THE BENEFICIAL USE OF COMPOSTED PAPER MILL SLUDGE AND ANIMAL WASTE FOR AN INDUSTRIAL LANDFILL CLOSURE

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INTRODUCTION

A 28-year old paper mill landfill in western Massachusetts was closed in 1997 using the mill's own wastes as final cover materials. This final cover design incorporates a soil-like paper mill primary clarifier sludge in lieu of compacted clay as the side slope infiltration barrier. A conventional PVC flexible membrane and synthetic drainage media were used to limit infiltration on the flatter landfill cap, but this covers a relatively small surface area. A relatively thick (30 cm) vegetative support layer consisting of composted blend of primary clarifier sludge, food wastes and animal manure was substituted for topsoil over the entire landfill. Water balance concepts were used to demonstrate that these permeability values, higher than typically required for compacted clay barriers in many jurisdictions, are sufficient to limit post-closure side slope infiltration to less than 3 percent of the total precipitation.

This project turned several unique waste products into viable landfill final cover material, which has long reaching implications for closure of industrial and municipal landfills, as well as generators of soil-like industrial wastes and agribusiness concerns. Paper mill wastes have been demonstrated through various studies to serve as a suitable soil substitute, in addition to a soil enhancement. This project conserved both land and material resources, but the project owner estimates that the unique final cover design saved his company over $2M in final closure costs, relative to a traditional cover. Cooperation with agribusiness provides this mill with a long-term alternative to land filling, which reduces future disposal costs and creates new outlets for beneficial use of the waste.

FINAL COVER MATERIAL PROPERTIES

Paper Mill Waste. Paper mill primary clarifier sludge, when partially dewatered, can be engineered and worked much like a soil. This specialty paper waste is a non-hazardous 3:1 blend of mineral filler (kaolin and titanium-dioxide) and short pulp fiber. The material is belt-filter pressed to achieve roughly a 50% solids content. The high mineral content enhances the soil-like characteristics, at once lowering the hydraulic conductivity (permeability) but limiting shear strength when wet. The combined effects of the mineral and fiber contents caused high moisture retention, which was a significant factor in engineering a closure for this landfill.

Geotechnical laboratory tests indicate that the waste exhibits a liquid limit of 256 and a plasticity index of 133. These values confirm a strong affinity for water. Tested field-moist unit weights were 1.26 gm/cm^3 (80 pcf), with dry unit-weight based moisture contents of 270 percent. Dry unit weights were estimated at 0.34 gm/cm^3 (20 pcf). The moisture-density properties and high sensitivity are typical of a low-strength material. Undrained triaxial shear strength testing resulted in an internal friction angle of 43° and cohesion of about 0.116 kg/cm^3 (200 psf). The laboratory shear strength values are misleading, though, because the waste is soft and heavy when wet, resulting in difficult access and requiring specialized handling and placement.

Agricultural Compost. A composted mixture of the paper mill sludge and other byproducts was developed (with the mill's participation) by a third party agribusiness. The compost consists of 30% high mineral-fill paper sludge, 30% institutional organic food waste, 30% chipped wood and yard wastes and 10% chicken manure. At the composting facility, the blended materials are placed in windrows, turned after 30 days, then allowed to stabilize for an additional 30 days, prior to screening. The resulting product is exhibits a topsoil-like texture and a rich, earthy color, with no objectionable odor or runoff. The paper mill sludge serves as a bulking agent and is the key agent to laboratory permeability tests results on the order of 10^{-5} to 10^{-6} cm/sec.

Normally, each of these waste products would require disposal space. The compost was placed over the compacted sludge to serve as the vegetative support layer for the entire landfill, in lieu of imported topsoil. The compost exhibited easy handling characteristics, contrary to the non-composted wastes, and is not susceptible to erosion.

Vegetation is an essential part of the water balance cover design. The composted blend did not require fertilizer. Grass seed germinated in just a few days and healthy vegetation was established in a matter of weeks. The only apparent drawback was some isolated pockets of vegetative distress, believed to be caused by methanogenesis within relatively fresh sludge placed on-slope prior to the final cover, but not due to the compost itself.

WATER BALANCE DESIGN CONCEPTS

Final Cover Infiltration - The purpose of a final cover is to reduce surface water infiltration to the waste. The final cover for the paper mill landfill was modeled with water balance calculations, which consider long-term climatic effects and specific conditions, e.g. slope geometry, vegetation, permeability, porosity. These calculations are based on relatively simple concepts that borrow from hydrogeology, soil mechanics and agricultural engineering. A simple water balance model for a single layer soil system is shown in Figure 1.

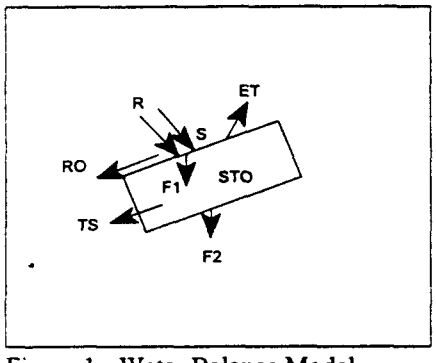

Figure 1 - Water Balance Model

The mass balance equation for the soil surface is:

$$R = F + ET + RO$$

Where:

$$R = \int_0^t r\,dt,\ r = \text{steady rainfall rate}$$

$$F = \int_0^t f\,dt = F_1,\ f = \text{infiltration rate}$$

$$\left.\begin{array}{l} S = \text{Surface Storage} \\ ET = \text{Evapotranspiration} \end{array}\right\} = 0$$

$$RO = \text{Direct Runoff}$$

The terms R and F can be considered as flux rates with units of [L/T]. Consider a steady rainfall associated with a 24-hour, 25-year storm, which might total 6 inches. The equivalent flux rate impinging on the ground is 0.25 inches/hour. Now consider a soil layer with a saturated hydraulic conductivity, K_s, of 10^{-4} cm/sec, or an equivalent flux of 0.142 inches/hour. At the onset of rain, the infiltration capacity, f_c, or boundary flux is governed by the capillary suction forces within the pore space but cannot exceed the rainfall rate, as shown in Figure 2.

The infiltration capacity, hence the boundary flux, decreases with time due to the reduction of the capillary forces as the pores near the surface fill with water. At time, t_p, when the surface pore space becomes saturated, runoff begins and the infiltration rate across the top boundary is limited saturated hydraulic conductivity. For a design storm event, t_p is relatively short compared to the duration of the rain, t, so the variation is typically neglected infiltration rate, f, is assumed to equal K_s. The cumulative infiltration, F, is calculated as K_s multiplied by time, t.

The fate of the water once it enters the soil system is of interest for completing the water balance calculation. The surface soil has a porosity that may vary up to 50%, that is, the potential volumetric pore water storage capacity is 0.5. This varies with soil type, compaction effort and root penetration. The available volumetric water content, θ, contained within the pore space can vary from near zero (in extreme drought conditions) to the full porosity value (completely saturated) depending on prevailing climatic conditions.

As the available pore space becomes saturated, a 'wetting front' moves downward through the soil, more from the influence of capillary suction forces than from gravity. The available storage in the surface layer of a soil cover system is expressed as the difference between the total porosity and the initial volumetric water content, multiplied by the average layer thickness.

During a seasonal or climatic wetting and drying cycle, the stored pore water at any given time is likely somewhere between dry and completely saturated, and the remaining pore space is available for storage of infiltrated water. In periods of drought or high potential evaporation conditions, the stored pore water is radiated back to the atmosphere, assisted by plant uptake. During wet spells or low evaporation conditions, pore water may migrate within the surface layer either as lateral seepage (parallel to slope) or as vertical seepage. The availability of water to migrate through the bottom of the surface layer is described by the mass balance equation:

$F_1 = STO + TS + F_2$

Where: STO = Soil Storage, $\theta_s - \theta_i$

θ_s = Saturated Volumetric Water Content

θ_i = Initial Water Content

TS = Tangential Seepage
May require drainage in surface layer

F_2 = Infiltration Below Surface Layer
(becomes leachate in a single-layer system

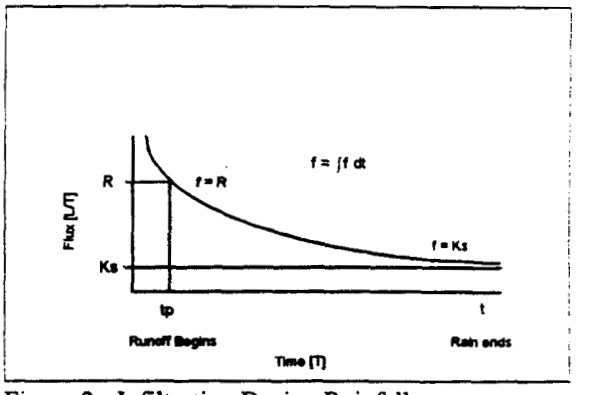

Figure 2 - Infiltration During Rainfall

In a landfill side slope cover, compacted soil layers offer anisotropic conditions that provide preferential pathways to seepage movement. The lateral or tangential seepage can be modeled as a confined porous layer, with the seepage rate governed by the horizontal saturated hydraulic conductivity, K_h. The vertical seepage, e.g. percolation into a deeper soil layer or into the waste, is controlled by the vertical saturated hydraulic conductivity, K_v. Typically, K_h is 2 to 4 times K_v in a compacted embankment or similar earth structure.

The vertical seepage or flux at the bottom of a given soil layer is limited by the lesser hydraulic conductivity on either side of the soil boundary. This is the 'path of lesser resistance' concept that forms the basis for the compacted barrier layer. Ostensibly, if the lateral conductivity of the surface layer is greater than the vertical conductivity of the barrier layer by at least an order of magnitude, the water in the surface layer is 10 times more likely to migrate as tangential seepage within the surface layer, rather than migrating down into the barrier layer. This concept is useful for modeling the removal of water from within the final cover system, and can be put into practice in the field by careful selection of cover soils. The tangential seepage component can be substantial, possibly requiring drainage to prevent excess pore pressures within the cover layer.

Tangential seepage, along with direct runoff and evapotranspiration, are the primary mechanisms that remove water from the final cover system, thus limiting infiltration to the waste. The process of water removal from the cover soil, i.e. 'infiltration recovery,' is enhanced by a well developed vegetative root system, which functions to

1. increase the soil porosity and pore water storage capacity,
2. provide a preferential lateral seepage pathway, and
3. enhance evaporation of pore water through root uptake.

Computerized modeling of final cover system balances precipitation and temperature and vegetation dependent evapotranspiration, e.g. Thornthwaite's equation, with estimated soil moisture levels. On a yearly basis with typical climatic conditions, PET can usually be shown to far exceed precipitation even in the wettest of regions. In other words, the annual water balance is negative, so provided that pore water storage within the surface layer is adequate, i.e. there is sufficient layer thickness and healthy surface vegetation, the calculated infiltration is relatively low. In practice, conventional final cover construction techniques result in built-in secondary porosity, e.g. clodding and/or inconsistent compaction. Conventional final covers lose long-term effectiveness due inherent drawbacks, described below, or due to loss of vegetation is that leaves the surface susceptible to erosion and dessication cracking.

CONVENTIONAL FINAL COVER DESIGN DRAWBACKS

Many regulatory jurisdictions require a maximum permeability of 1.0×10^{-7} cm/sec within the compacted clay layer over the entire landfill surface. This requirement is unrealistic for many industrial landfills, because the covers are constructed mainly on slopes, not level ground. The soft, highly compressible wastes yield under the weight of construction equipment, making the surface inaccessible to construction equipment. Compaction of clay over the yielding waste to meet the permeability requirements would have been difficult to achieve, if not impossible.

The biggest drawback to compacted clay covers is the tendency for cracking, typically through desiccation, which leads to increased surface water infiltration and promotes instability or ground water contamination. In colder climates, cracking and increases in permeability can be brought on by cyclical freezing and thawing. Nearly all wastes, including paper mill wastes and MSW, undergo long-term settlement, which induces cracking and loss of positive surface drainage. Cracking renders a conventional clay cover ineffective in a just a few seasons.

Compacted clay barriers typically add $20,000 to $40,000 *per acre* to the cost of the final cover. In areas where suitable clay is scarce, e.g. western Massachusetts, estimates for imported clay may run as much as $25 per cubic yard, which can add $100K *per acre* to the estimated landfill closure costs. Surface stabilization techniques required for construction of a conventional clay cover would have further added to the cover construction costs.

Many final cover designs incorporate flexible membranes with other geosynthetic components as the infiltration barrier. Such designs are accepted in nearly all regulatory jurisdictions and are in wide use. Though not as sensitive to settlement, synthetic membrane covers are not without drawbacks. Besides the initial capital costs, similar to that of a compacted clay barrier, side slope stability is a big concern. Numerous landfill cover failures have been attributed to veneer sliding of the cover soil above a flexible membrane, typically destroying the membrane itself.

More times than not, veneer failures are caused (or exacerbated) by inadequate internal drainage, i.e. build up of excess pore water pressure in the cover soils above the membrane. Pore pressure buildup can be prevented through the use of synthetic drain layers, but this can easily double the cost of a synthetic cover. In addition, the placement of geosynthetic components in contact on side slopes steeper than 4H:1V has been shown to create a potential low-friction interface boundary that can also promote veneer instability.

A problem inherent to both compacted clay barriers and synthetic covers is the tendency to trap the inherent moisture in the waste through the prevention of upflux. This can be a contributing factor to excess pore pressure buildup in side slopes constructed of paper mill wastes. The high initial moisture contents can persist indefinitely if drainage is inadequate and upflux is limited. An often overlooked problem is that the lack of upflux cuts off sustaining moisture to the vegetative cover during periods of drought. This condition promotes erosion and contributes to higher vegetation maintenance costs - in some cases, irrigation is required.

CONCLUSIONS

This project is a showcase of innovative technologies that turned several waste disposal liabilities into several economic and environmental benefits. The water balance cover design, with its less stringent permeability requirements, and the use of select industrial wastes and composted waste blends in lieu of soils, offer reduced construction cost relative to conventional landfill final cover designs. The composted paper mill and animal/food waste required no fertilizer, nor is the compost susceptible to erosion. The composted blend offers resistance to dessication with year-round support of vegetation. These key requirements for stability and final cover performance ultimately translate into reduced long-term cover maintenance costs. All of the waste products used to make this cover would normally require disposal space elsewhere. This effort conserves land and other resources.

Composting can provide select industries with a long-term waste disposal method that is less costly than traditional landfill disposal. Throughout the United States, emphasis is being placed on waste reduction, natural resource conservation, and the beneficial reuse of waste products in lieu of raw materials. The innovative use of paper mill residuals and other industrial byproducts as a component of "manufactured topsoil" or, even more simply, as daily cover for municipal landfills, can be used to solve difficult and expensive solid waste disposal problems. Mining and minerals processing, paper/pulp and other heavy industries annually produce thousands of tons of soil-like waste materials that can be composted with agribusiness wastes for beneficial use. These alternative disposal means require a certain degree of regulatory "buy in," thus more effort is required on waste generator's part than simply signing a contract with a waste hauler. However, the potential cost benefits far outweigh the effort.

This unique landfill closure met with strong regulatory support and required relatively minimal permitting effort. Landfill airspace is finite, and as future permitting and landfill construction, i.e. disposal costs, for new landfills inevitably becomes more expensive, alternative uses of industrial waste products, including composting and soil substitutes, becomes a sensible solid waste solution for both public and private sectors. Through beneficial use demonstrations, alternative waste disposal concepts will gain wider acceptance, alleviating permitting concerns.

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