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Advances in Environmental Geotechnics

Proceedings of the International Symposium on Geoenvironmental Engineering in Hangzhou, China, September 8-10, 2009

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Preface

The International Symposium on Geoenvironmental Engineering (ISGE 2009) was held on September 8-10, 2009 in Hangzhou, China. ISGE 2009 was organized by MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Chinese Institution of Soil Mechanics and Geotechnical Engineering (CISMGE), and Chinese Chapter of International Geosynthetics Society (CCIGS), under the auspices of ISSMGE TC5, sponsored by K. C. Wong Education Foundation, and National Natural Science Foundation of China, as well as Zhejiang University Zeng Guo-Xi Lecture Fund.

Issues associated with Environmental Geotechnics continue to be a major preoccupation for governments, public and private organizations and the general community worldwide. The Chinese Government has been putting great effort on environmental issues including sanitary disposal of solid waste, reuse of industrial wastes, remediation of contaminated land, prevention of groundwater contamination, environmental risk assessment, ecological techniques, etc. China also has much to share on the opportunities, challenges and responsibilities for environmental geotechnics with other countries, especially the developing countries.

Under the conference theme, “Reclamation of the Past and Toward a Sustainable Geoenvironment”, 168 abstracts in total were received and 125 papers in total were reviewed and accepted for publication in this proceeding. This proceeding encloses 2 Zeng Guo-Xi Lectures, 26 Invited Lectures and 97 papers. The topics covered include basic and advanced theories for modeling of geoenvironmental phenomena, testing and monitoring for geoenvironmental engineering, municipal solid wastes and landfill engineering, sludge and dredged soils, geotechnical reuse of industrial wastes, contaminated land and remediation technology, applications of geosynthetics in geoenvironmental engineering, geoenvironmental risk assessment, management and sustainability, ecological techniques and case histories. This proceedings include papers authored by core members of ISSMGE TC5 (International Society of Soil Mechanics and Geotechnical Engineering - Environmental Geotechnics) and geoenvironmental researchers from more than 23 countries and regions (i.e., Albania, Austria, Bengalese, Brazil, Canada, China, France, German, Hong Kong, India, Iran, Indonesia, Japan, Korea, Macau, Malaysia, Portugal, Russia, Taiwan, UK, USA, Uzbekistan, Vietnam).

It is our desire that the proceedings of International Symposium on Geoenvironmental Engineering (ISGE2009) provide an opportunity for the exchange of views among academic researchers, practical engineers and administration officers. “Advances in Environmental Geotechnics” presents the latest development in this interdisciplinary field.

Prof. Yunmin CHEN
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The 2009 Zeng Guo-Xi Lecture

SYSTEMS ENGINEERING THE DESIGN AND OPERATION OF MUNICIPAL SOLID WASTE LANDFILLS TO MINIMIZE CONTAMINATION OF GROUNDWATER

R. Kerry ROWE[1]

ABSTRACT: This paper discusses the need to adopt a systems engineering approach to the design and operation of municipal solid waste landfills. It discusses how the interaction between the different components affects the performance of the entire system and how, due to this interaction, the performance of the system as a whole is much greater than the individual contributions of each of the parts. Issues discussed in this context include: landfill covers and the role that they play, the effect of landfill operations such as the waste placement and leachate recirculation on liner temperature and leachate characteristics, leachate collection and the control of head on the liner, diffusion of contaminants through composite liners, the effect of geomembrane-clay liner interaction on leakage, the significance of wrinkles in a geomembrane, the effect of liner temperature on leakage, possible means of controlling liner temperature, geomembrane protection, the long-term performance of geomembranes and geosynthetic clay liners, and finally the contaminant transport implications of these issues. It is concluded that by taking a systems approach to design, construction and operations we can provide safer containment of waste and long-term environmental protection.

KEYWORDS: geosynthetics, landfills, leachate

INTRODUCTION

Despite reductions in waste generation, landfills will continue to be required for the safe disposal of municipal solid waste (MSW) for the foreseeable future. These landfills will generate both leachate and gas whose escape from the facility must be controlled to environmentally acceptable levels. The leachate is predominantly water but typically contains dissolved organic and inorganic chemicals and suspended solids (e.g. microbes, particulate matter etc.) whose escape from the landfill must be controlled to negligible levels. Landfill gas is predominantly comprised of methane and carbon dioxide which are of concern as greenhouse gases (especially methane) but it also contains trace amounts of volatile organic compounds. From an engineering perspective, the long-term performance of the modern MSW landfill will be governed by the performance of a system comprised of three primary subsystems: the barrier system below the waste, the landfill operations, and the landfill cover and gas collection system. To provide long-term environmental protection, this system must contain contaminants for what is called the contaminating lifespan of the landfill (i.e. the period of time during which the landfill will produce contaminants at levels that could have unacceptable impacts if they were discharged into the surrounding environment). For large modern landfills this could be hundreds of years (Rowe et al. 2005).

The release of contaminants contained in landfill leachate can be reduced to environmentally acceptable levels with a suitable barrier system below the waste that includes a leachate collection system and a liner system. The leachate collection system minimizes the driving force for leachate escape (i.e. the leachate head acting on the underlying liner). The liner system provides resistance to the migration of contaminants both by the pressure driven movement of leachate containing contaminants (often referred to as leakage or advection) and the concentration driven movement of contaminants by a process of diffusion (those not familiar with the terminology and contaminant transport processes should refer to Rowe et al. 2004 for details). The leachate collection system typically involves a series of perforated pipes in a granular drainage layer together with a means of removing the leachate that is collected. The barrier system may involve a single liner or a double liner with a secondary leachate collection system (also called a leak detection system) between the two liners. In either case, the liner will typically be comprised of a

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protection layer on top of a composite liner. The protection layer minimizes the damage from overlying coarse materials and the composite liner minimizes escape of contaminants. The composite liner involves a *geomembrane* (GM: 1.5-2 mm thick high-density polyethylene (HDPE) plastic sheet) overlying a *geosynthetic clay liner* (GCL: about 5-10 mm thick layer of low permeability clay, called bentonite, encased between two geotextiles) or a *compacted clay liner* (CCL: 600-1200 mm thick). In addition to controlling the escape of leachate and the contaminants in the leachate, the liner system also controls the escape of landfill gas to the subsurface.

The landfill cover and gas collection system will control both the ingress of moisture (which generates leachate) and egress of landfill gasses. In order to minimize the leakage of landfill gas to the atmosphere, the cover will include a liner system to provide resistance to gas escape and a gas collection system which reduces the driving force for gas escape by collecting the gas (thereby reducing gas pressures in the landfill). The liner system in the cover will often be similar to that in the bottom liner as described above. In addition to the liner and gas collection system, there may also be a moisture distribution system to provide moisture to the waste to encourage biodegradation and gas generation.

Landfill operations that can affect the performance of the entire system include: (a) the nature of waste that is accepted, (b) the sequence and location of waste placement, (c) operation and maintenance of the gas collection system, (d) the introduction of moisture or recirculation of leachate, (e) leachate-collection, (f) maintenances and cleaning of the leachate collection system, and (g) maintenance of the final cover.

This paper argues that in order to minimize the environmental impacts of this landfill, it is necessary to adopt a systems engineering approach to the design, construction and operation of the landfill. This will involve decomposing the entire system into subsystems as noted above. In turn, each subsystem is decomposed into simpler identifiable components, the performance of the individual components is examined, the interactions between different components of the system are assessed, and then the response of the entire system is assembled to quantify its overall engineering performance. It is essential that this evaluation consider how the interaction between different components affects the performance of the entire system and how, due to this interaction, the performance of the systems as a whole is much more than the individual contributions of each of the parts. In particular, it must be recognised that an action that may enhance the performance of one part of the system may have a negative effect on other parts of the system and the objective should be to ensure optimal performance of the system as a whole as will be discussed in the following sections.

THE ROLE OF THE LANDFILL COVER

The generation gas and leachate is related to the movement of fluid through the waste. For example, the volume of leachate generated in a landfill is directly related to the movement of water through the cover. The leachate concentrations and the contaminating lifespan of a landfill are also related to the infiltration through the cover and this, in turn, may influence the performance of the underlying leachate collection system and bottom line (Rowe et al. 2004).

Before the relatively recent concerns about the effect of methane from MSW landfills on climate change, the primary consideration in cover design was the control of infiltration and hence leachate generation. Here there were two distinct philosophies and the cover would be designed to accommodate these philosophies.

One approach (e.g. MoE 1998) involves encouraging a modest amount of infiltration (0.15-0.2 m/a) through the landfill cover to encouraged controlled biodegradation of the organic waste and flush out contaminants (e.g. chloride) that do not chemically stabilize with time. A simple soil cover that allows this level of infiltration is relatively cheap and, in an appropriately designed system, can reduce the contaminating lifespan of the landfill so that it is less than the service life of the barrier system. This provides good long-term environmental protection to the surface and groundwater. Experience indicates that landfills operated in this manner (e.g. the Keele Valley landfill in Toronto, Canada) generate a liner temperature in the 30-40℃ range (Rowe 2005, Rowe and Islam 2009). However, the downside to this approach is that a soil cover that permits the ingress of 0.15-0.2m of infiltration will not provide the same control on the egress of landfill gas as a low permeability cover.

The other approach is the dry tomb concept (e.g. US Subtitle D). This involved the desire for a very low permeability cover that would result in minimal leachate generation from infiltration though the cover (leachate would still be generated from the biodegradation of organic waste; e.g. see Fig. 1). This approach has the short-term operational advantage of reducing the amount of leachate that is generated (and the consequent cost of treating it) and minimizing the escape of landfill gas (provided there is a suitable gas collection system). This approach reduces the rate of gas generation by limiting availability of moisture needed to fuel the biodegradation processes, although, with time, enough moisture will accumulate in the waste to allow some biodegradation to occur (e.g. due to biodegradation of organic waste that was moist when placed and by some leakage through the cover). Koerner and Koerner report a case with this type of cover where the temperature of the liner remained essentially constant at about 20℃ for six years but then quickly increased to between 30-35℃. However, this approach has the unanticipated consequence that it substantially increases the contaminating lifespan of the landfill and the normal processes will commence as soon as the cover degrades. Thus, what appears to be good from the narrow perspective of minimizing leachate generation and treatment actually has negative environmental impacts when one examines it from a systems engineering perspective.

Landfill gas is comprised of methane and carbon dioxide in about equal proportions as well as small amounts of volatile organic compounds, nitrogen oxides, and carbon monoxide. For example, in the USA, landfills produce about 23 percent of the total anthropogenic methane emissions (USEPA 2008). As a result of concerns regarding the impacts of methane on climate change, there has been a concerted move to collect landfill gas and either flare (burn) the methane or use it for the generation of electricity. The latter has desirable environmental benefits. However, to effectively collect and use the landfill gas, there is a need for a suitable gas collection system to be installed below the liner in the landfill cover and one needs to ensure that there is sufficient moisture to provide economic quantities of gas. Thus, there is often a need to introduce moisture below a low permeability cover to accelerate biodegradation and consequent gas generation. If done, this has a beneficial effect in terms of making gas generation cost-effective. Within reason, more moisture results in more gas being generated and this has led to studies of the use of the landfill as an engineered bioreactor with a view to (a) maximizing gas generation, and (b) stabilizing the organic waste as quickly as possible. Thus, from this narrow perspective, the more moisture the better. From a slightly broader sub-system perspective there is a limit on what is a desirable moisture injection rate dictated by the need to avoid flooding the gas collection wells (which would then minimize gas production) and avoiding leachate seeps. However, to avoid unintended consequences such as shortening of the service life of both the leachate collection system and the underlying composite liner, a much broader systems engineering approach should be adopted in the design of bioreactors to ensure that the overall system performance, and hence environmental protection, is optimized even if it results in less than the preferred rates of gas generation. The interdependencies and potential implications of moisture addition on other aspects of the landfill system will be discussed in a following section.

Fig. 1 Leachate generated from biodegradation of organic waste at a landfill site located in a desert. Note black and brown leachate stain due the leachate leaking from the adjacent completed cell (upper left) into the operating cell (foreground)

LANDFILL OPERATIONS AND CONSEQUENT EFFECTS ON LEACHATE CHARACTERISTICS AND LINER TEMPERATURE

The manner and rate at which waste is placed can affect a number of aspects of the system performance. For example, with respect to providing the best performance of the GCL it is ideally hydrated (i.e. takes up moisture from the underling soil) when it has significant stress on it. This could be achieved by placing waste relatively quickly over a relative small part of the landfill. This also has the advantage of minimizing the size of the open operating area of the landfill at any time (thereby minimizing leachate generation). However there are a number of disadvantages from a broader systems perspective. For example, faster waste placement tends to result in the generation of higher liner temperatures (Collins 1993) which can substantially reduce the service life of the composite liner (Rowe 2005). Also, faster waste placement gives leachate with much higher levels of organic acids and inorganic contaminants such as calcium (Brune et al. 1991) which can rapidly clog the leachate collection systems (Rowe et al. 2004; Rowe 2009).

Armstrong and Rowe (1999) examined data relating to the effect of waste placement and total precipitation on the composition of the leachate produced at the Keele Valley landfill in Toronto, Canada. They observed that when fresh waste lifts are placed on older waste, the older waste acts as a bioreactor that "treats" the leachate generated by the newer waste. Thus, the beneficial effect of leachate percolation through older waste shown by

Ham & Bookter (1982) in a relatively small cell appears to be relevant to this large landfill site. These results suggest that planned waste placement and fluid addition (natural or irrigation) can play major roles in the treatment of leachate before removal from the landfill and hence reduction in clogging of the leachate collection system. However, to achieve this objective, one must have a much larger working area of the landfill with consequent increase in leachate generation.

The Solid Waste Association of North America has defined a bioreactor landfill as "a sanitary landfill operated for the purpose of transforming and stabilising the readily and moderately decomposable organic waste constituents within five to ten years following closure by purposeful control to enhance microbiological processes. The bioreactor landfill significantly increases the extent of waste decomposition, conversion rates and process effectiveness over what would otherwise occur within the landfill". While there are undeniable benefits from this approach, as previously noted, Rowe et al. (2004) identified a number of concerns regarding this approach, as summarized below:

1. Limited effectiveness—The heterogeneity of waste may lead to significant variations in the moisture content throughout the waste body. The presence of preferential flow paths may lead to large portions of the waste mass not experiencing the beneficial effects of increased moisture content, and thus not degrading at an optimal rate. Furthermore, the current practice of disposing household waste in plastic bags limits the effectiveness of moisture addition (Jones-Lee and Lee 2000).
2. Inorganic contaminants—The operation of a landfill as a leachate recirculating bioreactor does not decrease the concentrations of many inorganic contaminants. Thus, although the organic loading may decrease, other pollutants may remain in the landfill at significant concentrations
3. Reduced service lives—The enhanced biological activity brought about by leachate recirculation may have an adverse effect on the service lives of engineered components of the lining system. Clogging of the leachate collection system may occur at greater rate with recirculation than for conventional operation. Additionally, the operation of a landfill as a bioreactor generally results in increased temperatures of 50℃ -60℃ (e.g. Koerner and Koerner 2006) which may reduce the service life of geomembrane liners (Rowe 2005; 2009).
4. Extended contaminant lifespan—The potential effects of inorganic contaminant loading noted in (2) above is compounded if the accelerated waste settlement achievable in landfills with leachate recirculation is used to increase landfill capacity and hence place more waste. Since leachate recirculation is unlikely to have a significant effect on reducing many inorganic contaminants with the landfill, the placement of additional waste following settlement will serve to increase the total inorganic contaminant load and thus extend the contaminating lifespan of the landfill.
5. Optimal conditions—Recirculation of leachate is not, in and of itself, sufficient to achieve optimum conditions for bioreactor landfills (Phaneuf 2000).
6. Stability—Excess porewater pressures associated with leachate recirculation has led to instability in at least two cases. Additionally, increased densification and the placement of additional waste following settlement may lead to loading in excess of that for which lining systems and side slopes were designed if the landfill was not originally designed for recirculation.
7. Leachate seeps—Due to heterogeneity and anisotropy of waste, the addition of leachate during recirculation may give rise to leachate seeps created by lateral flow of leachate above relatively low permeability layers (e.g. intermediate cover soils).

Yuen et al. (1999) suggested that any consideration of operating a landfill as a bioreactor must be done in the context of an integrated waste management system and must consider the implications on all aspects of the system. The writer is in complete agreement of this statement.

The observed temperatures in different landfills reported in the literature range from 14℃ to 87℃ and at the liner from 7℃ to 60℃ (Rowe and Islam 2009). In all MSW landfill cases examined, peak temperatures in the range of 30℃ -40℃ were encountered at the top of the landfill liner with typical landfilling operations. Substantially higher peak liner temperatures (50℃ - 60℃) were observed in the case where there had been moisture augmentation as noted above.

LEACHATE COLLECTION AND CONTROL OF HEAD ON THE LINER

The primary purpose of a leachate collection system (LCS) is to control the head acting on the underlying liner systems and, in so doing, minimize the driving force (head) that gives rise to leakage through the liner system. Failure of these systems can arise from clogging of the drainage layer and/or leachate collection pipes (due to a build-up of biofilm, inorganic precipitates such as $CaCO_3$, and small particulates such as silt and sand). Failure is said to occur when the hydraulic conductivity drops sufficiently that the LCS can no longer control the leachate head to the design value (even if considerable