ROCKY FLATS ORIGINAL LANDILL GEOTECHNICAL INVESTIGATION REPORT

Jefferson County, Colorado

Prepared for:

S.M. Stoller Corporation

2597 B ¾ Road
Grand Junction, Colorado 81503
(970) 248-6487
Fax (970) 248-6040

Prepared by:

Tetra Tech

3801 Automation Way, Suite 100
Fort Collins, Colorado 80525
(970) 223-9600
Fax (970) 223-7171

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1.0 INTRODUCTION

This report presents the results of a geotechnical investigation by Tetra Tech, Inc. to evaluate localized occurrences of slope instability at the Original Landfill site (OLF) located at the U.S. Department of Energy (DOE) Rocky Flats Environmental Technology Site (RFETS). The investigation was performed for S.M. Stoller Corporation as part of their DOE contract No. DE-AM01-07LM00060 for the U.S. Department of Energy Office of Legacy Management, Grand Junction, Colorado.

The OLF and Rocky Flats are located 16 miles northwest of Denver in Jefferson County, Colorado. The general site location is shown on Figure 1.

This report contains background and descriptions of the existing site, limited discussion of the geologic conditions, a brief summary of some previous work conducted at the OLF, descriptions of Tetra Tech's field and laboratory investigations, and an evaluation of the subsurface conditions at the OLF. The results of the investigation were used to develop feasible alternatives for mitigation of the localized areas of slope instability at the OLF.

The U.S. Department of Energy (DOE) is managing the Legacy Management (LM) Program to provide operations and maintenance at Rocky Flats. S.M. Stoller (Stoller) is the Legacy Management Support Contractor. Rocky Flats is maintained by Stoller's office in Westminster, CO.

2.0 BACKGROUND

According to information provided to Tetra Tech by S.M. Stoller (2007), the OLF was used between 1952 and 1968. Accurate and verifiable records of the wastes placed in the landfill are not available. However, approximately 74,000 cy of sanitary waste and construction debris were reportedly disposed in the OLF. A raw water treatment plant filter backwash pond was also located within the OLF footprint, and probably abandoned without any backwash sludge removal by 1964. The effluent from the water treatment plant was discontinuous and probably made up of filter backwash, filter pre-wash, sludge blowdown, and other discharges from the water treatment process.

Under the Final Interim Measure/Interim Remedial Action (IM/IRA) for the Original, a 2-foot-thick soil cover was selected to address closure of the Original Landfill. To enhance the slope stability of the landfill, the existing slopes were regraded prior to placement of the soil cover, and a buttress fill was installed at the toe of the landfill. The remedial action also included installation of perimeter drainage channels and cover diversion berms to control surface water run-on and runoff around the landfill cover. Construction was completed in September 2005, with the final regulatory walk-down occurring on September 12, 2005.

Settlement cracks, differential settlement, subsidence in drainage channels, and seeps that created saturated areas or direct surface flows on the cover or near the buttress toe have been found on inspections, which triggered the need for a goetechnical investigation to determine if these conditions are likely to influence the integrity of the existing cover and surface water drainage over the OLF. Previous geotechnical engineering studies, slope stability analyses, groundwater modeling, and geologic investigation have been conducted on the OLF, and the remedy decision documents provide the objectives and implementation requirements for the OLF remedy.

The geotechnical investigation addressed in this report was conducted in accordance with the November 2007, Original landfill Geotechnical Investigation/Engineering Work Plan, DOE-LM/1545-2007, which was approved by the Colorado Department of Public Health and Environment.

3.0 SITE CONDITIONS

The OLF site is located on a south-facing hillside on the north side of Woman Creek and the Woman Creek Drainage. Woman Creek is an intermittent stream that flows from west to east through the area. Elevations range from about 5925 feet near the southeast corner of the OLF to about 6040 feet near the northwest corner of the OLF. The OLF measures approximately 1,800 feet in the east-west direction. The distance from Woman Creek upwards to the top of the hill that marks the northern boundary of the hillside is about 700 feet. The OLF encompasses about 20 acres of land within that area. The OLF has been graded to a slope of approximately 18 percent. A buttress fill was placed near the toe of the slope as part of previous closure work summarized above, and erosion control berms were added to direct runoff to two channels, one each on the east and west sides of the OLF. The ground surface is further protected from erosion by erosion control matting, straw wattles, and other manufactured products. A number of seeps have been mapped at locations on the hillside and at the toe of the buttress. The topography of the OLF and the approximate locations of the seeps are shown on Figure 2.

Closure design and final construction conditions are reflected in the May 2005, Accelerated Action Design for the Original Landfill prepared by Earth Tech, Inc. (Earth Tech, 2005).

4.0 GEOLOGY

The geology of the OLF was evaluated by reviewing geologic mapping and reports of the area, by site visits by Tetra Tech geologists, and by observation of test pit excavations and core samples recovered from exploratory borings. Comprehensive geologic investigations of Rocky Flats and the surrounding area have been completed by others, including a report by EG & G Rocky Flats, Inc. titled *Geologic Characterization Report for the Rocky Flats Environmental Technology Site*, dated March 1995. Tetra Tech examined the EG&G report, the geologic summary included in Earth Tech (2005), a publication by the USGS titled *Surficial Geology of the Louisville Quadrangle, Colorado,* dated 1955, and a map by Colton and Holligan titled *Photointerpretive Map Showing Areas Underlain by Landslide Deposits and Areas Susceptible to Landsliding in the Louisville Quadrangle, Boulder and Jefferson Counties, Colorado*, dated 1977. Those documents can be reviewed for detailed geologic information regarding the OLF. The following discussion of local geology is presented to provide background specific to the slope instability being examined at the OLF.

The OLF is located in a structurally stable area (EG&G, 1995) between the Front Range of the Rocky Mountains to the west and the Denver Basin to the east. The surface of the area is a broad pediment that is covered by a thin mantle of silty topsoil over clay, sand and gravel deposits of the Quaternary Rocky Flats Alluvium. More recent alluvial deposits exist locally and in stream channels and valleys. The Rocky Flats alluvium is described as reddish-brown, poorly sorted, coarse clayey sand with varying concentrations of pebble and cobble clasts derived from erosion of the mountains to the West. In the vicinity of Rocky Flats, the thickness is reported by EG&G to be 10 to 25 feet. The Rocky Flats Alluvium rests unconformably on the sedimentary bedrock. The Rocky Flats Alluvium provides for infiltration of surface water and recharge (EG&G, 1995).

The bedrock geology consists of comparatively flat-lying claystone and sandstone deposits of the Upper Cretaceous Arapahoe and Laramie Formations. The Arapahoe Formation is a fluvial deposit that locally includes a discontinuous sandstone or pebble conglomerate layer at the base and greenish claystone and siltstone overbank deposits. The thickness has been mapped at 0 to 50 feet locally (EG&G, 1995).

The upper Laramie Formation is described as a 300 to 500 feet thick sequence of gray and yellowish-orange kaolinitic claystones with ironstone nodules, and dark-gray to black, carbonaceous claystones, discontinuous coal beds and lenticular sandstones (EG&G, 1995). In comparison with the Arapahoe Formation, the Laramie generally contains more finer grained materials, and more abundant carbonaceous material.

The Tetra Tech investigation supports the published literature and geologic mapping. Based on these descriptions and observations of the subsurface during our field investigation, it appears the OLF is mostly underlain by a weathered portion of the Laramie Formation. The sandstone encountered near the northwestern edge of the OLF may belong to the lower part of the Arapahoe Formation. The weathered claystone and carbonaceous layers provide a low strength zone between the upper, water transmitting colluvial-alluvial materials and the underlying, low permeability clay-shale deposits.

The hillside that comprises the OLF is mapped by Colton and Holligan (1977) as landslide deposits that consist of masses of earth that have moved downslope as earthflows and slumps. Thus these deposits include alluvial and colluvial materials and may include masses of bedrock and weathered bedrock. Below the OLF, landslide deposits may also include fill and waste material that was placed on the hillside during the early operational history of Rocky Flats.

5.0 FIELD INVESTIGATION

Tetra Tech conducted field investigations that included site visits, geophysical surveys of the site, excavating test pits at 9 locations, and drilling exploratory borings at 7 locations. Soil and bedrock samples were collected, and a Professional Geologist logged the borings and test pits. Samples were scanned according to Stoller Health and Safety radiological control procedures. Wipes were taken for radioactive contamination measurement. All results were background, and samples were transported to a licensed laboratory, where they were examined by the Tetra Tech geologist and geotechnical engineer. The elements of the field investigation are described in more detail below.

5.1 Site Visits

Tetra Tech geologists, a geophysicist, civil and geotechnical engineers visited the OLF on several occasions to observe site characteristics, confirm the conclusions of literature and mapping that was provided for our review, and plan other facets of the geotechnical investigation. Stoller personnel provided required safety training and accompanied Tetra Tech staff while on site. Boring and test pit locations were identified on mapping, and then confirmed in the field. Note that several planned test pit locations were subsequently moved slightly based on field conditions, and one boring location (Tt-1) was moved to better position it with respect to observations of slope instability that were apparent in the field.

Several areas of distress were observed on the OLF. On the western side of the OLF, a curvilinear crack and "scarp" trending northeasterly was visible. Cracking extends through the final cover. Stoller reported the crack to have a displacement on the order of about 18 inches. A small bulge or mound of soil was apparent down the slope marking the apparent toe of the slope failure. The failure appeared consistent with a classical circular "slump" type slope failure.

Smaller slope failures were observed in sidewalls of the east and the west channels (see Figure 2). These failures also appeared to be slump type failures, and occurred in steeper portions of the drainage channel sidewalls.

A broad, shallow depression was pointed out by Stoller personnel in the eastern portion of the OLF that initially appeared to be a settlement feature because no cracking or displacement was apparent at the upper limit of the depression. These areas were identified as targets for more detailed field investigation.

5.2 Geophysical Investigation

A geophysical survey was completed by Tetra Tech to assist in characterizing the thickness and extent of waste placement area within the OLF. By characterizing the thickness and areal extent of the waste deposit, exploratory test pits and borings could be better positioned to evaluate the subsurface in areas where waste did and did not exist, and to determine if a direct correlation existed between areas of thick waste deposits and areas of slope instability. A third objective was to determine if a thick lobe of waste might exist below the area on the east side of the landfill where settlement was suspected to have occurred.

The geophysical methods used for this investigation consisted of seismic refraction and high resolution resistivity (resistivity). The geometry (source, geophone, electrode spacing, and line lengths) of the seismic and resistivity field investigations were maximized to map the presence of the lenticular waste deposit at the OLF. Background information indicated that the waste is located within approximately 30 feet of the ground surface.

The geophysical survey was conducted on December 3, 2007 through December 5, 2007. Seismic refraction and resistivity data were collected along three profiles at the OLF. The geophysical methods used at the OLF were successful in providing data to assist in mapping the presence and thickness of waste at the OLF. This section provides a brief summary and description of the seismic and resistivity methodology, field investigation activities, and interpretation of results from the geophysical surveys.

5.2.1 Geophysical Methods

Seismic methods require the generation of a sound wave into the subsurface of the earth and instrumentation to measure and record the refracted waves. This is accomplished by the use of a seismic source (hammer and plate, shotgun, explosive, etc.), a seismograph, and a length of cable with multiple geophones. The seismograph measures the travel times of elastic waves generated by the source through the subsurface. Geophones sense the seismic vibrations, convert them to electrical impulses and send them to the seismograph to be recorded.

The refraction method measures the compressional wave (p-wave) velocity to image the subsurface. Refraction wave paths cross boundaries between materials in a way that energy travels from source to receiver in the shortest possible time. Source to receiver travel time and the corresponding geometry of the geophone spread are then used to calculate velocities and depths. The seismic velocities are characteristic of the type and density of the unconsolidated material and or rock represented.

The seismic refraction data is interpreted using software for selecting first arrival times and calculating the seismic velocities for each unit and the depth to lithologies of contrasting density. This process provides high-resolution seismic refraction interpretations by providing depth information under each geophone to various geologic layers. Tomographic processing algorithms can also be used with multiple shot data and provide a higher resolution interpretation of spatial changes in subsurface velocities. Seismic data are typically presented in two-dimensional (2-D) cross section showing changes in velocity at depth.

Certain site-specific conditions, if present, can limit the resolution of the seismic refraction interpretation, which may include cultural noise (automobiles, machinery, etc.) and/or the presence of thin and/or slower velocity zones at depth, which can create erroneous depths in the interpretation of the data.

The method of electrical resistivity incorporates the introduction of an electrical current into the ground through a pair of electrodes (current electrodes) while measuring the resultant voltage field in the ground at an offset pair of electrodes (potential electrodes). The purpose of the resistivity survey is to delineate vertical variations with depth in the subsurface material. This is based on the fact that the subsurface penetration of the electrical current is a function of the electrode separation. The change in electrical properties with depth is determined by taking measurements at increased electrode spacings and modeling the change in apparent resistivity with electrode spacing. This type of survey is referred to as a resistivity sounding. By making a series of soundings along a profile line the lateral changes in layer resistivity can also be determined. The use of multiple electrode systems allow for collection of resistivity data that can be presented in the form of 2-D electrical cross section representative of hydrogeologic conditions.

The arrangement of electrodes in the field is referred to as the electrode array. Various types of arrays are available for use in collecting data. For this survey, dipole-dipole arrays were used. The dipole-dipole array separates the current electrodes from the potential electrodes as dipoles on opposite ends of the array.

Electrical resistivity is a physical property, which is diagnostic of the type of geologic material present. Unsaturated soils have higher resistivity (lower conductivity) than saturated soils. Sand and gravel material that contain low silt and clay content have higher resistivity than soils with high silt and clay content. Sandstone, limestone, and granites typically have higher resistivities than shales and siltstones. By determining the resistivity of the layers identified in a resistivity depth sounding, the nature and thickness of the geological material in each layer can be estimated. The depth to bedrock can usually be estimated through data interpretation. Voids and cavities filled with air will typically have a relatively high resistivity compared to surrounding materials while water filled voids will typically have a relatively lower resistivity than surrounding materials.

The resistivity values measured in the field are called apparent resistivity values because they are a composite measure of the resistivity of all layers that the current flowed through. The field data is typically modeled using inversion algorithms to distinguish the effects of each electrical layer penetrated in order to determine the thickness and true resistivity of each layer.

5.2.2 Field Seismic Investigation

The seismic data was collected utilizing a Seistronix RAS 24 (24-channel) seismograph, 4.5 Hz geophones and a 12-pound hammer as a seismic source. Each line consisted of 24 geophones each spaced ten feet apart for a total length of 230 feet each. Multiple seismic clines were combined to make seismic profiles. Seismic Profile A consisted of 3 seismic lines (660 ft.), Profile B consisted of four seismic lines (880 ft), and Profile C consisted of two seismic lines (450 ft). Each line along the profiles was overlapped by two geophones. Seismic source shots were performed at seven locations along each seismic line to increase data resolution and include: one off-end locations (generally 10 feet from each end geophone); geophones 1 and 24; and between geophone pairs 6 and 7, 12 and 13, and 18 and 19. Data from each shot were recorded at 0.5 millisecond intervals for one second and stored on a laptop computer connected to the RAS-24 seismograph. The autostacking feature of the seismograph was used to stack multiple hammer blows at each location in order to increase the signal to noise ratio of the data. Seismic data from three lines located as shown on Figure 3 was collected for this investigation.

5.2.3 Field Resistivity Investigation

An electrical resistivity survey was performed using an Advance Geophysical Systems Inc. (AGI) Super Sting R8 56-channel resistivity imaging system (the Sting). The survey equipment consisted of a transmitter/receiver, four 14-takeout electrode cables, each with evenly spaced takeout spacings. Data was collected from three resistivity profiles (1, 2, and 3) each consisting of 56 stainless steel electrodes placed in the ground and evenly spaced and attached to a cable connected to the Sting. Resistivity Profiles 1 and 2 were 1,100 feet long with electrodes at 20-foot intervals and Profile 3 was 550 feet long with electrodes 20 10-foot intervals. The Sting transmitter was positioned in the center of the line, between electrodes 28 and 29. Figure 3 shows the approximate location and orientation of resistivity profiles 1, 2, and 3. The resistivity profiles are parallel and adjacent to seismic Profiles A, B, and C.

The electrode spread geometry was controlled by the internal transmitter switching system of the Sting. For the dipole-dipole method, the switching system selects various electrodes to form dipole pairs of current electrodes and potential electrodes with different dipole spacing, dipole offsets, and array centers. Multiple measurements were made along each profile line to measure the lateral and vertical changes in subsurface resistivity. The array geometry for the surveys was limited by the length of the resistivity cables, electrode spacing, and equipment parameters. The array geometry and the geology limit depth of penetration.

The location of the seismic and resistivity survey lines were surveyed with a hand held GPS unit (Garmin GPSMAP 76) after completion of the geophysical investigation.

5.2.4 Data Interpretation

The interpreted cross-sections are included in the figures in Appendix B. The seismic data were analyzed using Geometrics' SeisImager and Rimrock Geophysics SIP software. P-wave data was determined by using SIP to pick the first arrival times which where input into SeisImager's tomographic modeling algorithms to interpret 2-D cross sections of P-wave velocities. Typically tomographic data provides interpretation of changes in horizontal and vertical spatial velocity.

The interpreted seismic cross sections from SeisImager's tomographic modeling indicate that the seismic velocities range from 1,000 feet per second (ft/s) to approximately 8,500 ft/s. The slower velocities (< 4,000 ft/sec) are interpreted to be representative of near surface unconsolidated material, fill, and/or waste, while higher velocities are interpreted to represent weathered rock to more competent rock (>7,000 ft/sec) at depth. The material present at depth between 4,000 and 7,000 ft/sec represent more unconsolidated material grading to weathered bedrock. The velocities measured at the OLF fall within the typical velocity ranges for weathered material and the shale and sandstone bedrock present beneath the OLF. Interpretation of the seismic refraction data indicates that competent bedrock is approximately 40 feet below ground surface (bgs) and that weathered bedrock may be present at a typical depth of about 30 feet bgs. The approximate location of competent bedrock is shown on the seismic profiles (see Appendix B).

Landfill waste and fill is interpreted in the seismic profile cross sections as velocities less then 3,000 feet per second. A dashed line on Figures B-4 through B-6 identifies this area on each cross section. However, natural material present at the OLF may also have similar velocities. This zone varies in thickness of 10 to 30 feet and is present from near surface to approximately 30 feet bgs in the thicker areas. Figure 3 shows the lateral extent of the lower velocity seismic zones within 30 feet of ground surface. This area is interpreted as the location where waste is most likely to be present at the OLF based on relative seismic velocity. The area shown is slightly smaller than that identified in the Earth Tech (2005) study.

The resistivity data were analyzed using the modeling package Res2Dinv to model the apparent resistivity data collected in the field. This program models the field data to image the lateral and vertical changes in subsurface resistivity. Modeling errors were higher then typical due to the presence of highly conductive buried waste and high contact resistance from surface materials. The interpreted data are presented in 2-D cross sections showing varying resistivities of the subsurface material at depth along each cross section. The interpreted resistivity profiles are shown in Figures B-1, B-2, and B-3. The title for each profile indicates the approximate compass orientation from left to right.

The interpreted resistivity cross-sections indicate that the average resistivities measured at the OLF range from less then 1 ohm-meter to over 200 ohm-meters. The maximum depth of penetration for the resistivity data along resistivity Profiles 1 and 2 was approximately 80 feet bgs and approximately 30 feet bgs for Profile 3. The higher resistivities near the surface of each cross-section appear to be representative of the unconsolidated gravely cover material on the surface of the OFL area.

Several areas of anonymously low resistivities (typically less then 5 ohm-meters) are identified on each of resistivity profiles as locations at depth that are potentially representative of buried waste and/or fill. The majority of these zones are within the upper 30 feet of each profile and are not continuous. Figure 3 shows the horizontal extent of these zones at the OLF. This area is interpreted as the location where waste is most likely to be present at the OLF based on relative resistivities.

5.2.5 Summary

The seismic refraction and resistivity investigation was successful in providing data to assist in interpreting the presence of landfill waste and the depth to the competent bedrock subsurface underneath the OLF.

Seismic refraction and electrical resistivity, like any remote sensing technique, require the interpretation of indirect methods of measurement. As such, there is an inherent margin of error, which is unavoidable. Our methods of data acquisition and interpretation are as complete as is reasonably possible, and we believe them to be a reasonable representation of the subsurface conditions. However, due to the subjective nature of any type of interpretation, we cannot guarantee that our results are accurate in all areas. The findings identified by this survey should be compared closely to selective in-situ methods such as the geotechnical borings and/or test pits completed at the OLF before designs are based on these findings.

5.3 Test Pits

Nine test pits were excavated between February 12 and February 20, 2008 at the approximate locations shown on Figure 2. The purpose of the test pits was to investigate subsurface conditions as indicated on Table 5.1.

The test pits provided important visual indications of the subsurface characteristics. The pits were excavated prior to drilling exploratory borings because they provided "big picture" information to guide the drilling and sampling locations. Observation of samples obtained during drilling are often limited or distorted because of the size of the borehole and sampling device. Trenches do not have that limitation. In this case, the test pits showed that the alluvial/colluvial material had a higher concentration of larger gravel within the clay matrix than was apparent by viewing the borehole samples. The test pits also provided a larger scale look at the fill material and the cover material.

Stoller personnel provided health and safety oversight and guidance during the drilling and sampling operations. Observation of the materials and trench sidewalls was made from the ground surface an approved distance from the pit as approved by Stoller health and safety personnel.

The test pits encountered sandy clay fill with varying concentrations of gravel, clayey sand, sandy clay, clay-sand-gravel mixtures (man placed fill, landslide materials, and/or landfill materials), weathered sandstone, and weathered claystone. Water was encountered in TtP-7 (see Figure 2). Logs of the test pits are presented in Appendix C.

Table 5.1 Test Pit and Boring Objectives

Boring/ Excavation	Depth (ft.)	Completion Stratum	Purpose/Objective	Location rationale	Other
Tt-1	29.5	unweathered Laramie/Arapahoe Formation bedrock	penetrate through the slide mass, failure planes, and weathered bedrock zone to obtain samples. Samples serve 2 purposes: (1) provide visual evidence of the distressed and intact zones; and (2) provide high quality, comparatively undisturbed samples of each stratum for triaxial, direct shear, and consolidation testing.	Above disturbed area	inclinometer installation above current distress to monitor future performance
Tt-2/TtP-1/TtP-2	35.5/12/12	soil below slide plane(s) and/or unweathered bedrock	determine depth/nature of failure; identify & correlate failure plane	in "evacuation zone" of disturbed area	inclinometer installation in scarp area to monitor current/future performance
Tt-3	39	unweathered bedrock	characterize conditions between evacuation zone and deposition zone of apparent circular slide mass	below/between disturbed areas	inclinometer installation in central failure area to monitor current/future performance
Tt-4/ TtP-4	30.5/12	soil below slide plane(s) and/or unweathered Laramie Fm bedrock	explore cause and location of distress; compare locations at different ends of the seep area and in "deposition zone"	in "saturated" area; will show water current water level stratigraphically in deposition zone; may clarify involvement of waste in failure	inclinometer installation within current distress to monitor current and future performance
Tt-5/Tt-6/TtP-5	35.5/30.5/12	soil below slide plane(s) and/or unweathered Laramie Fm bedrock	evaluate presence of multiple slide masses at different levels as reported by Earthtech (2004); investigate water level and relationship to existing drain	within pre-landfill drainage; should show water and slide plane relationship	inclinometer installation in current failure areas to monitor future performance
Tt-7/TtP-6	28.5/14	soil below slide plane(s) and/or unweathered Laramie Fm bedrock	evaluate consolidation vs slope failure for this area	in disturbed area; TtP-6 is in an area where a previous outfall pipe was located according to historical plans	inclinometer installation at approximate upper end of failure zone to monitor present future performance
TtP-9	2	native soil below gravel layer	evaluate/characterize overburden, gravel lense, and underlying stratum	investigate causes of seep 8	
TtP-3	12	soil below slide plane	determine extent of failure depth and relationship with prior sub-excavation	in area of localized slope failures	
TtP-7, TtP-8	11/13	soil below slide plane	observe source of seep water and soil conditions in associated strata	at upper and lower limits of visible seepage and in area of former interceptor ditch	investigate potential source of water collection due to differences caused by the prior interceptor

Several test pits were moved slightly from their originally proposed locations to improve access for equipment or to better align with local features. The locations of the test pits are shown on Figure 2 in the final locations excavated rather than in the originally proposed locations. One of the test pits, TtP-9, was moved north approximately 100 feet to avoid wet conditions near Seep 8 and access issues associated with the slope on the south boundary of the buttress. In the revised location, TtP-9 encountered the buttress drain layer at a depth of approximately 18 inches below the ground surface. The test pit was extended a short distance to observe the drain configuration in more detail. A comparison of the drain rock and geotextile fabric observed in the test pit with the construction plans showed that the drain appeared to have been constructed according to the approved design. No water was observed in the drain at the location excavated.

5.4 Exploratory Borings

Eight geotechnical borings were originally proposed at the OLF. Following excavation of the test pits, boring number Tt-8 at the east end of the buttress above seep 8 was eliminated from the program. The location of Tt-1 was moved about 20 feet south from the original location to better align with the field location of the prior distress cracks. The seven borings were drilled at the locations shown on Figure 2 between March 27, 2008 and April 8, 2008. The objectives of the borings were to obtain comparatively high quality and undisturbed samples for laboratory testing, to determine depth to water at critical areas, to look for failure planes and weak zones within the subsoils and bedrock, and to provide locations for the installation of instrumentation to monitor future movement. Table 5.1 presents specific objectives of the borings and test pits.

A track mounted, sonic drill rig was used to drill the seven holes. Access to the drilling locations was provided by removing, then repairing the diversion berms where needed. In general, continuous samples were obtained from the ground surface to the total depth drilled. Clear polycarbonate tubes were inserted in the core barrel to increase the quality of the recovered samples. In some situations, recovery was not possible due to mechanical malfunction of the drill rig, deformation or damage to the sampling tubes that occurred during drilling, and/or large rocks that occasionally became lodged in the core barrel. In addition to the continuous core samples, a split barreled sampler was pushed into the substrata between "runs" of the core barrel to obtain brass liner samples for laboratory testing. After drilling, inclinometer casing and vibrating wire piezometers were installed and grouted in the boreholes.

Drilling and sampling operations and inclinometer casing installation were observed, samples collected and lithology logged by Tetra Tech's Senior Geologist. The geotechnical engineer was also present on the OLF periodically during the operations to observe conditions and monitor the progress. Stoller personnel provided health and safety oversight and monitoring during the drilling and sampling operations.

Holes were drilled to between 28.5 feet and 39 feet deep. Each hole was terminated in comparatively unweathered bedrock. Inclinometer casing was installed in each of the borings to monitor current and future movement of the slide masses as well as to provide a method to document and measure future performance of the slopes. Vibrating wire piezometers were affixed to the outside of each inclinometer casing 2 feet above the lower end of the casing and the instrumentation/casing was grouted in place using tremie techniques.

6.0 LABORATORY TESTING

Geotechnical laboratory testing was performed by Tetra Tech in our Fort Collins, Colorado and Billings, Montana laboratories, and by Advanced Terra Testing (ATT), 833 Parfet Street, Lakewood, CO 80215 (303-232-8308). ATT is licensed by the Colorado Department of Public Health and Environment to handle, store, and test hazardous and radioactive materials (License No. Colo. 896-01, Amendment No. 4). Selected samples were tested to determine the organic content of the soils by Northern Analytical Laboratories, Inc.

During excavation of the test pits, representative bulk samples of the soils encountered were collected by Tetra Tech. During drilling, the continuous core samples and split barrel samples were collected, examined and logged by Tetra Tech. All materials removed from the test pits and borings were field scanned by Stoller to meet Health and Safety requirements and to identify the need for special sample handling or procedures.

Test pit samples were transported to Tetra Tech's laboratories where they were examined by the geotechnical engineer and geologist. Samples were selected for mechanical grain size analysis, Atterberg limits, Proctor compaction, and organic content testing. Test results were used to compare and correlate the test pit samples with continuous core samples and with data from prior studies at the OLF by others. Results of the laboratory testing are provided in Appendix D. Descriptions of the soils are provided in Section 7 of this report.

After health and safety screening and geologic/geotechnical logging, continuous core samples and split barrel samples were transported by Stoller to ATT where they were stored in a secured radiological area until additional scanning was completed by ATT. ATT personnel split the polycarbonate core tubes to facilitate sample observation. The Tetra Tech geologist and geotechnical engineer logged the continuous core, compared the core samples with logs prepared during drilling, and selected additional samples for laboratory testing. A photo log of the core samples is presented in Appendix A.

The goals of the core examination and laboratory testing were to assist in determining the subsurface characteristics of the OLF, identify strength and engineering properties of the soils, and compare/contrast the samples with the bulk samples obtained from the test pits. Small diameter geotechnical samples can provide a distorted perception of the gross soil characteristics of a site because of the size limitations. Testing of "distorted" samples can lead to over- or under- estimating the strength of the subsoils. In the case of soil samples from the OLF, it was noted that bulk and core samples showed a higher percentage of coarse gravel and cobbles, and a higher degree of variability in overall consistency, density, and soil composition than would have been determined from conventional geotechnical sampling alone.

Rather than repeating an extensive program of sampling and testing, Tetra Tech reviewed data from previous geotechnical testing at the OLF (by others), selected samples obtained in our field investigation that were determined to be consistent with the soils observed, and tested them to determine if soils encountered in this investigation were consistent with those identified in the previous work and used in prior slope stability modeling. Shear strength parameters (unit weight, water content, cohesion, and friction angle) used in slope stability modeling are described in Section 9 of this report.

7.0 SUBSURFACE CONDITIONS

The test pits and borings encountered clayey to sandy gravel, silty and clayey sand, sandy clay, low to high plasticity clays, carbonaceous clay/claystone and clay with variable concentrations of organic materials, weathered sandstone and claystone, and comparatively unweathered claystone to the maximum depths explored. Water was encountered in one test pit (TtP-7) at 8 to 9 feet, and in four of the 8 borings at depths of 5 to 19 feet at the time of drilling. Graphical and descriptive logs of the borings are presented in Appendix C.

On the basis of field observations, physical examination of the core and bulk samples, and laboratory analysis, the subsoils were classified into 7 groups that are listed and described below:

- Engineered cover soil;
- Landslide material;
- Man-placed fill and/or waste material;
- Weathered bedrock;
- Bedrock;
- Clay/weathered claystone with organic material; and
- Buttress fill.

Engineered Cover. Borings and test pits suggest that the engineered cover material generally ranges between 2 and 3 feet thick. Design documents specify a soil cover thickness of 2 feet, which was placed on top of a 1-foot graded fill soil layer. In the areas near borings and test pits, Tetra Tech used the cover thicknesses measured for our analyses. In other areas encompassed by the slope stability cross sections we assumed a thickness of two feet. Our investigation indicates the cover soil ranges from clayey gravel with sand to gravelly sand with clay. Silt and clay content (percent passing the number 200 sieve) ranged from 23.8 to 58.7 percent. Liquid limits ranged from 37 to 46, and the plasticity index ranged from 25 to 33. This material is believed to have been derived locally from naturally occurring deposits of Rocky Flats Alluvium (see Section 4).

Landslide Material. Below the cover was a layer of soil ranging in thickness from 0 to 30 feet that was classified as landslide material. This material was generally an unconsolidated and variable mixture of clay, sand, and gravel. In place density was measured at 105 to 123 pounds per cubic foot (pcf) and water content ranged from 2 to 20 percent. Mechanical particle size analyses indicated a range of silt and clay sized particles from 23 to 68 percent. In several of the borings, clay and/or sand lenses were encountered within the gravel deposit. In Tt-7 the gravelly material was not encountered. This material was likely derived from alluvial/colluvial materials present on the hill and slopes prior to historic landsliding. Three samples were tested for organic materials and had concentrations less than 2 percent. For slope stability calculations, Tetra Tech used an average unit weight of 120 (pcf), a cohesion of 50 pounds per square foot (psf), and an angle of internal friction (phi) of 20 degrees. Earth Tech used the same unit weight and phi angle but used a cohesion of 0 psf.

Man-Placed Fill And/Or Waste Material. Under and in some case co-mingled with the landslide material is the landslide waste of the OLF, the man-placed fill used to grade the landfill, and/or fill placed for other purposes during the site history. Two samples of fill from TtP-8 were classified as high plasticity clays (CH), had 81 and 83 percent silt and clay sized material, liquid limits of 53 and 59, and a Plasticity Index of 31 and 33. Two samples tested for organic content had 2.3 and 3.0 percent organic material. Other samples of the waste and/or fill material appeared similar to the landslide deposits. Observation of the core indicated that laboratory testing and previous studies likely overestimated the density and strength of the materials due to the necessity of testing small, uniform samples. Tetra Tech used slope stability calculations to back-calculate and check geotechnical parameters. We determined that average properties for unit weight of 110 pcf, cohesion of 20 psf, and phi angle of 20 degrees more appropriately characterized the waste deposit.

Weathered Bedrock. Below the waste and/or landslide materials, a variable layer of highly weathered bedrock was encountered in the test pits and borings. Tt-1 encountered a highly weathered sand/sandstone layer at 19 feet that included an organic-rich interval. The remaining borings encountered variably weathered claystone below the waste and/or landslide material. The weathered claystone was very moist to wet, had a soft, "greasy" texture, and generally included a lens or layer of organic material. A sample tested for organic content had a 5.9 percent concentration.

This layer was not modeled in previous studies; however it appears to be a weak zone that we opine is contributing greatly to the instability of the slope. Visual observations of test pits and core samples indicate this layer is where sliding has occurred. Our slope stability calculations modeled this material using a unit weight of 90 pcf, a cohesion of 0 psf, and a phi angle of 10 degrees.

Claystone Bedrock. A layer of comparatively less weathered claystone was encountered below the highly weathered zone in all but one of the borings (Tt-1). Laboratory samples used in triaxial testing had dry unit weights of 108 to 109 pcf and water content of 15.6 to 17.5 percent. A sample used in mechanical grain size analysis had 98 percent silt and clay sized particles (passing the number 200 sieve), a liquid limit of 58, and a plasticy index of 44. Properties used in the slope stability modeling included a unit weight of 130 pcf, a cohesion of 300 psf, and a phi angle of 28 degrees.

Groundwater. Vibrating wire piezometers were installed in the borings approximately 2 feet above the bottom of each boring. Water was encountered at various levels within the landslide deposit, waste and/or fill, and above the weathered bedrock. These levels were generally as anticipated. However, only two sets of readings have been collected to date, so data should be considered preliminary. Data are shown in Section 8 and Appendix F of this report.

8.0 INCLINOMETER/PIEZOMETER INSTALLATION AND MEASUREMENTS

Following the drilling of each of the exploratory borings, a 3.34 inch diameter ABS inclinometer casing manufactured by DGSI was capped and prepared for installation. A vented, vibrating wire piezometer was taped to the outside of the casing two feet above the bottom of the casing. The inclinometer/piezometer apparatus was installed in the borehole for the purpose of measuring water levels and monitoring movement of the ground above the base of the inclinometer. A piezometer completion diagram is provided in Appendix F.

The 3.34 inch diameter inclinometer casing is the largest diameter offered, and provides a longer useful life, because it can accommodate more deformation before access is closed to the probe. It is suitable for all uses and especially recommended for landslides and long-term monitoring. It is also appropriate for monitoring multiple shear zones or very narrow shear zones.

To date, a single set of inclinometer measurements has been recorded at the OLF. Thus, no conclusions can be drawn regarding movement of the OLF based on the inclinometer data. After a number of readings have been made, data can be evaluated. Readings to date are presented in Appendix F.

The vibrating wire piezometer consists of a vibrating wire pressure transducer and signal cable. Readings are obtained with a portable readout or a data logger. Measurements were made by Stoller on April 13 and May 12, 2008. The measurements to date are summarized in Table 8.1 (below).

Table 8.1 Water Level Measurements

Well Number (Boring No.)	4/13/2008		5/12/2008	
	Elevation	Depth (ft)	Elevation	Depth [(1)] (ft)
82108 (Tt-1)	6014.3	25.2	6014.2	25.2
82208 (Tt-2)	6000.2	27.6	6000.1	27.7
82308 (Tt-3)	5987.0	29.4	5986.8	29.6
82408 (Tt-4)	5979.8	16.8	5979.8	16.8
82508 (Tt-5)	5977.1	19.5	5977.7	18.9
82608 (Tt-6)	5969.4	17.1	5969.4	17.1
82708 (Tt-7)	5979.6	16.1	5975.8	19.9

(1) Depth measured from the ground surface.

Data from shallow "consolidation monitors" was also provided for our review. We understand these monitors consist of rebar stakes inserted approximately 3 feet into the ground. Survey measurements of the top of these stakes have been made at monthly intervals. We reviewed the survey data and plotted the apparent movement between April 2008 and September 2007. Data generated by these measurements does not appear to be conclusive, however the random nature of the movement suggests that no significant failure related movement is occurring. The data and a figure showing the nature of the movement is presented in Appendix F.

9.0 SLOPE STABILITY ANALYSES

Slope stability analyses were performed for seven sections, A through G, across portions of the original landfill within Rocky Flats. The cross-sections are shown on Figure 4, Locations of Slope Stability Cross Sections. The existing slope gradients range from approximately 6 to 1 (horizontal to vertical) to 2 to 1. The materials at the OLF include a cover material derived from the Rocky Flats Alluvium, a waste and construction debris deposit, remnant slide material, an organic layer, weathered claystone bedrock, and comparatively unweathered claystone/shale bedrock of the Laramie Formation.

Slope stability analyses were performed previously for the OLF by Earth Tech, Inc. in 2005 and were presented in a design report prepared for Kaiser-Hill Company. Tetra Tech reviewed engineering properties of soils used in the Earth Tech study, and utilized data collected from Tetra Tech's site investigation. Rather than repeating an extensive program of sampling and testing, Tetra Tech reviewed the Earth Tech data, selected representative samples obtained in our field investigation, and tested them to determine if soils encountered in this investigation were consistent with those identified in the previous work by Earth Tech. In general, laboratory test results indicated that soil properties were consistent, but strengths were lower in the Tetra Tech results. One difference that proved to be significant is the presence of a layer of weathered claystone that includes varying concentrations of organic material.

The stability of the hillside at the original landfill was initially modeled at the locations shown on Figure 4 using the material properties identified by Earth Tech. Soil properties were back-calculated from the slope stability analyses based on the known locations of slope failures to confirm strength parameters. An elevated, perched water table was used in this scenario to model existing conditions and conditions that were shown to exist at the time failures occurred. A third series of analyses were conducted using the lower soil strength parameters and with a lowered water table. The methodology and results for each of these conditions are described in more detail below.

9.1 Methods of Analyses

Slope stability analyses were performed using limit equilibrium methods with the computer program SLOPE/W (GEO-STUDIO, 2007). SLOPE/W solves limit equilibrium slope problems using several different methods. Spencer's method was chosen in this study because it considers both force and moment equilibrium. Interactive searches were performed to determine the most critical failure surface for each section analyzed.

Seismic analyses were not performed on the selected cross sections because the slope stability modeling was conducted as a forensic study rather than as a design study. If or when design measures are implemented, additional slope stability analyses should be performed using the mitigative design concepts, and pseudostatic seismic analysis should be included.

In conventional geotechnical design, a factor of safety of 1.5 is typically used for a steady state condition. However, for this analysis, safety factors greater than 1.0 indicate a stable slope. A safety factor of 1.0 indicates an unstable slope. It is recognized that, since the slope will fail when the safety factor decreases to 1.0, a safety factor less than 1.0 is not possible on a real slope. However, because of the mechanics of the computer model, safety factors less than 1.0 are calculated by the program and are reported as such in Appendix E.

9.2 Material Properties

Material properties used in these analyses were obtained from the previous investigation by Earth Tech, Inc. (2005) and from the data obtained from the current Tetra Tech investigation. The Earth Tech, Inc. properties are summarized in Table 9.1. The Tetra Tech properties are summarized in Table 9.2.

Table 9.1 Material Shear Strength Parameters Used in Stability Analyses – Earth Tech

Material Type	Total Unit Weight, γ (pcf)	Internal Friction Angle, φ (deg)	Cohesion, c (psf)
Cover	120	30	50
Slide	120	20	0
Waste	120	30	50
Weathered Bedrock	120	20	0
Bedrock	125	30	600
Buttress Material	130	33	50
Stream Alluvium	125	33	0

Table 9.2 Material Shear Strength Parameters Used in Stability Analyses – Tetra Tech

Material Type	Total Unit Weight, γ (pcf)	Internal Friction Angle, φ (deg)	Cohesion, c (psf)
Cover	125	24	100
Slide	120	20	50
Waste	110	20	20
Weathered Bedrock	125	21	50
Organic Layer	90	10	0
Bedrock	130	28	300
Buttress Material	130(1)	33(1)	50(1)
Stream Alluvium	125(1)	33(1)	0(1)

Note: Value from Earth Tech, Inc. (2005)

9.3 Analyses

Cross-sections A through G were chosen to model the stability of the slope in areas where distress and/or slope failures are known to have occurred. Several failure zones were analyzed for the cross sections based on field observations. The slope stability results for each cross section are presented in Table 9.3. Factors of Safety calculated for each cross section using the Earth Tech material properties ranged from 1.39 to 1.84. Factors of safety greater than 1.0 indicate a stable slope condition that will not fail under the modeled conditions. Failures have occurred on the Original Landfill, and failure zones were visible until repairs were made on the OLF. Therefore it is apparent that either the actual material properties or the physical conditions of the failed areas must be different than those presented in Earth Tech (2004). The physical condition that has the greatest variability is the water level in various layers below the ground surface under the original landfill.

Furthermore, the Tetra Tech borings and test pits encountered a zone of clay and highly weathered claystone that includes varying concentrations of organic materials. When added to the slope stability model at the upper surface of the weathered bedrock, as identified in the field investigation, the organic layer resulted in a weak plane that became the failure surface in the slope stability analyses. The organic layers contributed to the lowered safety factors calculated by Tetra Tech for cross-sections A through G. Cross section C was extended to include the buttress constructed as part of the previous stabilization at the OLF. In the computer model, failure was forced in a circular fashion consistent with the failures at the OLF, but the failure envelope was expanded to simulate a large, catastrophic failure that would include the engineered buttress fill. The intent of this analysis was to determine the risk of failure of the OLF on a large scale, resulting in sliding of the OLF materials into the Woman Creek Drainage. The calculated factor of safety for this analysis was 1.75, indicating a low risk of large scale failure.

The slope stability analyses show that the slopes are marginally stable using the strength parameters identified in the Tetra Tech investigation. An increase in the water table into the colluvium/slide material above the weathered claystone with organic material resulted in sufficient strength loss to create slope instability in the cross sections. This simulates a condition in which excess surface water infiltrates the sediments from above. When the water level was lowered in the cross section, the safety factors (and the stability) increased. However, a reduction in the water level alone was not sufficient to increase the safety factors to an acceptable design value of 1.5. Therefore providing a mitigation alternative that lowers the water level in the original landfill sediments will not be sufficient to protect the slopes from future failures. These concepts are discussed in greater detail in the Conclusions section of this report.

Table 9.3 Calculated Factors of Safety

Cross-Section	Material Properties	Location of Failure	Location of Water Table	Corresponding Figure	Factor of Safety
A	Earth Tech	Upper Section	Slide Material	E-1	1.63
		Middle Section		E-2	1.67
		Lower Section		E-3	1.77
	Tetra Tech	Upper Section	Slide Material	E-4	0.93
		Lower Section		E-5	0.86
		Upper Section	Weathered Bedrock	E-6	1.52
		Lower Section		E-7	1.37
B	Earth Tech	Upper Section	Slide Material	E-8	1.84
		Lower Section	Slide and Waste Material	E-9	1.72
	Tetra Tech	Upper Section	Slide and Waste Material	E-10	0.84
		Lower Section		E-11	1.01
		Upper Section	Weathered Bedrock	E-12	1.77
C	Earth Tech	Full Section	Slide Material	E-13	1.75
	Tetra Tech	Upper Section	Slide Material	E-14	0.80
		Upper Section	Weathered Bedrock	E-15	1.27
D	Earth Tech	Upper Section	Slide Material	E-16	1.45
	Tetra Tech	Upper Section	Slide and Waste Material	E-17	0.94
			Weathered Bedrock	E-18	0.97
E	Earth Tech	Upper Section	Weathered Bedrock and Slide Material	E-19	1.83
	Tetra Tech	Upper Section	Slide Material	E-20	0.99
			Weathered Bedrock and Slide Material	E-21	1.33
F	Earth Tech	Middle of Section	Weathered Bedrock	E-22	1.48
	Tetra Tech	Middle of Section	Slide Material	E-23	0.97
			Weathered Bedrock	E-24	1.30
G	Earth Tech	Middle of Section	Slide Material	E-25	1.39
	Tetra Tech	Middle of Section	Slide Material	E-26	0.88
			Weathered Bedrock	E-27	1.28

10.0 CONCLUSIONS

The geotechnical investigation of the Original Landfill at Rocky Flats provided a number of conclusive results. These are described in the following paragraphs. Section 11 of this report provides a range of mitigative alternatives that can be considered to mitigate the instability at the OLF.

The slope failures that have occurred to date are small scale, localized "slump" features that appear to be originating in a weak clay layer. The weak layer is a moderate to high plasticity, very moist clay that includes variable organic matter at and near the interface between the weathered clay/claystone below and the unconsolidated, variable historic landslide deposits, waste material, and cover above. The soil layers above the weak clay do not appear to be particularly weak themselves, however their unconsolidated, porous, and variable nature does not contribute to a stable slope configuration either. Slope stability modeling indicates that increasing the unit weight (i.e. compaction) and decreasing the water content of these layers will increase the factor of safety against slope failure.

In their present condition, the variable and comparatively loose waste and slide materials allow rapid percolation of surface water through them to the weak, underlying clay layer, which becomes further de-stabilized as water lubricates the weak zone and the overburden weight increases. As small failures occur, an equilibrium condition is likely achieved at that localized position on the slope. However, instability continues to increase in adjacent areas until a series of small failures occur. Therefore, we conclude that the failures are caused by an excess of surface water and a low-strength soil condition at or near the bedrock surface. Similar, small scale failures have likely occurred throughout the geologic history of the OLF.

Other localized slope failures that have occurred on the sideslopes of the east and west channels are similar in nature, but are occurring primarily in the cover and shallow fill/slide materials as a result of overly steep sideslopes of the channels. Measurements of slopes in the area where Diversion Berm 3 terminates at the West Channel indicate slopes are approximately 3 horizontal to 1 vertical (33 percent). In an area near the previous slope failure on the East Channel, the channel sideslope is about 3.6 horizontal to 1 vertical (28 percent).

Slope stability modeling does not indicate a large scale instability exists on the OLF. In our analysis (see Figure 4, Cross Section C), the model was extended to include the buttress constructed as part of the previous stabilization at the OLF. In the computer model, failure was forced in a circular fashion consistent with the failures at the OLF, but the failure envelope was expanded to simulate a large, catastrophic failure that would include the engineered buttress fill. The intent of this analysis was to determine the risk of failure of the OLF on a large scale, resulting in sliding of the OLF materials into the Woman Creek Drainage. The calculated factor of safety for this analysis was 1.75, indicating a low risk of large scale failure.

Consolidation testing of the materials does not indicate that the native soils or bedrock below the OLF are prone to consolidation upon loading after wetting. The total thickness of cover material and unconsolidated fill/slide material that overlies the bedrock was measured at about 10 feet in borehole Tt-7. Therefore we concluded that settlement or consolidation of the fill, cover, or clay/shale bedrock of the magnitude that would be required to produce a visible "sag" in the slope is extremely unlikely. It is more likely that a localized slope failure has occurred that is similar in nature, only thinner, to the slope failures that have occurred on the western part of the landfill. Although surface expression of cracking has not been noted, the curvilinear "depression" that was observed at the ground surface is believed to be the upper extent of a shallow slope failure in that area.

Seeps are the result of surface water that has flowed into the OLF subsoils in an upslope area and migrated through preferential pathways and porous zones until it intersects the ground surface. It appears that as slope failures have occurred, pathways for water have shifted somewhat, resulting in changes in volume and occurrence of seeps over time. The increase in volume of water observed at Seep 8 is likely due to a gradual filling of the subsurface sediments that the buttress drain originally fed, resulting in seepage to the ground surface at the toe of the slope instead of migration downstream through the subsurface.

Irregularities in the drainage/diversion berms are caused in part by minor settlement of the underlying fill, as well as by the localized slope distress.

11.0 RECOMMENDATIONS

A common alternative used to increase the stability of unstable slopes is to decrease the slope by excavating the slope back to a shallower, more stable configuration. In this case, where the instability is caused by a weak layer in the shallow subsurface, it is unlikely that flattening the slope alone would improve the stability sufficiently unless the weak layer was removed during the excavation. Further, such a plan may involve excavating large volumes of soils and waste materials. Therefore such an alternative is not considered feasible for this site. However, there is a range of alternatives available to stabilize the slope at the OLF.

We recommend a phased approach to the mitigation. Several comparatively straightforward techniques can be employed that will mitigate a number of issues at the OLF, but would not address all the issues, and would likely result in the need for on-going maintenance and repairs for small, localized areas of instability. These alternatives are discussed below in Section 11.1. If a complete and more "robust" approach is preferred, the additional repairs described in Section 11.1 and Section 11.2 can be implemented. If all recommended repairs are implemented, the initial cost would be higher, but future maintenance would be reduced.

11.1 Lowering the Water Level

As a first phase of design and construction, improving surface drainage and reducing infiltration of surface water are considered the most feasible alternatives for increasing the slope stability. We understand that revisions to and maintenance of the diversion berms is planned. Any improvements that increase the drainage of surface water and reduce standing water or slow-flowing water on the OLF will increase the stability of the slopes because the infiltration into the subsurface will be decreased. We recommend correcting the current drainage condition so that berms have an average slope of 2 percent in all areas. Rocky Flats Alluvium is a suitable construction material for this purpose. Additional means could be implemented that would reduce infiltration seasonally, such as construction of wind breaks or snow fences to reduce snow accumulation on the OLF. The introduction of plant species that would extract more water from the soil could be investigated.

As a secondary, more robust approach to lowering the water table, a slurry wall or a series of drains could be considered on the OLF to further reduce the water level. A slurry wall constructed up gradient of the OLF would deflect water flowing through the near surface soils and would reduce the volume of water flowing through the subsoils below the OLF. To be effective, the slurry wall would need to be "keyed" several feet into the bedrock so that water infiltration below the wall would be effectively stopped. The wall would need to extend laterally well beyond the limits of the OLF to ensure water would be deflected laterally from the OLF. This technique would not reduce infiltration of surface water from precipitation or runoff on the surface of the OLF, and may increase the volume of water flowing though the subsurface both east and west of the OLF. An advantage of the slurry wall concept is that much of the construction could occur "in-situ" without the need for huge trenches and large areas of disturbance.

A drain system would intercept subsurface water that flows below the OLF and would capture surface water and runoff that infiltrates from the ground surface. However, a drain system would involve excavating a series of trenches through the waste and slide material. Some of the trenches would need to be on the order of 30 feet deep or more in order to penetrate the bedrock. Therefore, we recommend the less invasive approach of repairing the surface drainage while monitoring changes in water levels and movement before or instead of this approach.

We understand that the existing East and West Diversion channels are larger than may be required. These channels can be partially filled in to reduce the sideslopes, thereby increasing the stability of slopes in those areas. Rocky Flats Alluvium is considered an acceptable material for that purpose. The amount of channel cross section to be filled should be based on the approved design criteria for channel depth and slope.

As shown on Figure 2, a subsurface drain was installed down the hill slope from the area where Seep 7 is observed. Details regarding the condition, depth, slope, or other aspects of the drain are not known to us. However, we understand there may be data available documenting the condition and extent of the drain. This should be investigated. It may be feasible to extend this drain system uphill or up gradient to increase the capture area and reduce surface water from this seep that is collected in the berm 3 channel. Prior to this construction, the outfall for the drain should be confirmed, and the condition of the existing drain should be determined so that additional flow is not introduced into a system that is already blocked, plugged or not functioning as designed for other reasons.

If it is desired to control the flow at Seep 8, a shallow toe drain could be designed and constructed that could be used to collect water near the toe of the buttress and divert it to a downstream point where the discharge can be more controlled and measurable. Such a drain may also improve upstream subsurface conditions if water is “backing up” in the drain.

11.2 Increasing Soil Strength

Slope stability modeling indicates the large scale, overall slope is stable. However, localized failures have occurred on the OLF under elevated water level conditions. A reduction in the water level alone is not considered adequate to ensure the long term stability of the slope. If the drainage/surface water repairs are made, localized failures will still be possible during or after large or prolonged precipitation events. Modeling showed that an increase in soil strength is also needed to increase the safety factor to typical long term levels.

As a phase 2 design concept, after implementation of surface drainage improvements, we recommend consideration be given to grouting the OLF soils from the claystone bedrock layer upwards to the base of the cover. Such a grouting program would involve drilling holes to the bedrock and injecting a cementitious grout mixture under low pressure to fill void spaces in the subsoils in a grid over the OLF. A schematic diagram of a typical grouting process is shown in Figure 5. Grout holes are typically drilled on a grid system with holes spaced approximately 10 feet on center. This process would both reduce the permeability of the soils and increase their strength. The cost of such a program is unknown at this time, however a specialty geotechnical contractor such as Hayward Baker could provide a cost estimate. In order to formulate an effective grout mixture it will be necessary to test the OLF soils to determine how they interact with the grout. In order to confirm that the planned grouting is effective at improving the long term local slope stability, strength parameters of the treated soil should be determined in the laboratory. Additional slope stability modeling should then be conducted to verify that safety factors are adequate.

Other methods such as dynamic compaction could be considered. Dynamic compaction is a process that involves dropping a large weight a calculated distance to increase the density of near surface soils. An increase in unit weight of the OLF soils would increase the slope stability, if done in conjunction with the drainage methods described above. Two disadvantages of the process are the irregular surface that would result, requiring extensive regrading, reseeding, and related work; and the requirement for a large crane to negotiate the steep slopes of the OLF. Therefore this method is not recommended.

11.3 Additional Investigation

Regardless of which mitigation alternatives are selected, observations of the OLF should continue to determine if additional failures occur. Periodic regrading, recompaction, and drainage control of the OLF should be anticipated. Monitoring of the recently installed instruments should be continued to confirm the conditions. Monitoring the inclinometers will provide valuable information regarding the depth of failure zones within the landfill area. Concurrent information from the piezometers should provide correlation between slope movement and water levels. Readings of the inclinometers and piezometers should be made on a monthly basis, and whenever significant precipitation events or visible slope movements occur. These conditions should be tracked over at least a year. However, if repair work is undertaken it can be done concurrently with the monitoring. In that case, logs of the inclinometer and piezometer readings should include a description of changes. For example, if diversion berm repairs are completed on October 31, 2008, instrument readings taken immediately after that work is completed should include a notation that specifies "modification of diversion berms completed on 10/31/08", or something similar.

Data provided by the consolidation monitors on the west side of the OLF appear inconclusive. Since movement of the slope can be monitored by the inclinometers that were installed as part of this project, readings of the earlier consolidation monuments can be discontinued and the monitors removed when/if it is practical to do so.

12.0 LIMITATIONS

This investigation was conducted to ascertain a reasonable picture of subsurface conditions. Variations in the subsoils not indicated in our borings should be considered likely. This report was prepared from data provided by others, information developed during our field exploration, laboratory testing, engineering analysis and experience with similar conditions. Our calculations and recommendations were based on assumptions of ground conditions, interpretation of geologic conditions, and uncertainties that are unavoidable in geologic and geotechnical studies.

If any of the conditions change, or if information becomes available that would alter our assumptions or our calculations, the opinions presented in this report should be considered invalid until we have been contacted to review the recommendations. We should review plans and specifications during the design, and we should observe the construction to confirm soils are as we anticipated from our borings. Placement and compaction of compaction fill, backfill, subgrade and other fills should be observed and tested by a representative of our firm during construction.

We believe this investigation was conducted in a manner consistent with that level of skill and care ordinarily used by members of the profession currently practicing under similar conditions in the locality of this project. No warranty, express or implied, is made. If we can be of further service in discussing the contents of this report or in the analysis planned project from the geotechnical point of view, please call.

13.0 REFERENCES

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