Slope Failure Report:

March 12, 2013 Chrin Brothers, Inc. Landfill Slope Failure

Submitted to the Pennsylvania Department of Environmental Protection Northeast Region Office

July 15, 2014

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SCI
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1.0 INTRODUCTION

This slope failure report has been prepared for the Pennsylvania Department of Environmental Protection (PADEP) in response to a directive to the Chrin Brothers Sanitary Landfill to prepare an assessment of the "root cause" of the landfill slope failure that occurred in Stages 3D and 3E of the Landfill on 12 March 2013. This report outlines my investigation, analyses, and conclusions regarding the "root cause" of the 12 March 2013 slope failure.

I have conducted over twenty landfill slope failure investigations. I have also investigated over 50 other failures of engineered slopes. My one page *curriculum vitae* is attached in Appendix "A".

2.0 STAGE 3D AND 3E SLIDE AND BACKGROUND INFORMATION

After 20:00 hours on 12 March 2013, approximately 12.2 acres of the landfill slope in Stages 3D and 3E of the Chrin Landfill moved downslope to the northwest. On average, the slide with an average waste depth of 38 feet, moved 73 feet downslope. The slide mass is estimated to involve approximately 770,000 yd^3 of waste. The slide area is pictured in Figure 1 and Appendix B; Figure B-1

Construction of Stages 3D and 3E started in 2002 and 2004 and was completed and certified in 2003 and 2005, respectively. Stages 3D and 3E accepted waste from 2003 to 2008 and the final geosynthetic composite cover system was installed over Stages 3D and 3E during 2006 to 2008. After the final cover installation was complete cracks and minor surface subsidence, which are encountered in most landfills, was noted but no failure in the final cover system was observed.

3.0 INVESTIGATION METHODOLOGY

This section outlines the methodology used to investigate the 12 March 2013 slope failure. The principal component of the investigation is the development of a slope stability model for Stages 3D and 3E that represents the slope conditions prior to failure on 12 March 2013. To develop the slope stability model, the following information was collected: ground surface topography; liner system elevations; location and geometry of the waste overlay area in Stages 3A, 3B, 3C, 3E, and 4; engineering properties of the waste, cover system and liner system; 2011 earthquake ground motions; landfill gas properties; and leachate levels. Several cross-sections of the landfill slope were then developed and calculations performed to estimate the factor of safety for these cross sections and various failure surfaces. A critical slip surface for each cross-section was identified in the area of principal slope movement to compare factors of safety.

Based on numerous field observations of the slope failure area, the 12 March 2013 slope movement occurred within the geosynthetic liner system, which is discussed below. Accordingly, samples of the liner system components and soils were obtained to measure their physical properties via laboratory testing. The results of the testing and analyses were used in the development of the slope stability model.

3.1 Liner Sampling and Analytical Methods

During waste excavation, the liner system geosynthetics and soils were inspected and found to be significantly damaged within the slide area and adjacent anchor trenches due to slope movement as shown in Figure B-2 in Appendix B. Laboratory testing of the damaged geosynthetics would not yield meaningful results in the pre-failure slope stability model so undamaged geosynthetics were sought. To obtain geosynthetics representative of pre-slide conditions, samples of the liner system components were obtained from areas just upslope and outside of the slide mass and in the anchor trench along the toe of the slide mass. In the areas excavated to date, undamaged geosynthetics have been obtained just upslope of the slide mass and from the anchor trench along the northwest perimeter of Stage 3D. These locations are identified in Figure B-3. The process of obtaining undamaged samples is pictured in Figure B-4.

These undamaged samples of liner system geosynthetics and various soil samples, e.g., subgrade and drainage soils, have been tested by state-of-the-art accredited testing laboratories for the following engineering properties: geosynthetic interface shear strength, asperity height, shear strength, unit weight, and index properties. The waste excavated was subjected to waste composition, moisture content, and unit weight testing.

3.2 Slope Stability Model Development

Following review of the design and construction documents, site inspections, and laboratory testing, a slope stability model was developed to represent the slope conditions in Stages 3D and 3E prior to the 12 March 2013 failure. Data from the physical testing of the liner system components and waste mass were used to develop the slope stability model and confirm the inverse analysis of the slope failure.

Static and dynamic limit equilibrium and continuum analyses have been and continue to be performed using the slope stability model to investigate the "root cause" of the slope movement and the factors that significantly contributed to the 12 March 2013 slope movement. Specifically the following parameters have been used in the analysis: geosynthetic interface shear strength, subgrade soil and protective cover stone shear strength and unit weight, waste strength and unit weight for both the overlaying and underlying wastes, leachate level, gas pressure, and slope geometry.

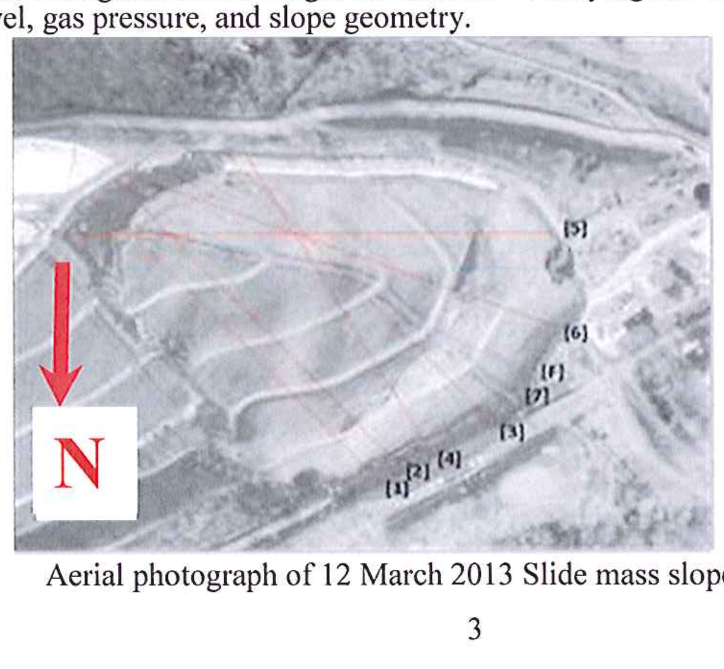

Figure 1: Aerial photograph of 12 March 2013 Slide mass slope failure; cross-sections

4.0 FINDINGS

This section presents our findings to date. Appendix B presents supporting information for the results and conclusions presented in this section. Appendix B contains Figures B-1 through B-15 some of which are specifically referenced below.

4.1 Slope Geometry and 12 March 2013 Slope Failure:

The aerial photograph in Figure 1 shows Stages 3D and 3E after the 12 March 2013 slope movement and the location of various cross-sections (labeled 1-7 and F) used to investigate the slope failure. (An enlarged version of Figure 1 is reproduced in Appendix B as Figure B-1). Figure B-5 illustrates the direction of the slide mass as referenced by the comparison of the pre- and post-slide movement of sideslope leachate primary collection risers and gas well wellheads, which guided the location and orientation of the cross-sections. The slope cross-section shown in Figure 2, which is cross-section F in Figure 1, is considered representative of the critical cross-section because it is in the direction of movement and yields the lowest representative static factor of safety. The green area in the cross-section in Figure 2 is the slide mass, which is being excavated and relocated to the active area of the Landfill; the dashed red line is the 2013 failure surface that primarily parallels the composite liner system; the brown area is the waste on the liner system that is still remaining on the slope; the olive area is the old waste; and the grey area is the bedrock and soil foundation underlying the above materials.

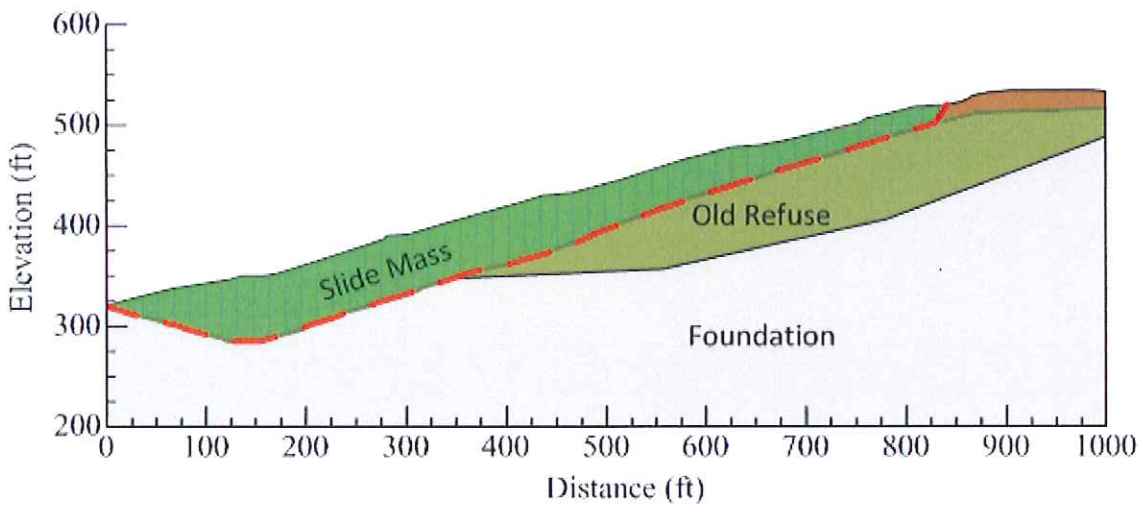

Figure 2: Representative cross-section of slope prior to failure

The slope geometry limited the slide from extending further east, i.e., into the remainder of Stage 3E, because of a significant change in the liner system subgrade topography at the eastern edge of the slide mass. Liner system contour elevations in Figures B-7(a) and B-7(b) show a significant change in liner system subgrade topography in Stage 3E and at the eastern edge of the slide mass where the subgrade topography flattens. Figure B-8 presents the topography of the subgrade ground surface and landfill liner system used to develop cross-sections 1-7. As shown on Figure B-9, part of the slide mass overlies previously disposed waste in Stages 3A, 3B, 3C, 3E, and 4.

4.2 Failure Mechanism

Based on the investigation to date, the 2013 slope movement occurred between the top of the secondary geomembrane and bottom of the geosynthetic drainage composite within the geosynthetic liner system. Figure 3 (also enlarged as Figure B-10) shows a cross-section of the liner system installed in Stages 3D and 3E and highlights the secondary geomembrane and bottom of the overlying leachate detection geosynthetic drainage composite interface (see red box) which combined to create the critical interface. Figure B-10 also shows photographs of the exposed liner system after waste excavation. The critical interface in a liner system is usually stress dependent (Stark and Poeppel, 1994). As additional waste is excavated, the critical interface will continue to be evaluated along the length of the slide mass. Photographs of the secondary geomembrane and critical interface appear in Figure B-6.

4.3 Laboratory Interface Shear Test Results

The table in Figure B-11 summarizes the direct shear interface test results completed on undamaged geosynthetics obtained from the slide area. These test results indicate a stress dependent interface shear strength for the secondary geomembrane/drainage composite interface. The test results indicate a peak friction angle at an effective normal stress of 2000 psf of 21 to 24 degrees, respectively. The test results also indicate a large displacement friction angle at an effective normal stress of 2000 psf of 10 to 13 degrees. The large displacement test results were used to estimate the residual interface strengths for the secondary geomembrane/drainage composite interface for use the stability analyses too.

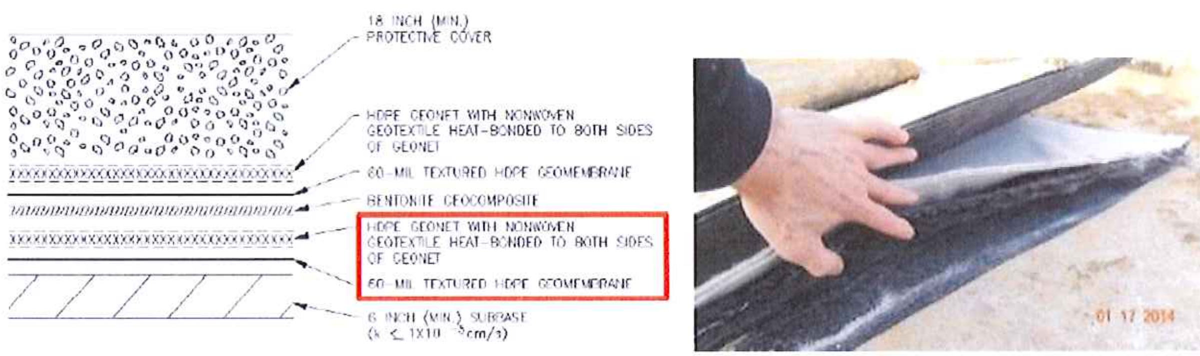

Figure 3: Cross-section of liner system in slope failure area and photograph of liner system components after waste excavation

4.4 Possible Causes of Slope Failure

A number of possible causes of the 12 March 2013 slope movement were considered in this investigation including:

- Landfill operation and management
- Excavation along the slope toe
- Inadequate design, CQA/CQC material testing, or construction
- Inadequate geosynthetic liner system materials
- Waste water content and shear strength
- Leachate generation
- Leachate recirculation
- Gas pressures
- Elevated temperatures
- Subgrade materials and geology
- Precipitation
- Seismic events
- Placement of new waste over old refuse

4.4 Root Cause of Slope Failure

The root cause of the 12 March 2013 slope movement is attributed to inadequate design, specification, and construction material conformance as discussed below:

- Design and stability analyses of Sections 3D and 3E not accurately modeling all possible failure modes for installed liner system components and not measuring and modeling appropriate liner system interface shear strengths
- Inadequate static and seismic slope design
- Inadequate specification of geosynthetic materials, such as specification of geomembrane asperity height and/or interface shear strength
- Inadequate manufacture of geosynthetic materials, such as manufacturing geomembrane with insufficient asperity height and/or interface shear strength
- Inadequate construction conformance testing because of a lack of shear strength testing to determine whether or not the supplied geosynthetics would yield the required design shear strength parameters

This opinion is based on my review of design and construction documents, site history, geologic setting, operational history, landfill performance, e.g., gas and leachate data, field observations, post-slide liner system investigation and testing, and static and dynamic analyses.

4.5 Trigger of Slope Failure

The trigger of the slope failure is defined as the event that initiates a sequence of events that eventually resulted in the 2013 failure. This differs from the root cause which is the factor(s) that allowed the trigger to initiate the sequence of events that resulted in non-uniform shear displacement and the progressive slope failure.

In my opinion the 12 March 2013 slope movement was triggered by the Central Virginia

Earthquake which occurred on 23 August 2011 (magnitude=5.8; acceleration~0.13g, depth 3.7 miles; distance 240 miles). Central Virginia Earthquake data is presented in Figure B-12. This shaking induced an estimated peak horizontal acceleration at the top of Stage 3E of approximately 0.03g which was sufficient to initiate shear displacement and a progressive failure mechanism in Stages 3D and 3E. Assessment of the earthquake accelerations at the Chrin Landfill are presented in Figures B-12 and B-13. This earthquake triggered some small downslope movement that progressed with time until the slope failed on 12 March 2013 due to shear movement along the critical liner system interface to date, i.e., top of secondary textured geomembrane.

Cracking in the final cover system, attributed to normal landfill subsidence, was observed at the landfill in Section 3D beginning at the end of September 2011. Consistent with normal maintenance practices, these cracks were filled and graded to promote surface runoff and reduce detrimental infiltration. Retrospectively, these cracks were the result of the progressive failure mechanism that was migrating through the slope causing additional shear movement until the entire slope yielded on 12 March 2013.

In my opinion with proper design and manufacturing, the liner system would have withstood the static and seismic forces induced by the 23 August 2011 earthquake.

4.6 Evaluation of other Possible Causes

Each of the following possible causes of the 12 March 2013 slope movement were evaluated and dismissed for the following reasons:

- Landfill operation and management – Stages 3D and 3E were closed areas so no operations were occurring in this area;

- Excavation along the slope toe –prior to the failure there is no evidence of a slope toe excavation because the final cover was installed and intact for over 5 years;

- Waste water content and/or shear strength of waste – no large area of high moisture content or low shear strength waste has been found during waste excavation to date. Figure B-14 provides a photograph of the typical waste excavated to date and Figure B-15 provides a table of waste moisture contents measured to date;

- Leachate generation – no significant leachate was generated prior to the slide because of the final cover system being installed and the cover system was found to be intact with no evidence of infiltration or excessive moisture underlying the cover or intermediate soil cover to date;

- Leachate recirculation – no leachate recirculation was performed in Stages 3D and 3E prior to or after final cover system installation;

- Gas pressures – no evidence of elevated gas pressures being present prior to the slope failure;

- Elevated temperatures – no evidence of elevated temperatures being present before the slope failure or during waste excavation;

- Subgrade materials and geology – not involved in slide because slope movement has only been observed above the secondary geomembrane to date; subgrade materials exposed for purposes of the investigation have all been intact;

- Precipitation – analysis of precipitation data and slope movement shows the slope movement observed between 23 August 2011 and 12 March 2013 is independent of precipitation events; and

- Placement of new waste over old refuse - This waste placement was not an apparent cause of the slope failure because the slide surface is located within the liner system which is located above the previously disposed waste.

Limitations:

My professional services have been performed, my findings obtained, my conclusions derived, and my opinions prepared in accordance with generally accepted geotechnical and geoenvironmental engineering principles and practices at the time of this report. The above evaluation, assessments, conclusions, and opinions constitute a reasonable degree of engineering certainty. SCI makes no warranties, either expressed or implied, as to the professional data, opinions, or recommendation contained herein. The professional opinions presented in this geotechnical report are not final and will be revised as additional data and information becomes available during excavation and relocation of the remaining waste from Stages 3D and 3E and examination of the liner system components.

Cited References:

Stark, T.D. and Choi, H. (2004). "Peak v. Residual Interface Strengths for Landfill Liner and Cover Design," *Geosynthetics International Journal*, Vol. 11, No. 6, December, pp. 491-498.

Stark, T.D. and Poeppel, A.R. (1994). "Landfill Liner Interface Strengths from Torsional Ring Shear Tests," *Journal of Geotechnical Engineering*, ASCE, Vol. 120, No. 3, March, pp. 597-615.

APPENDIX A:
TIMOTHY D. STARK, Ph.D., P.E., D.GE, F.ASCE

Vice President, Stark Consultants, Inc. &
Professor of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

EDUCATION

Ph.D., Virginia Polytechnic Institute, Geotechnical Engrg., 1987 (advisor J.M. Duncan)
M.Engrg., U. of California at Berkeley, Geotechnical Engrg., 1984 (advisor J. M. Duncan)
B.S., University of Delaware, Civil Engineering, 1981

EXPERIENCE

Participated in a variety of geotechnical and earthquake engineering projects with Woodward-Clyde Consultants in San Francisco from 1981 to 1983. Has conducted academic research on waste containment facilities, geosynthetics, static and seismic stability of natural and manmade slopes, earthquake induced soil liquefaction, and performance of compacted structural fills and slopes.

EMPLOYMENT RECORD

Professor of Civil Engineering: University of Illinois at Urbana-Champaign, 8/99 - date.
Associate Professor of Civil Engineering: University of Illinois at Urbana-Champaign, 8/94 – 8/99.
Assistant Professor of Civil Engineering: University of Illinois at Urbana-Champaign, 1/91 - 8/94.
Assistant Professor of Civil Engineering: San Diego State University, 1/87-1/91.
Staff Engineer: Woodward-Clyde Consultants, San Francisco, CA, 6/81-9/83.

AWARDS AND RECOGNITIONS

R.S. Ladd D18 Standards Development Award, Standard Designation D6467, ASTM, 2014
Thomas A. Middlebrooks Award for "best" paper in Geotechnical Engineering, ASCE, 2013 and 1998
Selected Editor, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 2012
Associate Editor Award, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 2012
Journal of Legal Affairs and Dispute Resolution in Engineering Scholarly, Paper, ASCE, 2011
R.S. Ladd D18 Standards Development Award, Standard Designation D7608, ASTM, 2011
Elected Diplomate, Geotechnical Engineering, Academy of Geo-Professionals, ASCE, 2010
Classic Paper in Geosynthetics, Geo-Americas Conference, 2008
Elected Fellow, American Society of Civil Engineers (ASCE), 2006
R.M. Quigley Award, "best" paper in Canadian Geotechnical Journal, Canadian Geotech. Soc., 2003
Standards Development Award, Standard Designation D6467, ASTM, 2002
Walter L. Huber Civil Engineering Research Prize, American Soc, of Civil Engineers (ASCE), 1999
University Scholar, University Scholars Program, University of Illinois, 1998-2001
Outstanding Section Campus Representative Award, American Society for Engrg. Education, 1998.
News Correspondent Award, American Society of Civil Engineers (ASCE), 1995
William J. Hall Scholar, Dept. of Civil Engrg., Univ. of Illinois (First Recipient), 1994-1996.
DOW Outstanding New Faculty Award, American Society for Engineering Education, 1994
Xerox Award for Faculty Research, College of Engineering, University of Illinois, 1993
Arthur Casagrande Professional Development Award, ASCE, 1992
Edmund Friedman Young Engineer Award for Professional Achievement, ASCE, 1991
www.tstark.net

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Appendix B

Supporting Information

Submitted to the Pennsylvania Department of Environmental Protection Northeast Region

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- Figure B-1:
Location of Cross-Sections in Slope Failure Area

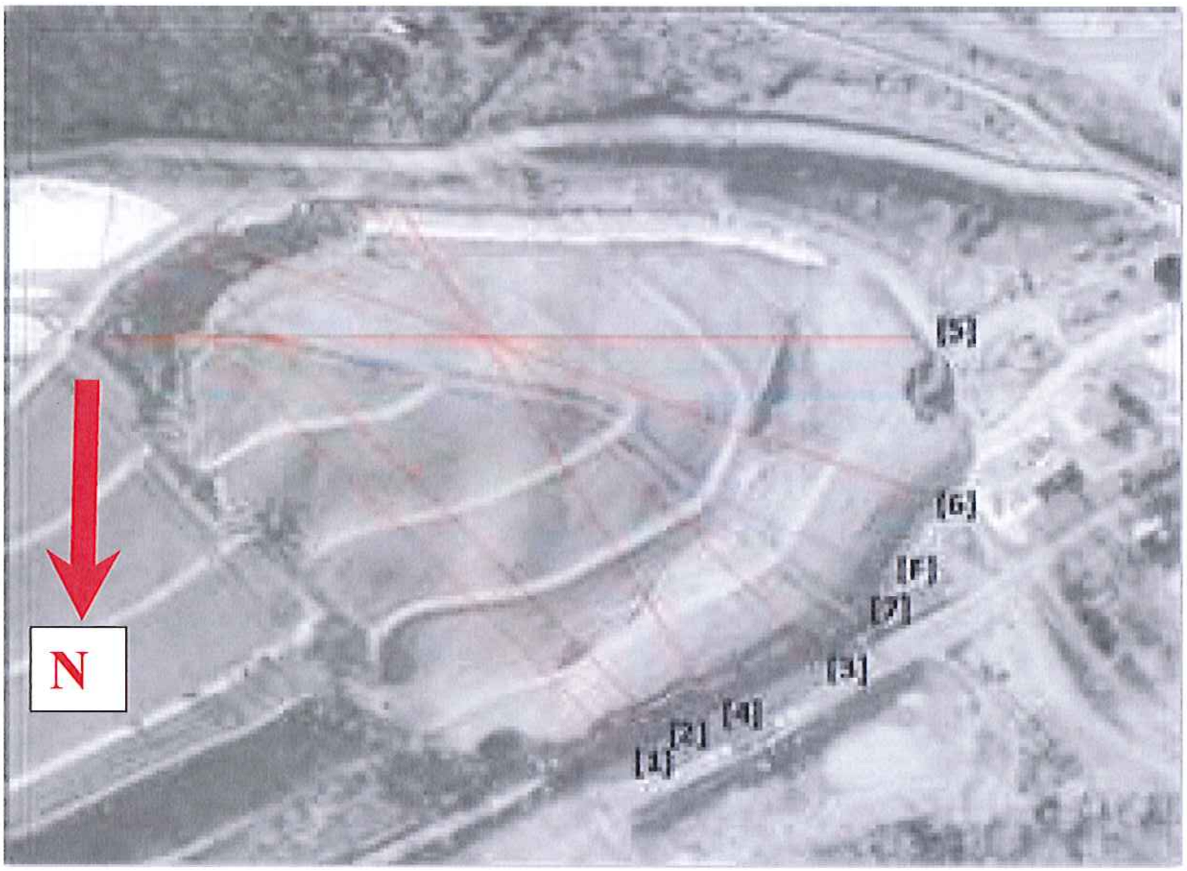
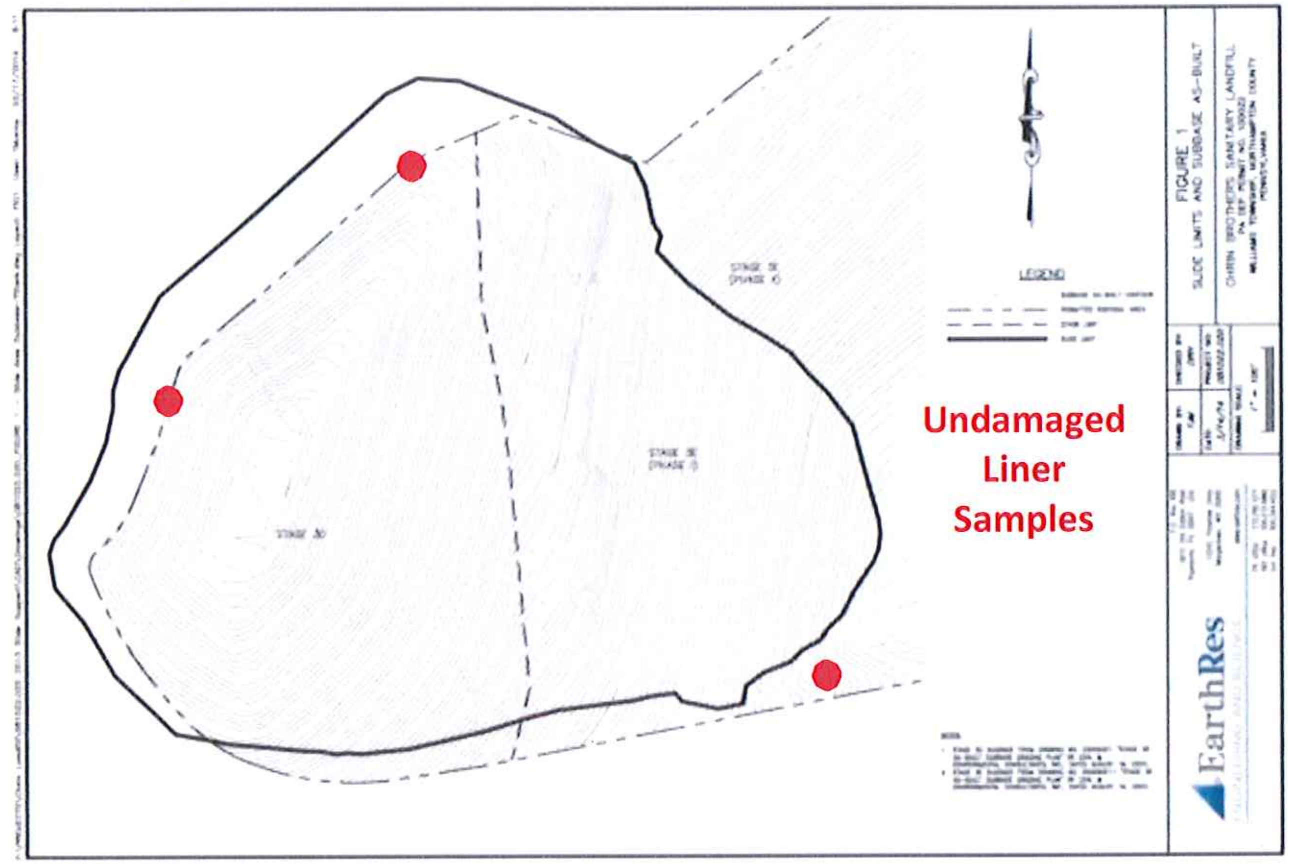


Figure B-2:
Post-Slide Geosynthetics

Figure B-2:
Post-Slide Geosynthetics

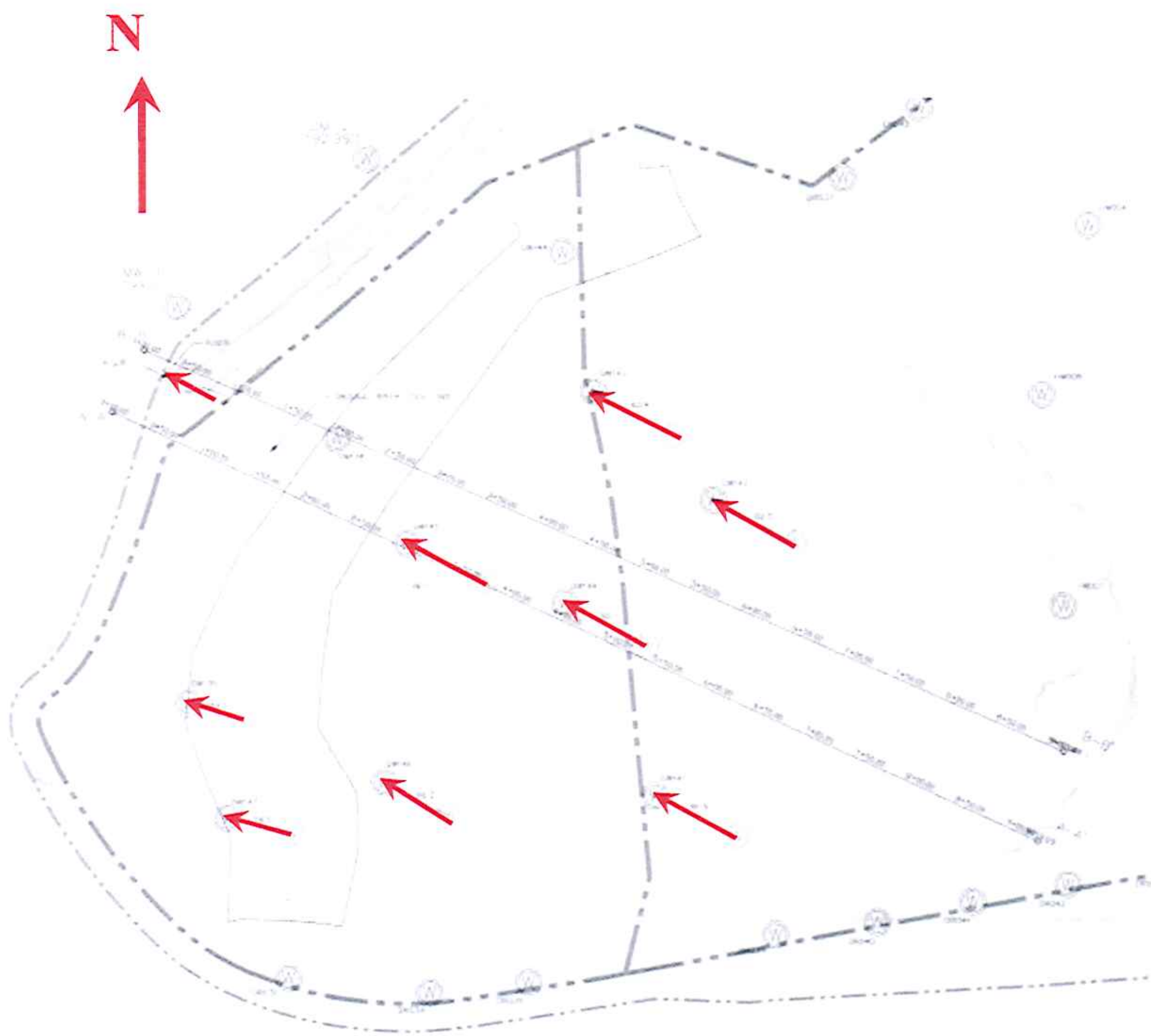
- Figure B-3
Undamaged Liner System Sample Locations



- **Figure B-4**
  Obtaining South Liner System Samples

- Figure B-5

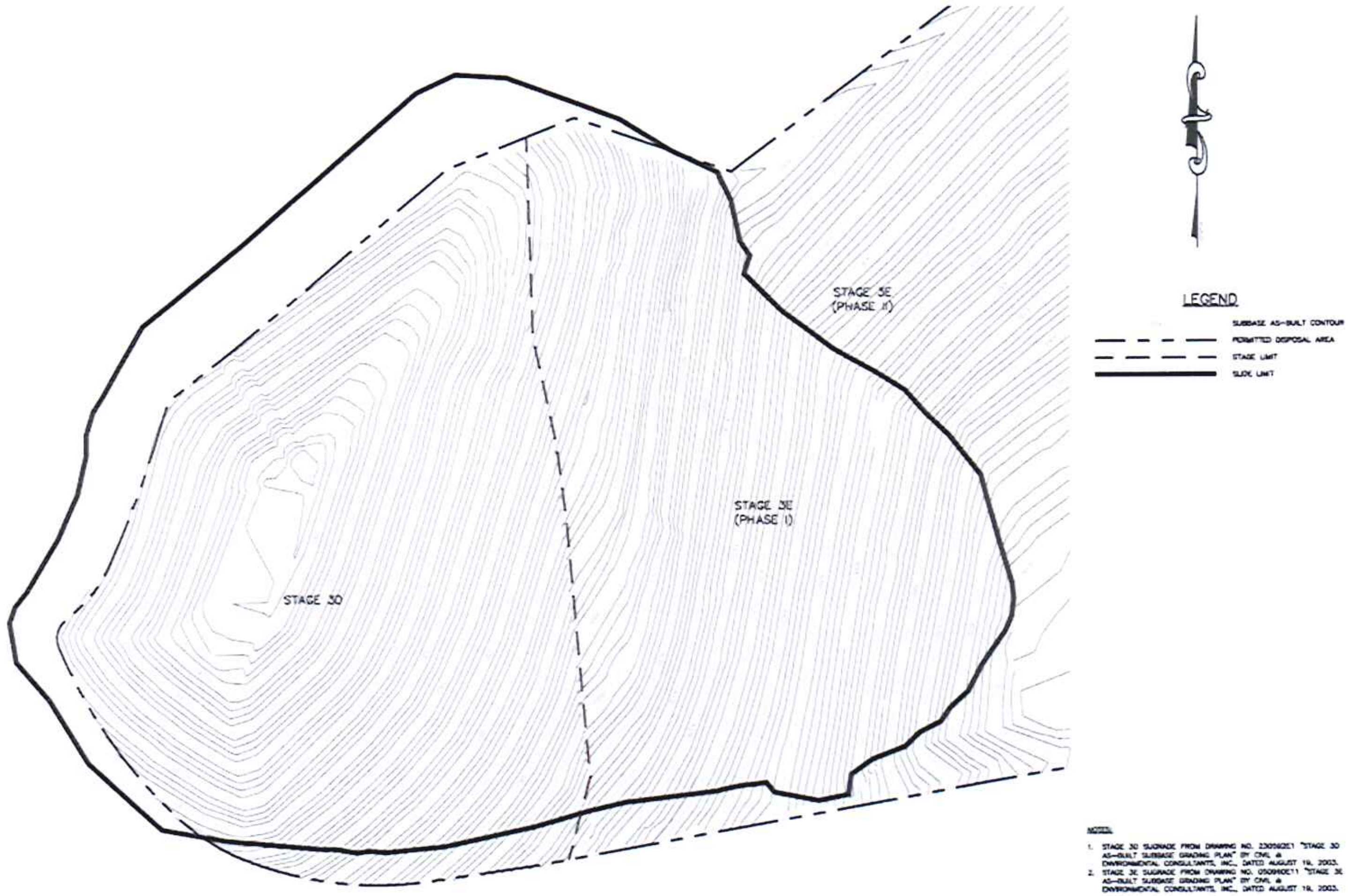
Slide Direction from Riser and Gas Well Movements



- **Figure B-6**
Critical Geosynthetics Interface

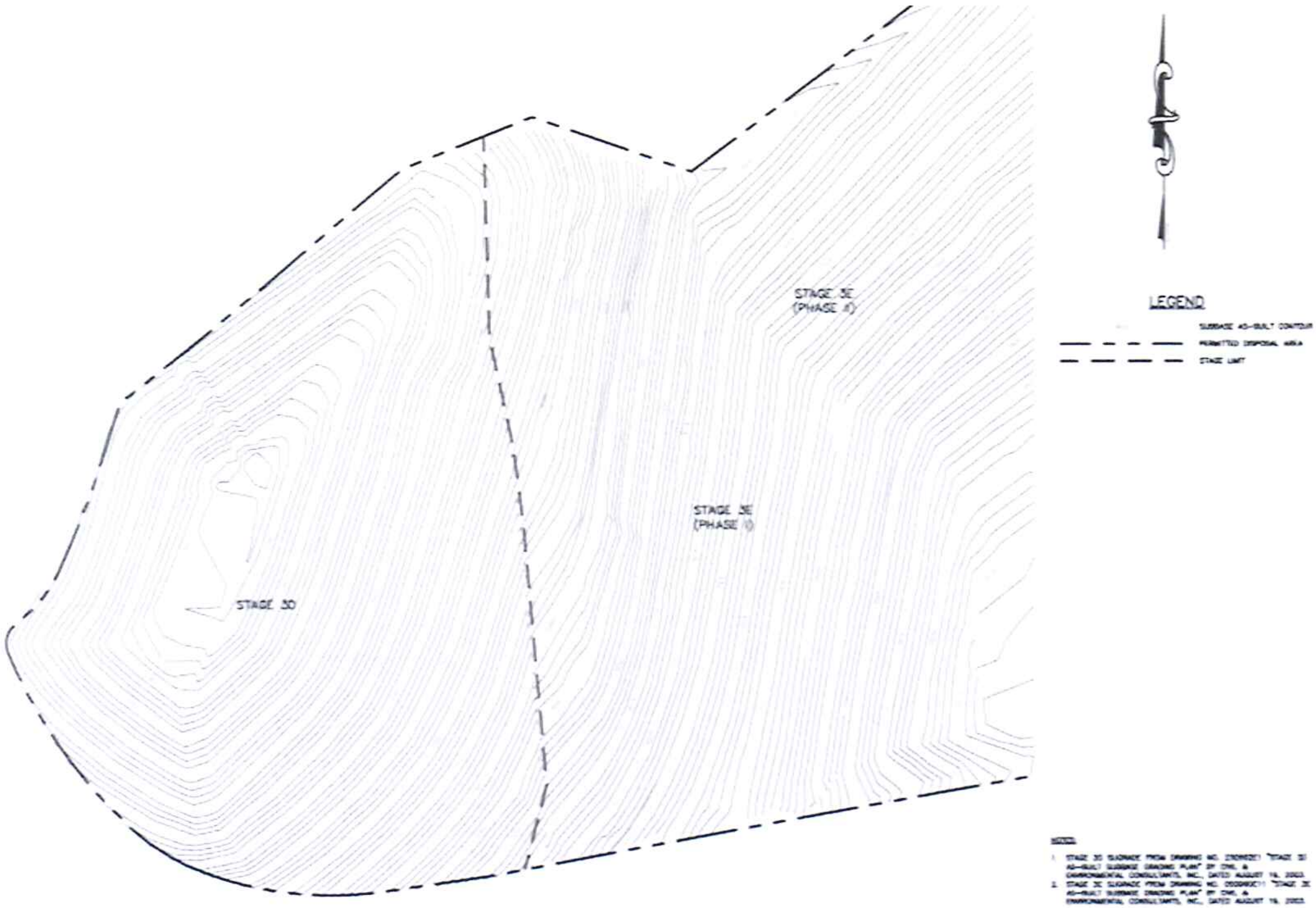
- Figure B-7(a)

As-Built Subgrade Contours with outline of slide mass superimposed



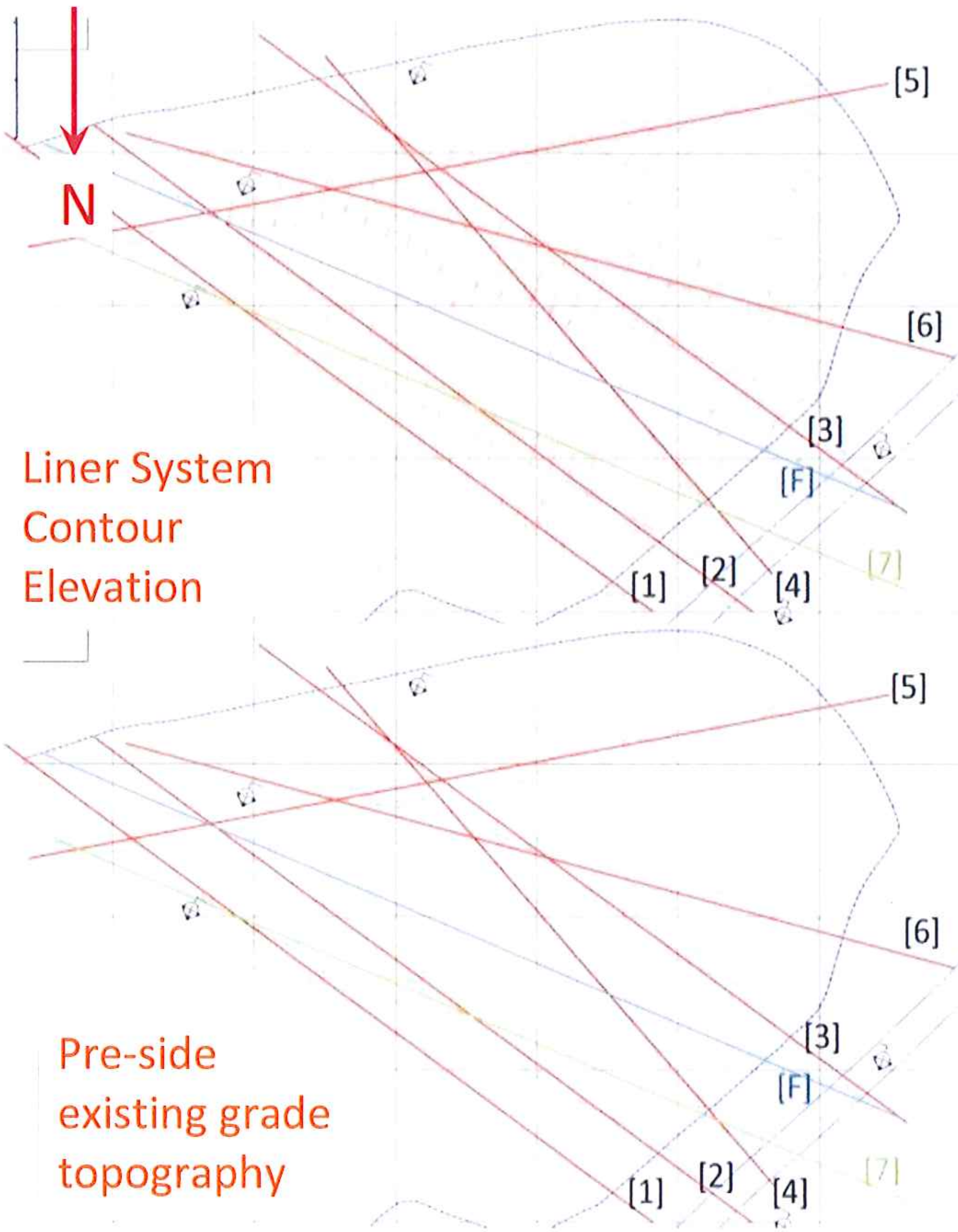
- Figure B-7(b)

As-Built Subgrade Contours without outline of slide mass superimposed

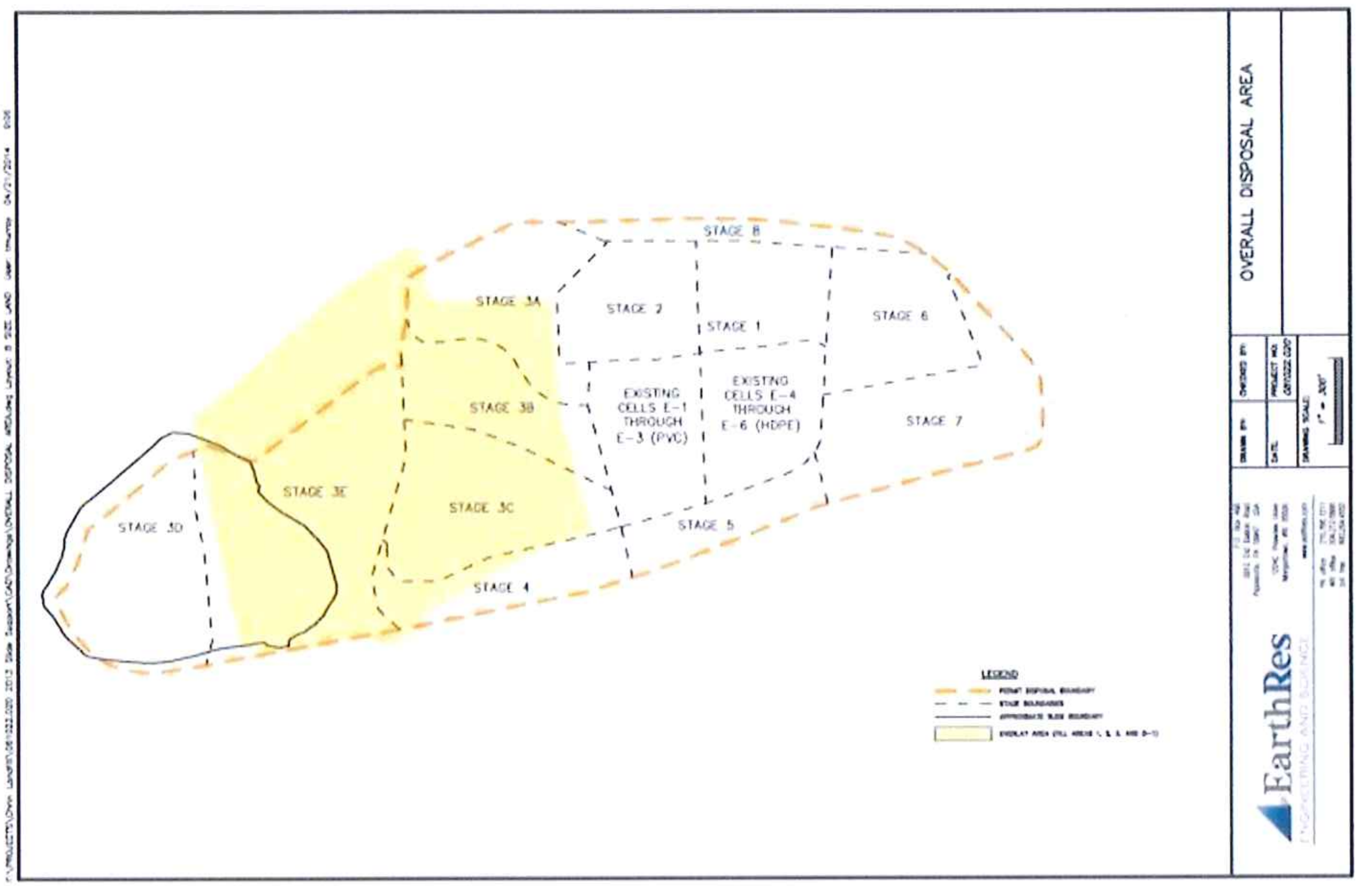


- Figure B-8

Liner System Topography and Pre-Slide Ground Surface



- Figure B-9:
Geometry of Stages 3D & 3E and Location of Old Waste Overlay



LEGEND

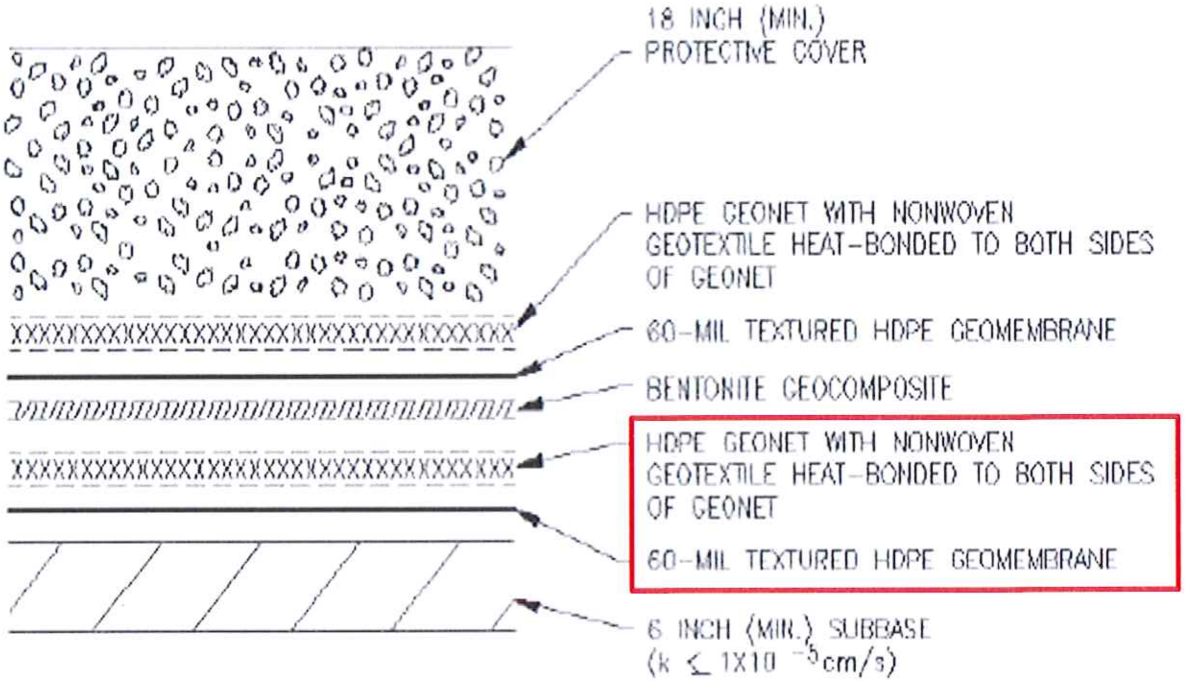
PERMIT DISPOSAL BOUNDARY

STAGE BOUNDARIES

APPROXIMATE SLIDE BOUNDARY

OVERLAY AREA (FILL AREAS 1, 2, 3, AND D-1)

- Figure B-10
Liner System Components



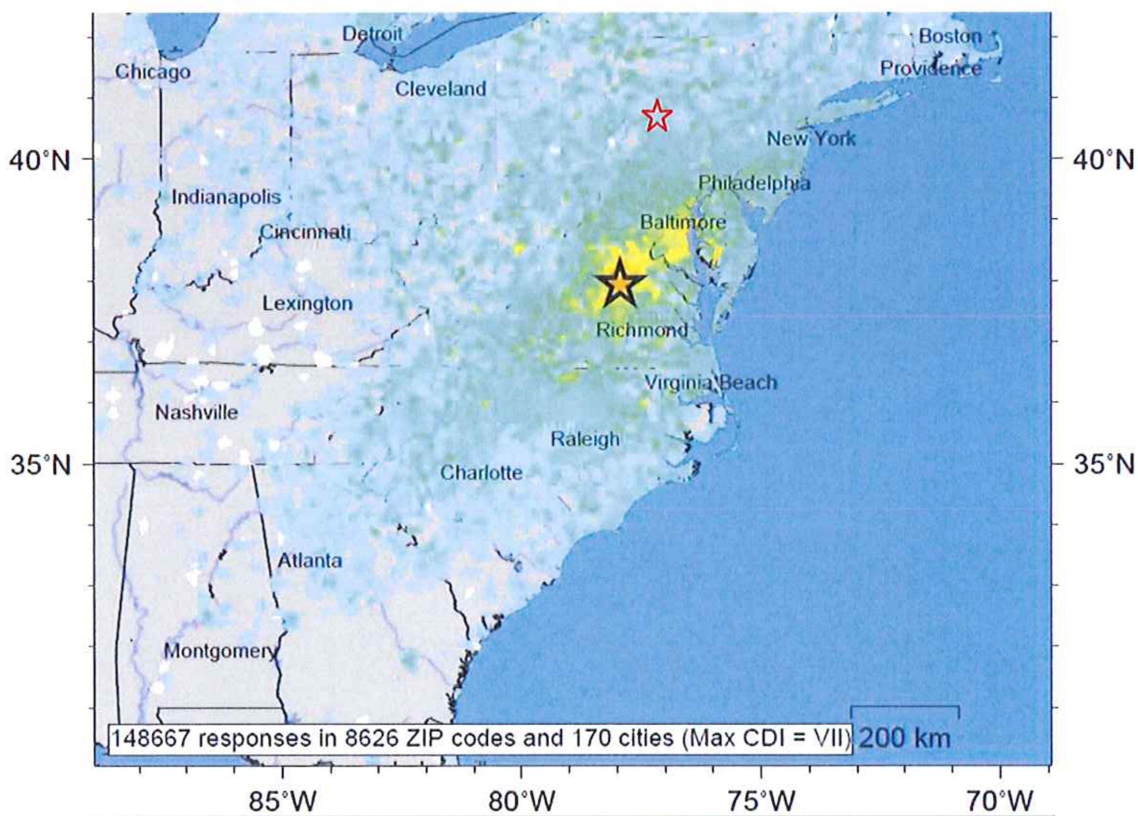
- Figure B-10
Liner System Components

- Figure B-11
Liner System Interface Test Results

Sample Number	Date Tested	Effective Stress Peak Friction Angle at 2,000 psf (degrees)	Effective Stress Large Displacement Friction Angle at 2,000 psf (degrees)
IF-04-02	9/3/2013	22	10
IF-04-05	9/3/2013	21	12
IF-07-02	3/5/2014	22	13
IF-07-05	3/5/2014	23.5	13

- Figure B-12
Earthquake Information

- August 23, 2011, 17:51:04 UTC, 1:51 pm EDT
- Magnitude 5.8 at a depth of 3.7 miles
- Corbin, Virginia Bedrock Acceleration: 0.135g



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

- Figure B-13
Estimated Peak Ground Accelerations

- Corbin, Virginia Bedrock Acceleration (34 miles from source):
  0.135g
- Chrin Landfill Ground Surface Acceleration (225 miles from source):
  0.03g
- Toro (1997) Attenuation Relationship: 0.002g
- Wald et al. (1999) Attenuation Relationship: 0.036g

- Figure B-14
Characteristics of Waste in Slide Mass

- Figure B-15
Moisture Content of Waste in Slide Mass

Sample ID	SAMPLE NO.	DEPTH (FT)	WATER CONTENT (%)
W-1	Bucket 1		26.7
W-1	Bucket 2		31.0
W-2			46.8
W-3			31.6
W-4			55.3
W-5			17.7
FC-1			0.3
IC-1			1.1
Subbase-1			16.9

Sample ID	SAMPLE NO.	DEPTH (FT)	WATER CONTENT (%)
W-6			40.5
W-7			40.8
W-8			36.4
W-9			36.6
W-10			20.0
W-11			12.5
W-12			33.3