), the answer to the question of "how much" is, in general, that it is so small that, for a MSW landfill, it presents no harm to human health and the environment (a finding oft-ignored by landfill opponents).

Giroud and Bonaparte's analysis was based upon two-dimensional (e.g., planer strain and axi-symmetric) analysis of flow through a defect in the liner system. These authors analyzed the flow through a circular defect in a geomembrane underlain by 0.6 m of low permeability soil with a hydraulic conductivity if 1×10^{-6} cm/s (at that time, the pending prescriptive standard for new liner system construction and a standard that is still employed today) that was in intimate contact with the overlying geomembrane. Bonaparte and Giruod also looked at the influence of impaerfect contact between the geomembrane and the underlying low permeability layer. Figure 1 shows the bounding cases analyzed by Giroud and Bonaparte (1989b) for two-dimensional plane strain flow through a geomembrane defect, including the case for perfect contact (Figure 1b) which they termed the correct solution, a lower bound solution for vertical flow through the defect and underlying layer (Figure 1c), and the uooer bound solution for radial flow (Figure 1d). They then introduced approximate solutions for three-dimensional flow through a circular defect (actually, two-dimensional axi-symmetric flow) with less than perfect contact. Their analysis showed that the flow through a composite geomembrane and low permeability soil system was over 1000 times less than the flow through a geomembrane with a 1 cm^2 circular defect that was not underlain by a low permeability soil layer, and was on the order of 1 liter per hectare per day if subjected to a maximum hydraulic head of 0.3 m.

The Giroud and Bonaparte (1989b) analysis has been enhanced by numerous authors. Enhancements have included three-dimensional analysis of flow through linear defects, imperfect contact including wrinkles in the geomembrane, defects in the low permeability soil layer, and other complicatiogn factors. However, all of these analyses follow the basic structure Giroud and Bonaparte laid out in their 1989 papers. Furthermore, the essential message from that study remains the same: a properly designed and constructed composite liner system provides a very high degree of environmental protection in a properly operated landfill.

INTERFACE SHEAR STRENGTH

Forensic analyses in the wake of the Kettlemen Hills landfill failure (Seed et al. 1990) highlighted the importance of the interface strength between a geomembrane and an adjacent low permeability soil layer. Working with colleagues from Geosyntec Consultants and industry, Dr.

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Bonaparte engaged in the first systematic study of the influence of the compaction conditions for the low permeability layer on interface shear strength (Swan et al. 1991). Interface direct shear tests were used to study the effect of compaction water content and dry unit weight on the interface shear strength between a cohesive soil and a 1.5-mm thick high-density polyethylene (HDPE) smooth geomembrane. All tests were conducted at a normal stress of 140 kPa. Seven different combinations of compaction water content and dry unit weight were employed in this study. Other test variables, such as the method of compaction, the effect of soaking the soil after compaction, rate of shear and length of time between compaction and shearing, were controlled but were not specifically addressed by the investigation.

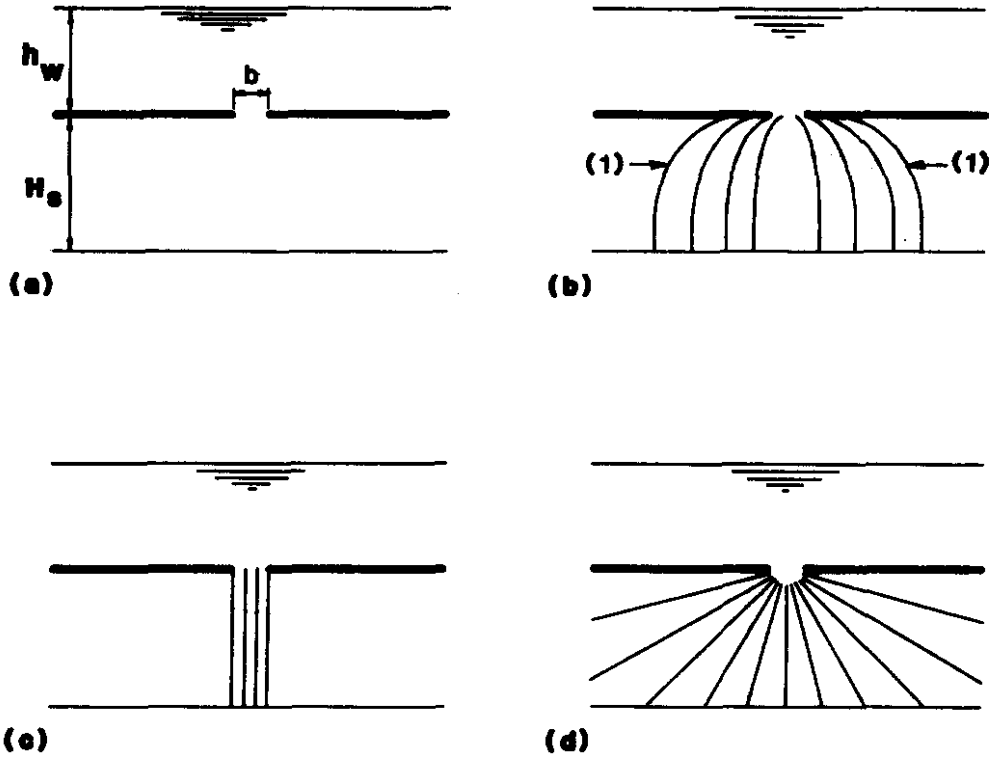


Figure 1. Two-dimensional flow through a composite liner due to a geomembrane defect assuming perfect contact between geomembrane and soil layer: (a) definition of the two-dimensional case (b) correct solution; (c) vertical flow (lower bound); (d) radial flow (upper bound) (Source: Giroud and Bonaparte 1989b).

Table 1 presents the results of the laboratory testing program. This study highlighted the influence not just of compacted dry density but also of relative compaction water content, defined as the optimum moisture content minus the compaction moisture content at 100% relative compaction, on interface shear strength. Two observations drawn from this data were that on the wet side of optimum (positive relative water content) there can be a drastic decrease in interface strength and that the optimum moisture content increases as relative compaction decreases. These are fundamental lessons that even today engineers often need to be reminded of.

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Table 1. Interface direct shear test results[a, b] (after Swan et al. 1991).

Test number	Dry unit weight (kN/m^3)	Water content (%)	Relative compaction (%)	Relative water content[c]	Peak interface shear strength (kPa)	Peak interface friction angle (degrees)
1	17.1	18.2	95	+ 3.7	17	7
2	18.1	15.8	99	+ 1.3	43	27
3	18.7	14.2	102	- 0.3	43	17
4	17.7	16.5	97	+2.0	36	14
5	18.7	15.9	102	+ 1.4	4939	19
6	18.7	12.2	102	- 2.3	34	13
7	18.8	12.3	103	- 1.2	43	17

a. All tests performed at a normal stress of 140 kPa
b. Dry unit weight and water content are "as compacted" values
c. Relative water content found by subtracting optimum water content from "as compacted" water content

SOURCES OF FLOW IN LEACHATE COLLECTION SYSTEMS

One of the questions that arose in the early days of geomembrane liner systems was the source of what appeared to be anomalously high flow rates into leachate collection systems during the initial stages of landfill operation. In their paper on "LDCRS Flow from Double-Lined Landfills and Surface Impoundments," Bonaparte and Gross (1990, 1993) evaluated data on flow rates into the leachate collections system (LCS) of 76 cells from 28 double-lined landfill and 8 surface impoundments with 17 cells. These cells were divided into two broad categories: landfills with single geomembrane liners, i.e., without an underlying low permeability layer (denoted Types I and II liners) and landfills with composite liners, i.e, with geomembranes underlain by a low permeability soil layer, denoted Types III and IV liners. Flow into the leachate collection system (LCS) in these cells was separated into four sources: primary liner leakage, construction water and compression water, consolidation water, and infiltration water. Figure 2 illustrates these sources of leachate collection system flow.

LCS flow rates and chemical constituent data was used to quantify the portion of LCS flow that could be attributed to primary liner leakage as opposed to the other sources. Analysis of the data indicated that while flow into the LCS of Type I and II landfills (single geomebrane lner) was primarily due to leakage of leachate through the liner, LCS flow into the Type III and IV landfills (composite liners) was primarily consolidation water, i.e., water being squeezed out of the low permeability soil layer as the overburden stress increased with placement of waste in the cell. The data also clearly showed the benefit of CQA, as LCS flow rates for liner systems constructed with a CQA program were consistently less than LCS flow rates for similar liner systems (i.e., single geomebrane or composite liners) constructed without a CQA program.

SEISMIC ANALYSIS AND DESIGN

One of Dr. Bonaparte's most frequently (and incorrectly) cited contributions on landfill design is from the 1992 paper on "Seismic Analysis and Design of Lined Waste Fills: Current

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Practice" (Seed and Bonaparte 1992). This paper, written in the shadow of the impending nation-wide seismic design requirements of Subtitle D, was often cited as the basis for the use of 6 to 12 inches (150 to 300 mm) of seismic displacement as the performance standard for seismic design of geomembrane-lined landfills. The statement that "Seed and Bonaparte recommended an allowable seismic displacement of 6 to 12 inches" was common in design reports in the 1990s and can still be found today in some reports and guidance documents today.

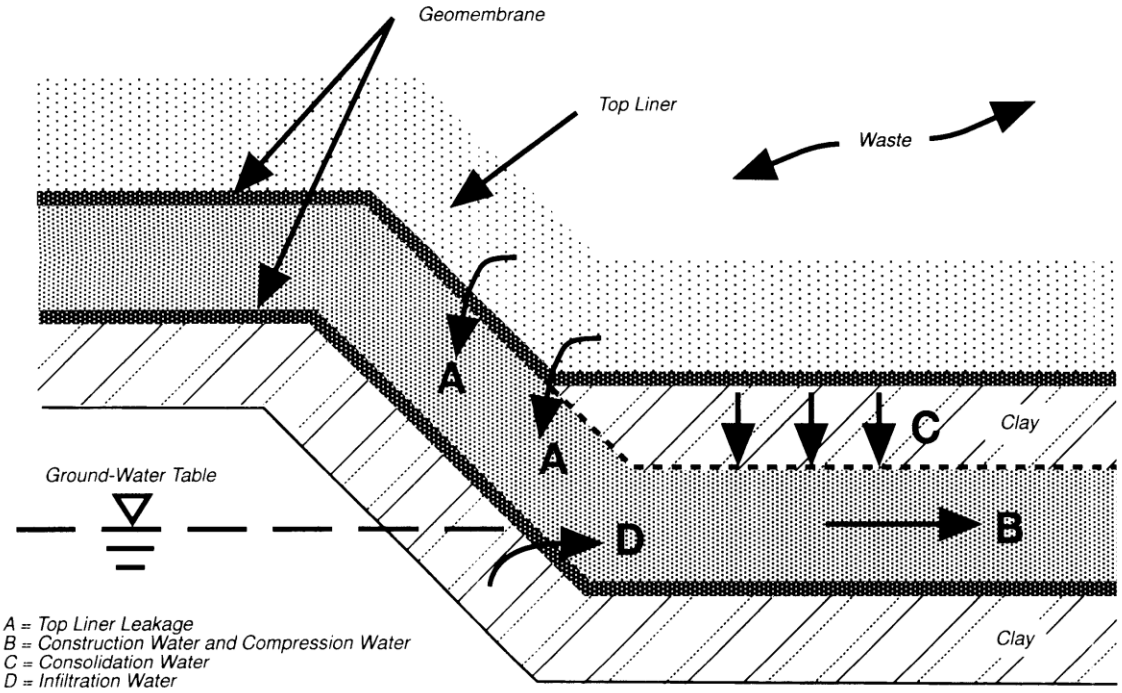


Figure 2. Sources of flow into leachate collection systems (Source: Bonaparte and Gross 1993).

In fact, Seed and Bonaparte (1992) merely reported they surveyed five firms engaged in landfill design practice in seismic regions and that "Three of the five firms currently consider likely maximum seismic displacements (calculated using the conservative procedures described previously) of on the order of six inches (15 cm). … The other two firms … occasionally consider slightly larger (based on conservative calculations) displacements of up to 12 inches (30 cm)". The fact that this was merely an observation of what was commonly used in practice (and not an endorsement of this criterion) and the important caveat that this criterion was associated with conservative analysis procedures was often forgotten. It is noteworthy that subsequent analyses conducted by Dr. Bonaparte's colleagues at GeoSyntec Consultants and other seismic design experts have subsequently confirmed the validity of this criteria when applied to conservative Newmark-type displacement analyses that employ large displacement shear strengths (e.g., Kavazanjian et al. 1998).

Dr. Bonaparte was also involved in reconciling the difference between California and federal Subtitle D seismic design standards for MSW landfills. The Subtitle D regulations, promulgated in 1991 and effective in September 1993, called for seismic design to be based upon ground motions with a 90% probability of not being exceeded in a 250 year period (equivalent to a

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recurrence interval of once every 250 years). Requirements in Title 17 of the California Code of Regulation (CCR17), which pre-dated Subtitle D, called for use of the "Maximum Probable Earthquake" (MPE) defined as "the largest earthquake expected to impact the site in a 100-year period. While some design firms had interpreted the California regulations to require use of an earthquake with a recurrence interval of 100 years, Dr. Bonaparte and his co-authors pointed out that this corresponded to an earthquake with a 64% chance of occurring in a 100-year period (Kavazanjian et al. 1995). Dr. Bonaparte and his co-authors pointed out the Subtitle D standard of a 90% probability of not being exceeded in 250 years corresponded to an earthquake with a 94 % probability of not being exceeded in 100 years, and suggested that this was a more rational probabilistic interpretation of the California standard of the largest earthquake expected in 100 years for consistency with the USEPA Subtitle D requirements.

GEOSYNTHETIC CLAY LINERS

Dr. Bonaparte was one of the principal investigators in an important USEPA-funded study on the performance of geosynthetic clay liners (Daniel et al. 1998). The stability of a landfill cover system containing a geosynthetic clay liner (GCL) was an important design issue in the 1990's due to concern over the internal shear strength of the GCL after hydration. Several manufacturers developed enhanced products to address these concerns, e.g., reinforced GCLs and membrane-backed GCLs). Furthermore, some engineers believed that, while at high overburden pressures the internal shear strength of an unreinforced GCL may be very low, these products had sufficient strength to remain stable even after hydration at the overburden pressures associated with typical landfill cover systems.

Daniel et al. (1998) describe the performance of 14 field scale GCL test plots. Five different types of GCLs were deployed on 2H: 1V (horizontal to vertical) and 3H:1V slopes for the purpose of assessing the stability of GCL cover systems. The cross sections of three of the GCLs used in the test plots are shown of Fig. 3 (there were 3 different variations of the needlepunched reinforced GCL shown in Figure 3a). A typical cross section of these test plots is presented in Fig. 4. Construction was completed in November 1994 and the plots were monitored until February 1998. All five of the 3H:1V plots remained stable over the monitoring period. However, three of the nine 2H:1V plots failed and four of the other six 2H:1V plots were subject to large deformations in the subsoil.

Of the three 2H:1V failed test sections, one failure involved an unreinforced GCL in which the bentonite became hydrated. The other two slides occurred at the interface between the GCLs woven geotextile component and the overlying textured HDPE geomembrane. Stability analyses based upon laboratory direct shear tests were consistent with the results of these test plots. These data gave engineers the information they needed to confidently design GCLs for use in landfill cover systems.

LONG TERM PERFORMANCE

Allowable Tensile Stresses. Dr. Bonaparte made several key contributions on the critical issue of long-term performance of geosynthetic landfill liner systems, helping establish the reliability of what was an emerging technology at the beginning of his career. One of the first issues he addressed was the long-term allowable tensile strength of geomembranes. In their paper on "Long-term allowable tensile stresses for polyethylene geomembranes," Berg and Bonaparte

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(1993) recommend reducing the allowable tensile stress on the welds of polyethylene geomembranes to between 0.4 and 0.8 times the allowable tensile stress on the geomembrane sheet. While the reasons for reducing the allowable tensile stress on a geomembrane seam have changed since that time, recognition that the seam strength may be less than the strength of the geomembrane sheet and the need to limit the allowable tensile stress or strain on the seam to account for this possibility is widely recognized among landfill designers today.

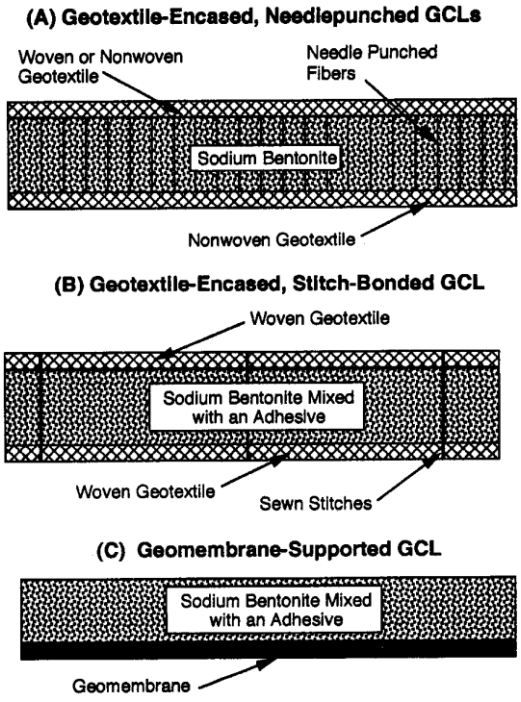


Figure 3. Types of GCLs used in the test plots (Source: Daniel et al. 1998).

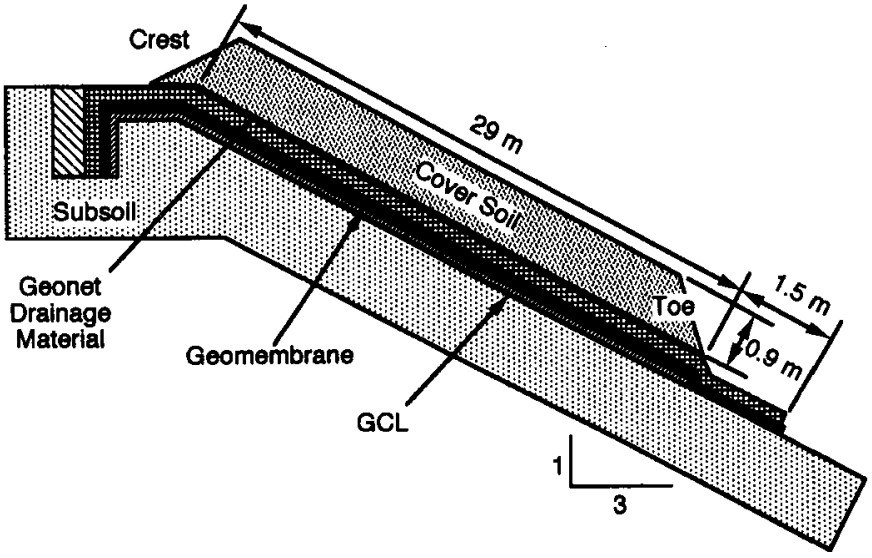


Figure 4. Typical cross section of a GCL test plot (Source: Daniel et al. 1998).

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Leachate Collection and Leak Detection System Flow Rates. In studies conducted over a 30-year period, starting with the study described previously on sources of liquids in the LCS, Dr. Bonaparte and his co-investigators compiled invaluable data on the performance of composite liner systems. This data provides convincing evidence of the long-term efficacy of composite liner systems constructed in accordance with current regulatory standards.

Figure 5, from the 1995 paper on "Long Term Performance of Landfills" (Bonaparte 1995), presents approximately five years of data on the performance of the composite liner system for one cell of an unnamed Pennsylvania MSW landfill. This figure documents the decrease in flows from the leachate collection and removal system (LCRS) during filling as the construction and consolidation water is expelled, a further reduction in LCRS flow rate after installation of the landfill cover system, and the continued suppression of LCRS flows for the first 3 years of the closure period. During cell filling, LCRS flows were up to 3,400 lphd (liters per hectare per day), with an average of just 70 lphd in the post-closure period.

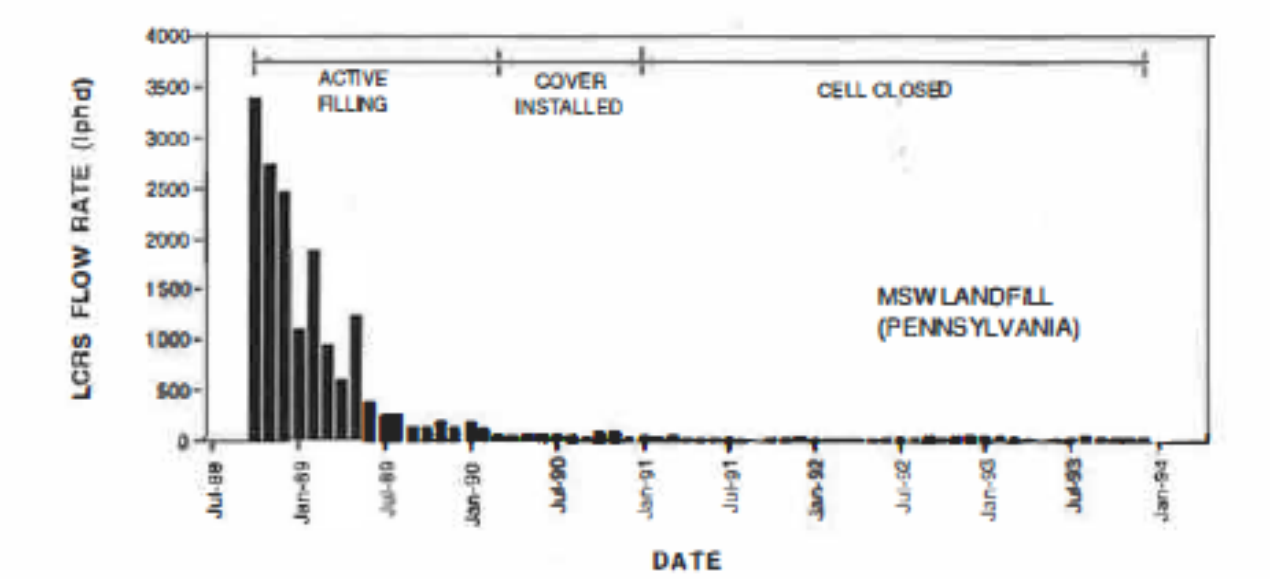


Figure 5. Leachate collection system flow rates for a Pennsyvania MSW landfill (Source: Bonaparte 1995).

A study on "Assessment and Recommendations for Improving the Performance of Waste Containment Systems" (Bonaparte et al. 2002) extended the database on liquids management to 187 double-lined cells at 54 landfills and extended the monitoring period over which liquid management data was reported. Figure 6 shows similar LCRS data to Figure 5, except for longer active period of operation, along with data on the flow in the leak detection system (LDS). Following the initial period of operation, LCRS flows over more than four years of active operation were generally less than 100 lphd. Furthermore, LDS flow rates were less than 10 lphd following the initial operations period and were negligible once the landfill was closed.

An important conclusion from this study was that geomembrane/compacted clay liner (GM/CCL) and GM/GCL/CCL composite liners are capable of substantially preventing leachate migration over the entire period of significant leachate generation for typical landfill operations scenarios without leachate recirculation or disposal or liquid wastes of sludges. Other findings included 1) average monthly active-period leak detection system (LDS) flow rates for cells with HDPE geomembrane primary liners constructed with CQA (but without ponding tests or

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electrical leak location surveys) will often be less than 50 lphd, but occasionally in excess of 200 lphd; 2) average monthly active-period LDS flow rates attributable to leakage through GM/GCL primary liners constructed with CQA will often be less than 2 lphd, but occasionally in excess of 10 lphd; (3) available data suggest that average monthly active-period LDS flow rates attributable to leakage through GM/CCL and GM/GCL/CCL primary liners constructed with CQA are probably similar to those for GM/GCL primary liners constructed with CQA; (4) GM liners can achieve true hydraulic efficiencies in the 90 to 99% range, with higher efficiencies occasionally being achievable; and (5) GM/GCL, GM/CCL, and GM/GCL/CCL composite liners can achieve true hydraulic efficiencies of 99% to more than 99.9%.

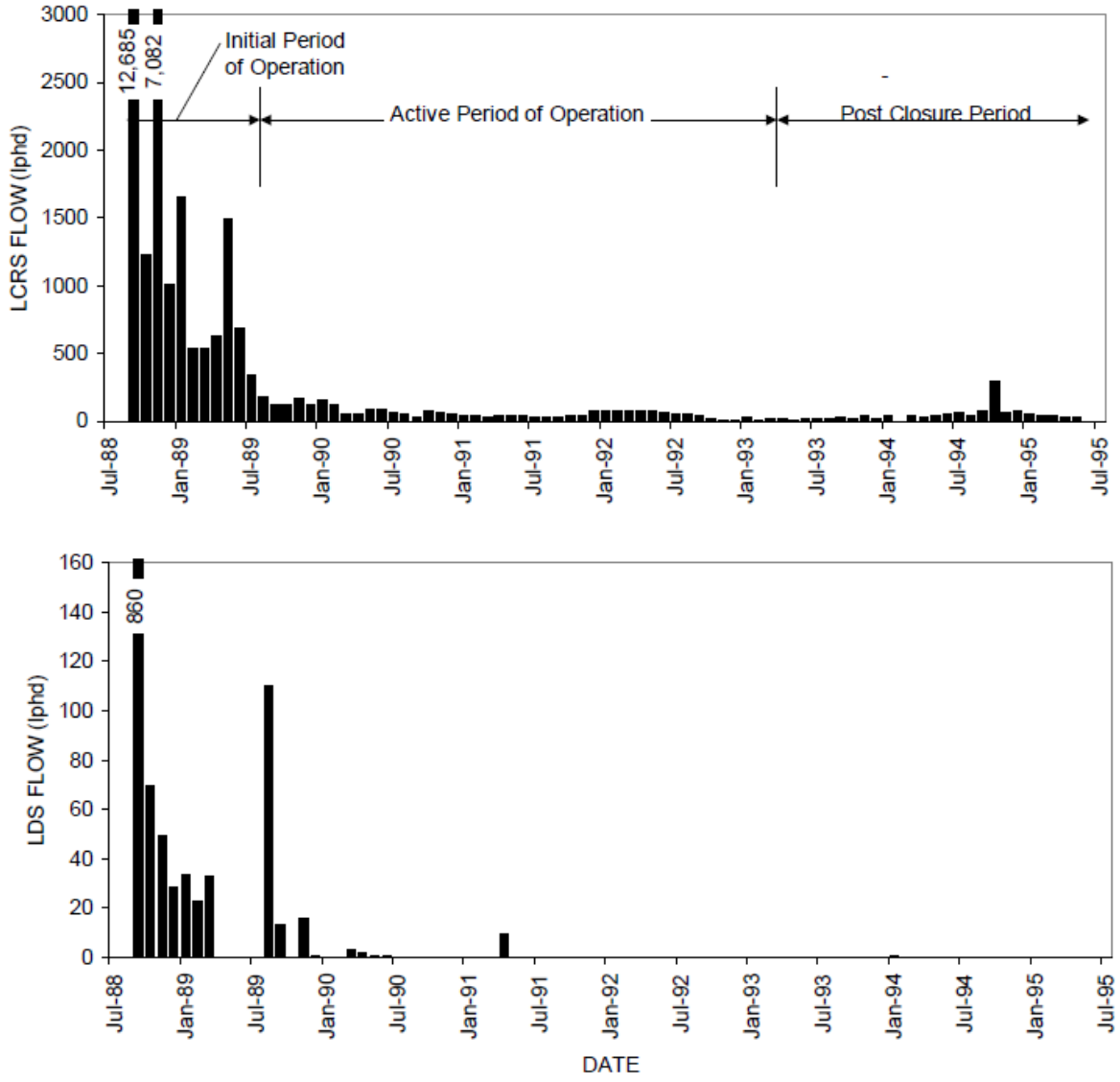


Figure 6. Leachate collection and leak detection system flow rates for a double-lined landfill (Source: Bonaparte et al. 2002).

These data clearly demonstrate the high level of environmental protection provided by a composite liner system constructed with a rigorous CQA program.

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CERCLA LINER SYSTEM DESIGN AND CONSTRUCTION

Dr. Bonaparte and his co-workers also made valuable contributions to the design and construction of hazardous waste landfills constructed in compliance with USEPA Subtitle C regulations. In "Design, Construction, and Performance of Low-Level Radioactive Waste Disposal Facility" (Bonaparte et al. 2008), these investigators documented the first 8 years of operation of a Subtitle C landfill cell designed and constructed to provide protection to human health and the environment for a minimum of 1000 years (in accordance with regulatory standards for landfills containing low-level radioactive waste). In "Design Approach for the U.S. Department of Energy (DOE) CERCLA Waste Disposal Facilities", Fountain, Bonaparte, Beech, and Griffin (2016) summarized the regulatory criteria applied to design of waste disposal facilities on US Department of Energy facilities under the Comprehensive Environmental Restoration Compensation and Liability act (CERCLA). Table 2 summarizes the regulatory standards applied to four different DOE facilities.

Table 2. Summary of design regulations employed for DOE CERCLA waste disposal facilities (Source: Fountain et al. 2016).

Facility	ROD Year	RCRA	TSCA	DOE Orders	NRC or State Equivalent	State Solid Waste	UMTRA	CAMU
Fernald On-Site Disposal Facility (OSDF)	1996	✓	✓	✓		✓	✓	✓
ORR Environmental Management Waste Management Facility (EMWMF)	1999	✓	✓	✓	✓			
PORTS On-Site Waste Disposal Facility (OSWDF)	2015	✓	✓	✓	✓	✓		✓
Weldon Spring Disposal Cell	1993	✓	✓	*		✓	✓	

Notes:
NRC – Nuclear Regulatory Commission
UMTRA - Uranium Mill Tailings Remedial Action
*DOE Orders are not cited as ARARs in the ROD; however, the ROD notes that the remedy will be performed in accordance with all pertinent DOE Orders (DOE, 1993).

Figure 7, from "Evaluation of Liquid Management Data for Double-Lined Mixed Low-Level Radioactive Waste Landfills" (Bonaparte et al. 2016), presents performance data from a Subtitle C facility for the period from 2001 to 2015. At the beginning of this performance period, cells within the facility were open to the environment (hence the relatively large LCS flows). The data in Figure 7 shows the steady decrease in flow rates as the landfill was closed and the steady increase in the apparent liner hydraulic efficiency (equal to 1.0 minus the LDS flow divided by the LCRS flow, in percent) following closure. Subsequently, in "Twenty-Year Performance of a Mixed LLRW/RCRA Waste Disposal Facility," Bonaparte et al. (2020) provided an update on the 20 years of satisfactory performance of the facility.

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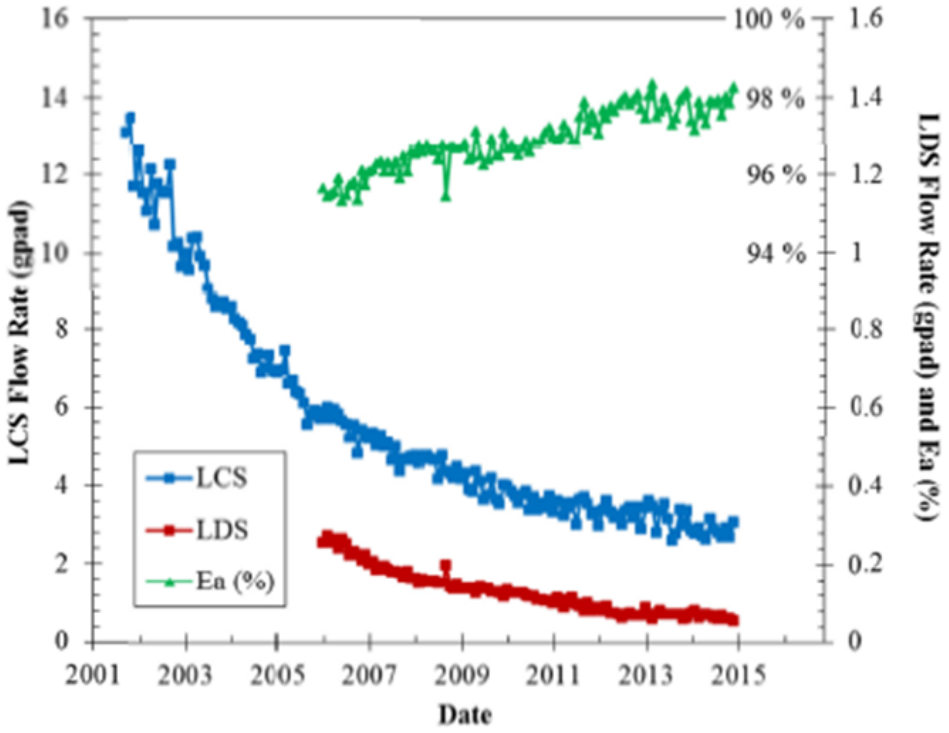


Figure 7. Monthly average LCS and LDS flow rate and apparent liner hydraulic efficiences for WSDC (Note: 1 gpad ≈ 10 lphd) (Source: Bonaparte et al. 2016).

CONCLUSION

For over 30 years, Dr. Rudolph Bonaparte has made numerous valuable contributions to the design and construction of geomembrane-lined landfills. In a series of papers from 1989 to 2020, he has documented the performance of modern landfill liner systems. This documentation has provided engineers with the information they need to design effective waste containment systems and to respond to public concerns about their integrity. He has also made valuable contributions on the long-term tensile strength of geomembranes and on seismic design. These contribution constitute a lasting legacy of valuable contributions to modern landfill design practice.

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Design and Construction of a Geosynthetic Cover System for the Final Closure of a Municipal Solid Waste Landfill in Ghana, West Africa

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ABSTRACT

An innovative geosynthetic cover system, consisting of the ClosureTurf system, was used for the final closure of a municipal solid waste (MSW) landfill in Ghana, West Africa. The ClosureTurf system is a three-layered soil-geosynthetic-turf product comprised of: (1) structured geomembrane; (2) nonwoven geotextile with high-density polyethylene glass blades as an engineered turf; and (3) sand infill ballast. This product was used as an innovative alternative final cover system in a design-build contract for the final closure of the MSW landfill as part of efforts to improve the overall environmental infrastructure in the country. The landfill is also the first in Africa, and one of the few landfills outside the US, to be closed using the ClosureTurf system. This paper presents the design and construction of the innovative geosynthetic final cover system under an aggressive schedule of a design-build contract dictated by the socio-economic political climate in the country during that period. Challenges and lessons learned during construction are also discussed.

INTRODUCTION

In 2020, the Ministry of Sanitation and Water Resources (MSWR) of the Government of Ghana awarded a design-build contract to Zoomlion Ghana Limited (Zoomlion) and an international team to close the Kpone Landfill, a municipal solid waste (MSW) landfill, with an innovative geosynthetic final cover system as part of efforts to improve the overall environmental infrastructure in Ghana, West Africa (Figure 1). The landfill site is at Kpone, which is along the coastal zone, and within a proximity of Tema in the Greater Accra Region of Ghana. The landfill occupied a total of approximately 16 hectares (ha) with an existing four cells (Figure 2). Each cell had a plan dimension of 175 meters (m) by 145 m and was initially used for disposal of MSW. The existing four cells were part of Phase 1 of two planned phases of landfill cells that were to be constructed and operated at the site.

The landfill was the only engineered landfill facility in the Greater Accra Region and was constructed and opened in January 2013 to receive approximately 500 tonnes per day (tpd) of MSW from the Tema metropolis and its surrounding communities (GECAS, 2020). However, due to the inadequate number of disposal facilities within the Greater Accra Metropolitan area, approximately 1,000 tpd of MSW was received at the site (GECAS, 2020). The increased waste disposal volume at the site resulted in drastically reducing the operational life of the landfill from eight to ten years to less than four years and consequently necessitating the final closure of the landfill. The final closure was also triggered from pressures (and at times protests) by the

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surrounding communities on the environmental conditions including leachate outbreaks/seeps and smoldering fires at the site. The MSWR awarded the project titled "Decommissioning and Re-engineering Works at Kpone Landfill Site" for the final closure of the landfill under a design-build contract (Zoomlion, 2020a, 2020b).



Figure 1. Site location map of the Kpone landfill.

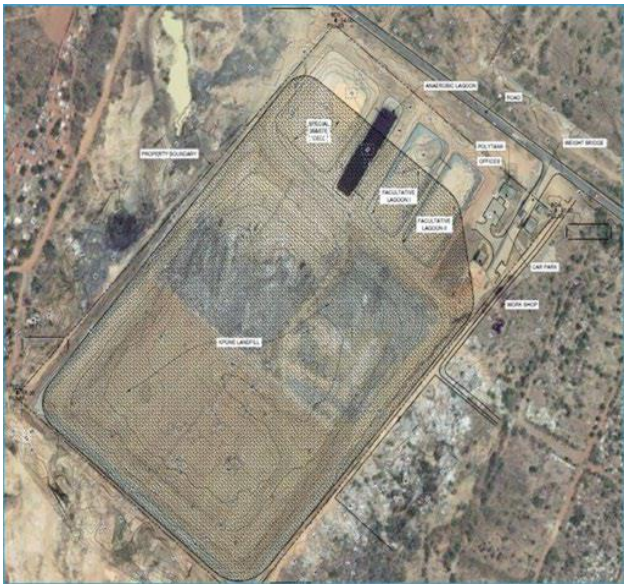


Figure 2. Site layout and conditions of the Kpone landfill.

The design-build team included, among others, Zoomlion as the general contractor; Watershed Geosynthetics, LLC (WatershedGeo) of Alpharetta, GA, USA, as the manufacturer and supplier of the ClosureTurf® product and other geosynthetics; Geosyntec Consultants, Inc. (Geosyntec) of Jacksonville, FL, USA, as the closure system design engineer; FEDEMS Limited as the local design/resident engineer; AESL as the geotechnical engineer, Construction Ambassadors Ltd as the earthwork contractor; and Landfill Technologies, Ltd. (a subsidiary of Zoomlion), under training/supervision by Hallaton Environmental Linings (Hallaton) of Baltimore County, MD, USA, as the geosynthetics installer.

BACKGROUND OF KPONE LANDFILL

Landfill Bottom Liner System. Phase 1 of the Kpone Landfill consisted of four main MSW cells, (Cells 1 to 4), and one special waste cell that were constructed and opened in January 2013 to receive approximately 450 to 500 tpd, initially, of MSW from the Tema metropolis and Tema Export Processing Zone (TEPZ). The landfill cells were constructed with a bottom liner system consisting of the following profile (top to bottom) (Tahal and MDC, 2011; GESAC, 2020):

- 300-mm thick crushed stone drainage layer;
- 500-g/m2 geotextile separation and protection layer;
- 1.5-mm thick high-density polyethylene (HDPE) geomembrane liner;
- 500-g/m2 geotextile separation and protection layer; and
- 300-mm thick compacted silty clay with a maximum hydraulic conductivity of 1×10-4 cm/s.

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Leachate was collected from each cell via 110-mm to 160-mm nominal diameter perforated HDPE pipes connected to respective manholes (MH-1 to MH-4) for each cell and conveyed by a 160-mm to 225-mm nominal diameter perforated HDPE pipes into a leachate sump at the eastern end of Cells 1 and 4 (Figure 3). From there, the leachate was pumped to leachate lagoons on the northern end of Cells 1 and 3 (Figure 4) for treatment. In addition, vertical extraction wells consisting of 225-mm nominal diameter slotted HDPE pipes with gravel bedding were installed from the bottom of each cell in a chimney or gabion fashion to vent landfill gas (LFG) to the atmosphere (Figure 3). Only 1 groundwater monitoring well was located, as shown in Figure 2.

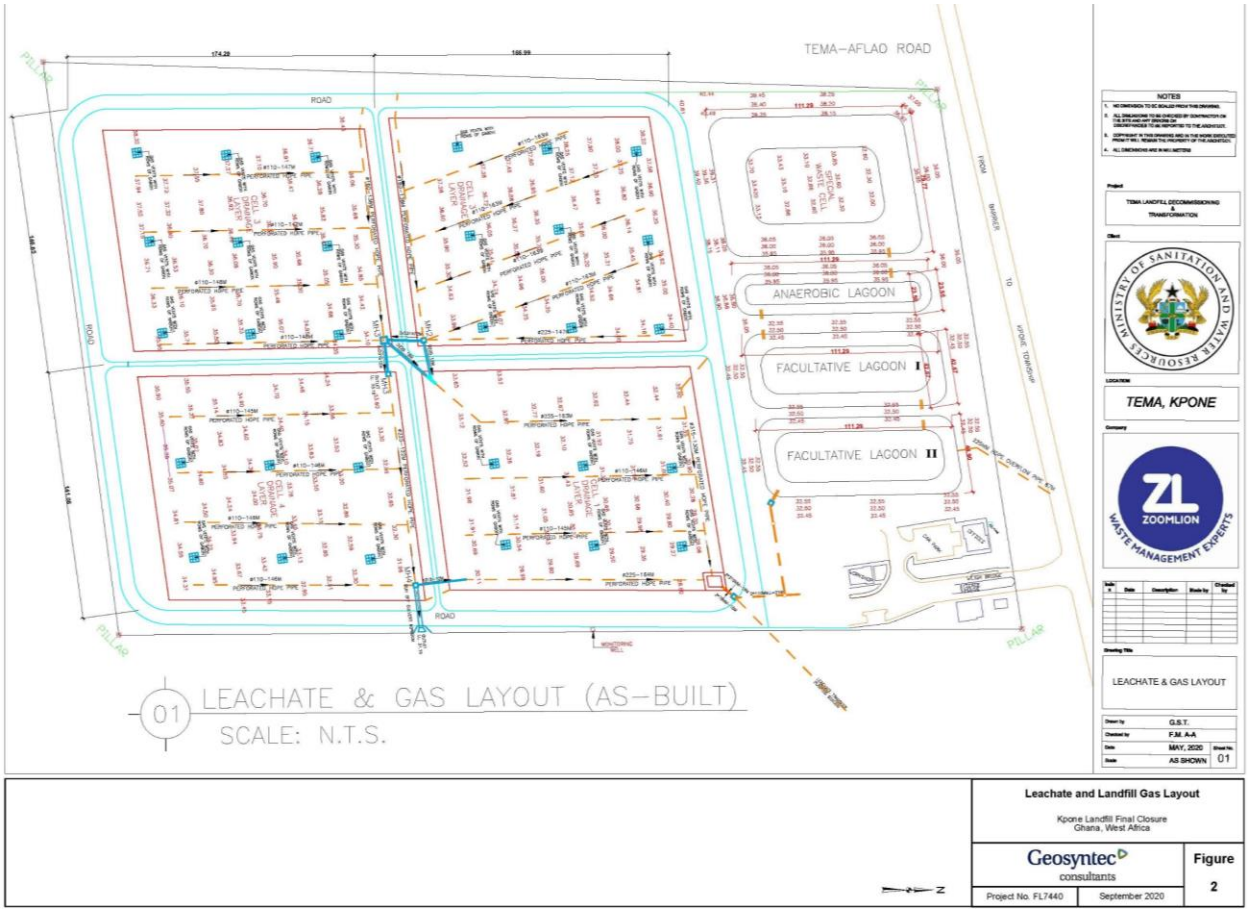


Figure 3. Landfill cells and leachate layout.

Landfill Capacity. The landfill was projected to reach its maximum design capacity of 2.4 million tons (2.9 million cubic meters) in November 2019 (Waste Landfills Co. Ltd, 2015). An in-place density or airspace utilization factor (AUF) of 0.82 ton/m3 was estimated. The annual average disposal rate was estimated to be 351,309 tons per year (tpy). However, waste acceptance data provided by Zoomlion for the period of January 2013 to August 2019 indicate that the landfill received a total of 2.3 million tons of waste.

Existing Conditions and Overall Closure Design Concepts. In addition to reducing the operational life, the landfill was also overfilled with slopes steeper than 3 horizontal to 1 vertical (3H:1V) side slopes, and in some cases as steep as 1H:1V. Therefore, final closure of the landfill required re-engineering by excavating and regrading the existing slopes to the required design

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slopes of 3H:1V or flatter (Zoomlion, 2020a). This necessitated extending the footprint of the landfill by constructing a new landfill cell north of the existing Cells 1 and 3 and within the footprint of the existing leachate lagoons (Zoomlion, 2020b) to receive the excavated waste discussed above. The conceptual layout of the landfill cell extension is shown in Figure 5. The design team recommended that a bottom liner and leachate control system be constructed for the new cell prior to placement of the excavated waste from existing Cells 1 to 4 of the Kpone Landfill.

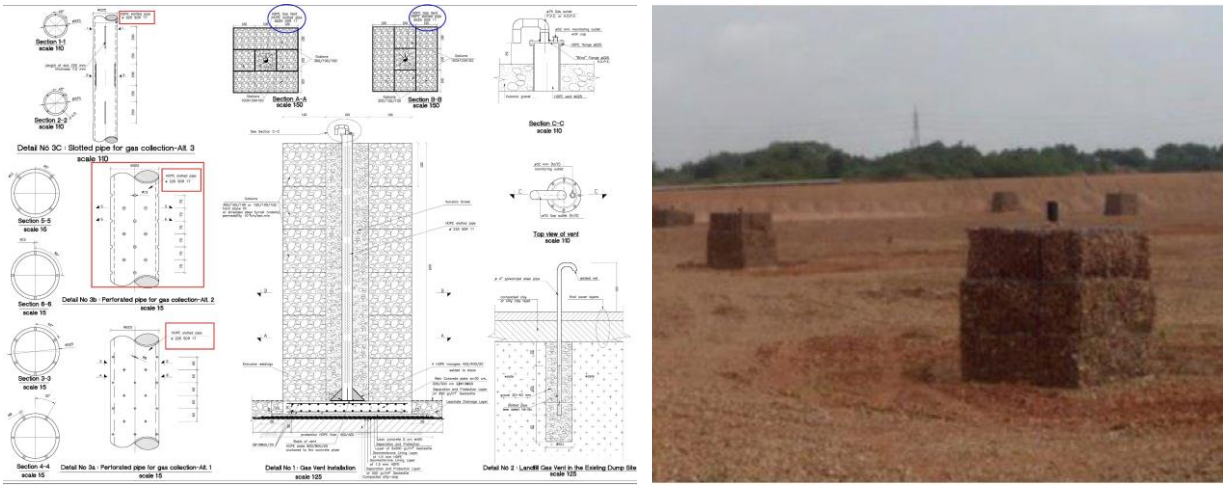


Figure 4. LFG vent design and as-built details.

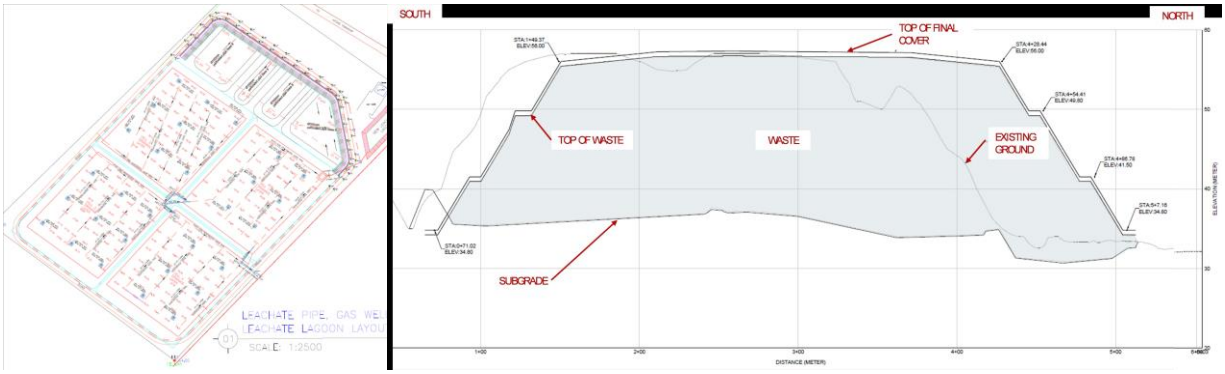


Figure 5. Conceptual layout of the landfill expansion footprint.

FINAL COVER SYSTEM DESIGN

Applicable Regulations and Design Guidelines. The final closure design was based on a review of applicable or relevant and appropriate requirements (ARARs) and design guidelines. These included: (i) "Landfill Guidelines" by the Environmental Protection Agency (EPA) and the Ministry of Local Government and Rural Development (MLGRD) of the Government of Ghana (EPA and MLGRD, 2002); (ii) "Solid Waste Disposal Facility Criteria Technical Manual" by the U.S. Environmental Protection Agency (USEPA, 1993, 2012), and "ClosureTurf® Design Guidelines Manual" (WatershedGeo 2019). Two final cover system options were initially proposed and evaluated: (i) a modified RCRA Subtitle D final cover

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system per USEPA regulations, which is considered as a traditional or prescribed cover; and (ii) a ClosureTurf® final cover system as an alternate innovative cover. After a thorough evaluation and community input, the design-build team selected the ClosureTurf® alternative due to its ability to provide state-of-the-art technology as a way to improve the management of solid waste in Ghana as well as technology transfer and application of geosynthetics sustainability in the country (Ahmed et al., 2022). It was also proposed to use the site, after closure, as a recreational facility and site tours and the alternative cover system appeared to meet this final use requirement.

Final Cover System Configuration. The closure design for the Kpone Landfill was developed to provide a final cover system design that applied to the entire landfill footprint (i.e., the initial Cells 1 to 4 plus the new expansion cell). The total footprint of the Kpone Landfill site requiring closure, including the new expansion cell, was approximately 12 hectares. Final cover was to be placed over the entire surface of the landfill with side slopes graded at approximately 3H:1V from elevation 34 m with benches at 8- to 10-m height increments to the top deck at elevation 57 m with a minimum of 2 percent slope on the top deck (Figure 6). It is noted that the 3H:1V side slopes between benches exceeded the maximum 5H:1V side slopes required by the Landfill Guidelines (EPA and MLGRD, 2002). However, the overall average slope from the crest of the top deck to the toe of the landfill was approximately 27 percent.

The use of 3H:1V side slopes is in accordance with the state-of-practice and was justified by the results of slope stability analysis performed as part of the closure design (Geosyntec, 2020). Stormwater runoff was to be collected by the benches and conveyed via downchutes along the landfill side slopes to the perimeter ditches at the toe of the landfill slope and ultimately to the stormwater pond, as shown on Figure 6. These stormwater runoff control features would help minimize erosion at the surface of the landfill cover system.



Figure 6. Final cover grading plan.

Final Cover System Cross Section. The final cover system on the top deck and side slopes of the landfill is shown in Figure 7 and consists of, from top to bottom:

- ClosureTurf® product, which is a three-layered soil-geosynthetic-turf system that is comprised of:

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  - 1.27-mm thick linear low-density polyethylene (LLDPE) MicroDrain® geomembrane;
  - an engineered synthetic turf layer comprised of polyethylene (PE) tufted through double layer of woven polypropylene (PP) geotextiles manufactured for high ultra-violet (UV) and heat resistance; and
  - a minimum 12.5-mm thick sand infill/ballast layer;
- 450-mm thick foundation soil layer;
- geocomposite drainage layer; and
- a minimum 150-mm thick soil leveling layer over the MSW.

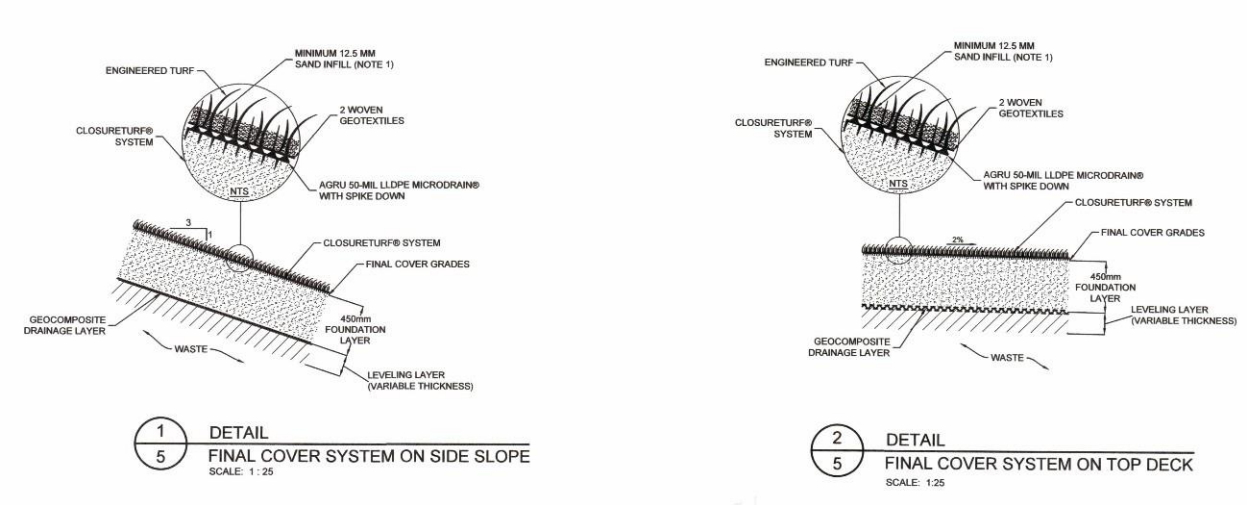


Figure 7. Details of final cover system components.

The geocomposite drainage layer served as underdrain for collection and removal of leachate and/or LFG and terminated at toe drains along the perimeter of the landfill (Figure 8).

Final Cover System Design Analyses. The design team performed design analyses for the final closure of the landfill for initial approval by the MSWR and regulatory agency (EPA) and finally to be used for construction. Design analyses and calculation packages prepared included slope stability (including veneer stability), final cover settlement, stormwater management system, active gas management system, infiltration analysis, and final cover system performance evaluation (e.g., erosion resistance, UV longevity, wind uplift, burrowing animals, and vandalism) by Geosyntec (2020). For infiltration analysis, WatershedGeo (2019) used the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder, 1994a, 1994b) and (ii) Giroud method (Giroud et al., 1997) to compare ClosureTurf® final cover system, which essentially has no soil cover with the prescriptive Subtitle D cover system. A summary of the results is presented in Table 1 which indicates that the ClosureTurf® system provides better infiltration protection than the prescriptive final cover system.

Additional infiltration analysis was performed using the HELP model and appropriate hydraulic, climatic, and soil properties for the Kpone Landfill site to evaluate the efficiency (or effectiveness) of the proposed final cover system. The results of the infiltration analysis indicated that the ClosureTurf® cover system significantly reduces infiltration by approximately 99.9 percent and thereby results in a decrease in the rate and quantity of leachate generation from the landfill with the construction of the final cover system.

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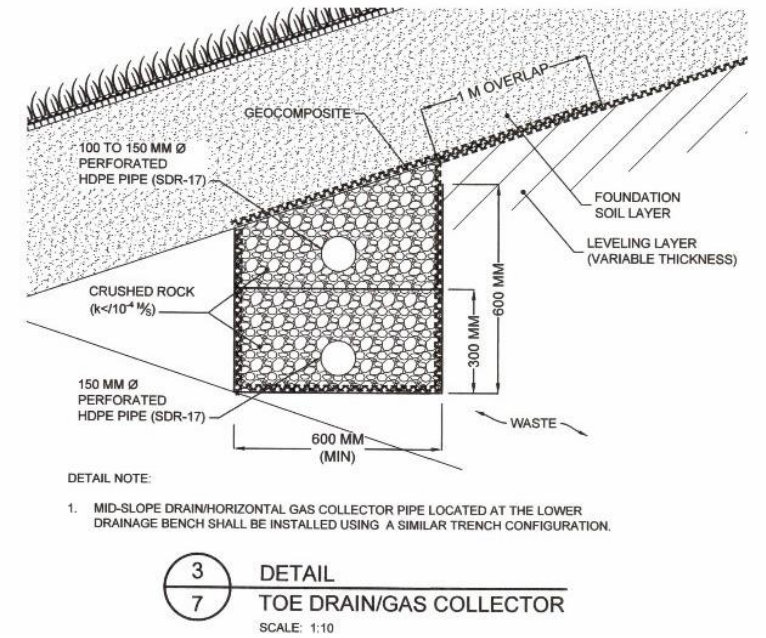


Figure 8. Toe drain/LFG collector.

Table 1. ClosureTurf® infiltration equivalency analyses (WatershedGeo, 2019).

Infiltration Equivalency Analyses	ClosureTurf® Cover System	Prescriptive Subtitle D Cover System
HELP model for Site in Georgia – Average Annual Infiltration (Cubic Feet / Acre / Year) [mm/year]	(8.3) [0.058]	(347) [2.428]
Giroud Method with Silty-Sandy Soil below the ClosureTurf (Gallons / Acre / Day) [mm/year]	(1.33) [0.454]	(4.51) [1.540]
Giroud Method with Silty-Sandy Soil with Some Clay below the ClosureTurf (Gallons / Acre / Day) [mm/year]	(0.24) [0.082]	(4.51) [1.540]

Vandalism was of significant importance under final cover performance evaluation. Most exposed geomembranes and other geosynthetics are susceptible to damage from vandalism (USBR, 2018; Oyegbile and Oyegbile, 2017). Even though the ClosureTurf® product has the engineered turf component that provides protection to the geomembrane component, it is rather the turf itself that could be potentially vandalized and thereby affect the performance of the final cover system during the aftercare period. Vandals could perceive other potential uses for the turf (e.g., as carpet for homes). Therefore, it was recommended that measures should be undertaken to prevent or discourage vandalism during the aftercare period. Examples include properly securing the site, use of closed-circuit television (CCTV) camera(s) for continuous surveillance, and full-time security guard(s). Other suggested measures were also provided (Geosyntec, 2020). It was recommended that these measures be included in the site's aftercare plan in accordance with the requirements of the Landfill Guidelines (EPA and MLGRD, 2002).

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Technical Specifications and CQA Plan. Other documents prepared for the final closure included design drawings, technical specifications, and construction quality assurance (CQA) plan. The technical specifications included material properties, testing, and construction/installation requirements for the final cover system components. Since the geosynthetic components of the ClosureTurf® and other geosynthetics were to be manufactured in the USA and supplied to Ghana for construction, conformance with the specifications was not a problem. However, the sand infill was supposed to be produced in Ghana, and having a manufactured sand meeting ASTM C136 graduation requirements (WatershedGeo, 2019) became a challenge that is further discussed below.

The final closure of the Kpone Landfill was to be constructed using industry standard construction practices and a CQA program. Therefore, a CQA Plan for the construction of the final cover system was prepared as part of the closure design package. The CQA Plan presented the quality assurance and quality control (QA/QC) monitoring and testing activities to be implemented during construction of the closure system utilizing ClosureTurf®.

CONSTRUCTION

The overall design-build project started on 5 June 2020 and was substantially completed by the end of August 2022 even though the original project schedule was to complete construction by the end of 2020. Preparation of the closure design documents started on 23 July 2020 (when notice to proceed was issued) and completed on 25 September 2024 (when the closure design package was submitted to Zoomlion). During this period, however, Zoomlion and its earthwork subcontractor worked on the re-engineering of the site by excavating overfilled waste and regrading the existing slopes to 3H:1V and to ensure slope stability of the landfill prior to final closure. Excavation works were executed using an excavator, bulldozer, pay loaders and dump trucks for transporting excavated waste to the new cell (Figure 9). The trimmed waste profile and excess waste placed in the new cell were compacted using a trash compactor.



Figure 9. Re-engineering of the landfill slopes.

Due to the political climate in 2020 (i.e., pending national elections), the senior author and another geotechnical engineer from Geosyntec travelled to Ghana between October and

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December to provide training and technical support to expedite closure construction (Ahmed et al., 2022). Only earthworks including excavation, grading and reshaping of the landfill and placement and compaction of waste in the new cell took place during the site visit. Technical support was provided to facilitate installation of additional LFG wells required by the closure design drawings.

Geosynthetic Installation. The geosynthetic components of the final cover system were manufactured in the USA and shipped to Ghana for installation. The manufacturer quality control (MQC) test results were reviewed in accordance with the technical specifications and CQA Plan and approved for shipment to Ghana. However, no conformance testing of the manufactured and delivered rolls was performed even though that was required by the CQA Plan. The inability to conduct third-party conformance testing was partly due to the unavailability of qualified geosynthetics testing laboratories in the country or nearby.

Training of Local Installers. Landfill Technologies, under the guidance of Hallaton and WatershedGeo representatives, successfully executed the geosynthetics installation. A comprehensive training program was conducted for local personnel, comprising initial online sessions and a one-week on-site training session commencing on April 27, 2021. The on-site training focused on equipment types and applications, equipment handling and maintenance, pre-deployment preparatory activities, quality seam production, safety protocols at the landfill site, geosynthetics deployment using spreader bars and telehandlers, and panel placement and layout requirements, including minimum overlaps, panel orientations (machine and cross-machine directions), and seam locations.

Practical exercises and corrective guidance were provided to supervisors, technicians, and laborers. Technical briefings were also conducted, covering key technical specifications for installation work and site-specific determinations by technicians and QA/QC personnel. Hallaton personnel provided training on equipment and tool holdings procedures, including the minimum required generators, tools, and materials for the LLDPE geomembrane and engineered turf installations. Additionally, Hallaton personnel provided on-site training and guidance between April and June 2022, while WatershedGeo conducted intermittent site visits for inspection and quality control.

Further training was provided by two Hallaton personnel during a 3-week visit in July 2022. Upon completing the training program, the local installation crew acquired the necessary expertise to execute the geosynthetic installation, including engineered turf deployment, with precision. Figure 10 shows select photos of some of the on-site training sessions provided to local installation crew.

Summary of Geomembrane Field Tests. The installation of the geosynthetics was completed by the end of August 2022. For the LLDPE geomembrane component of the ClosureTurf® system, the following tests were completed for the total of approximately 13.9 ha of geomembrane installed:

- 171 trial seams;
- 351 nondestructive seam continuity using the air pressure test (for double fusion seams only) out of which 9 failed portions were repaired by capping the seams;
- 72 destructive seams (66 on double-track fusion welds and 6 on extrusion welds) all passed; and
- Vacuum box nondestructive seam continuity testing was performed on T-joints, cap strips, and other repaired seams, of which all of them passed.

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Training on wedge welding machine



Training on use of spreader bar



Training on tensiometer use



Training on stacking and transportation of geomembrane rolls

Figure 10. Photographs of the various training sessions.

No performance testing of the engineered turf was performed following installation as required by the CQA Plan. Also, placement of the sand infill did not occur due to challenges discussed below during this construction period. As of writing of this paper, the sand infill is yet to be placed over the engineered turf component of the ClosureTurf®.

CONSTRUCTION CHALLENGES AND LESSONS LEARNED

Construction Challenges. The Kpone Landfill decommissioning and re-engineering works project encountered significant hurdles that made construction completion challenging. Three primary obstacles that impeded progress are: (i) availability of off-site borrow sources for fill material, (ii) inclement weather conditions; and (iii) ability of local quarries to produce sand for use as ballast for the engineered turf. The project struggled to secure from off-site borrow sources the specified lateritic soil for the final cover system's foundation and leveling layers. This was due to local availability limitations, with suitable soil scarce in the region, inconsistent material quality, frequently failing to meet specifications and logistical issues causing substantial delays. Heavy rainfall and strong winds severely disrupted progress, leading to earthworks suspension from 15 April to 15 July 2022, repeated erosion of downchutes, requiring costly repairs that were difficult and time consuming. Figure 11 shows select photographs of erosions to the foundation layer especially the down chutes that required repeated repairs.

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Figure 11. Impacts of erosion from repeated rains.

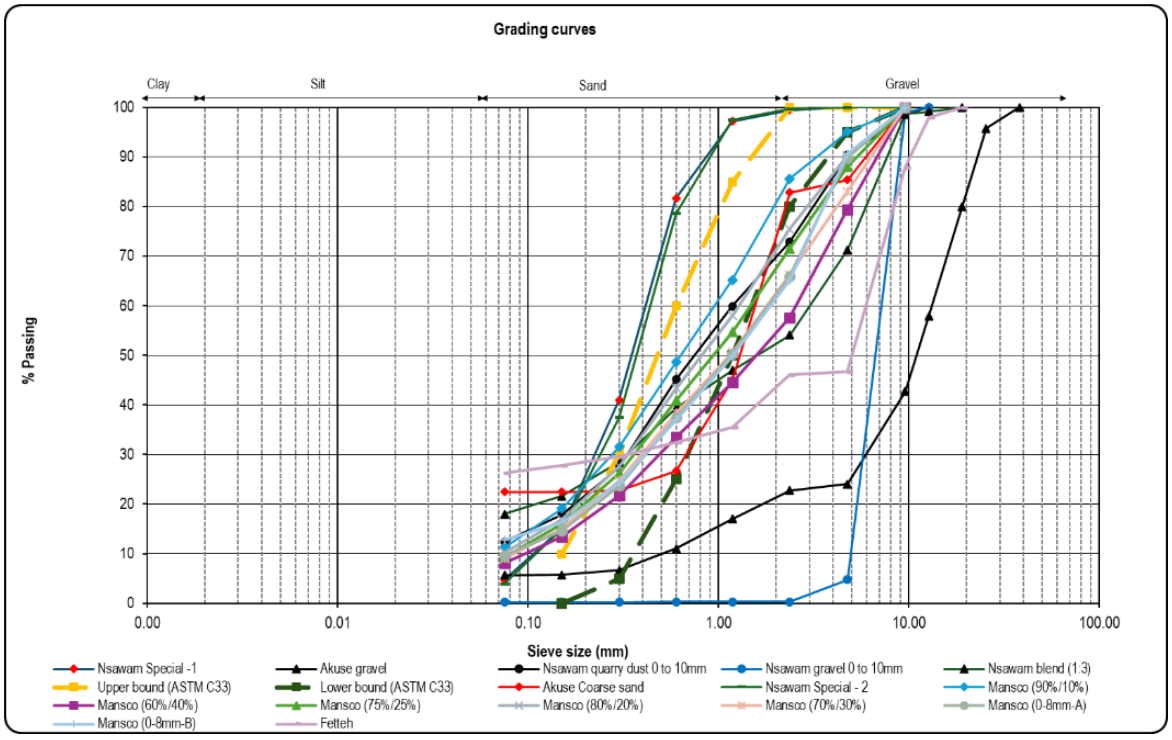


Figure 12. Gradation curves of various sands and blends compared with ASTM C136.

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Locally available material for sand infill ballast was a challenge. The team had to resort to different quarries to produce varying grades of material. None of these met the gradation limits of ASTM 136 and ASTM 33. Therefore, blending techniques were utilized to see if the mixed product would meet the gradation requirements. Figure 12 shows a summary of the various sand and blends compared to ASTM C136 gradation specifications. The figure shows that blending yielded about 90% better results; however, this design mix has not been implemented yet onsite.

The lack of required and appropriate tools for geosynthetics deployment resulted to the use of improvised tools. For example, motorized tricycles were used in lieu of ATV vehicles and skid steer to deploy the geomembrane (Figure 13).



Figure 13. Use of motorized tricycle as ATV for geosynthetics deployment.

These challenges significantly impacted the projected timeline (i.e., construction schedule from an initially estimated 3- to 6-month period to more than 2 years), increased costs, imposed environmental hazards from erosion and material exposure as well as safety risks for personnel due to harsh weather. By recognizing and acknowledging these challenges, valuable lessons can be learned from this project that can be applied to future projects, ensuring better preparedness and resilience.

Lessons Learned and Best Practices. Some key lessons learned from the project are summarized below:

- *Weather Risk Management*: Due to unpredictable rainy seasons, meticulous scheduling is crucial to avoid damage, rework, and project delays.
- *Earthworks Collaboration*: Effective partnership with earthworks contractors ensures proper subgrade preparation (compaction and slopes), minimizing delays.
- *Material Selection*: Utilizing materials similar to sand infill for sandbags prevents litter and mess on benches.
- *Just-in-Time Installation*: Deploying sand infill materials and equipment during installation, rather than after completion, enhances efficiency.
- *Equipment Maintenance*: Procuring spare parts and additional welding equipment enables timely repairs and minimizes downtime.
- *On-Site Accommodation*: Establishing a nearby camp facilitates prompt team deployment and reduces commuting time and delays.

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- *Training and Development*: Intensive training for local teams significantly improved installation quality. Ongoing learning platforms will keep the teams updated on the latest methods and technologies.

POST-CONSTRUCTION INSPECTION

On 13 September 2022, the authors made a site visit to inspect conditions of the as-constructed final cover system without the sand infill ballast. Figure 14 shows observations made during the inspection. There was localized ponding on the top deck of the final cover system. This could be due to potential differential settlement of the underlying waste but most likely as a result of difficulties constructing the design grades due to erosion challenges discussed above. Recommendations were made to repair these areas prior to placement of the sand infill ballast. There were also areas of the geosynthetics cover exhibiting uplift due to the lack of sand infill ballast. Debris including damaged sandbags were also found on top of the engineered turf especially in the swales of the benches. An additional recommendation is to conduct an annual survey of the final cover system to help evaluate settlement of the underlying MSW.



Figure 14. Photographs of as-constructed final cover during the 13 September 2022 site inspection.

CONCLUSIONS

The successful completion of the Kpone Landfill's final closure using the innovative ClosureTurf® system marks a significant milestone in Ghana's environmental infrastructure development. This design-build project, executed by a collaborative local and international team, demonstrates the effectiveness of alternative geosynthetic final cover systems in West Africa.

Despite challenges encountered during construction, valuable lessons were learned and addressed. Notably, the unavailability of locally sourced sand meeting the sand-infill ballast specifications delayed the completion of the final cover system. However, the installation of the

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geosynthetic components was successfully executed by local installers, trained and supervised by the manufacturer and a USA-based geosynthetics installer.

This project showcases the potential for innovative geosynthetic solutions in waste management and environmental protection in Ghana and beyond. The experiences and insights gained from this project will inform future initiatives, driving improvements in environmental infrastructure development in the region.

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