APPENDIX B

DESCRIPTION OF BIOREACTOR PROCESS

BIOREACTOR PROCESS – excerpt from Bioreactor Joint Technical Document (Shaw/Emcon, April 2006)

Leachate and Liquid Control Systems

Landfill B-19 will operate with a bioreactor and control unit. Liquids and high moisture content waste will be added to the bioreactor portion while the control unit will be operated in the traditional "dry-tomb" method.

Leachate is formed by the drainage of liquids through or from waste. Leachate generation in the control unit will emanate from the moisture content of the incoming waste, from natural biodegradation of the waste, and from rainfall that infiltrates into the waste either at the time of disposal or through the daily or intermediate covers. The amount of leachate generated in the control unit will primarily be related to the following factors:

- The KHF is located in a semi-arid climate, limiting the amount of rainfall that can percolate into the waste prism.
- Daily cover and intermediate cover will reduce the amount of rainfall that can percolate into the waste prism.
- Class II designated waste and Class III MSW disposed of at the site is relatively dry (i.e., estimated moisture content of 8 to 20 percent).

The Class II/III portion of landfill B-19 contains one leachate collection sump located beneath the area of the landfill to be operated as a bioreactor. Leachate within the control unit will flow to the sump and commingle with leachate from within the bioreactor unit.

The amount of leachate generated in the proposed bioreactor unit will be greater than the amount generated in the control unit because liquid and high liquid content wastes will be added to the bioreactor unit. These liquids will be added to promote anaerobic bioreactor conditions.

The existing LCRS system, described in Section 5.1.5, was installed during the initial construction of Landfill B-19. Although recirculation of leachate is allowed under regulations, to date CMWI has disposed of leachate in on-site surface impoundments. However, in order to provide an additional source of liquids to the bioreactor unit, leachate collected in the Class II/III LCRS will be recirculated to the bioreactor unit. The control systems for leachate and liquids management are therefore discussed jointly, below.

Figure 9 is a schematic that shows the liquid and leachate management system proposed for Landfill B-19 in conjunction with the bioreactor unit. Liquids injection plans are described in more detail in Appendix B. Following is a discussion of the elements shown on Figure 9:

1. LCRS Drainage Layer - This existing drainage layer is comprised of 12 inches of gravel. Flow rates for this element are discussed above. The maximum expected flow from the LCRS drainage layer is 10,079 gpad based on LCRS HELP Model calculations in Appendix C, Attachment 6. This unit flow rate would result in a maximum of approximately 188,000 gpd from the LCRS, assuming this maximum generation rate is from the entire 18 acres of the bioreactor footprint.

2. LCRS Pipe Flows - The constraining capacity of the LCRS collection pipe system is the flow through the sump gravel. This capacity is estimated at 259,000 gpd[1].

3. LCRS Sump – The system currently has a 50 gallon-per-minute (gpm) sump pump that is required intermittently to pump leachate that accumulates in the primary LCRS sump. When the bioreactor project is implemented, the leachate flow into the sump will gradually increase. An automated pumping system with float activation of the LCRS sump pump will be installed. This system will be set to provide automatic activation of the sump pump to maintain the hydraulic head on the liner system at less than 12 inches. The system will also be provided with a remote alarm to indicate if the system is not functioning adequately to maintain the hydraulic head. The expected maximum daily flow of 188,000 gpd into the sump equates to an average of approximately 130 gpm. The pump will be sized to maintain a head less than 12 inches above the liner system. The sump pump must be capable of pumping leachate from the bottom of the sump (approx. elevation 730 to the elevation of the leachate collection tank located at the top of the LCRS riser[2] (approx. elevation 835).

4. LCRS Riser – The existing LCRS riser is a 24-inch diameter HDPE pipe. This has adequate capacity to accommodate pumps on the order of 500 gpm, if required.

5. Leachate Collection Tank– The existing tank is a 5,000-gallon polyethylene storage tank with secondary containment. Prior to implementing bioreactor operations, this tank will be equipped with a float system to trigger pumping of liquids to the liquid storage tank on the top deck of the landfill. This pumping system will be equipped with an alarm to warn if the pumping system is not functioning adequately to maintain the head in the tanks at an

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[1] Calculations included in Joint Technical Document (Shaw, 2006).

[2] The existing 5,000 gallon leachate collection tank is currently at approximately elev. 795. It will be relocated to the final grades shown on the design plans.

adequate limit. As a contingency measure, a backup pump will be available or a dual pump system will be provided. Also, if the leachate tank is full and leachate must be pumped from the LCRS sump at a rate in excess of the pumping rate to the liquid storage tanks (#8, below), as a contingency, the excess leachate will be pumped to tanker trucks and disposed of in on-site evaporation ponds. The on-site evaporation ponds are adequately designed to accept Class II/III leachate, as they are used to evaporate leachate from the Class I landfill units on-site.

6. Pump - The pump installed from the leachate collection tank to the leachate storage tanks at the top of the landfill must be sized with a functional flow rate greater than the functional flow rate of the LCRS sump pump. The pump from the leachate collection tank will need to be sized to operate at a head of at least 150 feet (current tank elevation of 795 and maximum landfill grade of 945).

7. Pipe from Leachate Collection Tank to Leachate Storage Tanks – This pipe must be designed to accommodate the flow rates and pressures of the pumping system.

8. Liquid Storage Tanks – The liquid storage tanks will be placed on the top deck of the landfill to accommodate temporary storage of liquids and high moisture content waste delivered by trucks [9d], if required. The deliveries from trucks are limited to 170,000 gallons based on a 34-truck limit with 5,000-gallon payloads. The liquid storage tanks will be portable, and placed at strategic locations to support filling by delivery trucks and recirculated leachate and outflow to injection trenches, galleries and vertical wells. The tanks must be designed with valved and/or pump connections to provide out-flow pumping of liquids to the working face, gravity[3] out-flow of liquids to the liquid injection galleries [9c], and to pump out to injection trenches [9b] and vertical leachate injection wells [9e].

9. Liquid Injections - These include flows from direct discharge of liquids and high liquid content waste directly from trucks to the working face and infiltration galleries [9a]. Injection from the liquids storage tanks will primarily be to the vertical and horizontal injection wells [9e], but may also be made to the working face [9b] and the injection galleries [9c]. Injection of liquids to the galleries and injection wells may be facilitates by installation of pipe headers from the liquid storage tanks. The headers will be balanced by valves at each well or injection gallery.

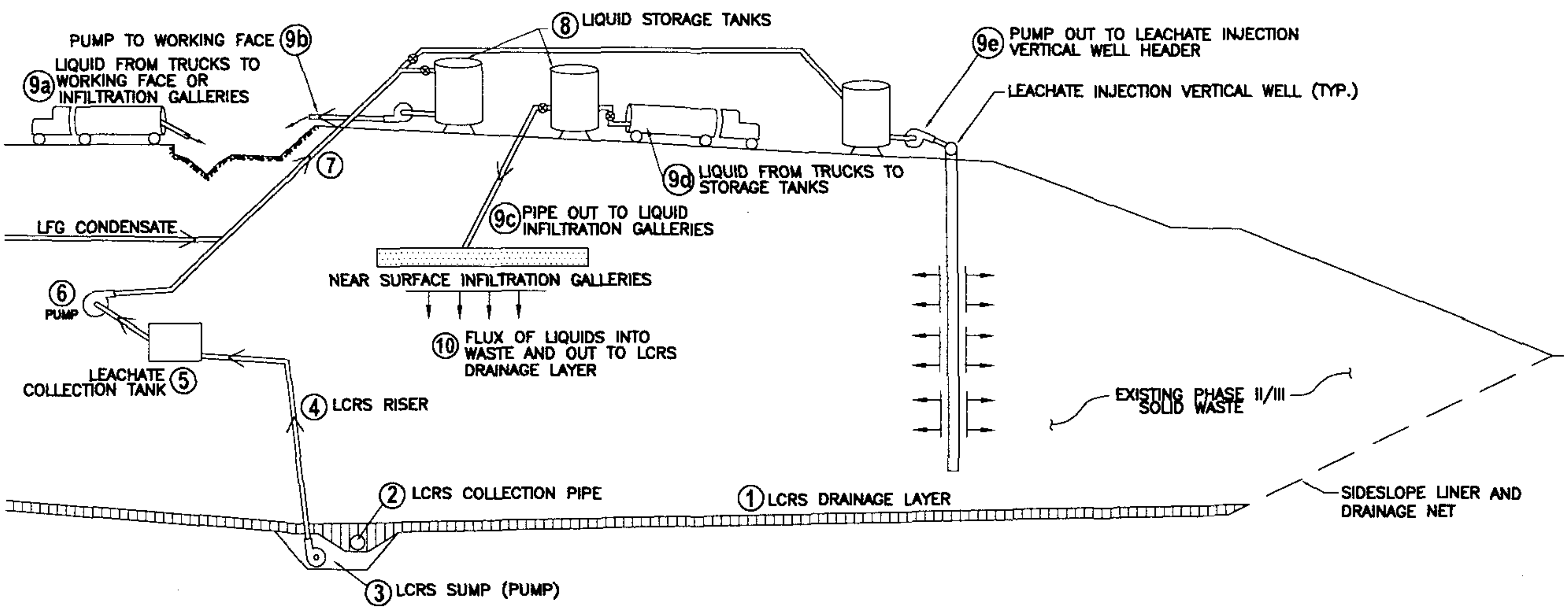
10. Flux Of Liquids Into The Waste And Out To The LCRS Drainage Layer – As the waste is brought to field capacity from liquid injections, leachate will

[3] It is anticipated that the gravity head from the leachate storage tanks will be adequate to provide flows to the horizontal leachate pipes in the injection galleries. The pressure will be controlled with a regulator so that flows at the injection pipes are adequate but do not over pressurize the system as to cause leachate seeps. In addition, the leachate injection pipes will each be supplied with valves and pressure regulators. A pump will be added to the supply line only if required to maintain adequate balanced pressure over the injection well system.

be formed as it migrates through the waste to the LCRS. The daily maximum liquid delivery rate of 170,000 gallons per day is roughly the amount estimated to bring 2,000 TPD from an assumed initial moisture content of 20% up to field capacity. Because a significant thickness of waste is present, it is anticipated that it will take some time before added moisture infiltrates down through the existing dry waste, causing a significant increase in leachate flows through the waste to the LCRS. In theory, it would take more than two years before the entire bioreactor waste mass could be brought to field capacity under the maximum rate of 170,000 gallons per day of outside liquid deliveries proposed, also assuming that half of the annual rainfall infiltrates into the bioreactor waste. This also assumes that the liquid injection flows are available continuously at the maximum level and the injections systems and landfilled waste will accept these flows. If these conditions are not experienced, which will likely be the case, the time before the LCRS reaches maximum flow rates will be increased. However, there is the potential to exceed 170,000 gpd of total inflow to the bioreactor during periods of wet weather or excessive on-site liquid generation from non-hazardous ponds and leachate. The flow of leachate in the waste and LCRS is discussed in more detail in the LCRS calculations in Appendix C, Attachment 6.

XREF Files: ⠀⠀⠀GE Files:
File: S:\FilesFromClients\Kettleman\10-23-06 Bioreactor Drawings from Shaw\FIGURE 9 PROCESSR1 MODIFIED.dwg Layout: Layout1 User: Irvine-Cad Oct 23, 2006 - 12:12pm

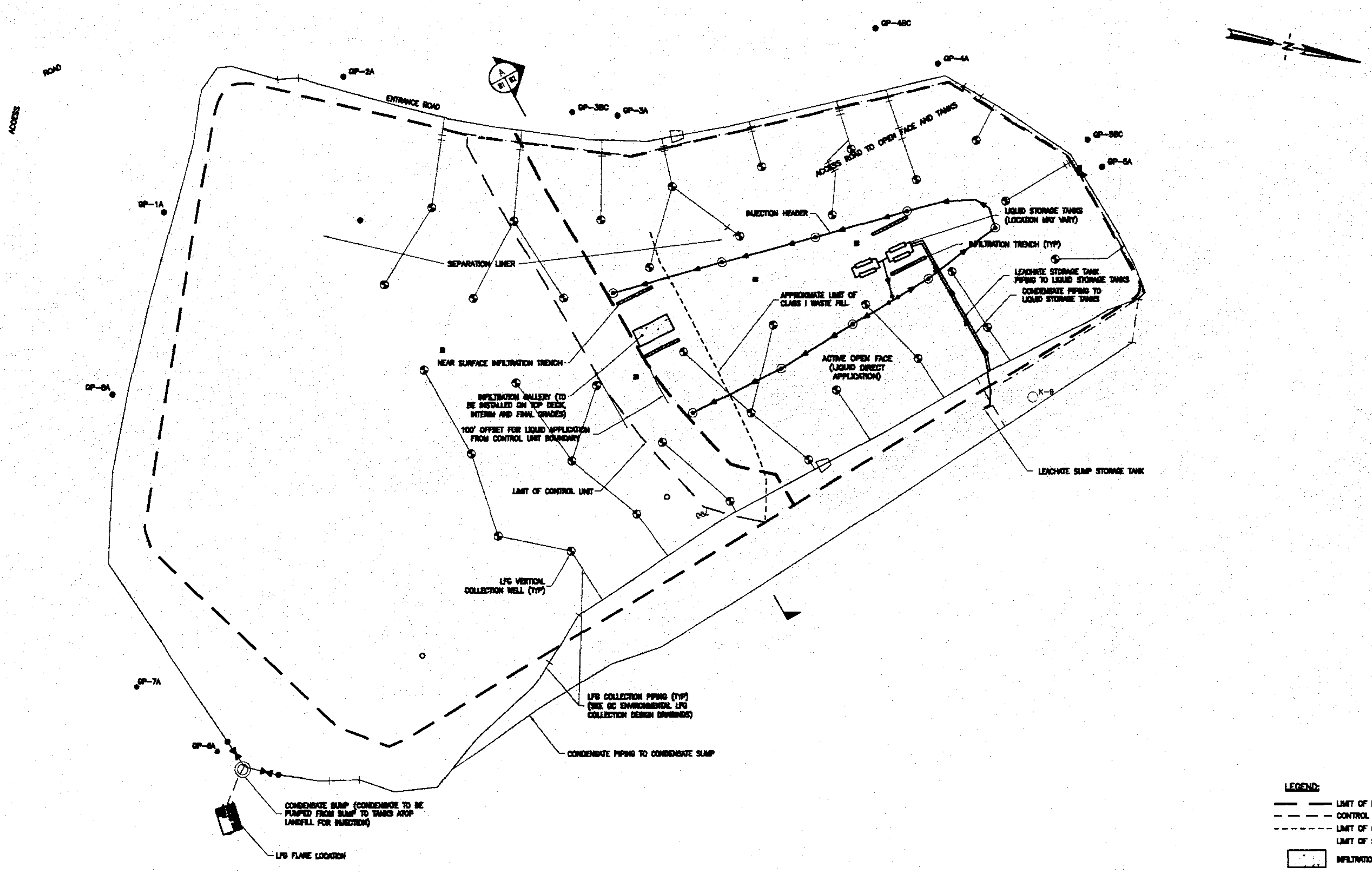
SCHEMATIC OF LIQUIDS MANAGEMENT FOR BIOREACTOR UNIT IN LANDFILL B-19 (NTS)



Shaw™ EMCON/OWT, Inc.

DATE MAR. 06
DWN CBD
APP
REV
PROJECT NO.
833760

FIGURE 9
CHEMICAL WASTE MANAGEMENT, INC.
KETTLEMAN HILLS FACILITY
KETTLEMAN CITY, CALIFORNIA
LIQUID INJECTION AND LEACHATE MANAGEMENT SCHEMATIC



LEGEND:

- LIMIT OF LANDFILL B-19
- CONTROL UNIT BOUNDARIES
- LIMIT OF CLASS I WASTE
- LIMIT OF SEPARATION LINER
- INFILTRATION GALLERY
- LIQUID STORAGE TANK
- INFILTRATION TRENCH
- INJECTION WELL
- LFG COLLECTION WELL
- LIQUID FLOW DIRECTION
- APPROXIMATE LOCTION OF SETTLEMENT PLATE

NOTES:

1. THIS DRAWING IS FOR PERMITTING ONLY. FIELD VERIFY LOCATIONS OF FIXTURES AND FACILITIES PRIOR TO AN CONSTRUCTION.
2. USE OF INFILTRATION GALLERIES AND TRENCHES WILL DEPEND ON AVAILABLE SPACE AND EFFICIENCY OF LIQUID INFILTRATION INTO THE WASTE MASS.
3. THIS CONCEPT PRESENTS POTENTIAL FACILITY LOCATIONS AT A POINT IN TIME. BASED ON THE STATUS OF THE TOPOGRAPHY AND THE LEVEL OF SATURATION OF THE WASTE, TANKS AND PIPING, WELLS, GALLERIES AND OTHER ITEMS MAY BE RELOCATED AS THE BIOREACTOR OPERATION PROCEEDS.

DATE OF TOPOGRAPHY: JUNE 5, 2005

0 100 200
SCALE IN FEET

REV	DATE	DESCRIPTION	DSN BY	DRN BY	CHK BY	APP BY
0	4/6/06	ISSUED FOR REG. REVIEW	RVW	RVW	MJU	RVW

DATE OF ISSUE: APRIL 06
DSN BY: R. WALL
DRN BY: R.WALL
CHK BY: M. URQUHART
APP BY: R. WALL

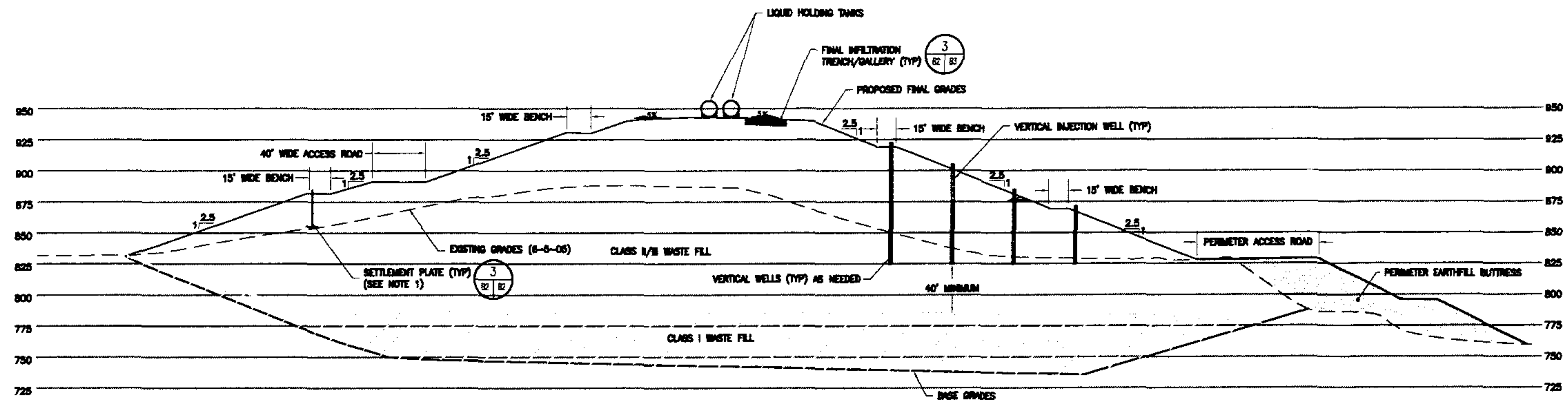
WASTE MANAGEMENT

Shaw EMCON/OWT, Inc.

CHEMICAL WASTE MANAGEMENT, INC
KETTLEMAN HILLS FACILITY
KETTLEMAN CITY, CALIFORNIA

LANDFILL B-19
LIQUID INJECTION CONCEPT

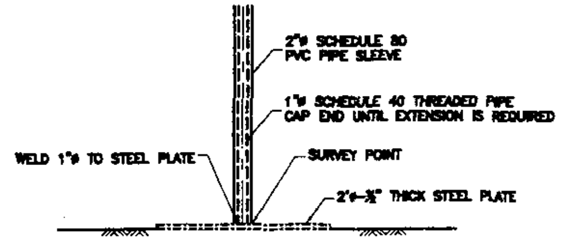
DRAWING NO. B1
PROJECT NO. 833780



SECTION A
1"=50'

NOTES:

1. INSTALL A MINIMUM OF FOUR SETTLEMENT PLATES. ONE IN THE CONTROL UNIT AND THREE IN THE BIOREACTOR AREA TO MEASURE THE SETTLEMENT OF THE WASTE MASS OVER TIME.



SETTLEMENT PLATE
DETAIL 3
N.T.S.

REV	DATE	DESCRIPTION	DSN BY	DRN BY	CHK BY	APP BY
0	4/5/06	ISSUED FOR REG. REVIEW	RVW	RVW	MJU	RVW

DATE OF ISSUE APRIL 06 — DRN BY R. WALL — DSN BY R.WALL — CHK BY M. URQUHART — APP BY R. WALL

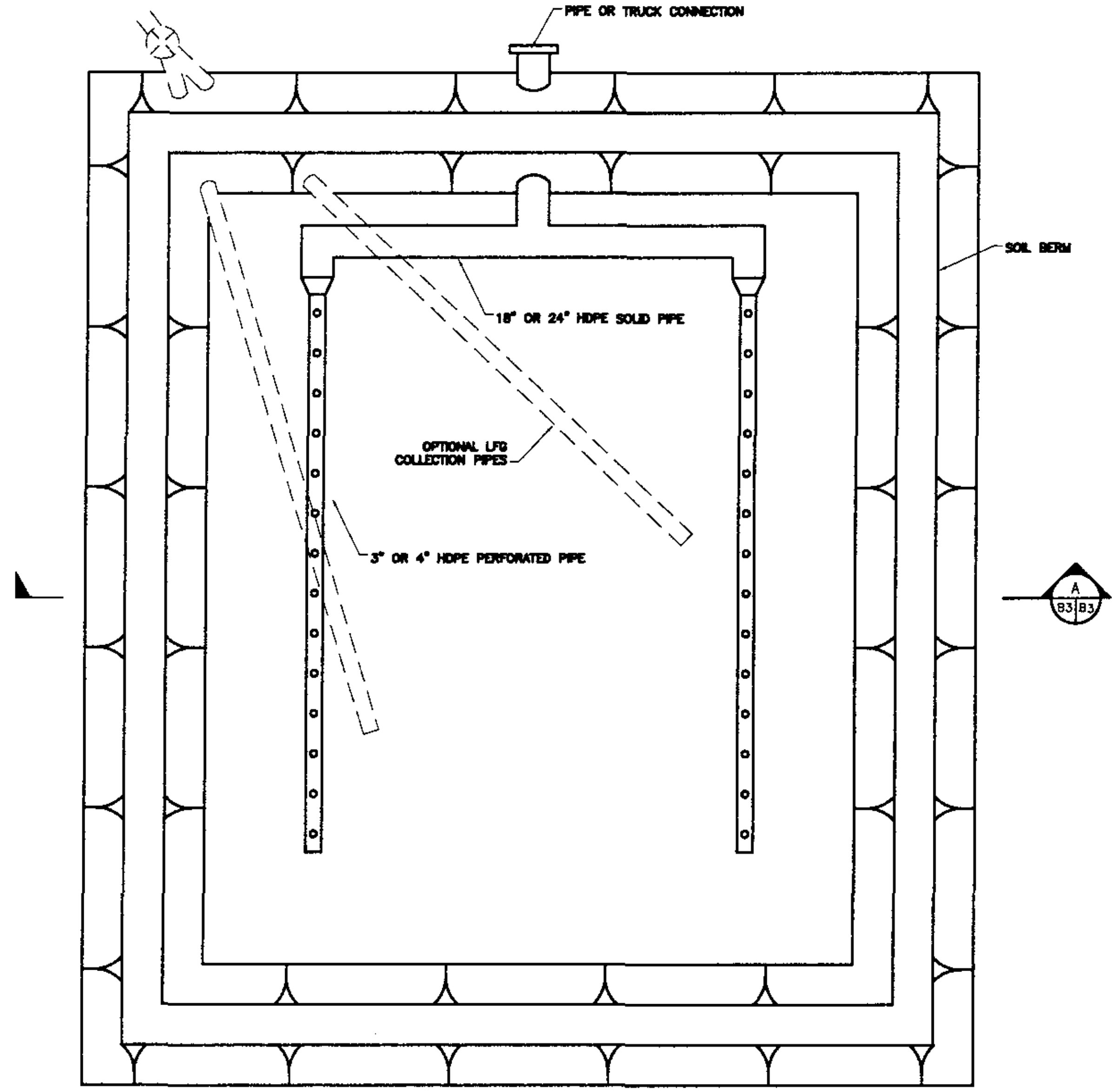
WASTE MANAGEMENT

Shaw EMCON/OWT, Inc.

CHEMICAL WASTE MANAGEMENT, INC
KETTLEMAN HILLS FACILITY
KETTLEMAN CITY, CALIFORNIA

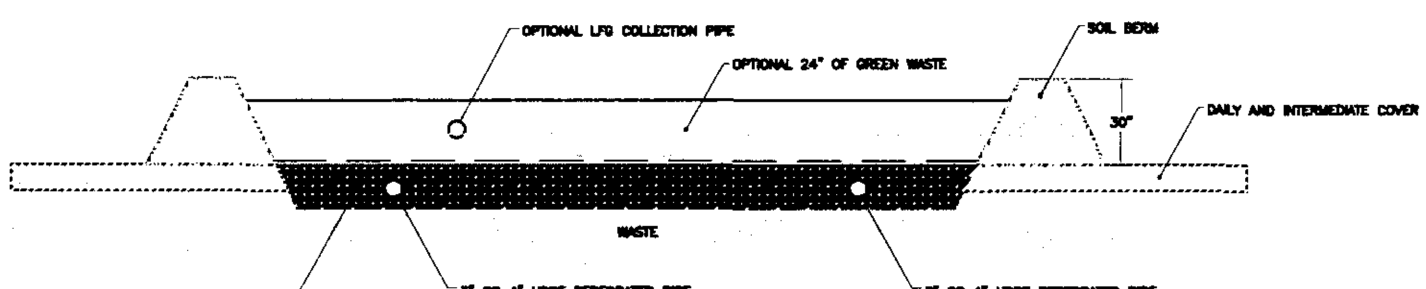
LANDFILL B-19
LIQUID INJECTION PLAN, SECTION AND DETAILS

DRAWING NO. B2
PROJECT NO. 833780



LIQUID INJECTION GALLERY (TYP)

DETAIL
N.T.S.
3
B2 B3



SECTION
N.T.S.
A
B3 B3

NOTES:

1. LIQUIDS APPLICATION TO GALLERY TO BE EITHER BY:

   A. DIRECT APPLICATION BY TRUCK TO SURFACE OR TO PIPE CONNECTION (IF INSTALLED IN GALLERY

   B. VIA PIPING SYSTEM FROM TOP DECK LIQUIDS TANKS.

2. LENGTH AND WIDTH OF GALLERIES TO VARY BASED ON SPACE AVAILABLE ON TOP DECK AND TRUCK ACCESS REQUIREMENTS.

REV	DATE	DESCRIPTION	DSN BY	DES BY	CHK BY	APP BY
0	4/6/06	ISSUED FOR REG. REVIEW	RVW	RVW	MJU	RVW

DATE OF ISSUE: APRIL '06
DSN BY: R. WALL
DES BY: R. WALL
CHK BY: M. URQUHART
APP BY: R. WALL

WASTE MANAGEMENT

Shaw® EMCON/OWT, Inc.

CHEMICAL WASTE MANAGEMENT, INC
KETTLEMAN HILLS FACILITY
KETTLEMAN CITY, CALIFORNIA

LANDFILL B-19
LIQUID INJECTION GALLERY, SECTION AND DETAIL

DRAWING NO.
B3
PROJECT NO.
833780

APPENDIX C

SLOPE STABILITY

HUSHMAND ASSOCIATES, INCORPORATED
Geotechnical, Earthquake and Environmental Engineers

April 14, 2006

Waste Management, Inc.
Kettleman Hills Facility
35251 Old Skyline Road
Kettleman City, California 93239

Attention: Mr. Rodney Walter II, P.E.
Group Engineer, Western Group

**SUBJECT: REVISED REPORT
SLOPE STABILITY ANALYSIS FOR CELL
REDESIGN AND BIOREACTOR EVALUATION
KETTLEMAN HILLS FACILITY
MUNICIPAL SOLID WASTE LANDFILL UNIT B-19
KETTLEMAN CITY, KINGS COUNTY, CALIFORNIA
HAI PROJECT No. 02-0207**

Dear Mr. Walter:

In accordance with Waste Management, Inc. authorization, Hushmand Associates, Inc. has completed the revised slope stability evaluation report for the Class II/III municipal solid waste and industrial waste landfill unit B-19 at Waste Management Kettleman Hills Facility.

We trust this report meets your present requirements. If you have any questions or require additional information, please contact this office at your convenience. We appreciate this opportunity to provide our professional services to Waste Management.

Respectfully submitted,

HUSHMAND ASSOCIATES, INC.

Ben Hushmand, PhD, PE
Principal

REGISTERED PROFESSIONAL ENGINEER
BEHNAM HUSHMAND
No. C 044777
Exp. 03-31-08
CIVIL
STATE OF CALIFORNIA

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HAI **Hushmand Associates, Incorporated**
Geotechnical, Earthquake and Environmental Engineers

SLOPE STABILITY ANALYSIS FOR CELL REDESIGN AND BIOREACTOR EVALUATION

KETTLEMAN HILLS FACILITY MUNICIPAL SOLID WASTE LANDFILL UNIT B-19 KETTLEMAN CITY, KINGS COUNTY, CALIFORNIA

Prepared for:

Waste Management, Inc.
Kettleman Hills Facility, 35251 Old Skyline Road
Kettleman City, California 93239

Prepared by:

Hushmand Associates, Inc.
15451 Red Hill Avenue, Suite A
Tustin, California 92780

Revised November 2006

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SLOPE STABILITY ANALYSIS FOR CELL REDESIGN AND BIOREACTOR EVALUATION

KETTLEMAN HILLS FACILITY MUNICIPAL SOLID WASTE LANDFILL UNIT B-19 KETTLEMAN CITY, KINGS COUNTY, CALIFORNIA

1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE OF WORK

This report summarizes the results of analyses performed by Hushmand Associates, Inc. (HAI) to evaluate the stability of slopes for the Class II/III municipal solid waste (MSW) and industrial waste landfill unit B-19 (Landfill B-19) at Waste Management, Inc. (WMI) Kettleman Hills Facility (KHF) due to proposed fill plan modifications. The KHF is located in Kings County, California approximately one mile north of State Route 41 and 2.5 miles west of Interstate Freeway 5.

The scope of this report is to evaluate the static and seismic slope stability for a proposed Landfill B-19 new fill plan and to optimize the fill plan configuration and perimeter stability soil buttress design based on the results of detailed analyses performed in several iterations. Stability of liner systems, MSW fill, soil buttress slopes, and final cover systems were analyzed to meet the design criteria discussed in Section 1.3.

1.2 BACKGROUND AND PROJECT DESCRIPTION

1.2.1 Background

The presently permitted design of the Class II/III Landfill B-19 was developed in 1997 based on the results of detailed seismicity and static and dynamic slope stability analyses (Rust Environment & Infrastructure, Inc., 1997). The Class II/III landfill is located in the footprint of an existing Class I hazardous waste landfill. The Class I landfill consisted of four separate cells designated as Phase IA, IB, II and III (Figure 1) with corresponding leachate collection and removal systems (LCRSs), leak detection systems (LDSs) and vadose zone monitoring systems (VZMSs). The Class I hazardous waste landfill was permitted to be converted to a municipal solid waste landfill in 1997. Currently, the MSW landfill is being constructed over the existing LDS and VZMS in the Phase IA area (no hazardous waste is located in Phase IA) and over the existing hazardous waste in the Phase IB, II, and III areas. The existing lining system in the Phase IA area, constructed before 1997, was modified to meet applicable California Code of Regulations (CCR) Title 27 requirements. A barrier "separation" liner to separate new Class II/III disposal from existing Class I materials was installed over the existing Class I waste in the Phase IB, II, and III areas. The limits of the existing Class I waste are shown in Figure 2 (top of hazardous waste plan). The configuration of the final cover plan for the 1997 design and existing lining systems in different areas of the landfill, Phase IB/II/III perimeter berm details and MSW/Hazardous Waste (HW) separation liner, and proposed final closure cover interface details are provided in the 1997 Rust E&I report. These figures are also presented in Appendix A of this report for reference and additional clarity.

1.2.2 Project Description

Recently, it was proposed by Waste Management to divide the MSW part of the landfill in two separate cells, one a bioreactor cell and the other to stay as a MSW cell. In a bioreactor MSW landfill, a large volume of water, liquid wastes or recycled leachate are introduced into the waste mass to accelerate biodegradation of the waste material and thus regain some of the landfill volume that was occupied by the waste and improve landfill waste storage capacity. Although converting MSW landfills to bioreactor units has the main advantage of accelerating the biodegradation process and increasing landfill capacity, it also creates new challenges in landfill design and operation listed below in the order of importance:

- static and seismic stability of landfill slopes influenced by modified physical and mechanical properties of the waste,
- increased and accelerated waste settlement affecting landfill operation and final cover design, and
- acceleration of landfill gas generation, which influences the landfill operation and requires a more effective gas collection system design compared to a normal MSW landfill.

The main reason for proposing to divide the MSW unit to a bioreactor cell and a normal MSW cell is to investigate and compare the long-term settlement and gas generation characteristics of these two landfill cells and to use the the normal MSW unit as a control cell for comparison purposes. The long-term evaluation of settlement and gas generation characteristics of these experimental cells are also proposed as a research study by the U.S. Environmental Protection Agency (USEPA) and Waste Management to improve design, construction, and operation of bioreactor landfill units.

This report addresses static and seismic stability of the landfill slopes and includes effects of converting part of the landfill to a bioreactor unit on slope stability evaluations. The stability report presented here will be included as part of the Joint Technical Document (JTD), Landfill B-19 being prepared by Emcon/OWT for the proposed landfill cell redesign and bioreactor evaluation. The design issues associated with the landfill settlement and gas generation due to the bioreactor unit are addressed in the JTD.

The proposed new design modifications to the 1997 RUST E&I fill plan includes cell configuration redesign, converting part of the landfill to a bioreactor unit, and modifying the soil buttress design to improve stability. Specifically, the following design changes are evaluated for static and seismic slope stability in this report:

- Final fill plan geometry will be modified in the Phase II and III areas to enhance stability by eliminating a thin sliver of MSW fill overlying the Class I waste.
- A portion of the MSW landfill in the north-northwestern area is proposed to be converted to a bioreactor unit to achieve higher efficiency in the waste decomposition rate and storage capacity.

- The design of the stability soil buttress along the landfill perimeter will be refined based on the results of static and seismic slope stability analyses for the new proposed landfill design modifications described above.

The proposed final fill plan and landfill cover grades modified from the 1997 RUST E&I final fill plan design are shown in Figure 3. A preliminary fill plan for the proposed new design of Landfill B-19 was initially developed; this was then refined based on the results of several slope stability analysis iterations to arrive at the final fill plan design shown in Figure 3. The borderline between non-bioreactor and bioreactor portions of the MSW landfill is also shown in Figure 3. The separation interface between these two material types will be approximately a vertical plane. Locations and configurations of the cross sections, which were evaluated for stability, are shown in Figures 1 through 6.

1.3 REGULATORY REQUIREMENTS FOR STATIC AND SEISMIC STABILITY

Requirements for the stability analyses of the Class II/III landfill are contained in Section 20370(f) and Section 21750 (f) (5) of Title 27. Section 21750 (f) (5) of Title 27 calls for "*A stability analysis, including a determination of the expected peak ground acceleration at the Unit associated with the maximum credible earthquake (for Class II waste management units) or the maximum probable earthquake (for Class III landfills). This stability analysis shall be included as part of the Report of Waste Discharge (ROWD) (or JTD) for the proposed Unit, and an updated stability analysis (if the original analysis no longer reflects the conditions at the Unit) shall be included as part of the final closure and post-closure maintenance plan. The methodology used in the stability analysis shall consider regional and local seismic conditions and faulting......*"

"*(A) The stability analysis shall ensure the integrity of the Unit, including its foundation, final slopes, and containment systems under both static and dynamic conditions throughout the Unit's life, closure period, and post-closure maintenance period......*"

"*(C) The stability analysis shall be prepared by a registered civil engineer or certified engineering geologist. Except as otherwise provided in ¶(f)(5)(D), the report must indicate a factor of safety for the critical slope of at least 1.5 under dynamic conditions......*"

"*(D) In lieu of achieving a factor of safety of 1.5 under dynamic conditions, pursuant to ¶(f)(5)(C), the discharger can utilize a more rigorous analytical method that provides a quantified estimate of the magnitude of movement. In this case, the report shall demonstrate that this amount of movement can be accommodated without jeopardizing the integrity of the Unit's foundation or the structures which control leachate, surface drainage, erosion, or gas.*"

The existing Class I landfill at B-19 has been designed in accordance with applicable regulations in CCR Titles 22 and 23 and specific conditions in the site hazardous waste facility permit. CCR Titles 22 and 23 require consideration of the Maximum Credible Earthquake (MCE) for Class I landfills. The Class II/III landfill at B-19 was designed to meet the applicable regulations in CCR Title 27 (Rust E&I, 1997). CCR Title 27, as explained above, requires consideration of the MCE for Class II, and consideration of the Maximum Probable Earthquake (MPE) for Class III landfills.

The MCE is defined by the California Geological Survey (CGS) as "the maximum earthquake that appears capable of occurring under the presently known tectonic framework." The MPE is defined by CGS as "the maximum earthquake likely to occur during a 100 year interval." By definition, for the same set of faults, the MCE will result in a larger earthquake. Thus, in order to maintain the integrity of the existing Class I system, for stability evaluations of Landfill Unit B-19, the MCE is used as the design earthquake and is evaluated for faults determined to produce potentially damaging ground motions at the site. Near- and far-field seismic events are evaluated to assure that both higher intensity and lower intensity earthquakes are considered. Near-field events at this site generate shorter duration, higher intensity, and higher frequency ground shaking compared to far-field earthquakes that result in longer duration but lower intensity and lower frequency ground shaking.

For seismic stability, the present state-of-the-practice is to estimate landfill slope displacements for design earthquakes, using a Newmark (Newmark, 1965) equivalent method, and demonstrate that they are below an allowable value that maintains the integrity of the landfill. Current engineering practice for slope stability evaluation along the landfill liner is to allow a maximum seismically-induced permanent slope displacement of six to twelve inches to correspond to acceptable performance for well-designed liner systems (Seed and Bonaparte, 1992). Class I landfills at KHF are, however, designed to an even higher safety standard by limiting the maximum allowable slope displacement along the landfill liner to only six inches, which is also used in the design of the Class II/III Landfill B-19 in this report. Slightly relaxed criteria is commonly used for landfill cover design, which allows a maximum seismically-induced permanent displacement of up to twenty four inches (2 feet) of the final covers, based on the understanding that these would be relatively easily accessible and thus quickly repairable in the event of damage by a major seismic occurrence.

2.0 SITE DESIGN GROUND MOTIONS

A detailed discussion of the site geology, faulting, and seismicity is presented in the 1997 Rust Environment & Infrastructure, Inc. report. Additionally, deterministic and probabilistic seismic hazard evaluations of the site were performed by RUST E&I and William Lettis & Associates, Inc. (WLA), which are presented in the 1997 Rust E&I report. Representative design ground motions were also developed for seismic displacement analysis of the landfill slopes (Rust E&I, 1997). The 1997 ground motion evaluations and selected design earthquake acceleration time histories have been reviewed and evaluated by the California Integrated Waste Management Board (CIWMB), State Water Resources Control Board (SWRCB), Department of Toxic Substances Control (DTSC), and Dr. Les Harder of Department of Water Resources (DWR) and were approved for seismic stability evaluation of B-19 Landfill. A recent evaluation of the site seismicity to update the site design earthquake parameters for the MCE (peak horizontal ground acceleration [PHGA], response spectrum, and selected ground motion time histories), based on more recent attenuation relations (e.g., Bozorgnia, Campbell, and Niazi, 1999) and information on the site faulting, provided similar results to the 1997 RUST E&I study. The following summarizes the results of the 1997 site seismicity evaluation:

- The closest seismic sources to the site are segments of the blind Ramp Thrust that is present beneath the site at distances of 10 to 27 km, while the most active sources are associated with the San Andreas fault zone at 35 km closest distance.

- No evidence of fault rupture hazard is known to exist at the project site (i.e., within 200 feet of Landfill Unit B-19).

- The Ramp Thrust Kettleman Hills North Dome segment (Magnitude [M] 6.6) of the blind Ramp Thrust faults and the San Andreas Slack Canyon-Cajon Pass segment (M 7.8) will produce the highest near-field and far-field ground motions at the site, respectively. The MCE associated with these faults were selected as the site design events.

- The deterministic values of PHGA's for the near-field and far-field design events were estimated as 0.57g and 0.21g, respectively. The calculated PHGA of 0.57g approximately corresponds to an average return period of 1,000 years.

- As discussed in Section 1.3, duration of ground shaking is a major factor influencing the level of seismic-induced slope displacements. Empirical relations are available that provide an estimate of earthquake shaking duration as a function of earthquake magnitude, distance, and site condition (Abrahamson and Silva, 1996). Using the Abrahamson and Silva empirical relation the ground shaking duration for Landfill Unit B-19, which is characterized as rock site, is estimated to be about 10 seconds and 32 seconds for the near-field design event ($M = 6.6$, $r = 10$ km) and far-field design event ($M = 7.8$, $r = 35$ km), respectively. Duration of ground shaking was considered in the selection of input ground motions used in seismic deformation analyses.

- One "distant" (far-field) and three "local" (near-field) earthquake records were selected and scaled to correspond to the design peak horizontal accelerations in rock as design input motions. These records have a peak acceleration, frequency content, and duration representative of the expected earthquake motions at the site. The selected records were:

- The Caltech A-1 synthetic acceleration time history simulating a M 8+ earthquake on the San Andreas Fault, scaled to peak amplitude 0.21g.

- The Seed-Hayward synthetic acceleration time history simulating a M ~ 7 earthquake to approximate the near-field MCE. Both peak amplitude and frequency content of this record were scaled to approximately match the site design PHGA and response spectrum.

- The Castaic Old Ridge Route, sedimentary rock outcrop, Ch 1 (90 deg Component) acceleration record from the 1994 ($M_W \approx 6.7$) Northridge, California earthquake scaled to a peak amplitude of 0.57g.

- The Pacoima-Kagel Canyon, sedimentary rock outcrop, Ch 3 (360 deg Component) acceleration record from the 1994 ($M_W \approx 6.7$) Northridge, California earthquake scaled to a peak amplitude of 0.57g.

These four records present conservative estimates of input ground motions at the landfill site. Input motions were selected to match site design ground motion and the following parameters as closely as possible:

- Magnitude of the design earthquake,
- Distance of the source to the recording station,
- Recorded peak acceleration versus the site design peak acceleration,
- Local site geology of the recording station, and
- Characteristics of the earthquake source, particularly the type of fault displacement in the event.

The selected records were used as input motion in two-dimensional seismic response analysis of the landfill, which provided average acceleration time history of a potential sliding mass in seismic deformation analysis of landfill slopes (see Sections 3.7 and 3.8).

Details of the site design earthquake parameters derivation, including figures illustrating time histories of the selected acceleration records and a comparison of their response spectra with the site design response spectrum are provided in Figures 30 through 33 of the 1997 Rust E&I report. These figures are also presented in Appendix A of this report for reference and use in seismic slope displacement evaluations.

2.1 LIQUEFACTION

The potential for liquefaction occurrence in the area of the proposed landfill expansion is considered to be very low or non-existent. The KHF site is underlain by Tertiary sedimentary rocks of the Etchegoin-Jacalitos (Te), San Joaquin (Ts), and Tulare (Tt) Formations. The Landfill Unit B-19 is located within the San Joaquin Formation sedimentary bedrock. The San Joaquin Formation consists primarily of fine-grained sedimentary rocks, principally shale, claystone, and sandstone, which are not susceptible to liquefaction. Groundwater at the site is also deeper than 50 feet. Therefore, based on the site subsurface geology, the potential for liquefaction at the site is very low.

2.2 SEISMIC SETTLEMENT

Similarly, the potential for seismically-induced settlements of the landfill foundation materials was estimated to be negligible based on the subsurface geology and cemented nature of the bedrock. The site foundation materials are classified primarily as the Tertiary sedimentary rocks, which are not susceptible to seismically-induced settlement.

3.0 SLOPE STABILITY AND LANDFILL DISPLACEMENT ANALYSIS

3.1 GENERAL

The slopes of the proposed Class II/III landfill and the existing Class I landfill (slopes made of either MSW, bioreactor MSW, or HW or a combination of these materials) were evaluated for stability under both static and dynamic loading conditions. As part of this evaluation, the effects of dynamic landfill deformations were considered relative to performance of the base liner system during the estimated design ground motions due to the MCE as required by the California Code of Regulations for seismic design of Class I and Class II landfills (see section 1 of the report). The approach used in evaluating the stability and deformation of the slopes involved conventional analytical methods of slope stability evaluation and a refined Newmark-type (Newmark, 1965) seismic deformation analysis including dynamic site response analysis using two-dimensional (2-D) equivalent-linear wave propagation and finite element models.

The information required for the slope stability and landfill deformation analyses consisted of the site geology and seismicity, geometry of the fill plan and landfill bottom excavation and side slopes, and material parameters for waste (MSW, bioreactor MSW, HW), foundation soil/rock, the liner system, the compacted fill/soil buttress, and the final cover systems. This information was based on the site-specific data gathered for the analysis including laboratory test data, design of previous and proposed excavation and fill plans, in-house compiled data base of material properties, and a literature survey of published data on slope stability and seismic deformation analysis of landfills. Since the final cover systems have yet to be constructed, information for final cover system components was developed based on a history of construction quality assurance testing on various other projects using soil types available at the Kettleman Hills Landfill. It is reasonable to assume similar soils will be available for construction of the evaluated final cover systems.

3.2 LANDFILL GEOMETRY AND ANALYSIS SECTIONS

Figures 1 through 3 present plan views of the Landfill Unit B-19 base contours, existing Class I waste fill condition, and final fill plan, respectively. Various cross sections of the landfill were analyzed for slope stability including waste slopes, liner system, and perimeter buttress fill slopes. These cross sections (A-A', B-B', D-D', G-G', H-H', I-I', J-J', and K-K') are shown in Figures 4 through 6, and their locations are shown on Figures 1 through 3.

Stability of the bottom/side slope and separation liners and waste fill slopes were analyzed using representative cross sections selected through critical areas of the landfill. Locations of the stability analysis sections were selected based on variations in the landfill geometry such as height and steepness of waste slopes, orientation, height, and steepness of landfill bottom and side slopes, and configuration of the soil buttress around the landfill perimeter. In particular, several analysis cross sections were located in the areas where the landfill configuration was modified from the 1997 RUST E&I final fill design, and where the landfill was divided into the bioreactor and normal MSW cells to evaluate stability of landfill slopes and refine the perimeter stability buttress design in these areas, if needed.

The impact of the liquid injection system on the stability of the landfill was investigated. The injection will be performed through vertical injection wells. The vertical injection paths are only small diameter (~ 2 ft diameter) cylindrical holes containing a 4-inch diameter PVC pipe with gravel backfill around the pipe. Therefore, due to small 3-D geometry of the holes and the fact that they are backfilled with gravel that has higher shear strength properties (higher friction angle) than waste, it is not expected that the injection wells will have any adverse effect on the landfill stability.

3.3 LANDFILL LINER DESIGN

Configurations of the existing landfill bottom/side slope and separation liners that comply with state and federal regulations are provided in the 1997 RUST E&I report.
Figures from the 1997 report are presented in Appendix A of this report illustrating the liner designs for the bottom/side slopes, perimeter berm, and separation zone between hazardous and municipal solid wastes. In the slope stability analyses, for each liner configuration, the weakest interface in the composite liner system is expected to provide the preferred failure path for potential failure planes.

3.4 MATERIAL PROPERTIES

Key material properties of various components of the landfill needed to perform static and seismic slope stability analyses are: (1) unit weight, (2) shear strength parameters (static and dynamic), and (3) dynamic small-strain stiffness and damping ratio properties. Material properties were selected based on the site-specific data from a number of recent testing (SGI, 2003; Golder, 2003) to determine liner interface and compacted fill strength properties and earlier work by different consulting firms at the KHF site. The data from the earlier investigations has been compiled and summarized in a table in the 1997 RUST E&I report. In addition, published data on municipal solid waste (MSW) fill and geosynthetic materials compiled from a number of MSW projects, particularly, the detailed investigations at the Operating Industries, Inc. (OII) Landfill in Los Angeles County has been utilized. In the past several years an increasing number of studies on properties of waste and liners for use in stability and seismic deformation analyses have been performed. Results of some of these studies have been summarized in a Geotechnical Special Publication on "Earthquake Design and Performance of Solid Waste Landfills" (Yegian and Finn, 1995), a recent EPA manual providing guidance on seismic design of solid waste landfills (EPA, 1995), and several more recent publications based on seismic performance of the OII Landfill during the 1994 Northridge Earthquake and other landfill stability investigations (Matasovic and Kavazanjian, 1998; Morochnik et al., 1998; Augello et al. 1998) have been utilized in this study.

Table 1 summarizes the selected unit weight, shear strength, and dynamic properties used for each of the materials and interfaces in the stability analyses.

The interface shear strength properties for the HW/MSW Separation Liner were selected based on the results of the recent interface direct shear testing performed for Waste Management, Inc. by SGI Testing Services (SGI), LLC of Norcross, Georgia on the materials to be used in the landfill construction (SGI, 2003). Shear strength parameters for compacted fill were derived from consolidated drained triaxial tests performed by Golder Associates on clayey soils from the borrow source to be used for buttress construction. The samples were prepared in the laboratory to reflect soil conditions at 90 percent relative compaction (Modified Proctor) near optimum moisture content.

The above liner interface and compacted fill strength properties should be further evaluated by performing additional confirmatory tests on the materials used for future landfill construction.

3.4.1 Bioreactor Impact on Material Properties

Of particular importance in the present investigation are material properties for MSW in the proposed bioreactor unit of the B-19 Landfill. The impact of the bioreactor unit is considered in the stability analyses by using lower shear strength properties and higher unit weights for the degraded waste.
The JTD report (Shaw EMCON/OWT, Inc., 2006), Section 5.2.5 "Leachate Generation and Collection System Calculations" states that the HELP model calculations for the conservative 10,000 gallons per acre per day (gpad) recharge condition in the bioreactor unit indicates that the maximum hydraulic head on the primary base liner system is estimated to be less than 12 inches. The LCRS calculations are based on major worst case assumptions that the "recharge" rate for the bioreactor unit will be a maximum of 10,000 gpad during the active stage of the landfill. Therefore, no perched water table condition or large confined volume of liquid will be generated inside the landfill except for some local, small pockets of liquid that may become trapped in the waste mass.

Unit weight and shear strength properties of the bioreactor MSW were derived from available information in the literature (Isenberg et al., 2001; GeoSyntec 1999; Hendron et al., 1999; Kavazanjian et al., 2001; Vector Engineering, 2001). Additionally, in order to specifically characterize these properties for the Landfill B-19 stability analyses presented in this report, a series of direct shear tests at Huston Geotechnical Testing Laboratory of Fugro South, Inc. in Texas was performed on typical bioreactor MSW materials obtained from WMI-Mohawk Valley Landfill in Utica, New York (Fugro South, 2003). The tests were conducted on remolded specimens, selected from re-sorted bag samples (particles larger than ½ in were removed). The samples were remolded in a 6-in diameter Proctor type mold to a stress level slightly (5%) lower than the target consolidation stress using a load frame. Since the small scale tests were run on samples with large pieces removed, they did not benefit from the reinforcing effect of the large pieces of refuse that would tend to strengthen the actual waste mass in the field. Thus, the small-scale tests would produce conservative values. The testing program included two Undrained and two Drained Static Direct Shear tests, with strain controlled loading. The specimens had a diameter of 6 in. (152 mm) and height of about 1.96 in. (50 mm).

The estimated bioreactor waste properties used in the analyses should be verified as more data for degraded waste properties will be available in the literature.

3.4.2 MSW and Bioreactor MSW Material Properties

The following subsections discuss unit weight, shear strength, and dynamic properties of MSW and bioreactor waste used in the static and seismic stability analyses presented in this report. Detailed discussion of material properties used for hazardous waste, foundation bedrock, liner, and compacted fill have been provided previously (SGI, 2003; Golder, 2003; Rust E&I, 1997).

Unit Weight

Values of unit weight for MSW reported in literature vary generally in the wide range of 40 to 90 pcf (EPA, 1995). Landfill-specific values of municipal solid waste unit weight, however, depend upon actual operation practice at the landfill (e.g., compaction rate and percentage of daily cover soil and age of the waste). For bioreactor MSW unit weight varies in the range of 60 to 100 pcf near the surface and 100 to 140 pcf at depth (for fully saturated waste), based on available information in the literature (Isenberg et al., 2001; GeoSyntec 1999; Hendron et al., 1999; Kavazanjian et al., 2001; Vector Engineering, 2001). The average unit weight of the bioreactor MSW used in the direct shear tests performed by Fugro, Inc. was approximately equal to 105 pcf. Variation of MSW or bioreactor MSW unit weight with depth due to mainly compressibility and the age of MSW over time was considered in slope stability and seismic response and deformation analyses in this report.
Figure 7 presents variation of MSW and bioreactor MSW unit weights with depth based on data obtained from several recent studies, the density curve recommended in the EPA guidance manual (EPA, 1995), and the density variation curves that were selected for the stability analyses of the proposed project. The selected density curves show an approximate average unit weight of 85 pcf for MSW and 105 pcf for bioreactor MSW.

Shear Strength

The available data on shear strength of MSW and bioreactor MSW is limited to few laboratory test results on reconstituted samples, to strength values back-calculated from field load tests, and case histories of landfill performance. Figure 8 presents a bi-linear strength envelope recommended in the EPA guidance manual on seismic design of landfills (EPA. 1995) based upon available data in literature. In the stability analysis of Landfill Unit B-19, for MSW, a friction angle of 33 degrees and a cohesion of 100 psf, consistent with the recommended values in the EPA guidance manual, were used. For bioreactor waste the shear strength properties reported in the literature generally range from 22 to 33 degrees for friction angle and from 50 to 400 pcf for cohesion (Isenberg et al. 2001, GeoSyntec 1999, Kavazanjian et al. 2001, Vector 2001). In the stability analyses of Landfill B-19 in this report, constant friction angle and cohesion values of 28 degrees and 150 pcf, respectively, were selected mainly based on the Fugro, Inc. direct shear test results (Fugro South, 2003). These values are within the range of strength properties reported in the literature. Recent observations of the satisfactory performance of waste slopes in MSW landfills in California during the Northridge, Landers, Big Bear, Loma Prieta, and Whittier earthquakes indicate that the dynamic shear strength of MSW may be significantly greater than static shear strength and thus, the values used in Table 1 are conservative (lower) compared to the dynamic shear strength values.

Dynamic Properties

Dynamic properties of MSW and bioreactor MSW used in two dimensional equivalent-linear dynamic site response analyses consist of low-strain shear modulus (or shear wave velocity), variation of the shear modulus with shear strain (shear modulus reduction curve), the damping ratio versus shear strain relationship, and total unit weight. The unit weights used in the dynamic response analyses were the same as those used for static stability analyses, which were discussed previously and are shown in Figure 7. Shear wave velocity of the MSW and bioreactor MSW materials was estimated from measured data available in literature. The shear wave velocity of MSW has been measured in-situ at a limited number of locations using different geophysical methods including cross-hole, down-hole, seismic refraction, and Spectral Analysis of Surface Waves (Kavazanjian et al., 1996). Values from this investigation and the curve recommended in EPA's landfill seismic design guidance manual for variation of shear wave velocity with depth are shown in Figure 9. Using the available measured wave velocity data, a shear wave velocity-depth relationship, close to the upper bound of the measured data, was selected for use in the dynamic response analyses at Landfill B-19. This relationship was used for both MSW and bioreactor MSW. The estimated shear wave velocity relationship and variation of unit weights with depth were used to compute small-strain shear modulus data.

Earthquake ground motions due to the local (near-field) design earthquake on the blind Ramp Thrust beneath the site produce larger seismic-induced slope displacements compared to ground motions due to the distant (far-field) design earthquake on the San Andreas fault zone.

Biodegradation and the resulting softening of the waste reduce its stiffness and shear wave velocity and therefore, increase landfill natural period of vibration. This results in attenuation of the local design earthquake ground motion (input ground motion with mostly high frequency energy content) and reduces the earthquake-induced slope displacements. Therefore, use of the higher MSW shear wave velocities for the bioreactor MSW results in more conservative estimates of seismic-induced slope displacements.

Because of variability and nature of MSW, only limited measurements of the modulus reduction and damping curves for MSW in the laboratory have been attempted. As a result, many seismic response analyses for landfills have been performed using curves estimated based on observed performance of landfills during earthquakes and engineering judgement.

Prior to the January 17, 1994 Northridge earthquake, however, no data was available to back-calculate MSW modulus and damping curves from the observed seismic response of landfills. The strong motion recordings at the OII landfill during the M 6.7 Northridge earthquake represent the first direct measurement of the seismic response of a solid waste landfill (Hushmand Associates, 1994). Using the observed response of the OII landfill in the Northridge event, Kavazanjian et al. (1995) developed preliminary estimates of the MSW modulus reduction and damping curves shown in Figure 10a. These curves were recommended for use in seismic response analyses of MSW landfills in the EPA guidance manual (EPA, 1995). More recent investigations performed to improve back-calculation of dynamic properties of MSW, using the Northridge earthquake data recorded at the OII landfill (Matasovic and Kavazanjian, 1998; Morochnik et al., 1998; Idriss, et al., 1995), resulted in shear modulus reduction curves (Figure 10a) showing stiffer dynamic properties (lower shear modulus reduction with shear strain increase) than the preliminary estimates by Kavazanjian et al. (1995). The analysis of the dynamic response of Landfill B-19 was performed using the most recent modulus reduction and damping curves developed by Matasovic and Kavazanjian (1998) which are based on the above back-calculations of the Northridge earthquake data for small strains and the data from cyclic laboratory simple shear tests performed on municipal solid waste material to define these curves for larger strain values (Figure 10b). Figure 10b also illustrates modulus reduction and damping curves used for hazardous waste (modeled as a sandy soil) and landfill soil buttress and bottom liner, modeled as clay.

Dynamic properties of the bioreactor MSW were assumed to be the same as those for MSW. This assumption most probably results in conservative (larger) seismically-induced deformations. This is because the bioreactor MSW is expected to be softer (less stiff material with lower initial shear modulus) with larger damping, and dynamic shear modulus reduction curve that decreases faster with the increase in shear strain compared to the stiffer MSW material.

3.5 ANALYSIS APPROACH

Landfill liners in seismically active areas such as California undergo dynamic loads during earthquakes in addition to static loads generated by the dead weight of the waste. Liners, particularly along landfill side slopes, are subjected to tensile stresses due to settlement and creep-induced downward movement of the waste mass. During earthquakes, the landfill mass moves dynamically under the effects of ground accelerations and generates additional stresses in the landfill liner.
CCR Title 22 and Section 21750(f) of CCR Title 27 require that slopes of a landfill and the foundation beneath the slopes maintain a minimum factor of safety of 1.5 under seismic loading conditions. The factor of safety is usually calculated using pseudo-static limit equilibrium analytical methods. Since achieving a pseudo-static factor of safety of 1.5 for relatively high accelerations generated during MCE events is difficult and costly, the regulations allow for an alternate, more rigorous and detailed design approach involving quantified evaluation of the seismic deformations and displacements of the landfill mass in lieu of the pseudo-static analysis. At present the evaluation of seismic deformations is the most common approach for seismic design of waste fills in California.

The present state-of-practice in seismic design of landfills is to use Newmark (Newmark, 1965) or a simplified Newmark-type method (Franklin and Chang, 1977; Makdisi-Seed, 1978; Hynes-Griffin and Franklin, 1984; Bray et al., 1998) to estimate the order of magnitude of seismically-induced permanent displacements of landfill slopes. Additionally, the current practice relies on engineering judgement by establishing an arbitrary allowable deformation (about 6 inches) to compare with displacements computed from Newmark method along the liner system.

Our analyses were conducted in the following evaluation/computational sequence:

- Static slope stability, and selection of critical failure surfaces;
- Pseudo-static slope stability, and evaluation of yield acceleration coefficient ;
- Dynamic site response analysis and calculation of potential slide mass average acceleration; and
- Estimation of seismically-induced permanent deformations for the design "local" and "distant" MCE events.

The above approach, originally developed by Seed and Martin (1966) and later used by Makdisi and Seed (1978) for seismic analysis of earth dams, generally results in conservative (larger) permanent displacements compared to more rigorous fully coupled nonlinear dynamic deformation analysis (Lin and Whitman, 1983). The four stages of the approach used in this study are further described in the following sections.

3.6 STATIC AND PSEUDO-STATIC STABILITY ANALYSES

Conventional two-dimensional (2-D) limit-equilibrium stability analyses were performed for the cut and soil buttress slopes and the existing or modified bottom/side slope liners as well as the proposed separation liner and soil and waste fill slopes using Landfill Cross Sections A-A', B-B', D-D', G-G', H-H', I-I', J-J', and K-K'. The results of these analyses are presented in Appendix B, and summarized in Tables 2a and 2b and on Figures 4 through 6.

The computer program PC STABL 5M (Achilleos, 1988) was used to calculate the factors of safety against potential failure. The program uses 2-D limiting equilibrium theory to provide general solutions to slope stability problems with provisions for using the Modified Bishop, Modified Janbu or Spencer Methods. Both circular and non-circular potential sliding surfaces can be prespecified or randomly generated. The Spencer, Modified Janbu, and the Modified Bishop Methods were used for this study. The minimum factor of safety was obtained by varying the initiation and exit points of the trial failure planes.

Figures 4 through 6 and PC STABL 5M output plots in Appendix B illustrate the 2-D cross sections analyzed and various potential failure surface conditions considered in the stability analysis of the final fill slopes of the proposed landfill.

The Modified Janbu Method of analysis, which normally provides conservative results, was initially used to evaluate a large number of potential failure mechanisms for each cross section analyzed (see Appendix B). In each analysis case, at least one thousand (1000) potential failure surfaces were randomly generated by the program and the most critical surface resulting in the lowest factor of safety was identified. For each cross section and analysis case, the most critical failure plane identified from the Modified Janbu Method of analysis was reanalyzed using the Spencer Method of analysis. This method satisfies both force and moment equilibrium and thus provides more realistic (usually higher) estimates of the factors of safety and yield acceleration coefficients. The Janbu method is generally more conservative compared with the more rigorous Spencer's Method and typically results in lower factors of safety than the Spencer Method (Duncan, 1992).

Appendix B presents sample printouts of a PC STABL 5M run input and output files, and computer plots for all the cases analyzed illustrating geometry of landfill cross-sections and the ten most critical potential failure planes searched by the program, as well as computed factors of safety. The failure surface with the lowest factor of safety is identified with two arrows at its initiation and termination points.

3.6.1 Liner and Waste Mass Static Stability

Eight cross sections at different locations across the landfill were selected for analysis. Figures 1, 2, and 3 show plan views of the Landfill B-19 excavation, Class I waste fill and separation liner, and the final fill/landfill cover geometry, respectively, and the locations of the cross sections selected for the analysis. In each part of the landfill where configuration of the landfill cross section changes, one or more sections were selected for two-dimensional stability evaluations. As described above in Section 3.2, several analysis sections were selected in the areas where landfill configuration was modified from the 1997 RUST E&I final fill design, and where the landfill was divided into the bioreactor and MSW cells in order to evaluate stability of landfill slopes and refine the perimeter stability buttress design in these areas, if needed. The configuration of the proposed Class II/III landfill final fill slopes are illustrated by the selected cross sections shown in Figures 4 to 6.

Slope stability analyses were performed for the final fill plan geometry including the landfill final cover thickness on the top of the landfill. The strength and dynamic properties of the cover soil are shown in Table 1. The assumed properties used for design need to be verified by performing site-specific shear strength tests on the actual materials that will be used during the cover construction.

The most important potential failure mechanism considered was for a wedge (block failure) sliding through the waste mass and along either the existing/modified landfill base or the HW/MSW separation liner interface. Potential failure surfaces were assumed to run along the weakest interface in the lining system and then through the landfill mass to the surface. Stability of the slopes against circular failure through the waste mass was also investigated.

Table 2a presents a summary of the computed static factors of safety for the critical cases analyzed in this study. Computer plots and sample printouts of input and output files providing details of the analysis results are presented in Appendix B.

For all final (long-term) static conditions, the minimum acceptable factor of safety is 1.5. This criterion was satisfied by the potential failure surfaces analyzed for the proposed fill plan, base and separation liner designs, and the estimated material properties.

3.6.2 Pseudo-Static Stability Analyses

Pseudo-static analyses, necessary to compute yield acceleration coefficients (K_y), were conducted for the critical potential failure surfaces through waste and base/separation liner systems, identified from results of the static slope stability analyses discussed in Section 3.6.1 for the selected cross sections (Table 2a and Figures 4 to 6). The yield acceleration is defined as the acceleration that results in a pseudo-static factor of safety of 1.0. The computed yield acceleration, K_y, represents limiting value of the horizontal seismic coefficient beyond which movement of a potential slide mass will occur.

Additionally, for each cross section new pseudo-static analyses, using the Modified Janbu Method of analysis, were performed to randomly search for the critical potential failure plane with the lowest yield acceleration coefficient (K_y). The most critical failure plane identified from the Modified Janbu Method of analysis was then reanalyzed using the Spencer Method of analysis to compute a more realistic estimate of yield acceleration coefficient and static factor of safety. Results of these analyses (plots of the most critical potential failure surfaces and values of computed yield accelerations and static factors of safety for these surfaces) are presented in Figures 4 to 6, Table 2b, and Appendix B of the report. Pseudo-static stability analyses were also performed using the computer program PC STABL 5M. Potential failure planes were anticipated to pass along the weakest interface of the liner system and through the waste material. Density and shear strength properties summarized in Table 1 were also used for the pseudo-static stability analyses.

Tables 2a and 2b present a summary of the computed static factors of safety and yield acceleration coefficients for the critical cases analyzed in this study. The results of these analyses show that the lowest yield acceleration coefficients were approximately equal to 0.12, 0.20 and 0.30 for failure along bottom/side slope liners, separation liner, and bioreactor waste, respectively. The combination of yield acceleration coefficient and slide mass geometry that could potentially result in the largest estimates of the seismically-induced displacements were used in the site response and Newmark displacement analyses described in the following sections.

3.6.3 Cut and Soil Buttress Slopes Stability

A detailed discussion of the revised fill plan and the new buttress geometry is provided in the Closure Plan report (Golder, 2006). Additionally, Figures 3 through 6 of this report shows the plan view and cross sections of the new revised fill plan and buttress geometry.

Cut Slopes

The Class II/III Landfill B-19 will be built on the existing landfill footprint (see Figures 1 through 3). Therefore, minimal or no new excavation in the foundation rock is required for the development of the landfill. The unsupported cut slopes around the landfill were analyzed by Golder Associates (1991) for static and dynamic stability using Bishop's method. Strength parameters used for the bedrock materials were obtained from samples and testing done by Wahler Associates (1988), and summarized in Table 1. Results for the temporary cut bedrock slopes with gradients no steeper than 2:1 (horizontal to vertical) exhibit factors of safety equal or greater than 2.3 with essentially no displacement under the design MCE.

Soil Buttress Slopes

Static and dynamic stability of the soil buttress was also analyzed. Due to the proposed modifications of the landfill final fill plan and conversion of part of the landfill to a bioreactor unit, the configuration of the perimeter soil buttress had to be modified in some areas to achieve stability while optimizing the buttress size. The portions of the buttress that had to be modified from the 1997 RUST E&I design are shown in Figure 3. A comparison of the proposed Landfill B-19 final fill plan (Figure 3 and analysis cross sections in Figures 4 through 6) with the 1997 RUST E&I final fill plan design (Figures 5, 13, 14, and 16 of the 1997 RUST E&I report repeated in Appendix A) shows that the buttress had to be widened by approximately 40 feet and increased in height by about 10 feet along the northeastern boundary of the landfill, and reduced in size slightly along the south-southeastern boundary. Results of the stability analyses (Tables 2a and 2b and Figures 4 to 6) showed that the revised engineered buttress fill will meet the design criteria and is stable under both static and dynamic design loads.

3.7 TWO-DIMENSIONAL DYNAMIC SITE RESPONSE ANALYSES

After yield acceleration coefficients were determined, dynamic response of the landfill and average acceleration time histories of the potential sliding masses were evaluated for three representative "local" (near-field) and one "distant" (far-field) input ground motions. The analyses provide a measure of earthquake energy attenuation/amplification characteristics of the landfill.

To account for the uncertainties introduced by variation of the landfill geometry, two-dimensional finite element computer program QUAD4M (Hudson et al., 1994) was used to evaluate dynamic response of the landfill and average acceleration time histories of the potential sliding waste masses identified from the stability analyses. The two-dimensional analyses provide a more realistic estimate of the seismically-induced displacements of waste slopes compared to one-dimensional site response analysis computer codes such as SHAKE91 (Schnabel et al., 1972; Idriss and Sun, 1991). However, it should be noted that because the landfill geometry is three-dimensional, the use of two-dimensional site response analyses generally provides a conservative estimate of the landfill dynamic response.

QUAD4M was recently developed by modifying and improving QUAD4 program which was initially developed in 1973 (Idriss et al., 1973). The main changes in QUAD4M are: 1) addition of energy absorbing boundaries that can be used to model the material underlying the finite element model as a linear elastic half space, 2) computing average acceleration time history (seismic coefficients) of a defined potential failure mass, and 3) a new method for formulation of damping. QUAD4M approximately incorporates the nonlinear material properties of soil and waste in the analyses by using the equivalent linear method (Seed and Idriss, 1970). In this method, the strain-dependent shear modulus and damping ratio of the material are selected to be compatible with the computed level of strain in each element. The dynamic response is computed repeatedly until the dynamic properties determined from the two sequential cycles differ by less than a specified value. This analysis is done in the time domain, and for any set of properties it is a linear analysis.

QUAD4M analyses were performed for Cross Sections A-A', B-B', G-G', H-H', and K-K' illustrated in Figures 4 through 6. These cross sections represent the most critical longitudinal and transverse sections of the landfill based on their geometry and the minimum K_y values computed from the pseudo-static stability analyses. The finite element meshes used to model these cross sections are shown in Figures 11, 12, 13, 14, and 15, respectively. The "seismic coefficient" option in QUAD4M was used to calculate the average acceleration time history of potential deep or shallow failure masses, sliding along the landfill bottom or separation liner. This is done using the computed time histories of the shear forces for the elements along the bottom or the HW/MSW separation liner and dividing the resultant shear force by the mass of the waste bounded by the potential failure plane along the liner (Seed and Martin, 1966).

The input design ground motions were applied as outcrop motions at the top of the bedrock underlying the landfill, i.e., the "elastic halfspace" below the finite element mesh. The analyses were performed for the near-field MCE scaled to PHGA of 0.57g. An analysis of the landfill response for the far-field MCE on the San Andreas fault was also performed using the Caltech A-1 synthetic record scaled to a PHGA of 0.21g. The finite element meshes for the cross sections analyzed (Figures 11 through 15) show the boundary between the hazardous and bioreactor/municipal solid wastes, and the critical potential failure surfaces that were specified for calculation of the average acceleration time histories (seismic coefficients) in the QUAD4M analyses. These seismic coefficient time histories were later used in a Newmark-type analysis method (Newmark, 1965) as described in the following section to estimate the order of magnitude of the permanent seismically-induced displacements along the liner.

3.8 SEISMICALLY-INDUCED PERMANENT DISPLACEMENTS

The acceptability of a slope for earthquake conditions is generally determined by the magnitude of the seismically-induced permanent displacement resulting from the design earthquake. A small allowable displacement is intended to preclude the possibility of large displacements that might disrupt the flexible membrane liner (FML)/clay composite layers or other components of the leachate collection and removal (LCR) system. A conservative value of the allowable displacement along the landfill liner on the order of 6 inches was considered acceptable for Landfill B-19. This is equal to the lower bound of the allowable displacement range commonly used in the industry (6 to 12 inches)

The consequences of earthquake shaking on the landfill slopes were evaluated using Makdisi and Seed's procedure (1978) which is a type of Newmark pseudo-dynamic double-integration displacement analysis. This approach is most appropriate for slopes consisting of materials that are not likely to suffer any significant loss of their shear strength due to seismic shaking. The waste and liner materials in the Landfill B-19 are such materials.
During an earthquake, over numerous cycles of loading, a slide mass can move incrementally along a potential failure plane through displacement accumulation. Based on this concept, the Newmark method computes, from a series of pseudo-static analyses, the yield acceleration, K_y beyond which movement of a slide mass will occur. The permanent displacement resulting from an earthquake is then computed by double integration of the slide mass average acceleration time history whenever the acceleration exceeds K_y.

The average acceleration time histories computed in the QUAD4M response analyses for the potential failure masses identified in the pseudo-static analyses were used as input for Newmark deformation analyses to evaluate the permanent seismically-induced displacements along the liner system. The displacement calculated by this method is a function of the yield accelerations which were computed in the pseudo-static stability analyses. Figures 16 through 31 illustrate variation of potential slide mass displacement (δ) versus the yield acceleration K_y for Cross Sections A-A', B-B', G-G', H-H', and K-K', respectively, and for the design ground motions used in the analyses. Table 3 and Figures 16 through 31 summarize the results of calculated seismically-induced permanent displacement (δ) using the average acceleration time history of the waste mass computed from the QUAD4M analyses as input in the Newmark double-integration method.

As seen from Table 3, for the potential deep failure planes along the landfill bottom liner the largest permanent displacements are induced in the southeastern part of Cross Section K-K' (Figures 6 and 15, Failure Plane 1) for the 1994 Northridge earthquake Pacoima-Kagel Canyon accelerogram scaled to a PHGA of 0.57g. The calculated displacements for this maximum case are on the order of 6 inches. Similarly, based on the geometries and computed yield accelerations for the potential shallow failure masses along the separation liner (see Figures 4 to 6), the largest displacements along the separation liner also occur in the southeastern area of the landfill at Cross Sections G-G' and K-K' locations (Failure Plane 2). As shown in Table 3, this displacement is approximately equal to 6 inches and is also induced by the 1994 Northridge earthquake Pacoima-Kagel Canyon accelerogram scaled to a PHGA of 0.57g. Additionally, the Newmark deformation analyses show that the calculated seismically-induced permanent displacements of the critical potential slide masses are nearly zero for the "distant" (Caltech A-1) earthquake record scaled to 0.21g. Therefore, for the yield acceleration coefficients K_y, calculated for the potential failure masses along bottom and separation liners (K_y larger than about 0.12 and 0.30, respectively), landfill deformations will be on the order of 6 inches or smaller.

Displacements for failure masses along circular failure planes are calculated for two critical cases, north-northwest end of Section A-A' (Figure 4, Failure Plane 3) and southwest end of Section H-H' (Figure 5, Failure Plane 3). The calculated displacements for these two sections are on the order of 4 and 8 inches, respectively. Both displacements are induced by the 1994 Northridge earthquake Pacoima Kagel Canyon scaled accelerogram. Therefore, the maximum computed displacement for shallow failure through waste is smaller than the allowable limit of 12 inches commonly used for landfill liner design (Seed and Bonaparte, 1992).

3.9 STATIC AND SEISMIC STABILITY OF FINAL COVER

Static and seismic stability of the landfill final cover were evaluated using the infinite slope stability analysis model.

The analyses were performed for two different cover systems: 1) the closure cover for the Class II/III waste, which will consist of a minimum 4-foot thick monolithic soil cover, having a maximum slope steepness of 2.5H:1V, and 2) the final cover for the Class I waste consisted of an underlying geotextile/40 mil textured HDPE geomembrane with an approximately 2.5-foot-thick vegetative soil layer on top of the geosynthetic layers. The final cover for the Class I waste area of the landfill has an approximately 4H:1V slope. The hydrologic modeling of the cover (Golder, 2006) indicates that the cover soils will not become saturated given the low annual rate of precipitation in the area, the slightly lower permeability of the cover soils than the underlying waste, drainage through geotextile in the cover, and the steepness of the final cover slopes.

Table 1 illustrates the cover soil and interface properties used in the stability analyses. Appendix C presents the detailed static and seismic stability calculations for the two cover systems described above. The appendix shows that the cover systems are stable for both static and seismic loading conditions.

4.0 SUMMARY AND CONCLUSIONS

This report addresses static and seismic stability of the landfill slopes and includes effects of converting part of the landfill to a bioreactor unit on slope stability evaluations. The stability report presented here will be included as part of the Joint Technical Document, Landfill B-19 being prepared by Emcon/OWT for the proposed landfill cell redesign and bioreactor evaluation.

The following changes from the original design were implemented and evaluated in this report:

- Final fill plan geometry was modified in the Phase II and III areas to enhance stability by eliminating a thin sliver of MSW fill overlying the Class I waste.

- A portion of the MSW landfill in the north-northwestern area was converted to a bioreactor unit to achieve higher efficiency in the waste decomposition rate and storage capacity.

- The design of the stability soil buttress along the landfill perimeter was refined based on the results of static and seismic slope stability analyses performed to incorporate the new landfill design modifications described above. The buttress design changes included:

  - Widened buttress by approximately 40 feet along east-northeastern boundary of the landfill.
  - Increased buttress height by about 10 feet along east-northeastern boundary of the landfill.
  - 2:1 (H:V) slopes were used.
  - A new stability soil buttress was placed on top of the hazardous waste along the southern-southwestern boundary of the landfill to enhance stability. This soil buttress provides additional resistance to prevent excessive deformations along the separation liner.

Seismic hazard analysis, and static and seismic stability evaluations of the existing and proposed slopes and the base and HW/MSW separation liner systems at Landfill B-19 were conducted. Computed static factors of safety were higher than 1.5 for all analyzed sections.

The seismic stability analyses were conducted for the MCE design ground motion. The postulated near-field and far-field MCEs for Landfill B-19 were characterized by a peak horizontal acceleration in lithified earth material of approximately 0.57g and 0.21g, respectively.

The analyses indicate that the proposed new landfill design (new final fill plan geometry and conversion of part of the landfill MSW to bioreactor waste) results in a stable configuration under both static and seismic loading conditions in compliance with applicable regulations. The acceptability of the landfill slopes for earthquake loading conditions was determined by the relatively small magnitude of the seismically-induced permanent displacements resulting from the local and distant MCE design earthquake events. The results of the conservative Newmark-type permanent displacement analyses presented in this study, indicated that computed maximum displacements along the liner system during the near-field MCE event, are on the order of 6 inches. Computed permanent displacements during the far-field MCE event are on the order of one inch. Maximum seismically-induced permanent displacements within the waste prism in the cover/gas collection system are about 8 inches which is less than the maximum allowable value of 12 inches.

Consequently, based on the calculated values of static factor of safety and seismically-induced permanent displacements within the waste prism and along liner systems for the postulated design earthquake events the new landfill design meets the design criteria stated in Section 1.3.

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