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ABSTRACT

Loyola College in Maryland is a land-locked University in dire need of increasing its academic space. Working with the Baltimore Development Corporation, Loyola purchased a 52-acre parcel of land within miles of their campus which consisted of three closed landfills. The site was Loyola's preferred location to construct a state-of-the-art athletic complex because moving their athletic facilities to an off-campus location would allow the expansion of their academic space. The athletic complex includes a home game field for lacrosse and soccer, two practice fields, administrative and maintenance buildings, stadium, and supporting infrastructure.

Filling at the three landfills began in 1930 and continued on and off until 1985. Landfill materials consist of construction debris, municipal solid waste (MSW), flyash and white goods. Landfill thicknesses range from approximately 60 ft to 190 ft. in the development area.

This paper describes the design and implementation of geotechnical systems to overcome the challenges of building a sports complex on the closed landfills. These systems include grade separation structures, ground improvement, utility protection, and geotechnical instrumentation. This paper will discuss landfill material properties and the design methodology associated with each of these systems.

INTRODUCTION

Loyola College in Maryland was founded in 1852 in downtown Baltimore, Maryland. The College is located in an urban setting and is surrounded by residential neighborhoods, which makes expansion of their existing campus impossible. In order to achieve its proposed Academic Core Master Plan Loyola needed to find more land for the construction of a new athletic complex so that academic buildings could be developed on the land currently occupied by the existing athletic facilities. A search for developable land within a reasonable distance from the college began in 1996. Working with the Baltimore Development Corporation, a site within several miles of the existing college was identified. The site contained three closed landfills: the Woodberry Quarry Landfill, the North Coldspring Landfill and the South Coldspring Landfill. The combined area of the three landfills is 52 acres, which was large enough to accommodate the athletic facility that Loyola wanted to build, so Loyola purchased the three landfill sites. At a later date, the adjacent Sinai property located to the west of Woodberry Quarry Landfill was purchased by Loyola, also for use in the athletic facility development.

The planned development includes a NCAA-standard lacrosse and soccer field with a synthetic turf, a 3-story athletic complex containing locker rooms, offices and associated athletic functions, stadium seating for 7,000 spectators, a synthetic turf practice field, a natural turf practice field with running track, roadways, parking lots and the infrastructure required to support the facility.

SITE HISTORY

Land filling began in 1930's along Coldspring Lane with household trash. This area is known as the North Coldspring Landfill (refer to Fig.1). In 1961, a 96-in. diameter pipe was installed to allow the tributary stream that crosses the site to maintain its flow into Jones Falls, a nearby river. Construction of this pipe allowed placement of landfill materials in the ravine south of the pipe in the area now designated as South Coldspring Landfill. The North and South Coldspring Landfills were used for disposal of mixed refuse and operated as a sanitary landfill. Landfill operations ceased in 1974 and the site was then operated as a transfer station from 1974 to 1979. Fill thicknesses in North Coldspring Landfill range from 10 to 50 ft. The fill thickness in South Coldspring Landfill is about 70 ft.

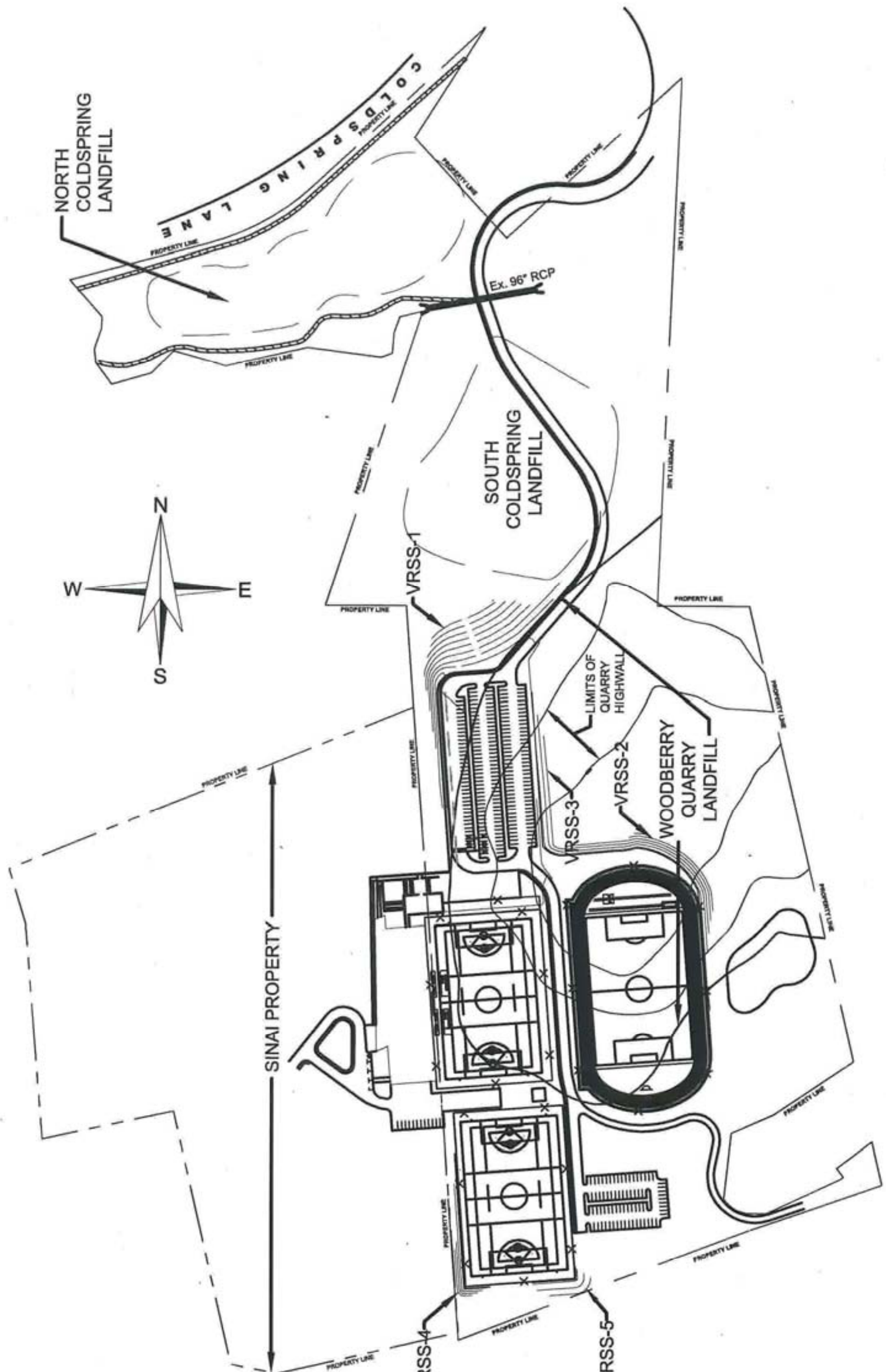


Fig 1. Site Plan

Woodberry Quarry was an aggregate mine from the 1950's until the early 1970's. The quarry has a plan area of approximately 10 acres and is located immediately south of South Coldspring Landfill and adjacent to Jones Falls. After mining of the quarry was completed, Woodberry Quarry was approved for sanitary landfill operations in 1980. It was designed to be a landfill, complete with a clay bottom liner, a leachate collection system and monitoring wells. The maximum depth of filling in the Woodberry Quarry Landfill was approximately 215 ft. The Woodberry Quarry Landfill remained in operation until 1985. A final cover consisting of a one-foot thick layer of clay stabilized with grass seed was placed in 1986.

In addition to these three landfills, available records indicate that soil and rock spoils were placed as a valley fill at the south end of the site. This soil/rock fill zone is located immediately south of the Woodberry Quarry Landfill and consists of spoils from the quarry operation before the municipal solid waste (MSW) was placed in the abandoned quarry.

SUBSURFACE CONDITIONS

Site Investigations

A review of available records indicated that there were at least 14 geotechnical and environmental studies performed at the site prior to 1998 for other proposed site developments. Data from the previous investigations were available to us from the City of Baltimore Department of Public Works, the agency who owned and operated the landfills. The previous data were used to plan subsurface investigations for design of the Loyola facilities.

During the design-phase studies conducted during the period 1999 to 2003, additional geotechnical investigations consisting of 82 test borings and 47 test pits were performed. During the investigations, samples of the MSW were obtained for classification and laboratory testing. The MSW was analyzed for organic content to assess the state of degradation of the waste to be used in conducting settlement analyses.

Subsurface Zones

The subsurface explorations conducted at the site revealed the following zones of subsurface conditions (refer to Fig. 2):

- Zone 1 - Natural soils weathered from bedrock which overlie bedrock;
- Zone 2 - Uncontrolled Soil / Rock fill (no MSW) overlying Zone 1 materials;
- Zone 3 - MSW landfill, 0 to 75 ft thick, overlying Zone 1 materials;
- Zone 4 - MSW landfill, 75 to 185 ft thick, over steep rock slopes of the former Woodberry Quarry; and
- Zone 5 - MSW landfill, 175 to 215 ft thick on the base of former Woodberry Quarry.

Ground Water Conditions

The subsurface explorations identified several ground water conditions across the 52-acre site. Ground water levels in Zones 1 and 2 were close to the natural bedrock surface and perched ground water was encountered in landfill areas.

Perched ground water levels were identified in Zones 3, 4, and 5. The perched water levels occurred at depths of approximately 30 to 40 feet below the surface levels in these zones.

In Zone 3, a deep ground water level was encountered below the North and South Coldspring Landfills near the top of the natural soils.

Deep ground water levels in the bedrock below the Woodberry Quarry Landfill, in Zones 3, 4, 5, are influenced by the leachate collection and pump system installed on the base of the Woodberry Quarry in 1981.

DEVELOPMENT CONSTRAINTS AND CONSIDERATIONS

Project Siting for Economical Design and Construction

In order to achieve a technically feasible and cost effective foundation system for the structures, the facilities were located on the site considering the subsurface zones indicated above. Because of the significant amount of filling, particularly in the Woodberry Quarry, the cost of the building foundations would be expensive if the facilities were located in this area of the site. Also, the depth of filling would result in significant long-term settlement of the facilities.

Due to the undulating surface topography, balancing the cuts and fills was also a significant design factor. Because the cuts would extend into MSW, Loyola was not allowed to export any excess borrow from the site. The City and the regulatory agency also required that all soil and MSW remain on site. Importing fill on a site of this size could also be a tremendous cost impact. Therefore, a design goal was to use all excavated site soils in the site grading while importing only a minimal quantity of soil.

To help with grade transitions, the design would require grade separation structures. However, because of the potential for significant settlements, the grade separation structures would have to be flexible. It was also desired to have them be "green" and blend into the environment.

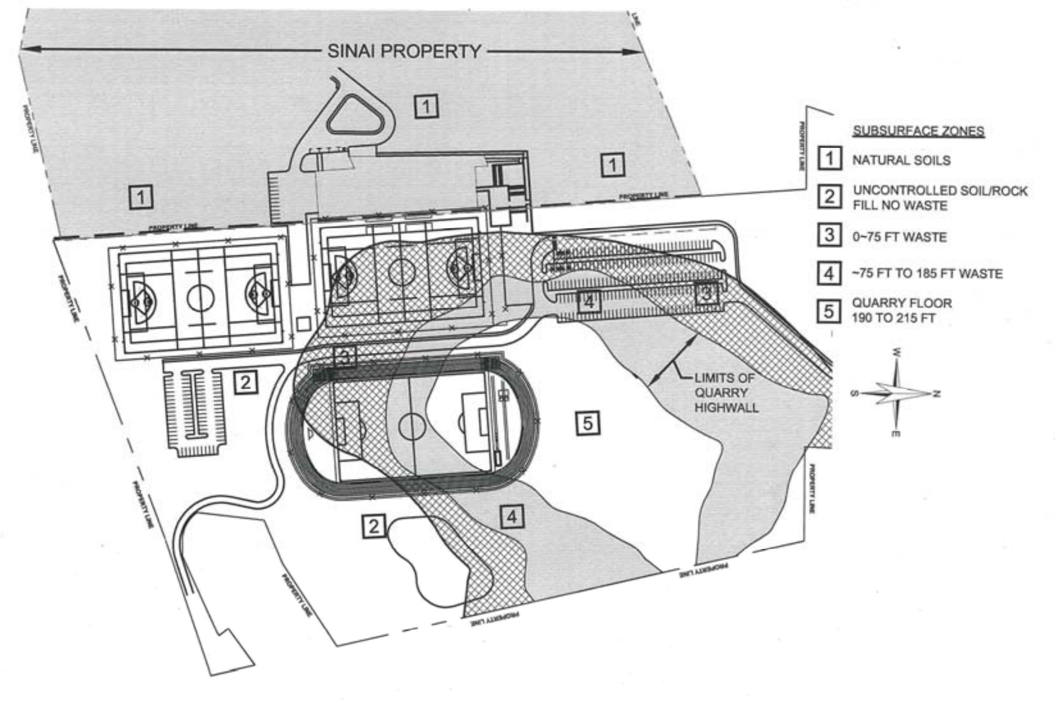


Fig. 2. Subsurface Zones

Finally, since the site was currently forested, the City of Baltimore and the neighbors wanted to keep as many trees as possible in the new development.

In consideration of these constraints and considerations, the facilities were located as shown on Figs. 1 and 2.

Grade Separation Structures

To locate the athletic facilities in consideration of the site constraints and design grades, five grade separation structures of varying length, face slope, and height were required. To accommodate the future settlements and to be as environmentally friendly as possible, vegetated reinforced steep slopes (VRSS) were used for the grade separation structures.

The locations of the VRSS grade separation structures are shown on Fig. 1 and a typical VRSS cross-section is shown on Fig. 3. A general description of each VRSS structure is provided below.

- VRSS-1 is approximately 850 ft long. The maximum face height is approximately 95 ft above the toe of slope. The design face slope varies from 0.5H:1V to 1.5H:1V. The subsurface information in this area indicates that the slope is underlain by natural soil estimated to be up to 35 ft thick.
- VRSS-2 is approximately 530 ft long. The maximum face height is approximately 65 ft above the toe of slope. The design face slope is 0.62H:1V. VRSS-2 is located over approximately 175 to 190 feet of MSW placed during filling of Woodberry Quarry Landfill.
- VRSS-3 is approximately 360 ft long and connects to the north end of VRSS-2. The maximum face height is approximately 45 ft above the toe of slope and the face slope is 0.62H:1V. Similar to VRSS-2, VRSS-3 is located over MSW materials up to 185 ft thick.
- VRSS-4 is approximately 390 ft long. The maximum face height is approximately 45 ft above the toe of slope. The design face slope is 0.5H:1V. The subsurface information indicates that the slope is underlain by approximately 10 ft. of uncontrolled soil/rock/debris fill over 10 ft of natural soil.
- VRSS-5 is approximately 130 ft long. The maximum face height is approximately 20 ft above the toe of slope. The design face slope is 1.5H:1V. VRSS-5 is located above approximately 35 ft of natural soil.

DESIGN CONSIDERATIONS

Design of the athletic facilities, and in particular the grade separation structures, included the following considerations:

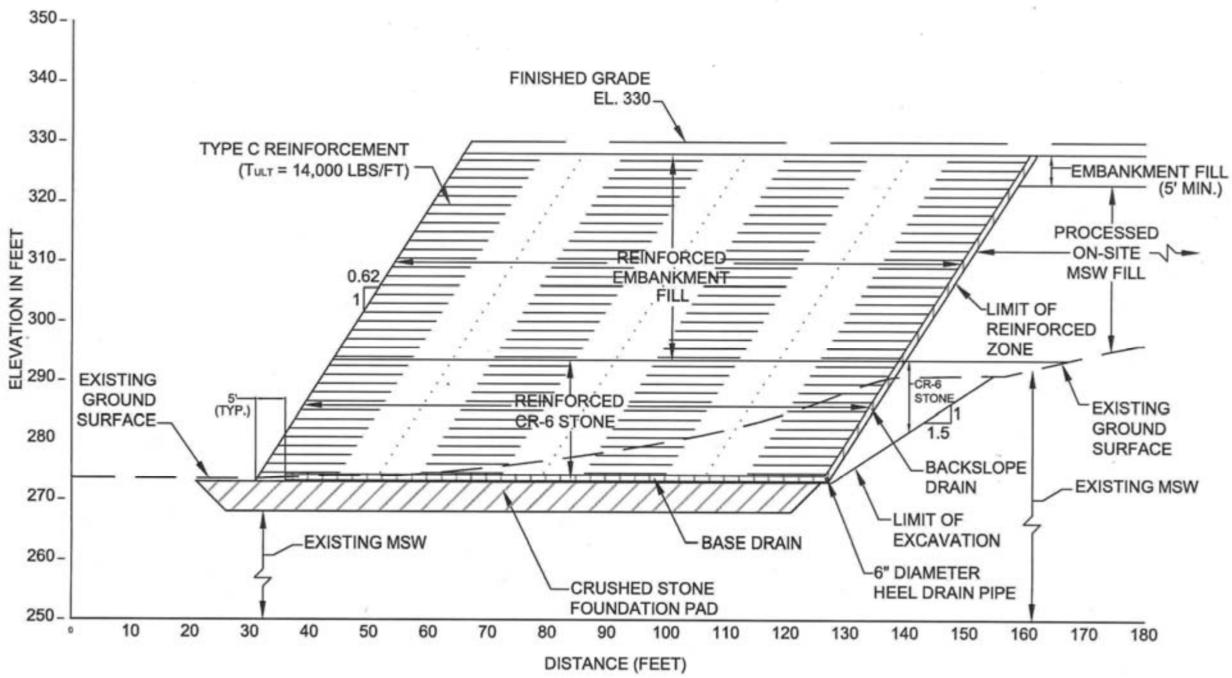


Fig. 3. Typical VRSS Cross Section

- immediate settlement of the MSW during construction;
- long-term MSW settlements during a 50-year service life of the facilities;
- weight and strength properties of the materials used to construct the proposed grade separation structures;
- weight and strength properties of materials below and behind the proposed grade separation structures; and
- achieving a minimum factor of safety against global stability, base sliding, and through the soil reinforcement of 1.5.

Landfill Settlement Relationships

Settlement of MSW landfill materials is characterized as a two-phase process. The first phase settlement consists of rapid mechanical compression as additional load is placed on a landfill. This phase usually ends shortly after the loading is completed and is commonly referred to as "immediate" settlement.

The second phase is characterized by relatively slow, "long-term" settlement, related to landfill degradation under constant load. Long-term settlement begins during landfill construction but it is most often calculated to start soon after a landfill is closed. The time to achieve the end of long-term settlement is not well defined. Some published references indicate the long-term settlement may be complete in 30 to 60 years, but other references indicate long-term settlement may extend more than a hundred years.

The rate and amount of long-term settlement is based on a number of factors, including type of waste, percent of organic material, age, compaction effort, thickness, moisture content, percent solids, lignin content, and the percentage of non-degraded organic material in the landfill at a point in time.

Landfill Settlement Formulas

Estimated settlement of MSW materials has typically been computed using modifications to traditional soil mechanics / geotechnical engineering theories for settlement of compressible soils. The formulas published in "Geotechnical Aspects of Landfill Design and Construction" (Xuede et al. 2002) were utilized to estimate immediate and long-term MSW settlements at the site. Immediate settlements can be estimated using the following relationship:

$$C_c^{'} = \frac{\Delta H}{H_0 \cdot \log(\sigma_1/\sigma_0)} \tag{1}$$

where $C_c^{'}$ = modified primary compression index (also commonly referred to as the compression ratio, CR);
ΔH = change in thickness of waste layer;

Table 1. Summary of Material Properties

Material – Source	Unit Weight (pcf)	Cohesion (psf)	Friction Angle (degrees)	Modified Compression Index, C_c'	Modified Secondary Compression Index, C_α'*	Notes
Bedrock	140	0	45			
Imported Crushed Stone for Embankment Fill and Foundation Pad	145	0	36			CR-6 Stone
On-Site Residual (Natural) Soil Embankment Fill	125	0	30			Silty or Clayey Sand
Existing Soil / Rock Fill	125	0	30			Uncontrolled Fill
Existing Landfill Cover Soils	125	0	30			
On-Site Residual Soil Embankment Fill	115	0	26			Silt or Clayey Silt
Existing Landfill Clay Barrier	120	500	17			
DDC Treated MSW	100	200	32			
Processed On-Site MSW Fill	95	150	25			Layered Soil & MSW
MSW	90	200	30	0.10 to 0.20	0.04 to 0.16	In-place (unexcavated)

* Values of C_α' were back-calculated from optical survey data.

H_0 = original thickness of waste layer;
σ_0 = initial effective vertical stress; and
σ_1 = final effective vertical effective stress.

Long-term settlements can be estimated using the following relationship:

$$C_\alpha' = \frac{\Delta H}{H_0 \cdot \log(t_2/t_1)} \qquad (2)$$

where t_1 = starting time of secondary settlement; and
t_2 = ending time of secondary settlement.

Material Properties

The material parameters that were used in the settlement and stability analyses for the Loyola project are listed in Table 1.

Immediate Settlements

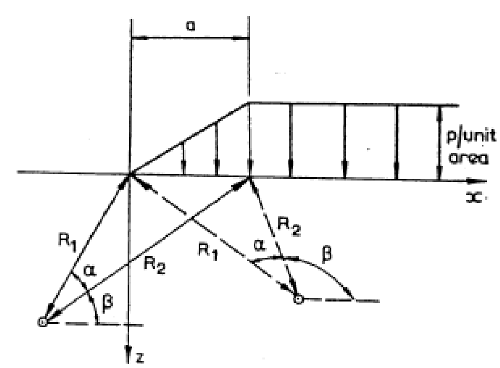
Immediate settlements were computed along the crest and toe of the VRSS-2 and VRSS-3 structures using a) the vertical stress of the embankment load at the crest of the embankment and behind the crest of the embankment and b) the distribution of the applied stress into the underlying MSW material.

Immediate settlements were calculated using the formula for "Loading over Half the Infinite Space" (Poulos 1974) as shown on Fig. 4.

The maximum estimated immediate settlement of VRSS-2 and VRSS-3 is shown in Table 2.

Long-Term Settlements

Long-term settlements are described in terms of strain or percent settlement observed in a log cycle of time following closure of a landfill. The percent settlement is calculated as settlement divided by original height of the MSW mass. The relevant log cycle of time usually relates to the 10 to 100 year time span.



$$\sigma_z = \frac{p}{\pi a}\left[a\beta + x\alpha\right] \qquad \ldots (3.12a)$$

$$\sigma_x = \frac{p}{\pi a}\left[a\beta + x\alpha + 2z \log_e \frac{R_2}{R_1}\right] \qquad \ldots (3.12b)$$

Fig. 4. Loading over Infinite Half Space

Table 2. Estimated Immediate Settlements

Location	Thickness of Existing MSW (ft)	Immediate Settlement (ft)
VRSS-2	155	8.4
VRSS-3	140	5.8

Rates of long-term settlement at the project site were estimated on the basis of optical survey and topographic data developed during the 1986 to 2003 time period.
The available data included:

- City of Baltimore Topographic Plan - This 1986 topographic plan for Woodberry Quarry indicates surface elevations near the time the Woodberry Quarry Landfill was closed and covered. A comparison of the 1986 surface elevations with the December 2002 survey indicates that apparent settlements of the area along the VRSS-2 alignment range from 10 to 20 ft. This settlement is equivalent to a settlement "strain" in the range of 7 to 10 percent of the estimated thickness of MSW materials; and

- Optical Survey of Settlement Points - Optical survey data for settlement point elevations during the May 2000 to December 2002 time period. Settlement points in the vicinity of the Woodberry Quarry highwall indicate an average settlement of 1.5 ft over a 2.6 year period where the estimated MSW thickness ranges from 165 to 215 ft.

Estimated Long-term Settlements

The estimated relationship of the long-term settlement with time for VRSS-2 is presented on Fig. 5. The plot includes:

- assumed 10 percent strain during long-term settlement from landfill closure in December 1986 to May 2000;

- a measured settlement from May 2000 to January 2006, with computed C'_α equal to approximately 8 percent strain per log cycle of time;

- a computed immediate settlement of 7.5 ft for the embankment at VRSS-2 during the period January 2006 to January 2007; and

- estimated range of post-construction settlements, based on C'_α values ranging from 8 to 16 percent, during a 50 year service life.

The computations indicate that the long-term estimated settlements range from 7.5 ft to 20 ft in a 50 year period.

Total Settlement for Stability Analyses

An estimate of total settlement was used in the stability analyses for VRSS-2 and VRSS-3 to compute the length and

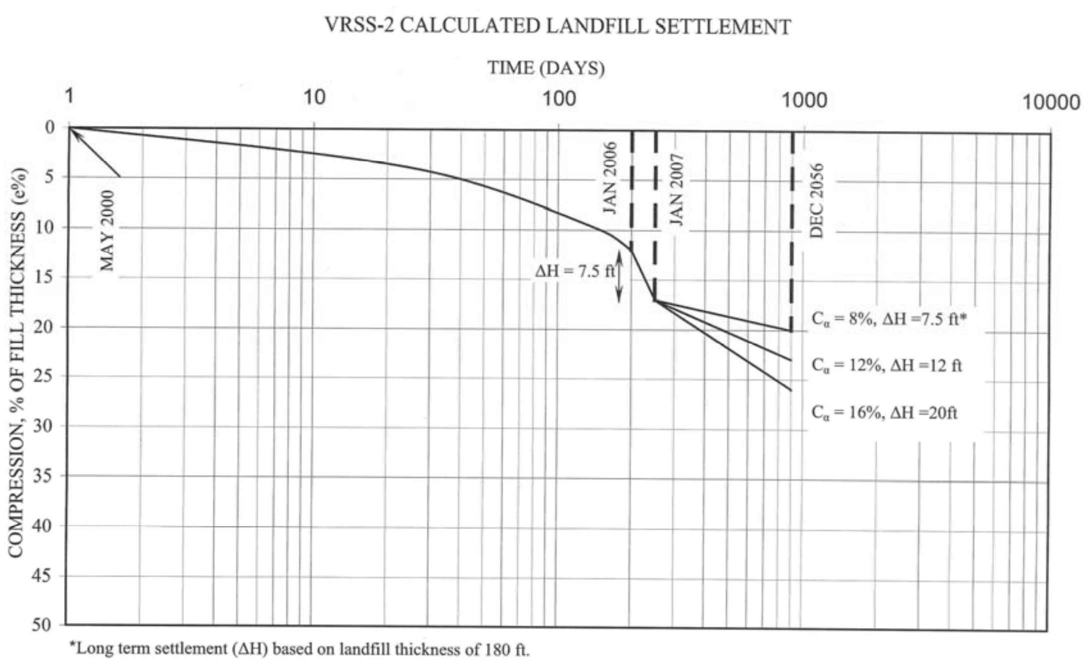


Fig. 5. Plot of Estimated Settlement during Design Life

strength of geosynthetic reinforcement required to provide a minimum factor of safety of 1.5 against all modes of failure over the 50-year design life. The estimated total settlement included the estimated immediate and long-term settlements at intervals along the crest of both VRSS structures. The maximum estimated total settlements used in the stability analyses ranged from 15 ft to 20 ft.

The estimated total settlement was added to the original design height of VRSS-2 and VRSS-3 for the long-term stability analysis. The resulting ultimate heights of VRSS-2 and VRSS-3 are on the order of 80ft and 60 ft, respectively, when considering the maintenance fills that will be required to maintain final design grades over the 50-year life.

STABILITY ANALYSES

Three computer programs were used to analyze the stability and to calculate a factor of safety for selected cross sections of existing and proposed slopes, including the maintenance fills that will be required to maintain final design grades as long-term settlement occurs. The three programs included XSTABL, RSS, and ReSSA as described below. All VRSS slopes were designed to have a minimum factor of safety of 1.5 for all failure modes.

- XSTABL - Computer program XSTABL version 5.2 was used for global stability analyses of unreinforced slopes utilizing Bishop (circular), Janbu (non-circular), and Rankine (block) methods. The Spencer method of slope stability analysis is included in XSTABL and was used for both circular and non-circular surfaces. However in XSTABL, each surface analyzed by the Spencer analysis must be separately specified. Therefore, the use of the Spencer method in XSTABL was generally limited to checking and verifying factors of safety for critical surfaces determined by the other methods.

- RSS - Computer program RSS, version 2.0 was used for local and global stability analyses of unreinforced and reinforced slopes using the Bishop (circular), Janbu (non-circular) and Rankine (sliding block) methods. The RSS program is based on the same algorithms as XSTABL, but does not include the Spencer method. The RSS program generates a range of potential failure surfaces and permits rapid evaluation of the Factor of Safety of the potential slip surfaces.

- ReSSA (2.0) - ReSSA version 2.0 was used to check the results of the RSS analyses and determine the stability and reinforcement requirements for the long-term service condition. ReSSA includes the AASHTO Bishop method to rapidly analyze potential circular failure surfaces with or without reinforcement. This program uses the Spencer method to analyze slope stability, with or without reinforcement, searching either 2-part or 3-part wedge surfaces. The search zones or control boxes are user defined. ReSSA was also used to analyze and check the critical failure surfaces identified by RSS. In addition, ReSSA was used during construction to analyze all of the VRSS slopes due to design changes that were required in order to accommodate differing site conditions.

GROUND IMPROVEMENT TECHNIQUES TO INCREASE STABILITY

Several ground improvement techniques were utilized to mitigate the effects of site conditions that were considered detrimental to the stability of the VRSS structures and other area-wide embankment construction. The selected techniques included:

- Excavation of uncontrolled soil/rock fills at VRSS-1 and VRSS-4.

- Excavation of loose landfill cover soils and a variable thickness of clay barrier material below VRSS-2 and VRSS-3.

- Application of deep dynamic compaction (DDC) to uniformly densify and compact the upper zone of MSW material below VRSS-2 and VRSS-3.

- Use of high-strength geosynthetic reinforcement with well-graded granular materials to construct the embankment slopes.

- Application of DDC to uniformly densify and compact MSW and landfill cover soils exposed at subgrade prior to the construction of area-wide embankments which are outside of the limits of the foundation pads and reinforced zones at VRSS-2 and VRSS-3.

- Use of heavy proof rolling to densify and stabilize cut and fill subgrades composed of soil/rock fill materials.

The limits of the selected ground improvement techniques are shown on Fig. 6.

PROTECTION OF UTILITIES AND LANDFILL GAS SYSTEM COMPONENTS

In early 2008, installation of underground utilities and the landfill gas control system began. A utility corridor was constructed that contains water, telecommunications, electrical, and storm drain lines. The corridor enters the site from the north, runs beneath Coldspring Lane Access Drive and continues beneath the east side of the North Parking Lot. From there, the corridor follows the alignment of Coldspring Lane Access Drive between the Home Game Field and Track and Field, then terminates near the South Parking Lot. The location of the utility corridor is shown on Fig. 7.

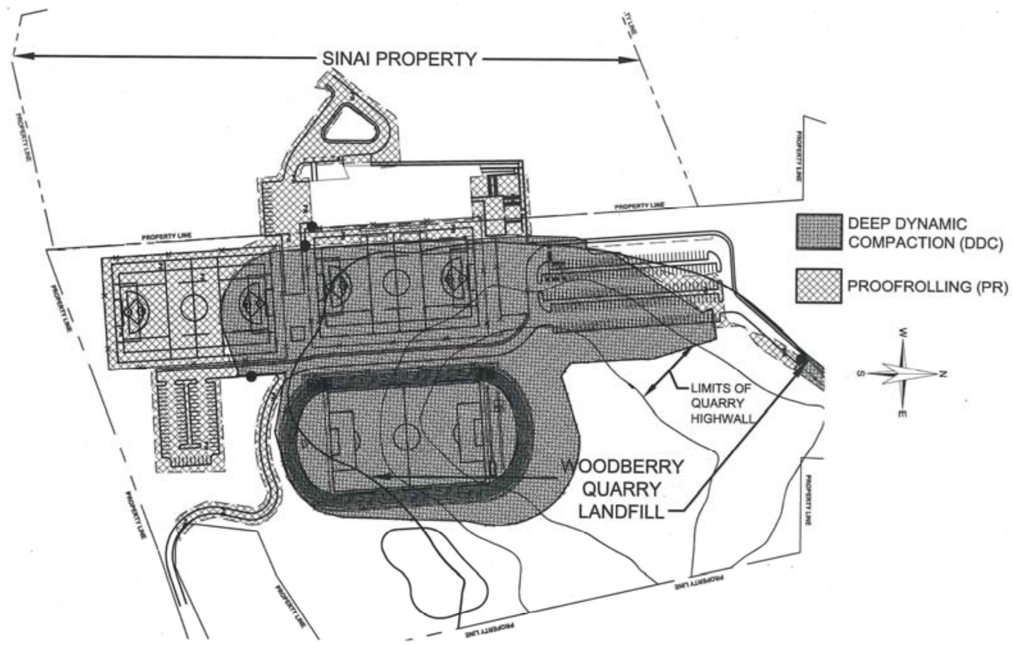


Fig. 6. Locations of Ground Improvement

The landfill gas control system consists of a network of pipes embedded in a layer of No. 57 stone. Above the pipes and No. 57 stone, there is a drainage composite (consisting of a drainage net thermally bonded on both sides to a non-woven geotextile), a geomembrane, and a non-woven geotextile. Above the non-woven geotextile, 12-in. to 24-in. of fill will be placed to reach final grade. The pipe network for the landfill gas control system consists of:

- 8-in., 10-in., and 12-in. diameter corrugated High Density Polyethylene (HDPE) vapor transmission lines;
- 6-in. diameter slotted corrugated polyethylene vapor collection pipes;
- 8-in. and 10-in. diameter corrugated HDPE air transmission lines; and
- 6-in. diameter slotted corrugated polyethylene air inlet pipes.

Estimated Differential Settlements

The thickness of existing MSW, height of new fill, and ground improvement methods along the utility corridor alignment influence the range of estimated settlements. However, the thickness of existing MSW has the greatest influence on the range of estimated settlements. As shown on Fig. 7, the steep highwalls of the former Woodberry Quarry are located beneath the North Parking Lot, northeast corner of the Home Game Field, and Track and Field area. Near the crest of the quarry highwalls, maximum MSW thicknesses are on the order of 10 to 50 ft. The maximum thickness of MSW increases to approximately 190 ft at the toe of the quarry highwalls. In all of the above mentioned areas, there are utilities and landfill gas control system components that could be negatively affected by long-term settlement of the MSW.

Differential settlements along the utility corridor and in the Track and Field Area were calculated to evaluate the long-term effects on utilities and landfill gas control system components. Calculations were performed using a secondary compression index, C'_{α}, of 0.10. This value is based on data cited in case histories of other landfill developments similar to the Loyola project. The results indicate that the majority of differential settlement will occur where the utility corridor and landfill gas control system components pass over the quarry highwalls. Table 3 summarizes the range of estimated differential settlements.

Protection of Landfill Gas Control System and Utilities

Landfill Gas Control System. The major landfill gas control system components of concern are the LLDPE geomembrane liner and the solid vapor and air HDPE transmission pipes, which must remain water-tight. The perforated HDPE pipes are not a component of concern because unlike the solid pipes, they do not have to remain watertight.

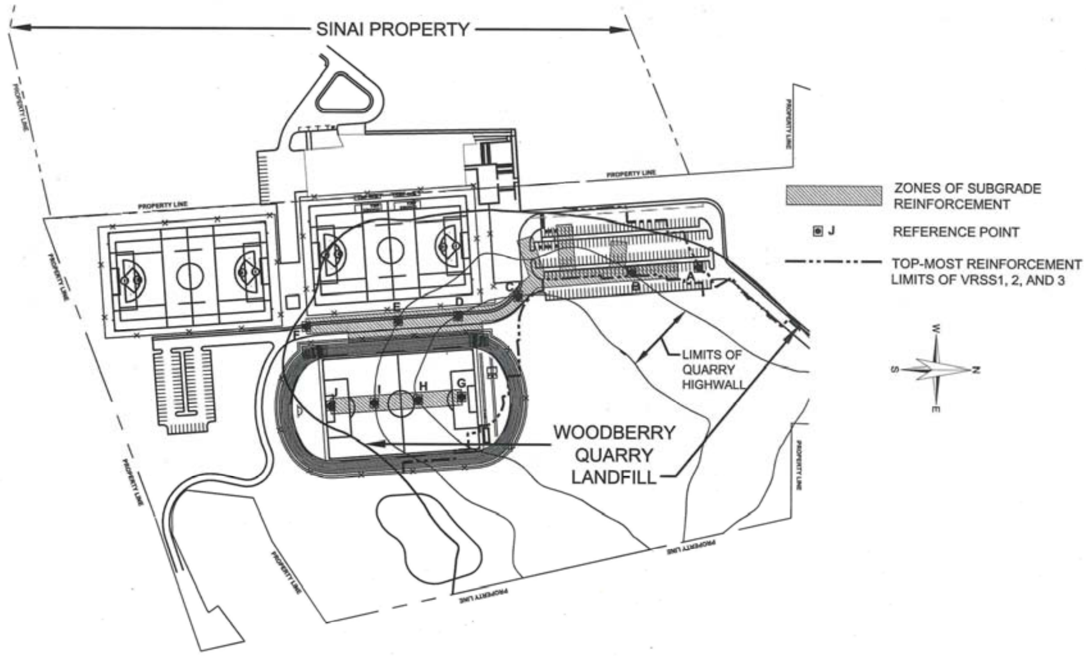


Fig. 7. Utility Subgrade Reinforcement

Table 3. Summary of Differential Settlements

Location	Estimated Differential Settlement[2]
North Parking Lot – north of quarry limits (A to B)[1]	0.0% to 2.0%
North Parking Lot – along quarry highwall (B to C)[1]	3.0% to 7.0%
Coldspring Lane Access Drive – along bottom of quarry (C to D)[1]	0.0% to 0.5%
Track and Field – along bottom of quarry (G to H)[1]	
Coldspring Lane Access Drive – along quarry highwall (D to E)[1]	2.0% to 6.5%
Track and Field – along quarry highwall (H to I)[1]	
Coldspring Lane Access Drive – south of quarry limits (E to F)[1]	0.0% to 1.5%
Track and Field – south of quarry limits (I to J)[1]	

[1] Reference points are shown on Fig. 7.
[2] The estimated differential settlement is a percentage of the plan length between the reference points on Fig. 7.

To reduce the risk of damage to the LLDPE geomembrane liner, the design of the landfill gas control system includes a liner with stress-strain (elongation) characteristics that will allow the liner to elongate by as much as 800 percent without compromising its performance. The system also includes a solid HDPE pipe with joints that can deflect up to 1 degree without breaking their water-tight seal.

To further reduce the risk of damage to the solid HDPE pipes, subgrade reinforcement will be performed beneath the vapor transmission pipes in the center of the Track and Field area and beneath the air transmission pipes adjacent to the utility corridor on the west side of the Track and Field area.

Utilities**.** The majority of differential settlement along the utility corridor will occur where the corridor passes over the quarry highwalls. To reduce the impact of the differential settlement, subgrade reinforcement will be performed beneath the utility corridor between points A and F as shown on Fig. 7. In addition, flexible connections/joints and pipes have been incorporated into the design. Specific comments relative to the individual utilities located within the corridor are provided below.

- Storm Drain Lines – HDPE pipes will be used for the storm drain lines, which can withstand up to 10 percent deflection. In addition bell and spigot joints that can withstand 2 to 3 degrees of rotation will be used. The connection of the HDPE pipes to the manholes will be designed to accommodate rotation.

- Electrical and Communications – Originally, it was planned to encase the PVC conduit in concrete for the

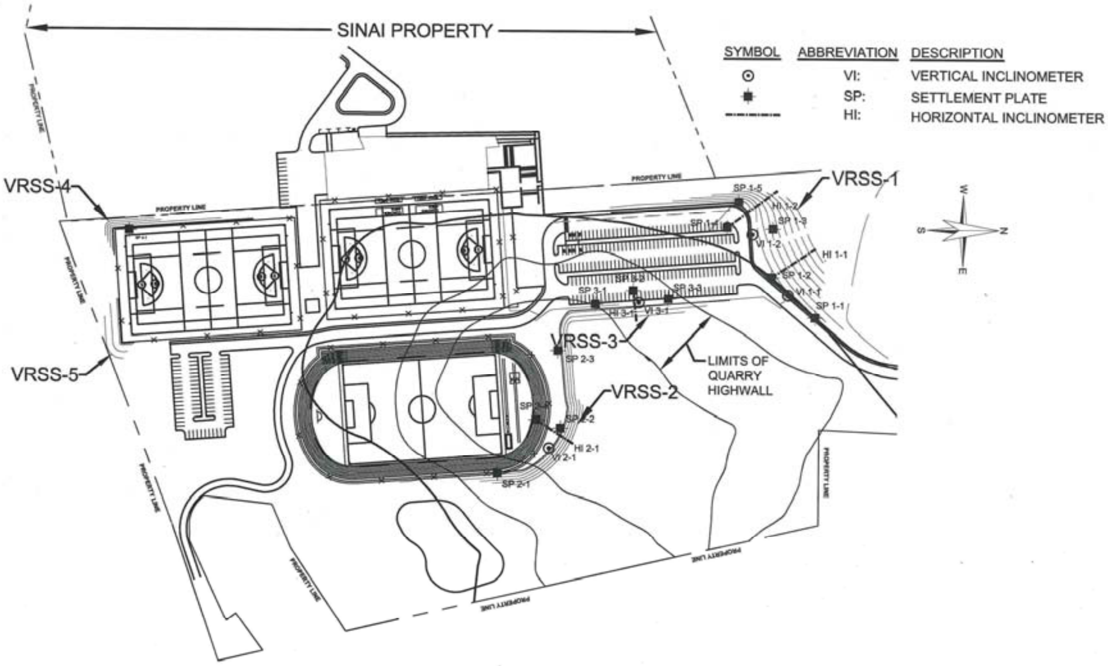


Fig. 8. Instrumentation Locations

electrical and communication lines. After considering the anticipated differential settlement that will occur along the utility corridor, it was decided to not encase the PVC conduit in concrete due to the high chance for the conduit and utility lines to shear as differential settlement occurs. The revised design also incorporates slack and extra wiring at handholes.

- Water – Ductile iron pipe will be used for the water lines. The design of the water line will incorporate connections that allow 15 degrees of deflection where the water line crosses over the quarry highwalls and connections that allow 5 degrees of deflection along other portions of the line.

Subgrade Reinforcement. To reduce the negative long-term impacts to the utilities and landfill gas control system components, the subgrade beneath the utility corridor and the transmission pipes at the Track and Field area will be reinforced with a high strength geogrid. The approximate limits of subgrade reinforcement are shown on Fig. 7. Subgrade reinforcement will consist of over-excavating to a depth of 24 in. below the utility trench subgrade level, installing a layer of high strength geogrid, and placing a 12-in. layer of compacted AASHTO No. 57 stone. Above the No. 57 stone, another layer of high strength geogrid will be installed followed by another 12-in. layer of compacted No. 57 stone.

INSTRUMENTATION

To date, settlement plates have been installed at all of the VRSS slopes. Movement of the settlement plates is being monitored by optical survey. Horizontal inclinometers have been installed at VRSS-1 through VRSS-3. Vertical inclinometers with Sondex sensing rings have been installed at VRSS-2 and VRSS-3. Two additional vertical inclinometers with Sondex sensing rings will be installed at VRSS-1 after construction of the embankment slope is completed. The locations of the instruments are shown on Fig. 8. The purpose of the various instruments is as follows:

- settlement plates monitor the settlement of the VRSS embankments at one specific depth within the embankment;
- horizontal inclinometers obtain high resolution profiles of settlement and/or heave within the VRSS embankments;
- vertical inclinometers monitor lateral movement in the VRSS embankments; and
- the Sondex settlement monitoring system measures settlement and/or heave at 5-ft depth intervals within the VRSS embankments.

Since the inclinometers and Sondex have been recently installed, we have not collected a sufficient amount of data to report. Accordingly, the performance of those instruments to

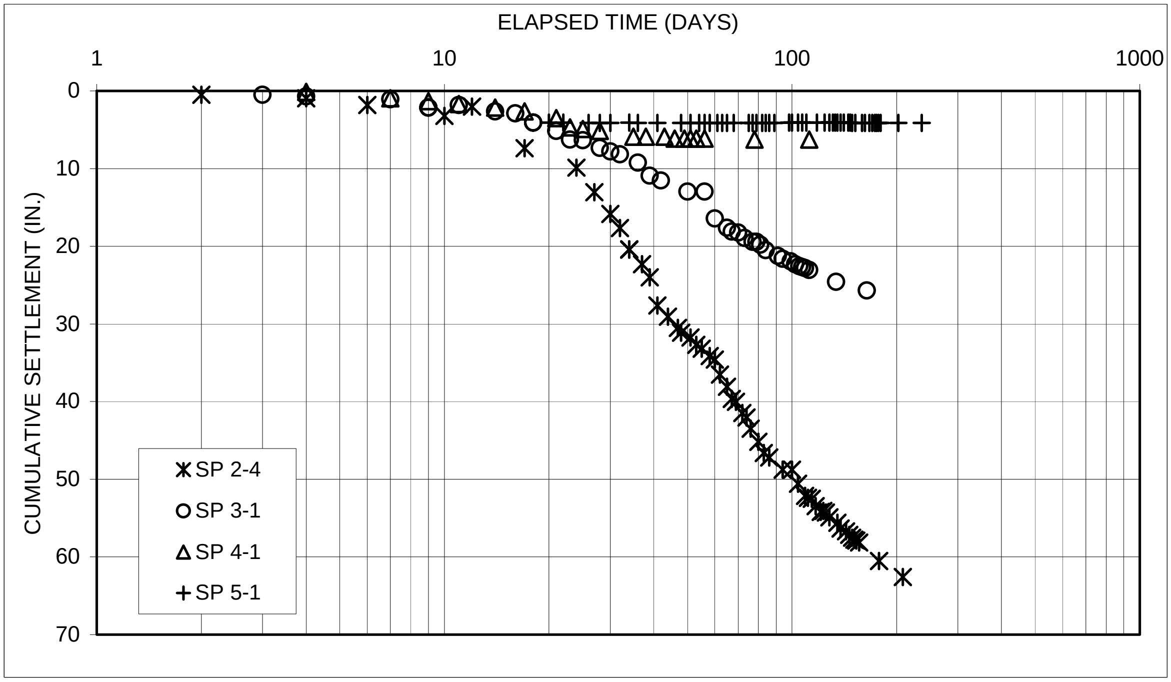


Fig. 9. Settlement Plate Survey Results

date is not discussed herein. However, a discussion of the settlement plates is presented below.

<u>Settlement Plates</u>

The settlement plates consist of 5-ft lengths of 1-in. diameter steel rods connected to a 3-ft square steel base plate. A PVC casing surrounds the steel rods to eliminate friction, allowing the settlement plate to settle without influence from the surrounding fill. The settlement plates were typically installed at the top of the VRSS foundation pad.

As discussed above, settlement plates have been installed at all of the VRSS slopes. The optical survey results for the settlement plates exhibiting the most settlement at slopes VRSS-2 through VRSS-5 are shown on Fig. 9. Settlement at VRSS-1 is not shown because VRSS-1 is still being constructed and has not reached its maximum height. As of January 2008, the data indicate the following maximum settlements at each reinforced steep slope:

- VRSS-2: 63 inches (at Settlement Plate 2-4)
- VRSS-3: 26 inches (at Settlement Plate 3-1)
- VRSS-4: 6 inches (at Settlement Plate 4-1)
- VRSS-5: 4 inches (at Settlement Plate 5-1)

POST-CONSTRUCTION MAINTENANCE AND MONITORING

Accurate measurements of landfill settlement can only be determined by careful long-term periodic surveys of settlement plates or cover elevations of closed landfills. Unfortunately, only a limited number of landfills have been monitored by accurate surveys for more than 5 to 10 years following landfill closure. Such long-term data are not available for the three closed landfills on the Loyola site. We intend to continue to monitor the instrumentation installed at the site during the remainder of construction and during the service life. In time, we hope to develop a comprehensive database of long-term settlement and performance data for the Loyola project.

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