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Design Rationale for Construction and Monitoring of Unsaturated Soil Covers at the Rocky Mountain Arsenal

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ABSTRACT: Unsaturated soil covers were designed for contaminated areas of the Rocky Mountain Arsenal, a high-profile hazardous waste facility located near Denver, Colorado, USA. The soil cover system has three functions: control infiltration, control erosion, and prevent biota intrusion. These three functions are achieved by means of unsaturated soil, capillary barrier material, and crushed concrete. This paper provides an overview of the rationale used to design each of these components, the challenges presented by the interdependent criteria, and the post-construction monitoring program.

INTRODUCTION

The use of unsaturated soil covers to isolate hazardous waste from the surrounding environment is considered an alternative approach for waste containment within the US regulatory framework. The Rocky Mountain Arsenal (RMA) site, located 18.5 km northeast of Denver, Colorado, USA, is a hazardous waste facility regulated under the US Environmental Protection Agency's (EPA) Superfund program. A key element of the cleanup remedy was to interrupt the exposure pathways by (a) placing the most contaminated soil and structure demolition debris in two regulated landfills constructed on-site; and (b) consolidating less-contaminated soil below unsaturated soil covers in six highly contaminated areas considered too risky for excavation. These unsaturated soil covers, which span over 183.3 hectares (ha) of RMA, were required to have an 'equivalent' performance to that of a US Resource Conservation and Recovery Act (RCRA) Subtitle C cover with a goal of zero percolation; hence, their designation at RMA as "RCRA-Equivalent Covers."

The RMA covers were required to control storm water infiltration, as well as prevent biointrusion and control erosion. An overview of the rationale used to design each of these components, the challenges presented by interdependent criteria, and post-construction monitoring are presented herein.

In 1942, the US Army established the RMA site to manufacture chemical warfare agents and incendiary munitions for use in World War II. Private companies, including the Shell Oil Company, manufactured pesticides at the site from 1952 to 1982. Disposal practices resulted in contamination of the soil, structures, surface water, and ground-

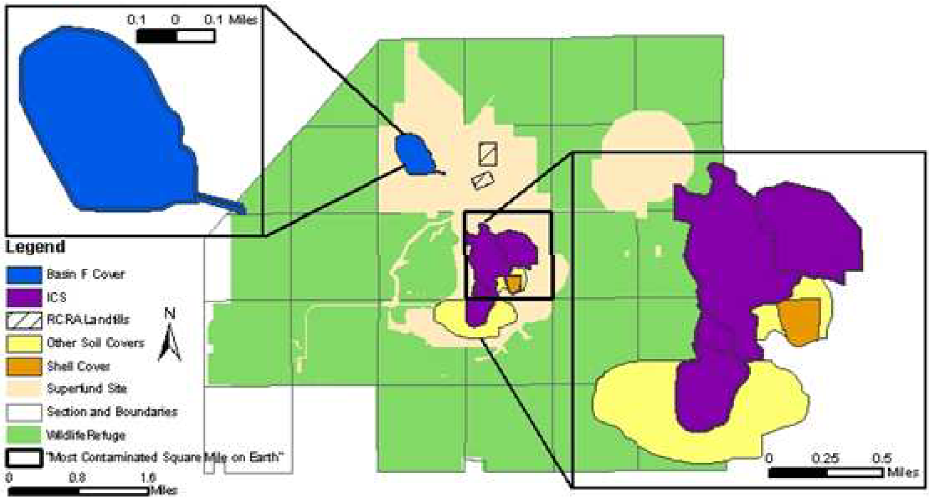

Fig. 1 RMA RCRA-Equivalent Covers (For colour figure, refer to CD)

water to levels that posed unacceptable health risks to humans and the environment.

RCRA-EQUIVALENT COVER DESIGN

The first RCRA-Equivalent cover system designed and constructed at RMA was over the Shell Disposal Trenches area (Shell Cover) and is approximately 8.5 ha. The five remaining RCRA-Equivalent covers (Fig. 1) are the Basin F Cover, which extends approximately 41.8 ha, and the Integrated Cover System (ICS), which encompasses 133 ha and consists of four adjacent consolidation projects (Basin A, Complex (Army) Trenches, Lime Basins, and South Plants Central Processing Area). A cross section of the RMA covers is shown in Fig. 2a and 2b.

The RCRA-Equivalent cover design used both evapotranspiration (ET) and capillary barrier concepts to control infiltration. Two different materials were used for the capillary barrier due to cost considerations and difficulties experienced during construction of the Shell Cover. As shown in Figures 2a and 2b, the RCRA-Equivalent cover systems include the following components, from bottom to top:

- **Biointrusion Component,** designed to prevent biota from accessing underlying contaminated soil and constructed of concrete cobbles (at least 0.41 m thick) overlain by a chokestone layer, which provides a uniform surface for placement of the subsequent capillary barrier material.
- **Capillary Barrier Component,** consists of a nonwoven geotextile for the cover constructed first (Shell Cover). The design for the subsequent covers (ICS and Basin F) was modified to use a 0.03 to 0.08 m-thick layer of well-graded, washed pea gravel.
- **Unsaturated Soil Component**, a 1.22 m-thick layer of soil with specific geotechnical and agronomic characteristics.
- **Vegetation Component**, uses native grasses compatible with a short-grass prairie habitat.

Site-specific objectives and conditions included the use of on-site borrow soil and compatibility of the final cover slopes and vegetation with the designated future use of the site as a National Wildlife Refuge. The large areas that required covers placed additional constraints on the resulting design and construction efforts.

DESIGN RATIONALE

Each of the cover components discussed above provides one or more functions. The biota control function of the covers is achieved by the biointrusion and vegetation components. The infiltration control function is achieved by the integrated response of the unsaturated soil, capillary barrier, and vegetation components. Finally, the erosion control function is achieved by the unsaturated soil and vegetation components, along with the grading and drainage control features of the cover system. The characteristics of each of the cover functions are described below.

Biota Control Function

The primary design criteria for the biointrusion layer were established for the predominant burrowing animal species present at RMA: badgers and prairie dogs. Because the covers must isolate the waste left in place in perpetuity, it was critical that the biota barrier material (BBM) be a highly durable material that was resistant to animals, freeze-thaw action, chemical breakdown from the overlying cover soils, and moisture-induced degradation (e.g. aggressive water attack, acidic aqueous solutions, sulfates) (RVO 1997).

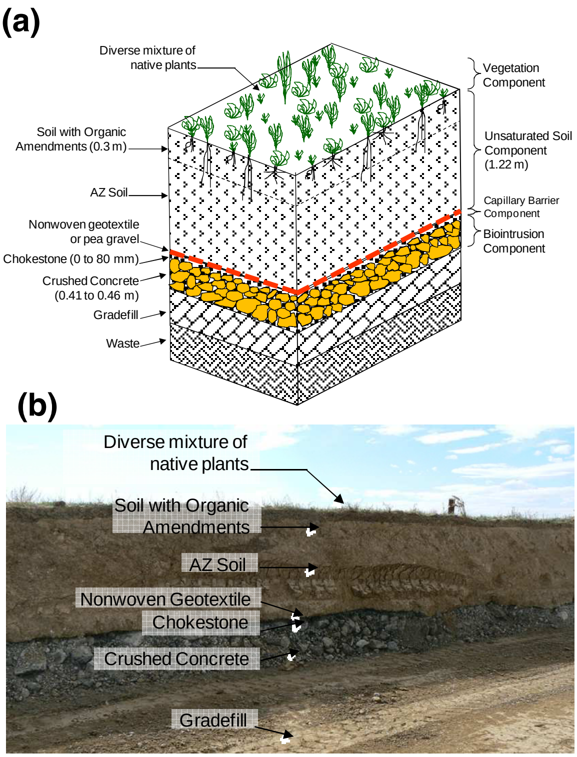

Fig. 2 Cross-section of the RMA Covers: (a) Schematic View; (b) Exposed cut in Shell Cover.

(For colour figure, refer to CD)

To deter invasion by prairie dogs, the seed mix for the cover vegetation included tall grass species. Based on a study (RVO 1997), a gradation with at least 33% of the cobble diameters ranging from 0.15 to 0.31 m would prevent a badger from pushing a cobble to the surface while, at the same time, having voids that are too small to provide access of small rodents like prairie dogs or pocket gophers. A thickness of 0.41 to 0.46 m for the (BBM) layer was selected and the BBM extended 15 m beyond the perimeter of the contaminated soils. The BBM was placed below the 1.22 m-thick unsaturated soil layer to address freeze-thaw and chemical degradation concerns (RVO 1997).

While natural materials, such as crushed granite, were a likely option for use as BBM, an opportunity arose to recycle high-strength concrete from the adjacent and recently decommissioned Denver Stapleton International Airport. Acceptability criteria for this recycled concrete option required a minimum compressive strength of 13.79 MPa and a unit weight of more than 20.4 kN/m^3 (RVO 1997). Laboratory testing of the Stapleton runways and aprons indicated that the concrete was acceptable due to its high density, durability, hardness and evidence of limited aggregate segregation or surface deterioration (RVO 1997). The volume of the Stapleton concrete was sufficient to construct the 183.3 ha of covers at RMA. In addition to meeting the design criteria, recycling the airport concrete was cost-effective, eliminated high truck traffic through the adjacent communities for constructing this cover layer, and promoted EPA's mission to protect human health and the environment through the reduction, reuse, or recycling of materials.

Infiltration Control Function

Unsaturated Soil

Unsaturated soil covers are an alternative approach that has been deployed at a number of sites worldwide (Zornberg *et al.* 2003, Dwyer *et al.* 2006). ET and moisture storage significantly influence the performance of unsaturated soil cover systems. The innovation of this approach is that basal percolation control is partly achieved through storage of moisture that infiltrates during precipitation events until it is released back to the atmosphere through ET.

Based on site conditions and studies available at the time (e.g. Melchior 1997), a quantitative percolation criterion (QPC) of 1.3 mm/year was selected for the RMA alternative cover design (RVO 1998). A field demonstration was conducted to prove the RMA covers would perform equivalent to a RCRA Subtitle C cap. This equivalence demonstration directly compared the measured field percolation from four test plots to the QPC.

Four test plots consisting of unsaturated soil layers, approximately 9.14 m by 15.24 m, were designed and constructed using on-site soils, but without a biointrusion or capillary barrier component. Data for each test plot was monitored between 1998 and 2003 for basal percolation, precipitation, moisture content and overland runoff (Kiel *et al* 2002). Basal percolation was collected in pan lysimeters, which involved a geocomposite drainage layer underlain by geomembrane (RVO 1998). Evaluation of the lysimeter data indicated that all the test plots satisfied the QPC. However, subsequent scrutiny of the moisture content data indicated that the design criterion had been achieved because a capillary barrier had developed within the constructed test plots at the interface between the soil layer and the underlying geocomposite drainage layer.

The requirement to duplicate in full-scale construction the successful infiltration control achieved in the test plots led to additional performance criteria on the cover design process. In addition to adopting a 1.22 m-thick soil layer and incorporating an underlying geotextile to create a capillary barrier as in the test plots, the cover design required quantification of the soil properties, soil placement conditions and agronomic characteristics. An important criterion for selection of onsite soils to be used for cover construction was that their texture be within a defined Acceptable Zone (AZ).

The AZ for soil texture was based on the field demonstration, hydraulic property testing and percolation modeling of the successful test plot soils. The AZ was defined using the U.S. Department of Agriculture textural triangle and identified acceptable ranges of silt, sand, and clay content. In addition, the RCRA-Equivalent Covers were to be compacted within a range from 75% to 85% of the Standard Proctor maximum dry density with the intent of promoting vegetation (TTECI 2005).

Capillary Barrier

Capillary barriers develop when placing a fine-grained soil over a coarse-grained soil or a geotextile. To further the assess the capillary barrier development in the test plots, column tests were conducted to assess four proposed capillary barrier interfaces using a fine-grained soil layer placed over: (a) a geocomposite drainage layer similar to that used in the equivalence demonstration; (b) geotextile with chokestone beneath it; (c) chokestone; and (d) gravel. Each of the proposed interfaces was equally successful in developing a capillary barrier (TTFWI 2005).

The Shell Cover includes a nonwoven geotextile as a capillary barrier material underlying the fine-grained unsaturated soil layer. Use of a geotextile layer also acts as a filter, minimizing the migration of soil particles into the underlying chokestone. The selected geotextile was bright orange to serve as a deterrent to human intruders from excavating into the underlying contaminated soils (Fig. 4)

Vegetation

A diverse mixture of native plants was identified in the design to maximize water removal, be compatible with the surrounding Wildlife Refuge and remain resilient given unpredictable changes in the environment resulting from pathogen and pest outbreaks, disturbances (overgrazing, fire, etc.) and climatic fluctuations. The design of the seed mix for the cover vegetation involved the following considerations:

- Erosion control

- A deep root system to increase the ET contribution
- Cool and warm season species to promote ET for long periods, increasing water storage capacity of the cover soils
- Wildlife deterrence
- Exclusion of forbs to allow the potential use of herbicides for weed control.

The borrow identified for cover construction was subsurface, on-site soil; thus, the design required micronutrients to be added to the top 0.30 m and the clay and calcium carbonate content was limited to 40% and 15%, respectively. As previously mentioned, the 1.22 m-thick soil layer was placed at a relatively loose density ranging from 75% to 85% of the Standard Proctor maximum dry density to enhance vegetation growth.

Erosion Control Function

The design objectives included minimizing erosion by wind and water as well as maximizing runoff and minimizing ponding. Calculations for long-term erosion due to storm water and wind predicted a soil loss below 10 mm in 100 years. As a result, an additional 0.15 m of soil was added to the minimum cover thickness estimated to be needed to meet the percolation criteria (1.07 m) for a total cover thickness of 1.22 m.

Vegetation

Once established, plants are expected to dissipate wind energy and reduce eolic erosion. The shallow root system of seeded native plants enhances the soil surface resistance to water and wind erosion. In addition, plants intercept some of the rain before it impacts the ground surface, thereby reducing the potential for water erosion.

Cover Configuration

The slope selected for the cover design was 3%. In addition, overland flow lengths were limited to 102 m to minimize rill and gully formation. Therefore, to minimize the amount of gradefill needed to achieve the overall 3% slopes, a “broken back” design was adopted that consisted of long, low slope drainage channels that cut through the large cover areas. This minimized the overall cover height and created multiple drainages to direct storm water flow. The final design for all the RMA RCRA-Equivalent covers includes approximately 34 km of drainage channels ranging from 31 to 460 m in length, at grades ranging from 0.3% to 1%.

Fig. 4 Soil placement over the orange nonwoven geotextile used as capillary barrier in the Shell Cover (For colour figure, refer to CD)

A full RCRA Subtitle C cover was designed where concentrated flow would occur in the low drainage slopes. The Subtitle C cover system includes a geosynthetic clay liner, a 1.5 mm-thick geomembrane, a geocomposite drainage layer, and gravel with a slotted drainage pipe down the flowline. In addition, the channel surface is lined with concrete to reduce variability in the final drainage surface and promote storm water flow off the cover.

POST-CONSTRUCTION MONITORING

Construction of the Shell Cover was completed in 2007. The five other RCRA-Equivalent Covers are expected to be completed in 2010. Until the vegetation is fully established, the performance of the RCRA-Equivalent Covers is rigorously monitored to assess functionality. Generally, monitoring of the covers includes visual observations of the cover for damage, inspection of the vegetation, and percolation monitoring using lysimeters. In addition, the Shell Cover is instrumented with water content reflectometers to measure moisture content within the cover soil. Visual inspections and percolation monitoring is conducted monthly, qualitative vegetation inspections are conducted semiannually, and quantitative vegetation inspections are performed annually. *Annual Cover Reports* that document inspection findings, percolation monitoring data, vegetation assessment data, and maintenance activities, are expected to be issued in November of each year.

Long-term monitoring of the biointrusion and capillary barrier components is not conducted because they are located beneath the 1.22 m-thick soil layer. However, any breach in these components can be observed during monthly inspections conducted for burrowing animals through the soil component of the cover. Immediate removal of prairie dogs is expected to keep badgers away from the covers, as prairie dogs are one of their chief prey. Settlement monuments were installed to monitor for soil loss and/or settlement of the entire soil cover. The monuments consist of a pipe and base plate that sit on top of the BBM layer and extends to the cover soil surface. These settlement monuments are monitored as part of the cover inspections to identify needed repairs such as rills, gullies, excessive sheet erosion, settlement, indications of ponding, and overall integrity of the cover drainages.

CONCLUSIONS

The design of an alternative cover for containment of highly contaminated waste has inherent constraints that result from the biota, infiltration, and erosion control functions that must be met by the cover system. In particular, design and construction of these components required integration of multiple site-specific criteria to achieve a compatible, interactive system design. As monitoring data become available, the functionality of the cover systems will be regularly evaluated and, ultimately, a determination of an “operational and functional” cover will be made.

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