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LESSONS LEARNED FROM CLOSING THREE MAJOR LANDFILLS – THE DEVIL REALLY IS IN THE DETAILS

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ABSTRACT

During the past 30 years the author has been involved in a number of landfill closure projects. No two were ever the same, and all were interesting. Three closure projects stand out for the level of effort involved, the rigor of regulatory review, and the issues that occurred during construction, a number of which could have been headed off during design. One site was a major hazardous waste disposal facility and Superfund site; the second, the Fresno Sanitary Landfill, was the oldest sanitary landfill for municipal solid waste in the United States, having opened in 1937 and is also a Superfund site; and the third the San Marcos Landfill in San Diego County underwent final closure with a monolithic evapotranspirative cover composed of blended soils and planted with native plants under a strict court ordered revegetation plan. All three facilities have now undergone final closure and are performing satisfactorily. However, in hindsight there are lessons to be learned and there could have been significant cost savings both in design and in construction.

INTRODUCTION

Final closure of landfills for sanitary waste or hazardous waste is an interesting aspect of geoenvironmental engineering design. Typically final closure occurs when revenue from landfill operations is no longer coming in or may be close to ending. Thus cost savings are often a key design criteria. Many states require that estimated final closure costs be set aside during the landfill operations, to ensure that sufficient funds are available at the time of final closure. For some hazardous waste facilities, particularly those that are Superfund sites under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), little or no funds may be available from the site operators and then potentially responsible parties (PRP), often those who lawfully sent wastes for disposal are required to pay some or all of the final closure costs. It is simply common sense that PRPs would be interested in cost control.

While there is an interest in cost savings at the time of final closure of landfills, there are also regulations that strictly govern the nature of final closure, in particular final landfill covers and also set design criteria that the final closure must be designed for. These include design storm events and design earthquakes. In California, where all the landfills described herein are located, the design earthquake and response of the landfill and final cover to it often governs design and selection of specific final cover components.

Thus it becomes somewhat of a balancing act to meet the regulations, but to do so in a cost effective manner. Cost effectiveness must be measure in both cost of construction and cost of maintenance.

HAZARDOUS WASTE DISPOSAL FACILITY

The first case history is about final closure design and construction at a major hazardous waste disposal site. The four hazardous waste landfills described are located at a closed facility in the Central Coast region of California which is currently listed on the National Priorities List as a Federal Superfund site. Additional information on the landfills and the design efforts can be found in De et al., [2004]. Much of this description comes from that reference. The landfills were constructed directly within existing canyons and liners and/or or leachate collection systems were not constructed beneath the landfills. A site map showing the locations of the landfills in plan view is presented in Fig. 1. Weathered and unweathered claystones, which form the native bedrock in the area, provided limited containment on the excavated base and side-slopes of the landfills. The landfills received bulk and containerized wastes during the period from 1979 to 1989.

After 1989 closure activities were initiated and sludge material removed from on-site ponds and pads was stabilized, mixed

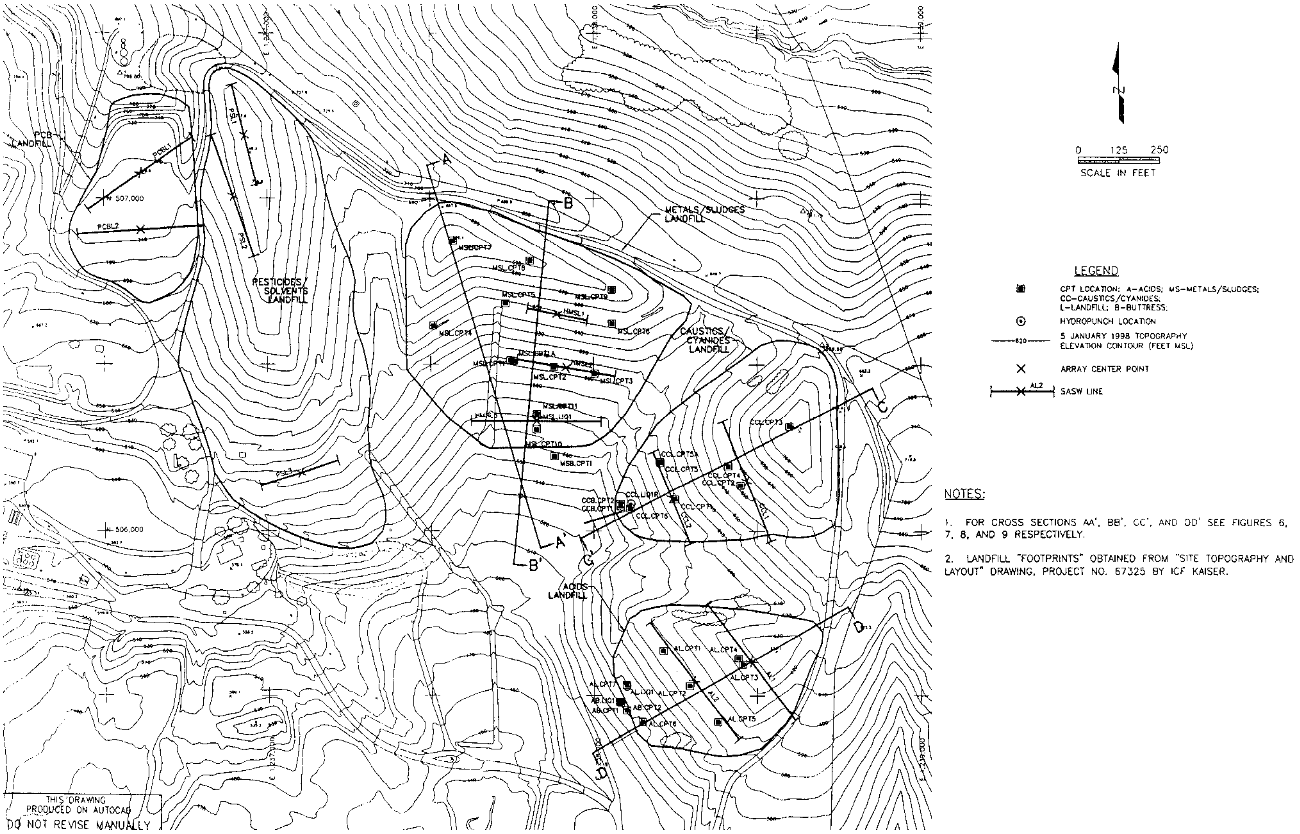

Fig. 1. Plan View of the Site, Showing the Locations of the Landfills and CPT and SASW Investigations

with on-site soil, and placed over the landfills. This pond-bottom material placed over the landfills was up to 40 ft. thick and is referred to as "existing cap material". No other cover had been constructed on the landfills. The total thickness of waste material and existing cap material were up to as much as 150 ft (50 m). The site characterization, design, and construction efforts described in this paper were part of closure activities, whereby engineered cover systems, approved for waste containment in hazardous waste landfills, was designed and placed on the four landfills. This work was conducted following a Consent Decree under oversight of the United States Environmental Protection Agency (USEPA), with the involvement of various environmental protection agencies of the State of California (California State EPA), and local authorities.

Site Characterization

Site characterization was initially conducted on five (5) hazardous waste landfills on the site. The final characterization, design and construction were completed for final closure of four (4) of the landfills, as follows: Pesticides/Solvents (P/S), Heavy Metals/Sludges (M/S), Caustics/Cyanides (C/C), and Acids Landfills. The fifth landfill (PCB Landfill) was scheduled to receive a final cap at a later date.

The site characterization was conducted to evaluate the characteristics of the following elements:

a) General site and subgrade conditions
b) Existing cap material
c) Landfill waste mass
d) Existing toe buttress, below one of the landfills

This characterization was necessary for engineering design analyses, environmental assessment, and for ensuring compatibility of the final cap system with the existing cap material and the waste material.

The site characterization process was challenging for several reasons. Minimal geotechnical data were available for the existing material and also very little technical guidance was available in literature regarding characterization of hazardous waste for geotechnical analyses. Further, any type of intrusive investigation was considered undesirable and difficult because of the potential for exposure to hazardous waste of largely unknown character and the consequent problem of disposal of cuttings and other exposed waste. Several of the key components of the site characterization are described in further details in the following sections.

Site-specific Seismic Hazard Evaluation. The seismic hazard evaluation for this project was based upon the results of the seismotectonic investigation for a nuclear power plant in the relative vicinity of the site, and the site conditions and site-to-source distances specifically evaluated for the site. The design basis earthquake was a Maximum Credible Earthquake (MCE) defined as "the maximum earthquake that appears credible of occurring under the presently known geologic framework." The results of seismic hazard evaluation indicated that MCE for the site is moment magnitude, $M_w = 6.6$ on a thrust fault underlying the site at a distance of 2.6 km. The corresponding bedrock peak horizontal ground acceleration (PHGA) and the significant duration of strong shaking equal 0.86 g and 10 s, respectively.

Geotechnical and Environmental Characterization of the Existing Cap Material and the Waste Material.

Owing to the difficulties of intrusive site investigations, it was initially proposed and accepted by the USEPA to utilize information from the literature to characterize the properties of the hazardous wastes in the landfills at the site. Because the landfills contained a variety of wastes and information in the literature on shear strength and dynamic properties of hazardous waste was limited, it was necessary to complete parametric evaluations utilizing a variety of parameters for the design. This resulted in ranges of performance, most notably deformation during the design earthquake, that were below generally accepted levels of 12 inches (300 mm) and well above this level as well. While the design team was comfortable with this range, and felt if the maximum deformation were to occur they could be readily repaired. This was not acceptable to USEPA. Key to this unacceptability was the responsibility of various PRP groups associated with the site, and that it would be very difficult to obtain the approval of the group responsible for post closure maintenance and repair for such an unknown level of future performance. Therefore, USEPA was insistent on obtaining site specific measurements of shear strength.

As part of the site characterization process, geotechnical and environmental properties of the existing cap material and the waste material were evaluated. The geotechnical properties included classification, index properties, undrained shear strength, and hydraulic conductivity. These properties were necessary for engineering design analyses such as slope stability, settlement and infiltration (for the final cover system). Gas flux tests were completed to assess gaseous emissions from the landfills. Environmental samples were tested for metals, volatile and semi-volatile organic compounds (VOCs and SVOCs), polychlorinated byphenols (PCBs), pesticides, and total recoverable petroleum hydrocarbons. These tests were done in order to evaluate the characteristics of existing cap materials that might be encountered and, possibly, excavated during the construction activities. It was also necessary to evaluate the compatibility of the geomembrane liner material proposed for use in the final cover system with the chemicals in the existing cap material.

Spectral Analyses of Surface Waves (SASW). A non-intrusive SASW investigation was conducted to evaluate the representative shear wave velocity profiles at the site required for seismic site response analyses. SASW measurements were made on lines established at thirteen locations over five landfills and at two locations over native soils. The locations of SASW lines are shown in Fig. 1. The SASW results provided indications regarding the shear wave velocities within the waste material and within the native material subgrade.

Cone Penetration Test (CPT) Soundings. CPTs were completed to evaluate the geotechnical properties of the existing cap material, waste material contained in the landfills, and existing toe buttress. A total of 43 CPTs were completed for four landfills. The CPT locations on the M/S, C/C, and Acids Landfills are shown in Fig. 1. The CPTs were conducted to a maximum depth of 130 ft (39.6 m) below ground surface. The CPT data were utilized to estimate undrained shear strength of the material, which was used in stability analyses.

The following equation [Robertson and Campanella, 1983a and b] was used to compute undrained shear strength, S_u, from measured CPT cone tip resistance:

$$S_u = (q_c - \sigma_o)/N_k \qquad (1)$$

where, S_u is the undrained shear strength, q_c is the measured cone tip resistance, σ_o is the total overburden stress, and N_k is the cone factor.

In geotechnical practice the value of cone factor is typically estimated based on a knowledge of soil type and soil index properties, such as plasticity index. Because of the widespread use of CPT in recent years extensive data currently exists in literature, making proper selection of N_k values for different types of soil fairly routine.

However, the material encountered in the CPTs that extended through the landfill waste mass was not exclusively soils, but included hazardous waste materials, which possess widely varying physical characteristics and consistency. No reference was available in technical literature for estimating the appropriate value of N_k for such material.

After significant amounts of discussion a relatively conservative cone factor of 20 was used. Interestingly this was a value suggested by the field correlations to soil type provide by the CPT contractor that indicated fine grained materials. A cone factor of around 20 is typical of some fine-grained soils.

The CPT data also provided information regarding the general nature of the subsurface material. The CPTs generally penetrated through different layers of material, including the existing cover, landfill waste mass, intermediate cover material between layers of waste, and in some cases the native subgrade of the landfill.

Waste material was typically placed either in bulk or within containers. The CPTs which were extended within the landfills, encountered containerized waste materials. The CPT cone tip resistance indicated penetration through the container as well as through the waste material within the container.

Final Cover System

As per regulatory requirements, the final cover system on the hazardous waste landfills is required to conform to RCRA (Resource Conservation and Recovery Act) requirements. Thus, the final cover system configuration had to be either a cover system prescribed in RCRA guidance (prescriptive) or an alternative cover system (alternative) that either met or exceeded the performance of a prescriptive cover system.

The prescriptive cover system was not considered suitable at this site because of two reasons. First, there is no suitable local source for the low hydraulic conductivity barrier soil (hydraulic conductivity, $k = 10^{-7}$ cm/s) that is required in the RCRA-prescribed configuration. Secondly, the RCRA-prescribed configuration includes an interface between the geomembrane layer and the barrier soil layer. Due to the high design seismic loading, it was deemed possible for a potential critical slip surface to develop below the liner along this interface. Because of this, it was necessary to evaluate the performance of alternative configurations.

In an early part of the design process, various alternative cover configurations were evaluated to identify the appropriate cover configuration for the landfills. The design criteria utilized to evaluate the performance of these alternative cover configurations included:

- Relative infiltration
- Static and seismic slope stability
- Settlement impacts
- Drainage and erosion resistance
- Constructability
- Operations and maintenance

The cover system that was proposed for the P/S Landfill is shown in Fig. 2 and consisted of the following layers (from top to bottom):

- 2-ft (0.6-m) vegetative cover soil
- geonet biotic barrier layer, embedded 1 ft (0.3 m) within the vegetative cover layer
- geocomposite (geonet/geotextile/geonet) drainage layer
- geomembrane (60-mil or 1.5-mm, HDPE double-textured)
- 2-ft (0.6-m) of low hydraulic conductivity ($k \leq 10^{-6}$ cm/s) soil foundation layer

The low hydraulic conductivity foundation layer was composed of recompacted existing soil cover material, mixed with additional soil from anon-site borrow source, thus eliminating the need for costly imported barrier layer soil.

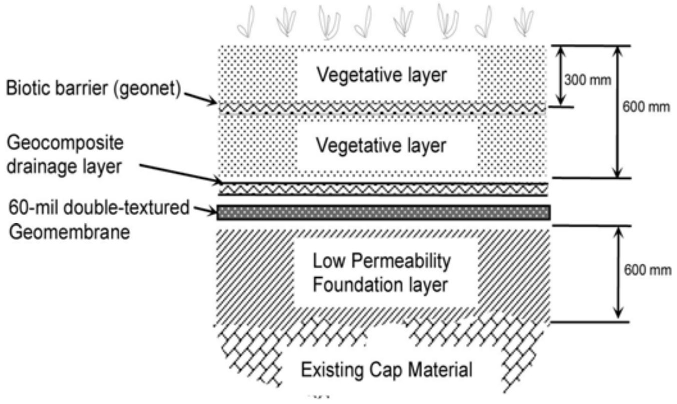

Fig. 2. Selected Final Cap Configuration for P/S Landfill

During the construction of the P/S Landfill cover system, it was found that compacting the existing soil cover material and on-site borrow soil to obtain the necessary low hydraulic conductivity caused the construction process to be extremely slow and difficult. Because of the highly plastic nature of the on-site borrow soil, there was a relatively narrow "window" of dry density and moisture content at which it was possible to achieve the required hydraulic conductivity. Therefore, during the design of the final cover system for the other three landfills, a different final cover configuration was considered, such that the construction process was more efficient, while the cover would perform as well as or better than the previous configuration. This configuration is shown in Fig. 3 and consisted of the following layers (from top to bottom):

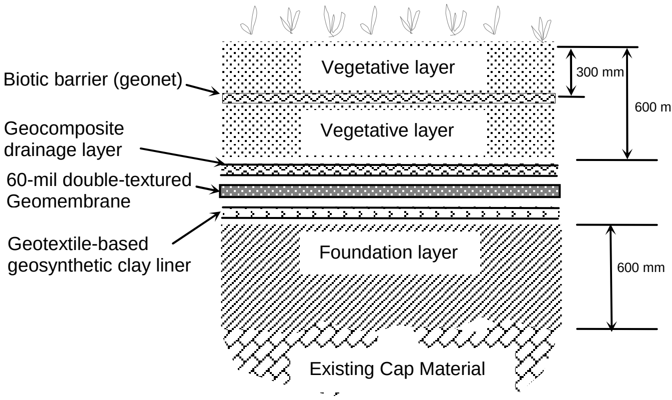

Fig. 3. Selected Final Cap Configuration for M/S, C/C, and Acids Landfills

- 2-ft (0.6-m) vegetative cover soil
- geonet biotic barrier layer, embedded 1 ft (0.3-m) within the vegetative cover layer
- geocomposite (geonet/geotextile/geonet) drainage layer
- geomembrane (60-mil or 1.5-mm, HDPE double-textured)
- geotextile-based geosynthetic clay liner (GCL) barrier layer
- 2-ft (0.6-m) of soil foundation layer

A final cover system, with the same configuration as above, was also installed over the interstitial areas between the landfills.

Lessons Learned

Lesson One, Pay Attention to Constructability Issues and Learn From Previous Work. Evaluation of the constructability of any design is a key element of the design process. However, issues still can arise due to items that are not well understood. Where it can be done, design changes may be appropriate during construction. In other cases such as in this project, the two phases of construction allowed for a good look back at what was learned from the P/S Landfill closure, which occurred first.

Changing a design between phases of a highly regulated project such as closure of a Superfund site can be risky, given the high level of regulatory review these types of projects go through. This is particularly the case where significant effort has already been expended to obtain approval of a design that does not follow prescriptive standards such as a final landfill cover. As noted above the final cover design changed after construction of the first landfill cover. The key change was just constructing the foundation layer as a compacted fill layer, not needing to meet a specific hydraulic conductivity requirement and adding a GCL. Given the highly plastic nature of the material, the high moisture contents needed to attain low hydraulic conductivity were problematic. When the low permeability layer function was instead provided by a geosynthetic clay liner, construction with this material became relatively much easier and thus quicker and cheaper. It was a limited change, but one that became significant.

Lesson Two, Field Investigations May Pay Dividends Even When they Look Difficult or Even Impossible. In the case of these landfills, intrusive investigations were not desirable. However, the use of information from the literature on engineering properties of hazardous wastes had to be used in a very conservative manner. Even if it had been approved, final closure for the worst case condition would have been unnecessarily conservative. But in the absence of site specific information, designing for anything but the worst case, even when professional judgment and experience indicated it was probably not necessary, would have been required. Use of CPT, which we seriously thought would not work given the nature of the waste in the landfills, indicated that the worst case conditions were very conservative. With the site specific data we were able to design final landfill closures that were much less conservative and less costly. In a time when sustainability is more and more important, being less conservative takes on greater importance.

Lesson Three, Pick Your Battles Wisely. As design professionals well versed in a specialty area of design, especially of highly regulated facilities, there is sometimes a level of frustration that develops when some small element of your analyses or design does not obtain approval right away. You may be quite sure your answer is correct, but you have to convince those charged with review and approval. Sometimes it will cost more to argue some aspect, than to simply accept a change. Put aside your frustration, communicate about the situation with your client, and decide whether to fight, or give in saving the battle for another more important issue.

FRESNO SANITARY LANDFILL

The City of Fresno Sanitary Landfill has now been closed and converted into a regional sports park and open space. What was an environmental liability has become a positive element for the citizens of the City of Fresno. However, it took a long time to get to this end result and was very expensive. It was not a complicated project and environmental impacts were not extreme. So why did it go the way it did?

The City of Fresno is located in the great Central Valley of California approximately 180 miles to the southeast of San Francisco. Operations at the landfill began in 1937 and historical investigations have indicated that the facility was operated as the first sanitary landfill in the United States. [Dunn, 2005] Waste disposal operations included the excavation of trenches in the silty sand subgrade materials to typical depths of 10 to 15 feet. No liners were installed below the waste disposal areas, so leachate would typically simply infiltrate into the subsurface. Excavated soils were stockpiled for use as operational cover, which was applied daily. No open burning of waste was allowed. As excavated trenches were filled new trenches were excavated and waste was disposed in a mound extending above the surrounding ground surface. By the time waste disposal operations were stopped in 1987, the landfill had grown to a rectangular configuration with plan dimensions of approximately 1340 m by 430 m or about 140 acres in area. Depths of waste are about 45 feet above surrounding grades and total thicknesses of up to 60 feet. Total volume of disposed waste was approximately 8 million yd^3. In 2000 the United States government granted the site status as a National Historic Landmark as the first sanitary landfill and a public health milestone. This status was not without controversy, since the site was a landfill and undergoing remediation at the time landmark status was awarded.

The City of Fresno took its first actions toward closure of the landfill back in 1981, after investigations begun in the 1970s indicated that the landfill was impacting groundwater below the site. The first closure plan was prepared and submitted to the State of California in 1989. The site became a Superfund site at just about this time as well, due to impacts to groundwater mainly by volatile organic compounds and migration of landfill gas to surrounding areas. The key organic constituents of concern were tetrachloroethylene (PCE), trichloroethylene (TCE), cis-1,2-dichloroethene (cis-1,2-DCE) and vinyl chloride. Some of these compounds were found above maximum contaminant levels for drinking water in the shallow most aquifer at the site. While the site was listed under Superfund the impacts were not serious and it has been debated whether listing was actually appropriate. Principal conclusions of the landfill closure feasibility study were that the landfill should be closed with a final cover using a high-density polyethylene (HDPE) low-permeability layer in the final cover. This varied from the use of a compacted clay barrier layer, which was listed in applicable state regulation. This conclusion was mainly based upon the general lack of suitable clay soils in the general area of the landfill land the enhanced performance of the geomembrane as compared to a compacted clay low permeability barrier layer.

Project Design

Design for the landfill closure project was mandated to consist of the following key elements

- Final cover system with a HDPE geomembrane
- Landfill gas collection and treatment system
- Surface water drainage system
- Contingency leachate recovery system if free leachate was encountered in the landfill.

Based upon negotiations with the United States Environmental Protection Agency (USEPA) the lead regulatory agency for the project, it was agreed that the design would include a Pre-design investigation and design submittals for review and comment at 30%, 60%, 90% and 100% levels of completion. This process would follow a work plan and sampling plan worked out at the outset of the project. This is fairly typical of Superfund projects were remedial design is monitored very closely, but well in excess of design on more conventional projects, where there might be two or at most three design submittals.

The Pre-design investigation proceeded smoothly, and resulted in a detailed characterization of the existing landfill cover, landfill gas quality, and potential borrow source evaluation. Because the project was going to require approximately 1,100,000 yd^3 of borrow soil to complete the final cover, sources of borrow material were a significant portion of the Pre-design evaluation. Testing included on-site soils, near-site soils and non-soil materials that were stockpiled by the City of Fresno at the City's wastewater treatment plant. This included 40,000 yd^3 of dried winery waste materials, and 290,000 tons of dried stabilized sewage sludge also known as biosolids. The biosolids material contained levels of heavy metals sufficiently high that it could not be used for agricultural applications, but could be used below the HDPE geomembrane in the cover as fill to construct the foundation layer of the final cover. This provided an economical borrow source only 3 miles from the landfill and provided the secondary benefit of removing this material from the City wastewater plant where it had long been stored.

Once it had been decided and approved to use the biosolids a full-scale test pad was constructed at the landfill to evaluate compaction behavior of the biosolids. While the material had a grain size distribution of silty sand, it was found that proper moisture was critical to successful compaction. Below optimum moisture content the material compacted very well. But at approximately the optimum moisture content the material began to exhibit sludge like properties and could not be compacted. This information was included in the bid documents for contractor use.

Key aspects of the cover components testing were interface shear tests between various geosynthetic components of the final cover and borrow soil materials that might be used in the final cover. Additionally, because much of the soils at the site were silty sand, hydraulic gradient ratio testing was completed to allow selection of appropriate geotextile materials for the geocomposite drainage layer for the cover. [Luettich et al, 1992]

As for essentially all landfill final closure design, design of the closure of the City of Fresno landfill was an interactive process in which specific cover components were selected and suitability and performance during the post closure care period were verified with engineering analyses.

At the time of design the overall landfill had a relatively uniform grades, but was not suitable for final closure without modification. The foundation layer-grading plan was prepared with the following constraints controlling design.

- Minimization of fill placement
- Minimum 2 feet thickness of foundation layer material
- Uniform slopes and transitions to facilitate geosynthetics layer placement and as an aesthetic consideration
- Minimization of waste relocation

The vegetative layer grading was set to “shadow” the foundation layer except in areas of access roads. Because it was a project requirement that all landfill gas wellheads and irrigation piping be located below grade and a minimum of 12 inches of soil cover be provided over all pipes, the vegetative layer was designed with a minimum thickness of 33 inches.

The final cover configuration utilized is shown in Fig. 4. It consisted of recompacted subgrade of interim soil cover or waste, foundation layer with a minimum thickness of 2 feet, 60 mil thick HDPE geomembrane, geocomposite drainage layer and vegetative layer with a minimum thickness of 33 inches. The cover had the same basic configuration on both the side-slopes and on top deck areas at slopes less than 10%, but differed in some very minor ways to reduce project costs.

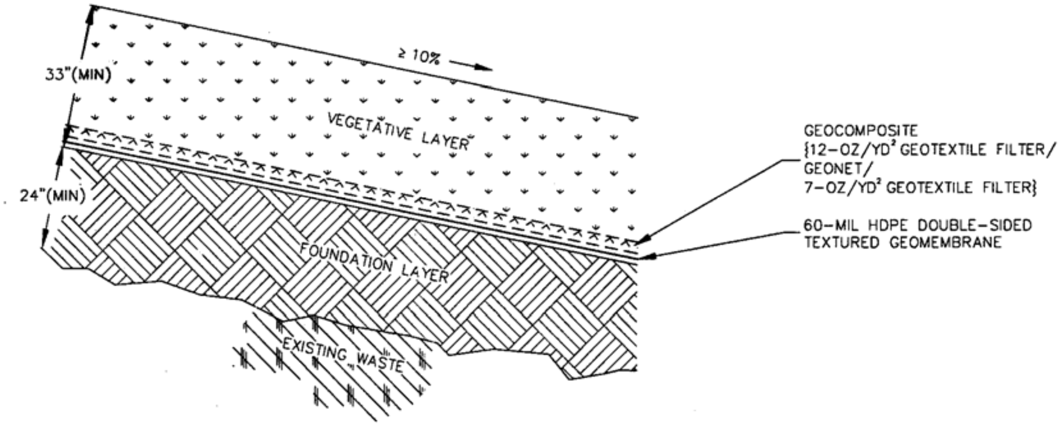

Fig. 4. Side-slope final cover configuration.

First the HDPE geomembrane was textured on both sides on slope areas and textured on the bottom only on the top deck areas. Secondly, a double-sided geocomposite was selected for the side-slopes with a single-sided for the top deck area. In order to facilitate construction compatibility the contractor could use either material on the top deck, but would not be compensated for any additional material cost.

The cover was evaluated for compatibility with waste settlement due to both mechanical densification and waste decomposition. While some wastes had been in place over 50 years, owing to the relatively dry setting of the landfill it was anticipated that significant biologic degradation would still take place in the future. This conclusion was based upon observation of waste materials observed during installation of the landfill gas wells for the pre-design investigation. Only at the very base of the landfill was material observed to be highly decomposed. Settlement estimates were based upon values cited in the literature. Total calculated settlements of up to about 3 feet were estimated with total differential settlement of 8 inches over a distance of 200 feet and localized differential settlements of 6 inches. All calculated settlements were compatible with allowable geosynthetic strains and it was not anticipated that there would be adverse grade changes or grade reversals due to waste settlement over time.

Slope stability was not a major design concern for the landfill cover as generally final slopes were at 5 horizontal to 1 vertical (5H:1V) or flatter. Results of the Pre-design interface testing program indicated that the critical interface for the side-slope cover system was between the geocomposite and the textured HDPE geomembrane with residual interface shear strengths of phi = 21^{o} and a cohesion of 40 psf. This resulted in calculated static factor of safety for slope stability of between 1.9 and 2.3 for the landfill. The peak ground acceleration at the site for the design earthquake was 0.10g and the landfill crest acceleration was calculated to be 0.20g. Using a pseudo-static method of dynamic analysis, yield accelerations were found to be 0.35 to 0.37g. [Makdisi and Seed, 1978] Thus deformations of slopes were determined to be negligible due to the design earthquake.

Late in the design process the City began to plan for post-closure landuse as a park. Their initial concept was to construct sports fields on top of the closed landfill. While considered feasible, discussions regarding additional costs to close the landfill and maintain the sports fields after landfill closure led the City to quickly decide to adopt an alternate plan of post-closure landuse of the landfill as open-space with hiking trails, and development of the area adjacent to the landfill toe as a regional sports park with softball and soccer fields. The City had purchased this property adjacent to the landfill that overlies most of the contaminated groundwater. The park layout is shown in Fig 5.

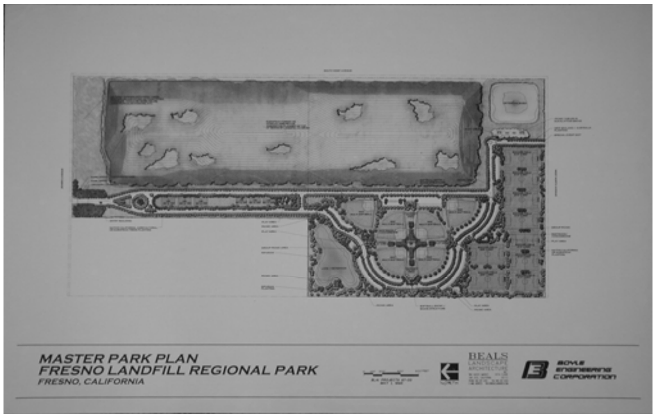

Fig 5. Conceptual plan for park development of the landfill and adjacent area overlying the groundwater contaminant plume. Landfill area is at upper portion of site.

Design Approval

Approval of the 100% design was issued by USEPA in August 1997. The design process had been a lengthy one, starting in early 1994. Review of the design submittals by the USEPA technical contractor had been thorough and comments on the design had been suitable. However, the process had been very slow and costly.

Construction

After approval of the closure design there began a period of negotiation between the City of Fresno and USEPA over the details of remedial construction. This took several years. However, this delay allowed time for design of the groundwater remediation system and sports park to proceed. The three projects, landfill closure, groundwater treatment plant and sports park came together into one construction project. Coordination between the three design teams was well executed, and since the landfill closure design was already approved, only minor non-substantive changes were allowed. These were all at the perimeter areas where the landfill closure interfaces with other elements. Finally in early 2000 the project was bid for construction. Construction started in June 2000 and was projected for completion in fall of 2001. After starting out well, construction came to a halt when the contractor became bankrupt. After some delay, the project restarted and was finally completed in spring 2003 with the park grand opening in August 2003, six years after approval of the closure design.

Overall the construction proceeded fairly smoothly as the design was readily constructible. Required changes to the design during construction were minimal and mainly dealt with perimeter areas to accommodate variations in the extent of waste between the exploration locations from the Pre-design investigation.

Performance

So far the landfill closure has preformed very well and is meeting the design function to control both the ground water contaminant source and landfill gas migration. Compliance monitoring indicates that the landfill gas systems are controlling landfill gas migration away from the landfill and the flare is functioning properly to destroy methane and other contaminants. In general the groundwater treatment system is working to improve groundwater quality and appears to be controlling contaminant migration.

The landfill closure project is complete and landuse is enhanced. What was an environmental liability is now an asset to the citizens of the City of Fresno. The sports and open-space park is in constant use, landfill gas migration is under control, and groundwater contamination is being remediated.

Lessons Learned

Lessons One, Closure Can Take a Long Time. For the City of Fresno Landfill the time span from the first closure plan in 1989 until construction completion in 2003, was an awfully long time. How much more did subsurface contamination impact groundwater in that time? How much more landfill gas migrated from the landfill into the atmosphere? In total what impacts did the slow final closure have on the environment? No data is available to quantify this impact, but we know the impact was there.

How could this process have been speeded up? First, if the site had not been listed as a Superfund site, then the design process would have been shorter, and the nearly three years that passed between final closure design approval and start of construction could have been significantly less as well.

However, the Superfund process was in place, so probably the best way to have streamlined at least the design process. Instead of a Pre-design investigation then four design submittals at 30%, 60%, 90% and 100% completion, it would have been more efficient to develop a conceptual design during the pre-design phase then have submitted draft and final design submittals. The closure design was conventional enough, that a process with fewer submittals would have worked just fine.

Lesson Two, Unconventional Materials are Often Suitable, but be Sure to Check All Aspects of Use. As discussed herein, a large volume of dried biosolids was used in construction of the foundation layer. In the initial evaluation of the suitability of the material, it was tested for engineering properties in the laboratory and performed in a suitable manner classifying as a silty sand material with good compaction and strength characteristics. However, after it had all been transported to the site, it was decided to construct a test pad of the material to evaluate construction characteristics further. While constructing this test pad, it was found that the material compacted very well unless it was wetted to moisture content just above optimum moisture. At that point, it then became a very soupy material that could not be compacted and was not even easy to dry. Fortunately, we found this out before the construction was bid and included the test pad report in the bid documents, including the strong warning about problems with too high of moisture content.

SAN MARCOS LANDFILL

The San Marcos Landfill is located in Southern California at the northern end of San Diego County (County). [Dunn and Gingery, 2006] The site is a canyon landfill of about 100 acres in area and opened in 1976. In the early 1990s the site was upgraded to meet Federal Subtitle D regulations for landfill lining systems by installing a lining system over existing waste, which was as deep as approximately 100 feet. It was planned to place additional waste up to about 200 feet deep over the new lining system. While the San Marcos

Landfill had originally been in a remote area, as is often the case, population growth pressures in the area have resulted in expensive housing being constructed on hillsides that overlook the landfill. New homeowners and others brought extensive pressure on San Diego County to prematurely close the landfill and divert the waste stream to other more distant landfills. After resisting the early closure, the County finally agreed to stop waste disposal operations and waste placement stopped in 1997, at a maximum elevation nearly 150 feet less than permitted.

From that time the County worked with outside consultants to prepare the final closure plan and obtain regulatory approval to allow for final closure construction. It was decided to construct an evapotranspirative (ET) final cover given the arid nature of the landfill area with average rainfall of 8 inches per year. Extensive modeling was completed by the County's design consultant team to support approval of the ET cover as an engineered alternative to the prescriptive cover required by State of California regulations.

Litigation against the County had been a prime consideration in the decision to close the landfill while it still had significant permitted airspace available for waste disposal. Requirements for revegetation were the one key aspect of the litigation that carried through and significantly impacted closure construction. A revegetation plan incorporating native plant types similar to those on natural hillsides in the area around the landfill was developed by landscape architecture professionals under the supervision of the Court and adopted by Court Order. The plan provided the basis for development of applicable project technical specifications for both the final closure construction and revegetation efforts, which were then bid and implemented as separate contracts. The revegetation plan included strict requirements for soil gradation, key soil chemistry parameters and also stipulated the plant palate of local native plant types and specific areas for the differing types of plant mixes.

At the time of project initiation an approved closure and post closure maintenance plan had been completed by consultants to the County. In the closure plan it was outlined that the ET final cover would be constructed of blended soil borrow materials. The closure plan also included unsaturated flow modeling of the ET cover to support the design and development of project technical specifications for the cover materials. The modeling studies indicated that for the soil characteristics evaluated, a maximum hydraulic conductivity of 7.4×10^{-6} cm/sec would provide suitable performance of the ET cover that met or improved upon the performance of the prescriptive cover. The ET final cover varied from 3 to 6 feet in thickness in addition to the existing intermediate cover at least 1 foot thick. Soil blending was required to prepare a material that met the project requirement of both cover infiltration control and revegetation.

In this case the author and the consulting firm he worked for were not the designers of the landfill closure, but instead provided construction quality assurance (CQA) services during closure construction. Unfortunately, the design firm was not contracted to provide services during construction however.

Difficulties with the construction documents were noticed prior to the time construction began and they became particularly problematic during construction. Key issues included the following:

- Inordinately tight gradation requirements based on both the United States Department of Agriculture and Unified Soil Classification System grading criteria, which do not agree.
- Hydraulic conductivity requirements defined by a single number, an allowable mean and finally an upper bound in three different places in the specifications.
- Difficulties attaining hydraulic conductivity levels below the specification over the entire range of allowable relative compaction densities of 87 to 90% relative compaction.
- An allowable compaction moisture content range of only two percent that was not predicated on any specific need for this tight of range.

Lessons Learned

Construction while often difficult was completed successfully and the landfill final closure is performing well, but the whole process could have been much easier and probably less costly too. In this case a number of the lessons were not new, but instead drove home some fundamental issues.

Lesson One, it is Highly Desirable Although not Always Possible to have the Designer Available During Construction. Questions related to the design always come up during construction. Unless an owner is willing to handle this role and has staff with the qualifications to do so, answering these questions can become problematic. When you are in the role of CQA and not designer, but are known to be a design firm, invariably the owner will ask for answers to the design related questions. First, you want to be responsive to your client, but second you do not want to take on design liability. It is a fine line to give advice, but not make decisions. However, strict adherence to the proper contracted role is necessary.

Lesson Two, Pay Attention to the Details of Plans and Specifications. In this project the key problems came from project specifications that were unnecessarily tight. Gradation requirements did not have to be as stringent as they were and they should not have been specified using two different grading systems. The native plants used for revegetation did not need such a tight grading specifications to thrive. There was no need for the very tight allowable compaction moisture content range. These items were not dictated by the needs of the project. The result of these unnecessarily tight specifications were quite simply increased cost which was wasteful. Instead it would have been highly desirable to modify the specifications to allow the contractor as much latitude in construction as would provide a product that met the requirements for the project outcome.

Lesson Three, Be Sure to Test all Required Material Properties over the Allowable Construction Range. In this project testing had been completed prior to construction that showed the required hydraulic conductivity could be attained at 90% relative compaction, but no tests had been done at the lower allowed compaction level of 87%. It was essential to test over this range of compaction moisture content, or there may be a strong potential for failure of materials in the field to meet project requirements. Fortunately this situation could be fixed by adding additional fine-grained soil to the blended soil mix. However, often that is not the case. Failure to do adequate testing before construction makes projects more prone to delays and additional costs, when materials fail to work.

CLOSURE

Landfill closure projects can be challenging to design and construct. They can undergo severe levels of regulatory review that sometimes seems to focus on very small items. Even with this they can still be properly designed, constructed at reasonable cost, and successfully protect the environment. The key is paying attention to the details. This includes the details of how the design is developed such as the number of design submittals, proper detailing of the design, preparation of suitable project plans and specifications that are carefully checked, and then high quality CQA to ensure the project is constructed as intended.

REFERENCES

De, A., R.J. Dunn, and N. Matasovic, [2004], "Site Characterization, Design and Construction for Closure of Four Hazardous Waste Landfills at a Superfund Site", *Proc. of the Fifth International Conference on Case Histories in Geotechnical Engineering*, New York, New York, Paper no. 8.13, 8 pgs.

Dunn, J. [2005], "After Many Years it is Now a Regional Sports Park – Successful Closure Of the Oldest Sanitary Landfill in the United States", *Proc. of Sardinia 2005 - Tenth International Waste Management and Landfill Symposium*, Cagliari, Italy, October 2005, CD proceedings.

Dunn, R. J. and J. Gingery, [2006] "Between a Rock and a Hard Place – Closing the San Marcos Landfill With a Blended Evapotranspirative Cover" *Proc. of the 11th Annual Landfill Symposium, Solid Waste Association of North America*, Nashville Tennessee, CD proceedings

Luettich, S.M., J.P. Giroud, and & R.G. Bachus [1992] Geotextile Filter Design Guide, *Geotextiles and Geomembranes* Vol. 11, pp.355-370.

Makdisi, F.I., and H.B. Seed [1978], Simplified Procedure for Estimating Dam and Embankment Earthquake –Induced Deformations, *Journal of Geotechnical Engineering Division,* American Society of Civil Engineers Vol.104, No. GT7, pp.849-867.

Robertson, P.K. and R.G. Campanella [1983a]. "Interpretation of Cone Penetration Tests, Part I: Sand", *Canadian Geotechnical Journal*, Vol. 20, pp.719-733.

Robertson, P.K. and R.G. Campanella [1983b]. "Interpretation of Cone Penetration Tests, Part II: Clay", *Canadian Geotechnical Journal*, Vol. 20, pp.734-745.